

EXOTIC MESONS, THEORY AND EXPERIMENT*

T. BARNES

Physics Division, Oak Ridge National Laboratory
Oak Ridge, TN 37831-6373, USA

Department of Physics and Astronomy, University of Tennessee
Knoxville, TN 37996-1501, USA

Institut für Theoretische Kernphysik der Universität Bonn
Nufallee 14–16, 53115 Bonn, Germany

Institut für Kernphysik, Forschungszentrum Jülich
52425 Jülich, Germany

(Received July 20, 2000)

The status of exotic mesons is summarized, including both theoretical expectations and experimental candidates. The current experimental candidates are “spin-parity exotics”; since these are most often considered possible hybrid mesons, the theoretical discussion will be mainly concerned with hybrids. The exotic meson candidates discussed are the surprisingly light $\pi_1(1400)$ and $\pi_1(1600)$.

PACS numbers: 12.39.Mk, 14.40.-n

1. Theoretical expectations*1.1. Exotics defined*

An “exotic meson” has J^{PC} or flavor quantum numbers forbidden to the $|q\bar{q}\rangle$ states of the nonrelativistic quark model.

The current experimental candidates are “spin-parity exotics”, which have J^{PC} forbidden to $q\bar{q}$ mesons. In principle one might also find flavor exotics in a multiquark sector, for example in $I = 2$, but no such (widely accepted) experimental candidates are known at present [1].

As a *caveat* we emphasize that every meson is a linear superposition of all allowed basis states, spanning $|q^2\bar{q}^2\rangle$, $|q\bar{q}g\rangle$, $|gg\rangle$, ... (where not strictly forbidden), with amplitudes that are determined by QCD interactions. For

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

convenience we usually classify resonances as “quarkonia”, “hybrids”, “glueballs” and so forth, and are implicitly assuming that one type of basis state dominates the state expansion of each resonance. Of course this may not be the case in general, and the amount of “configuration mixing” is an open and rather controversial topic in hadron physics. Exotics are special in that the $|q\bar{q}\rangle$ component must be zero, due to the quantum numbers of the state.

1.2. *What became of multiquarks?*

Multiquark systems such as $q^2\bar{q}^2$ were once expected to contribute a rich spectrum of resonances to the meson spectrum, and in the 1970’s there were many detailed calculations of the spectrum of multiquark resonances in various models. Now one hears little about this subject. What became of multiquarks?

The answer is that they “fell apart”. Even in the early work on $q^2\bar{q}^2$ multiquarks [2] it was realized that their decay couplings would be very different from conventional $q\bar{q}$ mesons; the latter decay mainly through the production of a second $q\bar{q}$ pair, whereas the $q^2\bar{q}^2$ system can simply be rearranged into a state of two $(q\bar{q}) + (q\bar{q})$ mesons. If the expected energy of a continuously deformed $q^2\bar{q}^2 \rightarrow (q\bar{q})(q\bar{q})$ system is monotonically decreasing, one would not expect to find a $q^2\bar{q}^2$ resonance. This was the situation found variationally in the scalar sector by Weinstein and Isgur for most light quark masses [3].

Life can be more complicated, Weinstein and Isgur also found that weakly bound deuteron-like $K\bar{K}$ states existed in their model. Presumably many more such weakly bound quasinuclear states exist, both in meson–meson and meson–baryon sectors. This subject of multihadron systems is at least as rich as the table of nuclear levels.

One often hears that the q^6 system may have a bound state in the $u^2d^2s^2I = 0$, $J = 0$ flavor sector, known as the “ H dibaryon” [4]. Caution is appropriate here. Some experiments that are nominally searching for the H dibaryon have “widened their net” to include states very close to $\Lambda\Lambda$ threshold; if one is found, it would more likely be a weakly bound $\Lambda\Lambda$ hypernucleus. It is important not to equate these two ideas. A $\Lambda\Lambda$ hypernucleus would certainly be a very interesting discovery, especially in its implications for models of the intermediate ranged baryon–baryon attraction, but it is *not* the H dibaryon envisaged in bag model calculations. The H dibaryon calculations assumed an SU(3) flavor-singlet $u^2d^2s^2$ system, and $\Lambda\Lambda$ is a quite different flavor state. Quark Model calculations actually find the $\Lambda\Lambda$ interaction to be repulsive, rather like the NN core.

