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A spin–parity analysis of $\gamma\gamma \to \rho^+\rho^-$

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A spin–parity analysis of the $\rho^+\rho^-$ system in the reaction $\gamma\gamma\to\rho^+\rho^-\to\pi^+\pi^-\pi^0\pi^0$ has been performed using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The cross section is found to be dominated by the amplitudes $J^P=0^+$, and $J^P=2^+$ ($J_z=2$).

The final state $\pi^+\pi^-\pi^0\pi^0$ produced in two-photon reactions has recently been measured by ARGUS [1], and, for the first time, the decomposition of the cross section in terms of $\rho^+\rho^-$, $\rho^\pm\pi^\mp\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$ (phase space) was determined. This report is an extension of that analysis to determine the spin–parity decomposition of the $\rho^+\rho^-$ system.

The cross section for $\gamma\gamma\to\rho^+\rho^-$ [1] has been found to be about a factor four lower than that for $\gamma\gamma\to\rho^0\rho^0$ [2,3]. This difference can be explained by models involving $qq\bar{q}\bar{q}$ states [4,5]. In ref. [4] the authors predict that the $\rho\rho$ system will be produced by a mixture of $qq\bar{q}\bar{q}$ states with masses around 1.4 GeV/c^2 and 1.6 GeV/c^2 and with $J^P=2^+$, whereas in ref. [5] the authors expect the production of mass degenerate $J^P=2^+$ and $J^P=0^+$ states.

Other experiments [2] have previously analyzed the spin–parity decomposition of the $\rho^0\rho^0$ system. Positive parities have clearly been found to dominate the cross section, but the separation between 0^+ and 2^+ leads to inconsistent results. Recently ARGUS has reported on the spin–parity decomposition of the $\gamma\gamma\to\rho^0\rho^0$ channel [3], using a much larger data sample than any previous analysis. It was found that the $\rho^0\rho^0$ channel is dominated by the 2^+ ($J_z=2$) amplitude with a relatively smaller contribution of the 0^+ amplitude.

In this paper the first measurement of the spin–parity decomposition of the $\rho^+\rho^-$ system is reported. The data correspond to an integrated luminosity of 234 pb^{-1} and are collected with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. ARGUS is a universal spectrometer with cylindrical symmetry and is described elsewhere [6]. The data sample and the selection criteria are identical to those of our previous measurement [1] of the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ and its decomposition in terms of $\rho^+\rho^-$, $\rho^\pm\pi^\mp\pi^0$, and $\pi^+\pi^-\pi^0\pi^0$.

Candidate events were selected by requiring two oppositely-charged particles which fit to a common event vertex and are identified as pions with likelihood ratios larger than 5%. Exactly four photons were required with minimum energies of 50 MeV. A π^0 candidate was defined as a combination of two photons with an invariant mass between 60 and 220 MeV/c^2 and with an opening angle smaller than 90°. The π^0 candidates were constrained to the π^0 mass by a kinematical fit. In events with more than two π^0 candidates, only the two which resulted in the smallest total transverse momentum, p_T, for the event were used. The scalar momentum sum of the four pions, $\sum|\boldsymbol{p}_i|$, was required to be less than 3.5 GeV/c and the total transverse momentum, $p_T=|\sum\boldsymbol{p}_{T,i}|\leqslant 100$ MeV/c. With these cuts, 1332 events were selected, of which 1203 were attributed to the reaction $\gamma\gamma\to\pi^+\pi^-\pi^0\pi^0$ and 129 events were background from incompletely reconstructed events or events containing noise photons [1].

The acceptance was determined by a Monte Carlo program which generated events according to the flux

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of two transverse photons [7], a constant two-photon cross section and a beam energy distribution as in the data sample. The final state $\pi^+\pi^-\pi^0\pi^0$ was generated according to a phase space distribution. For other final states, such as $\rho^+\rho^-$, the Monte Carlo generated $\pi^+\pi^-\pi^0\pi^0$ events were weighted with the relevant matrix elements (see ref. [1] and below). A detailed detector and trigger simulation was performed.

