Glueballs, Hybrids, Pentaquarks

EBERHARD KLEMPT
Helmholtz-Institut für Strahlen– und Kernphysik
Universität Bonn
Nußallee 14-16, D-53115 Bonn, GERMANY
E-mail: klempt@hiskp.uni-bonn.de

The low–energy interactions of quarks and antiquarks may be mediated by gluons, Goldstone bosons or indirectly, via instanton induced forces. These pictures lead to different expectations for the hadron excitation spectrum which are compared here with data.

HSQCD 2004, Hadron Structure and QCD: from LOW to HIGH energies
St. Petersburg, Repino, Russia, 18-22 May 2004

1 Introduction

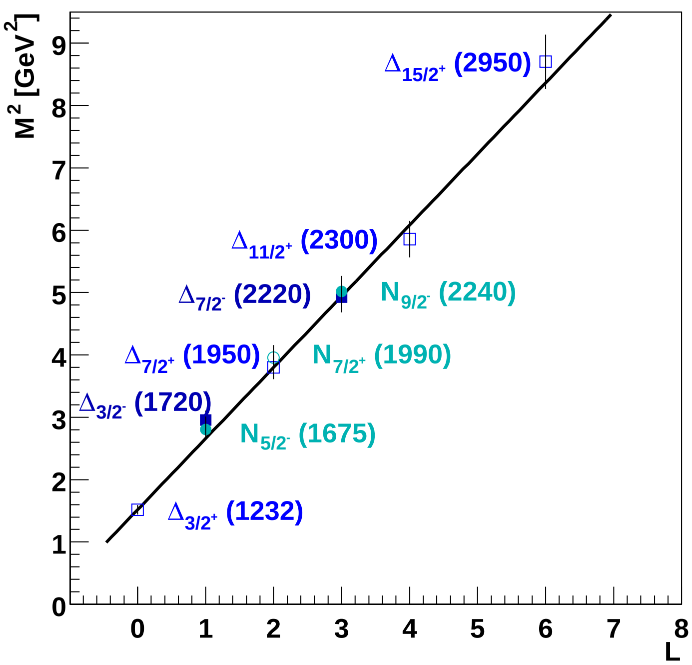
There is general conviction that the quark model which serves so successfully as a guide to meson and baryon spectroscopy needs to be refined. In quark models, mesons and baryons are described by constituent quarks in a confining potential. The full interaction is parameterized by adding some kind of 'residual' interaction, which can be 'effective' one–gluon exchange, the exchange of pseudoscalar mesons, or instanton induced interactions. From deep inelastic scattering it is known that baryons are more complex. Structure functions reveal a rich dynamical sea of quark–antiquark pairs and large gluonic contributions. However at present, there is no bridge from the high–energy partonic structure to the dynamics of constituent quarks and their interaction. In recent years, two interpretations of the physics of strong interaction dynamics in the confinement region evolved. One interpretation underlines the importance of the gluon fields. The residual interaction between quarks is given by an effective one–gluon exchange. Furthermore, gluons are predicted to manifest themselves in new degrees of freedom in spectroscopy, in glueballs and in hybrids. The proponents of this picture interprete the $\Theta^+(1540)$ as pentaquark, as bound state of four quarks and one (strange) antiquark. The second view is proposed in the chiral soliton picture. Quarks interact dominantly by changing the vacuum, like Cooper pairs interact via phonon exchange. The forces are transmitted by vacuum fluctuations of the gluon fields, not as direct quark–quark interactions. Glueballs and hybrids are no obvious features in this kind of theory. A recent experimental survey can be found in [1].

2 Gluon exchange or instanton–induced interactions in baryons ?

The three–quark valence structure of baryons supports a rich spectrum which is very well suited to study the effective interactions between quarks in resonances. Fig. 1 shows a Regge trajectory of Δ^* and of N^* resonances having intrinsic spin 3/2.

