NEW DATA ON OZI RULE VIOLATION IN $\bar{p}p$ ANNIHILATION AT REST

The OBELIX collaboration.

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Abstract

The results of a measurement of the ratio $R = Y(\phi\pi^+\pi^-)/Y(\omega\pi^+\pi^-)$ for antiproton annihilation at rest in a gaseous and in a liquid hydrogen target are presented. It was found that the value of this ratio increases with the decreasing of the dipion mass, which demonstrates the difference in the ϕ and ω production mechanisms. An indication on the momentum transfer dependence of the apparent OZI rule violation for ϕ production from the $^3S_1$ initial state was found.

In recent experiments with stopped antiprotons at LEAR (CERN) [1]-[5] strong violation of the Okubo-Zweig-Iizuka rule [6] was found. The ratio of the yields of ϕ and ω mesons $R(\phi X/\omega X)$ turned out about 30- 50 times larger than the OZI prediction $R(\phi X/\omega X) \approx 4 \cdot 10^{-3}$. In particular, the degree of the OZI rule violation was found [1],[5] to depend strongly on the quantum numbers of the initial state.

A number of theoretical models were developed for explaining these data. Approaches based on the traditional ideas [7],[8] are unable to reproduce *all* the features of ϕ production observed now (for a review, see [9]). It has been suggested [10]- [12] that the nucleon wave function contains some $s\bar{s}$ pairs already at small momentum transfer. Then the abundant ϕ production in $\bar{N}N$ annihilation should not be considered as a violation of the OZI rule, because it does not involve disconnecting quarks diagram. In this model the ϕ production is described in terms of rearrangment of the $s\bar{s}$ pairs already stored in the nucleons.

It is differ from a standard view that the ϕ, which is practically pure $s\bar{s}$ state, should be created in the interactions of the non-strange hadrons only due to small admixture of the light quarks in its wave function and the production amplitudes of ϕ and ω mesons should be rather similar.

In this paper, we study the production mechanisms of ϕ and ω mesons in the reactions

$$\bar{p} + p \longrightarrow \phi + \pi^+ + \pi^- \quad (1)$$
$$\bar{p} + p \longrightarrow \omega + \pi^+ + \pi^- \quad (2)$$

of antiproton annihilation at rest. The ratio $R = Y(\phi\pi^+\pi^-)/Y(\omega\pi^+\pi^-)$ was measured for different invariant masses of the dipion system. It was found that the value of this ratio increases with the decreasing of the dipion mass, which demonstrates the difference in the ϕ and ω production mechanisms.

Antiproton annihilations at rest were obtained using the OBELIX spectrometer on the M2 beam line of LEAR. A detailed description of the spectrometer can be found elsewhere [13]. The experimental setup consists of a number of subdetectors arranged around the Open Axial Field Magnet. The Time Of Flight (TOF) system contains two coaxial barrels of plastic scintillators for charged particle identification and trigger. The Jet Drift Chamber (JDC) provides geometry reconstruction of the event and particle identification by energy loss measurement. The High Angular Resolution Gamma Detector (HARGD) reconstructs the multiplicity, the direction and the energy of the detected gammas.

In order to investigate the reactions (1)-(2), events with 4 charged particles were analyzed. To study $\omega-$meson production the trigger, based on the TOF system, was used for selection of events characterized by 4 hits in the inner barrel of the scintillators and 3-4 hits is the outer one. To study $\phi-$meson production a sample of data was collected using also a "slow particle" condition - at least one time difference between hits in the inner and outer barrels had to be greater than 8 nsec. This condition was used to enrich the sample by charged kaons.

Data were taken using two hydrogen targets: liquid and gas at 3 atm pressure. In the former case, annihilations occur mainly from S-wave initial states, whilst in the latter one annihilations from S- and P-waves are possible with approximately equal probability. A sample of $16 \cdot 10^6$ annihilations in liquid target with the "slow particle" condition was collected and $1 \cdot 10^6$ events without it were taken. For the gas target, $1.5 \cdot 10^6$ and $3 \cdot 10^6$ events, respectively, were taken.

