RESULTS FROM GAMS

Madjid Boutemeur
CERN-Fellow
GAMS-NA12 collaboration

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ABSTRACT

We present an updated summary of the physics obtained by the NA12-GAMS collaboration on the studies of the exclusive production of neutral mesons decaying into multi-photon final states. We also discuss arguments for giving a glueball assignment to the $f_0(1590)$ ($G(1590)$) and present evidence for a new true exotic meson.
INTRODUCTION

Quantum Chromodynamics has the property of multi-gluon interactions which implies the possible existence of bound states of two or more gluons, called glueballs or gluonia, and bound states of quarks and gluons called hybrids or méiktons. The identification and the study of these states, which is one of the main motivations of our experiment, may yield important information about QCD forces in the confinement region.

We perform a systematic study of light meson spectroscopy in the range from $m_{\pi^0}$ to 3 GeV/c$^2$, where most glueball and hybrid states are expected [1]. Possible non $q\bar{q}$ states are searched by looking for mesons with properties which do not fit quark model predictions, states which fall in an already filled SU(3)-flavor nonets and states with quantum numbers not allowed for ordinary $q\bar{q}$ mesons (exotic quantum numbers). The main object of our study is the charge exchange exclusive reaction:

$$\pi^- p \rightarrow (M^0 \rightarrow k\gamma) n \quad \text{at 38, 100 and 230 GeV/c} \pi^-$$  \hspace{1cm} (1)

where $M^0$ stands for neutral particles or states decaying eventually into photons. Exclusive measurements offer the advantage that kinematic constraints can be applied to each event. This greatly reduces the error on the $M^0$ mass measurement. Furthermore the allowed angular momentum states of the $M^0$ system are often restricted, in particular in the small t region (OPE), which improves the ability to make spin assignment to the observed particle states.

EXPERIMENTAL SETUP

The GAMS collaboration is running two parallel experiments, the NA12 experiment at CERN and another smaller version at the IHEP 70 GeV/c proton synchrotron. The latter one is adapted to the lower energies available at Serpukhov. Both setups are similar, the central units are GAMS-4000 and GAMS-2000 respectively. A summary of the main characteristics of the two detectors is given below (see table 1).

A scheme of the experimental layout of the NA12 experiment is shown in fig. 1. The main unit in the setup is the Cherenkov hodoscope spectrometer GAMS-4000. With its cellular structure, it is able of measuring with high precision the impact coordinates and the energy of up to 20 simultaneous photons in the final state. The liquid hydrogen target 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 gamma emitted at large angle, mainly those emitted by excited nucleon states. The amount of Cherenkov light, in the liquid hydrogen, emitted by beam particles is a measure of the longitudinal position of the interaction vertex. Details on the calibration of GAMS, the acquisition system and the $\gamma$ reconstruction procedures are given in the references [2], [3] and [4].

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Events are classified according to their multiplicity of $\gamma$'s k. For each class the particles decaying into photons are reconstructed (from the energy and the coordinates of the gammas measured in GAMS) by recombining the photons into pairs ($\pi^0, \eta, \eta'$) or triplets ($\omega$). A final classification of events into possible decay channels for a given multiplicity of $\gamma$'s, (Example for 4-$\gamma$ events, the possible channels are: $\pi^0\pi^0, \pi^0\eta, \eta\eta, \ldots$) is done by a kinematical fit using a $\chi^2$ criterium. See reference [4] for a more comprehensive treatment. Figure 2 shows a reconstruction of a typical 8-$\gamma$ event, it illustrates the ability of GAMS in $\gamma$ reconstruction and neutral particle identification. A lego plot of all recombinations of the 4-$\gamma$ data into pairs is shown in fig. 3, even at this stage clear $\eta\pi^0$ and $\eta\eta$ peaks (channels) are seen over a small background. The $\pi^0\pi^0$ events, which contribute to a peak about ten times higher than the $\pi^0\eta$ one, have been left out.