In our previous report [1], a maximum likelihood method was used to determine the decomposition in three incoherent final states: isotropic $\rho^+\rho^-$, $\rho^\pm\pi^\mp\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$. Here the method is extended by analyzing the $\rho^+\rho^-$ system in terms of states with definite spin–parity, J^P.

The differential cross section for the reaction $\gamma\gamma\to X$ for fixed $W_{\gamma\gamma}$ was parametrized by

$$\frac{d\sigma}{d\xi}=C\, W_4(W_{\gamma\gamma})\,|g_X(\xi)|^2\,,$$

where C is a constant, W_4 the four-pion phase space density, and g_X the matrix element for the various final states X,

$$X=\rho^+\rho^-(J^P),\ \rho^\pm\pi^\mp\pi^0,\ \pi^+\pi^-\pi^0\pi^0\,.$$

The symbol ξ represents the set of seven variables needed to describe the four-pion system,

$$\xi=(m_{12}^2, m_{34}^2, \zeta_{1234})$$
$$=(m_{12}^2, m_{34}^2, \theta_\rho^{12}, \theta_\pi^{12}, \phi_\pi^{12}, \theta_\pi^{34}, \phi_\pi^{34})\,,$$

where the numbers 1, ..., 4 refer to the four pions using the convention: $\pi_1^+\pi_2^0\pi_3^-\pi_4^0$. The variable m_{ij} denotes the invariant mass of two pions i and j; θ_ρ^{ij} the production angle of the system ij in the $\gamma\gamma$ center-of-mass system with the $\gamma\gamma$ direction defining the z axis; θ_π^{ij} and ϕ_π^{ij} the polar and azimuthal angles of the charged pion in the ij center-of-mass system.

The matrix element $g_{\rho\rho}$ for a definite spin–parity J^P and a helicity J_z of the $\rho^+\rho^-$ system was defined as

$$g_{\rho\rho}^{J^P,J_z}=\frac{1}{\sqrt{2}}\,[\mathrm{BW}(m_{12})\mathrm{BW}(m_{34})\,\Psi^{J^P,J_z}\,(\zeta_{1234})$$
$$+\mathrm{BW}(m_{14})\mathrm{BW}(m_{23})\,\Psi^{J^P,J_z}\,(\zeta_{1432})]\,,$$

where BW denotes the Breit–Wigner amplitude for the ρ [1]. The angular part Ψ is given by

$$\Psi^{J^P,J_z}\,(\zeta_{1234})\propto\sum\alpha^{J^P,J_z}_{L,L_z,s_{12},s_{34}}\,Y_L^{L_z}\,(\theta_\rho^{12},\phi_\rho^{12})$$
$$\times Y_1^{s_{12}}(\theta_\pi^{12},\phi_\pi^{12})\,Y_1^{s_{34}}(\theta_\pi^{34},\phi_\pi^{34})\,,$$

where Y are the usual spherical harmonics. Since the $\rho^+\rho^-$ production is observed reasonably close to the threshold, only the lowest orbital angular momenta between the two ρ's which are allowed by parity conservation, $L=0$ and $L=1$, were used. Combining the orbital angular momentum L with the total spin S of the two ρ's one obtains the following J^P assignments: 0^+, 0^-, (2^+, $J_z=0,2$) and (2^-, $J_z=0$, $S=1,2$). Using a maximum likelihood method as in ref. [1] the relative contributions of the eight modeled final states, the six J^P states and the isotropic $\rho^\pm\pi^\mp\pi^0$ and the $\pi^+\pi^-\pi^0\pi^0$ states, were determined for 200 MeV wide $W_{\gamma\gamma}$ intervals. Possible interferences were neglected. The cross sections obtained from the fit are summarized in table 1.