The following criteria were used for event selection. The event should have 4 tracks with total charge zero. Data samples with the "slow particle" trigger were used to select events with $K^+K^-\pi^+\pi^-$ final state. Two kaons of opposite charge should be recognized by dE/dx and TOF. Finally, the events were submitted to kinematical fit to fulfill the hypotheses $\bar{p}p \to K^+K^-\pi^+\pi^-$ (4C fit) at $CL = 5\%$ and $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ (1C fit) at $CL = 10\%$.

For the liquid target sample, 59299 $KK\pi\pi$ events and 127904 5π events were selected. For the gas target sample, 7015 and 230769 events, respectively, were selected.

The K^+K^- and $\pi^+\pi^-\pi^0$ invariant mass spectra for the selected events are shown in Fig.1. Clear signals from ϕ and ω mesons are apparent. Approximation of them by the sum of a Breit-Wigner function with fixed $\phi(\omega)$ width, smeared by a Gaussian distribution gives the following values for mass and experimental resolution σ (for the gas target sample): $m_\phi = (1019.1 \pm 0.5)\ MeV/c^2$, $\sigma_\phi = (5.3 \pm 0.6)\ MeV/c^2$ and $m_\omega = (781 \pm 1)\ MeV/c^2$, $\sigma_\omega = (18.9 \pm 0.1)\ MeV/c^2$.

Background free $\pi^+\pi^-$ invariant mass distributions (uncorrected for apparatus acceptance) for the reactions (1) and (2) are shown in Fig.2 a)-d). For the reaction (1) (ϕ production) the spectra were obtained after subtraction of events from the bins nearby the ϕ peak.

For the reaction (2) (ω production), so-called λ-subtraction procedure[14] was used. The ω decay amplitude is proportional to the parameter

$$\lambda = \frac{|\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}|^2}{\lambda'}$$

where $\vec{p}$ are the three-momenta of the charged pions from the ω decay in its rest frame, and λ' is the maximum possible value of $|\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}|^2$. The distribution of this parameter for events coming from ω decay is proportional to λ, while for the background events the corresponding λ–distribution should be flat. This was verified for the analyzed sample. The events were separated into two samples: one with $\lambda < 0.5$ and the other with $\lambda > 0.5$. Subtracting the spectrum with $\lambda < 0.5$ from that $\lambda > 0.5$ one can obtain a background-free distribution.

In the $\pi^+\pi^-$ invariant mass distributions associated to ϕ production shown in Fig.2 a,b), there is no evidence of a ρ-meson peak. This is consequence of the apparatus acceptance. Charged kaons with a momentum less than 200 MeV/c cannot arrive at the JDC. As a result, it is not possible to observe high values of $M_{\pi\pi}$ created together with ϕ.

The dipion mass distributions associated to ω production are shown in Fig.2 c,d). They are dominated by the peak of ρ meson production, which turns out especially evident for annihilation in gas. In the case of liquid target (Fig. 2c), remnants of the $f_2(1270)$ peak, truncated by the phase space, can be seen. These distributions are rather similar to those measured in the previous experiments of ω production for annihilation in liquid [14] and gas [15] targets. From Figs.2 c,d) it turns out that at small masses, $300\ MeV/c^2 < M_{\pi\pi} < 500\ MeV/c^2$, the invariant mass distributions are rather flat. This interval is also suitable for detection of pions created together with ϕ mesons in the reaction (1).

The ratio $R = Y(\phi\pi\pi)/Y(\omega\pi\pi)$ (where Y is the yield of ϕ- or ω-mesons) was determined using the numbers of ϕ and ω obtained from the K^+K^- and $\pi^+\pi^-\pi^0$ invariant mass distributions for dipion mass within the interval $300\ MeV/c^2 < M_{\pi\pi} < 500\ MeV/c^2$ and compared with the same ratio obtained for all events. To avoid a loss of useful events, we not used the background-free distributions. To estimate the number of $\phi(\omega)$ mesons the corresponding part of the invariant mass spectrum was approximated by the sum of a Breit-Wigner function with fixed $\phi(\omega)$ width, smeared by a Gaussian distribution and a polynomial function to describe the background.

