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1988 CELLO, JADE AND PLUTO CONTRIBUTIONS TO "EXOTIC" MESON SPECTROSCOPY [1]

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ABSTRACT. This article reviews selected recent results on resonance formation in $\gamma\gamma$ reactions obtained with the CELLO, JADE and PLUTO spectrometers at the e^+e^- storage ring PETRA. New stringent limits on the $\gamma\gamma$ coupling of glueball candidates as well as new results on tensor and scalar mesons are presented. The recent observation of $\pi_2(1680)$ formation is confirmed by the CELLO group. Finally the two spin 1 states observed in $\gamma\gamma^*$ interactions, in particular the parity of the $X_1(1420)$ and the model dependence of present analyses are discussed.

GLUEBALL CANDIDATES. A quantitative measure for clarifying the glueball nature of a state X has been introduced by Chanowitz[1]: The *Stickiness* S is defined as the ratio of the squared amplitudes of the gluon gluon coupling to the photon photon coupling of X. Numerically it can be obtained from measurable partial widths. In principle a large S_X supports a glueball interpretation. However, also a pure $q\bar{q}$ state can have a very large stickiness due to destructive interference of different quark flavours.

quantity	helicity	interference	PLUTO	CELLO
$\Gamma_{\gamma\gamma}(\eta(1440)) \cdot B(K\bar{K}\pi)$	-	-	2.7	1.2
$\Gamma_{\gamma\gamma}(f_2(1720)) \cdot B(K\bar{K})$	2	no	0.07	0.06
	any	no	0.09	0.12
	any	any	0.20	0.22
$\Gamma_{\gamma\gamma}(X(2230)) \cdot B(K\bar{K})$	2	any	0.06	0.12
	any	any	0.07	

Table 1: 95%*c.l.* upper limits for the product of $\Gamma_{\gamma\gamma} \cdot B$ in keV (incl. 20% systematic uncertainty) for glueball candidates

The pseudoscalar ι (now called $\eta(1440)$) and the tensors Θ (now $f_2(1720)$) and ξ (X(2230)) have been considered prime glueball candidates. Recent analyses of the reactions $\gamma\gamma \to K^0_S K^\pm \pi^\mp$ and $\gamma\gamma \to K^0_S K^0_S$ by PLUTO [2,3] and CELLO [4,5,6,7] do not show excitation of these states, and the upper limits in table 1 have been obtained. These can be translated to the following stickiness ratios:

$$0^{-+}: \quad S_{\pi^0} : S_\eta : S_{\eta'} : S_\iota = 0.02 : 1 : 4 : > 80\,(95\%c.l.).$$

$$2^{++}: S_{f_2} : S_{f_2'} : S_{f_2(1720)} : S_{X(2230)} = 1 : 13 : > 28\,(95\%c.l.) : > 9\,(95\%c.l.).$$

An analysis combining the new CELLO numbers with the published spectra and results of TPC/$\gamma\gamma$ [8] and (most important) MARK II [9] leads to the upper limit $\Gamma_{\gamma\gamma}(\eta(1440)) \cdot B(K\bar{K}\pi) < 0.75\,keV$ at 95% c.l. (incl. 20% systematic uncertainty) and a relative stickiness of more than 128!

Although these ratios have been improved in recent years, their implication becomes less clear due to theoretical progress: also radial excitations might have a smaller $\gamma\gamma$ coupling than previously expected due to a dynamical suppression by chiral symmetry [10]. Moreover, recent results from lattice gauge theory [11] as well as the flux tube model [12] point to glueball masses well above 2 GeV (except for the 0^{++}). Last not least, the Θ may loose 2 units of spin [13] to become a $f_0(1720)$, whereas the ξ may gain two units [14] to a $f_4(2230)$, in which case the above mentioned numbers become meaningless.

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[1] Talk given at the BNL Workshop on Glueballs, Hybrids and Exotic Hadrons, Upton, New York, Aug. 27- Sep. 1, 1988

state	final state	reference	$\Gamma_{\gamma\gamma}[keV]$
$S^*(980)$	$\pi^0\pi^0$	JADE[15,16]	< 0.6 at $95\% c.l.$
$\delta(980)$	$\pi^0\eta$	JADE[15,16]	$(0.29 \pm 0.05 \pm 0.14)\,/B(\eta\pi)$
$f_0'(1530)$	$K_S^0K_S^0$	PLUTO,CELLO[7]	$< 0.7/B(K\bar{K})$ at $95\% c.l.$
f_2	$\pi^0\pi^0$	JADE[15,16]	$3.09 \pm 0.10 \pm 0.38$
f_2	$\pi^+\pi^-$	CELLO[17]	$3.0 \pm 0.1 \pm 0.5$
a_2	$\pi^0\eta$	JADE[15,16]	$1.09 \pm 0.14 \pm 0.25$
f_2'	$K_S^0K_S^0$	PLUTO[2]	$(0.10^{+0.04+0.03}_{-0.03-0.02})/B(K\bar{K})$
f_2'	$K_S^0K_S^0$	CELLO[4,7]	$(0.11^{+0.03}_{-0.02} \pm 0.02)/B(K\bar{K})$

