Okubo-Zweig-Iizuka Rule Violation and Possible Explanations

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Abstract

Violations of the Okubo-Zweig-Iizuka (OZI) rule in $s\bar{s} \leftrightarrow n\bar{n}$ mixing and $\phi$ production from $N\bar{N}$ annihilation are reviewed. Possible explanations are examined. We conclude that the two-step hadronic loops can explain these OZI violations naturally with proper consideration of cancellations between loops. No conclusive evidence exists for glueball states, $s\bar{s}n\bar{n}$ four quark states, instanton effects, and strange quarks in nucleon.

1 Introduction

The empirical OZI rule [1] has been proposed thirty years ago without a solid theoretical basis. Its usual statement is that diagrams with disconnected quark lines are negligible compared to those with connected quark lines, though there are other definitions in the literature [2]. A typical example is shown in Fig.1, where Fig.1b should be negligible compared with Fig.1a according to the rule. The narrow decay widths ($< 0.1$ MeV) of $J/\Psi$ and $\Upsilon(1S)$ states are clear evidence supporting the OZI rule, since these decays involve the annihilation of the $c\bar{c}$ or $b\bar{b}$ quarks corresponding to Fig.1b. As a comparison the decay widths of $\Psi(4040)$ and $\Upsilon(10860)$ are larger than 50 MeV, corresponding to Fig.1a.

The most extensive experimental tests of the OZI rule were on $\phi$ and $f_2'$ production; $\phi$ and $f_2'$ are close to pure $s\bar{s}$ states. With the assumption that the coupling of the $\phi$ and $f_2'$ to nonstrange hadrons are entirely due to their small nonstrange $n\bar{n}$ admixture parts, a stronger version of the OZI rule, named the “universal mixing model”, predicts [3]

$$\frac{\sigma(\pi N \to \phi X)}{\sigma(\pi N \to \omega X)} = \frac{\sigma(N\bar{N} \to \phi X)}{\sigma(N\bar{N} \to \omega X)} = \tan^2\delta_V$$

(1)

$$\frac{\sigma(\pi N \to f_2' X)}{\sigma(\pi N \to f_2 X)} = \frac{\sigma(N\bar{N} \to f_2' X)}{\sigma(N\bar{N} \to f_2 X)} = \tan^2\delta_T$$

(2)

where $X$ denotes any single or multiparticle final state containing no strange particles; the $\delta_V$ and $\delta_T$ are $s\bar{s} - n\bar{n}$ mixing angles for vector and tensor mesons, respectively. Usually

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when we talk about OZI rule violation, it means violation of this stronger version of the OZI rule.

Okubo [4] has reviewed the experimental evidence for the OZI rule, with emphasis on pion-induced reactions and meson decays. He concluded that the experimental data on $\phi$ and $f_2'$ at that time (1977) were reasonably consistent with the validity of the rule. In spite of its reasonable successes, the simple formulation of the OZI rule suffers an intrinsic logical flaw since OZI-forbidden processes can take place as the product of two OZI-allowed processes. This is the so-called “higher-order paradox” of Lipkin [5]. Lipkin clarified the microscopic origins of the OZI rule by showing how cancellations occur between the contributions of various hadronic loops. For example, for $s\bar{s}-n\bar{n}$ mixing, the $K^*\bar{K}$ and $\bar{K}K$ loops always have opposite phase to $KK$ and $K^*K^*$ loops. This sort of cancellation was also showed by Törnqvist’s unitarity quark model [6] and Geiger-Isgur’s calculations of hadronic loop contributions to meson propagators [7]. The degree of cancellation varies for different $q\bar{q}$ nonets [6,7].

Recently, abundant $\phi$-meson production in $N\bar{N}$ annihilation was observed by ASTERIX, CRYSTAL BARREL, JETSET and OBELIX collaborations at LEAR. Several $\phi$ production channels have branching ratios more than one order of magnitude larger than predictions of the OZI universal mixing model. The substantial OZI rule violations are intriguing and were described as evidence for glueball states [8], $s\bar{s}n\bar{n}$ four quark states [9], instanton effects [10] and the considerable admixture of $s\bar{s}$ components in the nucleon [11,12]. However it was shown [13-20] that the conventional hadronic loop diagrams can also explain these large enhancements.

In this talk, first I will show for $s\bar{s}-n\bar{n}$ mixing how the OZI rule evades large hadronic loop corrections for some $q\bar{q}$ nonets but is scuttled for other nonets. Secondly, I will review the hadronic loop contributions to $\phi$ production from $N\bar{N}$ annihilation. Then I will briefly introduce other possible explanations and examine whether there are any clear-cut predictions to distinguish them from the conventional hadronic loop mechanism in $N\bar{N}$ annihilations. Finally I will give my conclusion.

