Frascati Physics Series Vol. XLVI (2007), pp. 000-000
HADRON07: XII Int. Conf. on Hadron Spectroscopy – Frascati, October 8-13, 2007
Plenary Session

EXOTICS MESONS: STATUS AND FUTURE

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Abstract

The evidence for the existence of mesons with exotic quantum numbers and of hybrid candidates with non-exotic quantum numbers is critically reviewed, including candidates with hidden charm. Aims and methods of future searches for hybrid mesons are briefly discussed.

1 Introduction

The search for exotic mesons is at a turning point. The experiments at BNL, Protvino, and at LEAR which have reported evidence for exotic mesons have terminated data taking; data analysis is completed and the results are published since a few years. On the other hand, new experiments are ahead of us, COMPASS at CERN and BESIII in the immediate future, the Hall-D experiment at the upgraded Jlab facility and PANDA at GSI in the medium-range future. Hence it seems timely to review the status of exotic mesons to define the platform from which the new experiments are starting. It is custom to start from the assumption that glueballs and hybrids are firmly predicted by Quantum Chromo Dynamics, and experimental results have to concur with this prediction. Here, a different view will is adopted: the question is asked if a convincing argument can be made that the existence of exotic mesons, of hybrids and/or tetraquark mesons, can be deduced unambiguously from past experiments. The search for hybrids is part of the wider quest to understand the role of gluons in spectroscopy [1].

2 Exotic mesons

2.1 Flavor exotic mesons

Flavor exotic states have a flavor configuration with a minimum of four quarks like doubly charged states ($uu\bar{s}\bar{d}$) or tetraquark states with heavy flavor ($cs\bar{u}\bar{d}$). By definition, such states cannot mix with regular $q\bar{q}$ states. In light-quark meson spectroscopy, there is no accepted flavor exotic candidate (see also [2]). A $c\bar{c}u\bar{d}$ candidate will be discussed below.

2.2 Spin-parity exotics

Spin-parity exotic mesons have quantum numbers J^{PC} which are not allowed for fermion-antifermion systems, $J^{PC}_{exotics} = 0^{--},\ \ 0^{+-},\ \ 1^{-+},\ \ 2^{+-},\ \ 3^{-+}\cdots$. The quantum numbers 1^{-+} are part of the series 0^{-+}, 1^{-+}, 2^{-+}, $\cdots$; the isovector states are called π, π_1, π_2, π_3 $\cdots$. In this series, the J-odd states are exotic. A partial wave expansion of the $\pi\eta$ system, e.g., will have components with $L = 0, 1, 2, 3, \cdots$ leading to quantum numbers of the partial waves characterized by a_0, π_1, a_2, π_3, $\cdots$ where the π_1 and π_3 are exotic. Likewise, $\pi\rho$ in P-wave has 1^{-+} quantum numbers, $f_1\pi$ and $b_1\pi$ are $J^{PC} = 1^{-+}$ exotic when they are in S-wave. The corresponding isoscalar states are called η, η_1, η_2, $\cdots$.

Exotic mesons may be hybrid mesons ($q\bar{q}g$), multiquark states ($q\bar{q}q\bar{q}$...), multimeson states (M_1 M_2...) or, possibly, glueballs. Hybrids, tetraquarks (and glueballs) may also have quantum numbers of ordinary ($q\bar{q}$) mesons. In this case, they can mix. In this review, we comment on mesons with exotic mesons, and on hybrids. The lightest hybrid mesons should have a mass in the $1.7-2.2$ GeV/c^2 region even though smaller values are not ruled out. Tetraquark states should have about the same mass.

