HADRONIC PRODUCTION OF GLUEBALLS [☆]

C. PETERSON
Department of Theoretical Physics, Sölvegatan 14A, S-223 62 Lund, Sweden

Received 15 February 1984
Revised manuscript received 28 March 1984

Cross sections for glueball production in hadron-induced reactions are estimated using the gluon–gluon fusion mechanism. For pp → $\theta(1700, J^{PC} = 2^{++})$X one finds $\sigma_\theta \sim 2$–10 mb in ISR-collider energy range. This cross section should give a clean experimental signal given the substantial $K\bar{K}$ decay mode observed in $\psi \to \gamma\theta$.

Since the advent of quantum chromodynamics there has been much interest in states containing valence glue only, so-called glueballs (G) [‡1]. There are as yet no positively identified states, although there exist some promising candidates [‡2]. Theoretical predictions for the spectrum are available both from the MIT bag model [3] and lattice Monte Carlo calculations [4]. The results from these two approaches agree amazingly well with each other and also with the experimental candidates $\iota(1440, J^{PC} = 0^{-+})$ and $\theta(1700, J^{PC} = 0^{++}/2^{++})$ [5]. At present the lattice approach is limited to the pure gauge sector of QCD, however, and is therefore unable to yield predictions about mixing with $q\bar{q}$-states and decay properties.

Production of glueballs. The *radiative decay* $\psi \to \gamma G$ is considered to be a prime source of glueballs from perturbation theory arguments. Indeed the states $\iota(1440)$ and $\theta(1700)$ with widths ~ 100–150 MeV [‡3] found in this reaction are difficult to accommodate in $q\bar{q}$ families and might therefore be candidates of bound glue [7]. The present experimental status on θ is shown in table 1.

If glueballs do exist they should also show up in hadron–hadron collisions. Candidates have been reported in the *exclusive reaction* $\pi p \to \phi\phi n$ [11]. The choice of this particular reaction is based on Zweig rule arguments. By considering the pomeron as a multigluon object, it has been suggested that the so-called *double pomeron process* $pp \to ppX$ should be enriched with glueballs [12]. A recent analysis of this reaction [13] indicates a broad $0^{++}\pi\pi$ state (ϵ) around $m \simeq 600$ MeV [‡4]. (A 0^{++} glueball in this mass range is in fact predicted by both bag model and lattice calculations [5].) In this note we will focus on another possible glueball production mechanism, *gluon–gluon fusion* [15].

Gluon–gluon fusion. Due to the abundance of low-x gluons, the gluon–gluon fusion diagram should dominate several hard scattering processes, e.g. large p_T-production and heavy hidden flavour production [16]. There is experimental evidence for this dominance in ψ-production with the observed intermediate χ-states and consequent ψ'-suppression [17].

For glueball production the gluon–gluon fusion process is shown in fig. 1. The production cross section is given by [15]

[☆] Work supported in part by the Swedish Natural Research Council under contract NFR F 7019-104.

[‡1] For a recent review see ref. [1].

[‡2] For a recent review see ref. [2].

[‡3] Also a very narrow state has been observed at 2.2 GeV decaying into $K\bar{K}$ (see ref. [2]), for which there exist alternative explanations; see e.g. ref. [6].

[‡4] For a recent complete analysis of these data see ref. [14].

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Table 1
Experimental properties of $\theta(1700)$ in $\psi \to \gamma\theta$.

	Mass (MeV)	Γ (MeV)	$B(\psi \to \gamma\theta)B(\theta \to \eta\bar{\eta})$	$B(\psi \to \gamma\theta)B(\theta \to K\bar{K})$	$B(\psi \to \gamma\theta)B(\theta \to \pi\pi)$	$B(\psi \to \gamma\theta)B(\theta \to \rho_0\rho_0)$
Mark II [8]	1708 ± 30	156 ± 60		$(6.0 \pm 0.9 \pm 2.5) \times 10^{-4}$	$< 3.2 \times 10^{-4}$	$(1.25 \pm 0.35 \pm 0.4) \times 10^{-4}$ [10]
Crystal ball [9]	1670 ± 50	160 ± 80	$(3.8 \pm 1.6) \times 10^{-4}$		$< 6 \times 10^{-4}$	
Mark III (prel.) [2]	1719 ± 6 ± 10	117 ± 23 ± 10		$(4.8 \pm 0.7 \pm 0.9) \times 10^{-4}$	$< 3 \times 10^{-4}$	