2 OZI rule and $s\bar{s}-n\bar{n}$ mixing

For the $s\bar{s}-n\bar{n}$ mixing, the simplest quark line diagram shown by Fig.2a is an OZI forbidden process. If hadronic loop diagrams were negligible, the OZI rule would predict very small mixing angles. In Table 1 we list the mixing angles obtained from experimental data [6,21] for the low-lying $q\bar{q}$ nonets. Only for the $1^{--}$ nonet is the mixing angle close to zero. The mixing angles are still reasonably small for $2^{++}$ and $3^{--}$ nonets, but quite large for other nonets. So the OZI rule seems to be not working very well here. A natural explanation for this is that the hadronic loop diagrams shown by Fig.2b are not negligible. In fact the imaginary part of the loop amplitudes are fixed to be non-zero by the unitarity relation:

$$\text{Im} T_{s\bar{s}\rightarrow n\bar{n}} = \sum_c \rho_c T_{s\bar{s}\rightarrow c}^\dagger T_{c\rightarrow n\bar{n}}.$$  (3)
Here $c$ is a common channel for $s\bar{s}$ and $n\bar{n}$ decays, such as $K\bar{K}$ or $K^*\bar{K}$; $\rho_c$ is the phase space factor for channel $c$.

A simple estimation of the hadronic loop contributions can be made by considering the mass matrix in the basis of $s\bar{s}$, $n\bar{n}$:

$$ \hat{M} = \left( \sum_c (A_c - \frac{i}{2} \rho_c \sqrt{\Gamma_{s\bar{s} \to c} \Gamma_{n\bar{n} \to c}}) m_{s\bar{s}} - \frac{i}{2} \rho_c \sqrt{\Gamma_{s\bar{s} \to c} \Gamma_{n\bar{n} \to c}} m_{n\bar{n}} \right). $$  \(4\)

Here $\rho_c = \pm 1$ is the relative phase for loop $c$. Neglecting loop diagrams is equivalent to assuming a diagonal real mass matrix. In other words, all the imaginary parts and the real off-diagonal parts ($A_c$) of the mass matrix are coming from loop diagrams. All the imaginary parts of the mass matrix come from on-shell loops and their values at the mass of a corresponding resonance are well determined by the partial decay widths measured by experiments except relative phases $\rho_c$. The real off-diagonal parts $A_c$ come from virtual off-shell loops and can be obtained by dispersive relation from the energy dependent imaginary parts or from some quark model calculations [7]. But they are very model dependent. The physically observed states should be eigenstates of the mass matrix and therefore must be $s\bar{s}$-$n\bar{n}$ mixed states. Generally speaking, the larger the off-diagonal parts are, the bigger the $s\bar{s}$-$n\bar{n}$ mixing will be. If the off-diagonal parts are much smaller than $(m_{s\bar{s}} - m_{n\bar{n}})$, then the mixing angle can be obtained perturbatively:

$$ |\sin\delta|^2 \approx \frac{(\sum_c A_c)^2}{m_{s\bar{s}} - m_{n\bar{n}}} + \frac{1}{4} \left[ \sum_c \frac{\epsilon_c \sqrt{\Gamma_{s\bar{s} \to c} \Gamma_{n\bar{n} \to c}}}{m_{s\bar{s}} - m_{n\bar{n}}} \right]^2. $$  \(5\)

The unitarity limit is obtained by assuming the $A_c$ part to be zero and gives a lower limit for the mixing. For example, for $1^{-+}$ and $2^{++}$ nonets, at $\phi$ and $f_2'(1525)$ masses, the only observed on-shell strange meson loop is $K\bar{K}$. From quark flavor SU(3) symmetry, we have $\Gamma_{n\bar{n} \to K\bar{K}} = \Gamma_{s\bar{s} \to K\bar{K}}/2$. Then in the unitarity limit their $s\bar{s}$-$n\bar{n}$ mixing angles are given by

$$ |\sin\delta| \approx \frac{\Gamma_{s\bar{s} \to K\bar{K}}}{2\sqrt{2}(m_{s\bar{s}} - m_{n\bar{n}})}. $$  \(6\)

