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Production of G(1590) and other mesons decaying into η pairs by 100 GeV/c π^- on protons.

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Abstract: New data on the scalar G(1590)-meson which decays into $\eta\eta$ have been obtained in an experiment at CERN SPS. η pairs are detected with the electromagnetic calorimeter GAMS both through their decay into 4γ and into 8γ . $\epsilon(1300)$, $f(1270)$, $f'(1525)$ as well as the spin 4 $h(2030)$ -meson have also been observed to decay in the same mode. Their branching ratios have been evaluated. The presence of high mass spin 0 and spin 2 structures is discussed.

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1. Introduction

An unusual resonance, which preferentially decays into $\eta\eta$ and $\eta\eta'$, has been observed at IHEP [1] in the first part of an experimental program of this collaboration which aims at the study of exclusive production of neutral mesons in π^-p collisions [2]. This state, called G(1590), has quantum numbers $J^{PC} = 0^{++}$. Its observed properties make it a scalar glueball candidate [3,4].

Higher energy results on the production of this resonance and on other mesons like $\epsilon(1300)$, $f(1270)$, $f'(1525)$ and $h(2030)$, which decay with a significant branching ratio into η pairs, have been obtained at CERN in the NA12 experiment which is part of the same program [5]. They are reported in the present paper.

$\eta\eta$ states are produced in the reaction:

$$\pi^- + p \rightarrow M^0 + n \quad (1)$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \eta\eta$$

The η are observed through their neutral decay modes, either into 2γ (39%) or into $3\pi^0$, i.e. into 6γ (32%).

The experimental setup and the data taking system are described in the next section. Selection of events and their analysis are then discussed. Results are presented for G(1590) and other resonances, including the 4^{++} h -meson. Arguments on the nature of G(1590) are reviewed. Spin 0 and spin 2 structures which appear in the high mass range of the $\eta\eta$ spectrum are also discussed.

2. Experimental setup and data taking.

The experimental setup is similar in its principle to that used in the smaller scale experiment at IHEP. It relies on the properties of the hodoscope Cerenkov electromagnetic calorimeter GAMS as a multiphoton detector [6].

Schematics of the setup are shown on fig. 1.

GAMS-4000 at CERN is a matrix of 64×64 lead-glass cells with dimensions $38 \text{ mm} \times 38 \text{ mm} \times 450 \text{ mm}$. The granularity of this detector allows the measurement of the position and the energy of up to 20 γ per event. The four central cells of GAMS are missing to provide a hole for the passage of particles that did not interact in the target.

The liquid hydrogen target (60 cm long, 6 cm in diameter) is surrounded by a double guard system made of a layer of scintillators for the rejection of events with charged particles produced in the target and of a layer of lead-glass counters for the detection of gammas emitted at large angle, mainly those emitted by excited nucleon states. The liquid hydrogen in the target is also a Cerenkov radiator for the beam particles. The amount of emitted Cerenkov light is a measure of the longitudinal position of the point where the π^- interacts to produce a final state containing only neutral particles.

The setup is triggered on neutral events by requiring that no charged particle be detected by the scintillators surrounding the target. A fast processor evaluates the total energy deposited in GAMS. Events for which more than 50% of the beam energy is missing (mostly due to γ going through GAMS hole) are rejected before writing on magnetic tape. Recorded information consists of the pulse height of each hit GAMS cell, the pulse height of the lead-glass guard counters, addresses of hit beam hodoscope channels, the pulse height of the Cerenkov light emitted in the liquid hydrogen target and beam control data. Gamma multiplicity determination and η identification are made off-line.

The data acquisition system has been described in detail elsewhere [7], as well as the procedure for the calibration of GAMS [8].

Measurements have been performed with $100 \text{ GeV}/c \pi^-$ in the CERN-SPS H8 beam line. The distance (L) between the target and GAMS was fixed at 20 m for one third of the data and at 15 m for the other two thirds. These distances correspond to the region of maximum acceptance for the detection of type (1) events in a mass range up to 3 GeV. A total of about $2 \times 10^{12} \pi^-$ in bursts of 1.5×10^7 per second has given an ultimate sensitivity of 0.4 pb per event detected in GAMS.

3. Selection of events.

Gamma showers appear as clusters of hit GAMS cells. Reconstruction programs are used to determine energy and impact coordinates of each gamma after proper calibration of individual GAMS cells [8]. Two gammas distant from each other by more than about 20 mm may be individually reconstructed [8,9].

Events are classified according to their multiplicity. 4γ and 8γ events are selected for further $\eta\eta$ search.

3.1 Four – gamma events.

The main contributions to the class of 4γ events are due to pairs of π^0 , η and η' mesons. Out of all 4γ events, $\pi^0\pi^0$ and $\eta\pi^0$ systems are largely more numerous than $\eta\eta$ systems : 1.2×10^6 $\pi^0\pi^0$ and 8×10^4 $\eta\pi^0$ compared to 1.2×10^4 $\eta\eta$.

