91-2-168

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/91-02

11 January 1991

GAMS AND LIGHT MESON SPECTROSCOPY

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Abstract

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Invited talk to QCD'90. Montpellier. July 1990,
to appear in Nucl. Phys. B. Proc. Suppl.

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1. INTRODUCTION

A meeting on QCD is a very appropriate place to present the status of the studies that were started with GAMS in the field of light meson spectroscopy. I shall not say much about the setup itself. Suffice it to say that GAMS is the acronym designating an electromagnetic calorimeter which is capable of detecting many photon events with a good spatial resolution ($\approx 1\text{mm}$) and a reasonable energy resolution ($\delta E/E \approx 0.02 + 0.12/\sqrt{E}$). Such an apparatus is particularly suited for the detection of neutral mesons that ultimately decay into photons¹.

Meson spectroscopy was a field of experiments with little prospect in the middle seventies.

SU(3) and the quark model (QM) had been very successful in providing first a taxonomy for the many states that have been accumulated mainly by large bubble chamber experiments since the discovery of the first resonances. Later, they provided a theoretical frame that began to give hints on the physical substratum of the observed symmetries. Since then, QCD has been developed as the theory of strong interactions and, as such, has obtained considerable success, amongst which the quark and gluon sea distributions in hadrons and other problems that may be handled by perturbative methods.

On the other hand, there is still no means yet to calculate in QCD the spectrum of hadrons, i.e. the discrete levels, rather than quark distributions in the continuum, to an accuracy that would allow significant comparison with experiment, other than qualitative.

Experiment definitely shows the existence of partons. Gluons are at least indirectly detected by jet production. Measured hadron quantum numbers seem to be localized on two or three "valence" quarks whether they are mesons or baryons, giving credence to constituent quarks, even though they are highly relativistic in their small containment volume. When one compares with QED, dressed electron and positron of positronium are lying far from each other. Dressed quarks of light hadrons are overlapping. The conceptual meaning of the constituent quark in QCD needs elaboration.

QCD has also introduced new features. Gluons interact between themselves. There are thus good reasons to expect that the QCD hadron spectrum should involve other states than the $q\bar{q}$ and qqq QM states. There should be a whole spectrum of gluonic states, glueballs with two and three gluons, a spectrum of mixed quarks and gluons, the so-called hybrids or meikhtons, and a spectrum of many quark states, 4- and 6-quarks. Furthermore,

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nothing prevents these states from mixing. All these are exotics for QM and are still called this, although they are not exotic for QCD, even if their spectra cannot be better calculated than that of the "regular" hadrons. The situation is thus becoming more and more complex, as exotics do not differ significantly from regular mesons, except for a few J^{PC} quantum number values, like 0^{--} , 0^{+-} , 1^{-+} , 2^{+-} , 3^{-+} , ... as well as $Q=2$, $I>1$, etc, which are forbidden for $q\bar{q}$ states.

The GAMS program is part of the effort currently made by a series of experiments in many laboratories to provide systematic information on the light meson spectrum : searching for new states, measuring the branching ratios of their decay modes and their production rate in different dynamical situations.

2. $f_0(1590)$ AND THE GLUEBALL CANDIDATES

GAMS may only detect neutral states that decay into gamma rays or into other neutral states which themselves finally decay into gamma rays. This fact immediately excludes the detection of ρ^0 mesons which cannot decay into $\pi^0\pi^0$ or η pairs. π^0 and η pair production are thus free from the dominance of the vector meson.

GAMS is the first setup that has allowed the observation of a large variety of neutral final states produced in the exclusive charge exchange reactions :

$$\pi^- p \rightarrow M^0 n, \text{ where } M^0 \rightarrow k\gamma \quad (1)$$

at a few π^- energies : 38 GeV, 100 GeV and 230 GeV.

Let me first concentrate on the η -pair spectrum for two reasons :

- to illustrate some of the current experimental problems posed by the identification of new states,
- because peculiar new states have been found in this mode.