Approximating $\phi - f_2'(1525)$ as $s\bar{s}$ and $\omega - f_2(1270)$ as $n\bar{n}$, using PDG [21] mass and width values, the above equation gives $\delta_V = 0.3^\circ$ and $\delta_T = 4.9^\circ$. As lower limits, they are compatible with the observed values listed in Table 1. The very small contribution from the on-shell $K\bar{K}$ loop for $\phi$ and $f_2'(1525)$ is due to very small $K\bar{K}$ phase space for $\phi$ and suppression by the centrifugal barrier factor for $l > 0$ decays. The puzzle is why the contribution from virtual loops, $A_c$, should also be small for the $1^{-+}$ and $2^{++}$ nonets, as implied by their observed mixing angles. Lipkin suggested an explanation. He gave a general deduction [5] that $K\bar{K}^*$ and $\bar{K}K^*$ loops have opposite phase to $K\bar{K}$ and $K^*\bar{K}^*$ loops for $s\bar{s}$-$n\bar{n}$ mixing. It is these loop cancellations that make $A_c$ very small for $1^{-+}$, $2^{++}$ and $3^{--}$ nonets. This sort of cancellation was also shown by Törnqvist’s unitarized quark model [6] and Geiger-Isgur’s calculations of hadronic loop contributions to meson propagators [7].

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Table 1. $s\bar{s}-n\bar{n}$ mixing angles $\delta$ [6,21] and corresponding hadronic loop contributions. $A'(m_{s\bar{s}})$ are mixing amplitudes from the $^3P_0$ model [7] in units of MeV. $+$ and $-$ present the relative phase of loops. 0 stands for forbidden.

| $J^{PC}$ | $|\delta(m_{s\bar{s}})|$ | $A'(m_{s\bar{s}})$ | $K\bar{K}$ | $K\bar{K}^*$ | $K^*\bar{K}$ | $K^*\bar{K}^*$ |
|----------|----------------|------------------|----------|---------|---------|---------|
| $1^{--}$ | 0.7 $\sim$ 3.4° [21] | 8.6 | $+$ | $-$ | $-$ | $+$ |
| $2^{++}$ | 7 $\sim$ 9° [21] | -7.1 | $+$ | $-$ | $-$ | $+$ |
| $3^{--}$ | 6 $\sim$ 7° [21] | 7.4 | $+$ | $-$ | $-$ | $+$ |
| $1^{--}$ | $\sim$ 18° [6] | -59.4 | 0 | $-$ | $-$ | $+$ |
| $1^{++}$ | $\sim$ 26° [6] | 89.5 | 0 | $-$ | $-$ | $+$ |
| $0^{+-}$ | 45 $\sim$ 58° [21] | 0 | $-$ | $-$ | $-$ | $+$ |
| $0^{++}$ | $\sim$ 36° [6] | -537 | 0 | 0 | 0 | $+$ |

Now the question is why the hadronic loop contribution is much larger for other nonets shown in Table 1. Geiger and Isgur suggested [7] that it is due to $^3P_0$ dominance of the effective quark-antiquark pair creation operator which gives different $s\bar{s}$ ↔ $n\bar{n}$ amplitudes for different nonets. Using the $^3P_0$ model, they calculated the real parts of $s\bar{s}-n\bar{n}$ mixing amplitudes, $A'(m_{s\bar{s}})$, which are listed in Table 1 and consistent with the observed mixing angles. However we do not think that the $^3P_0$ mechanism is the main reason and have suggested a more general model-independent explanation [22], i.e., for some nonets either $K\bar{K}$ or $K^*\bar{K} + K\bar{K}^*$ loops are forbidden by parity conservation. In Table 1, we list the relative phase from each hadronic loop for the low-lying nonets, while 0 stands for forbidden. For $1^{--}$, $2^{++}$ and $3^{--}$ nonets, all four loops are allowed and we expect the largest cancellations; for $1^{--}$, $1^{++}$ and $0^{+-}$ nonets, the $K\bar{K}$ loop is forbidden and we expect weaker cancellations; for the $0^{++}$ nonet, $K^*\bar{K} + K\bar{K}^*$ loops are forbidden and there is NO cancellation! These simple model independent expectations are consistent with both observed mixing angles and the $^3P_0$ model calculations [7]. For $0^{+-}$ nonet, the large mixing angle can also be explained by hadronic loops [6] though its U(1) anomaly explanation is not excluded.

