# FIRST OBSERVATION OF $\gamma\gamma \to \omega\rho^0$

ARGUS Collaboration

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The reaction $\gamma\gamma \to 2\pi^+2\pi^-\pi^0$ has been studied using the ARGUS detector at the $e^+e^-$ storage ring DORIS II at DESY. The production of the vector-meson pair $\omega\rho^0$ is observed for the first time. The cross section for $\gamma\gamma \to \omega\rho^0$ and the topological cross section for $\gamma\gamma \to 2\pi^+2\pi^-\pi^0$ are given. The angular distribution in $\omega\rho^0$ events do not indicate any specific dominant spin–parity; they are consistent with isotropic production and decay of the $\omega$ and $\rho^0$ mesons over the available $W_{\gamma\gamma}$ range.

*Introduction*

The first observation of the reaction $\gamma\gamma \to \omega\rho^0$ together with a determination of its cross section is presented. Previous measurements of vector-meson pair production in photon–photon interactions have, except for $\rho^0\rho^0$ [1–4], resulted in upper limits only [5–7]. The $\rho^0\rho^0$ cross section showed an unexpectedly large enhancement in the threshold region, while the $\rho^+\rho^-$ cross section [5] was found to be suppressed. This disagrees with an explanation in terms of conventional resonances, where the decay into $\rho^+\rho^-$ is expected to occur with a rate twice of that into $\rho^0\rho^0$. The resonance interpretation can be maintained by invoking a model where states with different isospins interfere. Such a situation has been predicted [8,9] by incorporating four-quark states [10]. Here two degenerate states with isospin 0 and isospin 2 interfere in a way to suppress $\rho^+\rho^-$ production. The $\rho^0\rho^0$ is also found to be enhanced at threshold in a $t$-channel factorization model [11].

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To further test these models and to provide complementary information, measurements of photon–photon production of vector-meson pairs other than $\rho^0\rho^0$ are necessary. Such a measurement, the reaction $\gamma\gamma \to \omega\rho^0 \to 2\pi^+2\pi^-\pi^0$, is reported here. The data, corresponding to an integrated luminosity of 234.3 $pb^{-1}$, were collected using the ARGUS detector at the $e^+e^-$ storage ring DORIS II at DESY. The beam energies varied between 4.7 and 5.3 GeV.

ARGUS is a universal magnetic detector described elsewhere [12]. Besides its good momentum resolution and identification capability for charged particles, the most important feature for the present investigation is the good energy resolution of the ARGUS electromagnetic calorimeter [13] which covers 96% of the full solid angle.

*Event selection*

Candidate events for the reaction $\gamma\gamma \to 2\pi^+2\pi^-\pi^0$ were selected by requiring four charged particles with zero net charge originating from a common event vertex. These particles had to be identified as pions with a likelihood greater than 5% using information from the $dE/dx$ and time-of-flight measurements [12]. Exactly two photons had to be detected in the calorimeter with a minimum energy in the range between 50 and 70 MeV depending on the running conditions. A $\pi^0$ candidate was formed by combining the two photons. To be finally accepted, its mass had to lie between 60 and 220 MeV/$c^2$ and pass a 1-C fit to the nominal $\pi^0$ mass. A cut on the scalar momentum sum of the five pions $P^{\rm sum} = \sum |\boldsymbol{p}_i| \leqslant 3.5$ GeV/$c$ and a cut on the total transverse momentum $P_T^{\rm tot} = |\sum \boldsymbol{p}_{T,i}| \leqslant 100$ MeV/$c$ were used to enhance photon–photon interactions and suppress background from $\tau$ decays and incompletely reconstructed events. Finally, the total transverse momentum of the four *charged* pions was required to be larger than 40 MeV/$c$ in order to suppress background from $\gamma\gamma\to 2\pi^+2\pi^-$ with additional noise in the calorimeter. After imposing these selection criteria, 889 events remain.