Nucleon resonances with intrinsic spin 1/2 can be separated into groups of states with even parity coming from a symmetric 56-plet; odd–parity baryons may come from a 70-plet with mixed symmetry, from the totally antisymmetric singlet system, or from a decuplet. The mass square shift is proportional to the fraction of the wave function which is antisymmetric in spin and in flavor. This fraction is largest for singlet baryons, reduced for octet baryons from a 56-plet, even smaller for octet baryons from a 70-plet, and vanishes for decuplet baryons. This pattern can be formulated as simple baryon

Figure 1: The lowest–mass Δ^* resonances lie on Regge trajectories. If plotted against the intrinsic orbital angular momentum, also negative–parity resonances fall onto the trajectory. For even parity the mass for $J = L + 3/2$ is plotted, for odd parity that for $J = L + 1/2$. States with given L but different J are approximately degenerate in mass. This is the well known spin–orbit puzzle: from one–gluon exchange, large spin–orbit splittings are expected. Surprising, perhaps, is the observation that nucleon resonances with intrinsic spin $S = 3/2$ are degenerate in mass with the Δ series.



mass formula having four parameters only. It reproduces very well the observed baryon mass spectrum, with a χ^2 which is much better than for a model based on one–gluon exchange interactions (which suppresses spin–orbit effects by arbitrarily assuming that spin–orbit forces and the Thomas precession in the confinement field compensate each other).

$$M^2 = M_\Delta^2 + \frac{n_s}{3} \cdot M_s^2 + a \cdot (L + N) - s_i \cdot I_{sym}, \qquad \text{where}$$

$$M_s^2 = \left(M_\Omega^2 - M_\Delta^2\right), \qquad s_i = \left(M_\Delta^2 - M_\mathrm{N}^2\right),$$

M_N, M_Δ, M_Ω are input parameters taking from PDG, $a = 1.142/\mathrm{GeV}^2$ is the Regge slope as determined from the meson spectrum. I_{sym} defines the fraction of wave the function with a qq pair antisymmetric in spin and flavor (which can undergo instanton–induced interactions.) The mass pattern of baryon resonances must reflect the symmetry properties of the underlying interaction. Indeed, instanton–induced interactions follow this symmetry. Thus the pattern provides strong support for instanton–induced interactions being the residual interaction which complements the confinement forces.

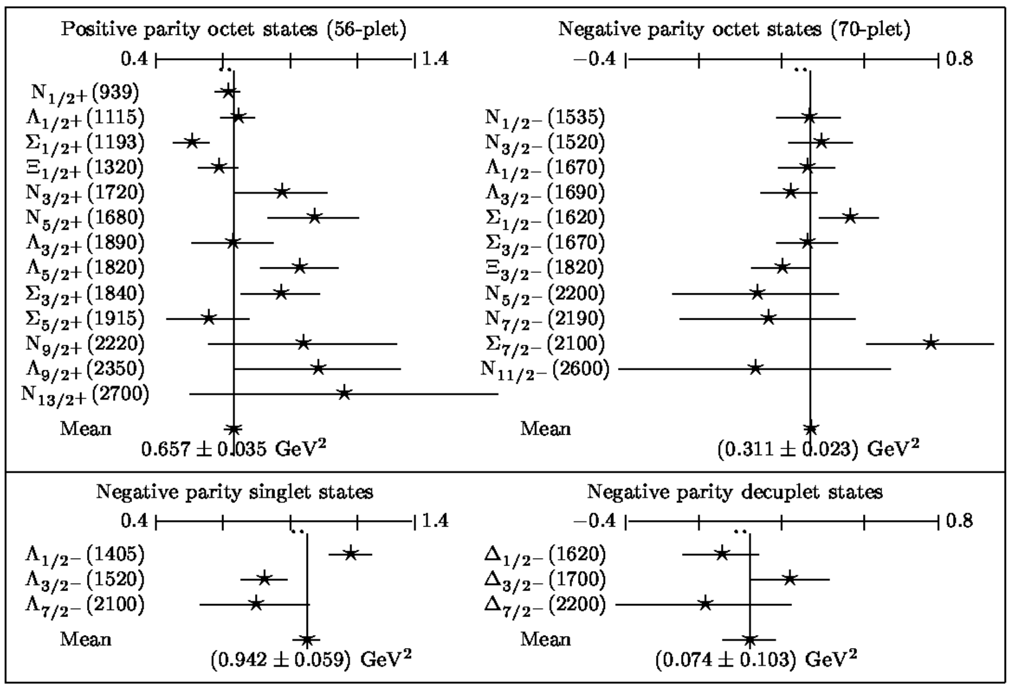


Figure 2: Mass shift (in GeV^2) with respect to the Δ Regge trajectory. The nucleon has a (squared) mass of $0.88\,\mathrm{GeV}^2$, the $\Delta(1232)$ of $1.52\,\mathrm{GeV}^2$. The difference, $0.64\,\mathrm{GeV}^2$, is plotted. For resonances with strangeness, the Regge trajectory starts at the $\Sigma^*(1385)$ mass but has the same slope.