Most experimental information on spin-parity exotic mesons comes from diffractive or charge exchange scattering of a π^- beam off protons or nuclear targets at fixed beam momenta (in parentheses), from E852 at BNL (18 GeV/c; $\eta\pi^-$, $\eta'\pi^-$, $\rho\pi^-$, $f_1\pi^-$, $b_1\pi^-$, $\eta\pi^0$) and VES at Protvino (28, 37 GeV/c; $\eta\pi^-$, $\eta'\pi^-$, $\rho\pi^-$, $f_1\pi^-$, $b_1\pi^-$, $\eta'\pi^0$). The Crystal Barrel and Obelix collaborations at LEAR, CERN, have reported evidence for exotic mesons from $p\bar{p}$ annihilation at rest ($\eta\pi^\pm$, $\eta\pi^0$, $\rho\pi$, $b_1\pi$). References to earlier experiments can be found in [1].

Resonances, hybrids or tetraquark states, and meson-meson molecular systems can possibly be differentiated. A resonance with $J^{PC} = 1^{-+}$ can decay into $\pi\eta$, $f_1\pi$, $\rho\pi$, and $b_1\pi$. Of course, the fractions are unknown but there is no selection rule expected which may suppress one of these decay modes. If exotic waves originate from diffractive meson-meson scattering, the ρ may be excited to b_1 in $\rho\pi$ scattering but not ρ to the η; in $f_1\pi$ scattering, the f_1 could be de-excited to the η but not excited to the b_1. If diffractive meson-meson scattering were responsible for the exotic-wave amplitudes, we might expect different production characteristics for $\pi\eta$ and πf_1, and for $\rho\pi$ and $b_1\pi$.

2.3 The $\pi_1(1400)$

The data in Fig. 1 exhibit a dominant $a_2(1320)$ in the D_+ and a clear bump at $M \approx 1.4\,\mathrm{GeV/c^2}$ in the (exotic) P_+ partial wave. The E-852 collaboration [3)4)] finds that the data are consistent with a simple ansatz, assuming contributions from two resonances, one in each partial waves. The D_+ wave returns the parameters of $a_2(1320)$, for the P_+ partial wave, mass and width are determined to $M = 1370 \pm 16\ ^{+50}_{-30}$ MeV/c^2; $\Gamma = 385 \pm 40^{+\ 65}_{-105}$ MeV/c^2. A similar fit was used by VES yielding compatible results [5]. The VES collaboration tried fits without resonance but with a phenomenological background amplitude. The fit gave a significantly worse but not unacceptable χ^2. Both fits are shown in Fig. 1.

The Indiana group [6] used t channel exchange forces to construct a background amplitude which could mimic $\pi_1(1400)$. The $\pi\eta$ P_+-wave interactions very similar to $\pi\pi$ S-wave interactions were constructed. The latter are characterized by the σ pole; as a consequence, $\pi_1(1400)$ is considered as σ-type phenomenon in $\pi\eta$ P_+-wave interactions. In the words of the authors of [6],

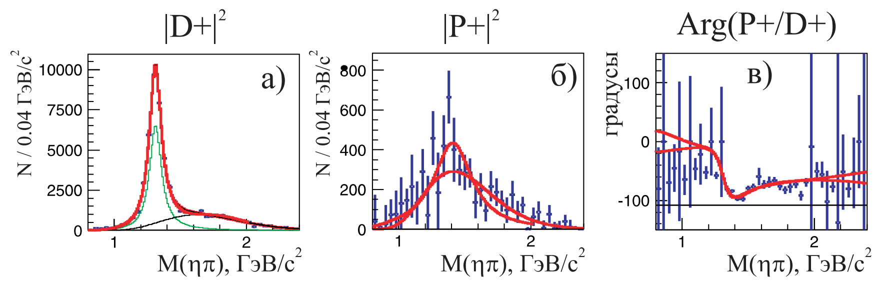

Figure 1: Results of partial-wave analysis of the $\eta\pi^-$ system: a) intensity of D_+ wave, b) intensity of P_+ wave, c) phase difference P_+/D_+ [5].

$\pi_1(1400)$ is 'not a QCD bound state' but rather generated dynamically by meson exchange forces.

Based on $SU(3)$ arguments, a P-wave resonance in the $\eta_8\pi$ channel must belong to a $SU(3)$ decuplet [7]. The decuplet-antidecuplet includes also $K^+\pi^+$ P-wave which shows practically no phase motion at all [8]. Very little phase motion should hence be expected for the $\pi\eta$ P_+-wave.

At BNL, the charge exchange reaction $\pi^-p \to \eta\pi^0 n$, $\eta \to \pi^+\pi^-\pi^0$ at 18 GeV/c was shown to be consistent with a resonant hypothesis for the P_+ wave, and a mass of $1257 \pm 20 \pm 25$ MeV/c^2, and a width of $354 \pm 64 \pm 60$ MeV/c^2 were deduced [9]. The authors left open the question if this object should be identified with $\pi_1(1400)$ or if it is a second state in this partial wave. The VES $\eta\pi^0$ spectrum is dominated by the $a_2^0(1320)$ meson; they did not find evidence for the neutral $\pi_1^0(1600)$.

The Crystal Barrel Collaboration confirmed the existence of the exotic $\pi\eta$ P_+-wave in $\bar{p}n \to \pi^-\pi^0\eta$ [10] and $\bar{p}p \to 2\pi^0\eta$ [11]. The Crystal Barrel [12] and Obelix [13] collaborations found a resonant contribution of the $J^{PC} = 1^{-+}$ wave in $(\rho\pi)$ in $p\bar{p}$ annihilation to four pions. However, the $\pi\eta$ P-wave is produced from spin triplet states of the $N\bar{N}$ system, the exotic $\rho\pi$ wave comes from spin singlet states. Hence these must be different objects, a $\pi_1(1400)$ and a $\tilde{\pi}_1(1400)$, plus a neutral $\pi_1(1260)$ if the latter is another separate resonance. In $p\bar{p}$ annihilation into $\pi\pi\eta$, triangle singularities due to final-state rescattering yield logarithmic divergent amplitudes. The inclusion of rescattering amplitudes was never attempted; it could possibly reduce the need for a true pole. In summary, there is evidence for the existence of a $\pi\eta$ resonance with exotic

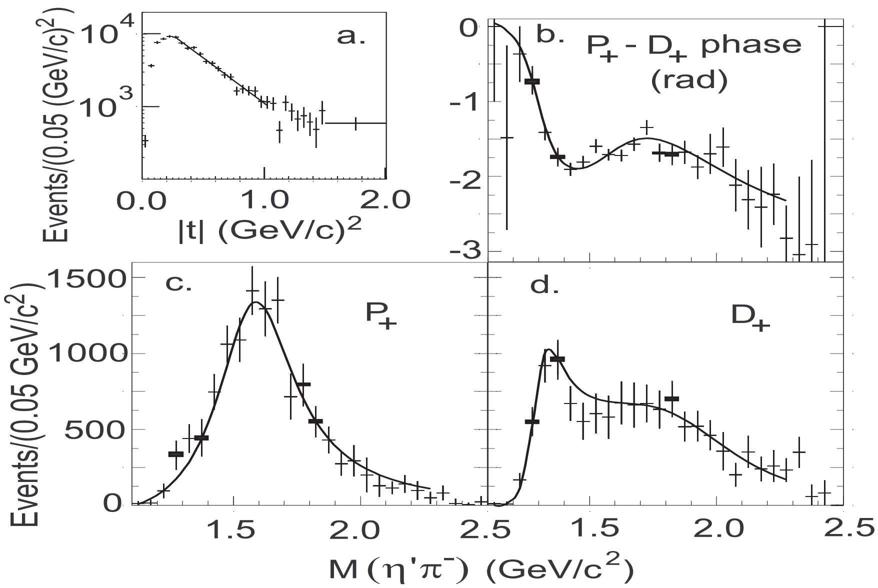

Figure 2: BNL data [4]: (a) The acceptance-corrected $|t|$ distribution fitted with the function $f(t) = ae^{b|t|}$ (solid line). (b), (c), (d) results of a mass-independent PWA and a mass-dependent fit (solid curve) for the P_+ and D_+ partial waves and their phase difference. (b) The $(P_+ - D_+)$ phase difference. (c) Intensity of the P_+ and (d) of the D_+ partial wave.

quantum numbers but there are severe inconsistencies in the overall picture associated with its existence.