It does appear likely that real multiquark $Q^2\bar{q}^2$ clusters will exist given sufficiently heavy quarks ($Q = c$, or perhaps only b) [5], but these are unfortunately not easily accessible to experiment.

1.3. Hybrid mesons

A hybrid meson is usually “defined” as a resonance whose dominant valence component is $|q + \bar{q} + \text{excited glue}\rangle$. This deliberately vague definition covers our present ignorance over how one can most accurately describe gluonic excitation. Possibilities include models with explicit transverse gluon quanta, such as the bag model, as well as an excitation of the flux tube that one sees in LGT simulations. Fortunately for experimenters, many of the model calculations reach rather similar predictions for the properties of these states.

One general conclusion is that, unlike $q\bar{q}$, *all* J^{PC} can be constructed from hybrid basis states. This conclusion is seen most rigorously in the list of gauge-invariant local operators that one may construct from a product of $\bar{\psi}, \psi$ and $F_{\mu\nu}^a$, since one may couple to physical states by operating on the vacuum $|0\rangle$ with such an “interpolating field”. This list of $\bar{\psi} \otimes \psi \otimes F$ operators covers all J^{PC} , including the so-called exotic combinations

$$J^{PC} \Big|_{\text{exotic}} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \dots$$

that one cannot construct from a $\bar{\psi} \otimes \psi$ quarkonium operator.

At present the experimental J^{PC} exotics are usually considered to be hybrid meson candidates, simply because theorists know of no other general class of J^{PC} exotic resonance, excepting multiquark systems that purportedly “fall apart” into light $q\bar{q}$ mesons. (Possible exceptions which merit future investigation are weakly bound quasinuclear states, which might exist near threshold in S -wave in attractive meson–meson channels.)

In any case, if a J^{PC} exotic meson is found, we can be certain that we have discovered something beyond the naive quark model. This is an extremely important possibility experimentally, and assuming that such states are clearly identified we may hope that the pattern of their spectroscopy will eventually make it clear just what has been discovered!

2. Specific models of hybrids

2.1. Introduction

Much of the work on hybrids has made use of very specific models of “excited glue”. These models are the bag model, the flux tube model, and the rather underexplored constituent gluon model. Finally, masses and other properties of J^{PC} exotic hybrids may be predicted by QCD sum rules and LGT using interpolating fields, and these approaches do not make model assumptions about the nature of gluonic excitation. We will discuss some of the more fundamental results of these models, especially as regards masses, quantum numbers and decay properties.

2.2. Bag model hybrids

Many early hybrids studies used the bag model, which assumed that quarks and gluons could be treated as spherical cavity modes of Dirac and Maxwell quanta, confined within the cavity by the choice of color boundary conditions. The “zeroth-order” bag model states were color singlet product basis states of quark, antiquark and gluon modes, for example

$$|q\bar{q}\rangle, \quad |q\bar{q}g\rangle, \quad |gg\rangle, \quad |q^2\bar{q}^2\rangle, \dots$$

The quark–gluon and gluon self interactions mixed these basis states, so that the physical levels were linear combinations of these “bare” basis states, just as we anticipated in our introduction. The distinction between “conventional $q\bar{q}$ meson” and “nonexotic hybrid” in the bag model was thus rather vague, and was clearest as a theoretical identification when the strength of the QCD coupling constant was made small. The bag model gave a rather good description of the light “conventional $q\bar{q}$ meson” spectrum as $|q\bar{q}\rangle + O(\sqrt{\alpha_s})|q\bar{q}g\rangle$ states, and the hybrids appeared as an extra set of $|q\bar{q}g\rangle + O(\sqrt{\alpha_s})(|q\bar{q}\rangle + |q\bar{q}g^2\rangle + \dots)$ states, which should appear as an “overpopulation” of the experimental meson spectrum relative to the naive $q\bar{q}$ quark model.

