Tasks in η_c Physics

CLEMENS A. HEUSCH
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064
and
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

Abstract

The design luminosity for the Tau/Charm Factory suggests the collection of 10^6 (10^7) events within one month (year), where the vector charmonium ground state decays radiatively to the pseudoscalar ground state. We point up physics possibilities that become accessible through these parameters.

Electron–positron annihilation through the vector ground state J/ψ of the charmonium system has yielded a bonanza of important physics results on (semi-) hard and soft quantum chromodynamics, and particularly on meson spectroscopy and its quark/symmetry basis. The total sample of fully recorded J/ψ decays is of the order of some 20 million events.[9] Only a fraction of these were recorded by a detection system capable of clean reconstruction of both photons (down to 100 MeV energies) and identified hadrons. As a result, the 1.3% of the above J/ψ sample that decay via

$$J/\psi \rightarrow \gamma\eta_c$$
$$\hookrightarrow \text{hadrons}$$

have not been sufficient to give us a quantitatively and qualitatively satisfactory sample of charmonium decay *via* two gluons: Table 1 shows the status of our

Table 1. Branching ratios of $\eta_c(2980)$. The measured product branching fractions have been corrected using the Crystal Ball values for $B(J/\psi \to \gamma\eta_c)$ and $B(\psi' \to \gamma\eta_c)$, respectively, and have been corrected for isospin where necessary. (From ref. 1.)

Decay Mode	$B(\eta_c \to X)$ in %	Reference
$K^*(892)\overline{K}^*(892)$	0.9 ± 0.5	MARK III [2]
$a_0(980)\pi$	$< 1.0/B(a_0(980) \to \eta\pi)$	MARK III [2]
$a_2(1320)\pi$	< 2.0	MARK III [2]
$f_2(1270)\eta$	< 1.1	MARK III [2]
$\eta\pi\pi$	$3.9^{2.7}_{2.6}$	C.B. [3]
	5.4 ± 1.3	MARK III [2]
$\eta'\pi\pi$	4.1 ± 1.3	MARK III [2]
$K\overline{K}\pi$	16^{+11}_{-7}	MARK II [4]
	4.8 ± 1.1	MARK III [2]
	5.9 ± 1.4	DM2 [5]
$K\overline{K}\eta$	< 3.1	MARK III [2]
$K^*(892)K^-\pi^+ + c.c.$	2.0 ± 0.5	MARK III [2]
$\pi^+\pi^-\pi^+\pi^-$	$2.0^{+1.5}_{-0.9}$	MARK II [4]
	1.3 ± 0.5	MARK III [2]
	$1.05 \pm 0.17 \pm 0.16$	DM2 [5]
$\pi^+\pi^-K^+K^-$	$1.4^{+2.1}_{-0.9}$	MARK II [4]
	2.1 ± 0.3	MARK III [2]
$\pi^+\pi^-p\bar{p}$	< 2.3	MARK II [4]
$p\bar{p}$	$0.29^{+0.3}_{-0.16}$	MARK II [4]
	0.11 ± 0.06	MARK III [2]
	$0.10 \pm 0.02 \pm 0.02$	DM2 [5]
$\Lambda\overline{\Lambda}$	< 0.63	MARK II [4]
$\phi\phi$	0.8 ± 0.2	MARK III [6]
	$0.32 \pm 0.07 \pm 0.06$	DM2 [5]
$\rho\rho$	< 1.4	MARK III [3]
	$2.6 \pm 0.2 \pm 0.5$	DM2 [5]
$\omega\phi$	< 0.13	MARK III [8]
$\omega\omega$	< 0.31	MARK III [3]
	< 0.8	DM2 [4]
$\gamma\gamma$	0.06 ± 0.03	World Average [7]

knowledge of η_c decay branching fractions, with its many upper limits where a precise number would be informative.

Given the plethora of insights into hadronization patterns that has emerged from J/ψ decay *via* three vector bosons, the hundredfold increase in luminosity the Tau/Charm Factory will bring over present facilities in this range, will put our η_c sample in a quantitative league with the existing J/ψ sample. What chances and challenges will that entail for our study of two-vector-boson hadronization?

