VIOLATION OF OZI RULE IN ϕ/ω MEASUREMENTS WITH OBELIX AT LEAR*

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A summary of all the results achieved so far by the OBELIX Experiment in various measurements of ϕ and ω mesons production rates, in different annihilation channels and with data taken under different experimental conditions, is reported.

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1. Introduction

A possible experimental evidence for the presence of a $\bar{s}s$ component in the nucleon even at low energies stands is the observed violation of the Okubo–Zweig–Iizuka rule in nucleon-antinucleon annihilation reactions with the production of ϕ mesons in the final state.

According to the naïve quark model the low energy structure of the nucleon can be simply described by means of three constituent u and d quarks. Therefore, ϕ mesons in annihilation processes should only be produced by means of their non-strange component, and the production rate should be highly depressed as compared to ω, the quasi-ideally non-strange isoscalar vectorial meson: this is the basic point of OZI rule. However, in the last years many experimental observations performed especially by experiments at the LEAR storage ring at CERN, in various annihilation channels, have found anomalously high rates for the ϕ production. The extent of OZI rule violation has been shown to be not only dependent on the annihilation channel, but also on the quantum numbers of the initial state. A measure for this violation is given by the ratio of the production branching ratios for ϕ and ω, recoiling against a non-strange system: $R_X = \bar{\sigma}(\overline{\mathcal{N}}\mathcal{N} \to \phi X)/\bar{\sigma}(\overline{\mathcal{N}}\mathcal{N} \to \omega X)$, properly corrected taking into account the different phase space available to

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the two reactions. According to OZI its value should be around 4.3×10^{-3}, and any deviation from this figure would be an indication for a violation.

The OBELIX Experiment, whose description has been already given extensively elsewhere [1], had been operational from 1990 to 1996. It had performed several measurements of the production rates of the ϕ and ω mesons in various channels and in different annihilation reactions, with antiprotons annihilating at rest on hydrogen targets in different pressure conditions — allowing therefore a precise selection of the initial state[1] — at rest on gaseous deuterium and in the annihilation in flight of antineutrons with momentum from 50 to 405 MeV/c on liquid hydrogen.

2. $\overline{\mathcal{N}}\mathcal{N} \to \phi\pi,\ \omega\pi$

The study of the $\phi\pi$ final state had been performed in different experimental conditions, which will be described in the following subsections.

In general, in annihilations at rest or in flight at low energy the $\phi\pi$ final state can only be produced, due to C, P and G conservation, from $^3S_1$ and $^1P_1$ initial states. A marked peculiarity, shown for the first time by the ASTERIX Experiment some years ago [3], is an anomalously abundant ϕ production coming especially from S-wave.

2.1. $\bar{n}p \to \phi\pi^+,\ \omega\pi^+$

The most complete study of ϕ and ω production in a two body annihilation reaction had been performed by OBELIX in the $\bar{n}p \to \phi\pi^+$, $\omega\pi^+$ channels [4]. Since the antineutrons were produced with a momentum ranging from ~ 50 to 405 MeV/c, and their annihilation occurred in flight, the production rates of these mesons could be traced as a function of the energy available to the reaction; a marked dependence of them on the two possible initial states was found: namely, a strong ϕ production from S-wave. The proof of this feature is twofold: on one hand, the ϕ decay angle distributions, reported in Fig. 1 for data belonging to different ranges of $\bar{n}$ momentum, are fully compatible with a $\sin^2\theta$ shape, as expected from $\phi\pi$ annihilation in S-wave. On the other hand, as can bee seen in Fig. 2a), the $\phi\pi^+$ cross sections follow nicely, as a function of $\bar{n}$ momentum, the trend predicted for S-wave annihilation by Dover–Richard's model [5]. The same does not hold, as shown in Fig. 2b), for the $\omega\pi^+$ channel, where a sizeable P-wave component is present. From the analysis of the ω decay Dalitz plots, the P-wave contribution was found to be as large as about 30%, for the highest $\bar{n}$ momenta.

[1] being the S-wave $\bar{p}p$ annihilation fraction about 87% in liquid hydrogen, 42% in gaseous hydrogen at normal pressure and temperature conditions, and 20% in hydrogen at 5 mbar, according to [2].