In the bag model the lowest quark mode is a conventional $J^P = 1/2^+$, but the lowest gluon mode is a (perhaps surprising) $J^P = 1^+$ TE gluon. Combining these lowest lying $q, \bar{q}$ and g modes, one finds hybrid basis states with

$$J^{PC} \Big|_{\text{bag-model hybrids}} = \left(0^-, 1^-\right) \otimes 1^+ = 1^{--}, 0^{-+}, 1^{-+}, 2^{-+}.$$

Thus the bag model predicts that the lowest lying hybrid multiplet should consist of these $4J^{PC}$, of which the 1^{-+} combination is exotic. Hybrid mass estimates required detailed calculations in which configuration mixing with the other quark+gluon basis states was included to $O(\sqrt{\alpha_s})$, and the resulting truncated Hamiltonian was diagonalized. The results depended somewhat on the bag model parameters assumed, with masses of ≈ 1.5 GeV being typical [6, 7]. Spin dependent splittings ordered the levels as $0^{-+} < 1^{-+} < 1^{--} < 2^{-+}$, with a total multiplet splitting of *ca* 500 MeV with the usual bag model parameters. Since each of these J^{PC} levels is a flavor nonet in the u, d, s system, many hybrid states are predicted that might be experimentally accessible.

One may also form baryon hybrids, since the basis states $|qqqg\rangle$ contain color singlets. The corresponding bag model calculations of the spectrum of baryon hybrids [8–10] predict a lowest multiplet of u, d “hybrid baryons” with a mean mass of about 2 GeV, and J^P , *flavor* content of $(1/2^+ N)^2$,

$(3/2^+ N)^2$, $(5/2^+ N)$, $(1/2^+ \Delta)$, $(3/2^+ \Delta)$. The spin-splittings due to quark-gluon and gluon-gluon forces predict rather large overall multiplet splitting of *ca* 500 MeV, resulting in a $(1/2^+ N)$ near 1.5 GeV as the lightest hybrid baryon. This result led to the speculation that the $N(1440)$ Roper might be the lightest hybrid baryon. Of course there are no J^P exotics in the baryons, since all J^P can be made from qqq . Since $|qqq\rangle \leftrightarrow |qqqg\rangle$ configuration mixing is large in the bag model, the distinction between hybrid and conventional baryons is problematic. One must simply conclude that, in the context of this model, there should be an overpopulation of baryons relative to the simple $|qqq\rangle$ quark model, due to the presence of the extra $|qqqg\rangle$ basis states.

2.3. Flux-tube model hybrids

In LGT simulations a roughly cylindrical region of chaotic glue fields can be observed between widely separated static color sources. This “flux tube” leads to the confining linear potential between color-singlet q and $\bar{q}$ that is familiar from quark potential models. The “flux tube model” [11] is an approximate description of this state of glue, which is treated as a string of point masses “beads” connected by a linear potential. This system is treated quantum mechanically, and has normal modes of excitation which are transverse to the axis between the (fixed) endpoints of the string. The orbital angular momentum of a transverse string excitation may be combined with the $q\bar{q}$ spin and orbital angular momentum using rigid body wavefunctions, which leads to predictions for the quantum numbers of these flux-tube hybrids. Since the assumption about the nature of excited glue is quite different from the 1^+ TE gluon mode of the bag model, one finds a different spectrum of hybrid states. The lowest flux-tube hybrids are predicted to span 8 J^{PC} levels, all degenerate in the simplest version of the model, with

$$J^{PC} \Big|_{\text{flux-tube hybrids}} = 0^{\pm\mp}, 1^{\pm\mp}, 2^{\pm\mp}; 1^{\pm\pm}.$$

The first 6 of these levels have $S_{q\bar{q}} = 1$ and the last 2 have $S_{q\bar{q}} = 0$.

