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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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ABSTRACT

Results of a measurement of the two-photon widths of the a_2, η', η with the detector MD-1 at e^+e^- collider VEPP-4 are presented. The specific feature of this experiment is tagging of at least one scattered electron. The following results have been obtained:

$$\Gamma_{a_2\to\gamma\gamma}=1.26\pm0.26\pm0.18 \text{ keV},$$
$$\Gamma_{\eta'\to\gamma\gamma}=4.6\pm1.1\pm0.6 \text{ keV},$$
$$\Gamma_{\eta\to\gamma\gamma}=0.51\pm0.12\pm0.05 \text{ keV}.$$

The study of C-even resonances produced in two-photon reactions provides a measurement of their radiative widths, which contain information about their nature [1, 2].

Here we present a study of the processes:

$$e^+e^-\to e^+e^-a_2, \quad a_2\to\pi^+\pi^-\gamma\gamma\,, \tag{1}$$

$$e^+e^-\to e^+e^-\eta', \quad \eta'\to\pi^+\pi^-\gamma\,, \tag{2}$$

$$e^+e^-\to e^+e^-\eta, \quad \eta\to\gamma\gamma\,. \tag{3}$$

The experiment was performed in 1984—1985 at the storage ring VEPP-4 with the detector MD-1 [3] at the center-of-mass energies between 7.2—10.4 GeV. The integrated luminosity was 20.8 pb^{-1}.

The layout of the detector MD-1 is shown in Fig. 1. The magnetic field in the detector is transverse to the orbit plane of the storage ring and equals to 12 kG at the beam energy of 5 GeV. On the both sides of the main magnet the additional magnets with the same field direction are installed. Further the detectors for tagging of the scattered electrons are situated [4]. This tagging system allows detection of the scattered electrons (positrons) emitted from the interaction region even at zero angle in the energy range of $0.5<E/E_0<0.85$ (E_0 is the beam energy) with the accuracy of $\sigma_E/E=1.3\%$. The specific feature of our experiment is detection of at least one such electron.

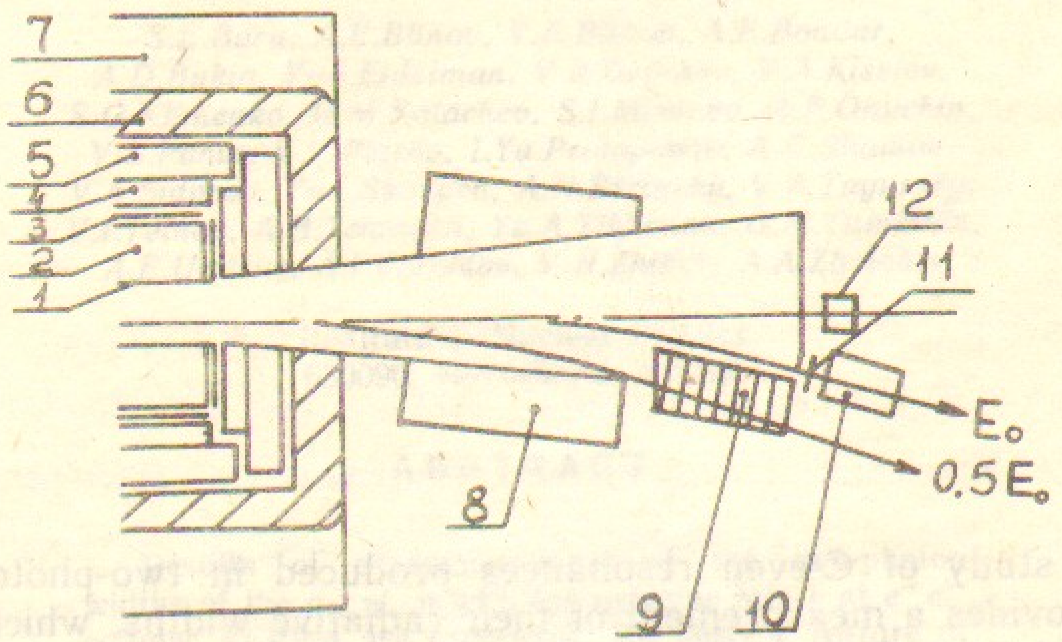

Fig. 1. Detector MD-1:

1 — vacuum chamber; *2* — coordinate chambers; *3* — scintillation counters; *4* — gaseous Cherenkov counters; *5* — shower-range chambers; *6* — magnet winding; *7* — magnet yoke; *8* — bending magnet; *9* — system of scattered electron detection; *10* — lense; *11* — luminosity monitor; *12* — scintillation sandwich.

In the central part of MD-1 charged particles are detected and their momenta measured by 38 proportional chambers. Coordinate system is covered by 24 scintillation counters. Photons are detected in shower-range chambers (SRC) compiled in 14 separate units. Each unit consists of 10 proportional chambers alternating with 13 mm thick stainless steel plates. Gaseous Cherenkov counters filled with ethelene at a pressure of 25 atm ($\gamma_{thr}=5$) serve for particle identification. In each counter Cherenkov light is detected by four photomultipliers.

The momentum resolution of coordinate chambers equals $\sigma_p/p=(4\div10)\cdot p$ (GeV)%. SRC measure the photon angles with the accuracy of $\sigma_\theta\sim\sigma_\varphi\sim1\div2°$. For a photon of energy 250 MeV, which is typical for the reactions (1) — (3), the energy resolution is $\sigma_E/E\sim40\%$.

The luminosity is measured by the processes of single bremsstrahlung and small angle Bhabha scattering. The accuracy of the luminosity measurement is 2.5% [5].

Photons emitted from the interaction point at zero angle are tagged by special scintillation sandwiches. When such a photon is detected, scattered electrons emitted in the same direction at the

angle relative to the orbit plane $|\theta_z|<0.09°$ is not used in the analysis of reactions (1—3). This cut decreases background from bremsstrahlung.

In the trigger firing of at least one scintillation counter and two shower-range units situated on the both sides from beam axis were required. In each unit at least two chambers measuring different coordinates must be fired. To reject the background from bremsstrahlung and other processes with small transverse momenta the stripe with the width of ±11 cm near to the orbit plane in SRC was switched off from the trigger. Then the fast on-line analysis was performed by a computer to reject cosmic ray events, as well as background events with the tracks near the orbit plane. The selected events were recorded with the rate of 3 Hz at the luminosity of $3\cdot10^{30}$ cm^{-2}s^{-1}. The trigger efficiencies for the processes (1) — (3) were 35, 20 and 11% correspondingly.

To study the reactions (1) — (2) events with two oppositely-charged particles with momenta of 0.1 — 2.5 GeV/*c*, 1 or 2 photons and at least one tagged electron were selected. Both tracks were required to arise from a fiducial cylinder around the interaction point with the length of ±100 mm along beam axis and radius of 30 mm.

The following cuts were used to reduce the background from reactions of the type $ee\to eeLL\gamma$, $ee\to LL\gamma$ ($L=e$, μ, π) and of the type $ee\to eeLL$, $ee\to LL$, which are accompanied by spurious photon or photon produced on the vacuum chamber, as well as the background from non-resonant hadron continuum:

a) the angle between photon and any charged particle is greater than 11°;

b) the transverse momentum of two charged particles is less than 600 MeV, its invariant mass equals 450 — 1200 MeV;

c) charged particles with momentum less then 700 MeV should not trigger two or more PM in Cherenkov counter and their clusters in SRC should be narrow. An event was rejected if both charged particles did not satisfy this requirement;

d) no more than 2 scintillation counters fired outside the trajectories of charged particles;

e) all SRC clusters within a radius of 20 cm around charged particle trajectory are not considered;

f) the angle of photon relative to the beam plane $|\theta_z|>4°$;

g) the acoplanarity angle between charged particles is greater than 6°;

h) the acoplanarity angle between the momenta of $\pi^+\pi^-$-system and of the photon is less than 30°.