To evaluate the detection efficiency of reactions (1)-(2), Monte-Carlo simulated events were reconstructed and analysed using the same selection criteria and kinematical cuts as for real data. The phase space distribution of the dipion mass was assumed both in case of ϕ and ω production.

In Table, the number of events N_{ev} selected for each reaction, the detection efficiencies ϵ, the yields Y of ϕ and ω meson production and the corresponding ratios R are reported. The yield is calculated as $Y = N_{ev}/(\varepsilon \cdot N_{ann} \cdot B)$, where B is fraction of ϕ decays into K^+K^-. Total number of annihilations in the target N_{ann} is equal to $33.6 \cdot 10^6$ for gas and $10.6 \cdot 10^6$ for liquid for the samples obtained without "slow particle" condition and $130.8 \cdot 10^6$ for gas and $494.3 \cdot 10^6$ for liquid for the samples obtained with "slow particle" trigger. The yield values are affected by a systematic uncertainty of about 6%. It is due to uncertainties of different selection procedures, particle identification, evaluation of the apparatus efficiency and the total number of annihilated antiprotons. In addition, the total yields are underestimated due to low acceptance of $\phi\rho$ channel.

The obtained total yield of the $\omega\pi^+\pi^-$ channel: $Y = (719 \pm 74) \cdot 10^{-4}$ for liquid and $Y = (628 \pm 34) \cdot 10^{-4}$ for gas are in general agreement with the results of previous measurements: $Y = (660 \pm 60) \cdot 10^{-4}$ for liquid [14] and $Y = (682 \pm 74) \cdot 10^{-4}$ for gas [15]. The yields of $\phi\pi^+\pi^-$ channel: $Y = (3.5 \pm 0.4) \cdot 10^{-4}$ for liquid and $Y = (3.7 \pm 0.5) \cdot 10^{-4}$ for gas are lower than those measured by other authors: $Y = (4.6 \pm 0.9) \cdot 10^{-4}$ for liquid [14] and $Y = (5.4 \pm 1.0) \cdot 10^{-4}$ for gas [1]. The reason is the lack of the events from $\phi\rho$ channel discussed above. It is important to stress that this lack of $\phi\rho$ events is not relevant to our subsequent analysis which based mainly on the measurements of $\phi\pi\pi$ yield at small dipion masses.

As one can see from the Table, for all events, without any cut on dipion invariant mass, the ratio $R(\phi/\omega)$ is about $5 \cdot 10^{-3}$ both in the case of annihilation in liquid and in gas. It is in agreement with the OZI rule prediction $R(\phi/\omega) \approx 4 \cdot 10^{-3}$. However, for small masses of the dipion system the values of $R(\phi/\omega)$ increase by 3-4 times leading to a significant deviation from the OZI rule prediction.

This effect was observed for the first time and it is important to demonstrate that it is not an artefact due to a difference in phase space for ϕ and ω production. The last column of Table contains the ratios R corrected for the difference in the phase space V for the reactions of $\phi\pi\pi$ and $\omega\pi\pi$ production.

$$R_C(\phi/\omega) = R(\phi/\omega)\frac{V(\omega\pi\pi)}{V(\phi\pi\pi)}$$

It turns out that after this correction the value of R only increases. It should be stressed that different forms of such correction have been discussed (see [1],[16] and references therein), including those with corresponding scaling factor about 1. So one could not conclude which ratio R or R_c is more correct, we will use whenever the R_c values.

The increasing of R at small dipion masses for annihilation in liquid could be explained as a manifestation of the difference in the amplitudes of ϕ and ω production. The conservation of C and P-parities in strong interactions unambigously couples the spin-triplet ${}^3S_1$ initial state with the $\phi(\omega)\pi\pi$ final state when two pions are in S-wave relative to each other. The spin-singlet initial ${}^1S_0$ state couples with the $\phi(\omega)\pi\pi$ system when the two pions are in P-wave, i.e. the final state is $\phi(\omega)\rho$. The partial wave analysis of the $\phi\pi\pi$ channel demonstrates [17] that in S-wave the production of ϕ mesons is completely dominated by the spin-triplet ${}^3S_1$ initial state, whereas for the ω meson production both the ${}^3S_1$ and ${}^1S_0$ states are important [14]. So the ratio R for annihilation in liquid, neglecting by the annihilation from the P-waves, is

$$R = \frac{Y(\phi\pi^+\pi^-)}{Y(\omega\pi^+\pi^-)} \approx \frac{Y(\phi(\pi^+\pi^-)_S)}{Y(\omega(\pi^+\pi^-)_S) + Y(\omega\rho)} \tag{3}$$