As a first step, a strong π^0 cut is applied to select $\eta\eta$ events: all events with any gamma pair mass in the range from 70 MeV to 190 MeV are rejected. At this stage $\pi^0\pi^0$ and $\eta\pi^0$ are excluded. Fig. 2a shows the mass spectrum of all gamma pairs (six combinations) of the remaining events. Fig. 2b shows the mass spectrum of the second pair of gammas after the first pair has been identified as an η , having a mass in the range from 509 MeV to 589 MeV. Most events are seen to be $\eta\eta$ systems. The small background around the η peak is rejected at the second step of the selection procedure.

The remaining sample, apart from $\eta\eta$, contains $\eta'\eta$ and background events. It is handled through a general fitting procedure [8], with the constraints that two pairs of gammas have an invariant mass equal to that of the η and that the recoil particle is a neutron. Final selection of events is made on the χ^2 criterion (97% C.L.) of the constrained fitting procedure. These constraints are not efficient to reject all isobars like $\Delta(1232)$ or $N^*(1440)$ which decay into π^0n . They can only be eliminated with the help of information from the lead – glass counters of the guard system (cf. 3.3).

The mass spectrum of $\eta\eta$ systems measured through their decay into 4γ is shown on fig. 3.

3.2 Eight – gamma events.

$\eta\eta$ systems in 8γ events are such that one η decays into two γ and the second into $3\pi^0$, decaying further into 6γ .

As a first step, all events whose gammas may be combined in $4\pi^0$ are rejected, thereby eliminating the important contributions from $\eta\pi^0$ (notably $A_2(1320)$) and direct $4\pi^0$ production.

Fig. 4a shows the invariant mass spectrum of the 6γ associated with an identified η without additional selection. In fig. 4b, only those events where the 6γ are compatible with $3\pi^0$ decay are used.

The fit of the remaining events requires:

- one pair of gammas in the mass range from 509 MeV to 589 MeV to be fitted as an η ;
- three pairs among the remaining six gammas, each with a mass in the range from 110 MeV to 155 MeV, to be fitted as a π^0 ;
- the $3\pi^0$ invariant mass in the range from 469 MeV to 629 MeV to be fitted as an η .

$\eta\eta$ systems are chosen on the same confidence level basis as for 4γ events. There is however a background that cannot be directly rejected. It is due to final states that involve three low – momentum non – resonant π^0 together with an η . These $3\pi^0$ may easily appear to be an η as the sum of their masses alone is 405 MeV. Monte – Carlo evaluations show that these events concentrate at low mass as expected, and that they contribute a significant background mainly in the threshold region of the spectrum. This background has been subtracted according to these calculations. The first evidence for its presence was a discrepancy between low mass data in 4γ and 8γ events.

Fig. 5 gives the mass spectrum of $\eta\eta$ systems measured through their decay into 8γ after background subtraction.

3.3 Final sample.

In spite of quite different multiplicities, the mass spectra of 4γ and 8γ decays of $\eta\eta$ systems shown on figs. 3 and 5 present similar structures. Apparent differences can be understood as both decay modes have very different acceptances. This gives further confidence in the applied selection procedure.

The total 100 GeV/c data amount to 12000 $\eta\eta$ events decaying into 4γ and to 8600 decaying into 8γ .

When the information from the lead – glass counters of the guard system is used to eliminate final states leading to the production of isobars, these numbers are reduced by a global factor of about 2. Partial wave analysis gives identical results both with or without this cut. All results that follow are based on the entire data sample.

4. Acceptance and efficiency of the detector.

The acceptance of the detector depends on the multiplicity of the event. Total efficiency, including effects of geometrical acceptance and shower reconstruction errors, has been evaluated by Monte–Carlo calculations as a function of the mass of the $\eta\eta$ system and of the decay angles θ and ϕ in the Gottfried – Jackson frame for both decay channels.

Events are simulated by straightforward kinematics up to the final decay into photons. Beam characteristics (momentum spread and lateral dimensions) and geometrical parameters of the setup are taken into account. Electromagnetic showers in GAMS are then simulated according to the experimentally measured mean shower profile [8,9]. Statistical shower fluctuations are applied to the content attributed to the various cells of GAMS that are hit by the shower. Analysis of the simulated events is then performed with the same programs that are used for the data. This procedure takes all parameters into account and includes all the selection criteria.

In the low mass region, the efficiency varies little with the angles θ and ϕ . In the high mass range it drops to quite small values when $|\cos\theta|$ approaches 1. It is well approximated by a formula of the type:

$$\epsilon(\cos\theta) = A/[1 + \exp\{B(\cos\theta - C)\}] \quad (2)$$

The three coefficients A, B and C are fitted at given values of ϕ and of $M_{\eta\eta}$. The ϕ dependence is approximated by a fourth degree polynomial in these coefficients. The mass dependence of the efficiency is obtained by linear interpolation between values at a discrete series of masses at which events are generated in the Monte – Carlo procedure.

