DOMINATING CONSTITUENT
OF THE Θ MESON

M. Majewski*

University of Łódź
Departament of Theoretical Physics
ul. Pomorska 149/153
90-236 Łódź, Poland

June 1995

Abstract

On the basis of the relation between values of the coupling constants determined from data fit it is concluded that the dominating constituent of the Θ meson is the glueball. The possibility that Θ meson decays into two σ(750) mesons is suggested.

*E-mail: mimajew@mvii.uni.lodz.pl
1 Introduction

Θ(1720) meson, since its first observation [1] was regarded as a glueball candidate with spin-parity $J^{PC} = 2^{++}$. Later its glueball assignment was put in question. The reason was that Lattice QCD (see e.g.[2]) and several phenomenological models [3] consistently predicted the mass of the lightest tensor glueball to be about 2 times bigger than the mass of the lightest scalar glueball, while an appropriate scalar candidate was lacking; the mass of the only serious scalar glueball candidate G(1590) [4] is far too high for that. As it is difficult to find another interpretation for the nature of the Θ meson, its spin was questioned: in one measurement [5] it has been determined as 0. Such assignment simply shifts the difficulty from the tensor multiplet to the much more mysterious scalar one and rather stops then stimulates the investigation of the Θ meson and the glueball search. Later it was argued [6] that the spin of the Θ meson is not yet firmly established and now it is considered to be 0 or 2 [7].

There are several reasons to reinvestigate the problem of the Θ meson, assuming $J^{PC} = 2^{++}$ for it.

First in a recent experiment [8] a new scalar glueball candidate has been discovered. Let’s call it $\sigma(750)$. If $\sigma$ and Θ are both glueballs, then the right hierarchy of the glueball masses is restituted and there is no reason to contest the spin 2 for Θ. Moreover, on account of the rate of their masses the reaction $\Theta \rightarrow \sigma\sigma$ is possible and since it is allowed, the $\sigma$ mesons should be copiously produced in the Θ decays. This enables us, possibly, to solve not only the controversial problem of the very existence of the $\sigma$ meson [7], but also the problem of the nature of both these mesons. Although this may be only done experimentally, room for such decay channel may be found by comparison of the $\Gamma_{\text{tot}}(\Theta)$ with the sum of its partial two $q\bar{q}$ meson widths.

Second we notice that hitherto analyses of the Θ problem [9,10,11,12,13] are inconsistent. They require exact realization of the OZI prohibition for the quarkonium - quarkonium transitions but not require it for the glueball - quarkonium ones which are also forbidden. Consequently, they use two coupling constants to describe data on the $f_2, f'_2, \Theta$ decays into pseudoscalar mesons, while the consistent description requires the three ones. Fitting the three coupling constants to the data we should be able to determine coupling constants for different OZI suppressed reactions and verify agreement between them.
It will be also seen that the known difficulty with smallness of the predicted $f_2 \Rightarrow \pi \pi$ width [10,11] does not appear in the consistent description.

