INTRODUCTION AND OVERVIEW

Hadron physics is concerned with the questions of what hadrons exist in nature and how these hadrons interact and decay. In each of these areas there are important issues that are poorly understood. Our nominal classification of hadrons as quarkonia, glueballs and hybrids (and perhaps multiquarks) is of course an oversimplification, and it is not yet clear what resemblance the real hadron spectrum has to our expectations for gluonics and other exotica. The most widely used model of open-flavor hadron strong decays, the $^3P_0$ model, is a naive pair-production prescription with no clear connection to QCD. Finally, the nature of the strong force between hadrons in general, which is clearly a very important issue in strong interaction physics, remains controversial.

The year 2001 is a transitional period for hadron physics, as was reflected in the material presented. Two high-statistics experiments using hadron beams, E852 at BNL and the Crystal Barrel at LEAR, ended several years ago. Results from several new final states studied at these experiments were presented here, and some of the results were very interesting indeed; nonetheless it is clear that we are near the end of new results from these experiments. Hadron spectroscopy using hadron beams will continue here in Protvino, but will not again be a major world enterprise until new facilities such as GSI and perhaps KEK join this effort.
In the near future we can expect to see exciting new results from electron beam and $e^+e^-$ facilities. For light hadrons this will most noticeably involve Novosibirsk (with an energy upgrade to an invariant mass of around 2 GeV) and Frascati (now studying the $\phi$ but with capabilities for operating at higher mass). These facilities will be complimented by studies of $c\bar{c}$ and charm spectroscopy at BES (very nice results for states above $D\bar{D}$ threshold were shown here), and in the near future, CLEO-c. These facilities can also study the very interesting questions in light meson spectroscopy that can be addressed using two-photon collisions and initial-state radiation.

Hadron spectroscopy of late has also received contributions from machines such as LEP and KEK, which were designed for electroweak physics but can make very interesting contributions to light meson spectroscopy, in this case through two-photon collisions. Experiments that are nominally studies of weak interaction physics, such as charm meson decays, have also rediscovered strong interaction physics in the form of important FSIs. The implications of these FSIs for light scalar mesons led to some interesting interactions between representatives of the "old" and "new" cultures in hadron physics in the course of this meeting.

In theory, we also have seen a mix of "old" and "new" approaches in this meeting. The traditional quark models of hadrons public references remain the most relevant to experimentalists over the largest part of the $q\bar{q}$ and $qqq$ spectrum, since the results are known to be reasonably accurate numerically, and the radial and orbital excitations of greatest current interest are readily accessible to these methods. In parallel, the "first principles" LGT approach public references has made great progress in its applications to the spectrum of pure
glue and mixed quark-gluon states. In the glueball sector the LGT results \[2\] (Fig.1) are widely regarded as near definitive (within the quenched approximation), which is why we no longer hear suggestions that the "σ" or η(1440) might be glueballs; LGT has eliminated these possibilities in favor of a much higher glueball mass scale. Similarly, the approximate agreement between the predicted LGT scalar glueball mass and the \(f_0(1500)\) has been considered to be a very strong argument in favor of a glueball (or mixed glueball-q\(\bar{q}\)) assignment. Similarly the LGT estimate of the hybrid mass scale reported at this meeting, which is quite similar to the flux-tube model estimate, is considered to be a serious problem for the light exotic candidate \(\pi_1(1400)\). Clearly LGT is now the leading theoretical approach for estimating the masses of gluonic states. Although predictions for the masses of the lower-lying excited mesons and baryons can similarly be extracted from LGT, and in some cases should be relatively straightforward since some are the lightest states in their sector, this important application has not yet received sufficient attention from LGT groups. The spectrum of excited q\(\bar{q}\) states in LGT is obviously a very important topic, which should be considered by LGT collaborations with improved statistics in future.

The next important step in theoretical technique, both in LGT \[1, 5, 6\] and in quark models \[7\], may be the removal of the "quenched approximation" through the incorporation of creation and annihilation of intermediate q\(\bar{q}\) pairs. This will lead to several perhaps very important effects, such as large mass shifts due to virtual decays. The reasons for the success of the naive LGT quenched approximation, and the closely related quark-model valence approximation, are important and long-standing questions that can be addressed in this work.
Exotica

"Exotica" generically refers to states that are not dominantly $q\bar{q}$ mesons or $qqq$ baryons, to the extent that this can be quantified. In this Hilbert space classification our current expectation is that the possible types of exotica are hybrids, glueballs and multiquark systems, with the latter category including quasinuclear "molecules" and possibly multiquark hadrons. There will of course be configuration mixing between these ideal "conventional" and "exotica" basis states, except in the cases of outright exotic quantum numbers such as $I=2$ or $J^{PC} = 1^{--}$. The amount of configuration mixing will be strongly channel-dependent, and in some cases may preclude a separation into exotica and conventional hadronic resonances. One now familiar example is the scalar glueball sector, in which the strong decays of the $f_0(1300)$, $f_0(1500)$ and $f_0(1710)$ are all far from expectations for pure $q\bar{q}$ or glue states, due perhaps to very large $|n\bar{n}\rangle \leftrightarrow |G\rangle \leftrightarrow |s\bar{s}\rangle$ mixing effects. Alternatively, in the cases of exotic flavor or $J^{PC}$ we can be certain that identification of a resonance is an indication of a state beyond the naive quark model of $q\bar{q}$ mesons and $qqq$ baryons. The identification of the spectrum of such states is the most important task for QCD spectroscopy at present.