In the earliest mass estimates in the flux tube model various approximations were made, such as a small oscillation approximation and an adiabatic quark motion approximation. After several studies of this system, Isgur, Kokoski and Paton [12] reached their well known estimate of 1.9(1) GeV for the mass of this lightest hybrid multiplet. This work has since been improved upon by Barnes, Close and Swanson [13] using a Hamiltonian Monte Carlo algorithm that does not make the small oscillation and adiabatic approximations. It appears that these approximations gave opposite and comparable

mass shifts, so their final result was a very similar 1.8–1.9 GeV for this lightest hybrid multiplet.

Since each of these $8J^{PC}$ levels has a flavor nonet of associated states, the flux tube model predicts a very rich spectrum, with an additional 72 meson resonances expected in the vicinity of 2.0 GeV, in addition to the conventional $q\bar{q}$ quark model states!

Finally, the very interesting question of the masses and quantum numbers of hybrid baryons in the flux tube model has only recently been considered, by Capstick and Page [14]. They find that the lightest hybrid baryon multiplet contains degenerate $(1/2^+N)^2$ and $(3/2^+N)^2$ states at a mass of 1870(100) MeV, with $(1/2^+\Delta)$, $(3/2^+\Delta)$ and $(5/2^+\Delta)$ partners slightly higher in mass. These conclusions are not so different from the bag model, which predicted a similar hybrid baryon content, with a lightest $(1/2^+N)$ hybrid near 1.6 GeV. The most obvious distinction (other than the 300 MeV difference in the lightest hybrid baryon's mass) is the high mass $(5/2^+N)$ (bag model) versus $(5/2^+\Delta)$ (flux-tube model).

2.4. LGT and QCD sum rules

These approaches both estimate exotic masses by evaluating correlation functions of the form $\langle 0|\mathcal{O}(\vec{x}, \tau)\mathcal{O}^\dagger(0, 0)|0\rangle$, where $\mathcal{O}^\dagger$ is an operator that can couple to the state of interest from the vacuum. When summed over $\vec{x}$, at large τ this quantity approaches $\kappa \exp(-M_{\mathcal{O}}\tau)$, where $M_{\mathcal{O}}$ is the mass of the lightest state created from the vacuum by the operator $\mathcal{O}^\dagger$. Thus by choosing various operators with exotic quantum numbers one may extract mass estimates for the lightest states with those quantum numbers.

Both methods are subject to systematic errors due to approximations. The QCD sum rules relate these operators to calculable p QCD contributions and to VEV's of other operators that are not calculated, but are inferred from experiment. Different choices for these parameters, algebra errors and uncertainties in higher-mass contributions have led to a moderately wide scatter of results. For example, for the 1^{--} exotic, which is of greatest phenomenological interest, the earliest work of Balitsky *et al.* [15] in 1982 estimated a mass of ≈ 1 GeV. Subsequently in 1984 Govaerts *et al.* [16] estimated 1.3 GeV, Latorre *et al.* estimated 1.7(1) GeV [17] and 2.1 GeV in 1987 [18]. The most recent work of Chetyrkin and Narison [19] finds ≈ 1.6 –1.7 GeV, with the radial hybrid only about 0.2 GeV higher. This reference also considers decay couplings; the partial width to $\pi\rho$ is found to be about 300 MeV, but to $\pi\eta'$ is only about 3 MeV. As we shall see, this is not what has been reported for either experimental exotic π_1 candidate.

Other exotic quantum numbers have been considered in QCD sum rules. For example, the 0^{--} has been considered by several of these references, and is found to have a rather high mass of *ca* 3 GeV.

Recently LGT groups have presented results for the masses of exotic mesons. The MILC collaboration [20] gave results for light 1^{-+} and 0^{+-} exotics, and UKQCD [21] considered these and 2^{+-} as well. (These are the three exotics predicted to be lightest, and degenerate, in the zeroth-order flux tube model.) At present the LGT results appear consistent with the expectations of the flux-tube model; signals in all these channels are observed, with the mass of the 1^{-+} (the best determined) being about 2.0(1) GeV. The 0^{+-} and 2^{+-} may lie somewhat higher, but this is unclear with present statistics.