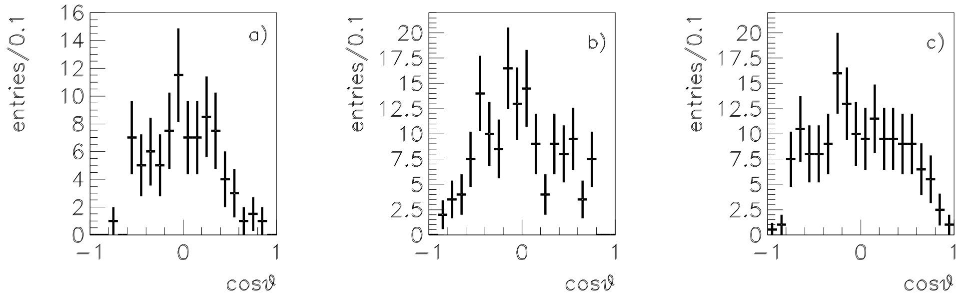

Fig. 1. Distributions of the ϕ decay angle (the angle between the direction of one kaon in ϕ c.m.s. and the ϕ line of flight, in reaction c.m.s.) for data selected in three different ranges for $\bar{n}$ momentum: a) $\sim 50 < p_{\bar{n}} \leq 200$ MeV$/c$, b) $200 < p_{\bar{n}} \leq 300$ MeV$/c$, c) $300 < p_{\bar{n}} \leq 405$ MeV$/c$.

As a consequence of the decrease of ϕ production with energy due to S-wave dilution, the ϕ/ω production rates ratio drops with $\bar{n}$ momentum as well (Fig. 2c)). Extrapolating to the condition of pure S-wave, one gets for the ratio the value $R^S_{\pi^+}(\bar{n}p \to \phi\pi^+,\ \omega\pi^+) = (112 \pm 14) \times 10^{-3}$, which exceeds the OZI expectation of a factor of 37.

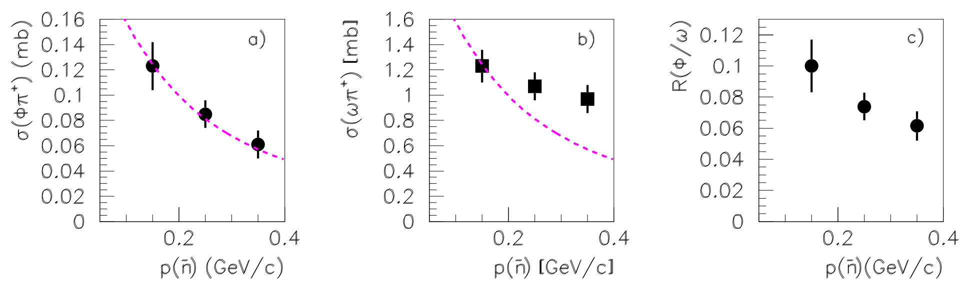

Fig. 2. Trends as a function on $\bar{n}$ momentum of: a) $\phi\pi^+$ and b) $\omega\pi^+$ cross sections, c) $R_{\pi^+}(\phi/\omega)$. The dashed curve is the predicted trend of S-wave as given by Dover–Richard model.

2.2. $\bar{p}p \to \phi\pi^0,\ \omega\pi^0$

OBELIX had measured the annihilation frequencies of the $\phi\pi^0$ final state in the reaction $\bar{p}p \to \phi\pi^0$ in hydrogen targets at three densities: liquid, gaseous at NTP and at 5 mbar pressure [6].

The ϕ annihilation frequency decreases almost linearly with the percentage of S-wave. By using the parameters from $\bar{p}p$ cascade process [2], the hadronic branching ratios from single initial partial waves had been evaluated:

$$\begin{aligned} \mathrm{BR}(\bar{p}p \to \phi\pi^0,\ ^3S_1) &= (7.57 \pm 0.62) \times 10^{-4}\,, \\ \mathrm{BR}(\bar{p}p \to \phi\pi^0,\ ^1P_1) &< 0.5 \times 10^{-4}, \quad \text{at } 95\% \text{ C.L.} \end{aligned}$$

hence the branching ratio from S-wave exceeds that from P-wave of a factor of about 15. This dynamical selection rule is again shown not to be valid for the production of the ω meson. In an analysis of the $\bar{p}p \to \omega\pi^0$ annihilation in liquid hydrogen targets at different densities [7] the production of ω from the $^1P_1$ initial state was found to be not negligible, going from about 10% for annihilations in liquid target to about 30% for annihilations in gas at NTP, and confirming therefore the trend observed in $\bar{n}p$ annihilation data.