Theorists derived the expected spectrum of hybrids (including $J^{PC}$-exotics) in various models beginning in the mid 1970s. It is now widely accepted that hybrid mesons span all $J^{PC}$, and the lightest hybrid exotic should be a $1^{--}$. In some models such as the flux tube model there are additional exotics present in the lowest multiplet, specifically $0^{+-}$ and $2^{+-}$. These states are also expected in the bag model, but at rather higher mass.) The search for such exotic quantum numbers was given a strong incentive by the flux tube calculations of Isgur, Kokoski and Paton[8], who predicted very characteristic decay modes for hybrids, specifically S+P final states such as $f_1\pi$ and $b_1\pi$. Their mass estimate of ca. 1.9 GeV was somewhat higher than was predicted earlier, for example using the bag model. The restricted S+P decay modes compensated for the increased phase space at the higher flux-tube mass scale, so the flux-tube decay calculations found that some hybrids, notably a $\pi_1(1900)$, should be relatively narrow. Of the other relatively narrow states predicted by this model, the most remarkable are an "extra" $\omega$ that would favor $K\bar{K}$ modes and an "extra" $\pi_2$ that would decay strongly to $b_1\pi$. (The $b_1\pi$ mode is forbidden to the quark model $\pi_2(1670)$ because the $^1D_2 \rightarrow ^1P_1 + ^1S_0$ transition is spin singlet to spin singlet, which vanishes in the $^3P_0$ decay model.)

Relatively recent theoretical results on the hybrid mass scale in LGT were presented at this meeting. These results are more accurate at higher quark masses, due to the use of a nonrelativistic expansion of the QCD action; this leads to mass predictions that have much smaller statistical errors for states that incorporate heavy quarks. The masses predicted for the $1^{--} b\bar{b}$- and $c\bar{c}$-hybrids in the most recent calculations (reported here by Morningstar [1]) are $M_{b\bar{b} \text{ hybrid}} \approx 10.9-11.0$ GeV and $M_{c\bar{c} \text{ hybrid}} \approx 4.3$ GeV, which should be very useful as motivation for future studies of the higher-mass $c\bar{c}$ system at CLEO and BES. (Models typically anticipate approximately degenerate $1^{--}$ and $1^{--}$ hybrids, so we expect to see an "extra" $c\bar{c}$ $1^{--}$ in $e^+e^-$ annihilation at about this mass.) The especially interesting $n\bar{n}$-hybrid with $1^{++}$ quantum numbers is predicted to lie at
about 1.9-2.1 GeV [1], quite close to the flux tube model estimate. As a final interesting point, NRQCD is now finding results for the masses of nonexotic hybrids as well; a level ordering of $2^{-+} > 1^{--} > 1^{-+} > 0^{-+}$ found by Drummond et al [9] using NRQCD LGT was reported at this meeting [1]; this ordering was predicted by the bag model. In contrast the usual flux tube model results predict these states to be degenerate. This may be another area in which LGT can act as de facto theoretical QCD data that can be used to distinguish between different intuitive models, pending experimental results.

Regarding the de jure data on exotics, two candidate $J^{PC}$ exotic meson resonances have been proposed, both with $I=1$, $J^{PC} = 1^{-+}$ quantum numbers; the $\pi_1(1400)$ and $\pi_1(1600)$. Obviously, establishing (or refuting) these candidate exotic resonances is of paramount importance for the future development of spectroscopy, since if confirmed they provide a benchmark for the mass of the lightest exotic resonance and the energy scale of exotic radial excitations. Unfortunately the $\pi_1(1400)$ signal (in $\eta\pi$) is rather weak, so it is difficult to distinguish this resonance interpretation from a nonresonant background phase. (This simple statement summarizes two decades of experiment.)

At this meeting we have heard from the VES collaboration [10] that they now have no clear preference for a $\pi_1(1400)$ resonance interpretation; they find fits of similar quality from a nonresonant signal. Since the favored theoretical methods anticipate a much higher mass of ca. 1.9-2.0 GeV for the lightest hybrid meson multiplet, which includes the lightest expected $I=1$ 1$^{-+}$ exotic, theorists would generally be happier if the $\pi_1(1400)$ were to be reinterpreted as a nonresonant signal, and the very clearly resonant $\pi_1(1600)$ were to replace it as the lightest exotic. Of course we must be cautious here because these predictions are for an unfamiliar system in the quenched approximation; the mass shifts due to couplings to virtual meson loops are currently unclear, and may be rather large. This will be a very important issue for future theoretical studies.

In contrast, the $\pi_1(1600)$, which is already claimed in $\eta'\pi$, $\rho\pi$ and $b_1\pi$ final states, may now be clearer. In their contribution [11], E852 showed results from the $\eta'\pi$ final state, in which the dominant low-energy resonance is the $\pi_1(1600)$ (see Fig.2). The usually dominant $a_2(1320)$ is much weaker in this channel due to small branching

![FIGURE 2. The E852 $1^{-+}$ wave in $\eta'\pi$, showing a dominant $\pi_1(1600)$ exotic.](image-url)
fraction of $B(a_2 \to \eta'\pi) \approx 0.5\%$; this leaves a remarkably robust $1^{-+}$ exotic wave, which if confirmed as resonant (see [10] for a cautionary note) will presumably be a benchmark for future studies of exotics. Note that the fitted width of $\Gamma_{tot}(\pi_1(1600)) = 340 \pm 40 \pm 50$ MeV is rather broader than the earlier estimates from the $\rho\pi$ final state.