The application of LGT to nonrelativistic heavy quark systems has been the topic of much recent research, and considerably smaller statistical errors follow from the use of a QCD action derived from a heavy quark expansion. This NRQCD has been applied to 1^{-+} heavy-quark exotic hybrids, with very interesting results; the $1^{-+} b\bar{b} - H$ is predicted to lie at $\approx 10.99(1)$ GeV, and the $1^{-+} c\bar{c} - H$ charmonium hybrid is predicted to lie at $\approx 4.39(1)$ GeV. With such small statistical errors in these heavy hybrid mass estimates, there is strong motivation for a careful, high statistics scan of R near these masses, since models of hybrids anticipate that the multiplet containing the 1^{-+} will also possess a 1^{--} state nearby in mass.

3. Hybrid decays

There appears to be universal agreement that hybrids should exist, and that the lightest of these states with u, d quarks should include a 1^{-+} resonance with a mass in the 1.5–2 GeV region, with the higher mass preferred by LGT and the flux tube model. For the experimental detection of these states we are faced with the crucial question of what their strong decay properties are. In the worst case they might be so broad as to be difficult to identify, a problem familiar from the f_0 sector.

Several models of strong decays have been applied to hybrids, and their results have motivated and directed experimental studies. The best known is the flux-tube decay model, which was applied to exotic hybrids by Isgur, Kokoski and Paton [12] and subsequently to nonexotic hybrids by Close and Page [23]. This model assumes that decays take place by $^3P_0 q\bar{q}$ pair production along the length of the flux tube. For the *unexcited* flux tubes of conventional mesons the predictions are quite similar to the conventional 3P_0 model; for hybrids in the flux tube model this decay assumption allows the calculation of hybrid meson decay amplitudes.

The orbital angular momentum gives the $q\bar{q}$ source produced during a decay a phase dependence around the original $q\bar{q}$ axis, and the hadronic final states produced are those which have similar angular dependence. Naively favorable modes such as $\pi\pi$, $\rho\pi$ and so forth are predicted to be produced

quite weakly due to poor spatial overlap with this $\exp(i\varphi)$ -dependent $q\bar{q}$ source. The favored modes are those that have a large $L_z = 1$ axial projection, such as an $S + P$ meson pair. This is the origin of the flux-tube $S + P$ selection rule, which in the $I = 11^{-+}$ case favors the unusual modes πf_1 and πb_1 over $\eta\pi$, $\eta'\pi$ and $\rho\pi$, despite their greater phase space.

In addition to the flux tube decay calculations, there are also QCD sum rule results (cited above), a decay model that assumes a specific relation between the flux tube excitation and the color vector potential [24], and constituent gluon decay amplitude calculations [25]. There is general agreement (with some variation between models) that in most cases the flux-tube result of $S + P$ mode dominance in hybrid strong decays is correct.

4. Experimental exotic meson candidates

4.1. Introduction

Since there are only two experimental candidate exotic meson resonances, the $\pi_1(1400)$ and the $\pi_1(1600)$, this section is relatively brief. I will first review the better established $\pi_1(1600)$, and then discuss the $\pi_1(1400)$. Both resonances are reported to have rather different properties than theorists expected for exotic hybrid mesons. Although I will compare these experimental exotic candidates to theoretical predictions for exotic *hybrids*, they might of course be another kind of non- $q\bar{q}$ state or even a misinterpreted nonresonant scattering effect.

4.2. $\pi_1(1600)$

The best established exotic candidate is the $\pi_1(1600)$. Evidence for this state has been reported in three channels, $b_1\pi$ (VES [26]), $\eta'\pi$ (VES [26]) and $\rho\pi$ (VES [26], E852 at BNL [27]). The $\rho\pi$ channel is the least controversial, since there are two independent experiments involved, and clear resonant phase motion against several well-established $q\bar{q}$ states is evident. The mass and width reported by VES and BNL are consistent,

$$M_{\pi_1} = \begin{cases} 1.61(2) \text{ GeV} & \text{VES, all three modes} \\ 1.593 \pm 0.008^{+0.029}_{-0.047} \text{ GeV} & \text{BNL E852, } \rho\pi, \end{cases} \quad (1)$$

$$\Gamma_{\pi_1} = \begin{cases} 0.29(3) \text{ GeV} & \text{VES, all three modes} \\ 0.168 \pm 0.020^{+0.150}_{-0.012} \text{ GeV} & \text{BNL E852, } \rho\pi. \end{cases} \quad (2)$$

One difficulty with interpreting this state as a hybrid is the ≈ 300 – 400 MeV mass difference between flux-tube and LGT estimates of $M \approx 1.9$ – 2.0 GeV and the $\pi_1(1600)$ mass.