2.4 The $\pi_1(1600)$ and $\pi_1(2000)$

Fig. 2 shows the $\eta'\pi^-$ system produced in a diffractive-like reaction at $p_{\pi_-} = 18\,\text{GeV/c}$. The data are from the E-852 collaboration [14]; VES using a beam at $p_{\pi_-} = 37\,\text{GeV/c}$ showed similar distributions [15]. The 1^{-+} wave exceeds in intensity the tensor wave and is readily fitted by a Breit-Wigner resonance at $M \approx 1600$ MeV/c^2 which is listed as $\pi_1(1600)$ in the Review of Particle Properties. The absence of $\pi_1^0(1600)$ can be understood by assuming that

- $\pi_1(1600)$ decouples from $\rho\pi$, or
- $\pi_1(1600)$ originates from meson-meson diffractive scattering

The wave $J^{PC} = 1^{-+}$ in the $\pi^+\pi^-\pi^-$ system was studied in diffractive-like reactions by the VES collaboration [16,17] and by the E-852 collaboration at $p_\pi = 18$ GeV/c [18,19] suggesting the existence of an exotic resonance in $\rho\pi$ which we call $\tilde{\pi}_1(1600)$. A new BNL data sample with 10-fold increased statistics was reported in [20], yielding negative evidence for a resonance in the P_+ wave. The $\tilde{\pi}_1(1600)$ must be different from the $\pi_1(1600)$ seen in $\eta'\pi$; firstly, because of the nearly vanishing coupling of $\pi_1(1600) \rightarrow \rho\pi$ and, secondly, for the different production modes: the $\pi_1(1600)$ is produced by natural parity exchange, the $\tilde{\pi}_1(1600)$ by both, natural and unnatural parity exchange in about equal portions.

The dominant wave in $f_1\pi$ is $J^{PC} = 1^{-+}$. It is produced via natural parity exchange; it resembles in production characteristics the $\eta'\pi$ exotic wave [17]. The E-852 collaboration fitted the PWA intensity distributions and phase differences with a superposition of Breit-Wigner resonances in all channels. In the exotic wave, two resonances are introduced at M=(1709±24±41), Γ=(403±80±115) MeV/c^2 and M=(2001±30±92), Γ=(333±52±49) MeV/c^2 [21].

Similar observations in $f_1(1285)\pi$ in the $\omega(\pi^+\pi^-\pi^0)\pi^-\pi^0$ channel studied by VES [17,22] and E-852 [23]. Three isobars $\omega\rho$, $b_1\pi$ and $\rho_3\pi$ were considered. The BNL collaboration interprets the data by resonances, two of them, called $\tilde{\pi}_1(1600)$ and $\tilde{\pi}_1(2000)$ here, are compatible in mass with the findings from $f_1(1285)\pi$ but are produced via natural and unnatural parity exchange. The VES data find consistency with a resonance interpretation but can describe the data without exotic resonances as well.

2.5 Conclusions on light-quark exotics

Partial waves with exotic spin-parity have been observed in several experiments. The data are consistent with the assumption that the exotic wave originates from diffractive meson-meson scattering. The interpretation of the observation as genuine resonances is controversial.

