Selected topics from Hadron 99—experimental summary

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I gave a summary talk on the experimental part of Hadron 99. However, this writeup is not a summary in its normal sense but rather a collection of a few topics *not fully covered* at the Conference.

1. INTRODUCTION

The focus of hadron spectroscopy has now shifted from the notion that a baryon is a three-quark system and a meson is a bound state of a quark and an antiquark. It has taken a very long time for the physics community to come to this conclusion, primarily because more complicated systems such as $(qqq+q\bar{q})$ or $(qqq+\text{gluon})$ are indistinguishable from a simple qqq state from their quantum numbers alone.

The situation improves in the case of mesons, since they can come in exotic J^{PC} combinations which lie outside of the realm of $q\bar{q}$. However, for a reason not entirely clear (at least to me), the exotic mesons are produced with cross sections at levels substantially lower than those of ordinary mesons. It may not be an overstatement, if one simply states the quark model was born in 60s and 70s, precisely because of the small production cross-sections of the exotic mesons.

Be that as it may, let me first start out by stating the well known result, at least for the readers of this proceedings. Let L and S be the orbital angular momentum and the total intrinsic spin of a $q\bar{q}$ system. Let s_1 and s_2 be the spins of q and $\bar{q}$, i.e. $s_1 = s_2 = 1/2$. Then, one finds readily

$$\begin{aligned} &\vec{J} = \vec{L} + \vec{S} \qquad \text{and} \qquad \vec{S} = \vec{s}_1 + \vec{s}_2 \\ &P = (-)^{L+1} \\ &C = (-)^{L+S} \end{aligned} \tag{1}$$

and the wave function in a state of J, L and S is given by

$$\Psi^J_{LS}(\Omega, M) = \sum_{\substack{m_1\, m_2 \\ m_s\, m}} (s_1 m_1\, s_2 m_2 | S m_s)\, (S m_s\, L m | J M)\, Y^L_m(\Omega) |s_1 m_1\rangle\, |s_2 m_2\rangle \tag{2}$$

where M is the z-component of spin J in a coordinate system given in the rest frame of $q\bar{q}$ and $\Omega = (\theta, \phi)$ specifies the direction of the breakup momentum in this rest frame. The wave function Ψ comes with indices and arguments: the rotational invariants are

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given as indices; the quantities that undergo transformation under a rotation are given as arguments. In addition, we use the notation $(j_1m_1\,j_2m_2|jm)$ to denote the usual Clebsch-Gordan coefficients. The formula given here is of course elementary; I will show later how this can be generalized to include a gluonic meson $q\bar{q}+$ gluon.

Given a set of relations (1), one finds that the following states are not allowed for a $q\bar{q}$ system, i.e

$$J^{PC}=0^{--},\quad 0^{+-},\quad 1^{-+},\quad 2^{+-},\quad 3^{-+},\ldots \tag{3}$$

In this note the exotic mesons listed above are given the notations

$I^G(J^{PC})$	Exotics	$I^G(J^{PC})$	Exotics
$1^+(0^{--})$	ρ_0	$0^-(0^{--})$	ω_0
$1^+(0^{+-})$	b_0	$0^-(0^{+-})$	h_0
$1^-(1^{-+})$	π_1	$0^+(1^{-+})$	η_1
$1^+(2^{+-})$	b_2	$0^-(2^{+-})$	h_2
$1^-(3^{-+})$	π_3	$0^+(3^{-+})$	η_3

In a flux-tube model pioneered by Isgur and Paton[1], an excited gluon in $q\bar{q}+$ gluon acquires a nonzero angular momentum component Λ along the $q\bar{q}$ axis. As a result, the C eigenvalue undergoes a transformation, so that one has, instead of (1),

$$\begin{aligned}&\vec{J}=\vec{L}+\vec{S}\qquad\text{and}\qquad\vec{S}=\vec{s}_1+\vec{s}_2\\&P=(-)^{L+1}\\&C=(-)^{L+S+\Lambda}\end{aligned}\tag{4}$$

It is this change in the eigenvalue that allows for existence of a J^{PC}-exotic gluonic hybrid. The corresponding transformation in the wave function is, suppressing the description for vibrational modes of a gluonic string[1],

$$\Psi^{J\Lambda}_{LS}(\Omega,M)=\sum_{\substack{m_1\,m_2\\m_s\,m}}(s_1m_1\,s_2m_2|Sm_s)\,(Sm_s\,Lm|JM)\,D^{L\,*}_{m\Lambda}(\phi,\theta,0)|s_1m_1\rangle\,|s_2m_2\rangle \tag{5}$$