The relative branching fractions for three channels $b_1\pi$, $\eta'\pi$ and $\rho\pi$, reported by VES for these final states are

$$\Gamma(\pi_1(1600) \rightarrow f) = \begin{cases} \equiv 1 & b_1\pi \\ 1.0 \pm 0.3 & \eta'\pi \\ 1.6 \pm 0.4 & \rho\pi \end{cases} \quad (3)$$

We can see immediately that there is a serious problem here, as the reported relative branching fractions are inconsistent with the predictions of the flux-tube model for hybrid decays (Table I). The theoretical expectation

TABLE I

Theoretical two-body partial widths (MeV) of a $\pi_1(2000)$ flux-tube hybrid.

$\pi_1(2000)$	πf_1	πb_1	$\pi \rho$	$\pi \eta$	$\pi \eta'$	$a_1 \eta$	$K_1 < K$	$K_1 > K$	Total
Theory [23]	60	170	5–20	0–10	0–10	50	20	~ 125	≈ 450

is that $b_1\pi$ should be dominant, with $\rho\pi$ weak and $\eta\pi$ and $\eta'\pi$ very small [12,23]. Some $\rho\pi$ coupling is expected in the flux tube model due to different ρ and π spatial wavefunctions [23], but this is expected to be a much smaller effect in the $\eta\pi$ and $\eta'\pi$ modes. Indeed, there is a generalized G -parity argument [28] that says these would be zero except differences in spatial wavefunctions. Either these three modes are not all due to a hybrid exotic, or our understanding of hybrid decays is inaccurate. Future experimental studies of $\rho\pi$ will be especially interesting here, since this channel is easily accessible for example in photoproduction at the planned HallD facility at Jefferson Laboratory [29,30].

4.3. $\pi_1(1400)$

This state is reported in $\eta\pi$, which is a channel with a long and complicated history. *Prima facie* $\eta\pi$ appears to be a very attractive channel in which to search for exotics, because there is no spin degree of freedom, and all the odd- L $\eta\pi$ channels are J^{PC} exotic.

The $\eta\pi^0$ channel was studied by GAMS in 1980 [31] before the idea of J^{PC} exotic resonances was widely accepted, and this collaboration was rather surprised to find a significant (exotic) P -wave. Of course the question was whether this exotic partial wave showed resonant phase motion or was simply a nonresonant background; GAMS had insufficient statistics to decide, but speculated that it was probably nonresonant. In a subsequent 1988 study of $\pi^- p \rightarrow \eta\pi^0 n$ [32] they concluded that $\eta\pi^0$ did indeed

support a 1.4 GeV 1^{-+} exotic P -wave resonance, although their analysis does not agree with subsequent studies of the same $\pi^{-}p \rightarrow \eta\pi^0 n$ reaction. This was followed by a KEK experiment [33] that concluded that $\eta\pi^{-}$ did show evidence for a resonant P -wave, *albeit* with a mass and width consistent with the $a_2(1320)$. Since the D -wave $a_2(1320)$ dominated this reaction, there were concerns that the reported exotic P -wave was actually due to feedthrough of the large $a_2(1320)$ signal in the partial wave analysis. This is now believed to be the case, perhaps due to the angular asymmetry of the detector. A subsequent VES experiment also found a resonant signal in the exotic $\eta\pi^{-}$ P -wave [34], but at a rather higher mass. Their $\pi_1(1400)$ was confirmed in 1997 by BNL experiment E852 [35].