Due to the large $s\bar{s}-n\bar{n}$ mixing for $0^{+-}$ nonets, $\eta\eta$, $\eta\eta'$ and $\eta'\eta'$ loops can also contribute to the $s\bar{s}-n\bar{n}$ mixing of some nonets. However, according to the flavor SU(3) symmetry [23]:

$$< f'|\eta\eta \rangle < \eta\eta|f > = \frac{\sin^2(2\delta_P)}{8} < f'|K\bar{K} \rangle < K\bar{K}|f > ,$$

$$< f'|\eta\eta' \rangle < \eta\eta'|f > = \frac{\sin^2(2\delta_P)}{8} < f'|K\bar{K} \rangle < K\bar{K}|f > ,$$

$$< f'|\eta\eta' \rangle < \eta\eta'|f > = -\frac{\sin^2(2\delta_P)}{4} < f'|K\bar{K} \rangle < K\bar{K}|f > .$$

So the contribution from $\eta\eta$, $\eta\eta'$, $\eta'\eta'$ loops is a second order effect and much smaller than strange meson loops for $s\bar{s}-n\bar{n}$ mixing of $J^{PC} = (even)^{++}$ nonets. Note also that the $\eta\eta$ loop has the same phase as $K\bar{K}$. The $\eta\eta$ loop is forbidden for $0^{-+}$, $1^{--}$, $1^{+-}$, $1^{++}$ and $3^{--}$ nonets.
There is another important point for the $0^{++}$ nonet. The on-shell $K\bar{K}$ loop can give a very large imaginary part to the $s\bar{s} \leftrightarrow n\bar{n}$ transition amplitude because no centrifugal barrier factor is present here for S-wave decay. The large coupling to $K\bar{K}$ is also the reason for the narrow peak structure of $f_0(980)$ \cite{6,24}. Due to the very large $K\bar{K}$ loop contribution and no cancellations, there should not exist nearly pure $s\bar{s}$ $0^{++}$ mesons.

In summary, the hadronic loop mechanism can explain naturally the $s\bar{s}-n\bar{n}$ mixing for all low-lying nonets with a proper consideration of loop cancellations. Therefore for other OZI violations, we should first examine the hadronic loop contributions.

3 Hadronic loop mechanism for the abundant $\phi$ production from $\bar{N}N$ annihilation

According to the universal mixing model, Eq.(1), the $\phi/\omega$ production rate from $N\bar{N}$ annihilation should be less than $1/280$, and the $\phi\phi/\omega\omega$ rate should be less than $1/80000$. The experimental data from LEAR collaborations (cf. \cite{12,25,26} for full review of the data) show many violations of these predictions. The JETSET collaboration \cite{27} found \( \sigma(p\bar{p} \to \phi\phi) : \sigma(p\bar{p} \to \omega\omega) \approx 1 : 150 \) at CM energies around 2.2 GeV, which is more than two orders of magnitude larger than the prediction of the universal mixing model. The ASTERIX, CRYSTAL BARREL and OBELIX collaborations found for $N\bar{N}$ annihilation at rest from initial S-wave the following $\phi/\omega$ ratios

\[
\begin{align*}
BR(\phi\gamma) & : \quad BR(\omega\gamma) \approx 1 : 4, \\
BR(\phi\pi) & : \quad BR(\omega\pi) \approx 1 : 10, \\
BR(\phi\omega) & : \quad BR(\omega\omega) \approx 1 : 50, \\
BR(\phi\rho) & : \quad BR(\omega\rho) \approx 1 : 160, \\
BR(\phi\eta) & : \quad BR(\omega\eta) \approx 1 : 170, \\
BR(\phi\pi^+\pi^-) & : \quad BR(\omega\pi^+\pi^-) \approx 1 : 140, \\
BR(\phi\pi^0\pi^0) & : \quad BR(\omega\pi^0\pi^0) \approx 1 : 170. 
\end{align*}
\] (7) (8) (9) (10) (11) (12) (13)

All of them are above the predicted value 1:280, especially, the $\phi\gamma$ and $\phi\pi$ channels are more than one order of magnitude larger than the prediction. In the following, I will examine one by one the three largest OZI violation channels ($\phi\phi$, $\phi\pi$ and $\phi\gamma$) with the hadronic loop mechanism. We will see that the $\phi\phi$ and $\phi\pi$ channels can be explained naturally by hadronic loops while the $\phi\gamma$ channel is due to the vector meson dominance mechanism. For other channels (9-13), no large loop contributions exist \cite{14}, therefore, their ratios are more closer to OZI predictions.

3.1 $\bar{p}p \to \phi\phi$

Its cross section was measured \cite{27} to be 3.7$\mu$b at the energy of 2.2 GeV while the universal mixing model predicts 0.01$\mu$b. The universal mixing model is in fact corresponding to a
two-loop diagram shown by Fig.3a. From Sect.2 we know there are strong cancellation among the $\omega$-$\phi$ mixing loops. Therefore this kind of diagram should be negligible compared with one-loop diagrams as shown by Fig.3b,c.