Vectors

The conference began with a summary by Donnachie of the status of light vectors [12]. Although this might appear to be a rather specialized topic, in my opinion it merits a special section because much of the future work on light meson spectroscopy will concentrate on the vector sector. This is because the new and upgraded $e^+e^-$ machines at Frascati and Novosibirsk produce vector mesons in $e^+e^-$ annihilation, and future photoproduction facilities such as HallD at Jefferson Lab will also produce $1^{--}$ states (not uniquely, but vectors should also dominate diffractive photoproduction).

This limitation to $1^{--}$ states is an advantage in disguise; as usual in the 1-2 GeV mass region we have broad overlapping resonances, but since only $1^{--}$ is important in $e^+e^-$ annihilation, we expect to produce only a few resonances per flavor channel. Thus it should be possible to establish clearly what states are present in the light meson spectrum, and whether there is indeed an overpopulation of states relative to the naive $q\bar{q}$ quark model.

Application of the quark potential model to the $n\bar{n}$ sectors leads to predictions of $2^3S_1$ radial excitations near 1.5 GeV, $L=2^3D_1$ $n\bar{n}$ states near 1.7 GeV, and a $3S$ radial excitation near 2.1 GeV. Experiment appears to support the existence of these $2S$ and $D$ states (Fig.3), with $\rho$ and $\omega$ flavor states roughly degenerate, and some evidence for $K$ and $\phi$ analogues expected about 0.12 and 0.25 GeV higher in mass. Note however that $K^*(1410)$ appears surprisingly light if it is a partner to $\rho(1465)$ and $\omega(1420)$ $2S$ states. (A parenthetical note: Could this indicate the presence of the $1^{-+}$ exotic, with $1^{-+}$-$1^{--}$ mixing in the kaon sector analogous to the $K_1$ states?)

Of course only the $\rho^0$, $\omega$ and $\phi$ are accessible to $e^+e^-$, and again we are fortunate in $e^+e^-$ because the relative flavor cross section ratios for $\rho^0 : \omega : \phi$ of 9 : 1 : 2 are known. (Some additional suppression of $s\bar{s}$ production is expected, due to the larger $m_s$.) With only two $q\bar{q}$ states anticipated by theorists per flavor sector between $\approx 1.5$ GeV and $\approx 2.0$ GeV, this problem sounds almost too simple!

There are two complications that have left the vector sector in a confused state despite decades of previous study, primarily using $e^+e^-$ and photoproduction facilities. The first and most important problem is that the more accessible $\rho^0$ and $\omega$ states are quite broad, so we face the famous problem of overlapping resonances. Another difficulty is that we anticipate a $1^{--}$ hybrid meson multiplet somewhere in this mass region (degenerate with the $\pi_1$, in the flux tube model), so we may have not two but three states ($2S$, $D$, $H$) in this mass region. Actually this is again fortunate, since it affords us the opportunity to study conventional $q\bar{q}$ and hybrid states in a very restricted slice through Hilbert space, in a channel in which the important mixing effects can also be investigated. What we learn from excited vectors as an isolated case study may be crucial in helping us to understand the other nonexotic sectors of light meson spectroscopy.
FIGURE 3. Experimental vector mesons below 2 GeV.

TABLE 1. Theoretical partial widths of 2S, 1D and hybrid ρ states.

| State        | ππ | ωπ | ρη | ρρ | KK  | K*K | h_1π | a_1π | total |
|--------------|----|----|----|----|-----|-----|------|------|-------|
| ρ_{2S}(1465) | 74 | 122| 25 | 35 | 19  | 1   | 3    |      | 279   |
| ρ_{1D}(1700) | 48 | 35 | 16 | 14 | 36  | 26  | 124  | 134  | 435   |
| ρ_{H}(1500)  | 0  | 5  | 1  | 0  | 0   | 0   | 140  |      | ≈ 150 |