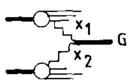

Fig. 1. Glueball production in the gluon–gluon fusion process.

$$\sigma_G(s) = K \frac{8\pi^2(2J+1)\Gamma_{G\to gg}}{m_G}$$

$$\times \int dx_1\, dx_2\, G(x_1)G(x_2)\delta(x_1 x_2 s - m_G^2)$$

$$= K \frac{8\pi^2(2J+1)\Gamma_{G\to gg}}{m_G^3} \tau \int_\tau^1 \frac{dx}{x} G(x)G(\tau/x) . \quad (1)$$

and its x_F-distribution

$$E_\theta \frac{d\sigma}{dp_\theta} = K \frac{8\pi^2(2J+1)\Gamma_{G\to gg}}{m_G^3} \frac{x_1 G(x_1) x_2 G(x_2)}{x_1 + x_2} , (2)$$

$$x_{1,2} = \tfrac{1}{2}[(x_F^2 + 4\tau)^{1/2} \pm x_F] ,$$

where s is the CMS energy squared, $x_F = 2p_\theta/\sqrt{s}$, m_G and J are the mass and spin of the produced glueball respectively, $G(x)$ is the gluon distribution and K is the so-called K-factor related to colour rearrangement. As essential inputs in eq. (1) we thus have $G(x)$, $\Gamma_{G\to gg}$ and K.

For $G(x)$ we use $\frac{1}{16}(n+1)(1-x)^n/x$ with $n = 5$ normalized according to $\Sigma_{\text{colour}} \int dx\, xG(x) = 0.5$.

The width $\Gamma_{G\to gg}$ is related to the overlap between the incoming gluons and the glueball wave function and is essentially unknown (unlike the $\chi \to gg$ case). We expect $\Gamma_{G\to gg}$ to be of standard hadronic order though, $\Gamma_{G\to gg} = 150$ GeV, since no Zweig rule suppression is involved. We will use this value below. For $K = 1$ in eq. (1) only gluons with matching colour annihilate. However, from the Drell–Yan process [18] and $pp \to \psi X$ [19] one has $K \approx 2$, indicating colour rearrangement. We use this K-value.

One might worry whether e.g. $m_\theta = 1700$ MeV is a large enough mass to make the use of eqs. (1) and (2) legitimate. One has support in this question from $pp \to \phi X$ phenomenology. It turns out that both magnitude and distribution shapes for this process are nicely described by $s\bar{s}$ fusion with $g_\phi^2/4\pi = 2.5$ for x_F

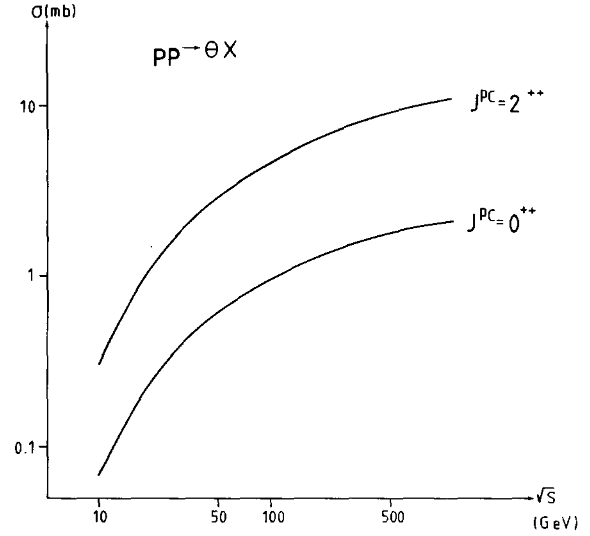

Fig. 2. Production cross sections using eq. (1) for $\theta(1700)$ with the $J^{PC} = 0^{++}$ and 2^{++} alternatives. Parameters as described in the text.