Third there is a problem of the mixing model. Looking for any nonexotic glueball we have to use some model describing mixing of the isoscalar $q\bar{q}$ states with pure glueball state $G$. The result of the analysis depends on the mixing model. During 70\textsuperscript{th} and early 80\textsuperscript{th} a number of the models has been formulated [9,10,12,14,15,16,17]. However, it is still unclear whether any of them is adequate and whether the same model will work in different cases. The most favoured was gluon exchange model (GEM) based on QCD inspired mass operator [18,16]. This model has been applied to describe mixing of the $\iota(1440)$ meson with the $\eta, \eta'$ mesons and (what is rather natural) completely failed [19]. Also it has been claimed unsatisfactory in an attempt to solve the problem of the $\Theta$ meson. So it remained unclear whether the gluon exchange model is adequate or not. It is thus reasonable to look for further mixing models and verify their predictions. We test the model which was formulated later than the models mentioned above [20,21,22]. The model has great predictive power and is transparent. Its transparency is mainly due to the set of inequalities restricting masses of the mixing particles. For example, if follows from these restrictions that mesons $\omega$ and $\phi$ cannot include the admixture of the state having higher mass, it also follows that the meson $\iota(1440)$ cannot have admixtures of the $\eta$ and $\eta'$ mesons. These qualitative predictions agree very well with data, as the vector glueball is not observed (and even not expected) in the region above 1 GeV; also the $\iota(1440)$ meson should mix first of all with the states from its nearest neighborhood which do exist [7]. The quantitative predictions of the model can only be made and verified for $2^{++}$ mesons, as they constitute the only well known multiplet obeying mixing conditions. It will be seen below that predictions of the model agree well with data. Here we merely notice that this investigation considerably vindicates GEM. Namely, GEM would give the same results, if the masses of the physical mesons were changed within 1—2 standard deviations. However GEM does not give any suggestion how the masses should be changed. We do not discuss this problem in detail in the present paper.
2 Notations and results

2.1 In a number of papers [23,20,21,24,22] a model for mixing the $q\bar{q}$ with any SU(3) singlet has been formulated. The isoscalar physical states of the decuplet of mesons formed in such a way may be expressed by the ideal quark states

$$N = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}), \quad S = s\bar{s}$$  \hspace{1cm} (1)

and an additional state $G$ which may be, in principle, any SU(3) singlet. We have

$$\begin{bmatrix} f_2 \\ f'_2 \\ \Theta \end{bmatrix} = V \begin{bmatrix} N \\ S \\ G \end{bmatrix}$$  \hspace{1cm} (2)

where the mixing matrix $V$ does not depend on free parameters and is completely determined by masses of the mesons belonging to the decuplet. As there are 5 different masses, the dependence on them is, in general, complicated, but for the decuplet of mesons $a_2, K_2, f_2, f'_2, \Theta$ it becomes simple: the elements of the matrix $V$ depend mainly on one variable $\Delta$ which may be chosen as the difference between $a_2$ and $f_2$ meson masses [22]

$$\Delta = m_{a_2} - m_{f_2},$$  \hspace{1cm} (3)

while their dependence on other mass variables is weak under reasonable mass variations.

We use the following notation for the elements of the matrix $V$

$$V = \begin{bmatrix} x_1 & y_1 & u_1 \\ x_2 & y_2 & u_2 \\ x_3 & y_3 & u_3 \end{bmatrix}.$$  \hspace{1cm} (4)

2.2 The relative radiative widths are calculated from the formula [10]

$$\frac{\Gamma_{\gamma\gamma}(f^{(j)})}{\Gamma_{\gamma\gamma}(a_2)} = \text{ph.space} \times (x_j + \frac{\sqrt{2}}{5} y_j)^2$$  \hspace{1cm} (5)

where $j=1,2,3$ correspond to $f_2, f'_2, \Theta$ mesons, respectively. Predictions for the radiative widths depend exclusively on $\Delta$ (3). Therefore the data on
these widths control this quantity. According to present data [7] only for $f'_2 \rightarrow \gamma \gamma$ width there is a disagreement. The predicted width is too small ($\Gamma_{\gamma \gamma}(f'_2) \simeq 0.1\text{keV}$) for $\Delta = 44\text{MeV}$ corresponding to the mean experimental masses of the $a_2$ and $f_2$ mesons (c.f. [10]). We increase $\Gamma_{\gamma \gamma}(f'_2)$ choosing the masses such that $\Delta = 34\text{MeV}$. As an input for further calculations we choose the following values of the masses (already satisfying the mass formula):

$$m_{a_2} = 1.316\text{GeV}, \quad m_{K_2} = 1.432\text{GeV}$$
$$m_{f_2} = 1.282\text{GeV}, \quad m_{f'_2} = 1.516\text{GeV}, \quad m_{\Theta} = 1.720\text{GeV}.$$  \hspace{1cm} (6)