3 Is there convincing evidence for glueballs ?

Glueballs, hybrid mesons and hybrid baryon are predicted by QCD inspired models and may even be a consequence of QCD on the lattice. But in spite of intensive searches, no convincing evidence for their discovery has been reported. Here, possible evidence concerning the pseudoscalar and the scalar glueball is discussed.

The pseudoscalar glueball The Particle Data Group [2] decided in their 2004 edition that there is sufficient evidence that the former $\eta(1440)$ is split into two components, the $\eta(1405)$ component decaying mostly into $a_0(980)\pi$ and $\eta\sigma$, and the $\eta(1475)$ with $\mathrm{K}^*\bar{\mathrm{K}}$ as preferred decay mode. In [3] it is shown however that 1^{st}, the $\eta(1295)$ has properties which exclude it to be a radial excitation, and that 2^{nd}, the $\eta(1405)$ and $\eta(1475)$ peaks can be explained by assuming that there is one radial excitation, the $\eta(1440)$ having a wave function with a node. The node has an impact on the decay matrix element

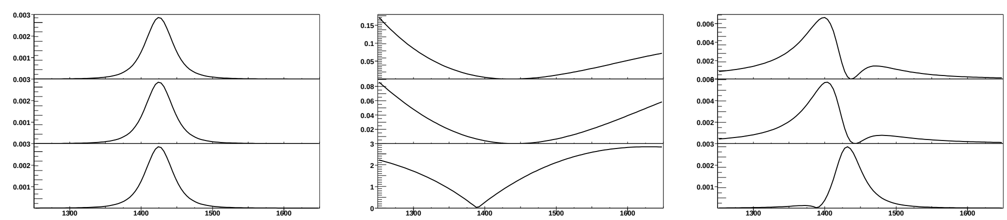


Figure 3: Amplitudes for $\eta(1440)$ decays to $a_0\pi$ (first row), $\sigma\eta$ (second row), and $\mathrm{K}^*\bar{\mathrm{K}}$ (third row); the Breit-Wigner functions are shown on the left, then the squared decay amplitudes [4] and, on the right, the resulting squared transition matrix element.

which were calculated by [4] within the $^3P_0$ model. The decay matrix element has a zero at a mass which is different for $\mathrm{K}^*\bar{\mathrm{K}}$ and $a_0(980)\pi/\eta\sigma$ decays shifting the former mode upwards in mass and the latter mode down in mass (see Fig. 3). Also, the $a_0(980)\pi$ phase motion of Fig. 4 does not support the presence of more than one state. Hence there is only one η state in the mass range from 1250 to 1500 MeV and not three. The following states are identified as pseudoscalar ground states and radial excitations:

1^1S_0	π	η'	η	K
2^1S_0	$\pi(1300)$	$\eta(1760)$	$\eta(1440)$	K(1460)