The events left after these cuts were kinematically reconstructed under the assumption that final state is $ee\pi\pi\gamma$. The energies of the photon and the second scattered electron (which travels beyond the detection acceptance) were obtained from equation of conservation of energy and momentum. The angle of the undetected electron was assumed to be zero. Extra equations were used for improvement of accuracy of particle parameters by means of procedure of kinematic reconstruction described in [6]. The events were rejected if the confidence level for the fit was less than 5%.

In fact the photon energy was calculated from transverse momentum conservation equation. Transverse momentum of produced in two photon reactions system is small, therefore for reaction (2)

$$E_\gamma \simeq p_\perp^{\pi\pi} / \sin\theta_\gamma , \qquad (4)$$

where θ_γ is the angle of the photon relative to the beam line.

By reconstruction the photon energy is determined with the accuracy of $\sigma_E = 40$ MeV. For the comparison the energy of the photon in reaction (1) is measured by SRC with the accuracy of $\sigma_E = 100$ MeV.

When two photons were in the event (as in the decay of the a_2) the photon with the better fit was taken. In fact we take into consideration the photon which is more coplanar to the system of charged particles. Ignoring of second photon in analysis leads to some broadening of the a_2 spectrum and shift to lower masses, but resonance structure conserves.

The detection efficiency was determined by the Monte Carlo simulation of two-photon formation of the a_2 and η'. The method of equivalent photons in most precise formulation was used [7]. The passage of particles through the detector was simulated taking into account all principal processes by means of the code UNIMOD, developed at INP [8]. In the simulation we took into account the correction due to the photon emission by scattered electron. About 11% of scattered electrons emit photon with energy greater than 50 MeV [9]. This process decreases the energy of tagged electron and reconstructed mass of the resonance shifts.

In the process (1) the interference between $\rho^-\pi^+$ and $\rho^+\pi^-$ decay modes was taken into consideration, so that

$$|M(a_2\to\pi^+\pi^-\pi^0)|^2 = |M(a_2\to\rho^+\pi^-\to\pi^+\pi^-\pi^0)\,BW(\rho^+) + M(a_2\to\rho^-\pi^+\to\pi^+\pi^-\pi^0)\,BW(\rho^-)|^2 , \qquad (5)$$

where

$$BW = \frac{m_\rho\sqrt{\Gamma_\rho}}{m_\rho^2 - m_{\pi\pi}^2 - im_\rho\Gamma_\rho}$$

is the relativistic Breit—Wigner amplitude. For a_2 helicity ± 2 state [10]:

$$M(a_2\to\rho\pi) \propto \pm i\,|\vec{k}_\rho|^2\,|\vec{p}_\pi|\,\sin\theta_\rho\,\sin\theta_\pi\,e^{\pm 2i\varphi_\rho} \times [\cos\varphi_\pi \pm i\cos\theta_\rho\,\sin\varphi_\pi] . \qquad (6)$$

For a_2 helicity 0-state [10]:

$$M(a_2\to\rho\pi) \propto |\vec{k}_\rho|^2\,|\vec{p}_\pi|\,\sin\theta_\rho\,\cos\theta_\rho\,\sin\theta_\pi\,\sin\varphi_\pi . \qquad (7)$$

where θ_ρ, φ_ρ are the angles of the ρ in cms $\gamma\gamma$ (z—axis along photon direction); θ_π, φ_π are the angles of the π-mesons in spiral system of the ρ; φ_π is measured from the plane defined by directions of the ρ and $\gamma\gamma$.