Table 2: Recent results on scalar and tensor mesons

TENSOR AND SCALAR MESONS. Table 2 summarizes some recent results on tensor and scalar mesons. From the radiative widths of the three totally neutral tensor meson nonet members one can determine the octet singlet mixing angle. A recent calculation [3] results in a mixing angle between 28 and 32°, taking into account uncertainties in mass correction and the f_2' branching ratio. It is worth noting that the GMO mass formula with latest mass values [18] results in 32° [19] rather than the frequently quoted 28° [18]. A study of SU(3) breaking effects shows that a probably larger s quark mass could lead to a value very near ideal mixing [3].

The small radiative widths of the scalars S^* and δ are very much in favour of a large $qq\bar{q}\bar{q}$ [20] or $K\bar{K}$ molecule [21] component in their wavefunctions, which can also explain their small total widths, the latter interpretation in addition the masses a few MeV below the $K\bar{K}$ threshold. So it seems likely that S^* and δ are not the scalar $q\bar{q}$ mesons (which, in turn, makes the use of their new names f_0 and a_0 questionable). The expected large $\gamma\gamma$ couplings of the (probably very broad) scalar $q\bar{q}$ mesons in the order of several keV are still to be found. The combined limit from PLUTO and CELLO [7] on the mainly $s\bar{s}$ candidate state $f_0'(1530)$ observed by LASS [14] is still in agreement with SU(3) expectations.

PSEUDOTENSORS. At the $\gamma\gamma$ workshop in Jerusalem early this year the Crystal Ball Collaboration presented evidence for the formation of the $J^{PC} = 2^{-+}$ meson $\pi_2(1680)$ (the former A_3) in the reaction $\gamma\gamma \to f_2\pi^0 \to 3\pi^0$ and quoted a preliminary radiative width of $1.4 \pm 0.3\,keV$. Now this observation is confirmed in a preliminary analysis of the reaction $\gamma\gamma \to \pi^+\pi^-\pi^0$ of the CELLO collaboration. This final state is dominated by the $a_2(1320)$ resonance, and some angular cuts to suppress this background and to enrich $J^P = 2^- - 2^+0^- - 0^-0^-0^-$ decays have been applied. Then the invariant $\pi^+\pi^-$ mass spectrum shows clear evidence for f_2 production (fig.1a). The shape of the background is justified from phase space and $a_2 \to \rho\pi$ Monte Carlo simulations. Counting the number of f_2 candidates as a function of the $\pi^+\pi^-\pi^0$ mass results in the spectrum shown in fig.1b. A Monte Carlo calculation of π_2 formation and decay using the standard PDG mass and width leads to the shaded histogram, in excellent agreement with the data. The preliminary value of the radiative width is $1.9 \pm 0.7\,keV$. A more refined analysis, also looking for the $\rho\pi$ decay mode, is underway.

SPIN 1 MESONS. The well-known Landau-Yang theorem [22] states that spin 1 mesons cannot couple to two real photons, their radiative width $\Gamma_{\gamma\gamma}$ vanishes. This is not true if one of the photons is off mass shell. In this case one can define a partial width $\Gamma_{\gamma\gamma^*}(Q^2)$ and the limit $\tilde{\Gamma}_{\gamma\gamma} = m^2 \cdot \lim_{Q^2\to 0} \frac{\Gamma_{\gamma\gamma^*}(Q^2)}{Q^2}$. The signature of a spin 1 meson in $\gamma\gamma$ interactions is a resonance signal in tagged data (where the electron tag indicates the exchange of a virtual photon and measures its Q^2) and the absence of a corresponding signal in the no-tag data (with both photons being nearly real).

