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Ψ CHOLOGY

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> Ψ chology, n. Science of nature, functions and phenomena of ψ-particles; treatise on, system of, this.
>
> (The concise Oxford dictionary, paraphrased.)

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FOREWORD

These informal notes represent the type of "instant analysis" offered by many theorists within the first two weeks after the discovery of the ψ (3105) particle. Many of the observations made here are well known and trivial. Others are only trivial. Few are non-trivial. None are profound.

The informal nature of these pages allows us to omit a list of references. At the same time, no claim of originality is made. If these notes will help experimentalists and theorists to exclude some ideas and to follow others, they will have fulfilled their aim.

Much of the material covered here was generated during marathon discussion sessions at SLAC. The participants of these sessions made many contributions to these notes. The errors are all mine.

The notes are organized as questions and answers, each on a separate page. A properly written review seems highly premature at this time. The reader may discard pages made obsolete by the data of the next few days, and replace them by new pertinent questions and answers.

A list of all the questions discussed here follows this page. A summary of our answers is offered at the end of these notes.

CONTENTS

A. GENERAL QUESTIONS

A1. What do we know experimentally about the ψ-particles?

(i) The first ψ-particle is observed in e^+e^- scattering as a resonance in the total hadronic cross sections, as well as in the $\mu^+\mu^-$ and e^+e^- final states.

$$M(\psi) = 3105 \text{ MeV} \quad ; \quad \Gamma(\psi) \leq 1.9 \text{ MeV} \quad .$$ (However, see A2).

(ii) A crude estimate (probably correct within 30%) gives:

$$\int \sigma (e^+e^- \rightarrow \psi \rightarrow \text{hadrons})\, dW \sim 8000 \text{ nb MeV}$$ (integrated over the ψ-peak)

To this we must add a $\sim 40\%$ radiative correction.

(iii) The relative size of the hadronic ψ-peak and the $\mu^+\mu^-$ peak gives:

$$\frac{\Gamma(\psi \rightarrow \text{hadrons})}{\Gamma(\psi \rightarrow \mu^+\mu^-)} \sim 15$$

(iv) The data are consistent with:

$$\Gamma(\psi \rightarrow \mu^+\mu^-) \sim \Gamma(\psi \rightarrow e^+e^-)$$

(v) $\psi(3105)$ is produced as an e^+e^- resonance in $p + Be \rightarrow e^+ + e^- + \text{anything}$, with a production cross section estimated around 10^{-34} cm^2 (for the e^+e^- decay mode only). Hence, the full ψ-production cross section in p + Be is probably around 10^{-33} cm^2 and in p + p around 10^{-34} cm^2.

(vi) A second ψ-particle is observed in e^+e^- scattering (but not, so far, in $p + p \rightarrow e^+ + e^- + \text{anything}$):

$$M(\psi') = 3695 \text{ MeV} \quad ; \quad \Gamma(\psi') \leq 2.7 \text{ MeV}$$

(vii) A crude estimate (probably correct within 30%) gives:

$$\int \sigma (e^+e^- \rightarrow \psi' \rightarrow \text{hadrons})\, dW \sim 3000 \text{ nb MeV}$$ (integrated over the ψ'-peak)

Here, again, a 40% radiative correction should be added.

A2. <u>What do we assume, without direct experimental verification</u>?

(i) Having no evidence to the contrary, we assume that each of the two observed ψ's is a single Breit-Wigner resonance.

(ii) We assume that the two ψ-particles have spin J = 1.

(iii) We assume that the partial decay width into e^+e^- and $\mu^+\mu^-$ are equal for a given ψ-particle.

(iv) We assume that if the ψ-particles are hadrons (see <u>A3</u>), then C, P, and T are conserved in their production and decay. Hence: $C(\psi) = -1$; $P(\psi) = -1$.

(v) From the integrated total e^+e^- cross section over the $\psi(3105)$ peak (see <u>A1</u>) we get (within 30%):

$$\Gamma(\psi \to e^+e^-) \sim \Gamma(\psi \to \mu^+\mu^-) \sim 6 \text{ keV}$$

(vi) Using the $\mu^+\mu^-$ branching ratio for $\psi(3105)$ we can deduce (within 30%):

$$\Gamma_{tot}(\psi \to \text{anything}) \sim 100 \text{ keV}$$

(vii) The above estimates for $\Gamma(\psi \to e^+e^-)$ and $\Gamma_{tot}(\psi)$ assume that <u>all</u> the decay modes of $\psi(3105)$ are <u>observed</u> in the $e^+e^- \to \psi$ experiment. If, however,

$$B = \frac{\Gamma(\psi \to \text{detected decay modes})}{\Gamma(\psi \to \text{anything})}$$

we have: $\Gamma(\psi \to e^+e^-) \sim (6/B)$ keV , $\Gamma(\psi \to \text{anything}) \sim (100/B^2)$ keV

(viii) The same considerations for $\psi'(3695)$ give:

$$\Gamma(\psi' \to e^+e^-) \sim \Gamma(\psi' \to \mu^+\mu^-) \sim 3 \text{ keV}$$

This should be, again, divided by the branching ratio to the detected decay modes.

<u>All of these assumptions will be tested in the near future in e^+e^- experiments</u>.

A3. Are the ψ-particles hadrons?

The production cross sections for $e^+e^- \to \psi$ (or ψ') are consistent with the hypothesis that ψ and ψ' are hadrons, but do not prove it.

The narrow widths of the two ψ-particles are smaller than all known widths for strong decays, and are even relatively narrow with respect to many electromagnetic decays (see A5). However, many hadrons decay only weakly (K, Λ, Σ, Ω, etc.). Hence the width proves nothing. The best way of directly determining whether the ψ-particles are hadrons is probably to measure

$$\sigma(\gamma + p \to \psi + p)$$

or, even better,

$$\sigma(\gamma + A \to \psi + A)$$

where A is a heavy nucleus. If ψ is a hadron, this cross section, at sufficiently high energy, should probably be within, say, one or two orders of magnitude of $\sigma(\gamma + A \to \phi + A)$. It cannot be inhibited by any hadronic selection rule (see B15, C11). If ψ has no strong interactions, its photoproduction cross section would probably be much smaller.

Assuming that ψ is a hadron we can estimate $\sigma(\gamma p \to \psi p)$ in terms of $\Gamma(\psi \to e^+e^-)$ and $\sigma_{tot}(\psi p)$. Assuming $\sigma_{tot}(\psi p) = K(\mathrm{mb})$, we find $\sigma(\gamma p \to \psi p) \sim$ (5 nb) $\times K^2$. Hence for $\sigma_{tot}(\psi p)$ between 1 and 10 mb, we predict $\sigma(\gamma p \to \psi p)$ between 5 and 500 nb.

Better knowledge of $\sigma(pp \to \psi + \text{anything})$ (including $p_\perp$ dependence, energy dependence, details of the "anything", etc.) would also be valuable in determining whether ψ is a hadron.

A4. If the ψ-particles are hadrons, why are they so narrow?

Considering the well established selection rules of the strong interactions, the ψ-particles would normally be expected to decay into other hadrons with a typical resonance width of, say, 100 MeV or so.

There are three logical possibilities for the narrow width of each ψ-particle:

(i) ψ is not a hadron.

(ii) ψ is a hadron but its strong decay is exactly forbidden by a new selection rule. The simplest selection rule would be obtained if ψ possesses a nontrivial eigenvalue of a new quantum number, while all previously discovered hadrons have zero eigenvalues of this quantum number. However, the new quantum number cannot be an additive quantum number (such as Q, Y, I_z, S, B, etc.). Any conserved additive quantum number which commutes with charge conjugation would have a zero eigenvalue for the ψ. Hence, ψ would not be prevented from decaying to other hadrons. The new quantum number must be non-additive (like isospin, SU(3), etc.). Color is an example of such a new quantum number (see Section C).

(iii) ψ is a hadron but its strong decay is inhibited by a new dynamical mechanism, possibly based on an approximate selection rule. Charm is an example of such a scheme (see Section B).

A5. What are the typical strong and electromagnetic decay rates of hadrons?