The decay $\eta'\to\rho\gamma$ was generated according to the distribution on invariant mass of $\pi\pi$-system ($m_{\pi\pi}$) and the angle θ^* between pion and photon in cms ρ [1]:

$$\frac{d^2\Gamma}{dm_{\pi\pi}\,d\Omega^*} \propto \frac{(m_{\eta'}^2 - m_{\pi\pi}^2)^3\,(m_{\pi\pi}^2 - 4m_\pi^2)^{3/2}}{(m_\rho^2 - m_{\pi\pi}^2)^2 + \Gamma_\rho^2 m_\rho^2}\,\sin^2\theta^* . \qquad (8)$$

The results of data analysis are shown in Fig. 2. Here the spectrum of $\pi\pi\gamma$ invariant masses is presented after all cuts. The solid line is a fit to the data, dashed curves show contributions of resonances and background. For the fit we have used shape of resonance curves of a_2 and η' taken from Monte Carlo simulation parametrised by Gaussians with power-law tails. The background was described by third degree polynomial with four free parameters. After fitting its form becomes practically linear, so final results were obtained for linear background. Masses of the a_2 and η' and background parameters were free. The results of the fit for the data of Fig. 2 are

$$M_{a_2} = 1311 \pm 29 \text{ MeV}, \quad M_{\eta'} = 974 \pm 15 \text{ MeV},$$

$$N_{a_2} = 38.8 \pm 7.5 , \quad N_{\eta'} = 23.2 \pm 5.6 ,$$

$$\chi^2 = 7.2 \text{ for 10 degrees of freedom} .$$

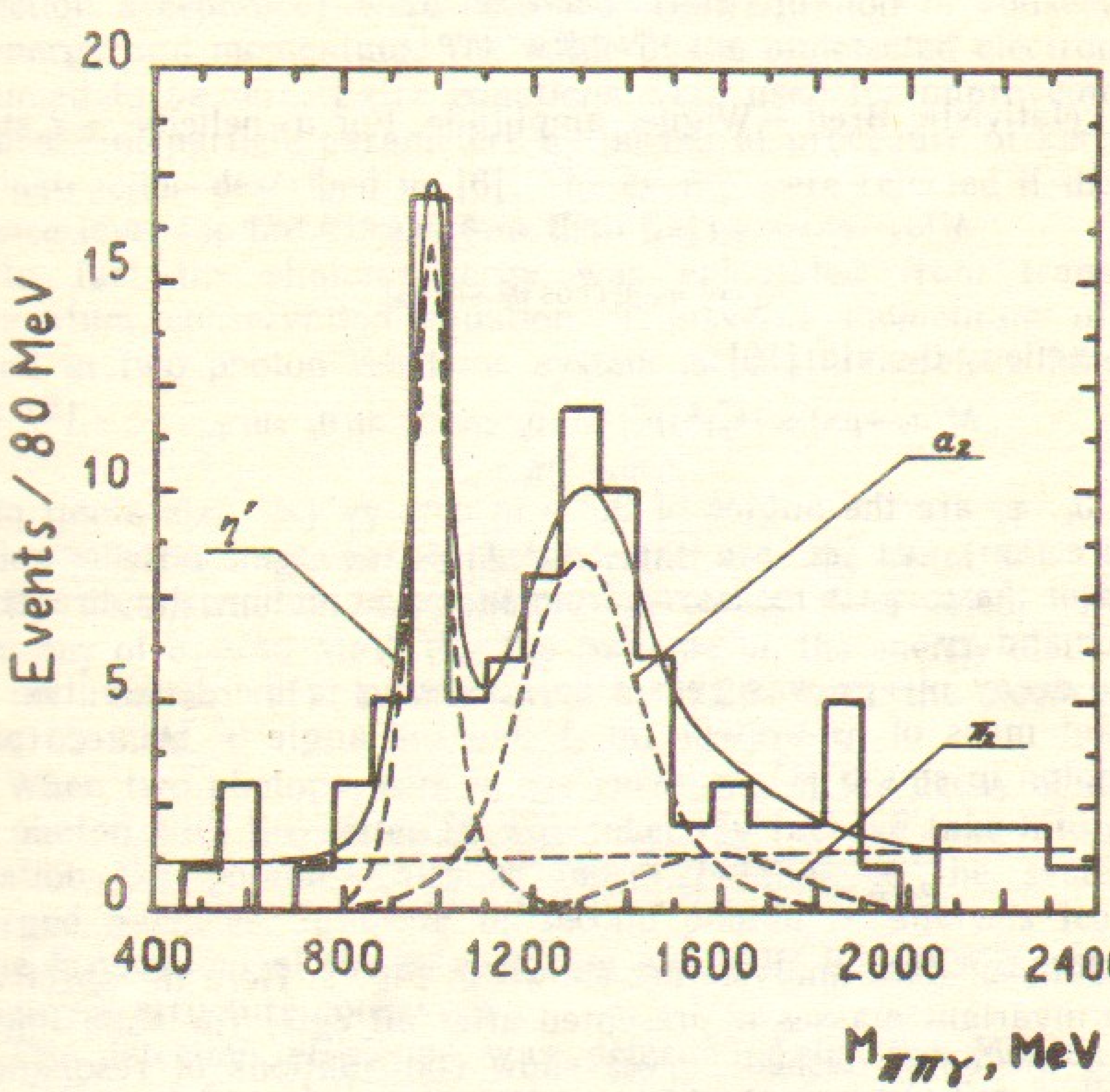

Fig. 2. $\pi\pi\gamma$ invariant mass distribution.
Solid line shows the fit, dashed curves show resonances and background.

We have estimated the contribution to processes (1) — (2) of other two-photon reactions. The following processes were simulated (two-photon widths were taken from [32, 33]):

$$e^+e^- \to e^+e^-\eta \qquad \eta \to \pi^+\pi^-\pi^0, \tag{9}$$

$$e^+e^- \to e^+e^- f_1\,(1285) \qquad f_1 \to \pi^+\pi^-\gamma\gamma, \tag{10}$$