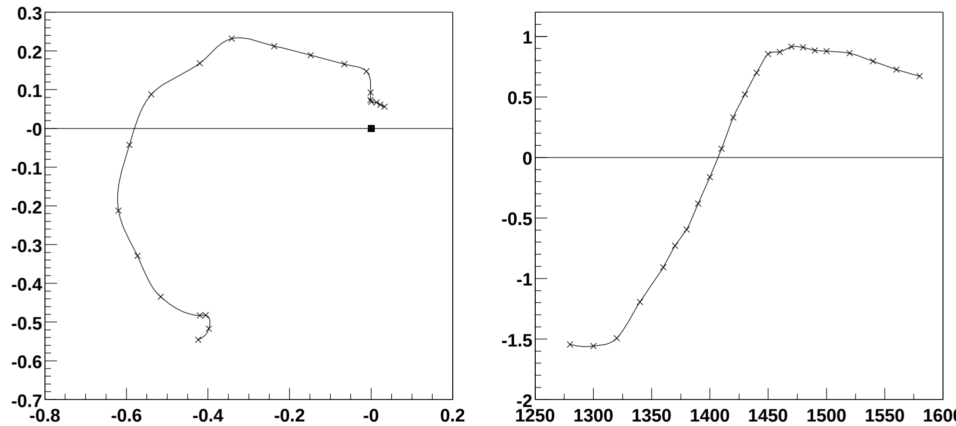


Figure 4: Complex amplitude and phase motion of the $a_0(980)\pi$ isobars in $p\bar{p}$ annihilation into $4\pi\eta$. In the mass range from 1300 to 1500 MeV the phase varies by π indicating that there is only one resonance in the mass interval. The $\sigma\eta$ (not shown) exhibits the same behavior.

The scalar glueball The lowest–mass glueball has scalar quantum numbers hence it may hide in the spectrum of scalar mesons. The spectrum has provoked an intensive discussion, and there are very different interpretations [5, 6, 7, 8, 9, 10, 11]. The Particle Data Group lists the following entries: $f_0(600)$, $K_0^*(800)$, $a_0(980)$, $f_0(980)$, $f_0(1370)$, $K_0^*(1430)$, $a_0(1490)$, $f_0(1500)$, $f_0(1710)$, $K_0^*(1950)$, $f_0(2020)$, $f_0(2100)$, and $f_0(2200)$, i.e. two a_0, two K_0^*, and 8 f_0. There is clearly an abundance of isoscalar mesons and thus the hope that the scalar glueball is part of this spectrum.

The most complete analysis of the scalar spectrum was presented in [6, 12, 13] This analysis takes into account that coupled–channel effects play a decisive role in S–wave meson–meson scattering. The opening of thresholds attracts pole positions and the resonances found experimentally do not need to agree with masses as calculated in quark models. Under normal circumstances, K–matrix poles, poles of the scattering matrix T and positions of observed peaks agree approximately, and the interpretation is unambiguous. In S–waves, the situation is more complicated. The mass of the resonance as quoted by experiments is the T–matrix pole. Quark models usually do not take into account the couplings to the final state. The authors of [6, 12, 13] give K–matrix poles, and these are compared in Table 1 to quark model results from the Bonn model [14] with the Lorentz

Table 1: The K–matrix poles of [15] show a remarkable agreement with the results of the Bonn model [14], version B. There is an additional pole at (1400 ± 200) MeV far off the real axis (i.e. ~ 1000 MeV broad), which is a flavor singlet and could be the glueball.

K-matrix poles			Bonn model, B		
	$a_0(980 \pm 30)$	$f_0(680 \pm 50)$		$a_0(1057)$	$f_0(665)$
$K_0^*(1230 \pm 40)$	$a_0(1630 \pm 40)$	$f_0(1260 \pm 30)$	$K_0^*(1187)$	$a_0(1665)$	$f_0(1262)$
		$f_0(1400 \pm 200)$			
		$f_0(1600)$			$f_0(1554)$
$K_0^*(1885^{+50}_{-100})$			$K_0^*(1788)$		
		$f_0(1810 \pm 50)$			$f_0(1870)$

structure B of the confinement potential. Excellent agreement is observed. The two lowest scalar nonets are identified, and there is one additional state, the $f_0(1400 \pm 200)$. Its couplings to two pseudoscalar mesons are flavor–blind, it is an isoscalar state. This is why it can be identified as a scalar glueball. The width is problematic, it exceeds 2 GeV.

Can the wide resonance be identified with a glueball? This is neither known nor tested. One critical point of the analysis is the neglect of left–hand cuts, of the possibility that t–channel exchanges do not generate poles in the scattering matrix. In particular broad states are suspicious but even the narrow $a_0(980)$ and $f_0(980)$ can be interpreted as $K\bar{K}$ states bound by the exchange of vector mesons in the t–channel.

A minimum requirement for a pole to be identified as an s–channel resonance is the request that its partial widths for decays into different final states be independent of its production. As pointed out in [5] this requirement does not seem to be met by the $f_0(1370)$, a resonance which falls into the center of the scalar mass spectrum and which plays a central role in all claims that the scalar glueball has been found.