The results show the reaction $\gamma\gamma\to\rho^+\rho^-$ to be dominated by the 0^+ and 2^+ ($J_z=2$) amplitudes. The corresponding cross sections are given in figs. 1a and 1b respectively and the sum of all the different J^P contributions in fig. 1c. Only the statistical errors are given.

As a test of consistency with our earlier results [1] where we had assumed isotropic production of $\rho^+\rho^-$, $\rho^\pm\pi^\mp\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$, a comparison was made with the corresponding fractions derived here. The $\rho^+\rho^-$ fractions derived with an isotropic matrix element were compared to the sum of the fractions for the six J^P amplitudes. When cross sections are compared the acceptance for the J^P is different than the one derived for isotropic $\rho\rho$ production. For example the acceptance of 2^+ ($J_z=2$) is about 50% higher than the acceptance for the isotropic $\rho\rho$ production. In all three cases the agreement was excellent.

The results of the J^P analysis were checked by comparing the one-dimensional distributions of the $\pi^\pm\pi^0$ masses, the five angles ζ and the angle between the charged pions to Monte Carlo expectations. Examples of such distributions are shown in fig. 2 for two different intervals of $W_{\gamma\gamma}$. The data points (crosses) agree very well with the Monte Carlo distributions (dotted histogram) using the fractions derived by the fit.

The maximum likelihood technique was tested extensively by Monte Carlo simulation [8]. Different admixture of the various J^P amplitudes for the $\rho^+\rho^-$

Table 1
Cross section in nb for $\rho^+\rho^-$ (different J^P states), $\rho\pi\pi$ and non-resonant $\pi^+\pi^-\pi^0\pi^0$.

$W_{\gamma\gamma}$(GeV/c^2)	$0^+,0$	$0^-,0$	$2^+,2$	$2^+,0$	$2^-,0$ $S=1$	$2^-,0$ $S=2$	$\Sigma_{\rho\rho}(J^P)$	$\rho^\pm\pi^\mp\pi^0$	Non-resonant 4π
1.2–1.4	3.01±3.27	2.71±1.39	11.88±3.59	−3.49±2.22	−1.02±1.55	−2.74±1.89	10.35±2.52	10.86±7.16	15.96±4.79
1.4–1.6	13.80±3.70	1.52±1.47	2.59±3.01	−0.32±2.64	−1.30±1.49	−2.78±1.99	13.51±3.71	22.85±6.35	17.72±3.67
1.6–1.8	9.40±3.75	3.56±1.53	10.17±3.57	1.71±2.52	−0.88±1.73	5.81±2.04	29.77±4.54	11.38±5.77	14.25±2.99
1.8–2.0	6.43±3.65	0.27±1.48	11.51±3.61	−2.57±2.99	−2.25±2.08	1.58±1.94	14.97±5.25	16.61±7.52	28.13±4.37
2.0–2.2	3.05±2.97	−1.86±1.77	9.01±2.32	−2.77±4.88	−1.47±2.12	−1.65±2.43	4.31±4.80	35.31±7.44	15.09±3.22

