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STUDY OF $\omega\omega$ SYSTEMS PRODUCED IN 38 GeV/c $\pi^- p$ COLLISIONS

IHEP¹⁾ - IISN²⁾ - LANL³⁾ - LAPP⁴⁾ - TSU/IHEP⁵⁾ Collaboration

(Joint CERN - IHEP experiment)

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Abstract

The $\pi^- p \rightarrow \omega\omega n$ reaction has been studied for the first time at the 70 GeV IHEP accelerator. The six photons from the decay of the two ω mesons were detected in GAMS-2000, a hodoscope multi-photon spectrometer. Two resonances decaying into $\omega\omega$, X(1640) and X(1960), have been observed. Their quantum numbers are $J^{PC} = 2^{++}$, $1^G = 0^+$. The reaction is dominated by the one-pion exchange mechanism. The production cross sections $\sigma \cdot BR(X \rightarrow \omega\omega)$ are $0.65 \pm 0.15 \mu b$ and $1.0 \pm 0.2 \mu b$, respectively.

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Results on the study of neutral mesons, decaying into two ω , produced in the charge exchange-reaction

are presented. This work is part of the GAMS program (see [1] and references therein).

The only existing information on the $\omega\omega$ decay mode of mesons comes from the radiative decay $J/\Psi \rightarrow \gamma\omega\omega$, where a wide bump has been observed in the 0^{-+} wave in the region of 1.6 GeV to 2 GeV [2] - [4] and from a small number of $\omega\omega$ -events (29 ± 8), concentrated near threshold, observed in $\gamma\gamma$ -collisions [5] (see also [6]).

The experiment has been performed at the 70 GeV IHEP accelerator with 38 GeV/c pions. Omegas are observed through their decay into $\pi^0\gamma$. The six photons produced in reaction (1) were detected with the hodoscope multiphoton spectrometer GAMS-2000 [7]. The experimental setup, the measurement and basic data treatment procedures have been described elsewhere [8].

The difficulty of this study lies with the small branching ratio of the $\pi^0\gamma$ decay mode of ω , ($BR^2(\omega \rightarrow \pi^0\gamma) = 0.76\%$), and with the large combinatorial background (15 gamma-pair combinations for each event). The main sources of background are $M^0 \rightarrow 3\pi^0$, $\eta\pi^0\pi^0$, $\eta\eta\pi^0$ and also $\omega\pi^0\pi^0$ (with one undetected γ).

In order to separate reaction (1) events from all other recorded neutral events, 640 thousand 6γ events were selected and submitted to a kinematical fit. Each event was tested for its compatibility with the reactions

and $\pi^- p \rightarrow \pi^0\eta\gamma\gamma n$ (3C fit, mass of each particle fixed) as well as with reactions having the following final states: $3\pi^0 n$, $\pi^0\pi^0\eta n$ and $\pi^0\eta\eta n$ (4C fit). Events with the best χ^2 in the case of hypothesis (2) ($\chi^2 < 11.5$) and $\chi^2 > 25$ and 15 for hypotheses $3\pi^0 n$ and $\pi^0\pi^0\eta n$, respectively, were retained for further treatment. Furthermore, the invariant mass of the unpaired photons in reaction (2) was required to be outside the mass intervals corresponding to π^0 (50–220 MeV), η (460–660 MeV) and η' (850–1060

MeV). In order to reduce the instrumental background (due to heavy load in GAMS because of the high beam intensity, shower fluctuations, electronic noise) the following additional selection criteria were applied: a) the distance of the impact points of the photons on GAMS-2000 to the beam axis is larger than 6 cm; b) the energy of each photon is at least 0.6 GeV; c) the energy of the unpaired photons (2) is not lower than 1.5 GeV.

The two-dimensional distribution of 17000 selected events of type (2) as a function of the invariant mass of $\pi^0\gamma$ subsystems (2 entries per event) shows a clustering of ω -pairs produced in reaction (1) (Fig.1).

The purity of the sample of $\omega\omega$ -events is illustrated by Fig.2, where the invariant mass spectrum of one $\pi^0\gamma$ subsystem is shown when the mass of the other lies in the ω interval $700 \text{ MeV} < M_{\pi^0\gamma} < 880 \text{ MeV}$. After background subtraction, 1700 events of reaction (1) are left in the peak (each event contributes twice to the peak as both ω are identical). The background under the peak was estimated using the surrounding mass intervals, $600 - 700 \text{ MeV}$ and $880 - 980 \text{ MeV}$.