Does this mean that a scalar glueball cannot be identified? A possibility to discriminate a glueball against dominant contributions from ordinary mesons and pole produced via t–channel exchanges is to compare different J/ψ decay modes:

1. $J/\psi \to \omega\pi\pi$, $J/\psi \to \omega K\bar{K}$, $J/\psi \to \omega\eta\eta$, $J/\psi \to \omega\eta\eta'$, $J/\psi \to \omega 4\pi$

2. $J/\psi \to \phi\pi\pi$, $J/\psi \to \phi K\bar{K}$, $J/\psi \to \phi\eta\eta$, $J/\psi \to \phi\eta\eta'$, $J/\psi \to \phi 4\pi$
3. $J/\psi \to \gamma\pi\pi$, $J/\psi \to \gamma K\bar{K}$, $J/\psi \to \gamma\eta\eta$, $J/\psi \to \gamma\eta\eta'$, $J/\psi \to \gamma 4\pi$

The data can likely be described by the pole positions given in Table 1. The glueball components of scalar mesons do not couple to processes (1) and (2) but only to (3). Thus the glueball component can be identified by a larger coupling of one pole to radiative decays (3). Channels containing $\eta\eta$ and $4\pi^0$ are best suited since a pion pair may also be produced from two primary gluons by pion or ρ exchange between the gluons, with colour neutralization by soft–gluon exchange. For $\eta\eta$ and $4\pi^0$ this process cannot occur.

4 Is there convincing evidence for hybrids ?

The status of $J^{PC} = 1^{-+}$ exotic mesons has recently been reviewed [16]. There are a series of observations which can be grouped to form four resonances at masses $1370, 1390$, 1625 and 2000 MeV. The lowest–mass candidate, $\pi_1(1370)$, decays into $\pi\eta$ and must be a four–quark state due to symmetry arguments. A plethora of further four–quark states is then expected, making unrealistic the attempt to identify one of them as hybrid. The N(1440) [17] and the $\Lambda(1600)$ [18] were proposed to be hybrid baryons, but these interpretations are not compelling.

5 Pentaquarks

Kubantsev gave, at this workshop, a very good and detailed overview about recent results on pentaquarks. The situation certainly deserves further experimental study. The $\Theta^+(1540)$ is suggested to be a member of an anti-decuplet with 7 states belonging to an octet and thus being allowed to mix with ordinary baryons, and 3 states having exotic quantum numbers which cannot be formed by adding flavours of three constituent quarks. The $\Phi^{--}(1860)$ decaying to $\Xi^-\pi^-$ has been claimed as second corner of the anti-decuplet. Here I would just like to point out that there are two different types of interpretations of these new baryons.

Pentaquarks were predicted on the basis of the chiral soliton model. In the quark model picture, the chiral soliton model describes nucleons by three valence quarks polarising the Dirac sea. Tentatively, I like to ascribe the three valence quarks to the large-x quark distribution in deep inelastic scattering, and the low-x quark distribution to the sea quarks. A photon hitting a strange sea quark may eject this, leaving a nucleon with

Table I: Evidence for $J^{PC} = 1^{-+}$ Exotic Mesons [a]

Experiment	Mass (MeV/c^2)	Width (MeV/c^2)	Decay Mode	Reaction
BNL [19]	$1370 \pm 16 \; {}^{+50}_{-30}$	$385 \pm 40 \; {}^{+65}_{-105}$	$\eta\pi$	$\pi^- \mathrm{p} \to \eta\pi^- \mathrm{p}$
BNL [20]	$1359 \; {}^{+16}_{-14} \; {}^{+10}_{-24}$	$314 \; {}^{+31}_{-29} \; {}^{+9}_{-66}$	$\eta\pi$	$\pi^- \mathrm{p} \to \eta\pi^- \mathrm{p}$
CBar [21]	$1400 \pm 20 \pm 20$	$310 \pm 50 \; {}^{+50}_{-30}$	$\eta\pi$	$\bar{\mathrm{p}}\mathrm{n} \to \pi^-\pi^0\eta$
CBar [22]	1360 ± 25	220 ± 90	$\eta\pi$	$\bar{\mathrm{p}}\mathrm{p} \to \pi^0\pi^0\eta$
CBar [23]	$\sim$1440	$\sim$400	$\rho\pi$	$\bar{\mathrm{p}}\mathrm{n} \to \pi^- 3\pi^0$
Oblx [24]	1384 ± 28	378 ± 58	$\rho\pi$	$\bar{\mathrm{p}}\mathrm{p} \to 2\pi^+ 2\pi^-$
BNL [25]	$1593 \pm 8 \; {}^{+29}_{-47}$	$168 \pm 20 \; {}^{+150}_{-12}$	$\rho\pi$	$\pi^- \mathrm{p} \to \pi^+\pi^-\pi^- \mathrm{p}$
BNL [26]	1596 ± 8	387 ± 23	$\eta'\pi$	$\pi^- \mathrm{p} \to \pi^- \eta' \mathrm{p}$
VES [27]	1610 ± 20	290 ± 30	$\rho\pi, \eta'\pi$	$\pi^- \mathrm{N} \to \pi^- \eta' \mathrm{N}$
BNL [28]	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	$f_1(1285)\pi$	$\pi^- \mathrm{p} \to \eta\pi^+\pi^-\pi^- \mathrm{p}$
BNL [30]	$1664 \pm 8 \pm 4$	$185 \pm 25 \pm 12$	$b_1(1235)\pi$	$\pi^- \mathrm{p} \to \omega\pi^0\pi^- \mathrm{p}$
CBar [29]	1590 ± 50	280 ± 75	$b_1(1235)\pi$	$\bar{\mathrm{p}}\mathrm{p} \to \pi^+\pi^-\pi^0\omega$
BNL [28]	$\sim 2003 \pm 88 \pm 148$	$306 \pm 132 \pm 121$	$f_1(1285)\pi$	$\pi^- \mathrm{p} \to \eta\pi^+\pi^-\pi^- \mathrm{p}$
BNL [30]	$2000 \pm 20 \pm 10$	$230 \pm 32 \pm 15$	$\omega\pi^0\pi^-$	$\pi^- \mathrm{p} \to \omega\pi^0\pi^- \mathrm{p}$

[a] States supposed to be distinct are separated by double-lines.
The six entries in the 1590 to 1710 MeV range might be one or two states.

a flavoured sea. In quark models, pentaquarks are described by four valence quarks and a valence antiquark, with some special sort of di-quark interactions to reduce the mass. The relation between the quark distribution in deep inelastic scattering and the chiral soliton model is certainly hypothetical only, but may point into a direction in which a synthesis can be formed of hadron spectroscopy and the quark model, and the quark distribution as seen in deep inelastic scattering.

6 Conclusions

The majority of established mesons and baryons can be interpreted within the quark model as $q\bar{q}$ or qqq bound states. This can be an approximation only; the ρ-meson e.g.

with its large coupling to $\pi\pi$ must have a four-quark component and could as well have contributions from gluonic excitations. The Fock space of the ρ or a f_0 must be more complicated than just $q\bar{q}$. We may write

$$f_0 = \alpha q\bar{q} + \beta gg + \gamma_1 b\bar{q}q\bar{q}q + ... + \delta_1 q\bar{q}g + ...$$

where we have used gg and $q\bar{q}g$ as short–hand for gluonic excitations. A similar expansion holds for baryons, of course with no glueball component. The orthogonal states may be shifted into the continuum. Now one might ask, "are higher-order terms important and what is the relative importance of the β, γ and δ series ?"

Presently, there is no compelling evidence for glueballs or gluonic hybrids in hadron spectroscopy. However, exotic states with no contributions from $q\bar{q}$ or qqq like the $\pi_1(1360)$ and the $\Theta^+(1540)$ suggest that multiquark configurations do play a significant role.

In summary, gluons seem to play a less decisive role in spectroscopy than thought for a long time. In baryon spectroscopy, instanton–induced forces give a better description than one-gluon exchange. There have been long searches for glueballs and hybrids but no convincing evidence was found. The chiral soliton model may give a more convincing interpretation of the pentaquarks than models based on five-quark dynamics.