In the unitarity limit (intermediate $K\bar{K}$ on-shell) for the $K\bar{K}$ loop diagram of Fig.3b, all the vertices are well determined by experimental data for the $\bar{p}p \to K\bar{K}$ cross section and $\phi \to K\bar{K}$ decay width. The only free parameter is the off-shell cutoff parameter $\Lambda_K$ for the t-channel $K$ exchange. With $\Lambda_K = 1.2 GeV$, the unitarity limit for Fig.3b gives a cross section of $2.4 \mu b$ [13]. The unitarity limit includes only the imaginary part of the amplitude. Usually we expect the real part of the amplitude has a similar order of magnitude to the imaginary part. Then the Fig.3b alone can reproduce the large measured cross section.

This calculation [13] was criticized [20] for not considering intermediate $K^*\bar{K}$, $K\bar{K}^*$ and $K^*\bar{K}^*$ states. According to [5], the $K^*\bar{K} + K\bar{K}^*$ loops may have opposite phase to $K\bar{K}$ and $K^*\bar{K}^*$ loops, and therefore there may be cancellations to the result by considering the $K\bar{K}$ loop alone. For the loops including $K^*$, all the vertices are not well known so that we cannot calculate them reliably. But a general argument [22] shows that the summation of four loops will give a similar result to considering only the $K\bar{K}$ loop. The key point is given in Table 2. In allowed partial waves for $\bar{p}p \to \phi\phi$, only half of them can go through the $K\bar{K}$ loop while all of them can go through $K^*\bar{K}$, $K\bar{K}^*$ and $K^*\bar{K}^*$ loops. Amplitudes from different partial waves cannot cancel each other. In Table 2, $A = 0$, $B$ was calculated by [13], $D$ may have opposite phase to $B$ and may cancel part of $B$, and $C$ stands alone without cancellations. It is reasonable to assume $C \approx D$. Then even if $D$ is as large as $B$ and has opposite phase to $B$, the summation of all loop contributions will still give a similar value to considering only the $K\bar{K}$ loop.

Table 2. Hadronic loops for $\bar{p}p \to \phi\phi$

| Allowed Initial States | $KK$               | $KK^*, KK^*, K^*K^*$ | $KK^*, K^*K, K^*K^*$ |
|------------------------|--------------------|-----------------------|-----------------------|
| $S = 0, \quad L = \text{even}, \quad J = L$ | forbidden (A)      | allowed (C)           |
| $S = 1, \quad L = \text{odd}, \quad J = L$ | $KK^*, K^*K, K^*K^*$ | allowed (D)           |
| $S = 1, \quad L = \text{odd}, \quad J = L + 1$ | allowed (B)        |                       |
| $S = 1, \quad L = \text{odd} > 1, \quad J = L - 1$ |                       |                       |

For Fig.3c, the vertex of $\bar{p}p \to \Lambda\Lambda$ can be determined from experimental data; the vertex of $\phi\Lambda\Lambda$ can be determined by SU(3) arguments. The only free parameter is the off-shell cutoff parameter $\Lambda_{\Lambda}$ for the t-channel $\Lambda$ exchange. With $\Lambda_{\Lambda} = 1.5 GeV$, the hyperon loop diagram gives a cross section about $1.5 \mu b$ [20]. The $\Sigma\Sigma$ loop diagram gives much a smaller contribution [20].

From these results for strange meson loops and hyperon loops, we see that the large $\bar{p}p \to \phi\phi$ cross section can be explained by the hadronic loop mechanism.

3.2 $\bar{p}p \to \phi\pi$

The hadronic loops with $K^*\bar{K}$ and $\bar{K}^*K$ intermediate states (Fig.4a) were found to give a large enhancement for $\bar{p}p \to \phi\pi^0$ from an initial S state [14-19]. The $\rho\rho$ loops (Fig.4b)
also give some contribution [14-16]. Other loops are much smaller [15]. These hadronic loops can explain the measured $\phi\pi^0$ branching ratio $(5.5\pm0.7) \times 10^{-4}$ [28] from antiproton annihilation in liquid hydrogen where S-wave annihilation dominates.

