Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

NON-$q\overline{q}$ CANDIDATES

We include here mini-reviews and reference lists on gluonium and other non-$q\overline{q}$ candidates. See also the section on Further States for possible bound states.

NON-$q\overline{q}$ MESONS

Revised December 2003 by C. Amsler (University of Zürich).

The constituent quark model describes the observed meson spectrum as bound $q\overline{q}$ states grouped into SU(N) flavor multiplets (see our review on the quark model). However, the self-coupling of gluons in QCD suggests that additional mesons made of bound gluons (glueballs), or $q\overline{q}$-pairs with an excited gluon (hybrids), may exist. Multiquark color singlet states like $qq\overline{q}\overline{q}$ or $qqq\overline{q}\overline{q}\overline{q}$ have also been predicted (JAFFE 77). Among the signatures naively expected for glueballs are (i) no place in $q\overline{q}$ nonets, (ii) enhanced production in gluon-rich channels such as central production and radiative $J/\psi(1S)$ decay, (iii) decay branching fractions incompatible with SU(N) predictions for $q\overline{q}$ states, and (iv) reduced $\gamma\gamma$ couplings. However, mixing effects with isoscalar $q\overline{q}$ mesons (AMSLER 96, ANISOVICH 97, WEINGARTEN 97, CLOSE 01B) and decay form factors (BARNES 97) may obscure these simple signatures.

Lattice calculations (BALI 93, SEXTON 95, MORNINGSTAR 99), QCD sum rules, flux tube, and constituent glue models agree that the lightest glueballs have quantum numbers $J^{PC} = 0^{++}$ and 2^{++}. On the lattice, the scale parameter (estimated from the string tension in heavy quark mesons) gives by extrapolation to zero lattice spacing a mass of 1611 $\pm$ 163 MeV for the ground state (0^{++}) glueball, while the first excited state (2^{++}) has a mass of 2232 $\pm$ 310 MeV (MICHAEL 97). Hence, the low-mass glueballs lie in the same mass region as ordinary isoscalar $q\overline{q}$

states, that is, in the mass range of the $1^3P_0(0^{++})$, $2^3P_2, 3^3P_2$, and $1^3F_2(2^{++})$ $q\overline{q}$ states. The 0^{-+} state and exotic glueballs (with non-$q\overline{q}$ quantum numbers such as 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, *etc.*) are expected above 2 GeV (MORNINGSTAR 99).

The lattice calculations assume that the quark masses are infinite, and therefore neglect $q\overline{q}$ loops. However, one expects that glueballs will mix with nearby $q\overline{q}$ states of the same quantum numbers. The presence of a glueball mixed with $q\overline{q}$ would still lead to a supernumerary isoscalar in the SU(3) classification of $q\overline{q}$ mesons.

For earlier experimental searches, we refer to the Notes in the 1996 and 1998 issues of this *Review*. For a detailed recent review on exotic mesons, see AMSLER 04.

We first deal with non-$q\overline{q}$ candidates in the scalar sector. Five isoscalar resonances are well established: the very broad $f_0(600)$ (or σ), the $f_0(980)$, the broad $f_0(1370)$, and the comparatively narrow $f_0(1500)$ and $f_0(1710)$ (see the Note on "Scalar Mesons," and also AMSLER 98). The $f_0(1500)$ was observed in many experiments, *e.g.*, in $\pi^- p$ reactions, in $\overline{p}p$ annihilations, in central collisions, in $J/\psi(1S)$ radiative decays, and in D_s decays (see the Meson Particle Listings). The $f_0(1710)$ decays mainly into $K\overline{K}$. This points to a mostly $s\overline{s}$ structure, although no signal was reported earlier in $K^- p \rightarrow K_S K_S \Lambda$ interactions (ASTON 88D). However, the assumption was that the spin would be 2. Also, the $f_0(1710)$ is not observed in $p\overline{p}$ annihilation (AMSLER 02), as expected from the OZI rule for an $s\overline{s}$ state.

In $\gamma\gamma$ collisions leading to $K_S K_S$ (ACCIARRI 01H) and K^+K^- (ABE 04), a signal is observed at the $f_0(1710)$ mass. Spin 2 is preferred, but the isospin cannot be determined, hence, the signal is possibly coming from $a_2(1700)$. A spin 0 component from the $s\overline{s}$ $f_0(1710)$ is compatible with data.