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

Analogous consideration for annihilation in gas is more complicated due to the significant contribution of the annihilation from P-wave. However, it is important to stress that the ratio R at small dipion masses in gas is high not due to increasing of the $\phi\pi^+\pi^-$ yield. As one could see from Table , the $Y(\phi\pi^+\pi^-)$ is the same for annihilation in liquid and in gas at small dipion mass, but it is the $\omega\pi^+\pi^-$ yield for $300 < M_{\pi\pi} < 500\ MeV/c^2$ mass interval in gas to be less than in liquid. Therefore again, as in case of annihilation in liquid, we observed the difference in the ϕ and ω production dynamics.

In Fig.3 the values of the R_c are compared with the results of other measurements of binary reactions of antiproton annihilation at rest. Some apparent dependence of the degree of the OZI-rule violation on the mass of the system created with ϕ is seen. For annihilation at rest $\bar{N}N \to \phi X$ a decreasing of the mass of X means an increase the momentum transferred to the ϕ. However, one should be cautious, because different binary reactions were measured for different initial states. Thus, the $\phi\gamma$,$\phi\rho$ and $\phi\omega$ final states for annihilation from S-wave produced from the $^1S_0$ initial state. Whereas the $\phi\pi$ and $\phi\eta$ channels come from the $^3S_1$ initial state. As discussed above, in liquid at small dipion masses both $\phi\pi^+\pi^-$ and $\omega\pi^+\pi^-$ channels come dominantly from the $^3S_1$ state. Therefore the corresponding ratio R could be directly compared with the values of $R(\phi\pi/\omega\pi)$ and $R(\phi\eta/\omega\eta)$. Doing so, it turns out that for the ϕ production from the $^3S_1$ initial state, the degree of the OZI rule violation increases with decreasing of the mass of the system created with ϕ, i.e. with the increasing of the momentum transfer.

It would be interesting to investigate further this possible dependence of the degree of the OZI rule violation on the momentum transfer. The same effect was found in ϕ production in $\pi^{\pm}N \to \phi N$ interaction [18] where the $d\sigma/dt$ distribution of ϕ production at large t differs significantly from the one for ω-meson, leading to the increase of ϕ/ω ratio at large t. The direct measurements of the t-dependence of the differential cross sections of $\phi\pi$ and $\omega\pi$ channels in $\bar{p}p$ annihilation in flight should clarify the problem.

In conclusion, the measurement of the ratio $R = Y(\phi\pi^+\pi^-)/Y(\omega\pi^+\pi^-)$ for annihilation of stopped antiprotons in gaseous and liquid hydrogen targets was performed. It was found that the value of this ratio increases with the decreasing of the dipion mass, which demonstrates the difference in the ϕ and ω production mechanisms. An indication on the momentum transfer dependence of the apparent OZI rule violation for ϕ production from the $^3S_1$ initial state was found.

We would like to thank the technical staff of the LEAR machine group for their support during the runs.

We are very grateful to J.Ellis and D.Kharzeev for interesting discussions.

The JINR group acknowledges the support from the International Science Foundation, grant No. ML9300.

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Table . Yields of ϕ and ω meson production in reactions (1)-(2) for annihilation of stopped antiprotons in liquid and gas targets (only statistical errors are taken into account). $R(\phi/\omega)$ and $R_C(\phi/\omega)$ are, respectively, the ratio of the yields without and with phase space correction.