References

[1] E. Klempt, "Glueballs, hybrids, pentaquarks: Introduction to hadron spectroscopy and review of selected topics", arXiv:hep-ph/0404270.

[2] S. Eidelman *et al.*, Phys. Lett. B **592** (2004) 1.

[3] E. Klempt, "The glueball candidate $\eta(1440)$ as η radial excitation", arXiv:hep-ph/0409148.

[4] T. Barnes, F. E. Close, P. R. Page and E. S. Swanson, Phys. Rev. D **55** (1997) 4157.

[5] E. Klempt, "Meson spectroscopy: Glueballs, hybrids and $q\bar{q}$ mesons", PSI Zuoz Summer School 'Phenomenology of Gauge Interactions' August 13-19, 2000. arXiv:hep-ex/0101031.

[6] V. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A **16** (2003) 229.

[7] S. F. Tuan, "Arguments on the light-mass scalar mesons and concluding remarks of the meson sessions", International Symposium on Hadron Spectroscopy, Chiral Symmetry and Relativistic Description of Bound Systems, Tokyo, Japan, 24-26 Feb 2003. arXiv:hep-ph/0303248.

[8] W. Ochs, "The scalar meson sector and the sigma, kappa problem", AIP Conf. Proc. **717** (2004) 295 [arXiv:hep-ph/0311144].

[9] J. Speth, F. P. Sassen and S. Krewald, Nucl. Phys. A **721** (2003) 679.

[10] C. Amsler and N. A. Tornqvist, Phys. Rept. **389** (2004) 61.

[11] D. V. Bugg, Phys. Rept. **397** (2004) 257.

[12] V. V. Anisovich, Y. D. Prokoshkin, A. V. Sarantsev, Phys. Lett. B **389** (1996) 388.

[13] A. V. Anisovich and A. V. Sarantsev, Phys. Lett. B **413** (1997) 137.

[14] E. Klempt, B. Metsch, C. Münz, H. Petry, Phys. Lett. B **361** (1995) 160.
M. Koll, R. Ricken, D. Merten, B. Metsch, H. Petry, Eur. Phys. J. A **9** (2000) 73.
R. Ricken, M. Koll, D. Merten, B. Metsch, H. Petry, Eur. Phys. J. A **9** (2000) 221.

[15] A. V. Sarantsev, Lecture at the PNPI Winter School, St. Petersburg (2003).

[16] S. U. Chung and E. Klempt, "Exotic Hadrons: Pentaquarks, hybrids and $q\bar{q}q\bar{q}$ mesons", submitted to EPJC.

[17] S. Capstick and P. R. Page, Phys. Rev. D **60** (1999) 111501.

[18] L. S. Kisslinger, Phys. Rev. D **69** (2004) 054015.

[19] D. R. Thompson *et al.*, Phys. Rev. Lett. **79** (1997) 1630.

[20] S. U. Chung *et al.*, Phys. Rev. **D60** (1999) 092001.

[21] A. Abele *et al.*, Phys. Lett. **B423** (1998) 175.

[22] A. Abele *et al.*, Phys. Lett. **B446** (1999) 349.

[23] W. Dünnweber and F. Meyer–Wildhagen, "Exotic states in Crystal Barrel analyses of annihilation channels", Hadron03 conference, Aschaffenburg (2003), www-kp3.gsi.de/∼orth/hadron03.tgz; Nucl. Phys. A**721** (2003) 605c.

[24] P. Salvini *et al.*, Eur. Phys. J. C **35** (2004) 21.

[25] G. S. Adams *et al.*, Phys. Rev. Lett. **81** (1998) 5760.

[26] E. I. Ivanov *et al.*, Phys. Rev. Lett. **86** (2001) 3977.

[27] Y. Khokhlov *et al.*, Nucl. Phys. A **663** (2000) 596.

[28] J. Kuhn *et al.*, Phys. Lett. B **595** (2004) 109.

[29] C. A. Baker *et al.*, Phys. Lett. B **563** (2003) 104.

[30] M. Lu, PhD thesis, Renssallaer Polytechnic Institute, quoted from J. Kuhn, "Evidence for exotic mesons", Hadron03 conference, Aschaffenburg (2003), www-kp3.gsi.de/∼orth/hadron03.tgz.