### Table 1. Main parameters of GAMS-2000 and GAMS-4000

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GAMS-2000</th>
<th>GAMS-4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation length $X_0$(cm)</td>
<td>2.6</td>
<td>2.9</td>
</tr>
<tr>
<td>Lead-glass cell dimensions (mm$^3$)</td>
<td>$38 \times 38 \times 450$</td>
<td>$38 \times 38 \times 450$</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>48 x 32 - 1 = 1535</td>
<td>64 x 64 - 4 = 4002</td>
</tr>
<tr>
<td>Useful area (m$^2$)</td>
<td>2.2</td>
<td>5.0</td>
</tr>
<tr>
<td>- Coordinate accuracy ($\sigma_x$(mm) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 25 GeV/c</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>at 200 GeV/c</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>- $\sigma_E/E$ for single $\gamma$(%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 25 GeV/c</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>at 200 GeV/c</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum number of simultaneous $\gamma$</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

### PHYSICS RESULTS

Most results come from studies of exclusive production of neutral final states in the charge exchange reaction (1). Studied processes include two-body cross sections of known mesons, rare decay modes of established mesons, reconfirmation and measurement of branching ratios of less well-established mesons, and the search for new states. Table 2 gives a summary of the recently discovered states with GAMS, it also gives references for already published results. Most of the new discovered states have been seen in $\eta\eta$ and $\eta\eta'$ channels and fall in an already filled $SU(3)$-nonets (mainly $0^+$ and $2^{++}$). On the other hand, it is believed [15][16] that the $\eta$ and the $\eta'$ couple strongly to gluons pairs. This is supported by the large branching ratios for radiative $J/\Psi$ decays into the $\eta$ and particularly into the $\eta'$. So, most of the new observed states are potential glueball candidates. In the following section, we will focus on the $G(1590)$ as a
serious candidate for a fundamental scalar glueball and the M(1400) as a true exotic meson.

Table 2. New states observed with GAMS

<table>
<thead>
<tr>
<th>Name</th>
<th>Decay mode(s)</th>
<th>JPC</th>
<th>Energies GeV/c</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>r(2520)</td>
<td>$\pi^0\pi^0 \rightarrow 4\gamma$</td>
<td>$6^+$</td>
<td>38</td>
<td>[5]</td>
</tr>
<tr>
<td>G(1590)</td>
<td>$\eta\eta \rightarrow 4\gamma$, $8\gamma$</td>
<td>$0^{++}$</td>
<td>38, 100, 230</td>
<td>[6], [7]</td>
</tr>
<tr>
<td></td>
<td>$\eta\eta' \rightarrow 4\gamma$</td>
<td></td>
<td>38</td>
<td>[8]</td>
</tr>
<tr>
<td></td>
<td>$4\pi^0 \rightarrow 8\gamma$</td>
<td></td>
<td>38, 100, 230</td>
<td>[9]</td>
</tr>
<tr>
<td>X(1850)</td>
<td>$\eta\eta \rightarrow 4\gamma$, $8\gamma$</td>
<td>$2^{++}$</td>
<td>100</td>
<td>[6]</td>
</tr>
<tr>
<td></td>
<td>$4\pi^0 \rightarrow 8\gamma$</td>
<td></td>
<td>100</td>
<td>[9]</td>
</tr>
<tr>
<td>X(1750)</td>
<td>$\eta\eta \rightarrow 4\gamma$, $8\gamma$</td>
<td>$0^{++}$ or $2^{++}$</td>
<td>38</td>
<td>[10]</td>
</tr>
<tr>
<td>X(1900)</td>
<td>$\eta\eta \rightarrow 4\gamma$</td>
<td>$0^{++}$</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>X(2100)</td>
<td>$\eta\eta \rightarrow 4\gamma$</td>
<td>?</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>X(2220)</td>
<td>$\eta\eta \rightarrow 4\gamma$</td>
<td>$2^{++}$ or $4^{++}$</td>
<td>38, 100</td>
<td>[11]</td>
</tr>
<tr>
<td>X(1640)</td>
<td>$\omega\omega \rightarrow 6\gamma$</td>
<td>$2^{++}$</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>X(1960)</td>
<td>$\omega\omega \rightarrow 6\gamma$</td>
<td>$2^{++}$</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>M(1400)</td>
<td>$\pi^0\pi^0 \rightarrow 4\gamma$</td>
<td>$1^{-+}$</td>
<td>100</td>
<td>[12]</td>
</tr>
<tr>
<td>S(1300)</td>
<td>$\pi^0\pi^0 \rightarrow 4\gamma$</td>
<td>$0^{++}$</td>
<td>100</td>
<td>[13]</td>
</tr>
</tbody>
</table>

And exclusive central production measurement of $\pi^- p \rightarrow M^0\pi^- p$ at 300 GeV [14].