(i) A typical strong decay width is $\Gamma \sim$ 10-200 MeV. An interesting exception is ϕ (see B3):

$$\Gamma(\phi \to \text{anything}) \sim 4.2 \text{ MeV}, \quad \Gamma(\phi \to 3\pi) \sim 0.7 \text{ MeV}.$$

(ii) Radiative decay widths are normally in the range 0.1-1 MeV:

$\Gamma(\omega \to \pi\gamma) \sim 0.9$ MeV $\qquad \Gamma(\phi \to \eta\gamma) \sim 0.1$ MeV

$\Gamma(\rho \to \pi\gamma) < 0.75$ MeV (theoretically: $\Gamma(\rho \to \pi\gamma) \sim 0.1$ MeV).

$\Gamma(\omega \to \pi^+\pi^-\gamma) < 0.5$ MeV

$\Gamma(\phi \to \pi\gamma) << \Gamma(\omega \to \pi\gamma)$ (theoretically — a few keV).

$\Gamma(X^o \to \rho\gamma) \sim 0.27\, \Gamma_{tot}(X^o) \sim 16\, \Gamma(X^o \to \gamma\gamma)$

$\Gamma(\eta \to \pi^+\pi^-\gamma) \sim$ 0.05-0.1 keV

$\Gamma(\Delta^+ \to p\gamma) \sim 0.8$ MeV $\qquad \Gamma(N^*(3/2^-, 1520) \to p\gamma) \sim 0.8$ MeV

$\Gamma(N^*(5/2^+, 1680) \to p\gamma) \sim 0.4$ MeV $\qquad \Gamma(\Delta(7/2^+ 1950) \to p\gamma) \sim 0.6$ MeV

(iii) Second order electromagnetic decays:

$\Gamma(\rho \to e^+e^-) \sim 6.5$ keV $\qquad \Gamma(\eta \to 3\pi) \sim$ 0.5-1 keV

$\Gamma(\omega \to e^+e^-) \sim 0.75$ keV $\qquad \Gamma(\eta \to \gamma\gamma) \sim$ 0.5-1 keV

$\Gamma(\phi \to e^+e^-) \sim 1.3$ keV

These numbers indicate clearly that:

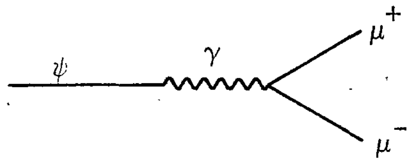
(i) the total ψ width is smaller by several orders of magnitude than typical strong decay widths

(ii) it is smaller than most radiative widths

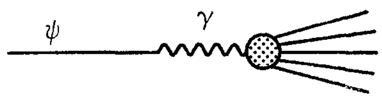
(iii) $\Gamma(\psi \to ee)$ is comparable to other $\Gamma(V^o \to e^+e^-)$.

A6. Does ψ decay into hadrons via a photon?

Assuming that ψ couples to leptons via a photon, we may use the following diagram for $\psi \to \mu^+\mu^-$



A similar mechanism should then produce a hadronic final state:



The simplest model indicates that the probability that a 3.1 BeV photon will produce hadrons or a $\mu^+\mu^-$ pair is independent of whether or not it came from a ψ. Hence:

$$\frac{\Gamma(\psi \to \gamma \to \text{hadrons})}{\Gamma(\psi \to \gamma \to \mu^+\mu^-)} \sim \left.\frac{\sigma(e^+e^- \to \gamma \to \text{hadrons})}{\sigma(e^+e^- \to \gamma \to \mu^+\mu^-)}\right|_{\text{outside } \psi \text{ peak}}$$

The latter ratio is R ~ 2.5 at 3 BeV. Consequently:

$$\frac{\Gamma(\psi \to \gamma \to \text{hadrons})}{\Gamma(\psi \to \gamma \to \mu^+\mu^-)} \sim 2.5$$

However:

$$\frac{\Gamma(\psi \to \text{hadrons})}{\Gamma(\psi \to \mu^+\mu^-)} \sim 15 \ .$$

Hence, approximately 15% of the hadronic final states of the ψ decay are produced via a photon. These 15% should have the same characteristics of events outside the ψ-peak (multiplicities, K/π ratio, inclusive spectra, etc.) while the other 85% should exhibit the unique characteristics of the ψ.

These statements ignore possible interference effects, higher order electromagnetic transitions, etc. Such effects should be studied more carefully.

B. ARE THE ψ-PARTICLES MADE OUT OF CHARMED QUARKS?

B1. What are the quantum numbers of the charmed quarks and who needs them?

We start with the usual three quarks u, d, s with electric charges $Q = 2/3$, $-1/3$, $-1/3$ respectively. The charmed quark c is a fourth quark with $Q = 2/3$, $Y = I_3 = 0$, belonging to an SU(3)-singlet. It has charm = +1, while u, d, s are charmless. The modified Gell-Mann-Nishijima formula is:

$$Q = \frac{1}{2} Y + I_z + \frac{2}{3} C .$$

The electromagnetic current is an octet-singlet combination in SU(3) and its quark description is

$$\frac{1}{3}\left\{2(u\bar{u}) - (d\bar{d}) - (s\bar{s}) + 2(c\bar{c})\right\} .$$

The singlet part of the current couples only to charmed quarks. The four quarks form an SU(4) quartet, and SU(4) becomes a (badly broken) symmetry of the strong interactions.

The introduction of charm is the most natural step after the introduction of strangeness. SU(4) is the obvious extension of SU(3). However, the main benefit of the concept of charm comes from the weak interactions. The four quarks presumably fall into two doublets of "weak isospin" analogous to the (μ, ν_μ) and (e, ν_e) doublets. The two quark doublets are supposed to be:

$$(u,\ d \cos\theta_c + s \sin\theta_c);\ (c,\ d \sin\theta_c - s \cos\theta_c) \quad ,$$

where θ_c is the Cabibbo angle. The main virtue of this classification is that, in the exact symmetry limit, it allows strangeness conserving neutral hadronic weak currents, but forbids strangeness changing neutral hadronic weak currents. Hence — $\nu + p \rightarrow \nu$ + hadrons is allowed (and observed); $K^0 \rightarrow \mu^+\mu^-$ is forbidden (and is experimentally very small).

B2. Which mesons should exist in a charmed spectroscopy?

The usual meson nonets ($3 \times 3 = 9$) should be replaced by hexadecimets ($4 \times 4 = 16$). Such a hexadecimet would include:

(i) An ordinary SU(3) nonet (octet + singlet).

(ii) A $C = +1$ SU(3) antitriplet (D^+, D^o, F^+).

(iii) A $C = -1$ SU(3) triplet $(D^-, \bar{D}^o, F^-)$.

(iv) Another charmless SU(3) singlet.

We then have seven new states, six of which have charm, and the seventh — a charmless meson, made out of $c\bar{c}$ quarks. The ψ is a suspected $c\bar{c}$ state in this scheme.

The new SU(3) singlet could be a pure $c\bar{c}$ state (in the same way that ϕ or f* are pure $s\bar{s}$ states). Alternatively, it could mix with the $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ states, creating two SU(3)-singlets, each with a $c\bar{c}$ component (in the same way that η and X^o are two isosinglets, each with an $s\bar{s}$ component).

The SU(4) multiplets of the 16 mesons are $\underline{15} + \underline{1}$. The pure $c\bar{c}$ state is a linear combination of the $\underline{15}$ and the $\underline{1}$ (in the same way that ϕ is an octet-singlet combination in SU(3)).

The entire discussion above applies to each spin-parity value: $J^P = 0^-, 1^-; 0^+, 1^+, 2^+$, etc. (see B7). The new SU(3) singlets may be pure $c\bar{c}$ states for certain J^P values and mixed states for other J^P values.

B3. What is so special about the ϕ-meson and why is it relevant to the ψ?

The ϕ is a striking example of a pure $s\bar{s}$ state. It has many interesting properties. If pure $c\bar{c}$ states exist, they may have some of these properties. It is therefore important to understand the ϕ.