	N_{ev}	$\varepsilon, \%$	$Y \cdot 10^4$	$R(\phi/\omega) \cdot 10^3$	$R_C(\phi/\omega) \cdot 10^3$
Liquid H_2					
All events					
$\phi\pi^+\pi^-$	853±94	1.08 ± 0.03	3.5±0.4	4.9 ± 0.8	10.3 ± 1.6
$\omega\pi^+\pi^-$	32042±1541	4.60± 0.41	719±74		
$300\ MeV/c^2 < M_{\pi\pi} < 500\ MeV/c^2$					
$\phi\pi^+\pi^-$	408±67	2.29 ± 0.09	0.7±0.1	16.5 ± 3.5	20.4 ± 4.3
$\omega\pi^+\pi^-$	1918±244	4.67± 0.40	42.4±6.5		
H_2 at 3 atm					
All events					
$\phi\pi^+\pi^-$	292±43	1.24±0.02	3.7±0.5	5.9 ± 0.9	12.5 ± 2.0
$\omega\pi^+\pi^-$	71640±1011	3.80± 0.20	628±34		
$300\ MeV/c^2 < M_{\pi\pi} < 500\ MeV/c^2$					
$\phi\pi^+\pi^-$	104±23	2.41±0.06	0.7±0.2	29.3 ± 8.6	36.2 ± 10.6
$\omega\pi^+\pi^-$	2701±578	3.74± 0.26	23.9±5.4		

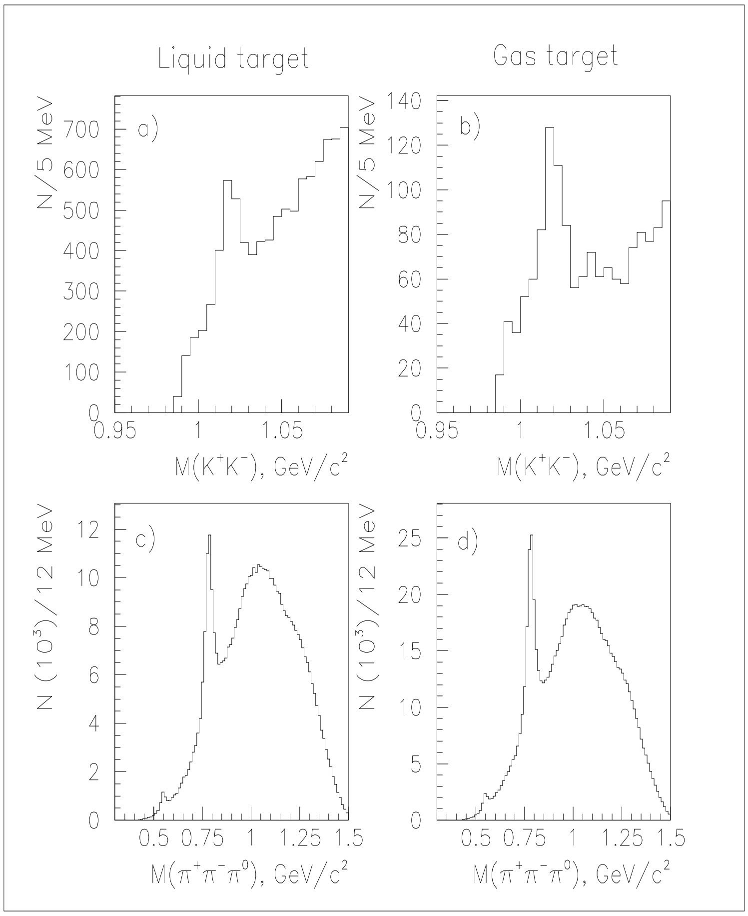

Figure 1: The K^+K^- and $\pi^+\pi^-\pi^0$ invariant mass spectra for the reactions $\bar{p}p \to K^+K^-\pi^+\pi^-$ (a,b) and $\bar{p}p \to 2\pi^+2\pi^-\pi^0$ (c,d) fr antiproton annihilation at rest in liquid target (a,c) and gas target (b,d) (uncorrected for apparatus acceptance) .