THE G(1590)

It was first observed in the partial wave analysis of the $\eta\eta$ events produced in reaction (1) with 38 GeV/c $\pi^-$. The G(1590) was seen as a clear peak in the S-wave with a mass measured to be $(1592 \pm 25)$ MeV/c$^2$ and a width of $(210 \pm 40)$ MeV/c$^2$. A similar peak has been observed in the $\eta\eta'$ mass spectrum. This peak is quite near threshold, but it cannot be accounted for by phase space or threshold effects. The partial wave analysis of the $\eta\eta$ data at 100 GeV/c has also been performed. Two peaks have been seen in the S-wave (fig. 4), they have been identified with the $f_0(1300)$ (ex $e(1300)$) and the G(1590) mesons. Similar results have been obtained with 230 GeV/c pions.

At 38, 100 and 230 GeV/c $\pi^-$ beam momenta, the most striking $\eta\eta$ resonance produced in reaction (1) is the G(1590). It is not observed at these energies to decay into $2\pi^0$. It has also not been observed by other experiment [17] looking for the production of K$^0$K$^0$ in reaction (1). The measured branching ratios for the G(1590) into $\eta\eta$ and $\eta\eta'$ are: $\text{BR}(G \rightarrow \eta\eta) = 0.12 \pm 0.03$ [8], and $\text{BR}(G \rightarrow \eta\eta') = 0.35 \pm 0.1$ [5]. It has been found that $\sum \text{BR}(G \rightarrow \pi^0\pi^0, K^0\bar{K}^0) < 5\%$. The suppression of $\pi^0\pi^0$ and K$^0\bar{K}^0$ decay modes makes it difficult to identify the G(1590) as a normal qq state. The G(1590) has also been observed to decay into $4\pi^0$ [9], this decay mode is expected to be
rare for q\bar{q} mesons in comparison with other 4\pi decay modes (\rho-dominance). A mechanism of gluon decoloration has been proposed [18] which would favor the decay of glueballs into \eta and \eta' mesons preferably to either \pi^0 or K^0 mesons. This mechanism gives branching ratios for the G(1590), assumed to be a glueball, which are in agreement with measured values. It has been shown [18][19] that the ratio BR(G \to 4\pi^0)/BR(G \to all 4\pi) \simeq 1/5 if the gluon decoloration mechanism is the main mechanism at work in this decay.

Another strong argument to give a glueball assignment to the G(1590) comes from its observation in the exclusive central production reaction: \pi^- p \to M^{0}\pi^- p with 300 GeV/c pions [14]. The G has been observed as a peak directly in the \eta\eta mass spectrum (fig. 5). Compared to the well known f_2(1270) meson, it has been found in the charge exchange reaction that \sigma(\pi^- p \to G\pi)/\sigma(\pi^- p \to f_2\pi) \simeq 1/25 with 40 and 100 GeV/c pions, and in central collisions that \sigma(\pi^- p \to G\pi)/\sigma(\pi^- p \to f_2\pi) \simeq 10 with 300 GeV/c pions. Neither G or f_2 are yet detected in central collisions with 40 GeV/c \pi^- at the sensitivity of the experiment. These observation, made in the frame of supposedly preferred gluonic processes, support the glueball hypothesis quite strongly.

**THE M(1400)**

The allowed values of J^P for the \pi^0\eta system are 0^+, 1^-, 2^+, 3^-, ... (natural series) and its charge quantum number is C=+1. However, if one assumes that the \pi^0\eta system is produced from a q\bar{q} state, the values J^P = 1^-, 3^-, ... are excluded as such q\bar{q} states have C=-1. If the \pi^0\eta system originates from a q\bar{q} state it will appear only in the even partial waves.