The eta pairs are detected as 4γ events, each η decaying into 2γ , or 8γ events, one η decaying into three π^0 which in turn give 6γ (12 γ events are

observed, but their acceptance is poorer). The complete agreement of the spectra obtained with these two different topologies is a measure of the reliability of the identification methods and of the evaluation of the detection efficiencies¹.

Fig 1 shows the low background level for the identification of an η which has decayed into 2γ .

FIGURE 1

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

Fig 2 shows the invariant mass spectra for 4γ events before efficiency correction.

Experimental evidence on mesons today requires high statistics data, that may be submitted to partial wave analysis (PWA), although such evidence might sometimes be doubtful, because of ambiguities.

In one case, we have been told that partial wave identification of a state, namely $G(1590)$ which decays into an η pair, is subject to the uncertainties and to the ambiguities of the method.

On the other hand, on another occasion, -this time the observation of the same $G(1590)$ as a peak in central production in hadron collisions, that will be discussed later, - we were objected that "nowadays it is not possible to get any confidence in data that

Spin	M(MeV)	Γ (MeV)	M(MeV)	Γ (MeV)	State
Solution 1			Solution 2		
0	1230 $\pm$ 30	280 $\pm$ 40	1210 $\pm$ 30	315 $\pm$ 60	f_0/ϵ
2	1310 $\pm$ 30	190 $\pm$ 30	1310 $\pm$ 30	215 $\pm$ 30	f_2
2	1525	50	1525	50	f'_2
0	1560 $\pm$ 30	230 $\pm$ 30	1590 $\pm$ 30	300 $\pm$ 30	f_0/G
2			1890 $\pm$ 90	250 $\pm$ 30	x (1810) ?
4	2070 $\pm$ 50	500 $\pm$ 100	(unique solution)		f_4/h

TABLE 1

had not been subjected to partial wave analysis".
There is some truth in both objections.

FIGURE 2

Mass spectrum of $\eta\eta$ events after 3C fit (η and n masses) before efficiency correction

For example, parameters of states obtained from the treatment of the invariant mass spectrum of η pairs produced in charge exchange reactions (1) with two different π^- momenta, 38 GeV and 100 GeV are shown in table 1. There is no ambiguity below a mass of about 1800 MeV. Above, a spin 2 structure appears in one solution, but not in the other. The structure is probably a real state as a spin 2 peak is observed in the $4\pi^0$ spectrum with a compatible mass (fig. 3)².

Although not a visible peak in the mass spectrum, G(1590) presents the minimum characteristics of a resonance. Confidence in its existence arises from the convergence of the results with data collected at different energies, in two different setups and, as far as 100GeV data are concerned, with $\eta\eta$ pairs observed as 4- γ as well as 8- γ events.

FIGURE 3

$4\pi^0$ invariant mass spectrum : a) after cut favoring spin 2 states : b) after cut favoring spin 0 states

On the other hand, the invariant mass spectrum of η pairs produced centrally in exclusive hadron collisions

$$h (\pi^- \text{ or } p) + p \rightarrow M^0 h p, \quad (2)$$

with 300 GeV pions or 450 GeV protons, shows a S-wave dominated peak around the mass of G (fig.4)³.

FIGURE 4

$\eta\eta$ invariant mass spectrum in central production before and after background subtraction

This means a quite lesser production of f_2 which dominates charge exchange reactions. Nevertheless the presence of a peak is not enough of a conclusion. A crude analysis indicates also the presence of a significant D-wave activity which may be linked with $f'_2(1525)$. $G(1590)$ is certainly observed but a complete understanding of the central production spectrum of η pairs needs partial wave analysis, requiring larger statistics which we are currently trying to collect at CERN.

2.1 $G(1590)$: a scalar glueball ?

$G(1590)$ is a scalar meson with $J^{PC} = 0^{++}$. It has now been observed through three different channels which seem to account for more than 90% of the decay modes. It is not observed to decay into

pion pairs nor into kaon pairs at levels making it incompatible with being a member of a regular $q\bar{q}$ nonet (by its mass it could be a radial excitation). Table 2 gives the branching ratios of $f_2(1270)$ for comparison.