We get following mixing matrix

$$V = \begin{bmatrix}
0.9585 & 0.0825 & 0.2730 \\
-0.1679 & 0.9370 & 0.3064 \\
-0.2306 & -0.3395 & 0.9119
\end{bmatrix}, \hspace{1cm} (7)$$

and the rates of the radiative widths

$$\frac{\Gamma_{\gamma \gamma}(f^{(j)}_2)}{\Gamma_{\gamma \gamma}(a_2)} = \begin{cases}
2.48 \\
0.04 \\
0.66
\end{cases}. \hspace{1cm} (8)$$

Notice that for the nonet mixing ($\Theta$ is absent) these rates are

$$\frac{\Gamma_{\gamma \gamma}(f^{(j)}_2)}{\Gamma_{\gamma \gamma}(a_2)} = \begin{cases}
2.64 \\
0.13
\end{cases}. \hspace{1cm} (9)$$

2.3 The widths of the strong two-body decays are calculated using the formula [25]

$$\Gamma_{mn}(k) = \frac{p^5}{M_k} g^{2}_{k_{mn}}, \hspace{1cm} (10)$$

where $k$ is the decaying particle; $m,n$ are decay products; $M_k$ is the mass of the decaying particle; $p$ is c.m. momentum of the decay product; $g^{2}_{k_{mn}}$ are quantities depending on the coupling constants and contents of the $N,S,G$ states. For $2^+ \rightarrow 1^0-0^-$ decays $g^{2}_{k_{mn}}$ are expressed by one coupling constant $g_V$. For $2^+ \rightarrow 0^0-0^-$ decays they are expressed by three coupling constants
$g_8, g_0, g_G$ corresponding to the $(q\bar{q})_{\text{octet}}, (q\bar{q})_{\text{singlet}}$ and $G$ states. Choosing de’Swart phases we get for the particle widths of the isoscalar mesons the following expressions

$$
\Gamma_{\pi\pi}(f_2^{(j)}) = \frac{3}{2} \frac{p^5}{M_j} \left[ \frac{1}{\sqrt{12}} (g_0 - \frac{2}{\sqrt{5}} g_8) x_j + \frac{1}{\sqrt{24}} (g_0 + \frac{4}{\sqrt{5}} g_8) y_j + \frac{1}{\sqrt{8}} g_G u_j \right]^2,
$$

$$
\Gamma_{K\bar{K}}(f_2^{(j)}) = \frac{2}{M_j} \left[ \frac{1}{\sqrt{12}} (g_0 + \frac{1}{\sqrt{5}} g_8) x_j + \frac{1}{\sqrt{24}} (g_0 - \frac{2}{\sqrt{5}} g_8) y_j + \frac{1}{\sqrt{8}} g_G u_j \right]^2, \quad (11)
$$

$$
\Gamma_{\eta\eta}(f_2^{(j)}) = \frac{1}{2} \frac{p^5}{M_j} \left[ \frac{1}{\sqrt{12}} (g_0 + \frac{2}{\sqrt{5}} g_8) x_j + \frac{1}{\sqrt{24}} (g_0 - \frac{4}{\sqrt{5}} g_8) y_j + \frac{1}{\sqrt{8}} g_G u_j \right]^2 \cos^4 \Theta
$$

where $\Theta_P$ is mixing angle of the pseudoscalar mesons and $x_j, y_j, z_j$ are elements of the mixing matrix (4). Coupling constants are determined in the following way: $1^0 g_V$ is determined from the fit to $a_2 \rightarrow \rho\pi$ partial width. Other $2^+ \Rightarrow 1^-0^-$ widths, including the non yet measured ones for $f_2', \Theta \Rightarrow K^*\bar{K}$ + c.c. are calculated. $2^0 g_8, g_0, g_G$ are determined from the fit to the width $\Gamma_{\pi\pi}(f_2)$ and to the rates

$$
\frac{\Gamma_{\pi\pi}(f_2^{(j)})}{\Gamma_{K\bar{K}}(f_2^{(j)}) + \Gamma_{K^*\bar{K}+K\bar{K}^*}(f_2^{(j)})}
$$

for $f_2^{(j)}$ equal $f_2'$ and $\Theta$. We add to the $f_2', \Theta \Rightarrow K\bar{K}$ widths the $f_2', \Theta \Rightarrow \bar{K}^*K$ + c.c. ones, as the latter reactions are not separately recorded.