In addition to the location of the individual levels, which may well be quite different from quark model expectations if q̅q ↔ hybrid mixing is important, the strong decay modes of the vectors will be especially interesting. This is because much of our theoretical "scaffolding" for hadrons and their strong decays relies on the so-called 3P_0 model, which assumes that strong decays take place through production of an additional q̅q pair with vacuum quantum numbers (J^{PC} = 0^{++}, hence 3P_0). Other popular decay models such as the flux tube decay model are relatively minor variants of the original 3P_0 model, introducing for example a smooth spatial modulation of the pair production amplitudes. Although this model has been employed by theorists to reach a broad range of conclusions about hadrons (such as S+P decay modes for hybrids, and a list of "missing baryons" which are purportedly missing because they couple weakly to πN), it has been tested in disturbingly few decays. The most sensitive and well known tests are in decays of axial vectors to vector plus pseudoscalar. This channel allows both S- and D-waves in the VPs final state, so one can determine the relative magnitude and sign of S and D through the decay product angular distribution. The D/S ratio is quite sensitive to the quantum numbers of the q̅q pair produced in the decay, and the observed value of ≈ +0.28 in b_1 → ωπ [11] strongly supports the 3P_0 model. The decay a_1 → ρπ is predicted to have a D/S ratio of -1/2 times the b_1 → ωπ ratio, which is also reasonably well satisfied. (Actually the D/S amplitude ratio is complex, since S- and D-wave VPs final states develop different FSI phases. This allows one to determine the phase shift difference δ_S – δ_D in the ωπ system at the b_1 mass, which has only recently been appreciated and exploited [13].) These two measurements, and some additional support from other axial vector decays in kaon and charm systems, are the only clear checks of this very widely used decay model.
When applied to these excited vector states, these strong decay models predict markedly different favored modes for the different states \([14, 15, 16]\), that may be useful as signatures and to establish mixing angles between different vector basis states. In Table 1 we show results for the three \(\rho\)-type excited vectors; evidently these have comparable theoretical widths but very distinct branching fractions. The broad \(4\pi\) states from \(h_1\pi\) and \(a_1\pi\) are predicted to arise from the 2D (comparable \(h_1\pi\) and \(a_1\pi\)) and H (\(a_1\pi\) only), whereas \(2S\) should couple strongly to neither, instead populating \(\pi\pi\) and \(\omega\pi\). If this is accurate, it shows the importance of measuring as many final states as possible, especially since mixing of these basis states may be important.

As noted by Donnachie, the existing data has many gaps in energy and final state coverage, but it is clear that the \(4\pi\) modes do not appear to agree with Table 1. There is evidence for \(a_1\pi\) dominance of broad \(4\pi\) states from the ratio of \(\pi^+\pi^-\pi^0\pi^0/2\pi^+2\pi^-\), which would only be expected from a hybrid! (This assuming the flux-tube model of hybrid decays is accurate.) With accurate measurements of the final states in Table 1, we should be able to distinguish the \(\rho\) excitations present in this channel, and should learn about state mixing and strong decay amplitudes in the process.

Table 1 lists only \(\rho\) states. Donnachie noted that the flux tube decay model predicts a very narrow \(\omega H\) \(1^{--}\) hybrid, coupled strongly only to \(K_1K\) decay modes \([13]\). If this state is near the \(\pi_1(1600)\) mass these modes are closed, and the flux-tube suppressed mode of \(\rho\pi\) is expected to lead to a total width of only \(\sim 20\) MeV \([12, 16]\). This remarkable prediction strongly motivates a simultaneous study of \(\omega\)-flavor \(1^{--}\) states.

It may be that the \(3^P_0\) model is inaccurate outside the \(1^+\) channel, in which case most of our predictions of hadron strong decays will be inaccurate. Evidence for a failure of the \(3^P_0\) model in \(\pi_2 \to \rho\omega\) was presented by E852 at this meeting, which I will mention in the section on higher-mass states.

**Scalars**

**Introduction**

I will first discuss the famous "980 states", in which there has been clear progress recently, and a close interplay between theory and experiment may have clarified much about the nature of these states. These results were clearly considered by many to be the most interesting presented at this meeting. Next I will briefly discuss the broad "\(\sigma\)" scalar and its purported strange partner, which were discussed at this meeting at some length but (as usual) no clear consensus as to the best description of the physics was evident. Finally I will suggest interesting future possibilities for clarifying the nature of the various scalars in the next round of experiments. Although the scalar sector includes the scalar glueball, and allows one to address the very important question of glueball-quarkonium mixing, little new experimental material was presented at this meeting, so I will not discuss glueballs as a separate topic.
"980" States

The two mesons near 980 MeV, once the $S^*$ and $\delta$, now the $f_0(980)$ and $a_0(980)$, have long attracted attention as being anomalous in many of their properties. Although close to degenerate, so that we might expect them to be nonstrange $n\bar{n}$ I=0,1 partners, their very strong coupling to $K\bar{K}$ suggests that these are actually not conventional $n\bar{n}$ quark model states. Other problems are that their strong total widths are much smaller than expectations for $n\bar{n}$ at this mass, their masses are well below those of other P-wave $n\bar{n}$ states and are just below the $K\bar{K}$ threshold, and their electromagnetic couplings (specifically $\gamma\gamma$) are much weaker than we would expect for $n\bar{n}$. This list of problems can be expanded considerably.

Historically three models of these states have been considered by theorists. These suggest that the $f_0(980)$ and $a_0(980)$ might be four-quark clusters (primarily supported by Achasov et al.), weakly-bound kaon-antikaon quasinuclear states (Weinstein and Isgur), or simply $q\bar{q}$ quark model states, whose properties happen to differ from our naive expectations for ordinary mesons. Of course all accessible basis states will mix in physical hadrons, perhaps significantly, so we should more properly regard these models as suggestions regarding which component dominates in the expansion

$$|980\rangle = c_{q\bar{q}}|q\bar{q}\rangle + c_{q^2\bar{q}^2}|q^2\bar{q}^2\rangle + c_{KK}|K\bar{K}\rangle + \ldots .$$ (1)

Of course the coefficients are actually spatial wavefunctions, so the distinction between $|q^2\bar{q}^2\rangle$ and $|K\bar{K}\rangle$ basis states is rather qualitative.

