Modelling glueballs

Francesco Giacosa[1,2,⋆]

[1] *Institute of Physics, Jan Kochanowski University, ul. Swietokrzyska 15, Kielce, Poland*
[2] *Institute for Theoretical Physics, J.W. Goethe University, Max-von-Laue-Str. 1, Frankfurt am Main, Germany*

Abstract. Glueballs are predicted in various theoretical approaches of QCD (most notably lattice QCD), but their experimental verification is still missing. In the low-energy sector some promising candidates for the scalar glueball exist, and some (less clear) candidates for the tensor and pseudoscalar glueballs were also proposed. Yet, for heavier gluonic states there is much work to be done both from the experimental and theoretical points of view. In these proceedings, we briefly review the current status of research of glueballs and discuss future developments.

1 Introduction

The fundamental particles of Quantum Chromodynamics (QCD) are quarks and gluons. Both are colored: quarks in the fundamental representation of the color group $SU_c(3)$ (red, green, blue), gluons in the adjoint representation (color-anticolor, minus the white configuration). The fundamental principle on which QCD is built is the invariance under local color transformations.

Color is not directly seen: confinement implies that the physical states emerging from QCD are 'white'. For instance all conventional quark-antiquark ($\bar{q}q$) states have the white wave function $\sqrt{1/3}(\bar{R}R + \bar{B}B + \bar{G}G)$. Such states constitute the majority of the mesonic resonances listed in the PDG [1], see also the review papers [2] and the predictions of the quark model [3].

From the early days of QCD [4–6] it was clear that bound states made solely of gluons, called glueballs, might exist. In fact, gluons interact strongly with themselves. The existence of glueballs was also predicted by various methods, most notably by lattice QCD, e.g. Refs. [7–9], both in the quenched and unquenched approximations. Yet, while their existence seems compelling from the theoretical point of view, up to now no resonance was found which can be *unambiguously* recognized as a predominantly glueball state. While in the low-energy sector (below 2.6 GeV) some candidates exist, in the high-energy sector no candidate is known. Experimental searches at low energies in the very soon upcoming experiments GlueX [10] and CLAS12 [11] at Jefferson Lab and at high energy at the ongoing BESIII [12, 13] and at the future PANDA [14] experiments are expected to improve our understanding.

The theoretical and experimental work on glueballs has been huge: up to now (status on 26/9/2015), there are 1404 papers which contain the world glueball in the title (for reviews, see Refs. [15–17]). In these proceedings we present some recent developments on this fascinating and still unsolved piece of QCD.

[⋆] e-mail: fgiacosa@ujk.edu.pl

Table 1. Central values of glueball masses from lattice (from [8])

J^{PC}	Value [GeV]
0^{++}	1.70
2^{++}	2.39
0^{-+}	2.55
1^{-+}	2.96
2^{-+}	3.04
3^{+-}	3.60
3^{++}	3.66
1^{--}	3.81
2^{--}	4.0
3^{--}	4.19
2^{+-}	4.22
0^{+-}	4.77

2 Existence and masses of glueballs

Photons do not interact with each other at tree-level. (A quartic photon interaction emerges through a fermionic loop, whose amplitude is suppressed by α^2.) Gluons are completely different: they shine, already at the leading order, in their own light. This fact, together with confinement, naturally leads to the idea that bound states made of solely gluons should exist.

The early studies of glueballs were performed within bag models, e.g. Refs. [4–6]. In particular, in Ref. [6] various microscopic currents were introduced and a glueball spectrum was shown. The lightest states were the scalar and tensor glueballs (at about 1 GeV), followed by pseudoscalar and pseudotensor ones.

The development of lattice QCD allowed to perform quantitative and model independent studies of the QCD spectrum. Already in 1999 a complete spectrum of glueballs (in the quenched approximations, i.e. without quarks) was presented [7]. The lightest state is a scalar glueball with a mass of about 1.7 GeV, followed by the tensor and the pseudoscalar states. This result has been confirmed by numerous and more recent lattice calculations, see Ref. [8], which is currently cited in the PDG in the review of the quark model [1]. The results are reported in Table 1.