The results of the calculation and the fitted values of the coupling constants are given in the Table. Similar predictions for nonet mixing and corresponding experimental values are also given. To determine the $g_8$ and $g_0$ in the nonet case we fit $\Gamma_{K\pi}(K^*_2)$ and the rate (12) for $f_2'$. 6
3 Discussion

3.1 The model gives us predictions of the three kinds:

- mass formula enabling us to calculate one of the masses
- rates of the radiative width testing difference between two of the masses
- two-body strong decay widths.

It follows from the mass formula that, in order to obey it, we must slightly shift the masses from their mean values (both for decuplet and the nonet). We also find that only one of the radiative widths, the $\Gamma_{\gamma\gamma}(f'_2)$ one, poses a problem. It is too high in the nonet pattern and too low in the decuplet one. In the latter case we must reduce the mass difference $\Delta$ to increase $\Gamma_{\gamma\gamma}(f'_2)$. As a result of these two modifications we shift the masses in the decuplet pattern within two standard deviations. Although for the nonet the mass formula is satisfied better, the agreement for the nonet $\Gamma_{\pi\pi}(f_2)$ is worse, as the calculated value is rather too high. Other $2^+ \rightarrow 0^-0^-$ widths are described well both in the decuplet and the nonet, with exception of $a_2 \rightarrow \eta\pi$ and $K_2 \rightarrow \eta K$ ones (c.f. [9]). The $2^+ \rightarrow 1^-0^-$ widths are described well in both multiplets, except the $K_2 \rightarrow K^*\pi$ one which is too high (c.f. [11]).

3.2 Having determined $g_8, g_0, g_G$ we can calculate the coupling constants of the OZI suppressed decay $S \Rightarrow \pi\pi$

$$g_{S\pi\pi} = \frac{1}{\sqrt{24}} (g_0 + \frac{4}{\sqrt{5}} g_8) = 0.112.$$  \hspace{1cm} (13)

Comparing it with the coupling constant of the $G \Rightarrow \pi\pi$ decay

$$g_{G\pi\pi} = \frac{1}{\sqrt{8}} g_G = 0.160,$$  \hspace{1cm} (14)

we find that $g_{S\pi\pi}$ and $g_{G\pi\pi}$ have the same order of magnitude

$$g_{G\pi\pi} \cong 1.43 g_{S\pi\pi}.$$  \hspace{1cm} (15)
This indicates that transition between G state and two pion (or any two pseudoscalar meson) state is suppressed by OZI mechanism. Therefore eq. (15) gives the evidence that G is the glueball state.

If we also define the coupling constant of the \( N \Rightarrow \pi\pi \) transition \( g_{N\pi\pi} \) as

\[
g_{N\pi\pi} = \frac{1}{\sqrt{12}} (g_0 - \frac{2}{\sqrt{5}} g_8) = 1.172, \tag{16}
\]

we can introduce the OZI suppression factor \( \gamma_{\text{OZI}} \)

\[
\gamma_{\text{OZI}} = \frac{g_{S\pi\pi}}{\frac{1}{\sqrt{2}} g_{N\pi\pi}} = 0.135. \tag{17}
\]

Observe that coupling constants \( g_8, g_0, g_G \), as well as the mixing matrix \( V \), are functions of only one mass variable \( \Delta \). It has been examined by multiple fit that \( g_{N\pi\pi} \) is insensitive to \( \Delta \), \( g_{S\pi\pi} \) and \( g_{G\pi\pi} \) depend on \( \Delta \) approximately linearly and eq. (15) is satisfied for \( 12 \text{ MeV} \leq \Delta \leq 40 \text{ MeV} \) with good accuracy.