On the other hand, $f_0(1500)$ is not observed in $\gamma\gamma \to K_S K_S$ nor $\pi^+\pi^-$ (BARATE 00E). The upper limit from $\pi^+\pi^-$ excludes a large $u\overline{u}+d\overline{d}$ content, and points to a mainly $s\overline{s}$ meson (AMSLER 02B). This is, however, in contradiction with the small $K\overline{K}$ decay branching ratio of $f_0(1500)$ (ABELE 96B,98, BARBERIS 99D). Hence, this state is hard to accommodate as a $q\overline{q}$ meson.

Since $f_0(1370)$ does not couple strongly to $s\overline{s}$ either (BARBERIS 99D), $f_0(1370)$ or $f_0(1500)$ appear to be supernumerary. Note that $f_0(1370)$ and $f_0(1500)$ have rather different 4π decay patterns. The former decays dominantly into two S-wave dipions, and the latter mostly into $\pi(1300)\pi$ (ABELE 01,01B). The narrow width of $f_0(1500)$, and its enhanced production at low transverse momentum transfer in central collisions (CLOSE 97,98B, KIRK 00) also favor $f_0(1500)$ to be non-$q\overline{q}$. In AMSLER 96, the ground state scalar nonet is made of $a_0(1450)$, $f_0(1370)$, $K_0^*(1430)$, and $f_0(1710)$. The isoscalars $f_0(1370)$ and $f_0(1710)$ contain a small fraction of glue, while $f_0(1500)$ is mostly gluonic. The light scalars $f_0(600)$, $f_0(980)$, $a_0(980)$, and $\kappa(800)$ are four-quark states or two-meson resonances (see AMSLER 04 for a review). In the mixing scheme of CLOSE 01B, which uses all recent data in central production and $p\overline{p}$ annihilation, glue is shared between $f_0(1370)$ and $f_0(1500)$, while $f_0(1710)$ remains mainly $s\overline{s}$.

Alternative mixing schemes have been proposed (see for example TORNQVIST 96, ANISOVICH 97, BOGLIONE 97, WEINGARTEN 97, MINKOWSKI 99).

As mentioned above, $a_0(980)$ and $f_0(980)$ could be four-quark states (JAFFE 77, ALFORD 00) or $K\overline{K}$ molecular states (WEINSTEIN 90, LOCHER 98) due to their strong affinity for $K\overline{K}$, in spite of their masses being very close to threshold. For $q\overline{q}$ states, the expected $\gamma\gamma$ widths (OLLER 97B, DELBOURGO 99) are not significantly larger than for molecular states (BARNES

85). A better filter is radiative $\phi(1020)$ decay to $a_0(980)$ and $f_0(980)$. Recent data (ALOISIO 02C, 02D) favor these mesons to be four-quark states (ACHASOV 00F). The $f_0(980)$ is strongly produced in D_s^+ decay (FRABETTI 97, AITALA 01A). Assuming a dominant Cabibbo favored $c \to s$ decay suggests a large $s\overline{s}$ component. However, the mainly $u\overline{u} + d\overline{d}$ $f_0(1370)$ is also strongly produced in D_s^+ decay, indicating that other graphs must contribute (CHENG 03B).

Two very narrow states, $D_{sJ}(2317)^{*\pm}$ and $D_{sJ}(2460)^{*\pm}$, were observed recently at the B-factories (AUBERT 03G, BESSON 03), the former with preferred spin 0^+, the latter with 1^+. They lie far below the predicted masses for the two expected broad P-wave $c\overline{s}$ mesons. These states have hence been interpreted as four-quark states (CHENG 03C, TERASAKI 03) or DK (DK^*) molecules (BARNES 03). However, strong cusp effects due to the nearby closed DK, respectively DK^* thresholds, could shift their masses downwards and quench the observed widths, an effect similar to that occuring for the $a_0(980)$ and $f_0(980)$ mesons, which lie just below the $K\overline{K}$ threshold.

We now turn to the 2^{++} sector. The isoscalar $1^3P_2(2^{++})$ $q\overline{q}$ mesons, $f_2(1270)$, and $f_2'(1525)$, are well known. Above the $f_2'(1525)$, none of the reported isoscalars can be definitely assigned to the 2^3P_2, 3^3P_2, or 1^3F_2 nonets, and therefore, the identification of the 2^{++} glueball is premature. Three states appear to be solid. The $f_2(1565)$ observed in $\overline{p}p$ annihilation at rest (MAY 90, BERTIN 98) is perhaps the same state as $f_2(1640)$, reported to decay into $\omega\omega$ (ALDE 90, BAKER 99) and 4π (ADAMO 92). This could be one of the 2^3P_2 isoscalars or a nucleon-antinucleon resonance. The broad $f_2(1950)$ is observed by several experiments, *e.g.*, in central production (BARBERIS 00C) and in $\overline{p}p$ annihilation in flight (AMSLER 02). The large

$\phi\phi$ cross section in $\overline{p}p$ just above threshold (EVANGELISTA 98) could be due to the production of the 2^{++} glueball, in accord with earlier observations in $\pi^- N$ reactions (BOOTH 86, ETKIN 88) and in central collisions (BARBERIS 98).

There is no evidence for a narrow meson, $f_J(2220)$ (possibly a tensor) in $\overline{p}p$ annihilation (see the Note under the $f_J(2220)$ section). The measured partial width to $\overline{p}p$ in radiative $J/\psi(1S)$ decay (BAI 96B) is too large and inconsistent with the upper limit from $\overline{p}p$ annihilation into $\pi\pi$ (AMSLER 01).

Let us now deal with hybrid states. Hybrids may be viewed as $q\overline{q}$ mesons with a vibrating gluon flux tube. In contrast to glueballs, they can have isospin 0 and 1. The mass spectrum of hybrids with exotic (non-$q\overline{q}$) quantum numbers was predicted by ISGUR 85, while CLOSE 95 also deals with non-exotic quantum numbers. The ground state hybrids with quantum numbers (0^{-+}, 1^{-+}, 1^{--}, and 2^{-+}) are expected around 1.7 to 1.9 GeV. Lattice calculations predict that the hybrid with exotic quantum numbers 1^{-+} lies at a mass of 1.9 ± 0.2 GeV (LACOCK 97, BERNARD 97). Most hybrids are rather broad, but some can be as narrow as 100 MeV (PAGE 99). They prefer to decay into a pair of S- and P-wave mesons.

A $J^{PC} = 1^{-+}$ exotic meson, $\pi_1(1400)$, was reported in $\pi^- p \rightarrow \eta\pi^- p$ (THOMPSON 97, CHUNG 99). It was observed as an interference between the angular momentum $L = 1$ and $L = 2$ $\eta\pi$ amplitudes, leading to a forward/backward asymmetry in the $\eta\pi$ angular distribution. This state was reported earlier in $\pi^- p$ reactions (ALDE 88B), but ambiguous solutions in the partial-wave analysis were pointed out by PROKOSHKIN 95B,95C. A resonating 1^{-+} contribution to the $\eta\pi$ P wave is also required in the Dalitz plot analysis of $\overline{p}n$ annihilation into $\pi^-\pi^0\eta$ (ABELE 98B), and in $\overline{p}p$ annihilation into $\pi^0\pi^0\eta$ (ABELE 99). Mass and width are consistent with THOMPSON 97.

Another 1^{-+} state, $\pi_1(1600)$, decaying into $\rho\pi$ (ADAMS 98B) and $\eta'\pi$ (IVANOV 01), was reported in the reaction $\pi^- p \rightarrow \pi^- \rho^0 (\pi^- \eta') n$. It was already observed earlier in the decay modes $\rho\pi$, $\eta'\pi$, and $b_1(1235)\pi$, but not $\eta\pi$ (GOUZ 92). A strong enhancement in the 1^{-+} $\eta'\pi$ wave, compared to $\eta\pi$, was reported at this mass by BELADIDZE 93. DONNACHIE 98 suggests that a Deck-generated $\eta\pi$ background from final state rescattering in $\pi_1(1600)$ decay could mimic $\pi_1(1400)$. However, this mechanism is absent in $\overline{p}p$ annihilation. The $\eta\pi\pi$ data require $\pi_1(1400)$ and cannot accommodate a state at 1600 MeV (DUENNWEBER 99).

Thus, we now have evidence for two 1^{-+} exotics, $\pi_1(1400)$ and $\pi_1(1600)$, while the flux tube model and the lattice concur to predict a mass of about 1.9 GeV, where a signal had been reported earlier (LEE 94). As isovectors, $\pi_1(1400)$ and $\pi_1(1600)$ cannot be glueballs. The coupling to $\eta\pi$ of the former points to a four-quark state (see also CHUNG 02C), while the strong $\eta'\pi$ coupling of the latter is favored for hybrid states (CLOSE 87B, IDDIR 01). Its mass is not far below the lattice prediction.

Finally, 0^{-+}, 1^{--}, and 2^{-+} hybrids were also reported. The $\pi(1800)$ decays mostly to a pair of S- and P-wave mesons (AMELIN 95B), in line with expectations for a 0^{-+} hybrid meson. This meson is also rather narrow if interpreted as the second radial excitation of the pion. The evidence for 1^{--} hybrids required in e^+e^- annihilation and in τ decays has been discussed by DONNACHIE 99. The $\rho(1900)$ seems too narrow for a $q\overline{q}$ radial excitation. A candidate for the 2^{-+} hybrid, the $\eta_2(1870)$, was reported in $\gamma\gamma$ interactions (KARCH 92), in $\overline{p}p$ annihilation (ADOMEIT 96), and in central production (BARBERIS 97B). The near degeneracy of $\eta_2(1645)$ and $\pi_2(1670)$ suggests ideal mixing in the 2^{-+} $q\overline{q}$ nonet, and hence, the second isoscalar should be mainly $s\overline{s}$. However, $\eta_2(1870)$ decays mainly to $a_2(1320)\pi$ and $f_2(1270)\pi$ (ADOMEIT 96), with a relative rate compatible with a hybrid state (CLOSE 95).

Non-$q\overline{q}$ Candidates

OMITTED FROM SUMMARY TABLE

NON-$q\overline{q}$ CANDIDATES REFERENCES

ABE 04 EPJ C32 323 K. Abe *et al.* (BELLE Collab.)
AMSLER 04 PRPL 389 61 C. Amsler, N.A. Tornqvist
AUBERT 03G PRL 90 242001 B. Aubert *et al.* (BaBar Collab.)
BARNES 03 PR D68 054006 T. Barnes *et al.*
BESSON 03 PR D68 032002 D. Besson *et al.* (CLEO Collab.)
CHENG 03B PR D67 054021 H.Y. Cheng
CHENG 03C PL B566 193 H.-Y. Cheng, W.-S. Hou
TERASAKI 03 PR D68 011501 K. Terasaki
ALOISIO 02C PL B536 209 A. Aloisio *et al.* (KLOE Collab.)
ALOISIO 02D PL B537 21 A. Aloisio *et al.* (KLOE Collab.)
AMSLER 02 EPJ C23 29 C. Amsler *et al.*
AMSLER 02B PL B541 22 C. Amsler
CHUNG 02C EPL A15 539 S.U. Chung, E. Klempt, J.G. Korener
ABELE 01 EPJ C19 667 A. Abele *et al.* (Crystal Barrel Collab.)
ABELE 01B EPJ C21 261 A. Abele *et al.* (Crystal Barrel Collab.)
ACCIARRI 01H PL B501 173 M. Acciarri *et al.* (L3 Collab.)
AITALA 01A PRL 86 765 E.M. Aitala *et al.* (FNAL E791 Collab.)
AMSLER 01 PL B520 175 C. Amsler *et al.* (Crystal Barrel Collab.)
CLOSE 01B EPJ C21 531 F.E. Close, A. Kirk
IDDIR 01 PL B507 183 F. Iddir, A.S. Safir
IVANOV 01 PRL 86 3977 E.I. Ivanov *et al.*
ACHASOV 00F PL B479 53 M.N. Achasov *et al.* (Novosibirsk SND Collab.)
ALFORD 00 NP B578 367 M. Alford, R.L. Jaffe
BARATE 00E PL B472 189 R. Barate *et al.* (ALEPH Collab.)
BARBERIS 00C PL B471 440 D. Barberis *et al.* (WA 102 Collab.)
KIRK 00 PL B489 29 A. Kirk
ABELE 99 PL B446 349 A. Abele *et al.* (Crystal Barrel Collab.)
BAKER 99 PL B449 114 C.A. Baker *et al.*
BARBERIS 99D PL B462 462 D. Barberis *et al.* (Omega Expt.)
CHUNG 99 PR D60 092001 S.U. Chung *et al.* (BNL E852 Collab.)
DELBOURGO 99 PL B446 332 R. Delbourgo, D. Liu, M. Scadron
DONNACHIE 99 PR D60 114011 A. Donnachie, Yu.S. Kalashnikova
DUENNWEBER 99 NP A 663 + 664, 592C W. Duennweber
Proc. XV Particles and Nuclei Int. Conf., Uppsala
MINKOWSKI 99 EPJ C9 283 P. Minkowski, W. Ochs
MORNINGSTAR 99 PR D60 034509 C.J. Morningstar, M. Peardon
PAGE 99 PR D59 034016 P.R. Page, E.S. Swanson, A.P. Szczepaniak
ABELE 98B PL B423 175 A. Abele *et al.* (Crystal Barrel Collab.)
ADAMS 98B PRL 81 5760 G.S. Adams *et al.* (MPS Collab.)
AMSLER 98 RMP 70 1293 C. Amsler
BARBERIS 98 PL B432 436 D. Barberis *et al.* (Omega Expt.)
BERTIN 98 PR D57 55 A. Bertin *et al.* (OBELIX Collab.)
CLOSE 98B PL B419 387 F.E. Close
DONNACHIE 98 PR D58 114012 A. Donnachie *et al.*
EVANGELISTA 98 PR D57 5370 C. Evangelista *et al.* (JETSET Collab.)
LOCHER 98 EPJ C4 317 M.P. Locher *et al.* (PSI)
ANISOVICH 97 PL B395 123 A.V. Anisovich, A.V. Sarantsev (PNPI)
BARBERIS 97B PL B413 217 D. Barberis *et al.* (WA 102 Collab.)
BARNES 97 PR D55 4157 T. Barnes *et al.* (ORNL, RAL, MCHS)
BERNARD 97 PR D56 7039 C. Bernard *et al.* (MILC Collab.)
BOGLIONE 97 PRL 79 1998 M. Boglione *et al.*
CLOSE 97 PL B397 333 F. Close *et al.* (RAL, BIRM)
FRABETTI 97 PL B391 235 P.L. Frabetti *et al.* (FNAL E687 Collab.)