*Monte Carlo simulation*

To determine the acceptance, photon–photon interactions were generated according to the exact QED expression for collisions of transverse photons [14]. Isotropic phase space was used to simulate the final states $2\pi^+2\pi^-\pi^0$, $\omega\rho^0$, $\omega\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $2\pi^+2\pi^-2\pi^0$ and $\omega\pi^+\pi^-\pi^0$. Of these final states, the first three are relevant for the reactions of interest here and the last two are dominant background reactions. The $\pi^+\pi^-\pi^0$ and the $\omega\pi^+\pi^-$ final states were used to estimate the contribution due to $a_2(1320)$ resonance formation. The $\omega$ meson decayed according to its matrix element into three pions. Each Monte Carlo data set was generated with a beam energy distribution identical to that of the data. The Monte Carlo events were passed through a full detector [15] and trigger simulation and subjected to the same selection criteria as the data. The trigger simulation uses thresholds of the detector components as determined from real data and accounts for the variation in actual trigger conditions. The simulation of random noise in the calorimeter was determined from data using $\Upsilon(1S)\to\ell^+\ell^-$ with $\ell=e$ or $\mu$ events, tagged by the pions from the transition $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$. In the range $1<W_{\gamma\gamma}<3.5$ GeV/$c^2$, the resulting sensitivity for $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$ falls smoothly from about 4 to 3 events/nb of the $\gamma\gamma$ cross section and per 100 MeV/$c^2$ of $W_{\gamma\gamma}$. The sensitivity for $\gamma\gamma\to\omega\rho^0$, with $W_{\gamma\gamma}>1.2$ GeV/$c^2$, is about 25% lower.

The systematic uncertainties in the final cross sections are estimated to be $\pm 13\%$ for $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$ and $^{+16}_{-30}\%$ for $\gamma\gamma\to\omega\rho^0$ by adding in quadrature the following contributions: trigger simulation ($\pm 5\%$); luminosity measurement ($\pm 5\%$); Monte Carlo calculated acceptance for $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$ ($\pm 10\%$) and for $\gamma\gamma\to\omega\rho^0$ ($\pm 12\%$); background estimates ($\pm 4\%$). For $\gamma\gamma\to\omega\rho^0$ there are additional uncertainties of ($\pm 5\%$) from the $\omega$ meson fits and ($^{0}_{-25}\%$) due to a possible $\omega\pi^+\pi^-$ contribution.

*Results*

*(a) The reaction $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$.* After correcting for background and acceptance, the topological cross section for $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$, shown in fig. 1, is obtained. The background is estimated to contribute 141 out of the total 889 events. Our result agrees with the measurement by the PLUTO collaboration [7] in the $W_{\gamma\gamma}$ range common to both experiments.

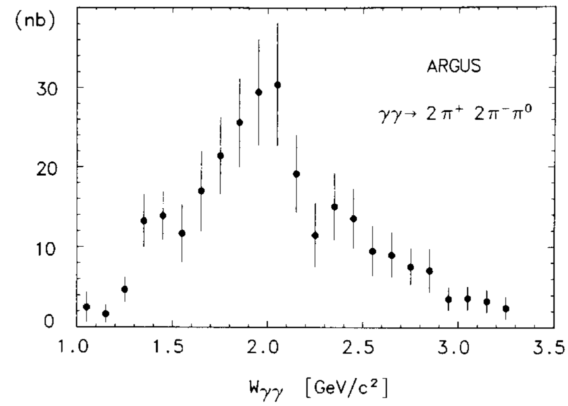


Fig. 1. Cross section for $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$ versus $W_{\gamma\gamma}$. The error bars are purely statistical.

The main background reactions are $\gamma\gamma\to 2\pi^+2\pi^-2\pi^0$ with two undetected photons, $\tau$ decays and incompletely reconstructed annihilation events. The background from $\gamma\gamma\to 2\pi^+2\pi^-2\pi^0$ is estimated from our data on this channel, together with a Monte Carlo calculation of the feeddown into $2\pi^+2\pi^-\pi^0$, to contribute 103 events. The remaining background was assumed to have a flat $(P_T^{tot})^2$ distribution, as indicated by events with 5 charged pions. It was estimated from a fit to the $(P_T^{tot})^2$ distribution, consisting of one part determined from the Monte Carlo shape and one constant term to account for the background. After applying the $P_T^{tot}$ cut, 38 background events were found comprising $\tau$ pair events, incompletely reconstructed annihilation events, and $\gamma\gamma\to 2\pi^+2\pi^-$ events with additional noise in the calorimeter. Events from $\gamma\gamma\to 2\pi^+2\pi^-\pi^0$ with one lost and one fake photon are expected to fall into this category as well, as was found by Monte Carlo simulation.