Detector Needs

The key to successful operations in this physics regime is efficient and accurate photon detection at low ($E_\gamma \sim 120$ MeV) energies: the M1 transition from the ${}^3S_1$ to the ${}^1S_0$ charmonium state is accompanied by the emission of a 119 MeV photon. The better we can define the detected photon energy in the hardware, the cleaner our sample of events. This argues in favor of *little* material between interaction point and electromagnetic calorimeter, of placing the coil for a solenoidal field *out*side that calorimeter, and of fine segmentation as well as good energy resolution of that detector. Specifically, a continuously sampling tracking calorimeter will give the best chances to optimize event recognition and background suppression.[11]

Symmetry Considerations

A comparison of the two radiative J/ψ decay graphs

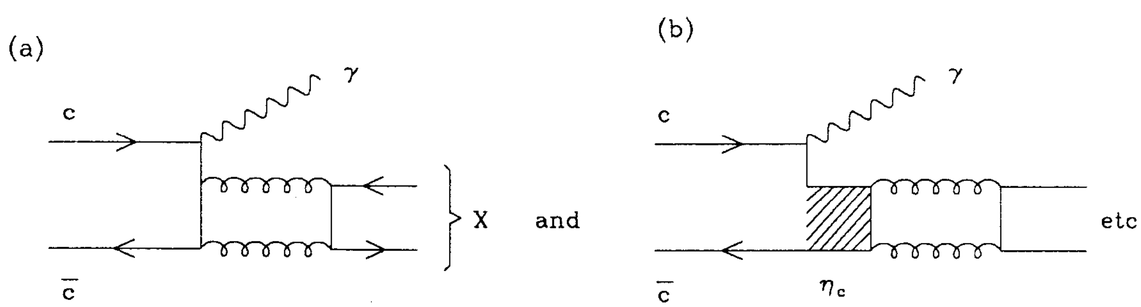

Fig. 1. Radiative decay graphs; a) continuum; b) η_c

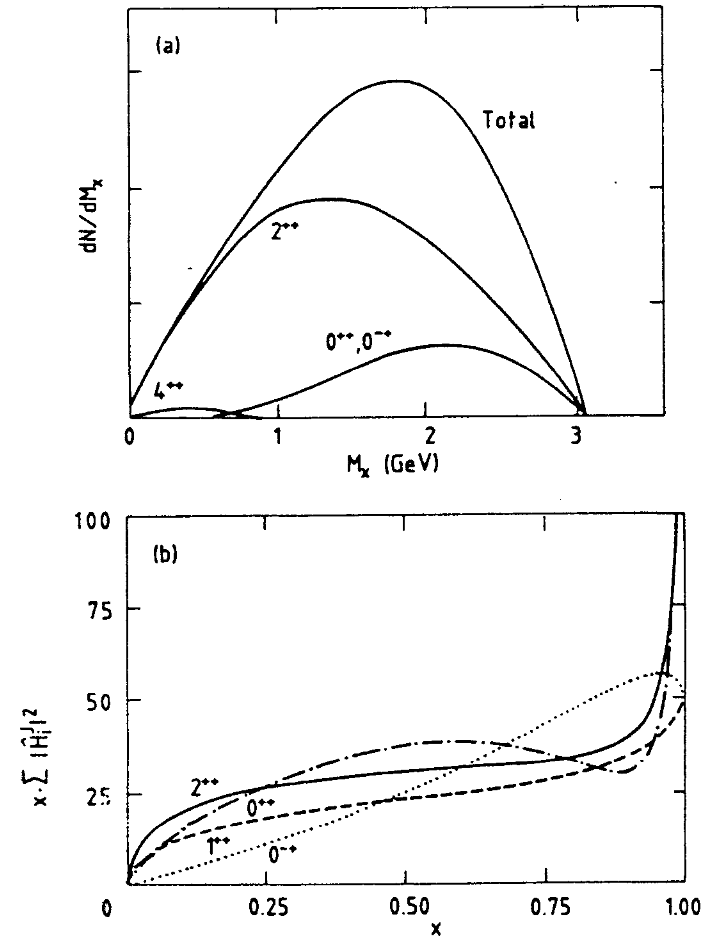

Fig. 2. QCD predictions for a) Spin-parity content of the 2-gluon system as a function of its invariant mass; b) summed squares of reduced helicity amplitudes as a function of $x = 1 - (m_{gg}/M)^2$.