LACOCK	97	PL B401 308	P. Lacock *et al.*	(EDIN, LIVP)
MICHAEL	97	Hadron 97 Conf.	C. Michael	
AIP Conf.	Proc.	432 657		
OLLER	97B	Hadron 97 Conf.	J.A. Oller, E. Oset	
AIP Conf.	Proc.	432 413		
THOMPSON	97	PRL 79 1630	D.R. Thompson *et al.*	(E852 Collab.)
WEINGARTEN	97	NPPS 53 232	D. Weingarten	
ABELE	96B	PL B385 425	A. Abele *et al.*	(Crystal Barrel Collab.)
ADOMEIT	96	ZPHY C71 227	J. Adomeit *et al.*	(Crystal Barrel Collab.)
AMSLER	96	PR D53 295	C. Amsler, F.E. Close	(ZURI, RAL)
BAI	96B	PRL 76 3502	J.Z. Bai *et al.*	(BES Collab.)
TORNQVIST	96	PRL 76 1575	N.A. Tornqvist, M. Roos	(HELS)
AMELIN	95B	PL B356 595	D.V. Amelin *et al.*	(SERP, TBIL)
CLOSE	95	NP B443 233	F.E. Close, P.R. Page	(RAL)
PROKOSHKIN	95B	PAN 58 606	Y.D. Prokoshkin, S.A. Sadovsky	(SERP)
		Translated from YAF 58 662.		
PROKOSHKIN	95C	PAN 58 853	Y.D. Prokoshkin, S.A. Sadovsky	(SERP)
		Translated from YAF 58 921.		
SEXTON	95	PRL 75 4563	J. Sexton *et al.*	(IBM)
LEE	94	PL B323 227	J.H. Lee *et al.*	(BNL, IND, KYUN, MASD+)
BALI	93	PL B309 378	G.S. Bali *et al.*	(LIVP)
BELADIDZE	93	PL B313 276	G.M. Beladidze *et al.*	(VES Collab.)
ADAMO	92	PL B287 368	A. Adamo *et al.*	(OBELIX Collab.)
GOUZ	92	Dallas HEP 92, p. 572	Yu.P. Gouz *et al.*	(VES Collab.)
Proceedings XXVI Int. Conf. on High Energy Physics				
KARCH	92	ZPHY C54 33	K. Karch *et al.*	(Crystal Ball Collab.)
ALDE	90	PL B241 600	D.M. Alde *et al.*	(SERP, BELG, LANL, LAPP+)
MAY	90	ZPHY C46 203	B. May *et al.*	(ASTERIX Collab.)
WEINSTEIN	90	PR D41 2236	J. Weinstein, N. Isgur	(TNTO)
ALDE	88B	PL B205 397	D.M. Alde *et al.*	(SERP, BELG, LANL, LAPP)
ASTON	88D	NP B301 525	D. Aston *et al.*	(SLAC, NAGO, CINC, INUS)
ETKIN	88	PL B201 568	A. Etkin *et al.*	(BNL, CUNY)
CLOSE	87B	PL B196 245	F.E. Close, H.J. Lipkin	
BOOTH	86	NP B273 677	P.S.L. Booth *et al.*	(LIVP, GLAS, CERN)
BARNES	85	PL B165 434	T. Barnes	
ISGUR	85	PRL 54 869	N. Isgur, R. Kokoski, J. Paton	(TNTO)
JAFFE	77	PR D15 267,281	R. Jaffe	(MIT)