However, a question is raised [12] why $\bar{p}p \rightarrow \phi\pi^0$ is not seen in the annihilation from initial P states where $K^*\bar{K}$ and $\bar{K}K$ have a similar branching ratio as from the initial S state. This fact is used as evidence for discriminating the rescattering mechanism and favoring a model assuming existence of strange quarks in the nucleon [12]. It was suggested [17] that possible destructive interference between $l = 0$ and $l = 2$ of the intermediate $K^*\bar{K}$ system may result in a small branching ratio for $\bar{p}p \rightarrow \phi\pi^0$ from initial P states. This argument is very shaky since it requires that $l = 2$ decay of $\bar{p}p \rightarrow K^*\bar{K}$ happens to be of similar strength with opposite phase to $l = 0$ decay. Here I give another reason for the suppression of $\phi\pi$ from the P state, which is more solid and important.

Both [12] and [17] missed an important fact that for $\bar{p}p$ annihilation from P states $K^*\bar{K}$ can come from $^1P_1$, $^3P_1$ and $^3P_2$ states with both isospin 0 and 1 while $\phi\pi$ can only come from the $^1P_1$ state with isospin 1. According to various optical potential models for protonium annihilation [29,30] the total decay width for the $I = 1^1P_1$ state is only about $1/8$ of the summation of the total decay width for all possible P states to $K^*\bar{K}$. The $K^*\bar{K}$ decay width may not be directly proportional to the total decay width for different P states due to some dynamic selection rule. The $K^*\bar{K}$ decay width from I=1 $^1P_1$ may be much smaller than $1/8$ of the total $K^*\bar{K}$ decay width from P states. It is reasonable to expect that $K^*\bar{K}$ from the $I = 1^1P_1$ state is only a very small part of $K^*\bar{K}$ from all the P states. Only this small part can contribute to the rescattering mechanism to the $\phi\pi$ final state. This is contrary to the case for $\bar{p}p$ annihilation from S states where the allowed partial wave ($I = 1^3S_1$) for $\phi\pi$ is found to be dominant for $K^*\bar{K}$ [31].

There is other experimental evidence suggesting that the $I = 1^1P_1$ state may have a very small total decay width. First, the ASTERIX Collaboration found the branching ratios for $\eta\rho$ and $\eta'\rho$ from P states are much smaller than from S states [26]. The $\eta\rho$ and $\eta'\rho$ from P states can only come from the $I = 1^1P_1$ state. Second, a recent analysis by the OBELIX collaboration [32] shows that the branching ratio of $\omega\pi$ from $I = 1^1P_1$ $\bar{p}p$ annihilation is also compatible with zero. So the ratio of $\phi\pi/\omega\pi$ for P state annihilation may be in fact not suppressed.

In summary, the small branching ratio of $\phi\pi$ from the P state may be due to the small total decay width of the $I = 1^1P_1$ state. It is desirable to measure among all $K^*\bar{K}$ productions from P states how many percent come from the $I = 1^1P_1$ state. If this suppression effect were still not enough to explain the small $\phi\pi$ branching ratio from the P state, we may consider the effect proposed by [17] and also a possible cancellation effect between $\rho\rho$ and $K^*\bar{K}$ loops. Therefore conventional physics can explain both S wave and P wave annihilation for $\bar{p}p \rightarrow \phi\pi^0$ very well. The explanation for the large branching ratios of $\bar{n}\bar{p} \rightarrow \phi\pi^+$ and $\bar{p}n \rightarrow \phi\pi^-$ [33] is straightforward from the charge symmetry argument [16].
3.3 $\bar{p}p \rightarrow \phi \gamma$

The measured branching ratio for this channel is $(1.7 \pm 0.4) \times 10^{-5}$ [28]. The hadronic loop contribution was found [14] to be two orders of magnitude smaller than this value. Here the vector meson dominance (VMD) mechanism becomes important [14]. In the VMD mechanism shown by Fig. 5, the branching ratio $BR_{\phi \gamma}$ of $\bar{p}p \rightarrow \phi \gamma$ is related to the branching ratio $BR_{\phi \rho}$ of $\bar{p}p \rightarrow \phi \rho$ and $BR_{\phi \omega}$ of $\bar{p}p \rightarrow \phi \omega$ by the following expression [14, 34],

$$BR_{\phi \gamma}/P_\gamma = g_{\gamma \rho}^2 \left[ BR_{\phi \rho}/P_\rho + \frac{1}{9}BR_{\phi \omega}/P_\omega + \frac{2}{3}\cos \beta \sqrt{BR_{\phi \rho}/P_\rho \cdot \frac{1}{9}BR_{\phi \omega}/P_\omega} \right], \quad (14)$$

where the $P_x$ are phase space factors, $\beta$ is the unknown phase between the amplitudes for the intermediate $\phi \rho$ and $\phi \omega$, and $g_{\gamma \rho}$ is the $\gamma \rho \rho$ coupling constant with $g_{\gamma \rho}^2 = 3 \cdot 10^{-3}$ [34].