As a consequence, the ratio of the yields depends on the target density:

$$\begin{aligned} R_{\pi^0}(\phi\pi^0/\omega\pi^0, \text{liquid } H_2) &= (114 \pm 10) \times 10^{-3}\,, \\ R_{\pi^0}(\phi\pi^0/\omega\pi^0, \text{NTP } H_2) &< (83 \pm 10) \times 10^{-3}\,. \end{aligned}$$

Extrapolating to pure S- and P-wave annihilations one sees that a large OZI rule violation occurs from S-wave, while it is practically absent when the same reaction proceeds from P-wave. The value obtained for the pure S-wave $\bar{p}p$ annihilation at rest, $R^S_{\pi^0} = (117 \pm 22) \times 10^{-3}$, is quite in agreement with the value reported in the previous paragraph for $\bar{n}p$.

2.3. $\bar{p}n \to \phi\pi^-$, $\omega\pi^-$

The $\bar{p}n$ annihilation at rest could be measured by OBELIX stopping antiprotons in a deuterium gaseous target [8]. The ratios for ϕ and ω production were measured in two intervals of momentum for the spectator proton, $p_{p_s} < 200$ MeV/c and $p_{p_s} > 400$ MeV/c, and in both the cases again a sizeable value for R_{π^-} was found:

$$\begin{aligned} R_{\pi^-}(\phi\pi^-/\omega\pi^-) &= (133 \pm 26) \times 10^{-3},\ p_{p_s} < 200\ \mathrm{MeV}/c\,, \\ R_{\pi^-}(\phi\pi^-/\omega\pi^-) &= (113 \pm 30) \times 10^{-3},\ p_{p_s} > 400\ \mathrm{MeV}/c\,. \end{aligned}$$

The value of the ratio, in agreement with $\bar{p}p$ and $\bar{n}p$ measurements, is moreover shown to be independent on the momentum of the spectator proton, so the dynamics of the process should have only connections to the basic $\overline{\mathcal{N}}\mathcal{N}$ annihilation process.

3. $\bar{p}p \to \phi\pi^+\pi^-$, $\omega\pi^+\pi^-$

The value of the branching ratios with ϕ recoiling against a $\pi^+\pi^-$ system were measured by OBELIX to gain some hints about the dependence of OZI violation on the momentum transfer in an annihilation reaction. Without any selection on the recoiling dipion mass, practically no OZI violation occurs. But if small dipion masses are selected, say in the range $(300\div 500)$ MeV/c^2, the ϕ/ω ratio becomes $R_{\pi^+\pi^-}(\bar{p}p \to \phi\pi^+\pi^-, \omega\pi^+\pi^-) = (16\div 30)\times 10^{-3}$ [9], which does not violate OZI rule in a very dramatic way but however gives a clear signal that the smaller is the mass of the system recoiling against the ϕ, *i.e.* the larger is the momentum transfer in the reaction, the larger is the violation. Another feature emerging from a partial wave analysis of the $\phi\pi^+\pi^-$ final state is that, in spite of both $^3S_1$ and $^1S_0$ initial states being allowed in this reaction, the production from spin triplet again clearly dominates.

4. $\bar{p}p \to \phi\eta$, $\omega\eta$

The annihilation into $\phi\eta$ was measured by OBELIX in hydrogen targets at three densities, like in $\phi\pi^0$ case [10]. The initial states from which this annihilation channel can proceed are the same as for $\phi\pi^0$, *i.e.* $^3S_1$ and $^1P_1$ (except that $\phi\pi^0$ is coupled to isospin 1), so one would tentatively expect similar trends. However, the production rates from S- and P-wave exhibit an opposite behavior: the production of $\phi\eta$ from $^1P_1$ is about 10 times higher than from S-wave; this effect could be due to an enhancement of η production from spin singlet initial states. Due to the overall ϕ suppression, the ratio of the branching ratios $R_\eta(\bar{p}p \to \phi\eta, \omega\eta)$ — using for $\omega\eta$ BR the value measured by Crystal Barrel in liquid hydrogen target [11] — is not violating OZI predictions: $R_\eta = (4.6 \pm 1.3)\times 10^{-3}$.