makes constraints from symmetry considerations immediately clear: fig. 1(a) sees the two gluons hadronize from an SU_3 singlet into any J^{PC} state permissible: 0^{++}, 0^{-+}, 1^{++}, 2^{++},... (always with positive charge conjugation). It turns out that the existing data prefer states accessible to a 2-massless-gluon intermediate state: 0^{++}, 0^{-+}, 2^{++}.* QCD calculations predict their ratios and the different helicity amplitudes, as shown in figs. 2(a) and (b). Graph 1(b), on the other hand, constrains the hadronization to one well established $J^{PC} = 0^{-+}$ value, and one

⋆ Accessible masses range from $m(\pi)$ to $m(\eta_c)$.

sharply defined mass: $m(\eta_c) = 2979$ MeV/c^2, with a width of only $\Gamma(\eta_c) = 10$ MeV. These restrictions imply a highly constrained hadronization process; we can use it to good avail.

A comparison of two-gluon and two-photon widths

$$\Gamma(\eta_c \to gg) = 4 \cdot 2/3 \frac{\alpha_s^2}{m_c^2} |R(0)|^2,$$

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{4\alpha_s^2}{m_c^2} e_c^4 |R(0)|^2,$$

with $e_c = 2/3$ the charge of the charmed quark, should permit us a measurement of α_s at the relevant mass parameter. A comparable ratio of the three-gluon decay of J/ψ with its one-photon decay width into e^+e^- leads to the prediction

$$\frac{\Gamma(\eta_c \to \text{hadrons})}{\Gamma(J/\psi \to \text{hadrons})} = \frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(J/\psi \to e^+e^-)} = 3e_c^2 \left(1 + 1.96 \frac{\alpha_s}{\pi}\right),$$

where the α_s/π term is due to lowest-order QCD corrections. This works out to give $\Gamma(\eta_c \to \gamma\gamma) \simeq 9$ keV. The measured value is about 6 keV,[12] but has fluctuated in the past. Since the total width enters into the above consideration, and is based mostly on the pioneering Crystal Ball observations,[13] it becomes clear that a precise measurement can do wonders for our knowledge of α_c at this low Q^2 value—a result we will *not* obtain from J/ψ decays into hadrons. Note that this entails a precise determination of *both* total and radiative widths.

Hadronization Patterns: $\eta_c \to$ VV

From observation of the J/ψ decays into a real photon and two vector mesons,

$$J/\psi \to \gamma X$$
$$\hookrightarrow \rho\rho,\ \omega\omega,\ \phi\phi, K^*\overline{K}^*,$$

we know that there are common features to be observed in the $J^{PC}(VV) = 0^{-+}$ channel: all display resonant structure above their respective thresholds, and all show clear η_c signals. The lowest-order graphs for these decays are