The ϕ coupling to $K\bar{K}$ has a "normal" strength. However, ϕ is so close to the $K\bar{K}$ threshold that $\Gamma(\phi \to K\bar{K})$ is relatively small (< 4 MeV). If the K-mass would have been larger by 20 MeV, $\phi \to K\bar{K}$ would be forbidden, and $\Gamma(\phi \to \text{anything})$ would be only 0.8 MeV.

Experimentally: $\Gamma(\phi \to 3\pi)/\Gamma(\omega \to 3\pi) \sim 0.08$; $\sigma(\pi N \to \phi N) \ll \sigma(\pi N \to \omega N)$; $\sigma(pp \to pp\phi) \ll \sigma(pp \to pp\omega)$; $g_{\phi NN} \ll g_{\omega NN}$. Somehow, the ϕ, which is made out of strange quarks, does not like to couple to particles made out of nonstrange quarks.

The theoretical "explanation" for this is supposed to be related to the so-called "Zweig rule" (see B5), but regardless of any theoretical ideas, the experimental facts are striking!

The ϕ does couple to the photon: $\Gamma(\phi \to e^+e^-) \sim 2\Gamma(\omega \to e^+e^-)$; $\sigma(\gamma p \to \phi p) \sim \frac{1}{2}\,\sigma(\gamma p \to \omega p)$ at high energy; etc. This is not surprising because the electromagnetic current is expected to couple to strange quarks.

If the ψ is a $c\bar{c}$ state, and if it behaves like the ϕ, it would refuse to couple to non-charmed particles, but would gladly couple to the photon. This might be the reason for the small ψ-width, and this is what makes the ϕ-ψ analogy so interesting.

B4. How far can we "push" the ϕ-ψ analogy?

Assuming that ψ-particles are pure $c\bar{c}$ states, it is not difficult to explain why they do not have the usual width for hadronic decays (~ 100 MeV). All we need to assume is that all charmed mesons are heavier than $\frac{1}{2}\,m(\psi')$.

We can estimate the mass of the charmed mesons, by analogy to strange mesons. We know that:

$$m^2(\phi) + m^2(\omega \text{ or } \rho) = 2m^2(K^*)$$

where: $\phi = (s\bar{s})$; $\rho, \omega = (u\bar{u} \pm d\bar{d})$; $K^* = (u\bar{s},\ d\bar{s})$

We might guess that:

$$m^2(\psi) + m^2(\omega \text{ or } \rho) = 2m^2(D^*)$$

where D^* is a $C=\pm 1$ vector meson and: $\psi = (c\bar{c})$; $\rho, \omega = (u\bar{u} \pm d\bar{d})$; $D^* = (u\bar{c},\ d\bar{c})$.

If $m(\psi) = 3.1$ BeV, we get: $m(D^*) \sim 2.25$ BeV.

We know that:

$$m^2(K^*) - m^2(K) = m^2(\rho) - m^2(\pi) \sim 0.55 \text{ BeV}^2$$

We then guess:

$$m^2(D^*, J^P = 1^-) - m^2(D, J^P = 0^-) \sim 0.55 \text{ BeV}^2$$

Hence: $m(D) \sim 2.15$ BeV and the threshold for $D\bar{D}$ production or decay is $E \sim 4.3$ GeV.

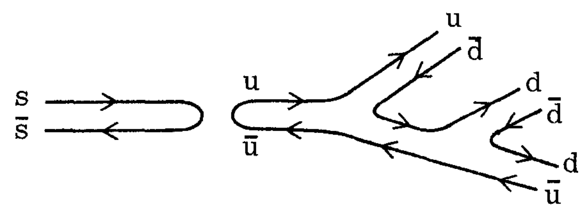
The only strong decay modes open to the ψ would then be into charmless particles. Since $\Gamma(\phi \rightarrow \text{nonstrange mesons}) \sim 0.7$ MeV, we might expect a similar magnitude for $\Gamma(\psi \rightarrow \text{noncharmed mesons})$. Actually, $\Gamma(\psi)$ should be even larger, since the ψ decay has a larger phase space volume and many more possible final states (3π, 5π, $K\bar{K}\pi\pi$, etc., see B8). However, the experimental width of the ψ is much smaller than this estimate. It is therefore clear that the decay $\psi \rightarrow$ charmless hadrons is inhibited by a larger damping factor than $\phi \rightarrow$ nonstrange mesons. Why? We do not know.

Except for this crucial difficulty the ϕ-ψ analogy appears to be extremely reasonable and could presumably be pursued for decays, production mechanisms, etc.

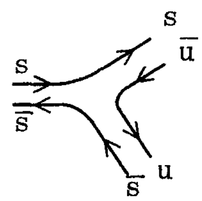
B5. What is the quark-diagram selection rule ("Zweig's rule")?

A simple empirical quark model rule can "explain" the approximate absence of $\phi \to 3\pi$, $\phi \to \pi\gamma$, $\pi N \to \phi N$, $pp \to pp\phi$, etc. The rule (sometimes known as "Zweig's rule") states that in the quark line diagram describing a hadronic process, the two ends of a given quark line cannot belong to the same hadron. In other words—whenever a $q\bar{q}$ pair is created, the "new" q and $\bar{q}$ must belong to different hadrons. Whenever a q annihilates a $\bar{q}$, they must have come from different hadrons (see B6). This immediately implies that $\phi \not\to 3\pi$, $\pi N \not\to \phi N$, etc. In all of these cases all quarks are nonstrange except for the $s\bar{s}$ quarks in the ϕ. Hence, there could be only one s-quark line in the diagram, and both its ends would belong to the ϕ, contradicting the empirical rule. Processes such as $\phi \to K\bar{K}$, $KN \to \phi\Lambda$, etc. are allowed by the quark diagram selection rule and they are, indeed, much stronger, experimentally.

$\phi \not\to 3\pi$

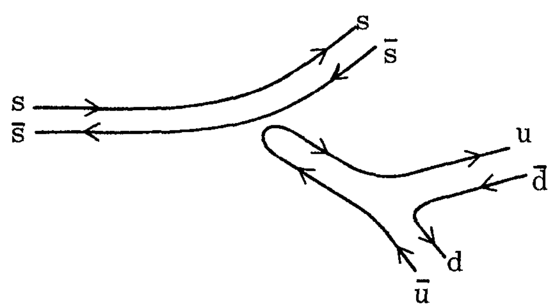


$\phi \to K\bar{K}$



The same rule also forbids decays such as $\phi^* \to \phi + M$ where ϕ^* is a hypothetical excited $(s\bar{s})$ meson and M is any meson (or mesonic system) including only non-strange quarks. In particular, the decay $\phi^* \to \phi + \pi^+ + \pi^-$ is forbidden. This has never been tested experimentally, but it may be extremely important for the ψ problem (see B13).

$\phi^* \not\to \phi\pi^+\pi^-$



The quark-diagram selection rule is not an exact selection rule, but it seems to significantly inhibit the "forbidden" processes.

B6. Does the quark-diagram selection rule have a theoretical foundation?

Consider a magnet. It has a north pole and a south pole. When we break the magnet into two pieces we create a new pair of poles, and we have two magnets — each having an "old pole" and a "new pole." The two "new poles" belong to different magnets. We can also combine two magnets by linking the south pole of one to the north pole of the other. We now have one magnet, thus "losing" two poles. The two poles of the new magnet belonged previously to two different magnets.

Consider now a childish picture of a meson as a "magnet" with a q-pole and a $\bar{q}$-pole. When the meson decays the "magnet" breaks, creating two new poles — a q and a $\bar{q}$. The two new poles do not belong to the same "magnet." The two "old" poles do not belong to the same "magnet." Each of the two "magnets" has a "new" pole and an "old" pole.

The only complication is the existence of four types of "north poles" (u, d, s, c) and four types of "south poles" ($\bar{u}, \bar{d}, \bar{s}, \bar{c}$). When we break a "magnet," the new pair of poles must be $u\bar{u}$ or $d\bar{d}$ or $s\bar{s}$ or $c\bar{c}$, but not $u\bar{d}$, etc. When we link two magnets, we can link u to $\bar{u}$ but not u to $\bar{d}$, etc.