Two such states have been observed in $\gamma\gamma^*$ reactions (see also the talks [23,24]): a resonance with a mass of $\approx 1285\ MeV$ in the $\pi^+\pi^-\eta$ final state can be identified as the $f_1(1285)$, the old D meson, with $J^{PC} = 1^{++}$. The parity assignment is unique since CELLO [6,25], JADE [26] and MARK II [27] proved that the decay proceeds mainly through $\delta\pi$, and a $1^- \rightarrow 0^+0^-$ decay is forbidden by parity conservation. The interpretation of the other state at $m \approx 1420 MeV$ in the $K\bar{K}\pi$ decay mode is both more unclear and more interesting, since it contributes to the longstanding discrepancies in the spin-parity assignment of the E meson. Furthermore it seems to be an exotic state in the quark model: If it is a 1^{++} state, we have one neutral axial vector meson too many: $a_1(1270)$, D(1285), E(1420) and the recently confirmed D'(1530) (or f_1') [28,29]. The E could then be interpreted as a 4-quark state [24] or a $q\bar{q}g$ hybrid. If on the other hand the signal is due to a negative parity spin 1 state, this will immediately be exotic, since a 1^{-+} state cannot be built from two spin 1/2 quarks. Chanowitz [30] favours such an assignment, since it can also explain some features of the $J/\psi \rightarrow \omega/\phi$"$E$" decays. In this case the state can be interpreted as a hybrid state, perhaps the isoscalar partner of the 1^{-+} isovector recently observed by GAMS [31] in the reaction $\pi^- p \rightarrow \eta\pi^0 n$. From this discussion it is clear that a spin parity analysis of the state seen in $\gamma\gamma$ interactions is very important.

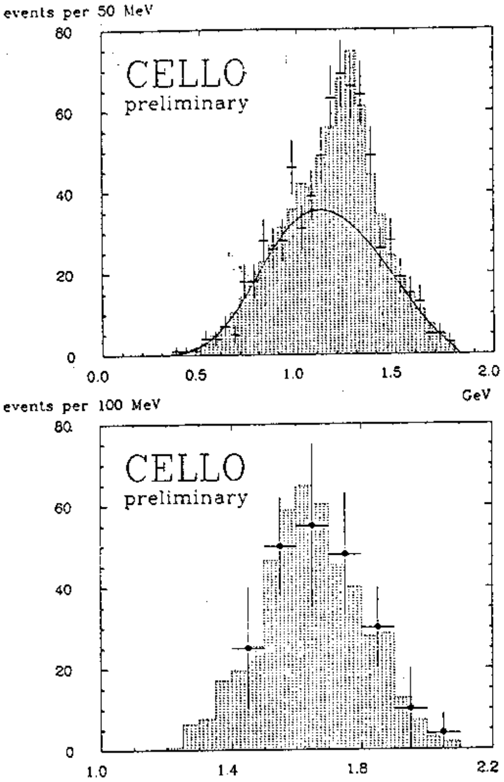

Figure 1: a) Invariant $\pi^+\pi^-$ mass spectrum for $\pi^+\pi^-\pi^0$ masses above $1.4\,GeV$ b) Invariant $f_2\pi^0$ mass spectrum

In the single tag mode spin 1 meson production can be described by 2 independent gauge invariant parity conserving Born term amplitudes [32]: M_{0+} determines the scattering of a longitudinal and a transverse photon leading to a helicity 1 state, and M_{++}

J^P	helicity 0 $\lvert M_{++}\rvert^2$	helicity 1 $\lvert M_{0+}\rvert^2$
1^+	$\frac{(q_2^2-q_1^2)^2}{W^2} F_{TT}^2$	$\frac{-q_1^2}{(q_1q_2)^2} X F_{LT}^2$
1^-	$\frac{4(q_2^2-q_1^2)^2}{W^2} X F_{TT}^2$	$\frac{-q_1^2}{(q_1q_2)^2} F_{LT}^2$

q_i: 4-momentum of virtual photon i
W: invariant $\gamma\gamma$ mass
$X = (q_1q_2)^2 - q_1^2q_2^2$
$F_i(Q_1^2, Q_2^2)$ form factors

Table 3: Helicity amplitudes for $\gamma\gamma^* \rightarrow 1^{\pm+}$

state	exp.	FF	$\tilde{\Gamma}_{\gamma\gamma}$ $[keV]$
$f_1(1285)$	CELLO	ρ	$7.2 \pm 2.2 \pm 2.4$
	JADE	ρ	$3.6 \pm 0.6 \pm 0.8$
$X_1(1420)$	CELLO	ρ	$3.0 \pm 0.9 \pm 0.7$
$/B(K\bar{K}\pi)$	CELLO	ϕ	$1.4 \pm 0.4 \pm 0.3$
	JADE	ρ	$4.2^{+1.8}_{-1.6} \pm 1.2$
	JADE	ϕ	$3.0^{+1.2}_{-1.0} \pm 1.0$
$f_1'(1530)$	CELLO	ρ	< 1.7 $(95\% c.l.)$
$/B(K\bar{K}\pi)$	CELLO	ϕ	< 1.0 $(95\% c.l.)$