Calculations within unquenched lattice QCD (i.e., with quark fluctuations) basically confirmed the same trend [9], in turn meaning that the mixing and the decays of glueballs should not be too large. This is indeed a very good information for model builders and experimental searchers.

While lattice QCD is the best theoretical proof of the existence of glueballs and the most reliable calculation of masses, other approaches were also used by theoreticians: QCD sum rules [18], Hamiltonian QCD [19], flux-tube model [20], anti De-Sitter approaches [21], and Bethe-Salpeter equations [22]. All of them find glueballs and the scalar state is the lightest.

In conclusion, there is nowadays a great confidence about the existence of glueballs and about the qualitative form of the spectrum. Nevertheless, the identification of glueballs has still to come.

3 Decays of glueballs

In the following we describe some general decay properties of glueballs and then we study separately some specific examples.

Large-N_c

According to the famous large-N_c limit [23] (simplifications occurs when the number of colors N_c is artificially increased to large values), glueballs' masses scale with N_c^0, just as $\bar{q}q$ masses. The decay of glueballs into mesons scales as N_c^{-2}, which is even more suppressed than regular $\bar{q}q$ states (that scale as N_c^{-1}). It is then expected that glueballs are narrow. This theoretical consideration is particularly important for the future PANDA project [14], which will search for glueballs between 2.2-5 GeV. Namely, only if glueballs are sufficiently narrow, they can be discovered experimentally.

Flavour and chiral blindness

Glueballs are flavour-invariant, hence they should decay in a flavour-blind way. For instance, for a glueball decaying into two pseudoscalar states and neglecting phase space, one obtains the ratios $\pi\pi : KK : \eta\eta : \eta'\eta' : \eta\eta' = 3 : 4 : 1 : 1 : 0$. In addition, the decays of a glueball are also chirally invariant, since it couples with the same strength to all chiral partners (such as $\rho\rho$ and $a_1(1230)a_1(1230)$).

Scalar glueball

The ground-state scalar glueball is undoubtedly the most studied gluonium. In the literature, many different scenarios concerning the identification of the scalar glueball in the realm of scalar states listed in the PDG were proposed. In most cases, the result was that the largest gluonic amount is either in $f_0(1500)$ or in $f_0(1710)$, e.g. Refs. [24–33]. A very short summary of the historical development is the following: in the pioneering work of Amsler and Close [24], later on confirmed by Close and Kirk [25], the largest gluonic amount sits in $f_0(1500)$. This conclusion was reached analyzing the decays of the three resonances $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$ into two pseudoscalar states using a $^3P_0$ approach. On the other hand, Lee and Weingarten [26] used a lattice QCD approach to study the mass of the scalar glueball and its couplings to pions and kaons: the outcome was that $f_0(1710)$ is mostly gluonic. In Ref. [27], Giacosa et al. used an hadronic model inspired by ChPT in which also the other members of the scalar nonet were included, $K_0^*(1430)$ and $a_0(1450)$. The fit to all decays showed the existence of two solutions, one in which $f_0(1500)$ is predominantly a glueball, and on in which $f_0(1710)$ is such. Shortly after, Cheng et al [28] also found a phenomenological solution in which $f_0(1710)$ is predominantly a glueball. Various other studies were performed which involved constituents quarks and gluons, e.g. Ref. [29], or which involved the decay of the j/ψ meson, e.g. Ref. [30].

The scalar glueball is also linked to the anomalous breaking of dilatation symmetry (at the composite level, a dilaton/glueball field is introduced [34, 35]). In Ref. [36] a peculiar fact was shown. Using the dilaton potential from Refs. [34, 35], the decay of the glueball into pions turned out to be about 4 GeV, hence definitely too large to be detected. The numerical value is obtained by assuming that the dilaton saturates the gluon condensate [37]. If this were true, large-N_c would badly fail in the scalar sector and one could never find such a broad glueball.