The events are weighted by a factor $1/\epsilon$ before further analysis. The total number of weighted events is 37000 in the 4γ channel and 60000 in the 8γ channel. Their ratio agrees with the evaluation made using the known η branching ratios into 2γ and $3\pi^0$.

5. Analysis.

5.1 t – distributions.

Fig. 6 shows distributions of events versus the four – momentum transfer squared for three mass bins in the $\eta\eta$ spectrum. In each of these bins, data show a shape and a slope that are compatible with dominant OPE (one – pion exchange mechanism).

To reduce the contribution of non – resonant $\eta\eta$ pairs, subsequent analysis bears only on events with $|t| < 0.25 \text{ (GeV/c)}^2$. This reduces the number of events by about 15%.

5.2 Angular distributions.

The mass spectrum of $\eta\eta$ events is rather complex. It gives no obvious information on the presence of resonances without further analysis.

Angular distributions are more indicative. These are plotted on fig. 7 (4γ events) and fig. 8 (8γ events) for a series of mass intervals after correction with the Monte – Carlo calculated efficiencies. Again, these plots show similar results in the two different multiplicities. The angular distributions change rapidly with mass, showing the presence of resonances with different spins.

5.3 Partial wave analysis.

A partial wave analysis is necessary to extract from the data the various spin contributions to the cross-section.

The angular distributions have been fitted with a formula of the type:

$$d\sigma/d\Omega \propto |H_0 + H_-|^2 + |H_+|^2 \quad (3)$$

where H_0 represents the helicity amplitude with $m=0$ projection, H_+ is the helicity amplitude for natural parity exchange with $m \neq 0$ and H_- is the corresponding one for unnatural parity. Terms with $|m| > 1$ have been found negligible. Furthermore the contribution of $\ell > 4$ waves has also been neglected in the studied mass range.

The various amplitudes may then be expressed as:

$$\begin{aligned} H_0 &= S P_{00}(\cos\theta) + \sqrt{5} D_0 P_{20}(\cos\theta) + \sqrt{9} G_0 P_{40}(\cos\theta) \\ H_- &= \sqrt{(5/6)} D_- P_{21}(\cos\theta)\cos\phi + \sqrt{(9/20)} G_- P_{41}(\cos\theta)\cos\phi \\ H_+ &= \sqrt{(5/6)} D_+ P_{21}(\cos\theta)\sin\phi + \sqrt{(9/20)} G_+ P_{41}(\cos\theta)\sin\phi \end{aligned} \quad (4)$$

where the $P_{\ell m}(\cos\theta)$ are associated Legendre polynomials, θ is the polar angle of one η in the Gottfried-Jackson frame, ϕ is the azimuthal decay angle and S , D_0 , G_0 , $D_{\pm}$ and $G_{\pm}$ are complex amplitudes.

Fitting the data shows that G_- and H_+ as a whole are small enough to be put to zero in further analysis. The absence of natural parity exchange is compatible with the OPE mechanism.

Below 1.7 GeV one is left with five parameters for three complex amplitudes only : $|S|$, $|D_0|$, $|D_-|$, Φ_{SD_0} , $\Phi_{D_0 D_-}$. Four complex amplitudes become necessary above 1.7 GeV because the spin 4 wave starts contributing.

Phase coherence in the OPE model with absorption decreases the number of parameters by imposing a value of 0 to $\Phi_{D_0 D_-}$. This condition had been used in the evaluation of the amplitudes in the first experiment [1] (in the notation of ref [1] the condition is $\beta = \pi$). It has not been imposed in the present analysis. The general solution does give values of $\Phi_{D_0 D_-}$ close to zero up to 2 GeV (figs 9 and 10). The results are essentially identical with or without imposing this phase coherence.

5.4 Ambiguities.

If only S and D waves contribute to the cross - section, a unique solution can be found from the procedure described above. However when spin 4 waves are present two solutions are possible. Ordinary fitting procedures may arbitrarily find the one or the other. The method of Barrelet's zeroes [10] has been used to determine both solutions.

H_0 is expressed as:

$$H_0 \propto \prod_{i=1}^{\ell} (\cos\theta - z_i) \quad (5)$$

where z_i is a Barrelet's zero . The $2^{\ell-1}$ different solutions may be explicitly written by taking all the possible forms of H_0 i.e. replacing each z_i with its complex conjugate.