Using ASTERIX values of $BR_{\phi \rho} = (3.4 \pm 1.0) \times 10^{-4}$ and $BR_{\phi \omega} = (5.3 \pm 2.2) \times 10^{-4}$ [35], assuming a simple $k_x^3$ form phase space factors for $P_x$, the VMD mechanism gives a range of $(0.4 \sim 2.7) \times 10^{-5}$ for $BR_{\phi \gamma}$ [14], which covers well the measured value.

4 Other possible explanations for the abundant $\phi$ production from $\bar{N}N$ annihilation

There are other very intriguing possibilities which could also explain the abundant $\phi$ production from $\bar{N}N$ annihilation. Production of glueball states [8] could explain the large cross section of $\bar{p}p \rightarrow \phi \phi$; coupling to broad $s\bar{s}n\bar{n}$ states [9, 36] could explain the large branching ratio for the $\phi \pi$ channel; the instanton effects [10] and the presence of substantial $s\bar{s}$ components in the $N/\bar{N}$ wave function [11, 12] could explain several channels. Though the conventional mechanisms (hadronic loops and VMD) can explain all channels very well, they cannot exclude these new possibilities since the relative phases between different mechanisms are not known. However, the abundant $\phi$ production from $\bar{N}N$ annihilation cannot be used as conclusive evidence for these new physics.

In order to distinguish new physics from the conventional physics, we need to find where the two mechanisms will give definitely different predictions. Ref. [12] for the $s\bar{s}$ mechanism gave many predictions. Here I will examine whether their predictions for $\bar{N}N$ annihilation can distinguish their mechanism from the conventional mechanisms.

- Prediction 1: maximum enhancement of $\phi$ production in the initial $^3S_1$ state and weaker enhancement in the initial $^1S_0$ state. Among measured channels, see Eqs. (7-13), (8,11) can only come from the $^3S_1$ state, (7,9,10) can only come from the $^1S_0$ state, (12,13) can come from both states. The predicted pattern is not obvious at all.

- Prediction 2: the $\phi \pi/\omega \pi$ ratio declines for $P$-state and in-flight annihilation. So does the hadronic loop mechanism as discussed in Sect.3.2.
Prediction 3: the branching ratio of $\bar{p}p \rightarrow \pi^0 f'_2$ from P-states is possibly as large as $(1 \sim 2) \cdot 10^{-3}$. The $f_2 f'_2$ mixing mechanism gives $(1 \sim 2) \cdot 10^{-4}$. There is no hadronic loop calculation for $\bar{p}p \rightarrow \pi^0 f'_2$ from P-states yet. Ref.[18] calculated the $K\bar{K}^*$, $\bar{K}K^*$ and $\rho\pi$ loop contributions for $\bar{p}p \rightarrow \pi^0 f'_2$ from the $^1S_0$ state. The result is smaller than the contribution from the $f_2 f'_2$ mixing mechanism. But they did not include a possible larger loop contribution from an $\eta - a_0(980)$ intermediate state.

For $\bar{p}p \rightarrow \pi^0 f'_2$, $^1S_0$ and $^3P_{1,2}$ $\bar{p}p$ states contribute, while for $\bar{p}p \rightarrow \pi^0 \phi$ $^3S_1$ and $^1P_1$ $\bar{p}p$ states contribute. As discussed in Sect.3.2, $K^*\bar{K}$ are dominantly coming from $^3S_1$ and $^3P_{1,2}$ states; we expect $K^*\bar{K} + K\bar{K}^*$ loops give a very large contribution to $\bar{p}p \rightarrow \pi^0 f'_2$ from P-states and $\bar{p}p \rightarrow \pi^0 \phi$ from the S-state, but small contributions to $\bar{p}p \rightarrow \pi^0 f'_2$ from the S-state and $\bar{p}p \rightarrow \pi^0 \phi$ from P-states. Once again the hadronic loop mechanism predicts a similar thing here as the $s\bar{s}$ mechanism.

Prediction 4: $\bar{p}p \rightarrow \phi \phi$ is more enhanced for initial spin-triplet states. Here the $K\bar{K}$ loop is allowed for initial spin-triplet states, but is forbidden from initial spin-singlet states.

Prediction 5: in $\bar{p}p \rightarrow \phi^+\pi^-$, $^3S_1$ should dominate. ASTERIX [35] found $^1S_0$ dominates while OBELIX [37] found $^3S_1$ dominates. These contradictory experimental results remain to be clarified. Even if the OBELIX result is correct, it is still not contradictory to conventional physics. The $^3S_1$ has a larger statistical weight than the $^1S_0$ state, i.e., 3:1. The branching ratio for this channel is not far away from the OZI prediction, see Eq.(12). Several hadronic loops can have small contributions. They may or may not cancel this statistical weight effect.