3 Non-exotic hybrid candidates

3.1 Light-quark hybrid candidates

Figure 3 shows the light quark mesons with known quantum numbers $I^G J^{PC}$ as a function of M^2. The ordering of states follows expectations from potential

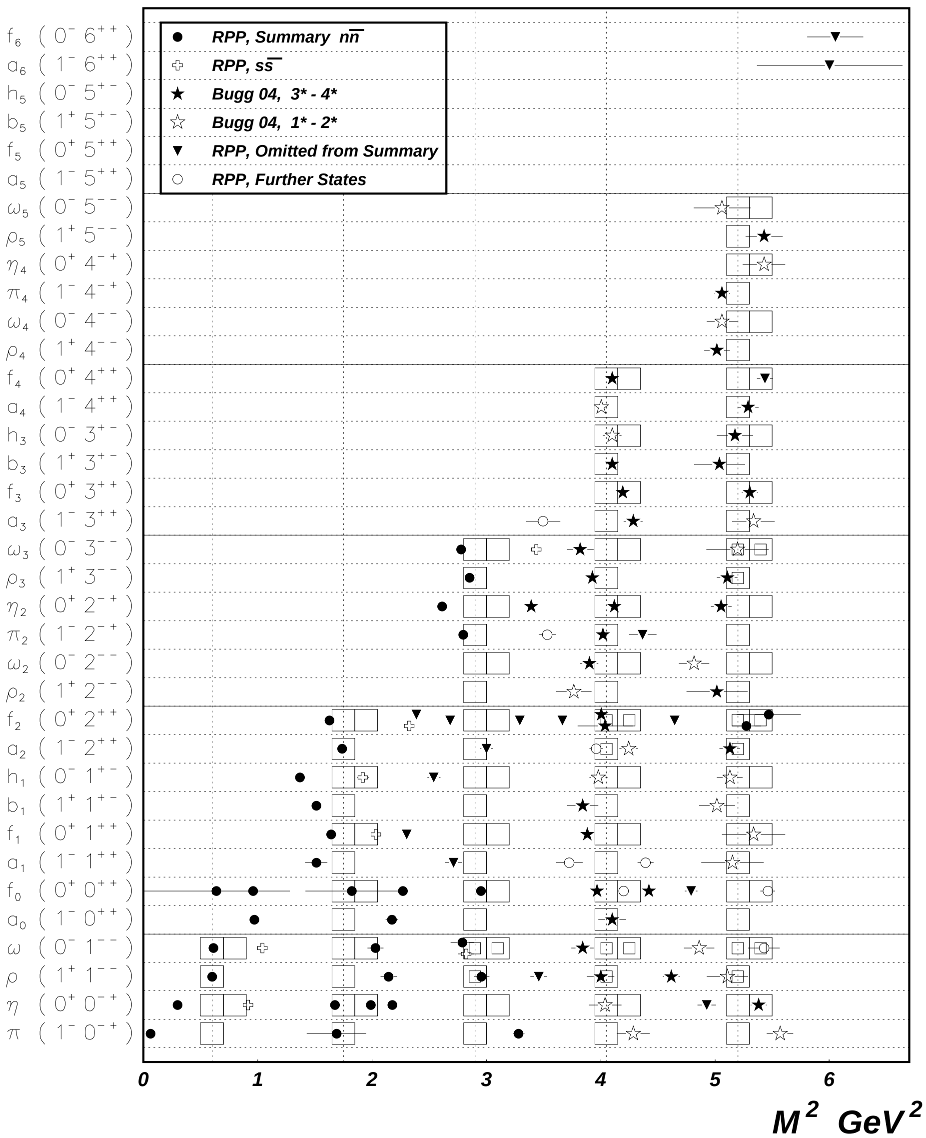

Figure 3: The pattern of light quark meson states.

models for $q\bar{q}$ mesons. The empty boxes indicate the position of states in a simplified model in which masses of mesons are proportional to $l+n$, where l is the orbital and n the radial quantum number. Mesons of zero isospin have two nearby boxes for $n\bar{n}$ and $s\bar{s}$ states or for $SU(3)$ singlet and octet states. Some boxes are doubled because two different states, with $J = l + 1, n$ and $J = l-1, n+2$, are expected. Nearly all observed mesons are compatible with a $q\bar{q}$ assignment, with two remarkable exceptions, $\pi_2(1870)$ and $\eta_2(1870)$ [24)–28)]. These two states are meaningful hybrid candidates. When scrutinizing these observation, we notice that comparatively narrow hybrids are predicted for the $J^{PC} = 2^{-+}$ wave which has important S-wave thresholds, $f_2(1270)\pi$ and $a_2(1320)\pi$. Narrow hybrids are also predicted for the $J^{PC} = 1^{++}$ wave. In this wave, there are no important S-wave thresholds, and no hybrid candidates, neither. Certainly, a good understanding of the threshold dynamics is required. High statistics data in several final states are mandatory to resolve this issue.