The charge exchange (CX) and central production (CP) cross-sections of $f_0/G(1540)$ and of $f_2(1270)$ vary in opposite manner as also shown by the table. $f_0/G(1540)$ is clearly visible in CP, whereas an upper limit can only be given for f_2 (errors are not given, because these numbers are only orders of magnitude). S.Narison and G.Venziano have pointed out reasons for $G(1590)$ to be a solid glueball candidate⁴.

TABLE 2

$f_0/g(1540)$ and $f_2(1270)$

- branching ratios	$f_0(1590)$	$f_2(1270)$
$\pi\pi$	-	0.86
$\eta\eta$	0.12	0.005
$\eta'\eta$	0.35	-
4π	0.5	0.09
$(4\pi^0)$	0.1	0.003
$K\bar{K}$	-	0.04
$\pi\pi + K\bar{K} + \dots$	< 0.03	

- cross sections

CX 38 GeV	240 nb	-
100 GeV	30 nb	800 nb
CP 38 GeV	< 40 nb	-
300 GeV	150nb	< 20 nb

2.2 The role of η and η'

The preferential mode of decay of $G(1590)$ into η and η' mesons is a first indication that it could be a scalar glueball and maybe the lowest lying glueball. The measurement of the rare decays⁵ of η and η' by our collaboration has permitted J.M.Frère⁶ to show that, although there is no evidence for an hypothetical constituent gluon component in neither

of these mesons, the gluon anomaly may account for as much as 80% of the η' state and up to 30% of the η . This might account for the preeminence of η and even more of η' in gluon hadronization.

Experimentally, J/ψ radiative decay, which is expected to be a source of glueballs, favors η' and η compared to π^0 in the ratio 80 / 4 / 1. S.S.Gershtein⁷ has proposed a "gluon decoloration" mechanism to explain with gluon planar diagrams, by analog with similar quark diagrams, the large branching ratio of $G(1590)$ into $\eta\eta'$ and $\eta\eta$ (its mass is below the threshold for decay into $\eta'\eta'$ pairs). The long unproductive quest for "exotics" may be linked to the fact that experiments made with bubble chambers or with charged particle spectrometers mostly provided detection of charged π and of both neutral and charged K , the particles least likely to show significant gluon "content", with little efficiency for η and for η' .

2.3 A tensor glueball ?

There is also a strong evidence for a new tensor state at a mass of 2180 MeV in the $\eta\eta$ spectrum produced in central collisions (2) both with 300 GeV pions and 450 GeV protons³ (fig.5). Its properties are very similar to those of $G(1590)$. We tentatively like to call it $G_2(2180)$. It has not been observed in charge exchange reactions due to the dominating presence of the spin-4 $f_4(2050)$ meson. Comparing the η pair data with the π pair spectrum that we observe in the same experiment and with the K pair spectrum observed in WA76, the branching ratio (BR) of $G_2(2180)$ into $\pi^0\pi^0$ is less than 1/3 and that into $K\bar{K}$ is less than 1/10 of the BR into $\eta\eta$.

The ratio $m_{G_2}/m_G = 1.4$ is also surprisingly near the ratio of tensor and scalar glueball masses of 1.5 that is predicted by the most recent lattice calculations. G and G_2 might be the lowest lying glueballs. More information should come soon from higher statistics runs on charge exchange reactions of type (1) which are proceeding at IHEP with an improved acceptance of the GAMS setup. The new

acceptance will be as near to 4π sr as possible. It will allow a full partial wave analysis in the high-spin high-mass region of the spectra.

FIGURE 5

As fig. 4 for masses above 1.7 GeV. Left : 300 GeV incident pions; right : 450 GeV protons