Reaction (1) has been simulated by the method of Monte Carlo. Detection efficiency ε has been evaluated using a bank of real photon showers in GAMS [9] and taking into account the experimental distribution versus t , the four-momentum transfer squared (see below). The resulting events were treated with the same set of programs that were used for the analysis of the experimental data, including the procedures of $\omega\omega$ -event selection and of background subtraction described below. The value of ε ($\approx 10\%$) shows no significant variation with the mass of the $\omega\omega$ -systems (in the region $< 3 \text{ GeV}$) as well as with the angles of M^0 and ω decays.

The simulation has shown that the most important source of background is the reaction $\pi^-p \rightarrow \omega\pi^0\pi^0n$ which, in the case of an undetected low energy photon ($\varepsilon \approx 0.5\%$), can be confused with reaction (1). However this background, which has a typical cruciform shape (Fig.3), does not significantly contribute to the measured events (Fig.1).

The number of $\omega\omega$ -events in 40 MeV invariant mass intervals has been obtained by subtracting the background which has been determined on Fig.2-like distributions in each interval. The shape of the $\omega\omega$ mass spectrum (Fig. 4) is not affected by efficiency corrections.

Two resonances are visible. Their masses are near 1640 MeV and 1960 MeV. Their statistical significance exceeds seven standard deviations. They are called X(1640) and X(1960) in what follows.

The mass and width of these mesons have been obtained after fitting the spectrum with two resonances and a continuous background (Fig.4). The continuum has been parametrized as follows: $(M - 2m_\omega)^{\mu} e^{-\nu M}$. The measured width of the peak near threshold is equal, within the experimental errors, to the instrumental resolution of the spectrometer. The mass and width of the resonances have similarly been evaluated from the mass spectrum of events which have satisfied a 4C fit of reaction (2) (fixing the mass of both π^0 , of the neutron and also of one of the $\pi^0\gamma$ -subsystems, $M_{\pi^0\gamma} = m_\omega$ in the combination which gives the lowest χ^2 value) (see Fig.2 and 4 and also Table 1). Fig.4 shows that in going from a 3C fit to a 4C fit a better mass resolution is obtained (Table 1); the left peak becomes more pronounced while the continuum decreases.

Table 1: Mass and width of the resonances (in MeV)

	X(1640)		X(1960)	
	3C fit	4C fit	3C fit	4C fit
M	1645 ± 8	1640 ± 5	1952 ± 17	1960 ± 20
Γ_{meas}	90 ± 23	76 ± 14	230 ± 70	260 ± 60
Γ_{instr}	100	45	120	80
Γ	< 80	< 70	190 ± 80	250 ± 60

The widths of the resonances have been determined from the measured widths of the peaks, taking into account the instrumental resolution of the spectrometer Γ_{instr} . The upper limits correspond to a C.L. of 90 %.

The parameters of the first resonance (near threshold) are:

$$M = (1643 \pm 7) \text{ MeV} , \quad \Gamma < 70 \text{ MeV} \quad (3)$$

(90% C.L. limits are given everywhere) and, in the case of X(1960), they are:

$$M = (1956 \pm 20) \text{ MeV} , \quad \Gamma = (220 \pm 60) \text{ MeV} \quad (4)$$

Spin and parity of these states have been determined from the angular distributions of their decay, using the formalism of helicity amplitudes for $\omega\omega$ -states with $J \leq 3$. The angular variables are [10] :

α , the angle between the ω decay planes in the M^0 rest frame, θ_{GJ} , the polar decay angle of $M^0 \rightarrow \omega\omega$ in the Gottfried-Jackson frame and β , the γ -emission angle in the rest frame of one ω relatively to the direction opposite to the momentum of the other one.

The angular distributions as a function of α and β may be written:

$$dN/d\alpha = A + B(4 \pm \cos 2\alpha) \quad (5)$$

(where the sign of the cosine depends on the parity of M^0 : $P = \pm 1$) and

$$dN/d\cos\beta = C + D\cos^2\beta. \quad (6)$$

The parameters A, B, C and D are functions of the square of the matrix elements of the decay $M^0 \rightarrow \omega\omega$ and of the density matrix elements of reaction (1).