As discussed in Ref. [31], the determination of the parameters of the dilaton potential through the gluon's condensate is not necessarily true. More in detail, in Ref. [31] the glueball was studied within the so-called extended Linear Sigma Model (eLSM). This is an hadronic model based on chiral symmetry and dilatation invariance together with their explicit and spontaneous breaking. The eLSM, first developed for two flavours [38], has shown to be capable to describe masses and decays of mesons up to 1.7 GeV, as the three-flavour study of Ref. [39] shows. The glueball as a dilaton is naturally included in this model. Quite remarkably, there is only a solution within the eLSM: $f_0(1710)$ is mostly gluonic. This result is in agreement with the original claim of Ref. [26], but also with the recent lattice study of Ref. [32], in which the decay $j/\psi \to \gamma G$ is numerically evaluated. Moreover, the very same conclusion has been reached in Ref. [33] by using an approach based on the AdS/QCD correspondence. Future information from the GlueX experiment is expected [40].

In conclusion, while a final assignment cannot yet be done, there is mounting evidence from different directions that $f_0(1710)$ is mostly gluonic.

Tensor glueball

According to lattice, the tensor glueball has a mass of about 2.2 GeV (it is second lightest). In Ref. [41] it was pointed out that the resonance $f_J(2220)$ does not lie on the Regge trajectories. Moreover, the state is very narrow, the $\pi\pi/KK$ ratio is in agreement with flavour blindness [42], and no $\gamma\gamma$ decay was seen. A necessary improvement would be the experimental assessment of this resonance. In particular, it is not yet clear if J is 2 or 4. Nevertheless, this is a promising starting point for future studies (for instance, employing the eLSM).

Pseudoscalar glueball

The pseudoscalar glueball has been also investigated in a variety of scenarios, see Ref. [43] for a review. One has investigated the gluonic content of the resonance η', e.g. Refs. [44] and [45]. In various other works, e.g. Ref. [46], the pseudoscalar glueball was assigned to the resonance $\eta(1405)$, while $\eta(1295)$ and $\eta(1475)$ are $\bar{q}q$ states. Such a scenario is controversial for two reasons: (i) At present, it is not clear if $\eta(1405)$ and $\eta(1475)$ are two independent states. (ii) The mass of the pseudoscalar glueball as predicted by lattice QCD is about 2.6 GeV, i.e. 1 GeV heavier.

In Ref. [47] the eLSM has been used to study the decays of an hypothetical pseudoscalar glueball (linked to the chiral anomaly [48]) with a mass of about 2.6 GeV, in agreement with lattice. The outcome was that the decay channels into $KK\pi$ and $\eta\pi\pi$ are dominant, while $\pi\pi\pi$ should vanish. A possible experimental candidate is the state $X(2370)$ measured by BES [13], yet future measurements on its decay rates are needed.

Other glueballs

The other glueballs listed in Table 1 need further studies. Very recently, two steps have been performed: (i) in Ref. [49] the decays of a pseudotensor glueball has been studied in a flavour-invariant hadronic model: sizable decay into $K_2^*(1430)K$ and $a_2(1320)\pi$ and a vanishing decay into $\rho\pi$ are predicted. (ii) The decays of a vector glueball in a fully chirally invariant approach (using the eLSM) have been investigated in Ref. [50]: a sizable decay into $\omega\pi\pi$ (both direct and indirect through $b_1\pi$) and into $\pi KK^*(892)$ are expected to be the main signal of a vector gluonium. Such simple predictions may help future experimental searches.

4 Conclusions

Glueballs are expected to exist but were not yet found in experiments. While GlueX and CLAS12 can help our understanding in the light sector, BESIII and, in the future, PANDA can search for glueballs in the heavy sector. Definitely, more work is needed: predictions about the decay channels of glueballs might be particularly helpful in the process of identifications of possible candidates. The aim is to close the gap between a basic theoretical expectation of QCD and the present experimental status.

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