By definition, the quantum number Λ is a rotationally invariant quantity, as it is simply a 'body-fixed' z-component of the orbital angular momentum, i.e. it is the helicity of the excited flux along the $q\bar{q}$ axis. So in this model, a gluonic hybrid depends on four quantum numbers, J, P, C and Λ. The lowest-order gluonic hybrid occurs evidently for $\Lambda=\pm1$, for which both the isovector and the isoscalar states are predicted to have masses as follows:

Constituents	Exotics	Mass (GeV)
$n\bar{n}+$ gluon	b_0, h_0, π_1, η_1, b_2, h_2	~ 1.9
$c\bar{c}+$ gluon	b_{c0}, h_{c0}, π_{c1}, η_{c1}, b_{c2}, h_{c2}	~ 4.3
$b\bar{b}+$ gluon	b_{b0}, h_{b0}, π_{b1}, η_{b1}, b_{b2}, h_{b2}	~ 10.8

So far we have found candidates for two π_1's at masses 1.4 and 1.6 GeV, and a review will be given in Section 3.

A short comment is in order on notations for the partial waves commonly encountered in the literature. For a pure wave coupling to a system of two pseudoscalars, it is sufficient for one to specify the orbital angular momentum (L), its z-component (M) and the reflectivity quantum number (ϵ). The latter is usually chosen such that it coincides with the naturality of the exchanged particles (Reggeons) in πN or $K N$ production processes The spin J is simply L and the parity P is given by $(-)^L$. The usual notation is $|J^{PC}M^\epsilon\rangle$ or $|\epsilon LM\rangle = L_{M\epsilon}$. Here C is the charge conjugation. If $M = 0$, there is only one ϵ, i.e. $\epsilon = -1$. In addition, one makes the usual assumption that the partial waves for $M > 1$ are negligible, so that M can be dropped from the subscript above. One then merely deals with the following three partial waves, without ambiguity: L_0, L_+ and L_-. One uses the notations S, P, D, F for $L = 0$, 1, 2, 3, etc.

It is much more complicated for one to specify a state, if it decays into three or more particles. Consider, as an example, a state which decays to an isobar and a pseudoscalar and the isobar which in turn decays into two or more pseudoscalars. Then, the state may be denoted by $|J^{PC}(\text{isobar})LM^\epsilon\rangle$ or $|J^{PC}LM^\epsilon(\text{isobar})\rangle$, the latter being merely a different way of writing down the former. The L above is the orbital angular momentum between the isobar and the pseudoscalar. If one makes the simplifying assumption that only the lowest allowed L is used in the analysis, then L may be dropped from the label above, for brevity.

2. GLUEBALLS

Glueballs, quarkless mesons consisting entirely of two or more gluons, are predicted to exist in QCD because of the self-coupling nature of gluons. The glueballs with $J^{PC} = 0^{++}$ and $J^{PC} = 2^{++}$ have been searched for a number of years and there exist several candidates. However, it would be fair to state that there are no unequivocal candidates, mainly because of the fact that they mix with the quarkonia of the same quantum numbers. In the flux-tube model of Isgur and Paton[1], some low-lying pure glue states are predicted at

Constituents	J^{PC}	Names	Mass (GeV)
Pure Glue	0^{++}	f_0	1.52
Pure Glue	1^{+-}	h_1	2.25
Pure Glue	$0^{\pm\pm}$, $0^{\pm\mp}$	f_0, ω_0, h_0, η	2.79
Pure Glue	$2^{\pm\pm}$, $2^{\pm\mp}$	f_2, ω_2, h_2, η_2	2.84
Pure Glue	1^{+-}	h_1	3.25
Pure Glue	3^{+-}	h_3	3.35

Of the states given above, one sees that ω_0, h_0 and h_2 are J^{PC} exotic and hence they are immune from the $q\bar{q}$ mixing. But their masses are predicted to be high, around 2.8 GeV.

For a scalar glueball candidate, the $f_0(1500)$ stands out as the most promising, see the presentations by M. Doser, K. Seth and D. Bugg at this conference. However, there exists an alternative interpretation put forward by P. Minkowski and W. Ochs[2]. They argue that the scalars $f_0(980)$ and $f_0(1500)$ should be classified as members of the 0^{++} nonet, with a mixing rather similar to that of the pseudoscalar nonet. In this context, one may recall the argument of Klempt *et al.*[3], who have conjectured that the $f_0(1500)$ is not the scalar glueball but belongs to a ground-state scalar $SU(3)$ octet, a counterpart of the η for the pseudoscalar sector. K. Seth asserted in this conference that the newly identified $f_0(1710)$ could be the closest relative of the pure scalar glueball. D. Bugg speculated in this conference that the $f_0(2105)$ observed in the Crystal Barrel could be identified as a radial excitation of the putative scalar glueball $f_0(1500)$.