Prediction 6: $\phi\gamma/\omega\gamma$ should increase for P-state annihilation. This can also explained by the VMD mechanism since the $\rho\phi$ and $\omega\phi$ branching ratios were found to be increasing for P-state annihilation [35].

Prediction 7: $\bar{p}p \rightarrow \phi\pi$, $\omega\pi$ should have different angular distributions due to different production mechanisms. In the hadronic loop mechanism, $\bar{p}p \rightarrow \phi\pi$, $\omega\pi$ also have different production mechanisms. The calculated angular distribution for $\bar{p}p \rightarrow \phi\pi$ in the hadronic mechanism was found to be compatible with experimental data [19].

Prediction 8: large $\phi/\omega$ ratio in the Pontecorvo reaction $\bar{p}d \rightarrow \phi n$. This is also consistent with the hadronic loop mechanism. Since the reaction can go through both $\phi\pi^0 n$ and $\phi\pi^- p$ intermediate states, the interference effect can make the $\phi/\omega$ ratio here larger than for $\bar{p}N \rightarrow \phi\pi$ as reported by the OBELIX collaboration [38].

After the above detailed examination, no clear-cut prediction for $\bar{N}N$ annihilation is found to distinguish the new $s\bar{s}$ mechanism. We note in passing that evidence for the presence of $s\bar{s}$ in the nucleon from other sources [11] was criticized by [39,40].
5 Conclusion

1) Hadronic loops can explain all $s\bar{s}$-$n\bar{n}$ mixing naturally. $1^{--}$, $2^{++}$ and $3^{--}$ nonets have smaller $s\bar{s}$-$n\bar{n}$ mixing due to strong cancellations between $KK^*$ and $K\bar{K} + K^*\bar{K}^*$ loops; $0^{-+}$, $0^{++}$, $1^{+-}$ and $1^{++}$ nonets have larger mixing due to selection rules against either $KK^*$ or $K\bar{K} + K^*\bar{K}^*$ loops, which leads to weaker or no cancellation.

2) No nearly pure $s\bar{s}$ $0^{++}$ meson exists due to a large $KK^*$ loop without centrifugal barrier factor and cancellation from $\bar{K}K^* + K\bar{K}^*$ loops.

3) Conventional mechanisms (hadronic loops and vector meson dominance) can explain all $\phi$ enhancements from $\bar{N}N$ annihilation naturally.

4) No conclusive evidence from $N\bar{N}$ annihilation exists for glueball states, $s\bar{s}n\bar{n}$ four quark states, instanton effects, and strange quarks in the nucleon, though they are not excluded.

5) There is no simple clear-cut prediction for $\bar{N}N$ annihilation to prove the presence of $s\bar{s}$ in nucleon yet. Not only $\phi$, $f_2^2$ production channels but also related channels ($K\bar{K}$, $K\bar{K}^*$, $\bar{K}^*K^*$, $\rho\rho$, $a_0\eta$, etc.) should be investigated with detailed partial wave analyses to see whether we can find a place where the hadronic loops fail. Only after such hard detailed studies, may we claim any conclusive evidence for new physics.

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Figure Captions

Fig.1. OZI (a) allowed, (b) forbidden diagrams.

Fig.2. Diagrams for $s\bar{s} \leftrightarrow n\bar{n}$ transition: (a) first order; (b) hadronic loops.

Fig.3. Loop diagrams for $\bar{p}p \rightarrow \phi\phi$: (a) $\omega$-$\phi$ mixing mechanism; (b) $K\bar{K}$ meson loop; (c) $\Lambda\bar{\Lambda}$ hyperon loop.

Fig.4. (a) $K\bar{K}$ and (b) $\rho\rho$ meson loops for $\bar{p}p \rightarrow \phi\pi^0$.

Fig.5. Vector meson dominance mechanism for $\bar{p}p \rightarrow \phi\gamma$ through (a) $\rho\phi$ and (b) $\omega\phi$ intermediate states.
Figure 1:

Figure 2:
Figure 3:

(a) \[ \bar{p} \rightarrow \omega, K, \phi \]

(b) \[ \bar{p} \rightarrow K, K, \phi \]

(c) \[ \bar{p} \rightarrow \Lambda, \Lambda, \phi \]

Fig. 3
Figure 4:

Figure 5: