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Experimental review on light meson spectroscopy

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The hadron spectrum provides crucial insights into the strong force dynamics, the quark confinement and the transition from quarks and gluons to observable particles. While hadrons' quark composition is well understood, most of their mass arises from the binding force among quarks —a largely unexplored domain that has driven extensive experimental efforts for decades.

Meson spectroscopy serves as a key tool for studying quark interactions and gluon dynamics, enabling the identification of conventional mesons and the search for exotic states such as multiquark aggregates, hybrids, and glueballs. Exotic quantum numbers offer unique discovery opportunities, but many observed candidates exhibit conventional signatures, complicating interpretation due to their broad widths and overlapping decay patterns.

This review examines recent progress in light meson spectroscopy, focusing on hadrons composed of light quarks (u, d, s) with masses below 2.2 GeV/c^2. It highlights results from various production processes, including e^+e^- and nucleon-antinucleon annihilation, hadron scattering, and electro- and photoproduction. Recent advances in analysis techniques and lattice QCD have provided powerful new tools to unravel these complex phenomena, deepening our understanding of the strong interaction and QCD non-perturbative regime.

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1. Introduction

The study of the meson spectrum has been ongoing for over fifty years, with significant progress in identifying structures and assigning their quantum numbers. Mesons, composed of quark-antiquark ($\bar{q}q$) pairs, are classified by their J^{PC} quantum numbers (total angular momentum J, parity P, and charge conjugation C). Standard configurations (*e.g.*, 0^{++}, 0^{-+}, 1^{+-}, 2^{++}) form the backbone of meson classification, while exotic combinations (0^{--}, odd^{-+}, $even^{+-}$) suggest physics beyond the Constituent Quark Model (CQM).

Light mesons (below $2.2\,\mathrm{GeV}/c^2$) appear usually as broad, overlapping resonances, which makes their identification challenging. Despite decades of studies, many aspects remain unclear: for instance, while three vector (1^{--}) nonets are now well established, many axial-vector states remain poorly understood, necessitating further study. Identification is complicated by interference, mixing, shared decay channels, and non-distinct resonant line shapes. Thus, a comprehensive approach using diverse experimental data and production mechanisms is essential.

As a non-Abelian theory, Quantum Chromodynamics (QCD) predicts the existence of hadrons composed entirely of gluons (*glueballs*) or quark-gluon hybrids ($\bar{q}qg$). These states can share quantum numbers with conventional mesons or exhibit exotic configurations. Results from increasingly precise Lattice QCD (LQCD) calculations align well with established experimental findings, reinforcing confidence in their theoretical predictions: the lightest $\bar{q}qg$ hybrid mesons were recently suggested to have 1^{-+} exotic quantum numbers [1]; predictions on their partial widths have been made available as well [2]. In Sections 3 and 4 a summary of the most recent discoveries will be reported for both glueballs and hybrid mesons.

2. Experimental facilities and techniques

Early spectroscopic studies relied on bubble chamber experiments, but these were soon surpassed by advanced magnetic spectrometers with superior particle identification and broader acceptance. Light quark spectroscopy searches have been conducted using both electromagnetic (electrons and photons) and hadronic (protons, antinucleons, pions, kaons) probes at low-to-medium energies. At low energies, the CLAS and GluEx experiments at JLAB study electromagnetic processes, while Crystal Barrel, HADES and COMPASS are examples of experiments exploiting $N\overline{N}$, pp and πp scatterings, respectively, with hadronic probes at increasingly higher energy.

Additional insights into light mesons come from high-energy experiments, that operate (or operated) at beauty factories ($e^+e^- \to \Upsilon(nS)$, like *B*a*B*ar and Belle II), or charm ($e^+e^- \to \psi(nS)$, like BESIII) and strangeness ones ($e^+e^- \to \phi$, like KLOE), as well as in $\bar{p}p$ and pp collisions at energies larger than hundreds of GeV (like CDF or the experiments at the LHC, respectively). In high-energy experiments, light meson properties can be inferred through the decays of high-mass mesons (which have an intermediate-heavy flavor content) produced in the annihilation. As an example, B meson decays can act as flavor filters: the neutral $B \to J/\psi X$ decay can filter the $d\bar{d}$ content of the light X product, while the same decay pattern for a B_s can filter the X $s\bar{s}$ content.

For the identification of new resonances, it is essential to explore multiple production mechanisms. Given the frequent interference and overlap of states in the light mesons mass region, employing multichannel analyses and coupled-channels techniques is crucial.

Charmonium radiative decays. Radiative decays of quarkonia and their radial excitations are particularly interesting as they exhibit a peculiar systematic behavior independent on the hidden flavor. Such decays provide an ideal environment for glueball searches, since these processes are mediated by two or three gluons exchange.

Charmonia and bottomonia have fixed quantum numbers (1^{--}), which act as spin-parity filters for the hadronic products in the radiative decays. Since for these recoiling systems $C = +1$, only states with $J^{PC} = 0^{-+},\ 0^{++},\ 1^{++},\ 2^{++},\ 2^{-+}$ can be produced alongside the radiated photon. Additionally, isospin conservation and the OZI rule favor the production of isoscalar final states. To-date, the primary source of glueball-related observations and information is the BESIII experiment at BEPCII (China), that has collected so far the largest charmonium dataset, consisting of about 10^{10} J/ψ and 3×10^9 ψ' decay events.

3. Search for glueballs: experimental observations and recent findings

Glueballs, composed entirely of gluons and lacking valence quarks, are expected to be preferentially produced in nucleon-antinucleon ($N\overline{N}$) annihilation and quarkonia decays, that are gluon-rich environments. Their most distinctive feature is the "flavor blindness", which means that their decays do not favor specific meson flavors. Typical decay ratios follow the pattern $\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3 : 4 : 0 : 1$, which highlights the suppression of the $\eta\eta'$ channel, that can therefore be considered as an anti-glueball peculiar decay mode.

According to LQCD predictions, the scalar glueball ground state is expected in the $1.5 - 1.7$ GeV$/c^2$ range, while the tensor and pseudoscalar ground states are predicted at higher masses, around $2.3 - 2.6$ GeV$/c^2$ [3].

Scalar glueballs. The $f_0(1500)$ and $f_0(1710)$ had been the two leading scalar glueball candidates since the Nineties. Most of the earliest spectroscopic observations for the $f_0(1500)$ came from $N\overline{N}$ annihilation experiments, particularly at CERN-LEAR, where the OBELIX [4] and Crystal Barrel [5] Collaborations reported evidence for such a state in multiple decay channels ($\pi^+\pi^-, 4\pi^0, 2\pi^0, K^+K^-, 2K^0_L, \eta\eta$). The $f_0(1500)$ existence was also confirmed by central collisions experiments [6]. However, this state appeared alongside two other isoscalar states in the same mass region, the broad $f_0(1300)$ and the mentioned $f_0(1710)$: this fact called for an extra state beyond the expected scalar nonet, and for this reason a glueball identification was suggested for the $f_0(1500)$. However, this state was found to couple more strongly to light (u, d) quarks, whereas the $f_0(1710)$ exhibited a stronger affinity to strangeness, and this questioned the glueball interpretation of the former.

More recently, the BESIII experiment examined these scalar states in J/ψ radiative decays, observing a significant $f_0(1500) \to \eta\eta'$ contribution [7] —the typical anti-glueball filter decay— while the expected $f_0(1710) \to \eta\eta'$ decay was notably absent [8]. This reinforced the glueball-nature interpretation of $f_0(1710)$ compared to $f_0(1500)$. Additionally, BESIII observed a large $f_0(1710)$ production in other decay channels ($\eta'\eta', K_SK_S, \pi^0\pi^0$) [8], indicating a significant gluonic component. Figure 1 shows the line-shape of the ($\eta\eta'$) invariant mass distribution observed by BESIII [7], to which both the $f_0(1500)$ and the $f_0(1710)$ contribute.

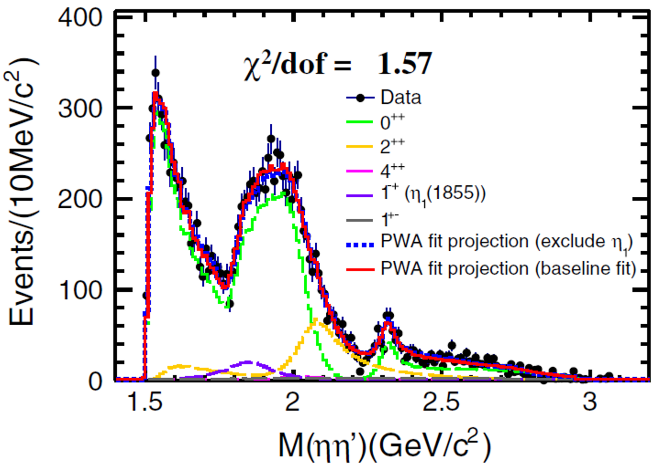

Figure 1: Background subtracted experimental data and partial wave analysis solutions for the $\eta\eta'$ invariant mass distribution (from Ref. [7]). The green curve represents the contributions from the scalar states, while the purple one is the contribution from $\eta_1(1835)$.

Pseudoscalar glueballs. The search for pseudoscalar glueballs dates back to the Seventies and was initially intertwined with the identification of axial states. The so-called "E/ι" puzzle, solved in the mid-Nineties by OBELIX through studies of $N\overline{N}$ annihilations in the $K\overline{K}\pi$ and $\eta\pi\pi$ final states [9], revealed that pseudoscalar and axial states were overlapping and sharing common decay channels in the $1.3 - 1.5\,\mathrm{GeV}/c^2$ mass region. Pseudoscalar 0^{-+} states were shown to decay into $a_0(980)\pi$, $K^*(892)\overline{K}$, and $K\overline{K}\pi$, while axial 1^{++} states did not seem to decay into $K^*(892)\overline{K}$. The early observations of the two isoscalar states E, seen in its $K\overline{K}\pi$ decay, and ι, seen in J/ψ radiative decays and considered for some time a glueball candidate, converged finally to a single state.

Two pseudoscalar states were observed in addition, mainly in the $\eta\pi\pi$ final state: the $\eta(1275)$, potentially the first radial excitation of η' [10], and the $\eta(1440)$, which, in turn, appeared to be split into two states, each with peculiar features. The first one, the $\eta(1405)$, was observed mainly in the $a_0(980)\pi$ decay channel [11] in gluon-rich environments like $\bar{p}p$ annihilations, J/ψ decays, and hadronic peripheral production, but neither in $\gamma\gamma$ collisions nor B meson decays. For this reason it was considered a viable glueball candidate, with an estimated glue content as large as 76%. However, LQCD calculations object that its mass is too light to be a true glueball. The second state, the $\eta(1475)$, was preferentially observed in $\gamma\gamma$ collisions at L3 [12] but not in K^-p interactions. Its most likely interpretation was a radially excited $\bar{s}s$ quarkonium state, with decays favoring the $K^*(892)\overline{K}$ channel. Recent results from BESIII provide further insights into the nature of the $\eta(1405)$, but its identification remains unclear. Both the above-mentioned η states fit well the prominent structure observed in the $K_SK_S\pi^0$ system from the J/ψ radiative decay [13], see Fig. 2. Additionally, the $\eta(1405)$ plays a significant role in the $J/\psi \to \gamma\gamma\phi$ decay, with a significance of 18.9σ, although the $\eta(1475)$ cannot be excluded [14].

BESIII suggests in addition the existence of a new higher-mass pseudoscalar state, the $X(2370)$ [15]. This state was observed in several channels in the J/ψ radiative decay (*e.g.*, $\eta'\pi^+\pi^-, \eta'K^+K^-, \eta K_SK_S, \pi^0K_SK_S, \eta\pi^0\pi^0, a_0(980)\pi^0$), with a decay pattern similar to η_c. Its mass and production rates are consistent with LQCD expectations for the lightest pseudoscalar glueball.

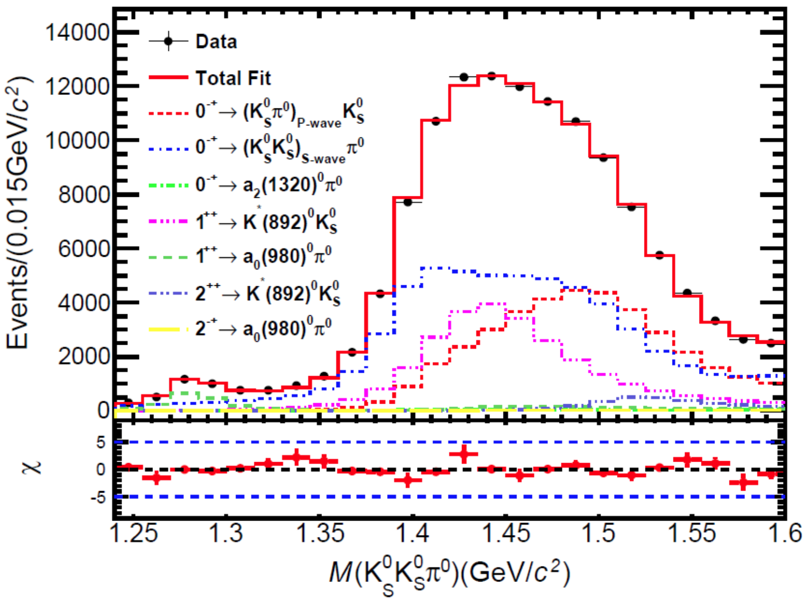

Figure 2: Distribution of the $K_S^0 K_S^0 \pi^0$ invariant mass: experimental data points with superimposed fits showing the lineshape around 1.45 GeV/c^2, with the contributions (in blue and red) from both $\eta(1405)$ and $\eta(1440)$. From Ref. [13]

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Concerning axial states, a few of them, such as the $f_1(1420)$ and, particularly, the $f_1(1510)$, were observed with low statistical significance [9]. The $f_1(1420)$ was initially considered a hybrid or tetraquark state. Conversely, the isovector $a_1(1420)$ was observed with high statistics at COMPASS in the $f_0(980)\pi$ decay channel [16]. However, a recent re-analysis suggests that this structure is not a true resonance but may be explained just by a three-body rescattering mechanism [17].

Tensor glueballs. A potential low-mass tensor glueball candidate, the $f_2(1950)$, was observed in the Nineties by several experiments, alongside the well-known tensor mesons $f_2(1270)$ and $f_2(1525)$, which couple to light quarks and $\bar{s}s$, respectively. The GAMS experiment identified it in the $\pi\pi$ decay channel [18]; for some time, this structure had been interpreted as the ground state of the tensor Pomeron [19]. In addition, a higher-mass structure beyond 2.2 GeV/c^2 attracted attention: the JETSET experiment at LEAR observed significant production of a state in the $\bar{p}p \to \phi\phi$ reaction [20], which was confirmed by a large cross-section in the $\pi^- p \to \phi\phi n$ diffractive reaction [21].

Recently, BESIII observed a relatively narrow state, called $f_2(2340)$, in the $J/\psi \to \gamma\phi\phi$ radiative decay [22]. Besides $\phi\phi$, it was also detected in other decay modes, including $\eta\eta$, $K_S K_S$, and $\eta'\eta'$, which would again support its interpretation as a glueball candidate. However, its mass is notably lower than expected from LQCD predictions.

4. Search for hybrid mesons: recent experimental observations of 1^{-+} candidates

Hybrid states, consisting of quarks, antiquarks, and excited gluons, are distinguishable from conventional mesons due to their exotic quantum numbers, 1^{-+}, 1^{+-}, and 2^{+-}. The lightest of them are expected in the $1.7 - 2.1$ GeV$/c^2$ mass range. Hybrid mesons typically decay into a pair of $(S+P)$-wave mesons, as the $b_1(1235)\pi$ $(\to \omega\pi\pi)$ channel. Experimental observations have identified a few isovector 1^{-+} hybrid candidates, such as the $\pi_1(1400)$, $\pi_1(1600)$, and $\pi_1(2015)$. Evidence for a 1^{-+} isoscalar hybrid is less clear.

The case of $\pi_1(1400)$ and $\pi_1(1600)$. Two axial isovector mesons, the $\pi_1(1400)$ and $\pi_1(1600)$, have been observed since the Nineties. The $\pi_1(1400)$, with a broad width of 350 – 400 MeV, was detected in the $\eta\pi$ decay channel in pion-induced peripheral production by the E852 experiment at BNL [23], and in $N\overline{N}$ annihilations by Crystal Barrel at LEAR [24]. The latter experiment showed that the $\pi_1(1400)$ was needed to describe satisfactorily the $(\pi\pi\eta)$ Dalitz plot, along with other intermediate states like σ, ρ, and $a_2(1320)$.

A second state, the $\pi_1(1600)$, was observed about 200 MeV/c^2 above the $\pi_1(1400)$ in $\eta'\pi$ and $\rho\pi$ decays (by E852 [25, 26], VES [27] and COMPASS [28–31]), but never in $\eta\pi$. A recent analysis of both COMPASS and Crystal Barrel data using a coupled-channels technique [32] suggests that the two states are poles of the same structure: the lower mass state preferentially couples to $\eta\pi$, while the higher mass one to $\eta'\pi$.

