Open Questions of Meson Spectroscopy: Lattice, Data, Phenomenology

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Abstract

Current status of hadron spectroscopy is reviewed with special attention paid to the manifestation of gluonic degrees of freedom in hadrons. The existing data are confronted to the results of lattice QCD on hadronic spectra, and some controversies are outlined.

1 Introduction

During last decade we have enjoyed the period of hadron spectroscopy blossoming. The fantastic amount of high-statistics data was presented, mainly from hadron beams experiments: LEAR (Crystal Barrel)at CERN, E852 at BNL and VES at Protvino. The first two of them ended, and VES is subject to unstable situation in Russia. The focus is shifted now to the photoproduction experiments at JLAB and e^+e^- facilities at Novosibirsk (VEPP) and Frascati (DAΦNE). Surprisingly, one can expect new results also from the experiments, which were not designed for meson spectroscopy, but are able to contribute, for example, through photon-photon collisions (LEP) and initial-state radiation (BaBar, Belle). So the field is not going to be abandoned, and new physics is guaranteed.

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In the striking contrast to this activity, the state-of-art in theory has nothing to boast about. Hadronic spectrum is formed at large distances, and there is no analytical methods to describe QCD in this nonperturbative region. This simple statement more or less summarises the theoretical efforts, and gives rise to various phenomenological approaches, which need some "nonperturbative input". The two main branches of phenomenology are QCD sum rules and quark models. These two branches differ in all possible respects. The former is respectable, while the latter is doubtful. The former deals with condensates, with no reference to confinement at all, while the latter describes interaction between quarks by means of confining potential. Ideologically, such things as condensates do exist, while quark model as quantum mechanical reduction of the field theory is surely an oversimplification. Surprisingly enough, both extremes are rather successful phenomenologically.

In the absence of analytical methods the lattice gauge calculations remain the only "first principles" source of knowledge. Lattice calculations are now accurate enough to provide description of the QCD observables, if, of course, the extrapolation to continuum limit is done properly. Indeed, lattice data, together with general arguments from QCD, tell that the theory is confining one. Direct measurements of the static $\bar{Q}Q$ potential demonstrate it explicitly: the $\bar{Q}Q$ force is nicely fitted by the so-called Cornell potential.

The most important contribution of lattice gauge theory is its application to the spectrum of glue. QCD, even quenched in quarks, possesses nontrivial spectrum, so that gluonic hadrons (glueballs and hybrids) should exist, and effective degrees of freedom for constituent glue should be introduced to describe QCD in the nonperturbative region. Not only lattice calculations should serve as a guide in model building. The results of lattice simulations should provide the necessary feedback for defining experimental strategy of glue hunting.

In this paper I am not going to review the current status of meson spectroscopy; instead I point to some selected topics, challenging both for lattice calculations and phenomenology, and underline some controversies which arise when lattice and data are confronted.

2 Glueballs

The most important development in hadron spectroscopy at the lattice is the convergence on the mass and quantum numbers of the lightest glueball

Table 1: 0^{++} mesons

$I=0$	$I=1/1$	$I=1$
$\sigma(\sim 600)$?	$\kappa(\sim 800)$?	
$f_0(980)$		$a_0(980)$
$f_0(1370)$		
$f_0(1500)$	$K^*(1430)$	$a_0(1450)$?
$f_0(1710)$		

in the quenched approximation. The lightest glueball is predicted to be a scalar, $J^{PC} = 0^{++}$, with the mass about 1.4-1.7 GeV [1]. The data also exist, though not so accurate, on the next lightest states [1], with the mass hierarchy $M_{0^{++}} < M_{0^{-+}} \leq M_{2^{++}}$. In the unquenched QCD, the lightest scalar qlueball should mix with the $\bar{q}q$ scalars in the same mass region.

There are more scalar mesons than the simple $\bar{q}q$ 1^3P_0 nonet can accomodate, with an obvious excess in the scalar-isoscalar sector, and with the natural inference of there being a glueball state present. The Table 1 poses a lot of questions:

- What is the nature of broad activities below 1 GeV, labelled as "σ" and "κ"? Whether these phenomena are resonant or happen due to t-channel exchanges?
- Where are scalar isoscalar $\bar{q}q$'s?
- What are $f_0(980)$ and $a_0(980)$? $\bar{q}q$, $\bar{q}^2q^2$ or $K\bar{K}$ molecules? In any case these states should enjoy the vicinity of the nearby $K\bar{K}$ threshold...
- Where is the place for lattice glueball in this picture?