Within the framework of such a model, the quark-diagram selection rule is a natural and necessary consequence. The skeptic reader may try to induce a ϕ-"magnet" (with s and $\bar{s}$ poles) to break into several pieces, all of which have only u, $\bar{u}$, d and $\bar{d}$ poles. This cannot be done. It is equally impossible to start with a hypothetical ϕ^* (also $s\bar{s}$) and break it into an $s\bar{s}$ "magnet" and a set of "magnets" involving only u, $\bar{u}$, d and $\bar{d}$ ($\phi^* \not\to \phi + \pi^+ + \pi^-$).

This naive "magnet" story is essentially what happens in the famous "string" model, and in most duality considerations. Why it works so well — we have no idea, but it is the only "explanation" of the quark-diagram selection rule ("Zweig's rule"). Incidentally, do monopoles exist?

B7. <u>What are the quantum numbers of a $c\bar{c}$-meson?</u>

All pure $c\bar{c}$-states have I = 0, Y = 0, Q = 0, Charm = 0, SU(3)-singlet quantum numbers. Their J^P-values follow the usual quark model sequence:

$$
\begin{aligned}
q\bar{q}:\ & L = 0 : J^{PC} = 0^{-+},\ 1^{--} \\
& L = 1 : J^{PC} = 0^{++},\ 1^{++},\ 2^{++},\ 1^{+-} \\
& L = 2 : J^{PC} = 1^{--},\ 2^{--},\ 3^{--},\ 2^{-+} \\
& L = 3 : J^{PC} = 2^{++},\ 3^{++},\ 4^{++},\ 3^{+-} \\
& \quad \text{etc.}
\end{aligned}
$$

<u>All 1^- states must have C = -1, G = -1.</u> The SU(4) quantum numbers are a mixture of an SU(4) <u>15</u>-representation and an SU(4)-singlet.

In addition to all of these states, there could be many radially excited $c\bar{c}$ states with the same J^P, C, G and SU(3) quantum numbers.

B8. How many ψ-like mesons do we expect in a $c\bar{c}$-model?

Assuming that the two observed ψ-particles at 3105 and 3695 MeV are $c\bar{c}$-states with $J^P = 1^-$, we exhaust the two vector meson multiplets of the quark model, ignoring radial excitations. These two states are the L = 0 and L = 2 $q\bar{q}$ vector mesons (see B7). Their mass difference can be crudely estimated from the $\rho'(1600)-\rho$ mass difference.

$$m^2(\rho') - m^2(\rho) \sim 2 \text{ BeV}^2 .$$

However

$$m^2(\psi(3695)) - m^2(\psi(3105)) \sim 4 \text{ BeV}^2 .$$

If we believe that the L = 0 $\longleftrightarrow$ L = 2 spacing is the same for ρ and ψ states we should expect an L = 2 ψ-state at 3.4 GeV. On the other hand, the spacing might be larger for the $c\bar{c}$ states, and ψ(3695) might be the L = 2 state. In both cases we expect, however, additional, radially excited $c\bar{c}$ states. Radial excitations are known to be present in the baryon spectrum and possibly in the meson spectrum. Hence we expect a large number of $c\bar{c}$ mesons for any given J^P-value. However, only those states which are below the $D\bar{D}$ threshold (see B4) would be narrow. Assuming 2m(D) ~ 4.3 BeV and a level spacing of 2 BeV^2 between the radially excited states, we might expect narrow states at 3.1, 3.4, 3.7, 3.95, 4.2 BeV. If the level spacing is 4 BeV^2, only the 3.1, 3.7 and 4.2 states are expected. The higher $c\bar{c}$ states would be much wider and would easily decay into $D\bar{D}$.

Needless to say, these are wild speculations based on a very crude picture. The level spacing between radial excitations is not well understood even for ordinary mesons and it need not be constant. The only important feature is the existence of many $c\bar{c}$ states, few of which could be narrow.

B9. What are the strong-interaction decay modes of a $c\bar{c}$ vector meson?

Using the known quantum numbers of the ψ in a $c\bar{c}$ model (see B7) we predict for both ψ and ψ':

(i) $\psi \not\to 2\pi$, 4π, 6π, etc. (G-parity).

(ii) ψ decays into 3π, 5π, etc.

(iii) ψ decays into $\rho\pi$, $\omega\pi^+\pi^-$, ρA_1, ρA_2, $f^0\omega$, $\rho'\pi$

(iv) The multiplicities and inclusive spectra of π^+, π^-, π^0 should be identical.

(v) $\psi \to \phi\pi\pi$ is doubly forbidden by "Zweig's rule" (see B5). Hence

$$\Gamma(\psi \to \phi\pi\pi) \ll \Gamma(\psi \to \omega\pi\pi) .$$

(vi) $\Gamma(\psi \to \bar{p}p\pi^0) = 2\Gamma(\psi \to \bar{p}n\pi^+)$

(vii) Many other isospin relations can easily be derived.

(viii) If ψ is indeed an $I = 0$, $C = G = -1$ state and if its decays respect the usual strong interaction selection rules, the decay mode $\psi \to \omega\pi^+\pi^-$ should be easy to detect. It provides us with a unique opportunity to study the $\pi^+\pi^-$ system in $I = 0$ and even angular momentum, free of the presence of the ρ^0. This would be extremely useful to $\pi\pi$ spectroscopy and would use the ψ as an experimental tool.

(ix) For strange particle decays — see B11.

(x) For ψ-decays into other ψ-particles see B13.

All the allowed strong decays listed above are, of course, inhibited by "Zweig's rule".

Note that some of the forbidden strong decays of the ψ could proceed through a second order electromagnetic decay. We know that outside the ψ peak, the $\pi^+\pi^-\pi^+\pi^-$ final state accounts for approximately 5% of the hadronic events. This means (see A6) that for $\psi(3105)$:

$$\Gamma(\psi \to \gamma \to \pi^+\pi^-\pi^+\pi^-) \sim 0.01\ \Gamma(\psi \to \text{anything})$$

Similarly,

$$\Gamma(\psi \to \gamma \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-) \sim 0.01\ \Gamma(\psi \to \text{anything}) ,$$

etc. See A6.

B10. <u>What are the electromagnetic decay modes of the ψ in a $c\bar{c}$-model?</u>

The $\psi \to e^+e^-$ coupling can be easily computed in a $c\bar{c}$ quark model, using the 2/3 electric charge of the c quark.

We find:

$$g^2_{\rho ee} : g^2_{\omega ee} : g^2_{\phi ee} : g^2_{\psi ee} = 9:1:2:8 .$$

The actual width $\Gamma(\psi \to ee)$ depends on the mass factors involved in the $\psi - \gamma$ coupling, and would be related to g^2 by a model-dependent power of m_ψ. However <u>the order of magnitude of $\Gamma(\psi \to e^+e^-)$ should be similar to that of $\Gamma(\rho \to e^+e^-)$.</u> Experiment is consistent with this prediction (see <u>A2</u>, <u>A5</u>).

The radiative width for $\psi \to \pi + \gamma$, $\pi + \pi + \gamma$, etc. should be inhibited by the quark-diagram selection rule relative to ordinary radiative decays of hadrons, and by a factor α relative to $\psi \to \rho + \pi$, etc. They are likely to be negligible in a $c\bar{c}$ model (see, in contrast, <u>C6</u>).

Approximately 15% of the purely hadronic final states in ψ-decay should be second order electromagnetic decays (see <u>A6</u>, <u>B9</u>).

Decays such as ($\psi \to e^+e^-$ + hadrons) should be smaller than ($\psi \to \gamma$ + hadrons) by a factor of α and would probably be totally negligible.

B11. How about strange-particle decays of ψ in a $c\bar{c}$ model?