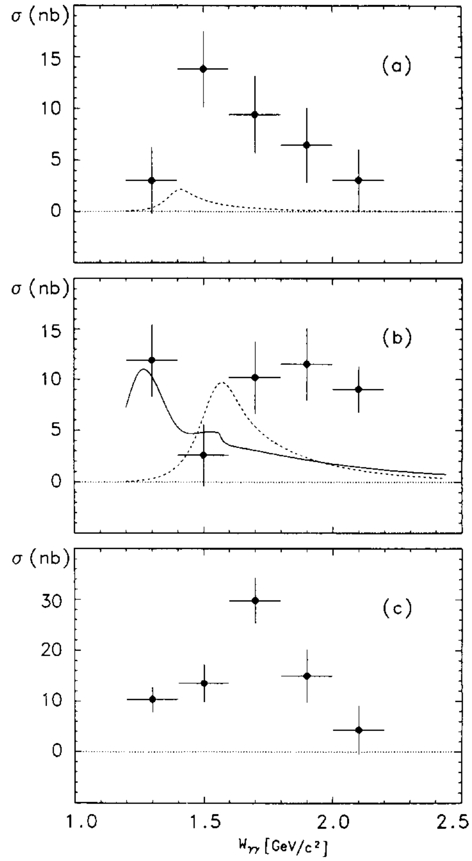

Fig. 1. Cross sections for the dominant spin–parity amplitudes for $\gamma\gamma\to\rho^+\rho^-$: (a) 0^+, (b) 2^+ ($J_z=2$), and (c) the sum of all the J^P contributions. The full line represents the prediction by Achasov et al. [4] and the dashed line the prediction by Li and Liu [5].

system were generated, and subjected to the same fitting procedure as the data. In all cases the input admixture was properly reproduced. In particular with only one J^P state as input, but with the full eight parameters used for the fit the migration between the different J^P amplitudes remained within the expected statistical fluctuations. The two amplitudes 0^+ and 2^+ ($J_z=2$), which dominate the data, were clearly separated.

Setting one of the dominant J^P contributions arbitrarily to zero the fit still converged and the likelihood function changed significantly to smaller values than the values for the full fit. In particular, when the 2^+ ($J_z=2$) was set to zero the fit compensates by increasing the contributions of the 0^+, 2^- and $\rho^\pm\pi^\mp\pi^0$.