Table 4: Recent results on the $\gamma\gamma$ widths of spin 1 mesons (Cahn convention). FF denotes the form factor assumed for the extrapolation to $Q^2 - 0$.

the scattering of two transverse photons to a helicity 0 state. Depending on the parity of the final state, these amplitudes are given in table 3. The form factors $F_{TT}(Q^2)$ and $F_{LT}(Q^2)$ are assumed to be relatively slowly varying functions of the photon mass, the steepest dependence usually considered is a ρ pole. However, dynamical effects can introduce zeroes, as e.g. assumed by Achasov [33]. The $\gamma\gamma$ cross section can be written as (with $X = (q_1 q_2)^2 - Q_1^2 Q_2^2$):

$$\sigma_{\gamma\gamma} = \sigma_{TT} + \sigma_{LT} = \frac{1}{4\sqrt{X}} \frac{m\Gamma}{(W^2 - m^2)^2 + \Gamma^2 m^2} \left(|M_{++}|^2 + 2|M_{0+}|^2\right)$$

which leads to the following small Q^2 behaviour: $\sigma_{LT} \propto Q^2 \cdot F_{LT}^2(Q^2)$, whereas $\sigma_{TT} \propto Q^4 \cdot F_{TT}^2(Q^2)$. Thus, one assumes that the LT contribution dominates at small Q^2. Qualitatively this is confirmed for the $f_1(1285)$ by the JADE measurement [26] of the $f_1(1285) \to \delta\pi$ decay angular distribution. However, no quantitative statements are available yet. Using the golden rule, the following model independent definition of $\tilde{\Gamma}_{\gamma\gamma}$ can be obtained:

$$J^P = 1^+ : \tilde{\Gamma}_{\gamma\gamma} = \frac{m}{24\pi} \cdot F_{LT}^2(Q^2 = 0) \quad ; \quad J^P = 1^- : \tilde{\Gamma}_{\gamma\gamma} = \frac{1}{6\pi m^3} \cdot F_{LT}^2(Q^2 = 0) \quad (1)$$

Note that due to the Q^{-4} behaviour of the TT contribution only the helicity 1 form factor contributes to $\tilde{\Gamma}_{\gamma\gamma}$.

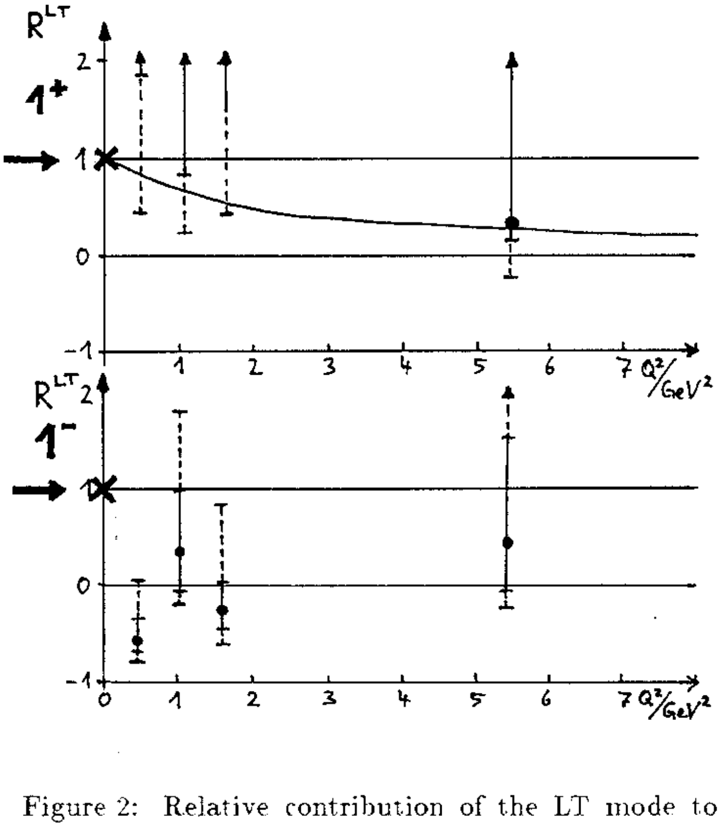

Figure 2: Relative contribution of the LT mode to the total $\gamma\gamma$ width as function of Q^2. a) 1^+ (solid line: Cahn model), b) 1^- hypothesis. Data points with 1 and 2 s.d. error bars.