A $c\bar{c}$ state is always an SU(3) singlet. In an exact SU(3) limit, half of its decays should involve strange particles. Since phase space factors and SU(3) breaking usually work against the strange particle rate, we might expect a reduction of this rate. We might guess that, perhaps, 20%-30% of the hadronic decays might involve K-mesons. In the exact SU(3) limit we have an extremely interesting list of selection rules for ψ-decays into strange particles:

$$\psi \not\to K\bar{K}$$
$$\psi \not\to K^*(890)\,\bar{K}^*(890)$$
$$\psi \not\to K^*(1420)\,\bar{K}, \text{ etc.}$$

More generally — if K_A and K_B are two strange particles in octet states and if the central members of their respective octets have charge conjugation eigenvalues C_1, C_2, then $\psi \not\to K_A K_B$ if $C_1 = C_2$.

These rules follow from the generalization of G-parity to SU(3) ("unitary parity"). In other words, they are direct consequences of exact SU(3) symmetry and charge conjugation invariance.

The decay $\psi \to K^+K^-\pi^+\pi^-$ is allowed in the exact SU(3) limit only when one $K\pi$ pair has $J^P = 0^+, 2^+, 4^+$, etc. and the other $K\pi$ pair has $J^P = 1^-, 3^-, 5^-$, etc.

Isospin and charge-conjugation predict:

$$\Gamma(\psi \to K^+K^-\pi^+\pi^-) = \Gamma(\psi \to K^0\bar{K}^0\pi^+\pi^-)\ .$$

The inclusive spectra for (K^+ + anything) and (K^0 + anything) in ψ decay, should be identical.

C-invariance predicts:

$$\psi \not\to K_1^0K_1^0, \quad K_2^0K_2^0 + \text{any number of } \pi^0.$$
$$\psi \to K_1^0K_2^0 + \text{any number of } \pi^0.$$

All of these allowed ψ-decays are, again, inhibited by the quark diagram selection rule.

B12. Is the charmed quark closely related to the strange quark ?

As far as the strong interactions are concerned, the answer is an unqualified no. The charmed quark is an SU(3) singlet and it should have approximately equal coupling, binding, transition, etc., to any one of the usual three quarks.

However, if we accept the charm modification of the Cabibbo current (see B1) we conclude that weak decays of charmed quarks will prefer the strange quark over the nonstrange quark by a factor of $\cot^2\theta_c$ in transition rates. Consequently, weak decays of charmed mesons (D-mesons) as well as weak decays of ψ-mesons would prefer strange particles. This is crucial for the D-meson, which can presumably decay only weakly by a charm-violating transition. It is not so important for ψ-particles where weak decays are presumably negligible.

The overall percentage of strange particle events in ψ-decay should therefore not be exceptionally large (see B11).

B13. Could ψ-like mesons decay into each other in a $c\bar{c}$ model?

Assuming that ψ's are $c\bar{c}$ mesons with $J^P = 1^-$, we find:

(i) All decays of the form $\psi' \to \psi + \gamma$ are forbidden by charge conjugation.

(ii) All $\psi' \to \psi + \pi$ decay are forbidden by isospin conservation.

(iii) $\psi' \to \psi + \pi^+ + \pi^-$ decays are allowed by all the usual selection rules but are approximately forbidden by the quark diagram selection rule (see B5, B6). Consequently they should have roughly the same inhibited matrix element as any other strong ψ decay, but a smaller phase space. Hence, such decays would exist but would not create a significantly larger total width for higher ψ states.

(iv) If χ is a $J^P = 0^-$ ($c\bar{c}$)-meson, the decay $\psi \to \chi + \gamma$ is allowed provided that $m_\chi < m_\psi$). Its rate depends on the available γ momentum. Such a decay should be allowed even if χ is not a pure $c\bar{c}$ state (in the same way that η and X^0 are not pure $s\bar{s}$ states).

(v) If χ is a 0^- $c\bar{c}$ state near ψ (3105), we expect:

$$\Gamma(\psi(3695) \to \chi(\sim 3100) + \gamma) \sim 100 \text{ keV}$$

(within a factor of 2). This estimate is based on a quark model calculation in which the c-quark emits a photon (similar to the well-known calculation of $\omega \to \pi + \gamma$). Assuming that the total width of ψ (3695) is not larger than a few hundred keV, and that $\chi(\sim 3100)$ exists, a substantial fraction of the decays of ψ (3695) might involve a photon in the final state.

B14. What are the other expected particles in a charmed spectroscopy ?

We have already mentioned the Hexadecimets of mesons including the usual nonet, a $c\bar{c}$ singlet, a charmed triplet, and a charmed antitriplet (see B2).

The lowest-mass charmed meson (presumably the D) should have only weak decays (mostly into $K\pi$, $K\pi\pi$, etc.) and a typical lifetime of 10^{-12} - 10^{-14} sec.

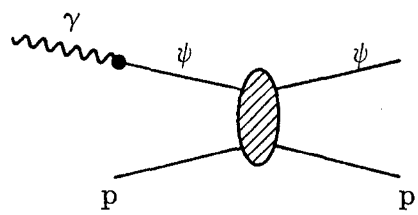
It should be observed in $e^+e^- \to D^o\bar{D}^o \to K^+K^-\pi^+\pi^-$ above the charm threshold (4.3 BeV? See B4). The ($K\pi$) invariant masses should show a very sharp peak at the D-mass. D mesons could be discovered, of course, in any hadronic reaction.

The existence of $c\bar{c}$ vector mesons implies the existence of a similar number of $c\bar{c}$ pseudoscalar mesons. These should have masses comparable to those of the ψ (3105) and ψ (3695). These states (we will denote them by χ) would not be easily produced in e^+e^- scattering. If they are pure $c\bar{c}$ states, they will be narrow and will reluctantly decay into hadrons. In addition to the inhibitions of "Zweig's rule," 3π and 5π decays are excluded by G-parity, 2π and $K\bar{K}$ decays — by spin-parity. The simplest hadronic decays would be into 4π and $K\bar{K}\pi\pi$. However, a strong $\chi \to \gamma\gamma$ decay mode is expected, with a partial width of the order of 10-100 keV. The χ-mesons might be discovered most easily through the decay $\psi \to \chi + \gamma$ (see B13).

The baryon spectrum will also include a large number of "charmed" baryons corresponding to SU(3) sextets, triplets and a (ccc) SU(3)-singlet (analogous to the Ω^-). The lightest C = 1 baryon might be stable against strong and electromagnetic decays, if its mass is below the m(D) + m(N) threshold.

B15. What is the $\gamma p \to \psi p$ cross section in a $c\bar{c}$-model?

If ψ is a $c\bar{c}$-hadron, the total ψp scattering cross section should be of the order of millibarns, at sufficiently high energies. The process $\gamma p \to \psi p$ would presumably proceed through the usual mechanism for vector meson photoproduction:



The overall $\gamma p \to \psi p$ cross section should therefore be anywhere between 5 and 500 nb at sufficiently high energy (see A3).

The important practical question in this case is: how high is "sufficiently high"? Presumably it should be above the threshold for production of charmed mesons.

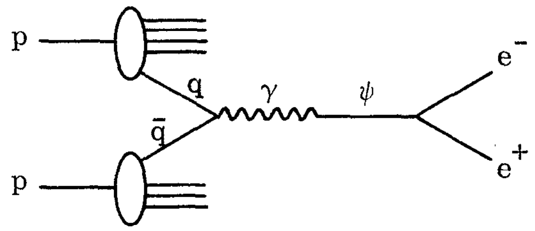
In order to understand this we must ask ourselves which mechanisms might produce a ψp total cross section of order millibarns. The usual ρ, ω, f, A_2 exchanges are forbidden by the quark diagram selection rule. Only "Pomeron exchange" is presumably allowed. But "Pomeron exchange" is only a reflection, through unitarity, of many production mechanisms. All production processes such as ($\psi + p \to \psi + p$ + pions) are again forbidden by the quark rule. The simplest allowed process is $\psi + p \to D + \bar{D} + p$ (+ pions). Hence the Pomeron contribution to ψp scattering will develop only above the $D\bar{D}p$ threshold (for $m(D) \sim 2.2$ BeV, we have $s \sim 28$ BeV^2). If we want to eliminate strong t_{min} effects we should probably be at least at $s \sim 40$ corresponding to a 20 BeV photon lab momentum. The easiest way to detect the photoproduced ψ is through its (relatively large) $\mu^+\mu^-$ decay mode.