$$e^+e^- \to e^+e^-\eta' \qquad \eta' \to \eta\pi^+\pi^-, \tag{11}$$

$$e^+e^- \to e^+e^-\pi_2\,(1680) \qquad \pi_2 \to \pi^+\pi^-\pi^0. \tag{12}$$

After the cuts only 9 ± 4 events of the reaction (12) passed ($\Gamma_{\pi_2 \to \gamma\gamma} = 1.4 \pm 0.3$ keV [32]). Taking into account this result we have obtained from the fit of the data of Fig. 2:

$$N_{a_2} = 36.3 \pm 7.5,$$
$$N_{\eta'} = 23.3 \pm 5.6,$$
$$N_{\pi_2} = 7 \pm 3,$$
$$\chi^2 = 8.8 \text{ for 10 degrees of freedom}.$$

Using the result of this fit and comparing with simulation we have obtained for the data of Fig. 2:

$$\Gamma_{a_2 \to \gamma\gamma} = 1.26 \pm 0.26 \text{ keV}, \quad \Gamma_{\eta' \to \gamma\gamma} = 4.6 \pm 1.1 \text{ keV}.$$

For calculation of radiative width of the a_2 we use experimentally measured helicity of the a_2 in two-photon production [15]:

$$\sigma(J_z = 2) = (0.81 \pm 0.22)\,\sigma_{tot}.$$

If the a_2 is produced only with helicity ± 2 then its two-photon width measured in our experiment should be increased by 8%.

The corrections connected with nonzero masses of colliding photons are negligible (less than 1%) in our case as soon as $\langle -q^2 \rangle < 0.001$ GeV^2, q is the four-momentum of virtual photon.

The detection efficiencies for the reactions under study are 0.8% for the a_2, 0.5% for the η'. Here the efficiency of detection of scattered electrons (55%) is included.

To study the reaction (3) events without charged particles with two photons and at least one tagged electron were selected. To reject the background from cosmic rays the events with scintillation counters fired inside of 6 ns interval around the moment of the beam collision were taken. Also events were rejected if it was possible to draw a straight line through hits of both photons in SRC.