In principle, it is possible to separate the LT and TT contributions using the decay angular distributions. With the small statistics available all experiments up to now used instead the nonrelativistic quark model calculation by Cahn [34] to relate both contributions to one coupling constant $\tilde{\Gamma}_{\gamma\gamma}$. In our notation the model reads: $F_{TT}^2 = 96\pi\, X/m^5\, F^2(Q_1^2) F^2(Q_2^2) \cdot \tilde{\Gamma}_{\gamma\gamma}$ and $F_{LT}^2 = 96\pi\, (q_1 q_2)^2/m^5 F^2(Q_1^2) \cdot F^2(Q_2^2) \cdot \tilde{\Gamma}_{\gamma\gamma}$.

Three comments are important here: Unfortunately the first two experiments reporting results used different conventions for the radiative width of a spin 1 state: the results of TPC/$\gamma\gamma$ [35] and JADE [36] have to be multiplied by 2 in order to compare to the results of MARK II [9] and CELLO [5], the conventions are usually referred to as TPC and Cahn conventions [37]. Further, the strong dependence of $\tilde{\Gamma}_{\gamma\gamma}$ on the assumed form factors $F(Q_i^2)$ has to be noted. Finally, the Cahn model can only be valid for positive parity, because, as indicated above, a $J^{PC} = 1^{-+}$ state is exotic in the quark model. The results obtained by the PETRA experiments are summarized in table 4. The CELLO group [5] also presents their results in a model independent way, separately for both parity hypotheses, as allowed regions in the $F_{TT}^2 - F_{LT}^2$-plane in four Q^2 bins.

The combined Dalitz plot of all four experiments prove the $K^*\bar{K}$ + c.c. dominance of the $K\bar{K}\pi$ decay. CELLO uses the $K^*\bar{K}$ decay angle correlations to separate the helicity 0 and 1 contributions to the signal for both parity assignments. Fig. 2 shows a representation of the fit results (with 1 and 2 standard deviation errors) as possible values of the relative contribution of the LT mode to the total $\gamma\gamma$ width: $R^{LT}(Q^2) = \Gamma_{\gamma\gamma}^{LT}(Q^2)/\Gamma_{\gamma\gamma}(Q^2)$. By construction, this quantity must have values between 0 and 1, and the small Q^2 behaviour mentioned above constrains R^{LT} to 1 at $Q^2 = 0$.

In case of a positive parity the results are in fair agreement with the expected helicity 1 dominance and the Cahn model, whereas a negative parity interpretation is hardly compatible with the $Q^2 = 0$ constraint. The natural scale for changes in the helicity structure is Q^2/m^2, which is 1 at $Q^2 = 2\,GeV^2$. Especially the lowest Q^2 point shows that one needs a dynamical suppression of the LT mode (i.e. $F_{LT}(Q^2) = 0$) in order to explain the data as a $J^P = 1^-$ state. However, if one is willing to accept that, there is presently no experimental possibility to distinguish this from a 1^+ interpretation. From this and eq. 1 it follows that all experiments are compatible with $\tilde{\Gamma}_{\gamma\gamma}(X_1(1420)) = 0$ (to be compared with the numbers in table 4!) One can instead define a quantity

$$\tilde{\Gamma}'_{\gamma\gamma} = \lim_{Q^2 \to 0} \frac{m^4}{Q^4} \Gamma_{\gamma\gamma^*}(Q^2) = \frac{1}{24\pi} m^5 F_{TT}^2(0) \text{ (for } J^P = 1^- \text{ with } F_{LT} = 0)$$

An analysis of the CELLO data in these terms leads to $\tilde{\Gamma}'_{\gamma\gamma} = 19 \pm 5\,keV$ using a ρ pole. In particular, it is interesting to note that despite of the Q^{-4} dependence of the cross section a ρ form factor describes the data well.

In conclusion, an interpretation of the signal seen in $\gamma\gamma^*$ interactions as a negative parity spin 1 exotic meson cannot be ruled out at all using present data, but it needs a dynamical suppression of the LT mode. And, important to note, the Dalitz plots of all four experiments show no sign of constructive interference in the $K^*\bar{K}/\bar{K}^*K$ overlap region. Although the statistics in every single experiment is meagre, this might be a hint against the usual isoscalar 1^{++} interpretation. Both, an $I^G J^{PC} = 1^- 1^{++}$ as well as $0^+ 1^{-+}$ assignment can explain the lack of events in the interference region. However, to come to a final conclusion, at least a combined partial wave analysis of all available experiments and, better, much more data is needed.

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