*(b) The reaction $\gamma\gamma\to\omega\rho^0$.* Fig. 2 shows the invariant $\pi^+\pi^-\pi^0$ mass distribution. Clear signals from the $\omega(783)$ and $\eta(549)$ mesons are seen. However, this study concentrates on events with an $\omega$ meson. Therefore the reaction $\gamma\gamma\to\eta\pi^+\pi^-$ will not be considered here. Also shown in fig. 2 is a fit to the data points using an s-wave Breit–Wigner distribution,

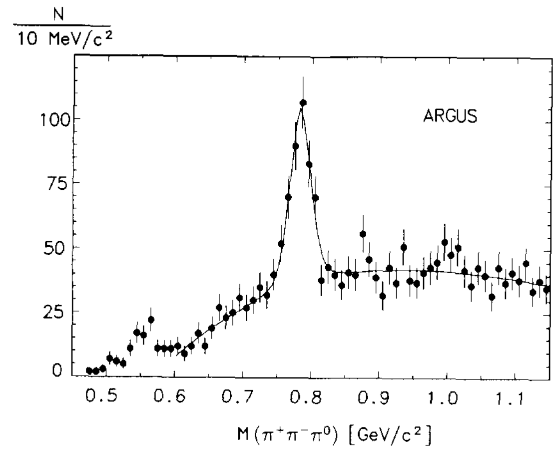


Fig. 2. Invariant $\pi^+\pi^-\pi^0$ mass spectrum in 10 MeV/$c^2$ per bin. The fit consists of a Breit–Wigner distribution, with parameters of the ω meson, convoluted with the gaussian mass resolution of the detector, and a third-order polynomial.

with the parameters of the ω meson [16], convoluted with a gaussian describing the mass resolution of the ARGUS detector, and the background parametrized by a third-order polynomial. The ω peak is found by the fit to contain $294 \pm 27$ entries.

Figs. 3a–3c show measured mass spectra of the two pions recoiling against the ω meson for different $W_{\gamma\gamma}$ intervals. They are compared to spectra from Monte Carlo simulations of $\gamma\gamma \to \omega\rho^0$ and $\gamma\gamma \to \omega\pi^+\pi^-$ events, with their resulting $W_{\gamma\gamma}$ distribution adjusted to agree with the $W_{\gamma\gamma}$ distribution of the ω mesons observed in the data. The measured mass spectra were obtained, for each mass bin, by determining the number of ω mesons from fits to the corresponding $\pi^+\pi^-\pi^0$ mass distributions. The expected background from $\gamma\gamma \to \omega\pi^+\pi^-\pi^0$ has been subtracted (see below). Note that at low $W_{\gamma\gamma}$ the $\rho^0$ meson has to be produced with a mass below its nominal value of 770 MeV/$c^2$. Clearly the data favour the $\omega\rho^0$ hypothesis over the whole $W_{\gamma\gamma}$ range. In what follows all events are assumed to be $\omega\rho^0$, although there is room for an $\omega\pi^+\pi^-$ contribution. The systematic error in the $\omega\rho^0$ cross section accounts for these uncertainties.

The cross section for $\gamma\gamma \to \omega\rho^0$ is shown in fig. 4, after correcting for acceptance and background as well as for the branching ratio for $\omega \to \pi^+\pi^-\pi^0$ [16]. It was studied by determining the number of ω mesons for each 100 MeV/$c^2$ bin of the total five-pion