For the nonet we find

\[
[g_{N\pi\pi}]_{\text{non}} = 1.261,
\]

\[
[g_{S\pi\pi}]_{\text{non}} = 0.191. \tag{18}
\]

Smallness of the G state content and of the \( g_{G\pi\pi} \) value explains weak influence of the glueball state on the widths of the \( f_2 \) and \( f_2' \) mesons. To choose on this ground between the nonet and decuplet pattern (if it is possible at all) more accurate data are required (especially the data on \( f_2' \Rightarrow K^*\bar{K} + \bar{K}^*K \) are lacking). However, it should be noticed that the value of the constant \( g_G \) is determined mainly by the data on \( \Theta \) meson (eq. (12) for \( \Theta \)) and consequently the weak influence of the state G on the \( f_2 , f_2' \) states is consistent with the information on \( \Theta \). On the other hand, to understand the properties of the \( \Theta \) meson, the mixing of the state G with the states \( N, S \) is necessary. For example, small value of the \( \Gamma_{\pi\pi}(\Theta) \) follows not only from smallness of the \( g_{G\pi\pi} \), but also from destructive interference of the states G and N.

3.3 Due to the smallness of the \( g_{G\pi\pi} \), the sum of the partial \( \Theta \) widths over two-body channels is also small
\[
\Gamma_{\pi\pi} + \Gamma_{KK} + \Gamma_{\eta\eta} + \Gamma_{K^*+K^*} = 32.8
\]  

(19)

This should be compared with the total width \(\Gamma^{\text{tot}}(\Theta) = 140\text{MeV}\) (see, however, [26]). So large disagreement needs some interpretation. Two possible explanations, not excluding each other, seem to be the most plausible.

1\(^{0}\) The observed \(\Gamma^{\text{tot}}(\Theta)\) includes part of the signal from scalar meson which do exists in this mass region [4].

2\(^{0}\) The sum (19) does not include the main decay channel

\[\Theta = 2\sigma(750).\]  

(20)

The second explanation looks especially exciting. It suggests measurement of the decay channel \(\Theta \to 4\pi\) in looking for the reaction (20) which should dominate the \(\Theta\) decay. Assuming 100 MeV for its partial width, we find \(g_{G\sigma\sigma} \approx 3.6\). Confirmation of this reaction would be important not only for understanding the nature of the \(\Theta\) and \(\sigma\) mesons, but for glueball search and the strong interaction physics as well.

Author thanks profs. V.A.Meshcheryakov, S.B.Gerasimov, W.Tybor and P.Kosinski for interest to this work and valuable comments.

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Table. Hadron decays of tensor mesons