For $\eta\eta$ decay, the zeroes are coupled in pairs (z_i , $-z_i$) as only even waves contribute. The expression for $\ell = 4$ is:

$$H_0 \propto (\cos^2\theta - z_1^2) (\cos^2\theta - z_2^2) \quad (6)$$

This solution is called (+ +). The other solution (+ -) is obtained by taking the complex conjugate of one of the zeroes:

$$H_0 \propto (\cos^2\theta - z_1^2) (\cos^2\theta - z_2^{*2}) \quad (7)$$

There are thus two zeroes giving two different solutions for each mass bin. The zeroes are made continuous by choosing the proper assignment for each of them. The amplitudes S, D_0 and G_0 are then recalculated by identifying the two expressions of H_0 (6) and (7) with the expression in formula (4). This procedure leads to two different sets of S and D_0 amplitudes above 1.7 GeV with an identical G_0 - wave contribution.

5.5 Evaluation of the parameters.

Differential cross - sections are fitted with formulae (3) and (4) in 50 MeV bins. The evaluation of wave amplitudes is made by maximizing a likelihood function calculated event by event for all events N_{ev} in a mass bin:

$$\ln L = \ln \prod_{i=1}^{N_{ev}} \epsilon_i f(\theta_i, \phi_i, M_{\eta\eta i}) \quad (8)$$

ϵ_i is the efficiency associated with event i ; $f(\theta_i, \phi_i, M_{\eta\eta i})$ is the density of probability to find an event with corresponding angles and mass.

In the case of 8γ events the Monte – Carlo evaluated spin 0 background (cf. 3.2) is subtracted.

The general form of f is:

$$f(\theta, \phi, M_{\eta\eta}) = (N_{ev} - N_{bg}) (d\sigma/d\Omega) / \int \epsilon (d\sigma/d\Omega) d\Omega + N_{bg} / \int \epsilon d\Omega \quad (9)$$

where N_{bg} is the number of background events evaluated for the given mass bin (in the case of 4γ events, $N_{bg} = 0$).

The overall normalisation is such that:

$$\int \epsilon (d\sigma/d\Omega) d\Omega = N_{ev} - N_{bg} \quad (10)$$

6. Results of the partial wave analysis.

6.1 Mass spectra.

The partial wave analysis reveals a complicated structure of different spins both in 4γ decays (fig. 9) and in 8γ decays (fig. 10). Similar structures are observed both in 4γ and 8γ multiplicities.

The mass region below 1.7 GeV, where the spin 4 wave is negligible, contains two resonances of spin 0. They are identified with the $\epsilon(1300)$ – meson and the $G(1590)$ – meson. Discrepancies occur in the first two bins at the threshold of the mass spectrum between 4γ and 8γ events. Partial wave analysis of the 8γ events yields in these bins abnormally high D_{-} values which are not observed in the 4γ case. The origin of these unphysical contributions cannot be traced with certainty. The values of fig. 10 (8γ data) have been obtained with D_{-} fixed to zero in the first two bins. This prevents a reliable

evaluation of the parameters of ϵ from the 8γ data but has no influence on the parameters of $G(1590)$. The fit in table 1 has been made with the mass of the epsilon fixed to that determined by the 4γ analysis.

The spin 2 wave is characterized by a clean peak around 1.4 GeV due to $f(1270)$ and $f'(1525)$ mesons decaying into a pair of η [1].

The high mass region (above 1.7 GeV) is complicated by the ambiguity problem leading to two different solutions. Solution I (+ -) shows a dip at 2.1 GeV in the spin 0 wave and a broad structure in the spin 2 wave. The other solution II (+ +) is characterized by a peak in the S wave around 2.1 GeV and another one in the D_0 wave at 1.85 GeV.

The spin 4 wave, which is determined without ambiguity, exhibits a peak around 2 GeV. This is identified to the $h(2030)$ -meson decaying into a pair of η .

6.2 Parameters of mass structures.

Independent fits of S, D_0 and G_0 waves have been performed in order to evaluate the parameters of the resonances and the corresponding cross-sections. The different waves have been fitted by a sum of Breit-Wigner functions, modified to take into account barrier factors,¹ and a complex background term (BG).

For the wave with angular momentum ℓ (0, 2 or 4):

$$A^\ell(M_{\eta\eta}) = \sum_{j=1}^n \frac{A_j \sqrt{R(M_{\eta\eta}, M_j, \ell)}}{M_j - M_{\eta\eta} - i\Gamma_j/2} + BG \quad (11)$$

¹ The general form for the Breit-Wigner function is:

$$A = \frac{\Gamma_k^{1/2} \Gamma_f^{1/2}}{M_R - M - i\Gamma/2}$$

where M_R is the mass of the resonance, Γ its total width, Γ_k the production width and Γ_f its decay width. In general all three widths are to be corrected for barrier effects. However Γ and Γ_k are dominated by the $\pi\pi$ decay width and are too far from threshold to be influenced. Consequently only Γ_f keeps a correction factor.

where A_j is the amplitude of the j^{th} Breit – Wigner function; M_j and Γ_j are the mass and the width of the j^{th} resonance, respectively; $R(M_{\eta\eta}, M_j, \ell)$ is the barrier factor :

$$R(M_{\eta\eta}, M_j, \ell) = B(M_{\eta\eta}, \ell) / B(M_j, \ell)$$

where $B(M, \ell) = q^{(2\ell + 1)} / [M(q^2 + r^{-2})^\ell]$; q is the η momentum in the $\eta\eta$ center of mass; r is the interaction radius (taken as $r = .5$ fm, but the fit is insensitive to r values between .25 and .75 fm).