The tensor glueball candidates are likewise in a state of flux. There exist two outstanding candidates for the tensor glueball, the $\xi(2230)$[4] and the three $\phi\phi$ states of Lindenbaum et al.[5]. K. Seth pointed out in this conference that the measured branching ratio $\xi(2230) \to p\bar{p}$ is incompatible with a recent search for the state in the in-flight $p\bar{p}$ annihilation data of the Crystal Barrel collaboration. The Beijing Spectrometer Group has just embarked on an ambitious program to collect some 50×10^6 of J/ψ decays. A definitive answer is expected soon from this data set not only on the question of the quantum numbers of the $\xi(2230)$ but also on its nature.

3. $J^{PC} = 1^{-+}$ EXOTIC MESONS

The subject of exotic mesons has received considerable attention from theorists over the years, who employed a variety of techniques to investigate the nature of these mesons. Hybrid meson spectra which contain valence gluons have been studied using the bag model[6], the constituent gluon model[7], the QCD sum rule calculations[8], the flux tube model[9] and the lattice gauge calculations[10]. A multiquark systems with exotic quantum numbers have been investigated in the diquark cluster model[11].

The $\pi_1(1400)$ state was originally reported by the GAMS group[12], seen in the reaction $\pi^- p \to \pi^0 \eta\, n$ at 100 GeV/c. The forward-backward asymmetry, obtained from the cosine of the Jackson angle in the $\pi^0\eta$ system, shows a substantial non-zero swing in the $a_2(1320)$ region. This can happen only if there is a strong interference effect between even-odd waves in the $a_2(1320)$ region. After a partial-wave analysis of the $\pi^0\eta$ system, the GAMS group reported that both the D_0 and the P_0 waves are resonant in the vicinity of the $a_2(1320)$. Because the $a_2(1320)$ and the $\pi_1(1400)$ are seen to be produced via unnatural-parity exchange, it could be concluded that the $b_1(1235)$ exchange is the dominant one. This also indicates that the $\pi_1(1400)$ should decay into the $b_1(1235)\pi$ final state. It should be noted, however, that the original analysis was brought into question[13].

The VES experiment[14] studied the reaction $\pi^- N \to \pi^- \eta\, N$ at 37 GeV/c. The $\pi_1(1400)$ signal is present but small with large errors in the $\pi\eta$ channel. Perhaps because of this, they did not claim the exotic meson in the paper. The E179 collaboration[15] at KEK studied the $\pi^-\eta$ system in the reaction $\pi^- p \to \pi^- \eta\, p$ at 6.3 GeV/c. Both D_+ and P_+ waves peak at the $a_2(1320)$ mass region; therefore, ρ- or f_2-exchange processes seem to play a central role in the production of these waves. The phase variation between these waves seems constant throughout the $a_2(1320)$ mass region, and they conclude that both are resonant.

More recently, there appeared two additional pieces of evidence regarding the $\pi_1(1400)$ meson. The BNL-E852 Collaboration[16] is in the process of carrying out a systematic study of exotic mesons in $\pi^- p$ interactions at 18 GeV/c. They have studied the reactions $\pi^- p \to \eta\pi^- p$ and $\pi^- p \to \eta\pi^0 n$ at 18 GeV/c, where the η decay is observed in the channels $\gamma\gamma$ or $\pi^+\pi^-\pi^0$. The results of their analysis on the '94 data, based on 45,000 events fitting the reaction $\pi^- p \rightarrow \eta\pi^- p$ with $\eta \rightarrow \gamma\gamma$, have already been published[17]. The $\eta\pi$ mass spectrum shows a strong $a_2(1320)$ signal and the t distribution indicates a typical peripheral production. Their key observation is that the relative phase motion of the P_+ wave with respect to the D_+ wave [the $a_2(1320)$ meson] requires presence of a resonant P wave, i.e. a $J^{PC} = 1^{-+}$ exotic state. The VES group also studied the $\pi\eta$ channel, but as already pointed out in the previous paragraph, they did not claim a 1^{-+} state in the 1.3–1.4 GeV region. However, remarkably, their phase motion is very similar to that of the BNL data.

The results of a very recent analysis of the '95 data from the BNL-E852 experiment have been reported, with the statistics comparable to their '94 data. Their new results are quite consistent with their published results[18]. The Crystal Barrel Collaboration studied $\bar{p}N$ annihilations at rest, specifically the reactions $\bar{p}n \rightarrow \pi^-\pi^0\eta$ and $\bar{p}p \rightarrow \pi^0\pi^0\eta$. They report[19,20] that the standard isobar decays, $\epsilon \rightarrow \pi\pi$, $\rho \rightarrow \pi\pi$ and $a_2(1320) \rightarrow \eta\pi$ are not sufficient to describe the data; they need, in addition, presence of the $\pi_1(1400)$ meson. The masses and widths of $\pi_1(1400)$ meson in the decay channel $\pi\eta$ are summarized in Table I.

Table I: Parameters for $\pi_1(1400) \rightarrow \eta\pi$

Expt.	Mass(MeV)	Width(MeV)
KEK	1323.1 ± 4.6	143.2 ± 12.5
BNL('94)	$1370 \pm 16 {}^{+50}_{-30}$	$385 \pm 40 {}^{+65}_{-105}$
BNL('95)	$1359 {}^{+16}_{-14} {}^{+10}_{-24}$	$314 {}^{+31}_{-29} {}^{+9}_{-66}$
CB($\bar{p}n$)	$1400 \pm 20 \pm 20$	$310 \pm 50 {}^{+50}_{-30}$
CB($\bar{p}p$)	1360 ± 25	220 ± 90

A second $J^{PC} = 1^{-+}$ exotic meson at mass 1.6 GeV was reported decaying into $\eta'\pi$[14] and $\rho\pi$[21] channels, but no parameters were given on its mass and width. BNL-E852 Collaboration carried out a partial-wave analysis of the 3π system in the reaction $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$ at 18 GeV/c. They find a $J^{PC} = 1^{-+}$ state at 1.6 GeV, the $\pi_1(1600)$ meson, with its phase motion characteristic of a resonance with respect to the $J^{PC} = 0^{-+}$, 1^{++}, 2^{++} and 2^{-+} waves[22].

Because of the questions raised by A. Zaitsev[23], it is necessary that some details should be given of the analysis by BNL-E852. For the purpose, three different fits are shown in Fig. 1: the first fit is as published in the Physical Review Letters[22], i.e. the analysis has been done on a set of 21 waves with rank 1; the second fit is same as the first but with rank 2; and the third fit involves a set of 42 waves but with rank 1. The intensities of the exotic wave, $1^{-+}[\rho(770)]P1^+$, $1^{-+}[\rho(770)]P0^-$ and $1^{-+}[\rho(770)]P1^-$, for the first fit are given in Figs. 1a, b and c. The same for the second and the third fits are shown in Figs. 1d, e and f, and Figs. 1g, h and i, respectively. In addition, the phase motion of the exotic wave in a rank-1 fit against several other partial waves were given in the publication and amplified here in Fig. 2, and the same for rank-2 fit are given in Fig. 3.

In the BNL data, there is very little difference between rank-1 and rank-2 fits in the amount, shape and phase of the exotic wave, but there is a considerable difference between fits with different numbers of partial waves. It is for this reason that the collaboration has quoted a large systematic error, especially for the upper limit on the width. The phase motions of the exotic wave against a number of major waves in the neighborhood of the 1.6 GeV—for the rank-1—fit are especially striking; this gives an additional proof that the BNL-E852 data are largely of rank-1 type, because a physical process with rank 2 is unlikely to exhibit strong interference effect with all the waves in the problem owing to the possibility of arbitrary degree of coherence among difference waves. The main uncertainty in the analysis is related primarily to the number of partial waves, which is unknown. The philosophy behind the E852 analysis has been that one limits the number of waves to a minimum consistent with the goodness of fit to the data.

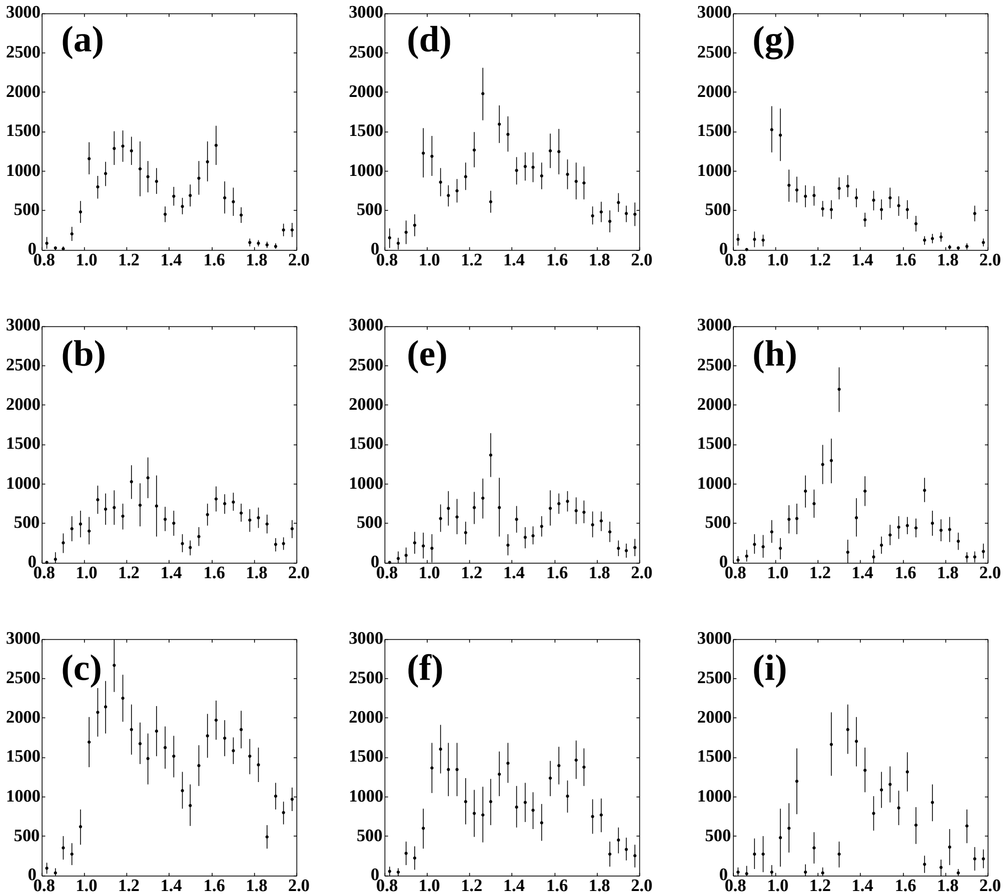

Figure 1. (a,b,c) The intensities of the exotic wave, $1^{-+}[\rho(770)]P1^{+}$, $1^{-+}[\rho(770)]P0^{-}$ and $1^{-+}[\rho(770)]P1^{-}$, for a fit with 21 waves and rank 1. (d,e,f) and (g,h,i) correspond to the fit with 21 waves and rank 2, and that with 42 waves and rank 1, respectively.

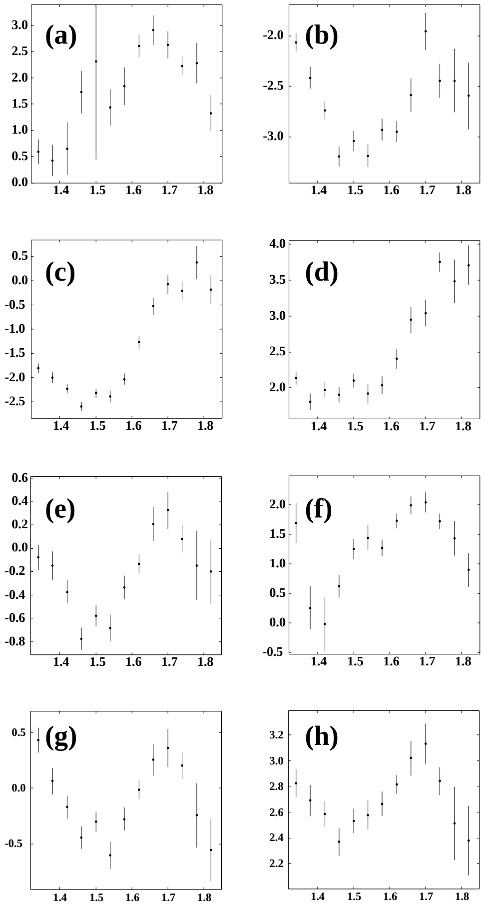

Figure 2. Results of a rank-1 fit: Phase difference (in radians) between the $1^{-+}[\rho(770)]P1^{+}$ wave and (a) the $0^{-+}[f_0(980)]S0^{+}$ wave, (b) the $2^{++}[\rho(770)]D1^{+}$ wave, (c) the $1^{++}[\rho(770)]S0^{+}$ wave, (d) the $1^{++}[\rho(770)]S1^{+}$ wave, (e) the $2^{-+}[\rho(770)]P0^{+}$ wave, (f) the $2^{-+}[f_2(1270)]D0^{+}$ wave, (g) the $0^{-+}[f_0(400-1200)]S0^{+}$ wave, and (h) the $2^{-+}[f_2(1270)]S0^{+}$ wave.

The BNL-E852 Collaboration studied, in addition, the $\eta'\pi^-$ system, and a preliminary result has been presented[18], which shows a prominent 1^{-+} wave characteristic of a resonance. At this conference, A. Zaitsev[23] presented the results of a coupled-channel analysis of the $\pi_1(1600)$ meson in the channels $\rho\pi$, $\eta'\pi$ and $b_1(1235)\pi$. Their results are consistent with the BNL results, as seen in Table II.

A. Zaitsev[23] quotes the following branching ratio

$$b_1\pi \; : \; \eta'\pi \; : \; \rho\pi \; = \; 1.0 \; : \; 1.0 \pm 0.3 \; : \; 1.5 \pm 0.5 \tag{6}$$

for the exotic state $\pi_1(1600)$. It is clear that further work is necessary for a better understanding of the branching ratios, but the $\rho\pi$ decay mode seems to have so far the largest branching ratio. One needs to search for other decay modes as well; in particular, one should look for $\eta\pi$ (or the upper bound), $f_1(1285)\pi$, $K_1(1400)\bar{K}$ and $K_1(1270)\bar{K}$.

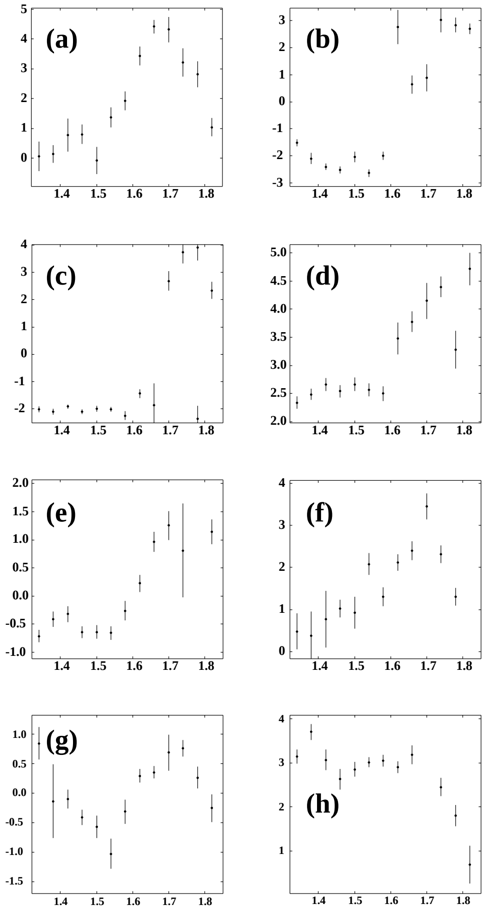

Figure 3. Results of a rank-2 fit: Phase difference (in radians) between the $1^{-+}[\rho(770)]P1^{+}$ wave and (a) the $0^{-+}[f_0(980)]S0^{+}$ wave, (b) the $2^{++}[\rho(770)]D1^{+}$ wave, (c) the $1^{++}[\rho(770)]S0^{+}$ wave, (d) the $1^{++}[\rho(770)]S1^{+}$ wave, (e) the $2^{-+}[\rho(770)]P0^{+}$ wave, (f) the $2^{-+}[f_2(1270)]D0^{+}$ wave, (g) the $0^{-+}[f_0(400\text{–}1200)]S0^{+}$ wave, and (h) the $2^{-+}[f_2(1270)]S0^{+}$ wave.

Table II: Parameters for $\pi_1(1600)$

Expt.	Mass(MeV)	Width(MeV)	Decay
BNL	$1593 \pm 8 \, {}^{+\,20}_{-\,47}$	$168 \pm 20 \, {}^{+\,150}_{-\,12}$	$\rho\pi$
BNL	1596 ± 8	387 ± 23	$\eta'\pi$
VES	1560 ± 6	340 ± 5	$b_1\pi$
			$\eta'\pi$
			$\rho\pi$

4. SURVEY OF RECENT AND FUTURE FACILITIES

It has become a tradition that a survey of the future possibilities on hadron spectroscopy is given at this series of the Conference. Although a session devoted to this topic was absent in the Beijing Conference, I thought that it might prove useful to cover such a topic in the Proceedings, so as to give the readers a clear, up-to-date view of the future of hadron spectroscopy.