The following cuts were used to reduce the background from reactions of the type $ee \to eeLL$, $ee \to LL$ ($L=e$, μ, π tagged only by shower-range chambers) and from beam gas interactions:

a) the energy of each photon is less than 2 GeV;

b) the angle of each photon relative to the orbit plane is greater than 8°;

c) acoplanarity angle between photons is less than 20°;

d) no tracks of coordinate chambers can be found near photons trajectories;

e) if we assume that we have an e^+e^--pair in an event then at least one particle must traverse coordinate chamber.

The events left after these cuts were kinematically reconstructed under the assumption that final state is $ee\gamma\gamma$ [6]. The measurement of scattered electron momentum and photon angles allowed us to reconstruct the η mass with the accuracy about 60 MeV. It is determined mainly by kinematical constraints.

The detection efficiency was determined by Monte Carlo simulation of two-photon formation of the η by the same formulae of the method of equivalent photons as in the case of a_2 and η'.

The results of data analysis are shown in Fig. 3, where the spectrum of invariant masses is presented. The solid line is a fit to the data, dashed curves show contribution of resonance and background. For the fit we have used shape of resonance curve from simulation parametrised by Gaussian with power-law tails and third degree polynomial with 4 free parameters for the background. Mass of the η was also free.

The results of the fit are

$$N_\eta = 36.5 \pm 8.8\ , \quad M_\eta = 588 \pm 17\ \text{MeV}\ ,$$

$$\chi^2 = 7.8 \ \text{for 13 degrees of freedom}\ .$$

From comparison with simulation we have obtained

$$\Gamma_{\eta \to \gamma\gamma} = 0.51 \pm 0.12 \ \ \text{keV}\ .$$

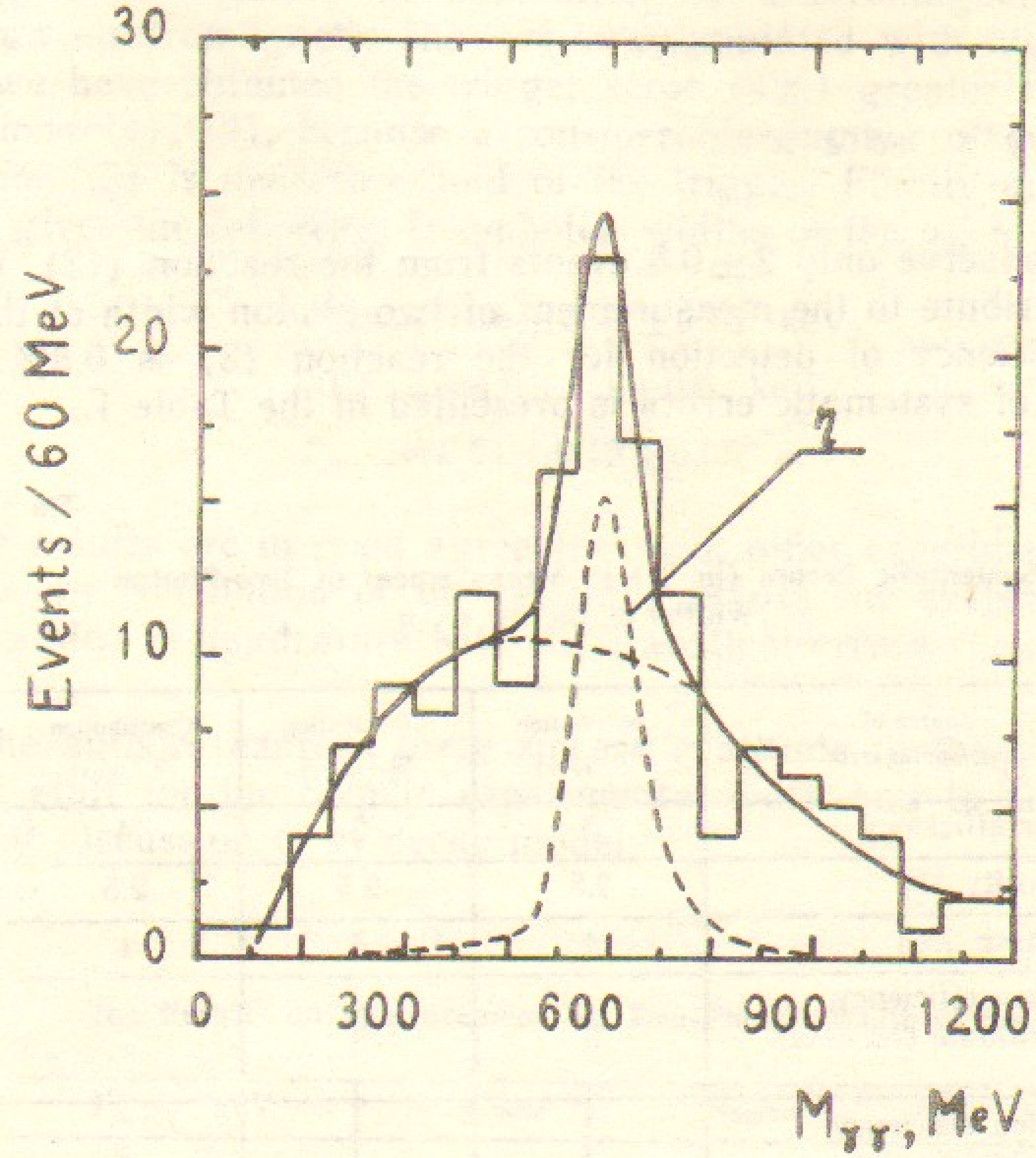

Fig. 3. $\gamma\gamma$ invariant mass distribution.
Solid line shows the fit, dashed curves show resonance and background.

For estimation of the contribution to process (3) of other two-photon reactions the following processes were simulated (two-photon widths were taken from [33]):

