Glueballs, Hybrids, Baryons and Pentaquarks: Hadron05 summary on light-quark spectroscopy

Eberhard Klempt

Helmholtz–Institut für Strahlen– und Kernphysik, Nussallee 14-16, 53115 Bonn

Abstract. Results on light–quark spectroscopy presented at Hadron05 are reviewed. Particular emphasis is given to the status of pentaquarks and of glueballs and exotic mesons. Experiments are proposed to decide on open issues.

Keywords: Scalar and pseudoscalar glueballs, J^{PC} exotics, baryon structure and spectroscopy, pentaquarks, dynamically generated resonances

PACS: 12.38Qk,13.25Jx,112.39-x,3.30Eg,13.75-n,13.85-t,14.20c, 14.40-n,13.60-r

11th International Conference on Hadron Spectroscopy (Hadron05), Rio de Janeiro, Brazil, 21-26 Aug 2005.
Published in AIP Conf.Proc.814:723-734,2006. Also in *Rio de Janeiro 2005, Hadron spectroscopy* 723-734

INTRODUCTION

New and exciting results were presented at Hadron05. In this first part of the conference summary, selected results on light quark spectroscopy are discussed while the field of heavy quarks is reviewed by Ted Barnes. Quark masses vary over a wide range, from a few MeV to the top quark mass, but their interactions do not depend on flavour, so we deal with the same physics. This is visualized in figure 1 showing the mass gap for the lowest angular momentum excitation and the hyperfine splitting between ρ and π, J/ψ and η_c, between $\Delta(1232)$ and the nucleon, and other baryon splittings.

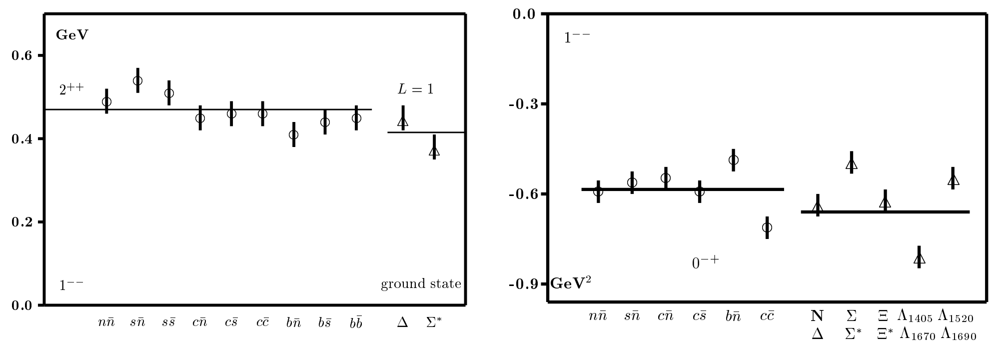


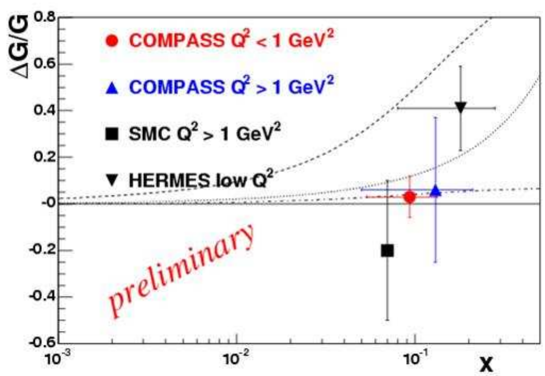
FIGURE 1. Flavor independence of the strong forces: Left panel: Mass differences for $L = 1$ excitations of mesons and baryons (for systems with aligned spin). Right panel: Mass square differences between PS and V mesons for $L = 0$ octet-decuplet and $L = 1$ singlet-octet baryons.

The report begins with a section on aspects of baryon structure and spectroscopy. The subsequent section is devoted to the status of pentaquarks. Scalar mesons and the search for the lowest mass glueball, pseudoscalar mesons and exotic mesons are covered in three separate sections. Dynamical generation of resonances is reviewed, and a few remarks are made concerning the quark–gluon plasma. The summary ends with an outlook on results expected from ongoing experiments and from forthcoming facilities.

BARYON STRUCTURE AND SPECTROSCOPY

"Why N*'s are important" was the title of the Baryon98 summary by N. Isgur, and he answered: "baryons are sufficiently complex to reveal physics which may be hidden from us in mesons". Also today, there is a gap in our understanding of the partonic structure of nucleons (see Haas [1]) and static properties of nucleons and their excitation spectrum. A first approach to bridge this gap was presented by Brodsky [1] who gave a fascinating 30 min talk presenting 125 transparencies.

Already neutrino scattering experiments had revealed a sizeable contribution ($\sim 15\%$) of strange quarks to the structure of nucleons [2]. Unknown so far is the effect of strange quarks to the electric and magnetic formfactors. Smith [1] reported measurements of the small parity violating contribution to electron nucleon scattering as a function of Q^2 from which rather small formfactors $\mathrm{G_E^s} = -0.01 \pm 0.03, \mathrm{G_M^s} = +0.55 \pm 0.28$ were determined. The puzzling observation that, in the infinite momentum frame, the largest fraction of proton spin is not carried by quarks is now accompanied by measurements by the COMPASS collaboration of the gluon spin contribution. The statistics of 'golden' events with open charm production is still too limited to allow for a significant constraint; from high-P_T events, Paul and Marchand [1] concluded that at medium x values gluons contribute to the proton spin at the 10% level. The results are shown in Fig. 2. Obviously, the orbital angular momentum wins the race to provide the most significant contribution to the proton spin; the old–fashioned idea of the magnetic moment being generated by a virtual pion orbiting (part time) around a neutron seems to find further experimental support (in addition to the neutron electromagnetic formfactor or to charge asymmetries in the n–p structure functions). The GDH sum rule connects the static magnetic moment of nucleons with their excitation spectrum (more precise: the helicity dependent photo absorption cross sections). Results were reported by Pedroni [1]).



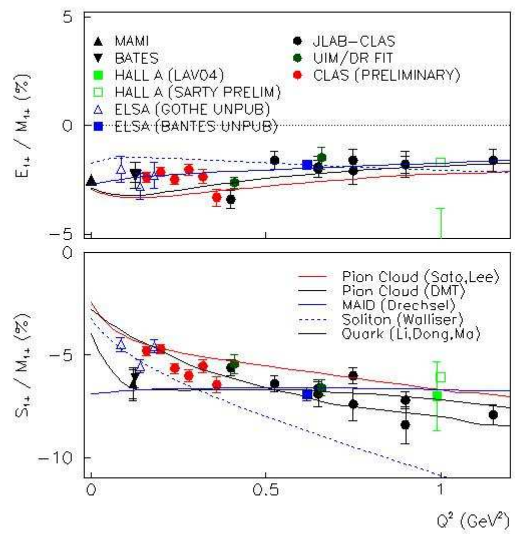


FIGURE 2. Left: $\Delta G/G$ for large p_T from COMPASS. Only curve (1) assigns the proton spin to the spin of quarks (from Paul [1]). Right: $N \rightarrow \Delta(1232)$ quadrupole transitions (from Smith [1]).

The $N \rightarrow \Delta(1232)$ quadrupole transitions (E_1^+ and S_1^+) are in the focus of interest since a few decades. It should reveal how the quark magnetic moments organise themselves as a function of their spin direction. Is there a preference for configurations in which quark spins align themselves with colour magnetic flux lines (like normal dipole magnets)? Results reported by DeVita, Gothe, Joo and Smith [1] are shown in Fig. 2b. Dynamical models reproducing the data attribute most of the deformation to the proton's pion cloud even though a small contribution from the expected oblate or prolate shape of the static nucleon or $\Delta(1223)$ is not excluded. With increasing Q^2 (for Q^2 up to $5\,\mathrm{GeV}^2$), the data show no trend for a transition to perturbative QCD.

It is interesting to note that photoproduction of $\Delta(1232)$ by the 2.7 Kelvin background radiation limits the range of energies of cosmic particles to about 10^{20} eV. The Agasa collaboration reported a sizeable yield above this energy [3], the Hires experiment is compatible with a suppression due to photoproduction of $\Delta(1232)$'s [4]. The final answer will comes from the Auger observatory, status and first results were presented by Mello Neto [1].

The Roper resonance, suspected to be of hybrid or pentaquark nature, was studied at Jlab in electroproduction; the couplings and their Q^2 dependence are compatible with quark model calculations and the interpretation of the Roper as ordinary qqq

resonance. Baryons as three-particle systems support a large number of excitations. The mass spectrum below 1.8 GeV is reasonably well understood even though certainly not yet in all aspects. Above 1.8 GeV the predicted level density becomes increasingly complex. It is unclear at present how the levels organise: is chiral symmetry restored [5] (see however [6]), is the level density reduced due to diquark effects [7], or should we expect the full richness of states as predicted in symmetric quark models [8]? Personally, I expect substantial new insight from an exploration of the high–mass baryon spectrum. Brodsky [1] presented an important step in relating the parton structure of baryons to the baryon excitation spectrum. Sarantsev [1] reported on a multichannel partial wave analysis of data on photoproduction of pseudoscalar mesons evidencing several new states. The cross section for η photoproduction is dominated by three resonances, the well known $S_{11}(1535)$, the $P_{13}(1720)$ (for which the large $N\eta$ coupling was not yet known), and a newly suggested $D_{15}(2070)$. These resonances have similar structure: their angular momenta couple with $\vec{J} = \vec{L} + \vec{S}; L = 1,2,3; S = 1/2; J = L - 1/2$. The reason for the pattern is unknown. Inconsistencies in electroproduction of data on $p\pi^+\pi^-$ at JLab (reported by Joo [1]) may indicate the presence of a NP_{13} doublet at 1720 MeV. More results on baryon spectroscopy are to be expected for the near future.

PENTAQUARKS

The new high–statistics data on photoproduction of pentaquarks from CLAS presented by Smith and Tedeschi [1] were awaited for impatiently. A large number of experiments had reported evidence for narrow peaks at about 1540 MeV with significance of 3-5 σ. The peaks were interpreted as a new baryon resonance and called $\Theta^+(1540)$. Its valence structure requires a minimum of five quarks, $udud\bar{s}$. Due to non-observation in KN scattering, tight bounds were set on the pentaquark width, $\Gamma_{\Theta^+(1540)} < 1$ MeV. Such a small width was exciting or, depending on the point of view, intriguing. Pentaquarks were predicted within the framework of chiral soliton models [9] but also quark models were formulated [10, 11] which account for the new type of hadrons. Difficult to understand is the extremely narrow width.

A common feature of the data was their low statistics. High–statistics data, mostly from hadronisation studies in high–energy experiments, did not show evidence for pentaquarks, except for a few cases where a peak due to the $\Theta^+(1540)$ was observed. A recent review can be found in [12]. In addition, new pentaquarks were suggested, the $\Phi^{--}(1860)$ [13] and the $\Theta_c(3100)$ [14].

The absence of the $\Theta^+(1540)$ in hadronisation was a point of concern, upper limits from the DELPHI detector were presented by Gavillet [1]. However, the production rates of pentaquarks in hadronisation are unknown. Hadronisation is a fascinating topic in itself (see Bigi and Atti [1]) with a well–understood phenomenology but there is no ab–initio understanding of the fundamental processes and the non-observation of $\Theta^+(1540)$ in hadronisation does not rule out its existence. The final answer has to come from the "discovery" experiments, from low–energy photoproduction. The new high–statistic CLAS data seem to overrule the first claims for a peak in the reactions $\gamma d \to \Theta^+(1540) p K^-$ and in $\gamma p \to \Theta^+(1540) K^0$; the new upper limits are incompatible with the yields determined from the first round of experiments. Hansen [1] reported on an experiment by Hall A. They presented null results in the search for a Θ^{++} (isotensor partner of the Θ^{+}) and the Σ^{0}_{10} (anti-decuplet member of the Θ^{+} with stangeness -1). Stringent upper limits from Babar for hadro- and electroproduction of the $\Theta^{+}(1540)$ and the $\Phi^{--}(1860)$ were presented by Hryt'nova and Muller [1]. The limits were incompatible with the findings of Hermes and Zeus. No $\Theta_c(3100)$ (see Eisenberg, Kluge [1]) was observed at ZEUS; the upper limit is in conflict with the H1 result. The existence of the ZEUS $\Theta^{+}(1540)$ was however confirmed in the ZEUS reanalysis.

Seth [1] asked: are pentaquarks on life support? The evidence for their existence is certainly shaken. Nevertheless, a few observations need to be clarified in further analyses. A 7σ $\Theta^{+}(1540)$ peak in $\gamma p \to \Theta^{+}(1540)K^{-}\pi^{+}$ was reported by CLAS [15]. Spring8 has taken higher statistics, and supporting evidence for the $\Theta^{+}(1540)$ was observed in a new reaction, in $\gamma d \to \Lambda(1520)\Theta^{+}(1540)$ [16]. At COSY, a seemingly convincing structure was seen in the reaction $pp \to \Sigma^{+}\Theta^{+}(1540)$ [17]. In all these cases, data are on tape, and the final results should be evaluated. The expectations of the community have certainly changed: so far, we all had hoped that the new data from CLAS would confirm the perhaps premature claims; now we have to hope for a miracle.

It is of course impossible that so many experiments have observed a statistically significant but nonexisting peak at the same mass. Cumulat [1] calculated the statistical probabilty that all these observations were unrelated statistical fluctuations, the probabilty is extremely small. There must be a physical or technical reason. A reflection, as advocated by the Indiana group [18], seems excluded by the new Jlab results. If the $\Theta^{+}(1540)$ is not resurrected, the most likely fault which may have happened is an incorrect pattern recognition of overlapping tracks. This may have accidently created a peak at 1540 MeV depleting the invariant mass distribution at both sides of the peak.

The $\Theta^{+}(1540)$ poses also new questions to theory: how stable are the claims for the $\Theta^{+}(1540)$ stability against falling apart in different models? I think both, experimentalists and theoreticians have to go back to their data and equations to find out what went wrong. Hence the study of the $\Theta^{+}(1540)$ must (and will) continue, both experimentally and theoretically (see talks by Eidemueller, Gavillet, Goldman, Hansen, Hry'nova, S. Ishida, Juge, Lee, Lesiak, Ma, Navarra, Noya, Reyes, Smith, and Tedeschi [1]).

SCALAR MESONS AND THE SCALAR GLUEBALL

The scalar mass spectrum and its interpretation remained one of the most controversial issues at this conference, see the contributions by Afanasev, Beveren, Bini, Borges, Bugg, Büscher, Dytman, Garmash, Göbel, Jin, Kleefeld, Khokhlov, Meadows, Maeda, Miranda, Ochs, Pelaez, Polosa, Polycarpo, Robilotta, Roca, Shen, Silvestre-Brac, Teshima, Yuan, Zhao, Zheng [1] and possibly others who all have discussed important aspects of scalar meson spectroscopy from threshold to 2 GeV.

Two–pion interactions at the lowest energy are explored in the Dirac experiment. In matter, $\pi^{+}\pi^{-}$ atoms have the chance to annihilate into $\pi^{0}\pi^{0}$ or to be broken apart in atomic collisions. The break–up can be detected and thus the natural life–time of $\pi^{+}\pi^{-}$ atoms be measured. The result of Dirac, $\tau = 2.9$ ps, is in excellent agreement with predictions from chiral perturbation theory (see Afanasev [1]).

The first hadronic scalar isoscalar meson, often called σ, is quoted as $f_0(600)$ by the Particle Data Group, with a mass between 400 and 1200 MeV and a width in the 600 and 1000 MeV range. Bugg [1] emphasized the need to constrain production data on the low–energy $\pi\pi$ interactions by removing the Adler–Weinberg zero present in $\pi\pi$ scattering. In his view, the correct treatment of the Adler zero enforces a low–mass pole in the scalar isoscalar S–wave, the $f_0(600)$. It is accompanied by the $K_0^*(900)$, $a_0(980)$ and $f_0(980)$, forming a natural nonet of dynamically generated resonances. The low–energy behaviour of the $\pi\pi$ S–wave is constrained by chiral symmetry and by dispersion relations (see talks by Pelaez and Borges [1]). The scalar isoscalar S–wave structure at 1300 MeV observed in several experiments is interpreted by Bugg as $f_0(1370)$; the 3 states $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$ are the observable signatures of a scalar glueball intruding the scalar meson spectrum and mixing with two quarkonium states. The additional $f_0(1790)$ observed in BES data on $\phi\pi\pi$ (see Jin and Yuan [1]) is interpreted as $f_0(1370)$ radial excitation.

Ochs [1] presented a different view. He underlined the model dependence of the σ mass and suggested that the σ and the $f_0(1370)$ may very well be separate regions of a common object, called red dragon or $f_0(1000)$, having a width of 1000 MeV or more. Its actual mass is suggested to depend on the parameterisation and mass range which is fitted. He reported on an analysis of B decays and demonstrated that the data can be interpreted naturally adopting his view. The scalar glueball is identified with the wide scalar background intensity.

Alternatively, the wide scalar $\pi\pi$ background amplitude can be understood quantitatively as dynamically generated by (mainly) ρ exchange, and there is no need to introduce additional poles due to s–channel resonances [19]. The $f_0(1370)$ is supposed to have strong couplings to 4π. The question arises if $f_0(1370)$ in 4π is a *s*–channel resonance or if it represents a background amplitude describing meson–meson interaction dynamics with a slowly rising phase. In central production, the $f_0(1370)$ decays only into $\rho\rho$ and not to $4\pi^0$ (see Fig. 4 (nor to $\eta\eta$) [20, 21]. The dip in the $\rho\rho$ scalar mass distribution is due to $f_0(1500)$ and unitarity constraints in the same way as unitarity produces a dip at the $f_0(980)$ in the $\pi\pi$ mass distribution. The Crystal Barrel collaboration observed both mesons, $f_0(1370)$ and $f_0(1500)$, in their $\rho\rho$, $\eta\eta$ and $\sigma\sigma$ decays. These

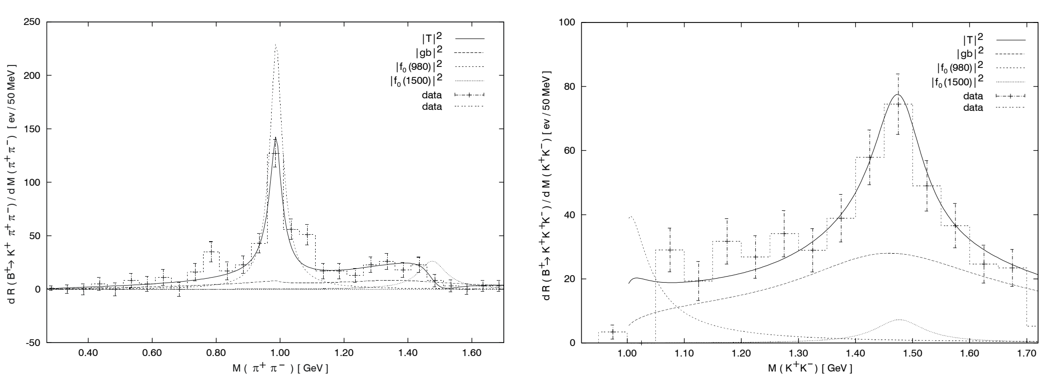


FIGURE 3. $\pi^+\pi^-$ mass spectrum in *B*-decays in comparison with a model including $f_0(980)$, $f_0(1500)$ and a broad glueball. The individual resonance contributions are also shown. In $\pi\pi$ the glueball interferes destructively, in $K\bar{K}$ constructively with both $f_0(980)$ and $f_0(1500)$ (from Ochs [1]).

discrepancies can be interpreted as evidence that (likely non–resonant) scalar isoscalar intensity is generated dynamically by isovector t–channel exchange (e.g. ρ exchange to yield $\pi\pi$, π exchange to yield $\rho\rho$) between two Pomerons leading to scalar intensity in $\rho\rho$ but not in two isoscalar particles like $\eta\eta$ or $\sigma\sigma$.

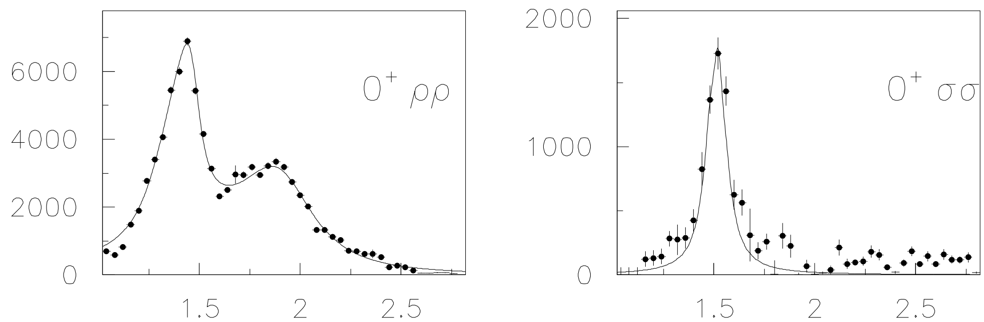


FIGURE 4. The $\rho\rho$ and $\sigma\sigma$ scalar intensity in WA102 [20]. The absence of $\sigma\sigma$ can be understood when the intensity is due to Pomeron–Pomeron interactions via isovector (e.p. pion) exchange.

These different views lead to experimental consequences. If the $f_0(1370)$ is a real particle, it will be observed as a dip in $\pi\pi \to 4\pi$ scattering [22]. Otherwise, it is part of the $f_0(1000)$. The glueball nature of the latter can be probed by radiative J/ψ decays into $\eta\eta$ and into $4\pi^0$. There is no reason for scalar mesons not to decay into theses two modes while background amplitudes for $\eta\eta$ or $4\pi^0$ in radiative J/ψ decays should be very small compared to the production of $f_0(1500)$. These are two crucial experiments, in particular the study of J/$\psi \to \gamma\eta\eta$ or $\gamma 4\pi^0$. It will yield the final answer to the question: does a scalar glueball exist as intruder mixing with scalar quarkonia, does it exist as a the broad object seen e.g. in central production or has nature chosen a different scenario. The search for glueballs has accompanied us for about 25 years. The answer could come in the very near future from CLEO. If they decide to continue with the $\psi(2S)$ program, the community will likely have to wait for the BESIII upgrade.

PSEUDOSCALAR MESONS

Masoni [1] suggested the pseudoscalar glueball should be identified with the low–mass component of the $\eta(1440)$ called $\eta(1405)$ by the Particle data group [23]. In his interpretation, the $\eta(1295)$ is the radial excitation of the η. Its mass is degenerate with the $\pi(1300)$, hence the pseudoscalar radial excitations seem to be ideally mixed. The $s\bar{s}$ partner should then have a 240 MeV higher mass. The high–mass component of $\eta(1440)$, called $\eta(1475)$, decays dominantly into $K\bar{K}^* + cc$ and is assigned to be the $s\bar{s}$ partner of the $\eta(1295)$. The $\eta(1405)$ does not find a slot in the spectrum of $\bar{q}q$ mesons; it is interpreted as a glueball.

This view could be wrong. The $\eta(1295)$ is observed only in πN scattering and in no other process. Radiative J/ψ decays into $\gamma K\bar{K}\pi$ show an asymmetric peak in the $\eta(1440)$ region [24]: both, $\eta(1405)$ and $\eta(1475)$, contribute to the process. Hence not only glueballs but also radial excitations are produced in radiative J/ψ decays. The $\eta(1295)$ should therefore be produced as well, but it is not - at least not with the expected yield.

At BES, $\eta(1295)$ and $\eta(1440)$ were studied in J/$\psi \to (\rho\gamma)\gamma$ and $\to (\phi\gamma)\gamma$ [25]. The $\eta(1440)$ (seen at 1424 MeV) is seen to decay strongly into $\rho\gamma$ and not into $\phi\gamma$. This is inconsistent with the peak being a glueball (which should not decay radiatively) or with its interpretation as $s\bar{s}$ state (which should decay into $\phi\gamma$ and not into $\rho\gamma$). The $\eta(1295)$ is missing again, a peak below 1300 MeV is assigned to $f_1(1285)$ (even though a small contribution from $\eta(1295)$ cannot be excluded). Finally, photons couple to charges; in $\gamma\gamma$ fusion a radial excitation is hence expected to be produced more frequently than a glueball. The L3 collaboration studied $\gamma\gamma \to K^0_s K^\pm \pi^\mp$ [26]. At low q^2, a peak at 1440 MeV is seen but no peak due to $\eta(1295)$. Neither a glueball nor a $s\bar{s}$ state can have stronger two–photon couplings than a $n\bar{n}$ state. Hence $\eta(1295)$ should have been seen if it were the η radial excitation. The latter argument is however weakened since CLEO$_c$ does not see neither $\eta(1295)$ nor $\eta(1440)$ and reports an inconsistency with L3 with more than two standard deviations [27]. The Crystal Barrel collaboration searched for $\eta(1295)$ and $\eta(1440)$ in the reaction $p\bar{p} \to \pi^+\pi^-\eta(xxx)$, $\eta(xxx) \to \eta\pi^+\pi^-$ [30]. A pseudoscalar resonance signal was observed at 1405 MeV decaying into $a_0(980)\pi$ and $\eta\sigma$. A scan for an additional 0^+0^{-+} resonance gave no evidence for $\eta(1295)$ but for a second resonance at 1480 MeV. The phase of the $a_0(980)\pi$ or $\sigma\eta$ isobar changed by π indicating the presence of only one resonance in the 1250 to 1500 MeV region instead of 3. The $\eta(1295)$ does not have the properties of a $q\bar{q}$ resonance; it might be faked by a combination of Deck effect and feed-through from the $f_1(1285)$. The splitting of $\eta(1440)$ into two separate peaks can be understood assuming that it is a radial excitation. Its node in the wave function has an impact on the decay matrix elements calculated by Barnes *et al.* [31] within the $^3P_0$ model. The node occurs at different momenta for $\eta(1440) \to a_0(980)\pi$ and K*K decays. The K*K distribution is shifted towards higher masses, the $a_0(980)\pi$ and $\sigma\eta$ distribution are split into a low-mass and a weak high–mass peak. One $\eta(1420)$ and the assumption that it is a radial excitation are sufficient to describe the data. There is no need to introduce two independent states.

What is the radial excitation of the η'? BES may have observed up to seven pseu-

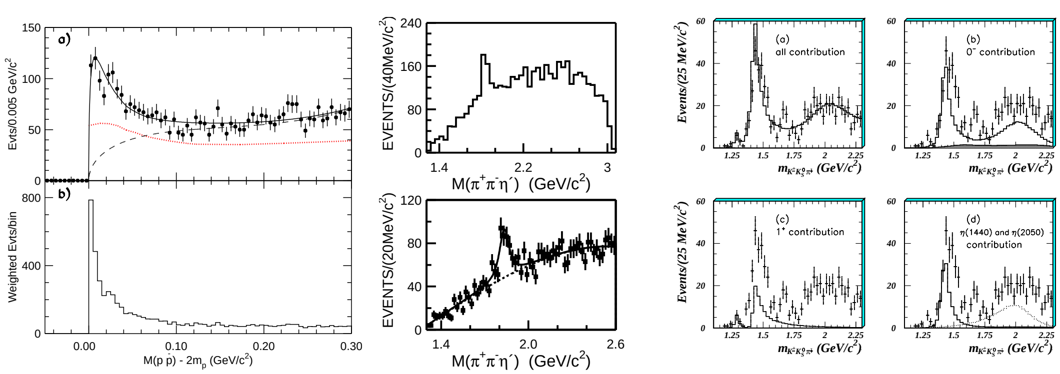


FIGURE 5. Left: The $p\bar{p}$ threshold enhancement from J/$\psi \to \gamma p\bar{p}$ after correction for phase space. Center: The $\eta'\pi^+\pi^-$ spectrum from radiative J/ψ decays. No partial wave analysis has been performed. (from Jin [1]). Right: In J/$\psi \to \gamma$K$\bar{\text{K}}\pi$ the $\eta(1440)$ is seen, and a (disregarded) $\eta(1650)$. The pwa gives additionally evidence for a $\eta(2040)$.

doscalar states in radiative J/ψ decays, $\eta(1440)$ in K$\bar{\text{K}}\pi$ and $\eta\pi\pi$, $\eta(1760)$ in $\eta\pi\pi$, possibly a $\eta(1650)$ in K$\bar{\text{K}}\pi$, X(1835) (likely $\eta(1835)$) in $\pi\pi\eta'$, $\eta(1860)$ in $p\bar{p}$ and

$\eta(2040)$ in K$\bar{\rm K}\pi$ and a broad $\eta(1800)$ background amplitude which is interpreted as glueball. In [28], $\eta(1650)$ was discarded because of its narrow widths of 30 MeV. However, the $\eta(1835)$ has about the same width. The $\eta(1835)$ and $\eta(1860)$, shown in Fig. 5, are suggested to represent two decay modes of one resonance which is interpreted as $p\bar{p}$ bound state (see talks by Yuan, Jin, and Shen [1]). I prefer to keep them separate and to link the $\eta(1860)$ to NN physics. The $\eta(1760)$ is seen with little evidence by BES, the original claim by MARK3 and DM2 [23] was later shown to be wrong [29]. From the masses one may speculate and attempt an identification as

1^1S_0	$\pi(138)$	$\eta(958)$	$\eta(548)$	K(495)	
δM^2 =	1.9	1.8	1.8	1.9	GeV^2
2^1S_0	$\pi(1375)$	$\eta(1650)$	$\eta(1440)$	K(1460)	
δM^2 =	1.4	1.4	1.3	1.2	GeV^2
3^1S_0	$\pi(1800)$	$\eta(\sim 2040)$	X(1835)	K(1830)	

EXOTIC MESONS

Adams [1] reported on the status of exotic mesons with quantum numbers $J^{PC} = 1^{-+}$. There are three regions in which exotic mesons were reported, at 1400, 1600 and 2000 MeV. A $\pi_1(1400)$ seen in $\eta\pi$ and $\rho\pi$, a $\pi_1(1600) \to \eta'\pi, \rho\pi, f_1(1285)\pi$ and $b_1(1230)\pi$, and a $\pi_1(2000)$ in its $f_1(1285)\pi$ and $b_1(1230)\pi$ decay modes. For the $\pi_1(1400)$ and $\pi_1(1600)$, the dynamics of the production process of the final states $\rho\pi$ and $b_1(1230)\pi$ (produced by both natural and unnatural parity exchange) is different from that of the $\eta\pi$, $\eta'\pi$, and $f_1(1285)\pi$ decay modes (which proceed only via natural parity exchange). Hence there must be four exotic states in the 200 MeV mass region. It is unlikely that these are hybrids, and also their mass is too low. Hence these four resonances must be four–quark states or generated by meson–meson interactions. The conjecture that a state doubling occurs is supported for the $\pi_1(1400)$ by the LEAR results: the Crystal Barrel $\pi_1(1400)$ in $\pi\eta$ is produced from the $^3S_1$ initial state of the $p\bar{p}$ atom; the Obelix $\pi_1(1400)$ decays into $\rho\pi$ but is produced from the $^1S_0$ state.

If we accept the $\pi_1(1400)$ and $\pi_1(1600)$ to be split and (likely) generated by meson–meson interactions, you expect (due to $3\otimes 3\otimes 3\otimes 3 = 1+8+8+8+8+10+\overline{10}+27$) several π_1 resonances. This is seen experimentally. Only the highest–mass resonance $\pi_1(2000)$ has the properties as expected for hybrid mesons. But how can one be shure of its hybrid nature given such an abundancy of four–quark exotic states ? A convincing case for observation of a hybrid can only be made when the observations at 1400 and 1600 MeV can be discredited.

Mitchel [1] reported on a reanalysis of the Indiana group of E852 data on the 3π final states with the aim to scrutinize the existence of the $\pi_1(1600)$. The older E852 analysis used 20 waves plus background to describe the data; the Indiana group 35. In this way they succeeded in reducing the intensity of the $\pi_1(1600)$ but the phase motion between the π_1 and π_2 partial waves (not shown in their paper) remained stable. The criticism of the Indinana group was refused by Adams speaking for the E852 collaboration. He presented a fit to the Indiana partial wave analysis result, and found (from their analysis !) the π_1 partial wave to demand a resonance with (M, Γ=1550,320) MeV, fully compatible with the published result ($1593\pm8^{+29}_{-47}$, $168\pm20^{+150}_{-12}$). The $\pi_1(1600) \to \pi\eta'$ is fitted by both groups with a Breit Wigner amplitude, hence in this decay mode the $\pi_1(1600)$ is not controversial. Adams also commented on another analysis of the Indiana group. The Indiana group constructed $\pi\eta$ interactions which allows them to generate the $\pi_1(1400)$ dynamically from final state interactions. They argue that the $\pi_1(1400)$ is not a 'QCD pole', intead, the physical origin responsible for intensity and phase motion are meson–meson interactions. Both groups agree however, at least qualitatively, on amplitude and phase. The $\pi_1(1400) \to \rho\pi$ decay has not been reported by BNL or VES since the $\rho\pi$ low–mass region is dominated by the Deck effect. Progress in the treatment of this background amplitude was reported by Dudek [1].

In summary, exotic mesons have been identified in different experiments. Their identification as hybrids is difficult since most of the observations are certainly not hybrids but rather tetraquarks or originating from meson–meson dynamics.

I would like to mention here the open issues in the spectrum of vector radial excitations and their interpretation, and refer to the talks by Sibidanov and Ishida [1].

DYNAMICALLY GENERATED RESONANCES

At low energies, QCD can be developed into an effective field theory which can be expanded systematically with q/Λ_χ and m_π/Λ_χ ($\Lambda_\chi \sim 1\,\text{GeV}$) as small expansion parameters. Hadrons coupling to an S–wave decay mode which is just closed due to phase space limitations can be generated from an effective chiral invariant Lagrangian in which pseudoscalar (and vector) mesons and octet (and decuplet) baryons are the 'fundamental' particles. Spectral functions can be calculated which can be confronted with experimental data. Several contributions to Hadron05 demonstrated the wide range of phenomena to which chiral perturbation theory can be applied.

Hofmann [1] reminded us of the rich history of dynamically generated resonances which goes back to Dalitz. The $\Lambda(1405)$ is one example, other well known cases are the $\text{N}^*(1535)$ coupling to $\text{K}\Sigma$ and $\text{N}\eta$, the $\Lambda(1520)$ coupling to K^*N. The question arises: are dynamically generated resonances distinct from $q\bar{q}$ states, do these resonances exist independently and in addition to quark model states ? Or can chiral dynamics predict properties of resonances like mass shifts due to hadronic interactions and couplings to different final states even though the resonances still have a $q\bar{q}$ seed ? This question has been posed since many years, I remind you of the $f_0(980)$ and $a_0(980)$ mesons which are interpreted as dynamically generated resonances, $qq\bar{q}\bar{q}$ states, as chiralons, or as 1^3P_0 $q\bar{q}$ states. Likely, they are a bit of all but need the $q\bar{q}$ seed. This has important consequences: if they have a $q\bar{q}$ seed attracting molecular components due to final–state interactions, they should not be disregarded when forming meson multiplets.

In some cases, dynamically generated resonances may have no overlap with quark model states. The doubling of the $\Lambda(1405)$ could be such an example. The $\Sigma\pi$ and NK pairs in S–wave have thresholds at 1332 and 1435 MeV. Their interaction is fully fixed by an effective chiral invariant Lagrangian; Oset [1] showed that the interaction leads to three poles, two are found just below the NK threshold, and he conjectured that the $\Lambda(1405)$ has a two–pole structure. The (low–statistics) data on $\pi^-\text{p} \to \Sigma^+\pi^-$ and $\pi^-\text{p} \to \Sigma^-\pi^+$ are consistent with this picture. Of course, the $\Lambda(1405)$ plays a role (and occupies a slot) in the spectrum of (qqq) baryon resonances. Its low mass may pose a problem for quark modelists, however it is known that strong couplings to S–wave decays may introduce considerable mass shifts. The two $\Lambda(1405)$ poles are predicted to have different flavour structures, one being dominantly a flavour singlet, the other dominantly a flavour octet state. In the quark model, the $\Lambda(1405)$ has a single pole (in the second Rieman sheet), and it is a flavour singlet. This is a prediction which can be tested experimentally at BES: J/ψ decays into a ground–state Λ plus $\Lambda(1405)$ are allowed only when the $\Lambda(1405)$ has a large octet component. The quark model predicts J/$\psi \to \Lambda\Lambda(1405)$ to be small compared to J/$\psi \to \Lambda\Lambda(1520)$ while Oset's model predicts the two reactions to have similar strengths. A second example are the axial vector mesons. The $f_1(1285)$, $h_1(1170)$, and $h_1(1380)$ can be understood as bound state of pseudoscalar and vector mesons generated dynamically, the $f_1(1420)$ (or $f_1(1510)$) however not (see Roca [1]). In quark models, all four states are predicted and indeed, all four are seen experimentally. A second point is the wave function. The generated $f_1(1285)$ is an octet state and has a $s\bar{s}$ component. In the quark model, $f_1(1285)$ is a $(u\bar{u}+d\bar{d})/\sqrt{2}$ state and should not be produced by J/$\psi \to \varphi f_1(1285)$. The sizable branching ratio of J/$\psi \to \varphi f_1(1285)$ can only be understood if $f_1(1285)$ is dynamically generated. In this case, the quark model gives the correct pattern of states, their properties are better understood from final–state interactions of their decay products. More work on the relation between dynamically generated resonances and quark model states is certainly needed [33].

THE QUARK–GLUON PLASMA

At high density and temperature, nuclear matter is predicted and possibly observed to undergo a phase transition. Takahashi [1] reported on results of the STAR collaboration at RHIC which has the goal to reconstruct from the final–state particles the dynamics of the quark–gluon plasma and its expansion in a hadronic gas from which the final state is reached via freeze out at 165 MeV. Munhoz [1] (see also Fraga [1]) showed impressive distributions of shower devolpments in Au Au collisions. The compound system is shown to dissipate the energy of a jet almost completely. Hence a thermal equilibrium seems to be reached. This is of course of considerable importance for the interpretation $c\bar{c}$ states and their interaction in a dense and hot environment.

Nuclear medium effects can be observed already in normal nuclei as Lolos [1] reported. The ρ spectral function from the reaction $\gamma^{12}C \to \pi^+\pi^- + X$ can still be understood without medium modifications but at larger densities (and heavier nuclei) in–medium mass shifts have been observed [34, 35].

OUTLOOK

The beautiful results on heavy quark spectroscopy are reviewed by Ted Barnes. The discovery potential of J/ψ decays for light quark spectroscopy and the search for gluonic degrees of freedom in spectroscopy is known since the pioneering experiments at Stanford and Orsay in the 70's and 80's. BESII has taken up the field providing a multitude of interesting results. Luminosity and detector performance will undergo a substantial upgrade to reach BESIII; CLEO$_c$ has the potential for substantial contributions also to quark–gluon spectroscopy. It was an unexpected surprise that B and D mesons contribute substantially to light–quark spectroscopy. Initial state radiation (see Aston, Berger [1]) is a further novel tool to study the spectrum of vector mesons from the ρ and ω up the X(4260) - suggested to be a $c\bar{c}$ hybrid [32] - and beyond, and to complement the work of DAΦNE and VEPP2. BNL has a rich data set on light mesons and will produce more results.

The Thomas Jefferson Lab is producing a wealth of beautiful data on the structure of nucleons. COMPASS will provide a solution to the proton spin puzzle and will yield new results on meson spectroscopy (see Colantoni, Paul [1]). And also FERMILAB has an active hadron program (see Appel and Maciel [1]). Several laboratories like ELSA, Spring8, MAMI, GRAAL and of course Jlab again are producing results on the baryon spectrum. At the low energy end, chiral perturbation theory provides a frame in which low-energy concepts of QCD can be tested with high precision. Active programs are persued at DAΦNE, MAMI and COSY and were presented at Hadron05 by Ambrosini, Filippi, Miscetti, Papandreou, Pedroni and Machner [1].

Two major new facilites are planned, GlueX and FAIR (see contributions of Carman, Peters and Boca [1]). GlueX is designed to optimise the identication of hybrid mesons. This task requires high luminosity to find small signals in the presence of a large background of conventional $q\bar{q}$ resonances and full solid angle coverage for both charged and neutral particles to fully reconstruct the complex decay chains predicted for hybrids. The use of a photon beam with linear polarisation constrains the naturality of the particle exchange and thus facilitates the analysis. FAIR is an umbrella which houses a broad spectrum of experimental facilities. Nuclear structure is studied using beams of radioactive isotopes; relativistic nuclear collisions will explore compressed hadronic matter; plasma physics, the physics of highly charged ions and the study of low–energy antiprotons are part of the scientific program. Of special interest for this conference are the prospects of a continuation of the successful Fermilab E835 experiment, with greatly improved luminosity and detector, a special pellet target (see Büscher's talk) and a much broader scientific program. The spin–dependence of antiprotons is proposed to be studied with two different techniques and aims. I believe that an eventual understanding of confinement will not come from heavy quark spectroscopy but from a study of high–mass excitations of light mesons and baryons. FAIR has the potential to scan the 2 to 3 GeV mass range in $p\bar{p}$ annihilation with a polarised target and possibly even with a polarised antiproton beam. Such experiments would be unique, with GSI being the only place in the world where such experiments could be carried out.

In summary, there are excellent facilities supporting intense studies of one of the most challenging issues of hadron physics: what is the nature of confinement, and what is the relation between the partonic degrees of freedom and the nucleon as a (qqq) bound state.

At the end, I would like to thank the organisers, in particular Alberto Correo dos Reyes, for setting up this interesting conference and for their warm hospitality.

REFERENCES

1. Contribution to Hadron05.
2. M. Abramowitz et al., Z. Phys. **C15** (1982) 19.
3. M. Takeda et al., PRL **81** (1998) 1163.
4. HiRes Collab., arXiv:astro-ph/0501317.
5. L. Y. Glozman, Phys. Lett. B **475** (2000) 329.
6. E. Klempt, Phys. Lett. B **559** (2003) 144.
7. E. Klempt, arXiv:nucl-ex/0203002.
8. S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. **45** (2000) S241.
   U. Löring, B. C. Metsch, and H. R. Petry, Eur. Phys. J. A **10** (2001) 395, 447.
9. D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. A **359** (1997) 305.
10. R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91** (2003) 232003.
11. M. Karliner and H. J. Lipkin, arXiv:hep-ph/0307243.
12. K. H. Hicks, Prog. Part. Nucl. Phys. **55** (2005) 647.
13. C. Alt *et al.* [NA49 Collaboration], Phys. Rev. Lett. **92** (2004) 042003.
14. A. Aktas *et al.* [H1 Collaboration], Phys. Lett. B **588** (2004) 17.
15. V. Kubarovsky *et al.* [CLAS Collab.], Phys. Rev. Lett. **92** (2004) 032001 [E.: **92** (2004) 049902].
16. T. Nakano, Int. Conf. on QCD and Hadronic Physics June 2005, Beijing, China, www.phy.pku.edu.cn/ qcd/.
17. M. Abdel-Bary *et al.* [COSY-TOF Collaboration], Phys. Lett. B **595** (2004) 127.
18. A. R. Dzierba, D. Krop, M. Swat, S. Teige and A. P. Szczepaniak, Phys. Rev. D **69** (2004) 051901.
19. B. S. Zou and D. V. Bugg, Phys. Rev. D **50** (1994) 591.
20. D. Barberis *et al.* [WA102 Collaboration], Phys. Lett. **B474** (2000) 423.
21. D. Barberis *et al.* [WA102 Collaboration], Phys. Lett. B **479** (2000) 59.
22. A. Sarantsev, private comminication, 2005.
23. S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592** (2004) 1.
24. L. Köpke and N. Wermes, Phys. Rept. **174** (1989) 67.
25. J. Z. Bai *et al.* [BES Collaboration], Phys. Lett. B **594**, 47 (2004).
26. M. Acciarri *et al.* [L3 Collaboration], Phys. Lett. B **501**, 1 (2001).
27. R. Ahohe *et al.* [CLEO Collaboration], Phys. Rev. D **71**, 072001 (2005).
28. J. Z. Bai *et al.* [BES Collaboration], Phys. Lett. B **476** (2000) 25.
29. D. V. Bugg *et al.*, Phys. Lett. B **353** (1995) 378.
30. E. Klempt, arXiv:hep-ph/0409148.
31. T. Barnes, F. E. Close, P. R. Page and E. S. Swanson, Phys. Rev. D **55** (1997) 4157.
32. F. E. Close and P. R. Page, arXiv:hep-ph/0507199.
33. U. G. Meissner, Int. J. Mod. Phys. A **20** (2005) 514.
34. D. Trnka *et al.* [CBELSA/TAPS Collaboration], Phys. Rev. Lett. **94** (2005) 192303.
35. M. Naruki *et al.*, arXiv:nucl-ex/0504016.