The number of resonances and their parameters have been fixed by χ^2 fit. It was found that two Breit – Wigner functions were necessary to account for the large unresolved bump centered at 1400 MeV in the spin 2 wave. They correspond to f and f' shifted to higher masses by the barrier effect. The mass of f' has been fixed at the tabulated value of 1525 MeV and its width to 50 MeV. The large high mass bump in solution I for the spin 2 wave has no Breit – Wigner shape. The mean mass and the full width (FWHM) of the bump are reported. The small G wave contribution is fitted as the h – meson in the interval from 1.7 GeV to 2.4 GeV.

The Breit – Wigner amplitude, the mass and the width are given for each resonance or structure in table I. Quoted widths are not corrected for the instrumental resolution (of about 70 MeV for a mass of 2 GeV).

Figs. 9 and 10 show, in particular, the variations of the relative phase between the various waves. Absolute values are not known. The presence of many states in a rather narrow mass interval blurs the observation of the individual variations which are expected to occur at resonance. Nevertheless, fast variations are observed in the S, D_0 and G_0 waves.

6.3 Normalisation and cross – sections.

No absolute normalisation of the data has been obtained yet. The sensitivity of the present measurements has been determined by comparing the number of observed η – mesons decaying into two photons in the reaction:

TABLE I.
Parameters of the mass structures.

(M_i , Γ_i and A_i in MeV)

	4 γ decay		8 γ decay	
	solution I	solution II	solution I	solution II
SPIN 0				
M_1	1230 ± 30	1210 ± 30	1220	1220
Γ_1	280 ± 40	315 ± 60	370 ± 80	330 ± 60
A_1	4100 ± 250	4500 ± 1000	5200 ± 1200	4900 ± 600
M_2	1560 ± 30	1590 ± 30	1610 ± 30	1600 ± 30
Γ_2	230 ± 30	300 ± 30	290 ± 50	350 ± 50
A_2	2200 ± 400	3200 ± 300	3800 ± 400	4300 ± 300
M_3		2090 ± 40		2160 ± 40
Γ_3		215 ± 30		315 ± 30
A_3		2200 ± 250		2900 ± 130
Im BG	2.9 ± 1.4	1.9 ± 1.2	4.5 ± 4.8	0.5 ± 2.0
SPIN 2				
M_1	1310 ± 30	1310 ± 30	1280 ± 30	1290 ± 30
Γ_1	190 ± 30	215 ± 30	220 ± 50	150 ± 30
A_1	1400 ± 290	1950 ± 300	3300 ± 500	1650 ± 250
M_2	1525	1525	1525	1525
Γ_2	50	50	50	50
A_2	-125 ± 40	-200 ± 40	-430 ± 100	-490 ± 60
M_3	1950 ± 50	1890 ± 40	1950 ± 50	1850 ± 40
Γ_3	550 ± 50	250 ± 30	600 ± 50	240 ± 30
A_3	$/^*$	-4800 ± 500	$/^*$	-5600 ± 500
Im BG	10.2 ± 1.0	6.6 ± 2.2	0.3 ± 1.1	9.9 ± 2.0
SPIN 4 (single solution)				
M_1		2070 ± 50	1900 ± 50	
Γ_1		500 ± 100	300 ± 70	
A_1		3400 ± 300	3500 ± 500	

* This structure does not have a Breit – Wigner shape. Reported mass and width are the mean mass of the structure and its full width half maximum.

with the measured cross-section of $(0.337 \pm 0.021) \mu\text{b}$ at 100 GeV/c [11]. It is about 0.4 pb/event after proper corrections for acceptance and efficiency calculated by Monte-Carlo. The production cross-sections of the different $\eta\eta$ systems have been evaluated using the number of events in the various resonances and structures under the peaks in the 4γ channel as acceptance-efficiency corrections are smaller and known to a better accuracy for this channel than for the 8γ channel. A correction factor of 0.5 takes into account the production of isobars in the final state. Using the tabulated value of the branching ratio for the decay of η into 2 photons, the final sensitivity per $\eta\eta$ event in reaction (1) is 1.4 pb.