The subject matter, by its very nature, does not change much in two or three years. For this reason, the reader interested in this topic is urged to consult K. Seth's writeup in the Hadron 97 Proceedings[24]—which gives a nice summary of the situation as of the fall 1997. I will attempt to summarize here the current status of recent and future facilities, which necessarily overlaps Seth's work but with emphasis on recent developments.

Tables III(a–d) show the summary in a compact form. The order of the listed facilities has been set with the rule that one starts out with the Beijing accelerator and goes west around the world. The reader will note that the established facilities, such as the BNL AGS, CERN LEAR, Elsa/Bonn, COSY/Jülich and CELSIUS/Uppsala, CERN LEP detectors, as well as the fixed-target and/or gas-jet experiments at KEK, IHEP/Protvino and Fermilab, are not covered. Instead, the tables cover recent and future facilities of interest, with a single exception of the KAON FACTORY which has been included for the purpose of comparison.

I have drawn from many sources to make the tables. In addition to the writeup by K. Seth[24], I consulted the Review of Particle Physics[25], as well as the talks given at this conference by R. Ehrlich, S. Giovannella, T. Liu, H. White and Z. Zhao. I have also consulted people who were not at the conference—I must cite, in particular, H. Koch of Bochum, S. Nagamiya of KEK and A. Brandt of U. of Texas for the information they have provided me.

It should be pointed out that the future of hadron spectroscopy at BNL AGS is uncertain. However, at BNL, the Crystal Ball Collaboration[26] aims to pursue baryon resonances and rare η decays, with the Crystal Ball Detector exposed to π^-, K^- and $\bar{p}$ beams up to 2.5 GeV/c at the low-energy separated beam line at the AGS. It is hoped this venture succeeds as the collaboration proceeds with their plans.

If light-quark hybrids ($n\bar{n}$ + gluon and $n\bar{n} + n\bar{n}$) exist, then the next obvious step one must pursue are the experiments designed to uncover the J^{PC}-exotic mesons containing $s\bar{s}$ pairs—and this requires a modern, intense RF-separated K^- beams with momenta in the range between 6 and 30 GeV/c. Such beam lines exist at IHEP/Protvino and Fermilab Main Injector. However, I am not aware of any proposals to carry out this type of search at these facilities. Such a beamline could be built at the AGS, but—regrettably—there are at present no such plans. A host of separated K^- beam lines was planned at the KAON FACTORY but the project is moribund at the moment. It is hoped that this plan could be realized elsewhere in the near future. To the best of my knowledge, there are no current plans, at both JHF/Japan and GSI/Darmstadt, to build medium- to high-momentum separated K^- beam lines.

Table IIIa. Recent and Future Facilities for Hadron Spectroscopy[a]

	τ-CHARM FACTORY Beijing	τ-CHARM FACTORY Novosibirsk	RF-Separated K^- Beam IHEP/Protvino	COMPASS CERN Geneva
Accelerator	e^+e^- Collider	e^+e^- Collider	Proton Synchrotron	Proton Synchrotron
Status/Date	?	?	2000	2001
Max Beam (GeV)	2.5×2.5	2.1×2.1	50	450
$\mathcal{L}\,(10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$	20	100		
Flux/spill			10^7	4×10^7
Detector	Upgraded BES			
Physics Process	e^+e^- s-channel	e^+e^- s-channel	Forward Production in K^-p Interactions	Double-Pomeron Fusion
Physics Interest	J/ψ decays ψ' decays ψ'' decays	J/ψ decays ψ' decays ψ'' decays	$s\bar{s}$ hybrids glueballs	$n\bar{n}$ hybrids[b] $c\bar{c}$ hybrids glueballs

[a] This list does not include established facilities.
[b] $n = \{u, d\}$.

Table IIIb. Recent and Future Facilities for Hadron Spectroscopy[a]

	LHC CERN Geneva	DAΦNE Frascati	GLUE/CHARM FACTORY GSI/Darmstadt	Hall-D JLab Newport
Accelerator	pp Collider	e^+e^- Collider	Cooled $\bar{p}$ Storage Ring	Tagged Photon
Status/Date	2005?	1999	2005?	2003?
Beam (GeV)	7,000	0.75×0.75	$\bar{p}$ at 14	8–10
$\mathcal{L}\,(10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$	100	1.35–5.4	1–2	
Flux/s				10^8
Detector	ALICE	KLOE		
Physics Process	Double-Pomeron Fusion	e^+e^- s-channel	$\bar{p}p$ s-channel	Forward Production in γp Interactions
Physics Interest	glueballs $n\bar{n}$ hybrids[b] $c\bar{c}$ hybrids $b\bar{b}$ hybrids	ϕ decays CP violation	$c\bar{c}$ states $c\bar{c}$ hybrids glueballs	$n\bar{n}$ hybrids[b]

[a] This list does not include established facilities.
[b] $n = \{u, d\}$.