Figure 3 shows, in different momentum transfer $t' \equiv |t| - |t|_{min}$ ranges, the intensity distributions

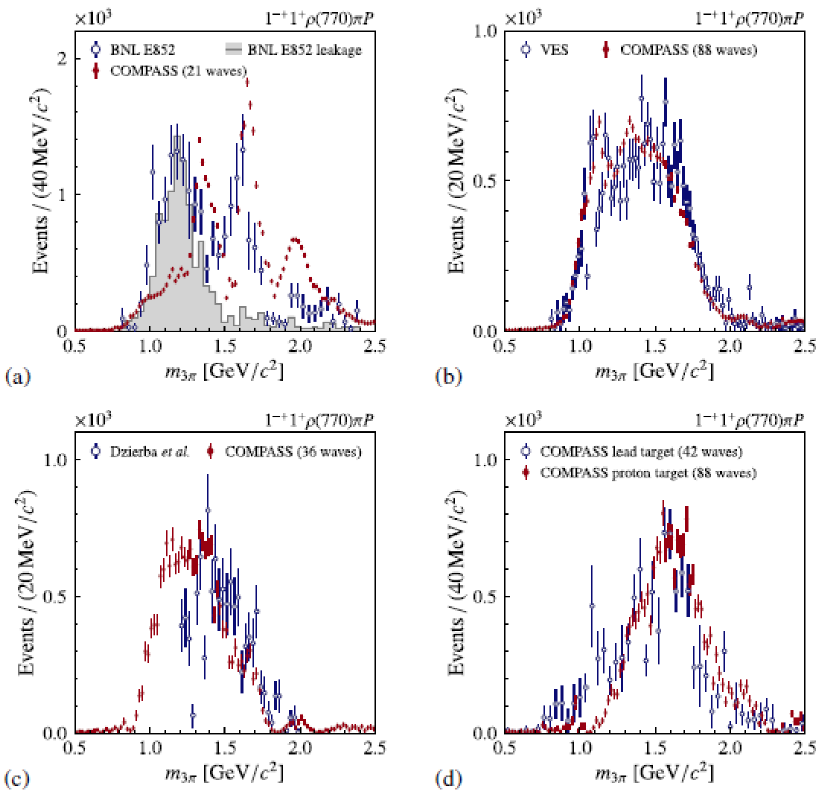

Figure 3: Comparison of intensity distributions of the 1^{-+} $(\rho\pi)$ wave as obtained by different experiments of diffractive dissociation of a pion beam into 3π in different t' ranges. The fits to the COMPASS data are displayed by the red points, while blue data points in (a) are from a fit of the BNL E852 data in the $0.05 < t' < 1.00$ (GeV/c)^2 range [25], in (b) from a fit of VES data in the range $0.03 < t' < 1.00$ (GeV/c)^2 [27], in (c) for a fit of BNL E852 data in the range $0.18 < t' < 0.23$ (GeV/c)^2 [26], and in (d) from a fit of COMPASS lead-target data in the range $0.1 < t' < 1.0$ (GeV/c)^2 [30]. Figure from Ref. [29].

of the spin-exotic 1^{-+} ($\rho\pi$) wave from a fit of the COMPASS data (red points) compared to the fits of E852 data ((a)[25] and (c)[26]), (b) of VES data [27] and (d) of COMPASS data on a Lead target [30], showing how the signal emerges from the data. The existence of the $\pi_1(1600)$ was further confirmed in COMPASS analysis of $\pi^- p \to \omega\pi^-\pi^0$ [33], focusing on the $b_1(1235)\pi$ decay, a favored mode for hybrids. The analysis also identified higher mass excitations with large quantum numbers, such as the $a_2'(1700)$, $a_3(1320)$, and $a_4(1970)$.

A recent search by the GluEX experiment for the $\pi_1(1600)$ in photoproduction reactions with polarized photons found no clear signal for π_1's [34]. Upper limits are set on the production and decay fractions, among which the most significant contribution is provided by $\eta'\pi$, consistently with previous findings.

A novel hybrid candidate: the η_1(1835). Recently, BESIII reported the first indications for an isoscalar hybrid signal decaying into $\eta'\eta$ with a statistical significance exceeding 19σ, in the $J/\psi \to \gamma\eta\eta'$ radiative decay [7]. This state, labelled as $\eta_1(1855)$, has a mass consistent with LQCD expectations and could be interpreted as the isoscalar partner of the $\pi_1(1600)$ in the 1^{-+} hybrid nonet. Alternative interpretations have been suggested, including the identification as tetraquark or a molecular state. The contribution of this state to the $\eta\eta'$ invariant mass can be seen in Fig. 1, as the purple component of the fit.

5. Conclusions

Over five decades of data collection and analysis have significantly advanced the knowledge of the light meson spectrum. However, unresolved challenges are still pending, including fully identifying multiplet components and distinguishing exotic states. Collaborative efforts across experiments and theoretical models are crucial to unlock the still hidden features of light mesons, hybrids, and glueballs.

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