7. G(1590) and the glueball hypothesis.

A spin 0 resonance with a mass of $(1580 \pm 30) \text{ MeV}$ and a width of $(280 \pm 40) \text{ MeV}$ is independently observed both in 4γ and in 8γ decay modes. It is unambiguously identified as the scalar G(1590)-meson. The measured parameters are in full agreement with those reported by the Vth Joint CERN-IHEP experiment with the smaller GAMS-2000 [1].

The production cross-section as measured at 100 GeV/c is:

$$\sigma \times \text{BR}(G \rightarrow \eta\eta) = (3.8 \pm 0.7) \text{ nb}$$

Comparing the cross-sections at 38 and 100 GeV/c yields the ratio:

$$\sigma(100 \text{ GeV/c})/\sigma(38 \text{ GeV/c}) = 0.12 \pm 0.04$$

It shows a $p^{-\alpha}$ energy dependence, with $\alpha \approx 2$ typical for the OPE mechanism. Also the shape of the differential cross-section in the region of the G meson is characteristic of that mechanism (fig.6). The fact that OPE is still the dominating mechanism for the production of meson pairs at 100 GeV/c and even at higher energies has been also observed in $\pi^+\pi^-$ production [12].

An important clue concerning the nature of this meson is given by the absence of a measurable $\pi^0\pi^0$ branching ratio. Data at 38 GeV/c revealed that the $\text{BR}(G \rightarrow \pi^0\pi^0)$ is less than $0.3 \times \text{BR}(G \rightarrow \eta\eta)$, a very conservative upper limit [1]. The present limit at 100 GeV/c is of the same order as that evaluated at 38 GeV/c. It has been estimated with the number of remaining events in the G region of the $\pi^0\pi^0$ mass spectrum after subtraction of the $f(1270)$ peak. It should be lowered after a full analysis of the $\pi^0\pi^0$ channel which is now in progress.

The branching ratio of G into $\eta\eta'$ is even larger than that into $\eta\eta$ [1]. G is not observed to decay into $K\bar{K}$ at the present level of sensitivity. All these peculiar properties are not compatible with those of a $q\bar{q}$ or even a $q\bar{q}q\bar{q}$ meson structure. If G(1590) were an ordinary ($u\bar{u} + d\bar{d}$) or $s\bar{s}$ meson its decay rate into $\pi\pi$ or $K\bar{K}$ would be an order of magnitude larger than the presently measured upper limits.

G(1590) appears as a strong scalar glueball candidate. Recent experimental searches conclude that the minimum mass of a scalar glueball is likely to be above 1.1 GeV [13]. G(1590) might experimentally set the glueball mass scale for which lattice calculations give values as different as 700 and 1300 MeV because of large discrepancies in the parameters of the theory [14].

G has not been observed in other processes which are expected to be gluonium sources, like J/ψ radiative decays and central particle production via double-pomeron exchange. The study of these processes dealt mainly with $\pi\pi$ and $K\bar{K}$ channels. However $\theta(1690)$, a spin 2 meson, has been observed in J/ψ radiative decay through η pairs as well as through π and K pairs [15].

$\theta(1690)$ is not found in the current experiment. A fit with a fourth Breit-Wigner function in the D_0 wave (fig. 9) has been attempted. Mass and width have been fixed to the accepted values for θ , 1690 MeV and 200 MeV, respectively. It gives an upper limit on θ production in reaction (1): $\sigma \times \text{BR}(\theta \rightarrow \eta\eta) < 0.5 \text{ nb}$ (95% C.L.).

It has been proposed that both mesons, G(1590) and $\theta(1690)$, may have been seen together in the J/ψ decay into $\gamma\eta\eta$ [4]. The spin assignment of the θ was made ignoring a possible $f(1525)$ contribution and the possible presence of two resonances in the low statistics sample of θ in $\eta\eta$ mode. This fact might change the values of the θ branching ratios [15]. It might be one explanation why θ is not observed in reaction (1) and why the measured helicity amplitudes are different in both $\theta \rightarrow K\bar{K}$ and $\theta \rightarrow \eta\eta$.

It has been pointed out that the existence of $G(1590)$ as a scalar glueball, which may mix with $q\bar{q}$ scalar mesons, helps to solve the 0^{++} nonet problem without the need of four-quark states [16].

8. Other mesons and structures.

8.1 $\epsilon(1300)$ meson.

The spin 0 peak observed near threshold is naturally associated with the $\epsilon(1300)$ resonance which decays mainly into $\pi\pi$ and $K\bar{K}$. The interpretation of this state as well as other 0^{++} mesons as members of the $q\bar{q}$ 0^{++} nonet is ambiguous [17]. The measured parameters are $M = (1220 \pm 40)$ MeV and $\Gamma = (320 \pm 40)$ MeV. This mass value is somewhat lower than that proposed by the Particle Data Group [18]. It coincides with the peak position of an S-wave resonance seen in the $\pi^0\pi^0$ system at 38 GeV [19].