Explicit expressions of the distributions are given in Table 2 for different quantum numbers [5], [6] In some cases they are rather simple. For pseudoscalar mesons it is :

$$dN/d\alpha \sim 4 - \cos 2\alpha \quad (7)$$

(maximum when the ω decay planes are perpendicular) while for scalar mesons it is :

$$dN/d\alpha \sim 1 + r^2(4 + \cos 2\alpha)/2 \quad (8)$$

(maximum in the case of coincident decay planes). Here $r = |t_{11}/t_{00}|$, $t_{\lambda\lambda'}$ is the matrix element of the $M^0 \rightarrow \omega\omega$ decay; λ, λ' are ω helicities. Thus, the α -distribution makes it possible to distinguish scalar from pseudoscalar states, and also to distinguish them from vector mesons for which $dN/d\alpha = \text{const.}$

The angular distributions of $\omega\omega$ -events in the mass intervals 1560–1720 MeV and 1780–2140 MeV, corresponding to X(1640) and X(1960), are shown on Fig.5. The background under the ω peak has been subtracted in each angular interval using the method described above. The detection efficiency has been normalized so that the number of $\omega\omega$ -events is conserved. The angular distributions obtained after 3C fit and 4C fit are in good agreement with each other.

Table 2: Angular distributions expected for different quantum numbers

J^{PC}	$dN/d\alpha$	$dN/d\cos\beta$
0^{++}	$1 + r^2(4 + \cos 2\alpha)/2$	$\sin^2\beta + r^2(1 + \cos^2\beta)$
0^{-+}	$4 - \cos 2\alpha$	$1 + \cos^2\beta$
1^{++}	constant	$3 - \cos^2\beta$
1^{-+}	constant	$3 - \cos^2\beta$
2^{++}	$1 + k_0^2(4 + \cos 2\alpha)$	$\sin^2\beta + k_1^2(1 + \cos^2\beta) + k_2^2(3 - \cos^2\beta)$
2^{-+}	$1 + q^2(4 - \cos 2\alpha)/8$	$2 + \sin^2\beta + q^2(1 + \cos^2\beta)$
3^{++}	constant	$2 + \sin^2\beta + g^2(1 + \cos^2\beta)$
3^{-+}	constant	$3 - \cos^2\beta$

$$r = |t_{11}/t_{00}|, \quad q \sim |t_{11}/t_{01}|, \quad g \sim |t_{1-1}/t_{01}|, \quad k_2 \sim |t_{01}/t_{00}|, \\ k_1^2 \sim |t_{11}|^2 + |t_{1-1}|^2 / |t_{00}|^2, \quad k_0^2 \sim |t_{11}|^2 / (4|t_{01}|^2 + 2|t_{1-1}|^2 + |t_{01}|^2)$$

Fig.5 shows that the distributions versus α as well as versus $\cos\beta$ for the X(1640) meson do not agree with a pseudoscalar interpretation of this state (Table 2). A simultaneous fit of both distributions gives a negligibly small probability for the hypothesis $J^{PC} = 0^{-+}$ (Table 3). Thus, X(1640) cannot be identified with the wide (300 MeV) pseudoscalar $\omega\omega$ -state observed in J/Ψ decays [2] - [4].

Table 3: Fits of the angular distributions

J^{PC}	C.L.	
	X(1640)	X(1960)
0^{++}	0.44	0.96
0^{-+}	$3 \cdot 10^{-6}$	10^{-7}
1^{++}	0.009	0.12
1^{-+}	0.009	0.12
2^{++}	0.20	0.90
2^{-+}	0.025	0.35
3^{++}	0.09	0.80
3^{-+}	0.009	0.12

The assignments $J^{PC} = 1^{++}, 1^{-+}, 2^{-+}, 3^{-+}$ are also excluded for X(1640). Confidence levels C.L. $> 10\%$ are only obtained for this state with scalar and tensor assignments 0^{++} and 2^{++} . In these two cases, the theoretical formulae provide acceptable fits of the measured angular distributions (C.L. = 44% and 20%, respectively).