$$e^+e^- \to e^+e^-\eta' \qquad (13)$$
$$\eta' \to \gamma\gamma\,,$$

$$e^+e^- \to e^+e^-\pi^0\,. \qquad (14)$$

Our cuts conserve only 2 ± 0.8 events from the reaction (13), which do not contribute to the measurement of two-photon width of the η.

The efficiency of detection for the reaction (3) is 0.8%. The calculation of systematic errors is presented in the Table 1.

Table 1

Systematic Errors (in %) in Measurement of Two-Photon Widths of the a_2, η', η

Source of systematic error	Contribution to $\Gamma_{a_2\to\gamma\gamma}$	Contribution to $\Gamma_{\eta'\to\gamma\gamma}$	Contribution to $\Gamma_{\eta\to\gamma\gamma}$
Trigger efficiency	3	3	4
Luminosity [5]	2.5	2.5	2.5
Branching [33]	4	5	1
Detection efficiency of coordinate chambers	3	3	—
Detection efficiency of tagging system	4	4	4
Uncertainty in resonance shape	4	3	6
Uncertainty in helicity of the a_2	10	—	—
Statistical error of simulation	5.5	8	5
Total systematic error	14	12	10

The main source of systematic error of trigger efficiency for detection of the a_2 and η' is uncertainty in simulation of the π-meson ranges in SRC. Estimation of this error (3%) was found from

comparison of π-mesons ranges in experiment and simulation. The main source of systematic error of trigger efficiency for detection of the η is uncertainty in simulation of electromagnetic showers. Though electromagnetic showers are simulated with high accuracy [8] we have obtained the trigger error (4%) greater than for the reactions (1), (2), because a considerable number of events of the reaction (3) is near threshold of the trigger. Finally our measurement gives the following two-photon widths of the a_2, η' and η:

$$\Gamma_{a_2\to\gamma\gamma} = 1.26 \pm 0.26 \pm 0.18 \quad \text{keV}\,,$$
$$\Gamma_{\eta'\to\gamma\gamma} = 4.6 \pm 1.1 \pm 0.6 \quad \text{keV}\,,$$
$$\Gamma_{\eta\to\gamma\gamma} = 0.51 \pm 0.12 \pm 0.05 \quad \text{keV}\,.$$

These results are in good agreement with other experiments (Tables 2—4). In calculation of the resulting errors the systematic errors were added in quadrature with the statistical errors.