An important test proposed to distinguish between these descriptions (assuming dominance of one basis state) arises in $\phi(1020)$ radiative decays. In both the four-quark and $K\bar{K}$-molecule models it is assumed that the 980 states are produced in $\phi$ radiative transitions by photon emission from a virtual $K\bar{K}$ loop, with a direct photon coupling to the $K^+K^-$ loop but not to $K^0\bar{K}^0$. The corresponding decay rate was evaluated by Achasov, Devya

Klempt will discuss the experimental results for these branching fractions from Novosibirsk and Frascati in his experimental summary. Here I will simple note that they are comparable in scale to the $\approx 1-3 \cdot 10^{-4}$ quoted above, but the weaker result that the branching fractions are equal,

$$B(\phi \to \gamma f_0(980)) B(\phi \to \gamma a_0(980)) |_{\text{theory}} = 1$$ (3)

is not at all well satisfied! Instead the experimental ratio is

$$B(\phi \to \gamma f_0(980)) B(\phi \to \gamma a_0(980)) |_{\text{expt.}} \approx 4 .$$ (4)
If we reconsider the charged-kaon-loop radiative decay models to see what might have gone wrong, we find that the ratio of unity follows from the assumption that both 980 states are isospin eigenstates. It was instead argued long ago in both $q^2\bar{q}^2$ \cite{17} and $K\bar{K}$ \cite{19} models that one should anticipate important isospin violation in these states. For $q^2\bar{q}^2$ this arises from mixing through nondegenerate $K^+K^-$ and $K^0\bar{K}^0$ loops, and for $K\bar{K}$ from the fact that these are weakly bound $K\bar{K}$ systems, with zeroth-order $K^+K^-$ and $K^0\bar{K}^0$ masses that differ by an amount comparable to the binding energy. There was already evidence for isospin mixing in these states, through $\pi\pi\rightarrow\pi\eta$ transitions evident in E852 data, and through evidence for central production of both the $f_0(980)$ and $a_0(980)$. The central production data suggests a mixing angle near $15^\circ$, which led Close and Kirk \cite{20} to a modified prediction for the radiative transition ratio of

$$\frac{B(\phi\rightarrow\gamma f_0(980))}{B(\phi\rightarrow\gamma a_0(980))}_{\text{theory}} = 3.2 \pm 0.8 ,$$

(5)

which is consistent with observation. The absolute scale of the rates suggests a hard form factor $F(R) \approx 1$, which supports the picture of a compact four-quark system. Close and Kirk interpret this as evidence for a combination of a $K\bar{K}$ system with a compact $q^2\bar{q}^2$ core.

In summary, we have clear and consistent evidence of a large isospin mixing angle in these states from three experimental processes, at a level not seen in other hadrons. This is a very interesting result indeed. A future calculation that is immediately suggested by this observation is to determine the mixing angles predicted by the two models of isospin violation, mixing through kaon loops versus mixing due to weak binding of nondegenerate $K^+K^-$ and $K^0\bar{K}^0$ systems.

This evidence of a large isospin mixing angle between the nominally I=0 $f_0(980)$ and I=1 $a_0(980)$ immediately suggests several interesting measurements, which might check this result and independently determine the mixing angle. These include 1) the $\gamma\gamma$ widths, which were also predicted to be equal for both states because of photon coupling to the charged kaon loop alone, and which we therefore expect to be skewed in favor of the $f_0(980)$ by the same ratio as the radiative transition; 2) the relative annihilation decay rates of $J/\psi\rightarrow\phi(\pi\pi)$ and $J/\psi\rightarrow\phi(\pi\eta)$ (with isospin eigenstates we would expect to see no 980 signal in $\pi\eta$, since this is driven by an $s\bar{s}$ source; similarly for $D_s\rightarrow\pi(\pi\pi)$ and $D_s\rightarrow\pi(\pi\eta)$). Finally, radiative transitions such as $a_0(980)\rightarrow\gamma\omega$ and $f_0(980)\rightarrow\gamma\omega$ can be used to quantify the $n\bar{n}$ components in the 980 states, since E1 radiative transition amplitudes of light quarkonia are reliably calculable in the quark model.

**Broad Scalars ("Let Sleeping Dragons Lie.")**

Discussions of the status of broad scalars have appropriately spanned decades. The contending "camps" in this area have long since settled on favorite explanations of the low-energy "$\sigma$" and "$\kappa$" effects, and these views are held with the tenacity of religious convictions. This situation makes for bad science, and we may need new, independent experimental information about the light scalar sector before we can make any progress in our understanding of broad scalar states.
At this meeting we have heard discussions of the relatively recent information on the light ππ and Kπ systems that has come from charm decay experiments. In these experiments it was noted that there are clear low-energy enhancements in I=0 ππ and I=1/2 Kπ subsystems, which can be fitted by very light scalar resonances. Specifically, masses of ≈ 480 MeV and ≈ 800 MeV were quoted for "σ" and "κ" states \[21\]. This is probably a premature conclusion, since only the low-energy tails of the purported resonance phase shifts are actually in evidence in the charm data; the crucial observation of a complete Breit-Wigner phase motion through 180° has not been made. It was noted here by Ochs \[22\] and by Pennington that the elastic ππ and Kπ phase shifts themselves do not show evidence of "complete" low mass scalar resonances, so concluding that these exist based on the charm decay data in isolation, which only covers part of the range of invariant mass that has already been studied in light hadronic processes, is unjustified.

The discussions at HADRON2001 following the charm decay presentations suggested that the charm decay analyses should include what is already known about these phase shifts over the full relevant mass range, for example through the parametrization of Au, Morgan and Pennington \[23\].