2.4 $\theta(1720)$ and $G(1590)$

The two main objections which have been raised against $G(1590)$ being a glueball are that this state has not been observed neither in J/ψ radiative decay, nor in WA76 at CERN in the measurement of central production of pion and kaon pairs. Both processes are expected to be gluon "factories". WA76 on the other hand shows significant production of $\theta(1720)$ in kaon pairs (fig. 6)⁸. This 2^{++} meson, an early glueball candidate, which is produced in J/ψ radiative decay into $K\bar{K}$, has been identified with a low statistics peak of $\eta\eta$ pairs measured by Crystal Ball at the quite lower mass of 1670 MeV in the same decay. Similar data have been obtained by MARK-III. It appears that their $J/\psi \rightarrow \gamma\eta\eta$ peak may be fit equally well by combined contributions of $\theta(1720)$ and $f'_2(1525)$ or by a single state with a mass compatible with that of $G(1590)$ (the choice between spin 0 or spin 2 being very uncertain with the available statistics). The presence of f'_2 accounting for roughly one third of the $\eta\eta$ peak in GAMS allows a comparison with WA76 data. The absence of $G(1590)$ in kaon pairs (less than 40% of

FIGURE 6

K^+K^- and $K_S^0 \bar{K}_S^0$ mass spectrum from experiment WA76 at Omega

observed η pairs) is in agreement with previous charge exchange reaction observations. By the same argument, θ has a low BR of a few % maximum into $\eta\eta$. With these evaluations its contribution to the $\eta\eta$ peak in J/ψ radiative decay would be quite small, contrary to that of $G(1590)$. This would bring the BR of J/ψ into G to a significant level⁹.

Further high statistics runs will help to clarify the matter, as well as the new J/ψ experiment at the Beijing collider and the LEAR $p\bar{p}$ experiments on meson spectroscopy.

3. $M(1405)$ AND INTRINSICALLY EXOTICS

The analysis of the production of the simple isovector $\eta\pi^0$ system has surprisingly shown the presence of a P-wave state, i.e. a 1^{--} intrinsic exotic¹⁰. It manifests itself as a significant asymmetry in the forward-backward distribution of η (fig. 7).

Such an asymmetry had already been observed in a lesser statistics experiment some ten years ago¹¹, but it was dismissed as a proof for the existence of a state that would be in conflict with QM. PWA analysis (fig. 8) shows evidence for a state with a mass of (1405 ± 20) MeV and a width Γ of (180 ± 20) MeV.

FIGURE 7

Forward backward asymmetry of η in the decay of $\eta\pi^0$ events

An upper limit of BR of this meson into $\eta'\pi^0$ has been evaluated from GAMS data¹². It is less than 0.8 of BR into $\eta\pi^0$. It is the only other available information that might give some light on its nature at the present stage. Being an isovector it cannot be a glueball. According to F.Close and H.Lipkin¹³ the small $\eta'\pi$ BR might indicate that this is a 4-q state.

Another state³, $X(1910)$, which decays into $\eta'\eta$ but that is not observed to decay into $\eta\eta$, a mode which allows even J only, might be another example of an intrinsic exotic with quantum numbers 1^{--} or even 3^{--} . It has the strange property of being produced at large $|t|$.

It is comforting to see states finally appear in a systematic search. The field is still wide open for further discoveries.

4. THE SCALAR NONET

The PWA analysis of the charge exchange production of the $\eta\pi$ system is also revealing the presence, under the dominating D-wave $a_2(1320)$, of an S-wave state with a mass of 1300 MeV with an amplitude of about 20% of that of the D-wave¹⁰. Its phase closely follows that of a_2 (fig. 8). The close

FIGURE 8

Partial waves in the decay of the $\eta\pi^0$ system

mass degeneracy of this 0^{++} state, $a_0(1300)$, with $a_2(1320)$ is similar to that of the new $f_0(1525)$ discovered by LASS¹⁴ under $f_2(1525)$. These new states might imply a new distribution of mesons in the 0^{++} nonet. Non-strange and hidden-strangeness components would then be $f_0(1400)$, $f_0(1525)$ and $a_0(1300)$. The scalar nonet would thus be quite comparable with the tensor nonet.

$f_0(975)$, the former S , and $a_0(980)$, the former δ , would not be regular $q\bar{q}$ mesons in such a scheme. The peculiar properties of these mesons already made them suspect to some theoreticians who

proposed that they might be 4- q states or KK-molecules. GAMS provides one more clue to the unusual properties of δ . The charge exchange production cross-section of δ is less than 1/10 of that of a_2 . On the other hand δ is very much enhanced in central collisions of hadrons where it appears as a prominent peak while a_2 is barely visible (fig. 9). The central production of $q\bar{q}$ mesons like a_2 and f_2 are depressed (cf. infra G(1590)).