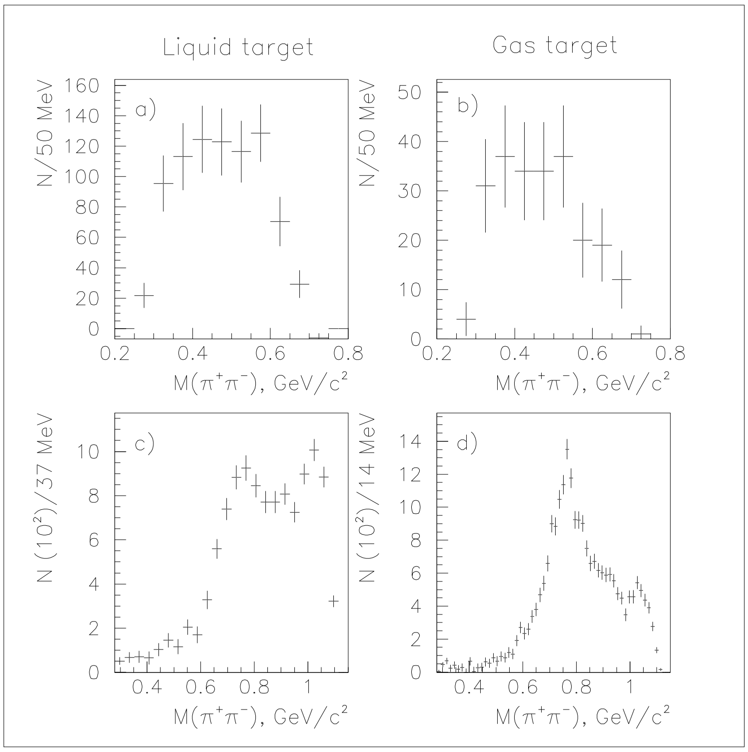

Figure 2: Background free $\pi^+\pi^-$ invariant mass distributions for the reactions $\bar{p}p \to \phi\pi^+\pi^-$ (a,b) and $\bar{p}p \to \omega\pi^+\pi^-$ (c,d) for antiproton annihilation at rest in liquid target(a,c) and gas target (b,d) (uncorrected for apparatus acceptance) .

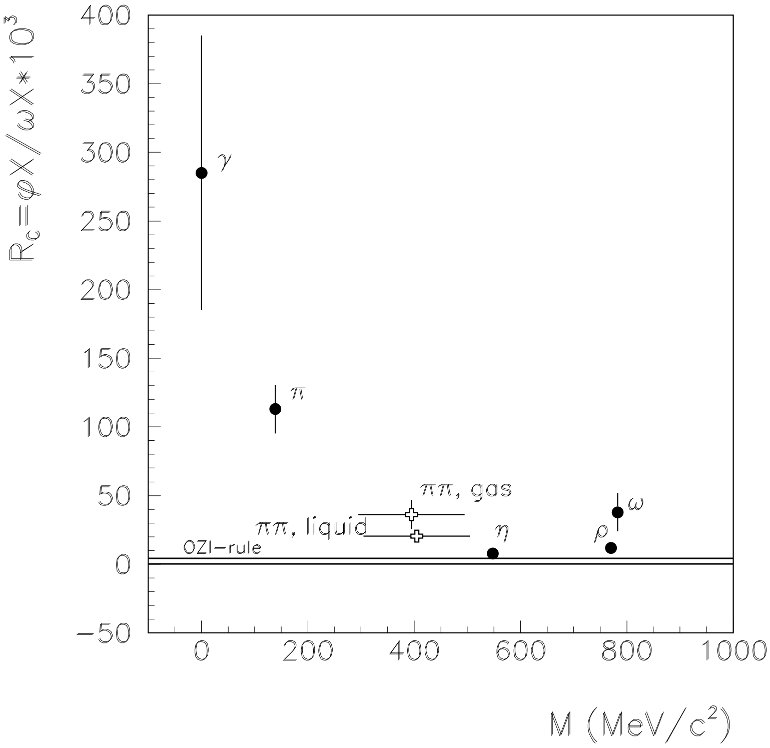

Figure 3: The ratio $R_C = \phi X/\omega X$ for different reactions of $\bar{p}p$ annihilation at rest as a function of the mass M of the system X. The crosses indicate the result of this experiment.