Experience suggests that progress may follow from a high-statistics study of a new production mechanism in the relevant mass region, as was provided by φ radiative decays for the 980 states. I would suggest that future high-statistics two-photon collisions, especially γγ → π⁺π⁻, may be definitive in resolving the resonances present in the light I=0 scalar channel. This reaction is quite simple (only S- and D-waves are produced significantly at low energies), and with high statistics it should be possible to determine the S-wave phase motion through interference with the \(f_2(1270)\) D-wave. This reaction was studied earlier by the Crystal Ball collaboration \[24\], albeit with quite limited statistics; their results showed a broad scalar signal under the \(f_2(1270)\), but the data was not adequate for a determination of the mass and width. If one could track the phase motion of the S-wave in this process (perhaps augmented by γγ → π⁺π⁻ and γγ → ηη data) it should be possible to identify the lighter \(f_0\) scalar resonances. We should be aware that slowly-varying background phases are also present, which may significantly modify the fitted resonance parameters in this channel; as an example, the Jülich group note that t-channel ρ exchange in ππ scattering with a realistic ρππ coupling strength can explain most of the low-energy ππ phase shifts in both I=0 and I=2 channels \[25\].

Thus we may not learn where the light scalar resonances lie until we have understood nonresonant "background" phase shifts as well.

LGT predictions for scalar \(q\bar{q}\) masses would also be of great interest. Although these would be "quenched" results, these bare numbers actually are used in some models of ππ scattering, and in any case there is so much uncertainty in this field at present that any more definitive theoretical result would be important. Just as the large LGT glueball mass scale in Fig.1 \[2\] has eliminated the "σ" and η(1440) from serious contention as glueball candidates, so LGT results for the scalar \(q\bar{q}\) spectrum could help to identify the more plausible scenarios in this most obscure and controversial sector of Hilbert space.
Higher-mass States

Heavy Quarkonium

We heard several interesting experimental contributions about heavy quarkonium at HADRON2001, specifically about the charmonium system. Although little new theoretical activity was reported in this field (the exception is heavy-quark hybrid masses from LGT), we will presumably see future theoretical interest in the charmonium system in response to high statistics studies at BES and CLEO-c. For this reason it seems appropriate to at least mention some of the charmonium results reported, and to suggest some possibly interesting questions for future experimental and theoretical investigation.

First, BES has reported results for the inclusive hadron cross section ratio \( R \) in the region above open charm threshold [26] (Fig. 4). This is an important advance, as the rather noisy previous results from the late 1970s suggested the higher-mass resonances \( \psi(3770), \psi(4040), \psi(4160) \) and \( \psi(4415) \) but were far from definitive. Only these four \( c\bar{c} \) resonances are regarded as established above open charm threshold, and their masses are consistent with potential model expectations for \( 1^3D_1, 3^3S_1, 2^3D_1 \) and \( 4^3S_1 \) levels (in order of increasing mass).

Despite this agreement of masses, there are serious problems with the properties reported for these states relative to potential model expectations. The \( \psi(3770) \) and \( \psi(4160) \) should both appear quite weakly in \( e^+e^- \) if they are D-wave \( c\bar{c} \) states, since the wavefunction at contact vanishes in this case. Instead the \( e^+e^- \) width of the \( \psi(3770) \) is much larger than expected, and the reported \( \psi(4160) \) \( e^+e^- \) width is comparable to the nominally \( 3^3S_1 \) \( \psi(4040) \). Of course this is based on the old, rather noisy, measurements. The \( \psi(4160) \) signal in the new BES data appears weaker, and when fitted this new \( e^+e^- \) width may be rather smaller than previous estimates.

The exclusive strong branching fractions of these higher-mass \( c\bar{c} \) states will also be very important measurements. The existing claims for strong branching fractions include an estimate that the \( \psi(4040) \) favors the \( D^*\bar{D}^* \) mode over \( D\bar{D} \) by about a factor of
\[ \alpha_2(1320) \]
\[ \alpha_2(1750) \]
\[ \text{Bkgd} \]

**FIGURE 5.** An example of $\gamma\gamma$ production of a higher-mass $q\bar{q}$ state, from Belle [29].

\[ \sim 500 \, [27, 28], \text{ despite the absence of } D^*\bar{D}^* \text{ phase space! (Recall } M(D^*) = 2.01 \text{ GeV.}) \]

This remarkable result previously led to suggestions that the $\psi(4040)$ might be a $D^*\bar{D}^*$ molecule. The conventional $c\bar{c}$ description nonetheless appears plausible, in view of the agreement with the predicted mass of the $3^3S_1$ $c\bar{c}$ level. The $\psi(4040)$ $e^+e^-$ width, which is comparable to the $e^+e^-$ widths of the $\psi(3686)$ and $\psi(4415)$ 2S and 4S radial excitations, also supports a $c\bar{c}$ $\psi(4040)$ assignment. The unusual strong branching fractions may be due to nodes in the strong decay amplitudes; the nodes in the 3S radial wavefunction may well have produced counterintuitive branching fractions for the $\psi(4040)$. Clearly, reasonably accurate measurement of the exclusive branching fractions of the higher $c\bar{c}$ states to all open charm final states will be an extremely interesting set of measurements, which can be used as detailed tests of strong decay models.

One limitation of $e^+e^- \rightarrow \gamma \rightarrow q\bar{q}$ annihilation is that it produces only $1^{--}$ states. One can extend these studies to the two-photon collision process $e^+e^- \rightarrow e^+e^-\gamma\gamma$, $\gamma\gamma \rightarrow q\bar{q}$, to search for states with even C-parity. These two-photon widths are intrinsically interesting to theorists, since they can be calculated in quark models, and may provide sensitive tests of the quark model states. Fig.4 shows a new measurement of a candidate $a_2(1750)$ radial excitation in $\gamma\gamma$, reported here by the BELLE Collaboration [29]. The relative two-photon partial widths of a given $J^PC$ flavor multiplet vary with flavor as $f : a : f' = 25 : 9 : 2$, so two-photon couplings can be used to identify flavor partners of a given state, or quantify the level of flavor mixing. (There is some suppression of the heavier $s\bar{s}$-$\gamma\gamma$ coupling.) Two-photon couplings may also be useful in distinguishing different types of scalar states, since we naively expect glueballs and multiquark states to have rather smaller $\gamma\gamma$ couplings than $n\bar{n}$ states. In contrast, in the quark model a light scalar $f_0^{(m\bar{m})}(1300)$ is predicted to have a two-photon width of $\approx 5$ KeV, larger than any other light $n\bar{n}$ meson.

Two-photon couplings of charmonia are very interesting in part because they allow
us to test calculations of $q\bar{q} \rightarrow \gamma\gamma$ widths in a regime in which the nonrelativistic quark model should give reasonably accurate results. Typical theoretical predictions are $\approx 5-7$ KeV for the $\eta_c(2980)$ and $\approx 0.5-2$ KeV for the P-wave $c\bar{c}$ states $\chi_0$ and $\chi_2$. The ratio of $\chi_0/\chi_2$ partial widths varies over the range $\approx 3-10$, depending on theoretical assumptions. These measurements of $\gamma\gamma$ charmonium widths have a long history of uncertainty, due to the intrinsically small $O(\alpha^4)$ cross sections. It is now clear that the experimental $\eta_c(2980) \gamma\gamma$ width $[30]$ is not far from theoretical expectations. The P-wave states have somewhat smaller $\gamma\gamma$ widths and less characteristic decays, and so have been more difficult to measure. One competing technique that proved quite successful was to use $p\bar{p}$ annihilation to make the $c\bar{c}$ state, followed by detection of $\gamma\gamma$ against a very large hadronic background. (This was done by E760 and E835 at Fermilab.) A new BELLE measurement of the $\gamma\gamma$ width of the tensor $\chi_2(3556)$ in $e^+e^-$ collisions was reported here $[29]$.

$$\left.\Gamma_{\gamma\gamma}(\chi_2)\right|_{\text{BELLE}} = 0.84(0.08)(0.07)(0.07) \text{ KeV}$$

which is about a factor of three larger than the Fermilab result

$$\left.\Gamma_{\gamma\gamma}(\chi_2)\right|_{\text{E835}} = 0.270(0.049)(0.033) \text{ KeV}$$

presented here by Tomaradze $[30]$. This is about a $4\sigma$ difference, so the discrepancy does appear significant. I am amused to note that a previous $\chi_2(3556) \rightarrow \gamma\gamma$ calculation $[31]$ found a value of $\Gamma_{\gamma\gamma}(\chi_2) \approx 0.56$ KeV, comfortably between the two experimental results.

**A Striking $^3P_0$ Decay Model Failure**

One especially interesting new result reported at this meeting concerned resonances observed in the $\rho\omega$ final state. This is very important theoretically because the $VV$ system can have $S = 0, 1$ and 2, so there is considerable scope for testing strong decay models. (Recall that we have all been using the $^3P_0$ model or variants to predict light meson decays, $D$ meson decays, hybrid decays, missing baryons and so forth for decades, but this model has seen little in the way of sensitive tests of the quantum numbers of the $q\bar{q}$ pair formed in the decay.) The historically convincing angular correlation tests were in $1^+ \rightarrow VPs$ decays to VPs final states, specifically $b_1 \rightarrow \omega\pi$ and $a_1 \rightarrow \rho\pi$, in which both $S$- and $D$-wave VPs final states are produced. The model does predict these two $D/S$ ratios approximately correctly, but it has seen few sensitive tests in other $J^P$ sectors. When applied to decays into $VV$ final states, the model typically predicts a nontrivial pattern of large, small or identically zero decay amplitudes, which can be compared to these new results on $\rho\omega$.

The $\pi_2(1670)$ is an interesting initial state for these decay model tests; it is a spin singlet ($^1D_2$ in the quark model), so many decay amplitudes are predicted to be zero due vanishing spin matrix elements. For example, the decay $\pi_2 \rightarrow b_1\pi$ is strictly forbidden in the $^3P_0$ model, since this would be an $S=0$ to $S=0$ transition (the mesons all have $S=0$); the $^3P_0$ transition operator has $S=1$ ($\vec{\sigma} \cdot \vec{p}$), so there is no $S=0$ to $S=0$ matrix element. The fact that this branching fraction is indeed quite small is one of the few recent decay model tests.
On considering the decay \( \pi_2 \to \rho \omega \), one immediately finds a dramatic failure, assuming that the newly reported experimental decay amplitudes are correct. The \( 2^-+ \rho \omega \) system can in general have the quantum numbers \( \text{^3P}_2, \text{^3F}_2, \text{^5P}_2, \) and \( \text{^5F}_2 \), but the \( \text{^5P}_2 \) and \( \text{^5F}_2 \) final states are forbidden to \( \pi_2 \to \rho \omega \) in the \( \text{^3P}_0 \) model, since we have an \( S=0 \) initial state and an \( S=1 \) transition operator. We should only find \( \text{^3P}_2 \) and \( \text{^3F}_2 \) final states. Of these we expect the \( \text{^3P}_2 \) wave to dominate \( \pi_2 \to \rho \omega \), since there is little phase space.