In order to determine the quantum numbers of X(1640), another step can be made in proceeding from a model-independent analysis to an analysis taking into account the dynamics of the interactions. Fig.6 shows that the t -dependence of the production cross section of X(1640) in reaction (1) has the shape characteristic for one-pion exchange (OPE):

$$dN/dt \sim -t(t - m_\pi^2)^{-2} e^{bt} \quad (9)$$

with a value of the slope parameter $b = (4.3 \pm 0.8) (\text{GeV}/c)^{-2}$, typical for OPE.

If OPE is the leading mechanism in reaction (1), only even states are allowed: $0^{++}, 2^{++}, \dots$. The distributions versus α and β for spin 0 and 2 are practically identical (Fig.5). The expected OPE angular distribution for spin 0 and 2 in the Gottfried-Jackson frame are also very similar (Fig.7). At the precision level reached in this work, the measured angular distributions do not allow to distinguish between the two hypotheses, $J^{PC} = 0^{++}$ or 2^{++} (C.L. = 60% and 35%, fitting the three distributions simultaneously).

The production cross section of X(1640) in reaction (1) has been determined from the number of events in the peak above the continuum, taking into account the detection efficiency ε (Fig.4). The 3C fit and 4C fit give the same result:

$$\sigma(\pi^- p \rightarrow X(1640)n) \cdot \text{BR}(X(1640) \rightarrow \omega\omega) = (0.65 \pm 0.15) \mu\text{b} \quad (10)$$

This result has been obtained by normalization to the measured cross section for $\pi^- p \rightarrow \eta' n$, $\eta' \rightarrow \eta\pi^0\pi^0$ [11], [12] which is observed simultaneously with reaction (1) in the course of this experiment.

The error quoted in (10) includes systematic errors connected with the uncertainty in the possible contribution of the continuum. In order to evaluate the fluctuations of this contribution, the parameters in the continuum expression (see above) have been varied. Similar results are obtained with a polynomial form.

The contribution to the cross section of the background process $\pi^- p \rightarrow \omega\pi^0\pi^0 n$ has been evaluated by studying events with seven photons in the final state. The resulting mass spectrum of $\omega\pi^0\pi^0$ events (a process observed for the first time) does not show any resonating structure. The contribution of this reaction (including that due to the decay $\omega(1670) \rightarrow \omega\pi^0\pi^0$) to the background does not exceed

12% in the case of the 3C fit and is less than 5% for the 4C fit as shown by the Monte Carlo evaluation of the "leakage" of $\omega\pi^0\pi^0$ events into $\omega\pi^0\gamma$ (one γ undetected).

The OPE model [13] links the production cross section to the spin, mass and width of the particle.¹ Using the mass and width values given in (3) one obtains the following limit for the production of X(1640)

$$\sigma(\pi^-p \rightarrow X(1640)n) < 3.4 (2J + 1) \cdot \text{BR}(X \rightarrow \pi^+\pi^-) \mu\text{b} \quad (11)$$

From this and (10) follows the inequality:

$$\text{BR}(X \rightarrow \omega\omega) \cdot \text{BR}(X \rightarrow \pi^+\pi^-) > 0.19 / (2J + 1). \quad (12)$$

As $\text{BR}(X \rightarrow \rho\rho) = 3 \cdot \text{BR}(X \rightarrow \omega\omega)$ and $\text{BR}(X \rightarrow \pi\pi) = 3 \cdot \text{BR}(X \rightarrow \pi^+\pi^-)/2$, it follows:

$$\text{BR}(X \rightarrow \omega\omega + \rho\rho) \cdot \text{BR}(X \rightarrow \pi\pi) > 1.14 / (2J + 1) \quad (13)$$

For $J = 0$ this inequality is not satisfied, i.e. at the left stands a value $\leq 1/4$ while the right side is equal to 1. For $J = 2$ the inequality can be satisfied.

Thus, in the framework of OPE a zero value for the spin of X(1640) is excluded. A spin value much larger than 2 is unlikely because in this case the cross section of reaction (1) would be strongly suppressed by the barrier factor $(p^*/p_0^*)^{2\ell+1}$ ($\ell \geq 2$). Moreover, the angular distribution of the decay $X(1640) \rightarrow \omega\omega$ in the Gottfried-Jackson frame (Fig.7) excludes a spin 4.

So, the quantum numbers of the X(1640) meson have the following values:

$$J^{PC} = 2^{++}, \quad IG = 0^+ \quad (14)$$

(Isospin and G-parity are deduced from the decay mode).