The measured cross-section is $\sigma \times \text{BR}(\epsilon \rightarrow \eta\eta) = (3.7 \pm 1.5)$ nb. Using the ϵ to f production ratio of about 0.2 which has been measured at 38 GeV [19], one obtains an estimate for $\text{BR}(\epsilon \rightarrow \eta\eta)$:

$$\text{BR}(\epsilon \rightarrow \eta\eta) \approx 2 \times 10^{-2}$$

This may be compared with the value 5×10^{-2} predicted by SU(3) if ϵ is a $(u\bar{u} + d\bar{d})/\sqrt{2}$ meson [20].

8.2 $f(1270)$ meson.

The spin 2 peak around 1.4 GeV is split into two resonances: $f(1270)$ and $f'(1525)$. The f -meson has a mass of (1300 ± 30) MeV in agreement with the tabulated value. Its width is (200 ± 30) MeV. The cross-section is $\sigma \times \text{BR}(f \rightarrow \eta\eta) = (2.2 \pm 0.5)$ nb. Using the measured number of $f(1270)$ mesons decaying into $2\pi^0$, (i.e. a cross-section of (220 ± 30) nb) and the tabulated branching ratio into a pair of π^0 [18], one obtains the branching ratio into a pair of η mesons:

$$\text{BR}(f \rightarrow \eta\eta) = (2.8 \pm 0.7) \times 10^{-3}$$

in agreement with the SU(3) prediction of $(3.9 \pm 1.0) \times 10^{-3}$ [20]. A QCD based model evaluation [21] of the partial widths of f gives 0.64 MeV for the $\eta\eta$ channel and 121 MeV for the $\pi\pi$ channel. Using the average $\pi\pi$ branching ratio [18], it gives a $\eta\eta$ branching ratio of 4.4×10^{-3} in agreement with the present and the previous [1] measurement.

8.3 $f'(1525)$ meson.

The $f'(1525)$ meson does not appear in the mass spectrum as a separate peak but is mixed with the $f(1270)$ meson. Its parameters cannot be extracted from the spectrum alone due to insufficient statistics. Its mass has been fixed to 1525 MeV and its width to 50 MeV in the fit. The cross-section is $\sigma \times \text{BR}(f' \rightarrow \eta\eta) = (0.14 \pm 0.05)$ nb. The $f'(1525)$ meson is observed with a phase opposite to that of $f(1270)$ as expected from reference [21]. If one assumes the QCD based model calculated $\text{BR}(f' \rightarrow \eta\eta)$ of 0.12 [21], which is also expected in SU(3), then $\sigma(f')/\sigma(f)$ is $(1.5 \pm 0.7) \times 10^{-3}$. Such a strong OZI suppression has already been observed at lower energies [18,21,22].

8.4 $h(2030)$ meson.

This is the first observation of the 4^{++} $h(2030)$ meson in the $\eta\eta$ decay channel. Its parameters are $M = (2000 \pm 60)$ MeV and $\Gamma = (400 \pm 100)$ MeV. The measured cross-section is $\sigma \times \text{BR}(h \rightarrow \eta\eta) = (1.32 \pm 0.35)$ nb. The branching ratio of h into $\eta\eta$ has been evaluated in two ways:

- a) The ratio between f and h production cross-sections measured through their $\eta\eta$ decay is 1.7 ± 0.5 at 100 GeV/c, while the same ratio measured in the $\pi^0\pi^0$ mode at 38 GeV is 6.1 ± 1.5 . Using the known values of f and h branching ratios, one obtains:

$$\text{BR}(h \rightarrow \eta\eta) = (2.2 \pm 1.0) \times 10^{-3}$$

- b) Assuming a p^{-2} dependence for the production of h and using the cross-section of (250 ± 40) nb measured at 38 GeV/c in the $\pi^0\pi^0$ decay mode [2], the branching ratio of h in a pair of η -mesons is:

$$\text{BR}(h \rightarrow \eta\eta) = (2.1 \pm 1.0) \times 10^{-3}.$$

Both values are compatible with that calculated by using the same method as for the $f(1270)$ (cf. 8.2).

The QCD evaluation [21] gives $\text{BR}(h \rightarrow \eta\eta) \approx 4 \times 10^{-3}$.

It is interesting to notice that the experimental ratio

$$\text{BR}(h \rightarrow \eta\eta)/\text{BR}(f \rightarrow \eta\eta) = 0.8 \pm 0.2$$

is also in agreement with the predicted value of 0.9 [21].