FIGURE 9

$\eta\pi^0$ invariant mass spectrum in central production.

5. OTHER STATES

Some other peculiar states have been observed by GAMS. They are statistically significant but data are not enough to make a PWA. Spin assignments have been made on the basis of angular distributions.

They are narrow and some are even very narrow. Also their t -distribution is usually quite wide in comparison with the typical OPE (one-pion exchange mechanism) values.

Decay mode	Γ (MeV)	JPC	b (ebt)	Ref.
X(1640) $\rightarrow \omega\omega$	narrow < 50 MeV	2 ⁺⁺	~4.3	15
X(1750) $\rightarrow \eta\eta$	narrow	0 ⁺⁺ (2 ⁺⁺)	~3.8	16
X(1910) $\rightarrow \eta\eta'$	~90 MeV	exotic ? 1 ⁻⁺ , 3 ⁻⁺ ?	~2	3
X(1920) $\rightarrow \omega\omega$	~90 MeV	2 ⁺⁺	~5	15
X(2220) ξ ? $\rightarrow \eta\eta'$	narrow	>2		17

6. CONCLUSIONS (VERY PROVISIONAL)

- Evidence continues to converge towards gluon dominance of G(1590) and of G₂(2180). Might these be the scalar and the tensor glueballs ?
- There is now evidence for a first intrinsic "exotic" JPC = 1⁻⁺ state, M(1405), and maybe for a second one, X(1910) which might be 1⁻⁺ or even 3⁻⁺. More data are needed on the decays that are already observed, mainly for X(1910) where statistics is not large enough for PWA.
A new field is opening, but this is not a surprise. The absence of such states would be more a problem than an acceptable solution for QCD.
- The scalar nonet which has posed such a problem might be as "regular" as any other, if a₀(1300) gets confirmed. δ (980) is likely not a $q\bar{q}$ state as expected already by many theoreticians. This is good news, but it is nonetheless puzzling because very good reasons had been given for a strange structure of this nonet and, to a certain extent, because the qualitative agreement of all nonets with the naive quark model remains somewhat of a mystery.

d. More states with odd properties occur amongst GAMS results :

- narrow states, like X(1750), ξ (2200)
- states that are produced at large $|t|$

In total the number of states that cannot be inserted in the $q\bar{q}$ classification is much increasing. They might even appear as a pest that brings more trouble than real answers. At least they show that the meson spectrum is much more complex than expected. The need is there to make a systematic experimental study with high statistics, large acceptance experiments so that the data analysis may provide unambiguous results. Many states exist in the region between 1200 MeV and 1500 MeV. They can be identified only with systematic PWA.

The effort to be achieved is still considerable. Experiments are long and tedious. But it is refreshing to see that the field of light meson spectroscopy is full of vitality again, at least with experimentalists. There is a long list of active collaborations with dedicated setups :

- LASS which still brings important results even though it has been dismantled since five years !;
- MARK III and DM2 which also keep going on the analysis of their old data with surprising results;
- MPS at BNL with the program to install a GAMS to supplement charge particle detection;
- Benkei at KEK;
- Beijing collider with a significant program for a high statistics study of J/ψ decays;
- Ω with a program to study both neutral and charge decays of meson in central production
- GAMS, still with an improvement program;
- LEAR which is producing first results of neutral decays with Cristal Barrel (notably a $3\pi^0$ spectrum which confirms the presence of a $\pi^0\pi^0$ state at 1565 MeV and a $\eta\eta\pi^0$ spectrum which shows a $\eta\eta$ peak around 1600 MeV which needs further spin analysis).

Let us hope that the incoming wealth of information will also bring young theoreticians to find

again that the calculation of the fundamental spectra of QCD is a rewarding challenge.

ACKNOWLEDGEMENTS

I would like to express my gratitude to all members of the GAMS collaboration whose work has made the substance of this report, but I alone bear the responsibility of controversial statements.

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