The X(1960) meson has many common features with the previous resonance. A model-independent analysis of its decay angular distributions (Fig.5) excludes also completely a pseudoscalar state (Table 3). Fig.6 shows that the reaction $\pi^-p \rightarrow X(1960)n$ is dominated by OPE ($b = 3.5 \pm 0.5 \text{ (GeV/c)}^{-2}$) which only leaves the possibility of even states: $0^{++}, 2^{++}, 4^{++} \dots$.

¹ The coefficient Λ of formula $\sigma = \Lambda(2J + 1) \cdot \text{BR}(X \rightarrow \pi^+\pi^-) M\Gamma/E^2$ in ref. 13 has been doubled according to a remark of N.N.Achasov.

The production cross section of $X(1960)$ in reaction (1) is equal to

$$\sigma(\pi^-p \rightarrow X(1960)n) \cdot \text{BR}(X(1960) \rightarrow \omega\omega) = (1.0 \pm 0.2) \mu\text{b}. \quad (15)$$

The OPE model mentioned above gives the following relation :

$$\text{BR}(X \rightarrow \omega\omega + \rho\rho) \cdot \text{BR}(X \rightarrow \pi\pi) = (0.5 \pm 0.1)/(2J + 1), \quad (16)$$

that can only be marginally satisfied with $J = 0$.

The decrease of the cross section due to barrier effects is not as large for $X(1960)$, which is comparatively far from threshold, as it is in the case of the $X(1640)$ resonance. So, it might have spin-parity 2^{++} and 4^{++} . But, the angular distribution in the Gottfried-Jackson frame (Fig.7) certainly favors spin 2. Thus, $X(1960)$ has most probably the same quantum numbers (14) as the first resonance. The angular distribution of Fig.7 does not exclude a possible contribution from the spin 4 $h(2030)$ meson [14] in the region of the second peak in the mass spectrum (Fig.4) at a level $< 0.5 \mu\text{b}$. This agrees with the estimation $\sigma(\pi^-p \rightarrow hn) \cdot \text{BR}(h \rightarrow \omega\omega) \approx 0.6 \mu\text{b}$.

A possible explanation of these mesons might be that they are radial excitations of $f(1270)$.

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Figure Captions

Fig.1 Two-dimensional distribution of the invariant mass of $\pi^0\gamma$ subsystems (1/3 of the total statistics). The arrows indicate the tabulated mass of the ω meson.

Fig.2 a) Invariant mass spectrum of one of the $\pi^0\gamma$ subsystems in reaction (2) when the second one has been identified as a ω ($700 < M_{\pi^0\gamma} < 880$ MeV); 3C fit. The dashed line is the background level. b) Same as a) but after 4C fit.

Fig.3 Two-dimensional distribution (analogous to Fig.1) obtained by Monte Carlo simulation of reaction $\pi^-p \rightarrow M^0n$, $M^0 \rightarrow \omega\pi^0\pi^0$ when one of the γ from a decaying π^0 is not detected in the spectrometer. The distribution is uniform in M^0 mass.

Fig.4 Invariant mass spectrum of $\omega\omega$ systems in reaction (1). The full curve is the result of a fit with two resonances and a continuum (dashed curve: $(M - 2m_\omega)e^{-\nu M}$). a) 3C fit, b) 4C fit. Here and further $|t| < 0.4$ (GeV/c)².

Fig.5 Angular distributions (5) and (6) of the decays $X(1640) \rightarrow 2\omega \rightarrow 2(\pi^0\gamma)$ and $X(1960) \rightarrow 2\omega \rightarrow 2(\pi^0\gamma)$. The curves are the result of a fit with parameters given in Table 2. Spin-parities J^P are marked on the curves. C.L. values are given in Table 3.

Fig.6 Differential distributions of events in reactions $\pi^-p \rightarrow X(1640)n$ and $\pi^-p \rightarrow X(1960)n$ versus the four-momentum transfer squared. The dashed curve is the OPE dependence.

Fig.7 Angular distributions of the decays $X(1640) \rightarrow \omega\omega$ and $X(1960) \rightarrow \omega\omega$ in the Gottfried-Jackson frame. The curves are the result of a joint fit of the distributions versus α , β and θ_{GJ} in the case of OPE for the states 0^{++} , 2^{++} , 4^{++} .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig.7