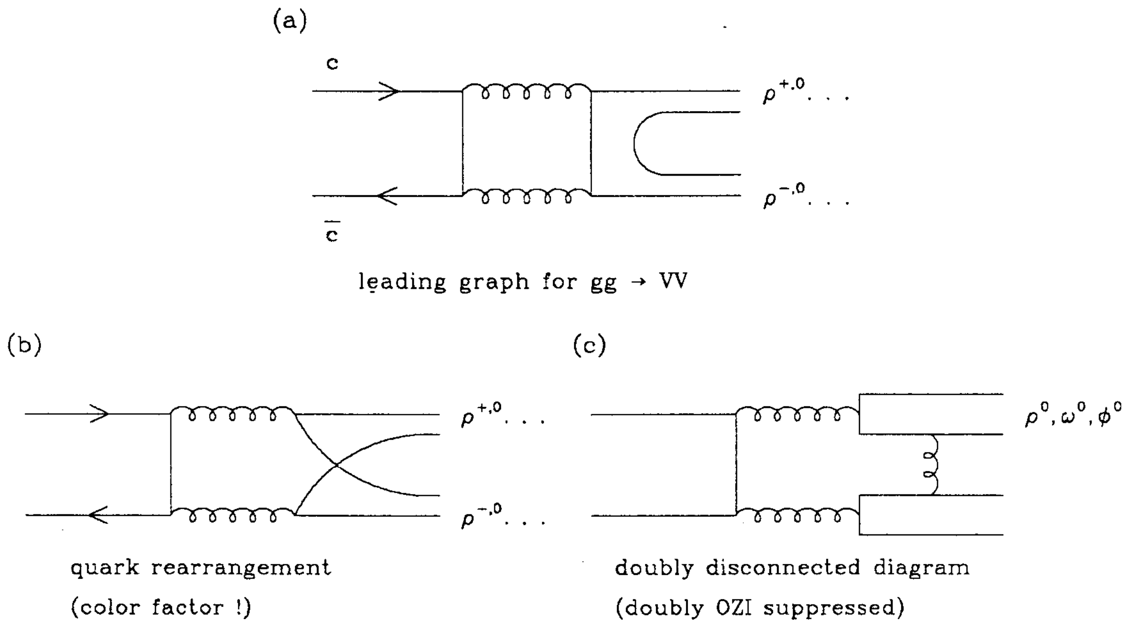

Fig. 3. Lowest-order graphs for the process $c\bar{c}(^1S_0) \to V\overline{V}$.

shown in figs. 3a–3c. The final states in figs. 3a and 3b cannot be told apart, but fig. 3b will be suppressed by a color factor. We expect the doubly disconnected diagram of fig. 3c to be further suppressed due to its topology (maybe by a factor of 10). It leads to V^0V^0 states only, and has the tell-tale possibility of permitting $\omega^0\phi^0$ final states, but no $\rho^\pm$ or K^* pairs.

Unbroken SU_3 predicts the neutral vector meson pair ratio $K^{*0}\overline{K}^{*0}/\phi\phi/\rho^0\rho^0/\omega\omega$ $= 0.5 : 1 : 1 : 1$, but experiment (normalized to the $\phi\phi$ channel) yields the incompatible ratios

$$0.39 \pm 0.18/1/0.62 \pm 0.23/ < .26 \quad (\text{MARK III})$$
$$1.48 \pm 0.5/1/2.66 \pm 0.5/ < 2.0 \quad (\text{DM}-2) \ .$$

If we now assume ideal mixing (i.e., the singlet/octet mixing angle for the isoscalars is $\theta_V = 35.26^\circ$), and assign coupling strengths,

$$g_1 \text{ for } \eta_c \to \mathbf{1} \otimes \mathbf{1}$$
$$g_8 \text{ for } \eta_c \to \mathbf{8} \otimes \mathbf{8} \ .$$

Table 2 shows the resulting parameterization of the various observable vector-vector decay amplitudes:

TABLE 2

Decay	Amplitude
$\eta_c \to \phi\phi$	$g_8 \cos^2\theta_V + g_1 \sin^2\theta_V$
$\to \omega\omega$	$g_8 \sin^2\theta_V + g_1 \cos^2\theta_V$
$\to \omega\phi$	$\sin\theta_V \cos\theta_V (g_8 - g_1)$
$\to K^* \overline{K}^*$	$\sqrt{2}\, g_8$
$\to \rho\rho$	$\sqrt{3}\, g_8$

The DM-2 Collaboration then quotes[14] a coupling ratio

$$\frac{g_1}{g_8} = 0.65 \begin{pmatrix} +0.29 \\ -0.14 \end{pmatrix},$$

which is compatible with nonet symmetry. The implication is that the discrepant MARK III results are clearly *not* compatible. A closer look at the data shows that the separation of $\eta_c \to \rho\pi\pi$ from $\eta_c \to \rho\rho$ may be a source of serious errors: data samples larger than those seen in fig. 4 are obviously needed to make reliable fits and background subtractions, and to permit meaningful Dalitz plots for the requisite mass range.

Table 2 also shows that only in the case of exact nonet symmetry ($g_1 = g_8$) do we not expect to observe $\eta_c \to \omega\phi$. This decay via the doubly disconnected graph fig. 3c is probably seen (fig. 4d) and has to be quantitatively studied.

Another interesting study becomes possible with the advent of 10^6 to 10^7 η_c decays. A comparison of the graphs

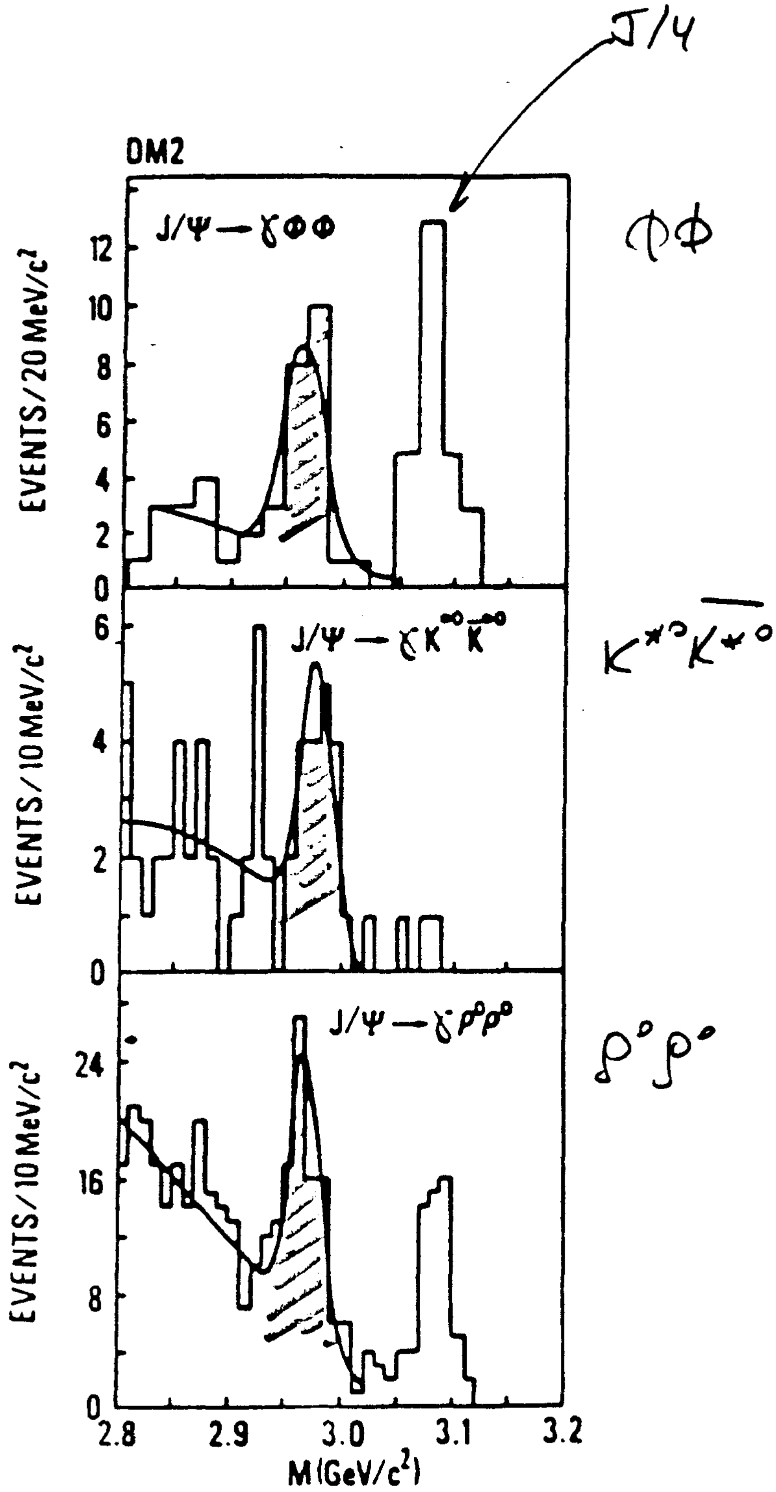

Fig. 4. $\eta_c \to VV$ graphs (mostly DM-2).