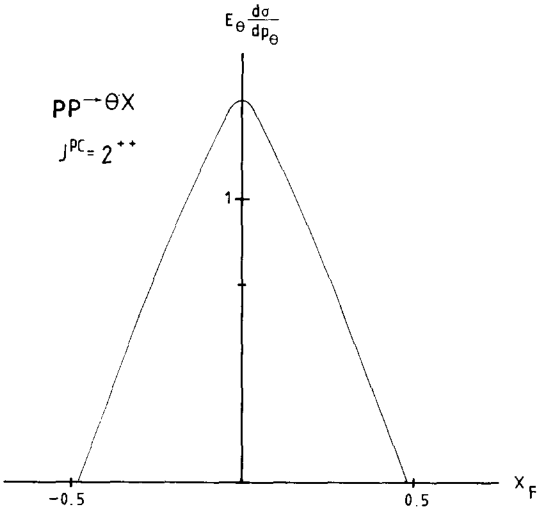

Fig. 3. Feynman x_F-distributions for θ-production using eq. (2) for the $J^{PC} = 2^{++}$ option. Parameters as described in the text.

$< 0.3, p_T < 1$ GeV [20]. This ϕ-production mechanism was suggested in ref. [21].

We will restrict ourselves to study the production of θ via gluon fusion since it has larger mass than the $\iota(1440)$ and also because of its dominant two-body decay modes (see below). The production cross section σ_θ is shown in fig. 2 for both the spin 0 and spin 2 options. As is seen the cross section is substantial. (For spin 2 every 8th event will contain a θ at the ISR). Fig. 3 shows the momentum distribution, which reflects the soft spectrum of the incoming gluons. Possible higher glueball states will be suppressed by M^{-3} according to eq. (1). In order to judge whether σ_θ will give rise to observable signals we now turn to the decay properties of θ.

Decay properties of θ. The decays of glueballs are poorly known theoretically. Since bound glue is $SU(3)_c$ symmetric one expects strange decays to occur as frequently as nonstrange decays. Furthermore one has speculated on the basis of helicity conservation in perturbation theory that strange decays might in fact be dominant [22]. Also explicit bag model calculations show s-quark dominant decays for some J^{PC} states [23]. Indeed the experimental candidates $\iota(1440)$ and $\theta(1700)$ have only been seen in decays containing at least one kaon with one possible exception [‡5] (see table 1).

One must keep in mind that in the reaction $\psi \to \iota(\theta)X$ the absolute branching ratio $B(\iota(\theta) \to \text{hadrons})$ are unknown since one lacks the total production cross sections $\Gamma_{\psi\to\iota(\theta)\gamma}$. Due to the very strong $K\bar{K}$ signal in θ one might however make reasonable estimates (see table 2). The two alternatives in table 2 correspond to including the $\rho_0\rho_0$-signal or not. Clearly $B(\theta \to K\bar{K}) \approx 0.3$–$0.6$ seems to be a reasonable value.

Combining this estimate with σ_θ (fig. 2) one obtains for $pp \to \underset{\hookrightarrow K^+K^-}{\theta} X$ the values given in table 3 for SPS-, ISR-, and collider energies.

Table 2
Estimates of $B(\theta \to h_1h_2)$

BR	Alternative 1	Alternative 2
$\theta \to K\bar{K}$	0.6	0.3
$\theta \to \eta\eta$	0.2	0.1
$\theta \to \rho_0\rho_0$		0.3
$\theta \to \pi\pi$	0.1	0.1
$\theta \to$ others	0.1	0.2

[‡5] Maybe θ is also seen in $\rho_0\rho_0$; see ref. [10].

Table 3
Cross sections for $pp \to \underset{\hookrightarrow K^+K^-}{\theta} X$ with $J^{PC} = 2^{++}$ and BR($\theta \to K\bar{K}$) = 0.5.

$\sqrt{s}$ (GeV)	σ_θ (mb)	σ_{Bg} (mb)
20	0.27	0.7
63	0.9	0.8
540	2.5	2.3

The main background for detecting θ this way comes from non-perturbative low-p_T events. The non-diffractive part of these can be successfully parametrized with cascade models [24]. Using the Lund Monte Carlo [25] and normalizing $\sigma_{\mathrm{inel}} = 25$, 28 and 45 mb respectively we estimate the background by integrating the $m_{K^+K^-}$ spectrum from 1.6 to 1.8 GeV. The resulting background cross sections are shown in table 3.

From table 3 we conclude that the gluon–gluon fusion process gives very clean signals for θ-production in the ISR-collider energy range in particular in the spin 2 case (in the case of spin 0 the numbers for σ_θ should be divided by 5).

I am indebted to T. Sjöstrand for help with the Monte Carlo estimate of the background.

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