The ψ-photoproduction experiment is probably the simplest and most direct experimental test on the question of whether ψ is a hadron.

B16. How is the ψ produced in pp collisions in a $c\bar{c}$ model?

The ψ-particles could be produced in pp collisions through several mechanisms.

(i) Through a photon (Drell-Yan mechanism):



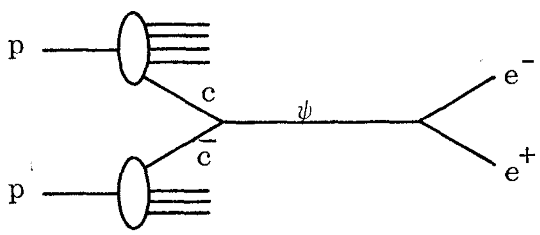
In this case the signal to noise ratio of the $\psi(3105)$ peak in $e^-e^+ \to \mu^-\mu^+$ and in $pp \to e^-e^+$ + anything should be the same. Experimentally, it is much larger in the pp experiment.

(ii) We could have events such as:

$$pp \to pp\psi D\bar{D} \qquad \text{or} \qquad pp \to pX\psi\bar{D}$$

where D is a charmed meson and X a charmed baryon. Such strong-interaction processes are allowed by the quark diagram selection rule, but their cross sections are very small and very hard to estimate. In any event, the threshold for both of them is presumably above p_{lab} = 30 BeV, while the ψ was observed at Brookhaven.

(iii) If the proton includes some $c\bar{c}$ quark pairs in its "infinite sea" we could have:



This could be compared with the measured cross section for ($pp \to \phi$ + anything) assuming that the ϕ is produced in a similar way and that the $s\bar{s}$ and $c\bar{c}$ pairs in the "infinite sea" of the proton are equally abundant (or equally rare).

B17. What would be the effect of charmed quarks on the parton model predictions for ep, νp, and e^-e^+ scattering?

The $c\bar{c}$ content of the nucleon is presumably extremely small. Consequently, it will have a small (if any) effect on the parton model predictions for eN or νN scattering. If, for example, the $c\bar{c}$ quark pairs are as probable as the $s\bar{s}$, $u\bar{u}$ or $d\bar{d}$ pairs in the "infinite sea" of quarks, the mean squared charge of the "infinite sea" will be 0.28 instead of 0.22. However all eN and νN data indicate that the "infinite sea" contributes a very small part of the scattering. Hence the effect of c-quarks would be negligible.

On the other hand, the effect of c-quarks on e^+e^- scattering should be important. The parton model predicts

$$R = \frac{\sigma(e^-e^+ \rightarrow \text{hadrons})}{\sigma(e^-e^+ \rightarrow \mu^-\mu^+)} = \Sigma Q_i^2$$

In a 4-quark (u, d, s, c) model $\Sigma Q_i^2 = 10/9$. If we further assume that we have three quartets of quarks ("red, yellow and blue") with identical quantum numbers, $R = 3\frac{1}{3}$. Hence, we would expect R to approach this value at some point well above the charm threshold (4.3 BeV??). In that case, R will have to decrease from its value of approximately 5 at $\sqrt{s} \sim 5$ BeV.

C. ARE THE ψ-PARTICLES "COLORED" MESONS?

C1. Who needs color?

Color is introduced in order to cure the following difficulties in the quark model:

(i) In the "uncolored" quark model, baryons are produced by a totally symmetric wave function of three spin -$\frac{1}{2}$ quarks. The introduction of color allows a totally antisymmetric wave function, as expected for fermions.

(ii) In the Han-Nambu model, quarks have integer charges.

(iii) Models with colored quarks have three times as many quarks as "uncolored" model. Hence the parton model prediction for $\sigma_{tot}(e^+e^- \to \text{hadrons})$ is larger, as demanded by the data.

(iv) A similar correction is obtained in the Adler anomally calculation of the π^o lifetime.

In all color models a new SU(3) group is introduced. Its generators correspond to color transformations (red → blue, blue → yellow, etc.). All known hadrons are presumed to be singlets under the new SU(3) group. This means that such hadrons can be made only from $q\bar{q}$ or 3q but not 2q or 4q. ($2q + 2\bar{q}$, $4q + \bar{q}$, are allowed, however). Baryons are totally antisymmetric in the color index, since the singlet is the totally antisymmetric product of three SU(3) triplets.

The total number of quarks is nine (unless charm is introduced in addition).

The above features are common to the Han-Nambu three-triplet model and to the Gell-Mann-Zweig color model.

C2. What is the difference between the Han-Nambu model and the Gell-Mann-Zweig color model?

In the Han-Nambu model all nine quarks have integer charges. The charges of the quarks in the three triplets are not the same. The usual Gell-Mann-Nishijima formula has to be modified and the photon is not a color singlet (see C3).

In the Gell-Mann-Zweig color model the three quark triplets are identical in all respects, except for their "color". All quarks are fractionally charged and the photon is a color singlet. The Gell-Mann-Nishijima formula is preserved.

The ratio $$R = \frac{\sigma(e^- e^+ \rightarrow \text{hadrons})}{\sigma(e^- e^+ \rightarrow \mu^- \mu^+)}$$

obeys

$$R = 4 (\text{Han-Nambu}); \quad R = 2 \ (\text{Gell-Mann-Zweig}) .$$

It is clear from this discussion that if the ψ is a colored object it is probably related to the Han-Nambu model, in which the photon has a colored component and in which $R = 4$. The Gell-Mann-Zweig color model does not help us to solve any of the mysteries of the ψ.

Remember, however, that if ψ is a $c\bar{c}$ state, the GMZ color model may be valid (see B17) although it does not affect any property of the ψ.

C3. What are the properties of the nine quarks in the Han-Nambu model?

We will denote the three triplets by $(u_A, d_A, s_A)(u_B, d_B, s_B)(u_C, d_C, s_C)$. Each (u, d, s) set is a triplet under ordinary SU(3). The sets (u_A, u_B, u_C) (d_A, d_B, d_C), (s_A, s_B, s_C) form antitriplets under SU(3)' (the color SU(3)). The overall symmetry is SU(3) × SU(3)'. The nine quarks belong to a $(3, \bar{3})$ representation. Their antiquarks are in a $(\bar{3}, 3)$, SU(3)' includes the operators Y', I', I_z' defined in an analogous way to the ordinary Y, I, I_z. The revised Gell-Mann-Nishijima relation reads:

$$Q = (\frac{1}{2}Y + I_z) + (\frac{1}{2}Y' + I_z').$$

All ordinary hadrons are SU(3)'-singlets. It is clear that all SU(3)'-singlets have $Y' = I' = I_z' = 0$. Hence, they obey the usual Gell-Mann-Nishijima relation.

Mesons can be formed from $q\bar{q}$. The allowed $q\bar{q}$ states are (1, 1); (8, 1); (1, 8); (8, 8). However, the ordinary (low-lying) mesons are in (1, 1) and (8, 1)—the usual SU(3) singlet and octet.

The quantum numbers of the nine quarks are:

	u_A	d_A	s_A	u_B	d_B	s_B	u_C	d_C	s_C
I_3	1/2	-1/2	0	1/2	-1/2	0	1/2	-1/2	0
Y	1/3	1/3	-2/3	1/3	1/3	-2/3	1/3	1/3	-2/3
I_3'	-1/2	-1/2	-1/2	1/2	1/2	1/2	0	0	0
Y'	-1/3	-1/3	-1/3	-1/3	-1/3	-1/3	2/3	2/3	2/3
Q	0	-1	-1	1	0	0	1	0	0

C4. What are the properties of the photon in the Han-Nambu model?

The revised Gell-Mann-Nishijima formula (see C3) clearly indicates that the photon is not an SU(3)' - singlet. We have:

$$Q = (\frac{1}{2}Y + I_3) + (\frac{1}{2}Y' + I_3') .$$

Y and I_3 are generators of SU(3). They commute with all SU(3)' generators. Hence, they belong to an (8, 1) representation. Y' and I_3' are generators of SU(3)'. They clearly belong to a (1,8) representation. We know that the photon does not respect ordinary isospin or SU(3). We now see that it breaks the "colored isospin" I' as well as SU(3)'.

The photon has components in both the (8, 1) and the (1, 8) representations. The (1, 8) piece never contributes to first order electromagnetic transition among ordinary hadrons. Any transition of the form $X \rightarrow Y + \gamma$ where X and Y are SU(3)' singlets (i. e. ordinary hadrons) involves only the (8, 1) part of the photon. However, if ψ is a colored meson in the (1, 8) multiplet, the transition $\gamma \rightarrow \psi$ is allowed, and ψ can be produced in $e^- e^+$ collisions without any difficulty.

The $q\bar{q}$ description of the electromagnetic current is determined by the quark charges (see C3). It is

$$u_B \bar{u}_B + u_C \bar{u}_C - d_A \bar{d}_A - s_A \bar{s}_A .$$

C5. Can a colored ψ decay via the strong interaction?

Let us assume (temporarily) that SU(3)' is an exact symmetry of the strong interaction and that ψ is in an SU(3)' octet. Since all ordinary hadrons are in SU(3)' singlets, it is obvious that ψ is absolutely forbidden from decaying into ordinary hadrons via the strong interactions.

This would be the color-model explanation for the narrow width of the ψ.

Let us now assume that SU(3)' is only an approximate symmetry of the strong interactions (like the usual SU(3)) but that its "colored" isospin is an exact symmetry (like the usual isospin). In that case, an $I' = 1$, $I_3' = 0$ meson would not decay into ordinary hadrons, while an $I' = I_3' = 0$ meson in an SU(3)' octet will decay via an SU(3)'-breaking interaction. The $I' = 1$ state will then be a very narrow state, while the $I' = 0$ state will be wider but not as wide as a "normal" hadron at that mass region.

In such a model, only one ψ-particle can be very narrow. However, it might be possible to invent an SU(3) -breaking mechanism which would prevent the second ψ from decaying, by invoking the quark diagram selections rule (see B5). We do not know of any way of achieving this (without spoiling other predictions), but this point deserves further study.

C6. Can a colored ψ decay electromagnetically?

It is always true that if the $\gamma \to \psi$ transition is allowed, the transition $\psi \to \gamma + H$ is allowed, provided that H is a hadronic system with the quantum numbers of the vacuum. If ψ is a colored vector meson in a (1, 8) multiplet of $SU(3) \times SU(3)'$ it could decay by emitting a photon (using the (1, 8) component of the photon), into an I = 0, C = +, SU(3)-singlet hadronic system. Typical allowed decays would be:

$$\psi \to \gamma + \pi^+ + \pi^-$$
$$\psi \to \gamma + \pi^0 + \pi^0$$
$$\psi \to \gamma + \pi^+ + \pi^+ + \pi^- + \pi^-$$
etc.

It is difficult to estimate the total width for $\psi \to \gamma +$ hadrons. However, a glance at the known radiative decay widths of ordinary hadrons (see A5) tells us that it is very hard to explain a total width under 100 keV. In fact, almost any estimate of $\Gamma(\psi \to \gamma +$ hadrons) indicates a width of an MeV or so.

A colored ψ could also decay via second order electromagnetic decays. If ψ is an $I' = 1$ member of an SU(3)' octet, $g^2_{\psi ee} = g^2_{\rho ee}$. The width for $\psi = e^+ e^-$ involves some model dependent mass factors. However, the experimental value (see A2) is approximately correct. For an $I' = 0$ member of an SU(3)' - octet we have

$$g^2_{\psi_0 e^- e^+} = \frac{1}{3} g^2_{\psi_1 e^- e^+}$$

where ψ_0 and ψ_1 are the $I' = 0, 1$ states respectively. This is consistent with the data for the two known ψ-particles (see A2).

The ψ should also decay into hadrons via a second order electromagnetic transition (see A6).

C7. What is the overall pattern of hadronic ψ-decays in a Han-Nambu model?

Most "hadronic" decays of ψ are predicted by the Han-Nambu scheme to be radiative decays. A photon should be found in approximately 85% of the so-called "hadronic" decays. The other 15% should not involve a photon in the final state (see A6).

Consequently, any well determined purely hadronic (no γ) final state must be consistent with the requirements of the decay $\psi \rightarrow \gamma \rightarrow$ hadrons (see A6). For instance, if much more than 1% of the ψ-decays result in a 4-prong, 4-constraint hadronic final state — the color scheme is in grave trouble. Similarly, if the absence of a photon can be proven for significantly more than 15% of the decays — the model is in trouble.

C8. How many ψ-like states should exist in a Han-Nambu model?

An SU(3)' octet would include only two $I_3' = Y' = 0$ states, i.e. only two states which couple to the photon. One of them, the $I' = 1$ state, should be narrow while the $I' = 0$ state could decay via SU(3)'-breaking (see C5). We could have a large number of additional colored mesons in the (8, 8) representation, but those will not couple directly to the photon (which is (1, 8) or (8, 1); see C4).

The Han-Nambu model, like any quark model, could allow many radial excitations (see B8), but these would probably not be narrow (see C9).

One could assign ψ(3105) and ψ(3695) to the lowest SU(3)' octet, and hope that both would be narrow. However, if these two states belong to the same SU(3)' octet, SU(3)' breaking must be strong, in order to account for their mass difference. In that case, it is hard to see how both could be so narrow.

In any event, no additional narrow vector mesons are expected in such a model.

C9. Could ψ-like states decay into each other in a Han-Nambu model?

Assuming that ψ's are colored mesons with spin 1^- in (1, 8) multiplets of $SU(3) \times SU(3)'$, we find (see also B13):

(i) All $\psi' \to \psi + \gamma$ decays are forbidden by charge conjugation.

(ii) All $\psi' \to \psi + \pi$ decays are forbidden by isospin conservation.

(iii) If ψ' and ψ have different values of I' (such as the I' = 1 and I' = 0 members of the same octet) all the decays of the type:

$$\psi' \to \psi + \text{ordinary hadrons}$$

are forbidden. In particular $\psi' \not\to \psi + \pi^+ + \pi^-$.

(iv) If χ is a $J^P = 0^-$ meson in a (1, 8) multiplet of $SU(3) \times SU(3)'$, the decays

$$\psi \to \chi + \gamma$$

are allowed (provided that $m_\chi < m_\psi$). Its rate depends on the available photon momentum (see B13).

C10. What are the other expected states in a Han-Nambu colored spectroscopy?

If the ψ-states are in a (1,8) multiplet of SU(3) × SU(3)' we should find the six other members of the same octet somewhere around the same mass regions. They should include a ψ^+ and ψ^- near the I' = 1 ψ^o, as well as two I'-doublets with Y' = ±1 (with electric charges +, 0, -, 0).

In addition, we expect a $J^P = 0^-$ (1,8) multiplet not too far in mass from the ψ-states. The χ-state (see C3) would be one of them.

In general, all $q\bar{q}$ mesons are in the (8,1); (1,8); (1,1) and (8,8) multiplets of SU(3) × SU(3)'. Baryons are in the usual (10,1)(8,1) and (1,1) colorless multiplets as well as in $(10,8)(10,\overline{10})(8,8)(8,\overline{10})(1,8)$ and $(1,\overline{10})$.

Some of the excited mesons and baryons should be "exotic" according to the usual terminology (i.e., Q = ± 2 mesons, etc.).

The lowest colored baryons are likely to be extremely narrow. If they are below the ψ + N threshold, they would decay only electromagnetically.

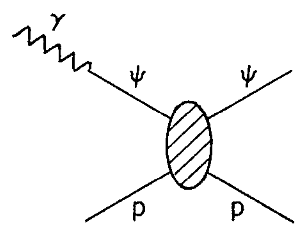
Such narrow states would be produced in photoproduction and electroproduction experiments. In photoproduction they would appear as narrow bumps in the γN total cross section. In electroproduction, they would appear as narrow peaks in the missing hadronic mass in:

$$e + p \to e + \text{anything} .$$

The Han-Nambu spectroscopy is, of course, extremely rich, and it would not be appropriate to review it here in detail.