3.2 Is there restoration of chiral symmetry?

There is a degeneracy of the masses with positive and negative parities which has been interpreted as evidence for restoration of chiral symmetry in highly excited mesons [29)–31)]. A new QCD scale $\Lambda_{CSR} = 2.5\,\mathrm{GeV/c^2}$ is suggested at which chiral symmetry is restored [32) 33)].

The l, n degeneracy follows also from a model based on the dual superconductor mechanism of confinement [34)] and from a model guided by the correspondence of the dynamics of quarks in QCD and of strings in a five-dimensional Anti-de-Sitter space [35)]. Both approaches suggest

$$M_n^2(l) = 2\pi\sigma\left(l + n + \frac{1}{2}\right) .$$

which shows that the squared masses are linear in l and n, and degenerate in $n + l$. The string model and the conjectured restoration of chiral symmetry thus both lead to a $n + l$ degeneracy of excited states. The two models make however different predictions for ‘stretched’ states, for states with $J = l + s$. The string model predicts no parity partners for $a_2(1320)$–$f_2(1270)$, $\rho_3(1690)$–$\omega_3(1670)$, $a_4(2040)$–$f_4(2050)$, $\rho_5(2350)$–ω_5, $a_6(2450)$–$f_6(2510)$ while their existence should be expected if chiral symmetry restoration is at work. Experimentally, there are no chiral partner for any of these 10 states. Hence, at the first glance, data do not support the hypothesis of chiral symmetry restoration.

3.3 J/ψ excitations

With the discovery of the $h_c(1P)$ and $\eta_c(2S)$ resonances, an important milestone was reached: all charmonium states predicted by quark models below the $D\bar{D}$ threshold have been found, and no extra state. Above the $D\bar{D}$ threshold, several surprisingly narrow states were found called $X(3872)$, $X(3940)$, $Y(3940)$, and $Z(3930)$. In spite of some anomalous properties, these states can be assigned to $\chi_1(2P)$, $\eta_c(3S)$, $\chi_0(2P)$, and $\chi_2(2P)$. Reasons for this assignment are discussed in [1]. A particularly demanding state is the $Y(4260)$ which is discussed next.

3.4 The $Y(4260)$

The $Y(4260)$ was discovered by the BaBaR collaboration as an enhancement in the $\pi\pi J/\psi$ subsystem in the initial state radiation (ISR), in $e^+e^- \to \gamma_{\rm ISR} + J/\psi\pi\pi$ [36]. Its mass was determined to $4259 \pm 8 \pm 4$ MeV/c^2, the width to $88 \pm 23 \pm 5$ MeV/c^2, the spin-parity to $J^{PC} = 1^{--}$. The $Y(4260)$ resonance was searched for in the inclusive e^+e^- annihilation cross section [37]. In the $\sqrt{s} = 4.20 - 4.35\,\mathrm{GeV/c^2}$ region, the cross section exhibits a dip-bump-dip structure which makes it difficult to extract a reliable estimate for a possible $Y(4260)$ contribution. The apparent absence of $Y(4260)$ in this reaction has stimulated the interpretation that it could be a hybrid [38]–[40] or a tetraquark resonance [41]. The upper limit of $Y(4260)$ in the inclusive e^+e^- annihilation cross section depends however on the flexibility of the fit. If constructive and destructive interferences are allowed, the upper limit for $Y(4260)$ is less stringent and a scenario as suggested in Table 1 is not excluded.