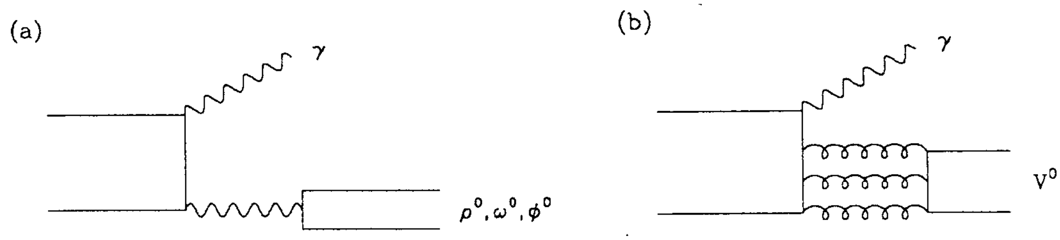

Fig. 5. Radiative η_c decay: a) via one-photon b) via three-gluon hadronization.

permits a clean separation of one-photon and three-gluon hadronization. Figure 5a should permit a clean test of vector-dominance ideas, unencumbered by almost all backgrounds; fig. 5b, on the other hand, should be a locus for SU_3 *singlets* formed by three gluons: We expect it to project out the SU_3 singlet combination of ω and ϕ mesons. It may also lead to new insights on three-gluon glue-balls (if they exist at these low masses).

Process 5a will occur with a branching fraction of the order 10^{-4}, excluding large data samples; 5b may well be at the 0.1–1% level, and allow meaningful searches.

Light-Meson Spectroscopy

The highly constrained decays

$$\eta_c \to 2g \to 2 \text{ mesons}$$
$$\to 3 \text{ mesons}$$

can, given the conservation of $J^{PC} = O^{-+}$, help clean up various spectroscopic problems for the systematics of light mesons. To wit,

- Scalar mesons: Here, our understanding is fractional at best. The only firmly established scalars are $a_0(980)$ and $f_0(975)$. A recent coupled-channel analysis[15] by MARK III assigns a normal hadronic width to this isosinglet state—at variance with all previous work; the triplet a_0 is being studied, also by MARK III[16] within the data samples of $\eta\pi\pi$ events in radiative

J/ψ decay. There may be a problem with equal or compatible rates for $a_0 \to \pi\eta$ and $a_0 \to \overline{K}K$. The mass degeneracy of isosinglet and isotriplet is not understood; there are persistent questions about the $q\bar{q}$ basis for these states.

A data sample more highly constrained than that due to J/ψ decay can be expected to make a noticeable difference in our chances to distinguish the scalar sector: a high-statistics sample of η_c decays can open up a systematic investigation of two-gluon decays

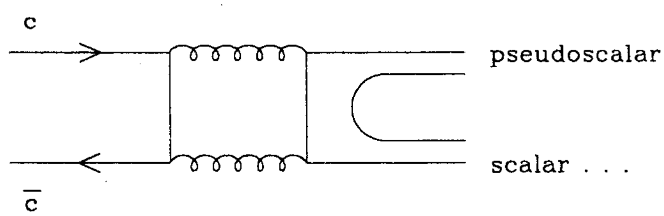

Fig. 6. Basic 2-gluon decay graph.

with clean angular distribution criteria. The isoscalar mass spectrum can be studied in the decays

$$\eta_c \to \eta\pi^+\pi^- \to \text{study } m(\pi^+\pi^-)$$
$$\eta\pi^0\pi^0 \to \text{study } m(\pi^0\pi^0)$$

and be compared to

$$\eta_c \to K^+K^-\pi^0 \to \text{study } m(K^+K^-)$$
$$K_SK_S\pi^0 \to \text{study } m(K_SK_S).$$

Similarly, the isovector $a_0(980)$ can be looked for in

$$\eta_c \to \eta\pi^+\pi^- \to \text{study } m(\eta\pi^\pm)$$
$$\eta\pi^0\pi^0 \to \text{study } m(\eta\pi^0).$$

Lastly, the ill-understood isospinor κ states can, given good particle identification for $K^{\pm}$ vs. $\pi^{\pm}$, be studied in a highly constrained form:

$$\begin{aligned} \eta_c &\rightarrow K^+K^-\pi^0 \rightarrow \text{study } m(K\pi^0), \\ &\rightarrow K^{\pm}K_S\pi^{\pm} \rightarrow \text{study } m(K\pi), \\ &\rightarrow K_SK_S\pi^0 \rightarrow \text{study } m(K_S\pi^0). \end{aligned}$$

Note that the $\eta_c \rightarrow \eta\pi\pi$ and $\rightarrow \overline{K}K\pi$ decays jointly account for some 10% of all η_c decays; a 10^6 or $10^7\eta_c$ sample could find excellent use in these studies.

– Scalar Gluonia?

Further, recall that the search for gluon-based scalars remains high on our list of urgent projects in this energy range. Notwithstanding changing results from lattice calculations, which may indicate $m(gg)_{0++} \gtrsim 1.5$ GeV/c^2, the fact that gg-based scalars are L=O states whereas $q\bar{q}$-scalars are L=1 configurations, together with many indications from fits to $\pi\pi$ interactions keep our attention riveted on the possibility that

$$m(gg, O^{++}) \leq 1 \text{ GeV/c}^2 \ .$$

Radiative J/ψ decay produces a continuous gg mass spectrum over the entire range of interest. In η_c decay, the fixed gg initial intermediate state permits only the graphs

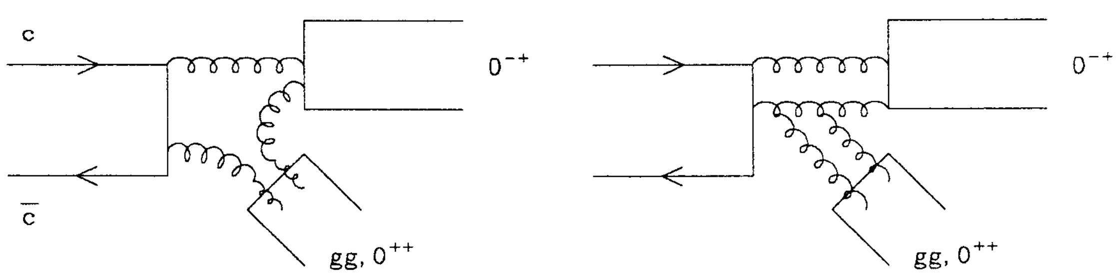

Fig. 7. Scalar gluonium production graphs in η_c decay.

While these configurations are hard to calculate, it can safely be argued that any scalar observed in η_c decay is much more likely to be $q\bar{q}$ based than gg based.

This adds to the interest in performing interpretable scalar $q\bar{q}$ meson searches, notoriously hard in the continuous $m(gg)$ spectrum of J/ψ decay, in η_c physics.

Exotic Meson Spectroscopy

Valence gluons are not, however, altogether out of the picture for η_c decay products: this is a good place to keep our eyes open for $q\bar{q}g$ hybrids (or 4-quark states).

For $m(q\bar{q}g) \lesssim 1.4$ GeV/c^2, consider the diagram

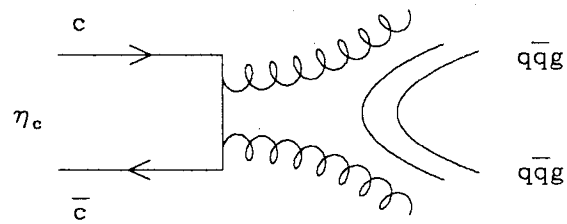

Fig. 8. Pair production of hybrid mesons in η_c decay.

Recall that two-gluon annihilation into baryon pairs is observed ($\eta_c \rightarrow p\bar{p}, J/\psi \rightarrow \gamma p\bar{p}$, etc.). They also involve "pulling" two quarks out of the vacuum.