Table IIIc. Recent and Future Facilities for Hadron Spectroscopy[a]

	RHIC BNL Upton	RF-Separated K^- Beam Fermilab	TEVATRON Fermilab Batavia	CESR Cornell
Accelerator	pp Collider	Main Injector	$\bar{p}p$ Collider	e^+e^- Collider
Status/Date	1999	2002	2001	1999
Max Beam (GeV)	30–250	25	1000	6×6
$\mathcal{L}\,(10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$	0.1		2.1	8.5
Flux/spill		10^8		
Detector	STAR		Upgraded D0[b]	CLEO-III
Physics Process	Double-Pomeron Fusion	Forward Production in K^-p Interactions	Double-Pomeron Fusion	e^+e^- s-channel
Physics Interest	glueballs $c\bar{c}$ hybrids	glueballs $s\bar{s}$ hybrids	$c\bar{c}$ hybrids $b\bar{b}$ hybrids	$c\bar{c}$ hybrids $b\bar{b}$ hybrids

[a] This list does not include established facilities.

[b] The upgraded D0 includes a central charged-particle detector system in a magnetic field and a set of forward proton detectors on both sides.

Table IIId. Recent and Future Facilities for Hadron Spectroscopy[a]

	SLAC Stanford	RF-Separated K^- Beam Vancouver	KEK Tsukuba	JHF[b] Japan
Accelerator	e^+e^- Collider	KAON FACTORY	e^+e^- Collider	Proton Synchrotron
Status/Date	1999	terminated	1999	2004?
Max Beam (GeV)	3×9	21 GeV	3.5×8	50
$\mathcal{L}\,(10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$	20		20	
Flux/spill		0.75×10^6/s		4×10^{14}
Detector	BaBar		Belle	
Physics Process	e^+e^- s-channel	Forward Production in K^-p Interactions	e^+e^- s-channel	Forward Production in K^-p Interactions
Physics Interest	$c\bar{c}$ hybrids $b\bar{b}$ hybrids	$s\bar{s}$ hybrids glueballs	$c\bar{c}$ hybrids $b\bar{b}$ hybrids	glueballs $s\bar{s}$ hybrids

[a] This list does not include established facilities.

[b] Japan Hadron Facility (JHF) is to be run by Japan Atomic Energy Research Institute (JAERI), located north of Tokyo.

5. CONCLUDING REMARKS

Finally, it may be appropriate to comment on possible existence of an exotic meson with one particular combination of J^{PC}, which could shed light on its constituents. An exotic meson with the quantum numbers $J^{PC} = 0^{--}$ is a particularly interesting one, because such a state is not allowed for a gluonic hybrid in the lowest-order flux-tube model and possibly in other models as well containing a valence gluon. One sees from (4) that a gluonic hybrid with $J = 0$ must necessarily have $L = S = 1$, which implies that $J^{PC} = 0^{+-}$. So a $J^{PC} = 0^{--}$ is not allowed for a gluonic hybrid.

If a gluonic hybrid exists with the quantum numbers $J^{PC} = 0^{--}$, then its mass must be large, compared to those allowed in the flux-tube model. Indeed, according to the calculations of the QCD sum rule by Latorre *et al.*[8], a $J^{PC} = 1^{-+}$ $n\bar{n} + g$ should come with a mass in the range 1.6–2.1 GeV, whereas a $J^{PC} = 0^{--}$ $n\bar{n} + g$ should have a mass around 3.8–4.2 GeV, well into the mass range of charmonia.

In the diquark cluster model, several $I^G(J^{PC}) = 1^+(0^{--})$ exotic mesons are predicted[27] in the mass region 1.3 to 1.7 GeV, coupling to $a_0(980)\pi$, $\rho\eta$, $\omega\pi$, and $a_1(1260)\omega$—among others—depending on the mass. Any future search for exotic mesons should include those with $J^{PC} = 0^{--}$. Discovery of a $J^{PC} = 0^{--}$ with mass < 2.0 GeV signals existence of an exotic meson which cannot be ascribed to a gluonic excitation. For example, a ρ_0 meson with $I^G(J^{PC}) = 1^+(0^{--})$ can couple to the decay channel $\omega\pi$ via P wave, while a meson ω_0 with $I^G(J^{PC}) = 0^-(0^{--})$ could decay into $\rho\pi$ via P wave. Such a discovery should be exciting indeed.

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