5. An interpretation: the polarized intrinsic strangeness model

Among the several different theoretical models proposed so far, one of the most appealing, able to explain many experimental observations, was suggested by Ellis *et al.* [12]. According to it a sizeable $s\bar{s}$ condensate, with a fixed polarization, is present in the proton wave function and its effects should be relevant even at low energies. This hypothesis is based on the EMC effect (and related) observed in deep inelastic scattering experiments, according to which a sizeable contribution to the total proton spin is carried by the $\bar{s}s$ pairs, which are though polarized oppositely respect to the proton.

According to this model the $\bar{s}s$ pair exists inside a nucleon in a long-living configuration, with well defined quantum numbers, upon which the possible phenomenology of strangeness production in the final state heavily depends. Two are essentially the mechanisms by which a strange particle can be produced, as shown in Fig. 3: by means of the knocking out of one $\bar{s}s$ pair from one nucleon only, of by rearrangement of a couple of s and $\bar{s}$ quarks belonging each to different nucleons. The net effect of both the mechanisms is to allow the production of ϕ by means of connected quark lines, so in this way the OZI rule is only apparently violated.

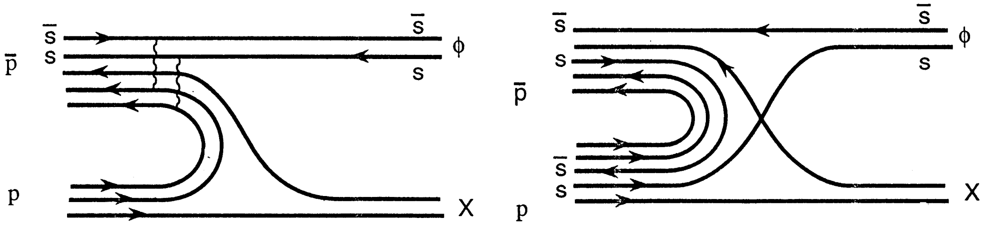

Fig. 3. Shake-out and rearrangement diagrams for ϕ meson production in $\bar{p}p$ annihilation.

The shake-out picture is actually not completely satisfying to explain the observed phenomenology of ϕ production. Indeed, one could think of ϕ's as being already stored in one nucleon with the correct quantum numbers, and produced by a kind of knock-out. But if this hypothesis were true, one would expect a sort of "universal" enhancement of ϕ production in all annihilation channels, and this does not happen.

The rearrangement scenario could be somehow more realistic. Since each of the strange quarks is polarized opposite to the nucleon spin, if the initial state is in spin triplet even the $\bar{s}s$ pair will be in this spin triplet configuration, and the same would hold for spin singlet initial states. Now, if in the spin triplet case the relative angular momentum between the two strange quarks is zero, then a strangeonium with ϕ quantum numbers may be formed in the final state. Therefore, according to this mechanism one expects ϕ production to occur especially from $^3S_1$ initial state, as actually is experimentally observed.

On the other hand, from spin singlet initial states one expects to favour the production of pseudoscalar mesons. Even this prediction is verified, by the experimental observations in the $\phi\eta$ channel described before.

Also concerning the production of tensorial mesons the experimental issues [6] are in nice agreement with the predictions from this model: $f_2'(1525)$ production is expected to be enhanced from spin triplet states with $L = 1$ relative angular momentum of the $\bar{s}s$ pair. This is actually experimentally verified, since $f_2'(1525)$ is indeed produced more abundantly than foreseen by OZI rule, and, moreover, mainly in spin triplet P-wave annihilations.

Of course alternative explanations have been proposed to explain the observed effects, but under some aspects they are not thoroughly satisfying.