| Particle | Decay Mode | Width | Experim. | Calculated (MeV) |
|----------|------------|-------|----------|------------------|
| $a_2$    | $\Rightarrow \rho \pi$ | $1318.4 \pm 0.7$ | $(70.1 \pm 2.7\%)$ | $67.6^{\text{exp}}$ | $68.6^{\text{exp}}$ |
|          | $\Rightarrow \bar{K}K$ | $102.7 \pm 2.2$ | $(4.9 \pm 0.8\%)$ | 6.0 | 5.7 |
|          | $\Rightarrow \eta \pi$ | | $(14.5 \pm 1.2\%)$ | 11.0 | 10.5 |
|          | $\Rightarrow \eta' \pi$ | | $< 1\%$ | 0.01 | 0.01 |
| $K_2$    | $\Rightarrow \rho K$ | $1425.4 \pm 1.3$ | (8.7 ± 0.8)MeV | 9.5 | 9.5 |
|          | $\Rightarrow K^* \pi$ | $98.4 \pm 2.4$ | (24.8 ± 1.7)MeV | 32.1 | 32.1 |
|          | $\Rightarrow \omega K$ | | (2.9 ± 0.8)MeV | 3.1 | 3.1 |
|          | $\Rightarrow K \pi$ | | (48.9 ± 1.7)MeV | 50.4 | 47.6^{\text{exp}} |
|          | $\Rightarrow K \eta$ | | (0.14 ± 0.28)MeV | 1.6 | 1.6 |
| $f_2$    | $\Rightarrow \pi \pi$ | $1274 \pm 5$ | (156.7 ± 3.0) MeV | 155.1^{\text{exp}} | 177.8 |
|          | $\Rightarrow \bar{K}K$ | $185 \pm 20$ | (8.6 ± 0.9)MeV | 9.7 | 11.9 |
|          | $\Rightarrow \eta \eta$ | | (0.83 ± 0.19)MeV | 0.5 | 0.7 |
| $f_2'$   | $\Rightarrow \pi \pi$ | $1525 \pm 5$ | (0.70 ± 0.14)MeV | 0.48 | 0.74 |
|          | $\Rightarrow \bar{K}K$ | $76 \pm 10$ | (61 ± 5)MeV | 41.7 | 55.0 |
|          | $\Rightarrow \eta \eta$ | | (23.9 ± 2.2) MeV | 11.3 | 14.1 |
|          | $\Rightarrow K^* \bar{K} + \bar{K}^* K$ | | 7.2 | 8.6 |
|          | $\Rightarrow \pi \pi$ | | 0.0115 ± 0.0022 | 0.0097^{\text{exp}} | 0.0117^{\text{exp}} |
|          | $\Rightarrow K \bar{K} + (K^* \bar{K} + \bar{K}^* K)$ | | | | |
Table. Hadron decays of tensor mesons-continuation

| Particle | Decay Mode | Width          |
|----------|------------|----------------|
|          |            | Experim.       | Calculated (MeV) |
|          | $M$ $\Gamma_{\text{tot}}$ (MeV) $|VP$ $PP$ | V $P$ $|PP$ | Decuplet | Nonet |
| $\Theta$ | $\Rightarrow \pi\pi$ | $(3.90 \pm 0.20 )\%$ | 10.0 |
| 1713.2 ± 1.9 4.5 | $\Rightarrow \bar{K}K$ | $(38 \pm 9 )\%$ | 16.6 |
| 138 ± 12 9 | $\Rightarrow \eta\eta$ | $(18 \pm 2\% )\%$ | 3.8 |
|          | $\Rightarrow K^*\bar{K} + \bar{K}^*K$ | 2.4 |
|          | $\Rightarrow \bar{K}K + (K^*\bar{K} + \bar{K}^*K)$ | 0.39 ± 0.14 | 0.53$^{\text{inp}}$ |

The values of the constants

Decuplet

Mass input:

$a_2 = (1.316\text{GeV})^2, K_2 = (1.432\text{GeV})^2,$

$f_2 = (1.282\text{GeV})^2, \Theta = (1.720\text{GeV})^2;$

Coupling constants determined from fit

$g_V = 1.862, g_8 = -1.315,$

$g_0 = 2.885, g_G = 0.4525$

Nonet

Mass input:

$a_2 = (1.318\text{GeV})^2, K = (1.432\text{GeV})^2,$

$f_2 = (1.275\text{GeV})^2,$

Coupling constants determined from fit

$g_V = 1.862, g_8 = -1.278, g_0 = 3.224$

For the decay products we assume:

$0^- : m_\pi = 139.6\text{MeV}, m_K = 495.6\text{MeV}, m_\eta = 548.8\text{MeV}, \Theta_P = -10^0$

$1^- : m_\rho = 768.3\text{MeV}, m_{K^*} = 894.0\text{MeV}, m_\omega = 781.95\text{MeV}, \Theta_V = 35^0$