The main question is of course whether the physical glueball is localised around 1.5 GeV or the gluonic component is diluted over the whole range down to $\pi\pi$ threshold.

The first possibility, [2], suggests that the regions below and above 1 GeV are governed by quite different dynamics. It is argued in [2] that the low-lying phenomena are due to strong attraction in the $\bar{q}^2q^2$ system, either in the form of compact four-quark states or in the form of meson-meson molecules (see also [3]).

In such a way, the 1^3P_0 $\bar{q}q$ mesons are placed above 1 GeV, revealing large mixing with the nearby glueball. The detailed pattern of mixing was analysed in [4] by studying the complete set of decay branching ratios into pseudoscalar pairs [5]. The preferred scenario gives the bare masses as $m_g = 1443 \pm 24$ MeV, $m_{n\bar{n}} = 1377 \pm 10$ MeV and $m_{s\bar{s}} = 1674 \pm 10$ MeV. Other solutions have been found which have either a heavy glueball, $m_g > m_{s\bar{s}}$, or a light glueball, $m_g < m_{n\bar{n}}$, and although less consistent with the data they cannot be ruled out completely. The preferred solution is consistent with what one could expect naively from the $s\bar{s} - n\bar{n}$ mass difference of about 300 MeV, and places the glueball at the lower end of the mass range given by the lattice calculations. The heavy glueball solution was obtained also in the lattice studies of mixing [6].

Quite different scenario is suggested by the sum rules analysis [7]. The unmixed glueball masses from the unsubtracted QCD spectral sum rules were found to be in nice agreement with lattice results. For a consistency of the sum rules, however, one needs a second resonance with a lower mass of about 1 GeV. For the unmixed scalar quarkonia, sum rules support the $(\bar{u}u - \bar{d}d)$ assignement for the $a_0(980)$, and its strange partner is $K^*(1430)$, while a quarkonium- gluonium decay mixing scheme gives the large mixing angle, implying that the σ and $f_0(980)$ have equal admixtures of quarks and gluons in their wave functions. The wide σ and narrow f_0 do have strong couplings to meson pairs. More complicated mixing scenarios happen in the 1.5 Gev mass region.

Similar results have been obtained in [8], where it is argued that a single very broad object observed in the $\pi^0\pi^0$, $K_s^0 K_s^0$ and $\eta\eta$ mass spectra is the lightest glueball with the mass of around 1 GeV and the width of 500-1000 MeV. The members of 0^{++} $q\bar{q}$ nonet are identified as $a_0(980)$, $K^*(1430)$ together with isoscalars $f_0(980)$ and $f_0(1500)$, with the former being close to flavour singlet and the latter close to flavour octet.

The K-matrix analysis of the Crystal Barel data on $p\bar{p}$ and $n\bar{n}$ annihilation combined with the analysis of radiative decays (see [9]), also supports the idea of a glueball state accumulating the widths of neighboring $q\bar{q}$ resonances and becoming very broad. In such a manner this group claims the broad $f_0(1420)$ as a descendent of a bare glueball. The 1^3P_0 nonet is supposed to be populated by $\sigma(f_0(300-500))$, $f_0(980)$, $a_0(980)$ and κ.

Clearly, if indeed bare glueball is spread along wide mass range due to effects of coupled mesonic channels, the validity of quenched lattice results is seriously questioned.

The discovery potential of standard glueball-hunting experiments like $\gamma\gamma$ production or $\Psi \to \gamma G$ is far from being exhausted, as well as of radiative decays $\phi \to \gamma a_0, \gamma f_0$. New flavour filtering experiments like radiative decays of excited light vector mesons into scalars also offer interesting opportunities [10].

Among other experimental questions to be resolved one should note the existence and properties of the isovector state, a_0 with the mass of about 1400 MeV. There is an indication that this state has been observed [11]. Any confirmation of this controversial $a_0(1450)$ is of paramount importance. There are also doubts on $f_0(1370)$ being a true resonance and not the dynamical (t-channel exchage) effect ([8],[12]).

The relationship between $a_0(980)$, $f_0(980)$ and $K\bar{K}$ threshold remains an intriguing issue. Large couplings and threshold S-wave cusps point to large $K\bar{K}$ molecular components in the wave functions of these mesons. Strong $f_0 - a_0$ mixing [13] confirms this too. More efforts are needed from phenomenology side as well as from measurements of $K\bar{K}$ spectra near threshold, to establish whether these states are of similar nature, or some significant extra (glueball) component destroys this similarity.

3 Hybrids

Gluonic degrees of freedom should also manifest themselves as hybrids with the glue excited in the presence of $q\bar{q}$ pair. Lattice simulations measure the spectrum of the glue in the presence of static quark and antiquark separated by some distance R [14]. This system is a simplest one, as the gluonic effects are not obscured by light dynamical quarks.

The short range limit of hybrid adiabatic potentials is relevant to heavy hybrid mass estimations: in the case of very heavy quarks the hybrid resides in the bottom of potential well, which, in accordance with lattice data [14] is somewhere around 0.25 fm for the lowest curves. An important comment is in order here. The ground state curve is nicely described by Cornell potential, with attractive Coulomb interaction, corresponding to colour-singlet state of the $Q\bar{Q}$ pair. The behaviour of excited curves displays short-distance repulsion, compatible with $Q\bar{Q}$ pair being in colour octet. Such behaviour comes out naturally in the models with point-like gluons, carrying colour quantum numbers.

The large distance limit of hybrid adibatic potentials is interesting too, as

Table 2: Light quark 1^{-+} hybrid meson masses. W-Wilson fermion action; SW-improved clover fermion action; N_f is the number of dynamical flavours.

Ref.	Method	N_f	Mass(GeV)
UKQCD 97	SW	0	1.87
MILC 97	W	0	1.97
MILC 99	SW	0	2.11
LaSch 99	W	2	1.9

one expects the formation of the confining string at large R. Nevetheless, for separations less than 2 fm the measured energies [14] lie well below Nambu-Goto curves, and there is no universal behaviour even for R as large as 4 fm. This observation casts doubts about the validity of naive string models for constituent glue.

The *in vitro* measurements described above seem rather academic. In contrast to constituent models, in the QCD with dynamical quarks distinction between $q\bar{q}$ mesons and hybrids is rather arbitrary, with the exception of low-lying states with exotic quantum numbers. The results of light-quark $J^{PC} = 1^{-+}$ hybrid mesons lattice calculations are given in Table 2.

With the exception of the last line in the Table 2 ([15]), all results are in quenched approximation. It seems at first glance that sea quark effects do not change the results drastically. All estimates point to 2 GeV region. It is interesting to note that the same mass range was predicted long ago in the flux-tube model [16].

Results from QCD sum rules show considerable variations from each other [17], with predictions for the 1^{-+} hybrid lying between 1.3 and 1.9 GeV. Most recent calculations (last entry in [17]) give a preference for the lower end.

Now consider the experimental situation. A clear exotic $J^{PC} = 1^{-+}$ resonance, the $\pi_1(1600)$ is seen [18] in the $\eta'(958)\pi$ channel in the reaction $\pi^- N \to \eta'(958)\pi N$. Two experiments [19] have evidence for this exotic in the $\rho^0\pi^-$ channel in the reaction $\pi^- N \to (\pi^+\pi^-\pi^-)N$. The $\pi_1(1600)$ is also seen in $b_1\pi$ mode. A peak in the $\eta\pi$ mass spectrum at about 1400 MeV with $J^{PC} = 1^{-+}$ in $\pi^- N \to (\eta\pi^-)N$ has also been interpreted as a resonance [20]. Supporting evidence for the 1400 MeV state in the same mode comes from $\bar{p}p \to \eta\pi^-\pi^+$ [21].

Existence of exotic meson, if confirmed, is of paramount importance, but two neighboring exotic mesons would not make theorists happy. Good news is that VES collaboration is able to present fits describing the $\pi_1(1400)$ phenomenon from a nonresonant signal. Generally, the $\eta\pi$ signal is rather weak, and it is difficult to disentangle it from a nonresonating background. In any case, if the exotic hybrid is at 1400 MeV, it nicely fits recent sum rules results, but contradicts lattice findings. If the exotic hybrid is at 1600 MeV, it could be accomodated by the sum rules, but not by lattice calculations.