The \pi^0\eta data produced in reaction (1) with 100 GeV/c \pi^- beam has been analyzed. A strong forward-backward asymmetry at M_{\pi^{0}\eta} \simeq 1400 MeV in the Gottfried-Jackson frame of the \pi^{0}\eta system has been observed (fig. 6). This asymmetry, which has been noticed previously [20] may only arise through the presence of an odd wave interfering with the dominant a_2(1320) peak [21]. Three methods have been used for the partial wave analysis [13]. The two first methods consist respectively of an energy independent and energy dependent fit of the helicity partial wave amplitudes to the spherical harmonic moments. The moments have been evaluated from the measured angular distributions in each 35 MeV mass bin using a maximum likelihood method [22]. The third method consists of a direct fit of the differential cross section, expressed in term of the partial wave amplitudes to the \pi^{0}\eta experimental angular distributions [7]. Results of the three methods have been found to converge to a unique interpretation of the observed \pi^{0}\eta angular distributions [13]; the production of a non q\bar{q}, J^{PC} = 1^{-+}, I^G = 1^- meson has been observed in the P_0^2 amplitude (fig. 7) at M_{\pi^{0}\eta} = 1406 \pm 20 MeV with a width of 180 \pm 20 MeV. Being an isovector, this exotic state cannot be a glueball. Two interpretations have been proposed: that it is a hybrid state containing a valence gluon, q\bar{q}g [23], or that it is a four-quark state [24]. A new structure, X(1300), has been also observed in the S-wave (J^{PC} = 0^{++}), it could be the right a_0 member instead of the a_0(980) (ex \delta(980)) in the ^3P_0 nonet. The a_0(980) has been proposed as a
K$\bar{K}$ molecule [25].

CONCLUSION

Hadron spectroscopy is still far from being completely understood, but new important steps have been made through: the studies of the neutral decays of light mesons produced in hadron interaction, and the studies of the end products of the radiative and hadronic decays of $J/\Psi$. The emergence of numerous states that do not find their place either in SU(3) or in simple gluonic schemes show the need for a systematic exploration and a thorough knowledge of the light meson spectrum. The observed M(1400) exotic state should normally be the first of a series which has been searched and expected for quite some time. One may hope that out of the present complexity of the meson spectrum, theory will be able to refine its methods and to bring QCD on the same footing as QED.

GAMS is expected to keep playing a significant role in this work. The collaboration plans to start a very high statistics experiment on exclusive pion charge exchange reaction with GAMS-4π, an upgrade of GAMS-2000 at IHEP in Protvino. Meanwhile statistics is being increased in the experiment on central production of neutral mesons with GAMS-4000 at CERN. Much is also expected from LEAR and other antiproton experiments in planning.

FIGURE CAPTIONS

Fig. 1 Experimental layout. $S_i$: beam definition; $H_i$: beam hodoscopes; GS: guard system surrounding the target; AC and AH;: scintillation counters; SW; + Albedo: lead-scintillator sandwich counters.

Fig. 2 Isometric reconstruction of a typical $8-\gamma$ event produced in reaction (1) at 100 GeV.

Fig. 3 Isometric view of all $4-\gamma$ into pairs. The $\pi^0\pi^0$ events, which contribute to a peak about 10 times higher than the $\eta\pi^0$ one, have been left out.

Fig. 4 $|S|^2$ amplitude of the $\eta\eta$ system produced in the reaction $\pi^- p \rightarrow (\eta\eta)n$ at 100 GeV/c.

Fig. 5 Mass spectrum of the $\eta\eta$ system produced in the reaction $\pi^- p \rightarrow (\eta\eta)\pi^- p$ at 300 GeV/c.

Fig. 6 Forward-backward asymmetry in the Gottfried-Jackson frame of the $\eta\pi^0$ system produced in the reaction $\pi^- p \rightarrow (\eta\pi^0)n$ at 100 GeV/c.

Fig. 7 Intensities of S, P and D waves (events/35 MeV) versus the $\eta\pi^0$ mass.
REFERENCES

Fig. 1

Fig. 2