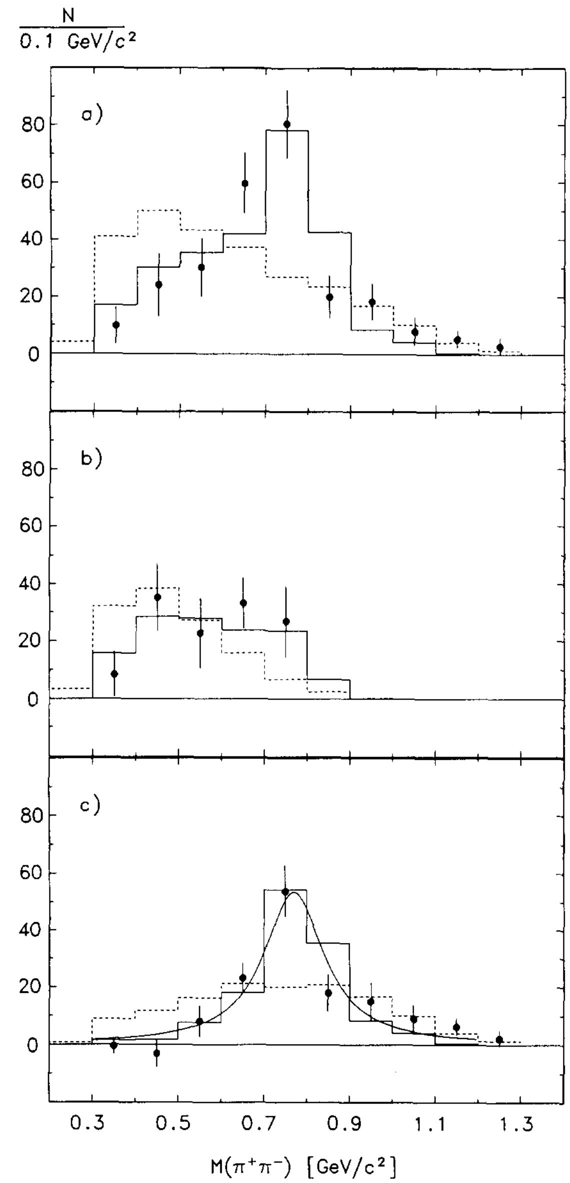


Fig. 3. Invariant mass spectra of the $\pi^+\pi^-$ pair recoiling against the ω. Data points are shown with error bars and the expected Monte Carlo distributions as full ($\omega\rho^0$) and dashed ($\omega\pi^+\pi^-$) histograms. A division into regions of $W_{\gamma\gamma}$ is made: (a) all, (b) $\leqslant 1.7$ GeV/$c^2$ and (c) $> 1.7$ GeV/$c^2$. Also shown in (c) is a Breit–Wigner curve with the parameters $\Gamma = 150$ MeV/$c^2$ and $M = 770$ MeV/$c^2$ of the $\rho^0$ meson.

mass $W_{\gamma\gamma}$ from fits to the respective $\pi^+\pi^-\pi^0$ mass distributions. The only significant background comes from $\gamma\gamma \to \omega\pi^+\pi^-\pi^0$. There are no published mea-

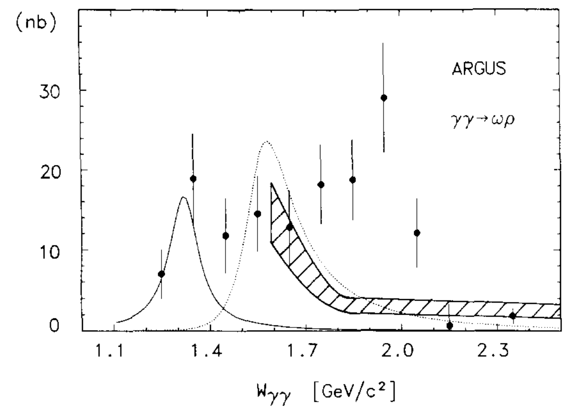


Fig. 4. Cross section for $\gamma\gamma\to\omega\rho^0$. The error bars are purely statistical. Also shown is the expected $a_2(1320)$ contribution (full line), a four-quark state prediction [8] (dotted) with $m=1.65$ GeV/$c^2$ and $a_0=0.5$, and the prediction by a $t$-channel factorization model [11] (hatched region).

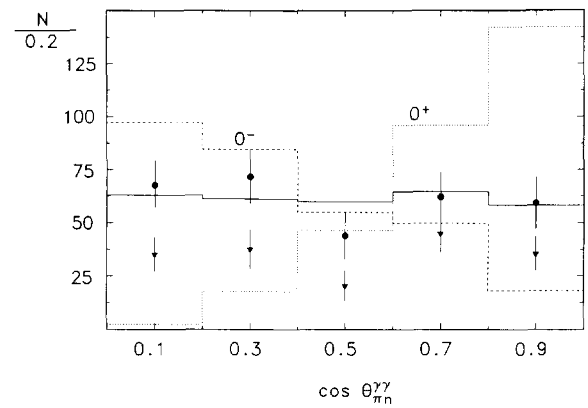


Fig. 5. Measured cos $\theta_{\pi n}$ distribution in $\omega\rho^0$ events (not acceptance corrected). Data points are shown with error bars for all $W_{\gamma\gamma}$ (circles) and $W_{\gamma\gamma}>1.7$ GeV/$c^2$ (triangles). A comparison is made to Monte Carlo predictions (which are normalized to data for all $W_{\gamma\gamma}$) shown as histograms: isotropic production and decay of the $\omega\rho^0$ system (full histograms); and two spin-parity states $J^P=0^+$ (dotted) and $J^P=0^-$ (dashed).

surements of this reaction available. However, using our own data sample of this reaction together with a Monte Carlo calculation of the feeddown into $\omega\rho^0$, this background is estimated to be 23 events. Contributions from $\tau$ pair events, where one $\tau$ decays into $\pi^+\nu$ and the other into $\omega\pi^-\nu$, and from inclusive $e^+e^-\to\omega X$ are negligible due to the $P_T^{tot}$ and $P^{sum}$ cuts.