The authors express there sincere gratitude to the VEPP-4 and MD-1 staff for the help in experimental work and to G.N. Shestakov for discussion of a_2 decay model.

Table 2

The Results on Measurements of Two-Photon Width of the a_2

$\Gamma_{a_2\to\gamma\gamma}$, keV	Decay mode	Experiment		Ref.
$0.77 \pm 0.18 \pm 0.27$	$\eta\pi$	Cr. Ball	(1982)	11
$0.81 \pm 0.19 \pm 0.27$	$\rho\pi$	CELLO	(1982)	12
$0.84 \pm 0.07 \pm 0.15$	$\rho\pi$	JADE	(1983)	13
$1.06 \pm 0.18 \pm 0.19$	$\rho\pi$	PLUTO	(1984)	14
$1.14 \pm 0.20 \pm 0.26$	$\eta\pi$	Cr. Ball	(1985)	15
$0.90 \pm 0.27 \pm 0.16$	$\rho\pi$	TASSO	(1986)	16
$1.26 \pm 0.26 \pm 0.18$	$\rho\pi$	MD-1	(1990)	this exp.
0.94 ± 0.10		averaged		

Table 3

The Results on Measurements of Two-Photon Width of the η'

$\Gamma_{\eta'\to\gamma\gamma}$, keV	Decay mode	Experiment	Ref.
$5.8\pm1.1\pm1.2$	$\rho\gamma$	MARK II (1979)	17
$5.0\pm0.5\pm0.9$	$\rho\gamma$	JADE (1982)	18
$6.2\pm1.1\pm0.8$	$\rho\gamma$	CELLO (1982)	12
$3.8\pm0.3\pm0.4$	$\rho\gamma$	PLUTO (1984)	19
$5.1\pm0.4\pm0.7$	$\rho\gamma$	TASSO (1984)	20
$4.5\pm0.3\pm0.7$	$\rho\gamma$	TPC/2γ (1986)	21
3.3 ± 0.8	$\gamma\gamma$	JADE (1985)	22
$4.7\pm0.6\pm0.9$	$\eta\pi\pi$, $\eta\to\gamma\gamma$	MARK II (1987)	23
$4.6\pm0.4\pm0.6$	$\eta\pi\pi\to6\gamma$	Cr. Ball (1987)	24
$3.76\pm0.13\pm0.47$	$\rho\gamma$	ARGUS (1987)	25
$4.7\pm0.5\pm0.5$	$\gamma\gamma$	Cr. Ball (1988)	26
$3.8\pm0.7\pm0.6$	$\eta\pi\pi$	TPC/2γ (1988)	27
$4.71\pm0.22\pm0.70$	$\gamma\gamma$	ASP (1989)	28
$4.6\pm1.1\pm0.6$	$\rho\gamma$	MD-1 (1990)	this exp.
4.30 ± 0.21		averaged	

Table 4

The Results on Measurements of Two-Photon Width of the η

$\Gamma_{\eta\to\gamma\gamma}$, keV	Decay mode	Experiment	Ref.
$0.56\pm0.12\pm0.10$	$\gamma\gamma$	Cr. Ball (1983)	29
$0.53\pm0.04\pm0.04$	$\gamma\gamma$	JADE (1985)	30
$0.64\pm0.14\pm0.13$	$\gamma\gamma$	TPC/2γ (1986)	31
$0.514\pm0.017\pm0.035$	$\gamma\gamma$	Cr. Ball (1988)	26
$0.481\pm0.010\pm0.047$	$\gamma\gamma$	ASP (1989)	28
$0.51\pm0.12\pm0.05$	$\gamma\gamma$	MD-1 (1990)	this exp.
0.511 ± 0.026		averaged	

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Измерение двухфотонной ширины a_2, η', η-мезонов

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