Finally, the Crystal Barrel Collaboration [36] also find that their $\eta\pi\pi$ Dalitz plots in both charged ($\eta\pi^0\pi^{-}$) and neutral ($\eta\pi^0\pi^0$) final states show evidence for a broad resonant P -wave exotic, and fits give a $\pi_1(1400)$ mass and width consistent with VES and BNL. The BNL [35] and Crystal Barrel (CB) [36] masses and widths are:

$$M_{\pi_1} = \begin{cases} 1.370 \pm 0.016^{+0.050}_{-0.030} \text{ GeV} & \text{BNL E852, } \eta\pi^{-} \\ 1.400 \pm 0.02 \pm 0.020 \text{ GeV} & \text{CB, neutral and charged } \eta\pi \\ 1.360 \pm 0.025 \text{ GeV} & \text{CB, neutral } \eta\pi, \end{cases} \quad (4)$$

$$\Gamma_{\pi_1} = \begin{cases} 0.385 \pm 0.040^{+0.065}_{-0.105} \text{ GeV} & \text{BNL E852, } \eta\pi^{-} \\ 0.310 \pm 0.050^{+0.050}_{-0.030} \text{ GeV} & \text{CB, neutral and charged } \eta\pi \\ 0.220 \pm 0.090 \text{ GeV} & \text{CB, neutral } \eta\pi. \end{cases} \quad (5)$$

There has been much concern expressed regarding various possible experimental problems with this rather light and broad $\pi_1(1400)$, for example the size and energy dependence of backgrounds, and possible nonresonant inelastic scattering mechanisms that might mimic a resonance [37,38]. One should certainly be extremely careful in establishing the lightest exotic meson. Nonetheless it is evident that VES, BNL and Crystal Barrel have all found evidence for a $\pi_1(1400)$ with comparable mass and width in $\eta\pi$, despite theoretical expectations that a light, broad exotic hybrid should not exist.

It is a great pleasure to thank the organizers for their kind invitation to discuss exotics at Meson 2000. This research was supported in part by the DOE Division of Nuclear Physics, at ORNL, managed by UT-Battelle, LLC, for the US Department of Energy under contract No. DE-AC05-00OR22725, and by the Deutsche Forschungsgemeinschaft DFG at the University of Bonn and the Forschungszentrum Jülich under contract Bo56/153-1.