In such an embarrassing situation lattice authors tend to assume that experimental candidates in the mass range 1.4 - 1.6 GeV are not hybrids, and may be four-quark states. On the other hand, more careful studies of sea quark effects on the lattice could resolve this disctrepancy.

Together with open exotics, one should expect hybrids with nonexotic quantum numbers to exist in the sama mass range. There is experimental evidence [22] for two isovector 0^{-+} states in the mass region 1.4 to 1.9 GeV; $\pi(1600)$ and $\pi(1800)$. The quark model predicts only one. The data on strong decays of ligh-quark vector-meson excitations at 1.5 - 1.7 GeV pose questions which could be resolved invoking vector hybrid mixed with excited quarkonia [23].

4 Strong Decays

The possibility for nonexotic hybrids to exist calls for the signatures allowing to disentangle between hybrids and quarkonia. In principle, strong decays should offer such opportunity. The constituent picture intuition tells that the wave function of hybrid differs from the one of quarkonia excitations with the same J^{PC}, as extra degree of freedom is added. Indeed, there exists a famous selection rule for hybrid decay, [24] valid both in flux-tube model and in constituent gluon model: the main decay mode of the lowest hybrids is $S + P$ final state. For example, exotic 1^{-+} hybrid decays into $b_1\pi$ and $f_1\pi$, and vector hybrid decays into $a_1\pi$.

In addition, the $^3P_0$ model for strong decay [25] predicts small branching ratios for the $S+P$ decay of radials, making possible to discriminate betweeen quarkonia and hybrid assignements.

The $^3P_0$ approach which models string breaking is quite successful in describing several well known decays, mainly decays of axial vectors into vectors and pseudoscalars, including D/S ratios. But there is not a lot of theoretical background behind it, so it could be premature to draw conclusions on hybrid admixture solely on the basis of $^3P_0$ decay pattern violations.

One knows from heavy quarkonia that radial excitations do decay into ground state, or a lower radial excitation, plus $(\pi\pi)_S$. These decays cannot proceed via string breaking. A similar phnomenon is seen in light quarkonia: $\eta'(1295) \to \eta(\pi\pi)_S$ and $\pi(1300) \to \pi(\pi\pi)_S$. Assuming that both $\eta'(1295)$ and $\pi(1300)$ are radial excitations, one calculates these decays to be essentially zero in the $^3P_0$ model.

Another source of concern is that the naive pair creation models are based on the constituent picture and do not respect soft pion theorems; in particular, there is no hope to obtain Adler selfconsistency condition for the decay amplitudes with pions in the final state. Now, the $b_1\pi$ and $f_1\pi$ 1^{-+} final states are in the relative S-wave, as well as $f_0\pi$ 0^{-+} and $a_1\pi$ 1^{--} ones, and the nominal thresholds are not far from the resonance positions. This is just soft pion theorems environment.

The $S+P$ decay modes are rather challenging experimentally: the cusp-like threshold behaviour might have a drastic effect on observables, obscuring the interpretation of the data in terms of bare states. Moreover, the strength of the cusp might be smoothened over some mass range, because the P-wave mesons are usually broad, and it confuses the picture even more.

There is no hope at present to acquire knowledge on decay mechanisms from the lattice. This topic remains *terra incognita*. Decay pattern described above is a nightmare for lattice calculations, as S-wave decay thresholds are to be taken into account accurately, as well as resonance properties in the finite volume.

5 Conclusions

Despice real progress achieved by Lattice Gauge Theory, our current understanding of meson spectroscopy remains rather poor. When data are concerned, optimistic viewpoint is that lattice tends to overestimate the masses. More pessimistically, it might happen that sea quark effects completely rearrange the spectrum of pure Yang-Mills theory.

Nobody doubts at present that the QCD is correct theory for strong interaction, and that the lattice QCD is potentially powerful tool to deal with confining properties. In practice, however, the problems start when one wants to remove the word "quenched" from lattice results. Incorporation of virtual quark-antiquark pairs dramatically increases the computational costs, and extrapolation to realistically light quark masses is extremely tedious.

Nevertheless, the physics that can be extracted merits every effort in this direction.

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