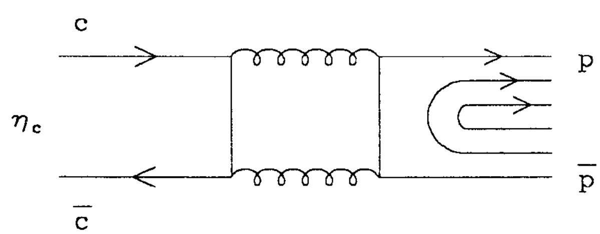

Fig. 9. $c\bar{c}$ decay into baryon pairs, $BR \sim 0.1\%$.

The penalty to be paid is expressed in the modest branching fraction of some 0.1%; clearly, however, the hybrid pair production graph has two powers of α_S advantage over baryon pair production.

The unconfirmed reports of the GAMS Collaboration[17] on the observation of a hybrid state of mass 1.3 GeV/c^2, decaying into $\eta\pi$ with quantum numbers

$J^{PC} = 1^{-+}$, can certainly be tested in this favored environment for pair production in the decay

$$\eta_c \rightarrow (\eta\pi)(\eta\pi) \ .$$

It has been speculated[18] that Russian reports of an enhancement in the $\phi\pi$ mass spectrum (observed by Bilyukov *et al.*[19] in the reaction $\pi^- p \rightarrow \phi\pi^0 n$ with a 32 GeV/c pion beam), are to be interpreted as a related exotic state of opposite G parity: $(m(\phi\pi^0) = 1.48, \Gamma(\phi\pi^0) = 0.13, J^{PC} = 1^{--})$. Although there is essentially no phase space available for the pair production of this reported state, its considerable width may still make a look for the decay

$$\eta_c \rightarrow (\phi\pi)(\phi\pi)$$

worthwhile. The message we wish to convey here is that we see η_c decay as a unique place to look for pairs of the controversial hybrids, none of which have been clearly established: all QCD phenomenology stands to gain by clear answers that this channel may provide.

REFERENCES

1. L. Köpke and N. Wermes, *Phys. Rep.* **174**, 68 (1989).
2. R.M. Baltrusaitis *et al., Phys. Rev.* **D38**, 629 (1986).
3. R. Partridge *et al., Phys. Rev. Lett.* **45**, 1150 (1980).
4. T. Himel *et al., Phys. Rev. Lett.* **45**, 1146 (1980).
5. B. Jeanmarie *et al.,* in *Proceedings of XXIII International Conference on High Energy Physics,* Berkeley, 1986, edited by Stewart C. Loken (Singapore, World Scientific, 1987).
6. R.M. Baltrusaitis *et al., Phys. Rev. Lett.* **52**, 2126 (1984). see also J. Eigan, contribution to these proceedings.

7. See J. Olsson, *Proceedings of the 13th International Symposium on Lepton and Photon Interactions at High Energies,* Hamburg, 1987, edited by W. Bartel and B. Ruckl (Amsterdam, North-Holland, 1988), *Nucl. Phys. B (Proc. Suppl.) 3, 1988.*

8. *R.M. Baltrusaitis et al., SLAC-PUB-3468 (1986).*

9. *Data samples are roughly 8.6 M for the DM2 Collaboration, 5.8 M for the MARK III, and about 2 M each for the Crystal Ball and MARK II Collaborations.*

10. *Particle Data Group, Phys. Lett.* **B204**, 1 (1988).

11. C.A. Heusch, contribution to the Detector Section of these proceedings.

12. P. Baglin *et al., Phys. Lett.* **B187**, 1917 (1987).

13. T. Gaiser *et al., Phys. Rev.* **D34**, 722 (1984).

14. A. Falvard, LAL 87-43 (1987).

15. W. Lockman, in *Proceedings of Intersections Between Particle and Nuclear Physics,* edited by Donald F. Geesaman (American Inst. Phys., New York, 1986) 776.

16. M. Burchell, private communication.

17. D. Arde *et al., Phys. Lett.* **B205**, 397 (1988).

18. F. Close and H. Lipkin, *Phys. Lett.* **B196**, 245 (1987).

19. S.I. Bilyukov *et al., Phys. Lett.* **B188**, 383 (1987).