At this conference, W.S. Hou reported observation of $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S)\pi^+\pi^-$ at $\sqrt{s}$ 10.87 GeV, near the peak of the $\Upsilon(10860)$. If these signals originate from the $\Upsilon(10860)$ resonance, the corresponding partial widths are much larger than expected and would suggest that $\Upsilon(10860)$ – and $Y(4260)$ as well – be a hybrid.

3.5 Is there a $\psi(2S)\pi^+$

A narrow $\psi'\pi^\pm$ resonance was observed by the Belle collaboration in B decays to $K\pi^+\psi'$, with a statistical evidence exceeding 7σ [42]. The resonance, called $Z^+(4430)$, has $4433 \pm 4 \pm 1\,\mathrm{MeV/c^2}$ mass and a width of $\Gamma = 44^{+17+30}_{-13-11}\,\mathrm{MeV/c^2}$.

Table 1: Charmonium states with $J^{PC} = 1^{--}$ in our interpretation. The partial widths are given in keV/c^2, the masses in MeV/c^2.

J/ψ	$\psi(3686)$	$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$Y(4260)$	$\psi(4415)$
	$2S$	$1D$	$3S$	$2D$	$4S$	$5S$
$\Gamma_{e^+e^-}$	2.48 ± 0.06	$0.242^{+0.027}_{-0.024}$	0.86 ± 0.07	0.83 ± 0.07	*0.72*	0.58 ± 0.07
$\Gamma_{\mathrm{J}/\psi\pi^+\pi^-}$	107 ± 5	44 ± 8	< 360	< 330	670 ± 240	-
$M_{\psi(nS)} - M_{J/\psi}$	589	674	943	1056	1163	1318
$M_{\Upsilon(nS)} - M_{\Upsilon}$	563		895		1119	

It is the first charged resonance with hidden charm; evidently, it can not belong to the charmonium family. It was interpreted as tetraquark radial excitation [43]. Rosner noticed that the $Z(4430)$ mass is at the $D^*\bar{D}_1(2420)$ threshold and proposed that the state is formed via the weak $b \to c\bar{c}s$ transition, creation of a light-quark pair, and rescattering of the final-state hadrons [44]. Hence at present, there not yet the need for an interpretation beyond the standard quark model using $q\bar{q}$ only.

4 Conclusions and outlook

In the view presented here, there is not yet a convincing answer to the question if hybrid mesons exist. When data are analyzed assuming the existence of hybrids, evidence is observed in several places. If this conjecture is examined with scrutiny, the evidence for hybrids fades away. There are, however, specific predictions for the outcome of future experiments. If exotic partial waves are due to diffractive meson-meson scattering, the π_1 partial wave should not be produced in the charge exchange reaction $\pi^-p \to n\pi_1^0(1400)$. The $\pi_1^0(1400)$ observed in [9] is in conflict with this conjecture, but in conflict with VES data, too. Likewise, there should be no production of $\pi_1^0(1600)$ or $\pi_1^0(2000)$. In central production, a large contribution to the cross section will come from Regge-Pomeron fusion which should be a good place to search for hybrids. With two detected protons, no charged Reggeon is exchanged (with Reggeon exchange = Regge or Pomeron exchange); diffractive meson-meson scattering leads to neutral final states and no hybrids with exotic quantum numbers should be found. At Jlab, the initial state γp is charged, and partial waves with exotic quantum numbers due to diffractive meson-meson scattering should be observed in their charged state only.

The new BELLE results on $\Upsilon(10860)$ decays reported by W.S. Hou are very suggestive. If the signals are due to an extremely large $\Upsilon(10860) \to \Upsilon(nS)\pi^+\pi^-$ decay mode, hybrids with hidden beauty seem to be a natural consequence. Similarly, the $Y(4260)$ might be of hybrid nature as well. Hence there is room left; Panda at GSI (or, earlier, BELLE) will have to give us the final answer. The existence or not of glueballs – which were not discussed here – is a question which should find its answer from BESIII.

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