REFERENCES

- [1] S. Godfrey, J. Napolitano, *Rev. Mod. Phys.* **71**, 1411 (1999); hep-ph/9811410.
- [2] R.L. Jaffe, K. Johnson, *Phys. Lett.* **B60**, 201 (1976); R. Jaffe, *Phys. Rev.* **D15**, 267 (1977).
- [3] J. Weinstein, N. Isgur, *Phys. Rev. Lett.* **48**, 659 (1982); *Phys. Rev.* **D27**, 588 (1983); *Phys. Rev.* **D41**, 2236 (1990).
- [4] R. Jaffe, *Phys. Rev. Lett.* **38**, 195 (1977); *err.* **38**, 617 (1977).
- [5] J.-M. Richard, *Nucl. Phys. Proc. Suppl.* **86**, 361 (2000); nucl-th/9909030.
- [6] T. Barnes, PhD thesis, Caltech (1977); *Nucl. Phys.* **B158**, 171 (1979); T. Barnes, F.E. Close, *Phys. Lett.* **116B**, 365 (1982); T. Barnes, F.E. Close, F. deViron, *Nucl. Phys.* **B224**, 241 (1983).
- [7] M. Chanowitz, S. Sharpe, *Nucl. Phys.* **B222**, 211 (1983); *err.* **B228**, 588 (1983).
- [8] T. Barnes, F.E. Close, *Phys. Lett.* **123B**, 89 (1983); *Phys. Lett.* **128B**, 277 (1983).
- [9] C.E. Carlson, T.H. Hansson, C. Peterson, *Phys. Rev.* **D27**, 1556 (1983).
- [10] E. Golowich, E. Haqq, G. Karl, *Phys. Rev.* **D28**, 160 (1983); *err.* **D33**, 859 (1986).
- [11] N. Isgur, J. Paton, *Phys. Rev.* **D31**, 2910 (1985).
- [12] N. Isgur, R. Kokoski, J. Paton, *Phys. Rev. Lett.* **54**, 869 (1985).
- [13] T. Barnes, F.E. Close, E.S. Swanson, *Phys. Rev.* **D52**, 5242 (1995);
- [14] S. Capstick, P.R. Page, *Phys. Rev.* **D60**, 111501 (1999), nucl-th/9904041.
- [15] I.I. Balitsky, D. Diakanov, A.V. Yung, *Phys. Lett.* **B112**, 71 (1982); a subsequent paper, *Z. Phys.* **C33**, 265 (1986).
- [16] J. Govaerts, F. deViron, D. Gusbin, J. Weyers, *Nucl. Phys.* **B248**, 1 (1984).
- [17] J.I. Latorre, S. Narison, P. Pascual, R. Tarrach, *Phys. Lett.* **B147**, 169 (1984).
- [18] J.I. Latorre, P. Pascual, S. Narison, *Z. Phys.* **C34**, 347 (1987).
- [19] K. Chetyrkin, S. Narison, *Phys. Lett.* **B485**, 145 (2000), hep-ph/0003151v2.
- [20] C. Bernard *et al.* (MILC Collaboration), *Phys. Rev.* **D56**, 7039 (1997).
- [21] P. Lacock *et al.* (UKQCD Collaboration), *Phys. Lett.* **B401**, 308 (1997).
- [22] D. Toussant, hep-lat/9909088v2.
- [23] F.E. Close, P.R. Page, *Nucl. Phys.* **B443**, 233 (1995).
- [24] P.R. Page, E.S. Swanson, A.P. Szczepaniak, *Phys. Rev.* **D59**, 034016 (1999).
- [25] M. Tanimoto, *Phys. Lett.* **B116**, 198 (1982); A. LeYaouanc *et al.*, *Z. Phys.* **C28**, 309 (1985); F. Iddir *et al.*, *Phys. Lett.* **B207**, 325 (1988); **B433**, 125 (1998); hep-ph/9803470; Yu.S. Kalashnikova, *Z. Phys.* **C62**, 323 (1994).
- [26] V. Dorofeev (VES Collaboration), in Proceedings of WHS99, hep-ex/9905002.
- [27] G.S. Adams *et al.* (E852 Collaboration), *Phys. Rev. Lett.* **81**, 5760 (1998).

- [28] P.R. Page, *Phys. Lett.* **B402**, 103 (1997).
- [29] A. Afanasev, P.R. Page, *Phys. Rev.* **D57**, 6771 (1998).
- [30] A. Szczepaniak, *Acta Phys. Pol.* **B31**, 0000 (2000).
- [31] W.D. Apel *et al.*, *Nucl. Phys.* **B193**, 269 (1981).
- [32] D. Alde *et al.*, *Phys. Lett.* **B205**, 397 (1988).
- [33] H. Aoyagi *et al.*, *Phys. Lett.* **B314**, 246 (1993).
- [34] G.M. Beladidze *et al.*, *Phys. Lett.* **B313**, 276 (1993); D.V. Amelin *et al.*, *Phys. Lett.* **B356**, 595 (1995).
- [35] D.R. Thompson *et al.* (E852 Collaboration), *Phys. Rev. Lett.* **79**, 1630 (1997); S.U. Chung *et al.* (E852 Collaboration), *Phys. Rev.* **D60**, 092001 (1999).
- [36] A. Abele *et al.* (Crystal Barrel Collaboration); for $\eta\pi^0\pi^-$ see *Phys. Lett.* **B423**, 175 (1998), for $\eta\pi^0\pi^0$ see *Phys. Lett.* **B446**, 349 (1999); C. Amsler, *Rev. Mod. Phys.* **70**, 1293 (1998). The figure is the $\eta\pi^0\pi^-$ Dalitz plot, from the CMU Crystal Barrel web site, <http://www.phys.cmu.edu/cb/plots/dalitz.html>.
- [37] A. Donnachie, P.R. Page, *Phys. Rev.* **D58**, 114012 (1998), [hep-ph/9807433](#).
- [38] T. Barnes, N. Black, E.S. Swanson, [nucl-th/0007025](#).