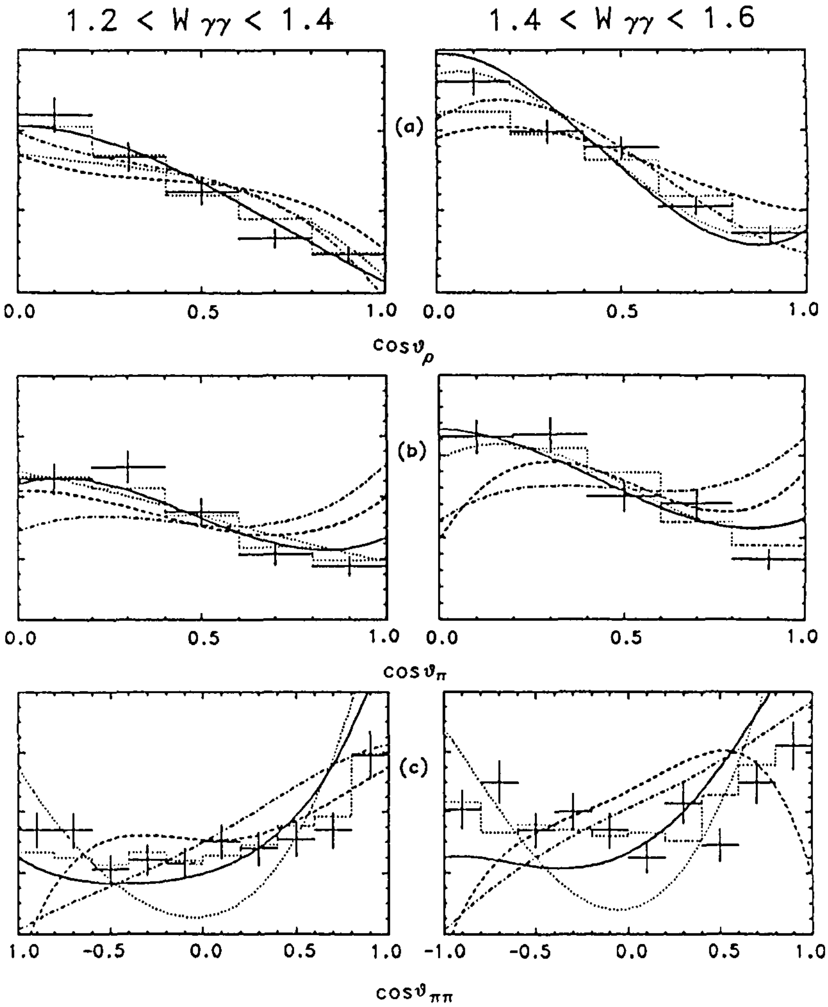

Fig. 2. Comparison of the measured one-dimensional distributions (crosses) with Monte Carlo simulations of all fitted contributions (histogram). The curves show the expectations for different spin-parity states, 2^+ (full line), 0^+ (dotted line), 0^- (dashed line) and 2^- (dash-dotted line). The left side shows the distributions for $1.2 < W_{\gamma\gamma} < 1.4$ GeV/c^2 and the right side for $1.4 < W_{\gamma\gamma} < 1.6$ GeV/c^2: (a) the polar angle of the ρ with respect to the direction of the γγ center-of-mass system, (b) polar angle of the pions with respect to the ρ center-of-mass system, (c) the angle between the two charged pions each taken in the corresponding ρ rest frame.

When the 0^+ contribution was set to zero then the fractions of the 2^+ ($J_z=2$) and the $\rho^\pm\pi^\mp\pi^0$ were influenced. This effect was reproduced very well by Monte Carlo studies where a known mixture of different states was given as input and the fit tried to reproduce it. The fit results are sensitive to the normalization of the probabilities in the likelihood function which has to be derived by Monte Carlo simulation. We varied this normalization within the uncertainty estimated for the Monte Carlo. From these tests the systematic uncertainty of the likelihood method to reproduce the input fractions was estimated to be less than 10%. We have neglected interference between amplitudes mainly because of the relatively small statistics and a strong model dependence for the interference between the ρρ and the non-ρρ terms. However, some justification for the ansatz comes as feedback from the fact that the two dominant J^P amplitudes, having different J_z values, do not interfere.

The overall systematic uncertainty in the measured cross sections is estimated to be $\pm 17\%$ for all the reactions. It is composed of the contributions from event generation and detector simulation ($\pm 11\%$), experimental luminosity ($\pm 3\%$), trigger simulation ($\pm 5.5\%$), background estimation ($\pm 5\%$), and uncertainty from the maximum likelihood technique ($\pm 10\%$).

Consistent with the predictions of the $qq\bar{q}\bar{q}$ models, the $\rho^+\rho^-$ cross section is dominated by the amplitudes $J^P=2^+$ and 0^+. The measured cross sections for the $J^P=2^+$, $J_z=2$ amplitude is about a factor four lower than the corresponding one of the reaction $\gamma\gamma\to\rho^0\rho^0$ measured by ARGUS [3], whereas in the case of $J^P=0^+$ they are of the same magnitude.

In fig. 1, the measured cross sections are compared to the model prediction of refs. [4,5]. The 2^+ cross section (fig. 1b) shows in the data an enhancement of about 12 nb between 1.2 and 1.4 GeV which agrees with the $f_2(1270)$ contribution predicted in ref. [4]. At higher $W_{\gamma\gamma}$, however, the data exhibit a broad peak at $W_{\gamma\gamma}\sim 1.8$ GeV reaching about 11 nb where the model [4] predicts only about 2 nb. The model of ref. [5] does not include the $f_2(1270)$ and predicts a peak around 1.6 GeV which is inconsistent with the structure of the measured cross section. A 0^+ contribution is only included in ref. [5] but the predicted cross section is about a factor of 5 smaller than the observed one.

Both models succeed in the prediction of the suppressed $\rho^+\rho^-$ compared to the $\rho^0\rho^0$ cross section, but they both fail to give the correct absolute scale for the cross section as well as its structure. It should be mentioned that similar problems have been found in comparing the two models to recent ARGUS measurements [9] of other vector-meson pairs produced in two-photon reactions.

In conclusion, a spin–parity analysis has been performed for the $\rho^+\rho^-$ system produced in two-photon interactions. The $\rho^+\rho^-$ cross section was found to be dominated by two amplitudes, $J^P=0^+$ and $J^P=2^+$ with helicity 2.

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