8.5 Other resonances and structures.

a) The high mass region of the spin 0 wave is characterized by a peak in solution II. Its characteristics are $M = (2100 \pm 40) \text{ MeV}$, $\Gamma = (250 \pm 40) \text{ MeV}$. The measured cross-section is $\sigma \times \text{BR} = (3.4 \pm 0.9) \text{ nb}$. This peak, which appears only in solution II, cannot be associated with a known meson.

b) The high mass region of the spin 2 wave shows either a broad structure (solution I) or a narrow peak (solution II). Solution I characteristics are :

$$\langle M \rangle = (1950 \pm 50) \text{ MeV}, \text{FWHM} = (600 \pm 50) \text{ MeV}$$

$$\sigma \times \text{BR}(\eta\eta) = (15 \pm 4) \text{ nb}.$$

Solution II shows a structure with a Breit - Wigner shape with characteristics:

$$M = (1870 \pm 40) \text{ MeV}, \Gamma = (250 \pm 30) \text{ MeV}$$

$$\sigma \times \text{BR}(\eta\eta) = (10 \pm 3) \text{ nb}.$$

This structure is probably not connected to the 1810 MeV spin 2 resonance reported in the Particle Data Group compilation [18]. This has been seen in $\pi^0\pi^0$ and K^+K^- decay modes in two experiments at 8 GeV/c and 10 GeV/c respectively. It is however not observed in the high statistics $\pi^0\pi^0$ data at 38 GeV/c from this collaboration [19].

c) The $\xi(2220)$ -meson [23] is not seen in the present data. This is a narrow state : $\Gamma < 50$ MeV. An upper limit has been put on its production : $\sigma \times \text{BR}(\xi \rightarrow \eta\eta) < 0.5$ nb (95 % C.L.) which would correspond to a peak of 360 events in a single mass bin of 50 MeV.

9. Conclusions.

The present experiment has brought new complementary evidence to the existence of the 0^{++} $G(1590)$ -meson which is now observed in two quite different event multiplicities. New branching ratios of known mesons in $\eta\eta$ have been produced.

Ambiguous spin 0 and 2 structures at masses higher than 1.7 GeV should be analysed through other decay channels.

Present data on $\eta\eta$ systems in various mass bins are dominated by the mechanism of one pion exchange in agreement with other observations that OPE is predominant in the production of two pseudoscalar meson resonances even at high energies.

Data which have been collected at 230 GeV show similar structures in all waves over the whole mass range as well as the same t -dependence. Detailed analysis is under way.

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FIGURE CAPTIONS.

Fig. 1 : Experimental layout.

S_i : beam definition counters, H_i : beam hodoscopes; SG: guard system surrounding the 60 cm long liquid hydrogen target (12 scintillation + 96 lead glass counters).
AC and AH_i : scintillation counters; SW_i : lead – scintillator sandwich counters.

Fig. 2 : a. Invariant mass spectrum of all two by two gamma combinations of 4γ events. Events with an identified π^0 have already been rejected.

b. Invariant mass spectrum of the second gamma pair after the first one has been identified as an η .

Fig. 3 : Mass spectrum of 4γ events identified as $\eta\eta$ systems after 3 – C fit.

Fig. 4 : a. Invariant mass spectrum of the six gammas associated with an identified η in 8γ events. Events with $4\pi^0$ have been removed.

b. Same as above when $3\pi^0$ are identified amongst the 6 gammas.

Fig. 5 : Mass spectrum of 8γ events identified as $\eta\eta$ systems after 6 – C fit.

Fig. 6 : t – distributions for three mass bins.

Fig. 7 : $\cos\theta$ distributions of $\eta\eta$ events (4γ decay) for successive mass bins (indicated in GeV in the upper part of each figure). Dashed line curves are Monte – Carlo evaluations of the efficiency.

Fig. 8 : $\cos\theta$ distributions of $\eta\eta$ events (8γ decay) for successive mass bins (indicated in GeV in the upper part of each figure). Distributions have been folded over $0 \leq \cos\theta \leq 1$ for comparison with 4γ events . Dashed line curves are Monte – Carlo evaluations of the efficiency.

Fig. 9 : S, D and G amplitudes and phases (4γ events).

a. Solution I (+ -).

b. Solution II (+ +).

G_0 and D_- amplitudes are identical for both solutions.

Fig.10 : S, D and G amplitudes and phases (8γ events).

a. Solution I (+ -).

b. Solution II (+ +).

G_0 and D_- amplitudes are identical for both solutions.

$M_{\gamma\gamma}$ (MeV)

FIG. 2a

$M_{\gamma\gamma}$ (MeV)

FIG. 2b

FIG. 3

$M_{6\gamma}$ (MeV)

FIG. 4a

FIG. 4b

FIG. 5

FIG. 6

$\cos \theta$

FIG. 7

$\cos \theta$

FIG. 8

$M_{\eta\eta}(\text{GeV})$ FIG. 9a

$M_{\eta\eta}$ (GeV)

FIG. 9b

$M_{\eta\eta}(\text{GeV})$

FIG. 10a

$M_{\eta\eta}(\text{GeV})$

FIG. 10b