The most convincing one is based on the evaluation of contributions from all intermediate two- and three-steps rescattering diagrams, that are able to reproduce the strange meson production by means of OZI allowed reactions. Even if the experimental results can be reproduced within a factor of 2 of accuracy (the $\phi\pi^0$ production rate, for instance), these models are based on some assumptions, as a $K^*\overline{K}$ suppression from P wave, which do not find experimental verification. In fact, the study of $\bar{p}p \to K^*\overline{K}$ annihilation [6] shows quite a similar production both from ${}^3S_1$ and from ${}^1P_1$ initial state; on the other hand, a measurement of the cross-sections for the reaction $\bar{n}p \to K^+\overline{K^{0*}}$ [4] exhibits a flat trend as a function of $\bar{n}$ momentum, contrasting with the drop one would expect if P-wave production were depressed.

Moreover, the rescattering models fail in a rather sizeable way (about two orders of magnitude) in the evaluation of the production rate of $f_2'(1525)$.

6. Summary and conclusions

The main experimental observations performed by the OBELIX Experiment concerning ϕ and ω mesons production may be summarized as follows:

- an enhanced ϕ production has been measured, occurring in spin triplet S-wave. The ω meson production does not seem to follow this selection rule, as a sizeable fraction of these mesons is shown to be produced in P-wave;
- the enhancement in ϕ production is higher for larger transferred momenta, *i.e.* the lowest the mass of the system recoiling against ϕ is;
- the ϕ/ω yields ratio shows a violation of OZI rule of an average factor ~ 30. This violation becomes more diluted as the reaction energy increases, as a consequence of the lower ϕ rate due to the weaker S-wave relative contribution.

These observations can be explained in a satisfactory way by means of the polarized intrinsic strangeness model.

Up to now, no experimental issue has been found against it. The model can be applied in a variety of hadronic reactions and provides quite a wide spectrum of predictions, not only concerning ϕ production. For instance, it predicts the production of $\Lambda\overline{\Lambda}$ from $\bar{p}p$ spin triplet initial state only, fact that has been experimentally verified [13]. Other predictions concern ϕ production rates in reactions with polarized beams and/or targets, the size of the spin-transfer coefficient in reactions with Λ production, the magnitude and sign of Λ longitudinal polarization in deep inelastic scattering reactions with polarized leptonic beams.

It is therefore likely that several forthcoming experiments will provide in the near future many results which will help to further validate, or rule out, the proposed model.

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REFERENCES

[1] A. Adamo *et al.*, *Sov. J. Nucl. Phys.* **55**, 1732 (1992).
[2] C.J. Batty, *Nucl. Phys.* **A601**, 425 (1996).
[3] J. Reifenrother *et al.*, *Phys. Lett.* **B267**, 299.
[4] The OBELIX Collaboration, A. Filippi *et al.*, *Nucl. Phys.* **A655**, 453 (1999).
[5] C.B. Dover *et al.*, *Prog. Part. Nucl. Phys.* **29**, 87 (1992).
[6] The OBELIX Collaboration, A. Alberico *et al.*, *Phys. Lett.* **B438**, 430 (1998).
[7] The OBELIX Collaboration, R. Donà, *Proc. LEAP98 Conference*, Villasimius, 1998, *Nucl. Phys.* **A655**, 213c (1999).
[8] V.G. Ableev *et al.*, *Nucl. Phys.* **A585**, 577 (1995).
[9] The OBELIX Collaboration, A. Bertin *et al.*, *Phys. Lett.* **B388**, 450 (1996).
[10] The OBELIX Collaboration, A. Alberico *et al.*, *Phys. Lett.* **B432**, 427 (1998).
[11] C. Amsler, *Rev. Mod. Phys.* **70**, 1293 (1998).
[12] J. Ellis *et al.*, *Phys. Lett.* **B353**, 319 (1995); J. Ellis, M. Karliner, D. Kharzeev, M. Sapozhnikov, hep-ph/9909235 (1999); M. Sapozhnikov, *Proc. LEAP98 Conference*, Villasimius, 1998, *Nucl. Phys.* **A655**, 151c (1999).
[13] PS185 Collaboration, P.D. Barnes *et al.*, *Phys. Rev.* **C54**, 1877 (1996).