Photon-photon production of the $a_2(1320)$ meson decaying into $\pi^+\pi^-\pi^0$ is well known. As this meson also has a decay mode $\omega\pi^+\pi^-$, a contribution is expected in the reaction studied here. From our data on $\gamma\gamma\to\pi^+\pi^-\pi^0$, which show the formation of about 1050 $a_2(1320)$ mesons, $67\pm19$ $a_2(1320)$ mesons are expected in the $\omega\pi^+\pi^-$ channel. This agrees with the data as is shown in fig. 4 by the Breit–Wigner distribution for the $a_2(1320)$ meson [16]. Two model predictions are shown as well: a four-quark model [8] and a $t$-channel factorization model [11]. The four-quark state has a mass of 1.65 GeV/$c^2$ and a parameter $a_0$ equal to 0.5 as in ref. [8]. $a_0$ is related to the OZI suppression of other decay modes. The data allows for either of these contributions. However, the data show around at 1.9 GeV/$c^2$ an excess over the model predictions with an abrupt decrease above 2.1 GeV/$c^2$. This is not expected within these models [8,11] and cannot be related to any known resonance [16]. Notice that the model [8] can allow for a change in its parameters leading to a different shape and position of the four-quark state, but not in such a way as to account for the excess around 1.9 GeV/$c^2$. No $\omega$ mesons are seen for $W_{\gamma\gamma}>2.5$ GeV/$c^2$, which is not due to any acceptance effect as the sensitivity is still comparatively large in this region, about 75% of the sensitivity for $W_{\gamma\gamma}<2.5$ GeV/$c^2$.

The presence of a resonance with a definite spin–parity would manifest itself in the angular correlations of the $\omega\rho^0$ production and of the decays of the $\omega$ and $\rho^0$ mesons. The lowest possible spin–parity states in interactions between two real photons have $J^P=0^+, 0^-, 2^+$ and $2^-$. These states occur only with a $\gamma\gamma$-helicity $J_z=0$, except for $J^P=2^+$ which can also be produced with $J_z=2$. The possible states are unique except for $J^P=2^-$ which can occur with the spin $S=1$ or $S=2$ of the $\omega$ and $\rho^0$. Restricting the analysis to the lowest orbital angular momenta in the $\omega\rho^0$ system, one obtains 6 independent amplitudes.

Fig. 5 shows as an example of measured angular distributions the cos $\theta_{\pi n}$ distribution, compared to Monte Carlo simulations. $\theta_{\pi n}$ is the angle between the $\pi^+$ from the $\rho$ decay and the normal to the $\omega$ decay plane. The data points were obtained by determining the number of $\omega$ mesons by fits to the three pion mass spectra divided into five bins of the respective angles and are not corrected for acceptance effects. Fig. 5 shows data points both for all

$W_{\gamma\gamma}$ and for $W_{\gamma\gamma} > 1.7$ GeV/$c^2$ together with the expectation from $0^-$ and $0^+$ spin–parity states and from isotropic production and decay. The present statistics do not allow a sub-division into finer bins of $W_{\gamma\gamma}$. The Monte Carlo distributions were obtained by weighting the phase-space generated $\omega\rho^0$ Monte Carlo events with the matrix element of the corresponding spin–parity state and normalizing them to the data for all $W_{\gamma\gamma}$. The acceptance is approximately the same for both ranges of $W_{\gamma\gamma}$ chosen.

In a further test, the angular distributions were decomposed into 16 orthogonal functions as in ref. [3]. The moments (coefficients) of these functions obtained from data were compared to Monte Carlo.

The result of both these methods is that none of the spin–parity states considered dominates. The data agree with isotropic production and decay in all angles and all moments and for all $W_{\gamma\gamma}$. This does not exclude the presence of resonances, since a suitable mixture of a few spin–parity states, or two helicity states of a single resonance (i.e. $J^P = 2^+$), could simulate an isotropic production. At present, the limited statistics do not allow this question to be settled.

*Conclusions*

The reaction $\gamma\gamma \to 2\pi^+2\pi^-\pi^0$ was studied using the ARGUS detector at the $e^+e^-$ storage ring DORIS II at DESY. For the first time, the reaction $\gamma\gamma \to \omega(783)\pi^+\pi^-$ has been observed. These events were found to be consistent with being pure $\omega\rho^0$ for all $W_{\gamma\gamma}$. The topological cross section for $\gamma\gamma \to 2\pi^+2\pi^-\pi^0$ and the cross section for $\gamma\gamma \to \omega\rho^0$ were measured. For $W_{\gamma\gamma}$ around 1.9 GeV/$c^2$, the $\omega\rho^0$ production exceeds appreciably that predicted by both a four-quark and a $t$-channel factorization model. The angular distributions in $\omega\rho^0$ events do not indicate any dominant spin–parity.

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