Experimentally only the \( S=2 \) final state is observed to peak in the \( \pi_2(1670) \) region, which implies that this decay is dominated by a spin tensor transition. This final state might be generated by \( q\bar{q} \) pair production from a transverse gluon, but it is certainly not anticipated by the usual \( \text{^3P}_0 \) strong decay model. Subsequent angular analysis of the \( VV \) system may provide other interesting results regarding the mechanism of these still poorly understood strong decays.

**SUMMARY**

In this report I have briefly summarized several interesting topics that were discussed in presentations at HADRON2001. These included evidence of and expectations for exotic mesons, the status of light vector mesons, the very interesting new results on the 980 states, new results for \( R \) in the open-charm region, and evidence for a failure of the \( \text{^3P}_0 \) model. Although this is nominally a theory summary, hadron physics is largely driven by experiment, so I have actually cited some new experimental results that seemed of special interest to theorists.

I have been rather selective in this report, due primarily to a lack of time available for completion of this summary. For this reason many of the results presented at HADRON2001, notably relating to heavy quark and quarkonium physics and baryon physics, were not discussed here. The "future facilities" discussions have clearly shown that this concentration on light \( u,d,s \) hadrons will change in future meetings, at which
time we can expect to see exciting new results on charmonium states, both regarding
the states themselves and their decay products. The traditional concentration of the
HADRON conference series on meson physics was also discussed at this meeting, and it
was suggested that in future there should be a serious effort to include developments in
baryons as a major part of the meeting. With new results from facilities such as Jefferson
Lab, this will certainly be appropriate, and will make the job of the conference summary
speakers even more difficult.

ACKNOWLEDGMENTS

It is a great pleasure to thank Prof. Zaitsev and the organisers of HADRON2001 for their
kind invitation to review some of the theoretical aspects of the physics discussed at this
meeting. I would also like to thank E. Klempt for our collaboration in preparing our joint
HADRON2001 summary presentation, and E. S. Swanson for proofreading this report.
This work 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 US National Science Foundation under Grant No.
INT-0004089.

REFERENCES

1. C. Morningstar, these proceedings.
2. C. J. Morningstar, and M. J. Peardon, Phys. Rev. D60, 034509 (1999).
3. E. S. Swanson, these proceedings.
4. Yu. S. Kalashnikova, these proceedings.
5. T. Kaneko, these proceedings.
6. P. Mackenzie, these proceedings.
7. E. van Beveren, these proceedings.
8. N. Isgur, R. Kokoski, and J. Paton, Phys. Rev. Lett. 54, 869 (1985).
9. I. T. Drummond et al., Phys. Lett. B478, 151 (2000).
10. V. Dorofeev, these proceedings.
11. A. Popov, these proceedings.
12. A. Donnachie, these proceedings.
13. M. Nozar and J. Napolitano (E852 Collaboration), personal communication.
14. A. Donnachie and Yu. S. Kalashnikova, Phys. Rev. D60, 114011 (1999).
15. T. Barnes, F. E. Close, P. R. Page and E. S. Swanson, Phys. Rev. D55, 4157 (1997).
16. F. E. Close and P. R. Page, Nucl. Phys. B443, 233 (1995).
17. N. N. Achasov, S. A. Devyanin, and G. N. Shestakov, Phys. Lett. B88, 367 (1979).
18. F. E. Close, N. Isgur, and S. Kumano, Nucl. Phys. B389, 513 (1993).
19. T. Barnes, Phys. Lett. B165, 434 (1985).
20. F. E. Close, and A. Kirk, Phys. Lett. B515, 13 (2001).
21. C. Göbel, these proceedings.
22. W. Ochs, these proceedings.
23. K. L. Au, D. Morgan, and M. R. Pennington, Phys. Rev. D35, 1633 (1987).
24. H. Marsiske et al., Phys. Rev. D41, 3324 (1990); H. Bienlein, Proc. of the IXth Internatl. Workshop
   on Photon-photon Collisions, La Jolla, CA, 22-26 March 1992, pp.241-257, eds. D. O. Caldwell and
   H. P. Paar (World Scientific, 1992).
25. D. Löhse et al, Nucl. Phys. A516, 513 (1990); G. Janssen et al, Phys. Rev. D52, 2690 (1995).
26. W. Li, these proceedings.
27. K.Seth, these proceedings.
28. S.F.Tuan, these proceedings.
29. S.Hou, these proceedings.
30. A.Tomaradze, these proceedings.
31. T.Barnes, Proc. of the IXth Internatl. Workshop on Photon-photon Collisions, La Jolla, CA, 22-26 March 1992, pp.263-282, eds. D.O.Caldwell and H.P.Paar (World Scientific, 1992).