C11. <u>If ψ is colored, what is the cross section for $\gamma p \to \psi p$?</u>

Since the direct $\gamma \to \psi$ coupling is allowed the process $\gamma p \to \psi p$ would probably proceed through the usual mechanism (see B15):



Our estimates for $\sigma(\gamma p \to \psi p)$ are, again, for a cross section of the order of a fraction of a microbarn (see A3).

It seems that while the photoproduction process is an extremely good test of the question of whether ψ is a hadron (see A3), it cannot easily distinguish between various hadronic models of the ψ (compare B15).

C12. <u>How is a colored ψ produced in pp collisions?</u>

Since the initial pp state is a color singlet, and the ψ is a color octet in such a model, another colored object must be produced together with the ψ. Typical reactions would be:

$$p + p \rightarrow \psi + \gamma + \text{anything}$$

$$p + p \rightarrow \psi + \psi + \text{anything} .$$

The latter reaction has a threshold above 30 BeV/c proton momentum. The observation of ψ in the MIT pp experiment, must have proceeded through the first reaction, according to this model.

<u>The production of ψ is then predicted to be accompanied by a photon in all hadron-initiated reactions at incident proton momenta below 30 BeV/c.</u>

It is very difficult to estimate the production cross section for $\psi+\gamma$, and we do not know how to compare it with the observed production rate. An intuitive guess would say that the observed cross section (see <u>A1</u>) is actually too large for $\psi+\gamma$ production, but no definite conclusions can be reached.

C13. <u>If ψ's are colored states, how would they affect the Parton model predictions for ep, νp and e^-e^+ scattering?</u>

The Han-Nambu model assumes that all 9 quarks exist in ordinary hadrons. Hence, the parton model predictions for such hadrons are different from the usual quark model predictions.

Above the threshold for the production of colored objects in deep inelastic electron and neutrino scattering (the "color thaw"), a new scaling region would have to exist. This threshold would presumably be around $\sqrt{s} = 5\text{-}6$ BeV, namely, above the $m(\psi) + m(N)$ threshold.

A typical prediction in that region would be

$$\frac{\nu W_2(n)}{\nu W_2(p)} \geq \frac{1}{2}$$

(compared with the 1/4 bound in the usual quark model). The n/p ratio is known to be smaller than $\frac{1}{2}$ for $x \gtrsim \frac{1}{2}$. However, all present $x > \frac{1}{2}$ measurements are well below the color threshold.

Many other parton model relations between ep, en, νp and νn structure functions and inclusive hadronic spectra are predicted to be different in the Han-Nambu model. They can be tested only at e, μ and ν experiments at high energies (probably above SLAC energies).

The ratio

$$R = \frac{\sigma(e^- e^+ \to \text{hadrons})}{\sigma(e^- e^+ \to \mu^- \mu^+)}$$

is predicted in the Han-Nambu model to reach a value of R = 4 above the color threshold.

D. OTHER POSSIBILITIES

D1. Could the ψ-particles be weak vector bosons?

Such a possibility exists and it is not ruled out by anything that we know today. However, the following questions need to be answered:

(i) Why do we have (at least) two ψ-particles?

(ii) If the neutral weak vector boson is at a mass of 3-4 BeV, why don't we have charged W-mesons around the same mass?

(iii) Do the Fermilab neutrino experiments give the same neutral to charged ratio, the same $\nu/\bar{\nu}$ ratio for neutral currents and the same energy slope of $\sigma_{tot}(\nu)$ as the CERN experiments? If yes—why shouldn't the ψ influence these results? If no—what is the observed change?

We do not attempt to cover this topic here, and we mention it briefly only for the sake of completeness.

D2. Can we think of selection rules other than color or charm, which might inhibit ψ - decays?

It is possible, of course, that the ψ - particles are hadrons which possess a new non-additive quantum number other than color. We could have a new isospin-like entity I', unrelated to color (or to hitherto postulated quarks). The conservation of such a quantum number would prevent a strong ψ - decay. It is equally possible to think of a new multiplicative quantum number which would be negative for ψ - particles and positive for all ordinary hadrons. If such quantum numbers are conserved by the strong interactions and are not conserved by electromagnetic interactions, ψ would be completely stable against strong decays, but would have a variety of electromagnetic decays.

These and similar schemes usually are too fuzzy to be ruled out. Their main drawback is the fact that they would explain nothing and would lead nowhere, even if true.

D3. Could the ψ - particles be excited ϕ- mesons?

Any excited meson which is made out of $s\bar{s}$ quarks is approximately forbidden by the quark diagrams selection rule from decaying into nonstrange mesons (even to $\phi + \pi + \pi$. See B5). However, such states would easily decay into strange mesons with a normal width of many MeV's. It is conceivable that excited ϕ- mesons are approximately prevented from such decays because of hitherto unknown selection rules, but we find such a possibility extremely unlikely.

E. Summary

Our questions and answers indicate that the two detailed hadronic models for the ψ-particles (charm and color) differ in many respects and provide us with many ways of distinguishing between them.

We conclude these notes with a table summarizing those predictions which can serve as experimental tests. The interested reader could keep a score card and update it as the new data unfolds, and as the telephone and the jungle drums bring new rumors.

We repeat that, in our opinion, the cleanest test of whether ψ is a hadron (of any kind) is the measurement of $\sigma(\gamma p \rightarrow \psi p)$ at high energy.

It is important to remember that no hadronic model of the ψ-states has, so far, provided a convincing explanation for the extremely small width (~ 100 keV for ψ and possibly not much more for ψ'). Both the charm and the color hypotheses would feel much more comfortable with a 1-2 MeV width.

Unfortunately we have no wisdom to add on this subject except for the obvious following remark: The $c\bar{c}$-model for the ψ would have been extremely attractive and completely satisfactory if we could only explain why the width is 100 keV. The fact that the ψ-width is not 100 MeV is based, in this model, on the mysterious quark diagram selection rule ("Zweig's rule"). This rule is, at present, entirely empirical. We cannot hope to understand the ψ-problem better without a dynamical understanding of this crucial rule.

Such an informal set of notes would not be complete without a guess. Among the existing models (weak boson, color, $c\bar{c}$) we believe that the $c\bar{c}$ idea is most likely to be correct. However, it would be foolish to preclude the possibility of a totally new idea which will explain it all.

Comparison between the predictions of the charm and color schemes

Test	ψ is a $c\bar{c}$ state		ψ is a colored state	
"Hadronic" decay modes	Mostly strong decays	(B9)	Mostly radiative decays	(C7)
$\psi \rightarrow 4\pi, 6\pi$	Forbidden by G-parity	(B9)	Forbidden like all other strong decays	(C5)
$\psi \rightarrow \pi^+\pi^-\pi^o, \pi^+\pi^-\pi^+\pi^-\pi^0$	Allowed	(B9)	Forbidden	(C5)
$\psi \rightarrow \pi^+\pi^-\gamma, \pi^+\pi^-\pi^+\pi^-\gamma$	Completely negligible	(B10)	Allowed. A major decay mode.	(C6)
$\psi \rightarrow K\bar{K}$	Forbidden by SU(3)	(B11)	Forbidden	(C5)
$\psi \rightarrow K^+K^-\pi^+\pi^-$	Allowed	(B11)	Forbidden	(C5)
$\psi' \rightarrow \psi + \gamma, \psi + \pi$	Forbidden	(B13)	Forbidden	(C9)
$\psi' \rightarrow \psi + \pi^+ + \pi^-$	Allowed	(B13)	Forbidden	(C9)
$\psi \rightarrow e^+e^-, \mu^+\mu^-$	A few keV width	(B10)	A few keV width	(C6)
$\psi \rightarrow \gamma \rightarrow$ hadrons	Allowed. 15% of ψ(3105) decays	(A6, B9)	Allowed. 15% of ψ(3105) decays	(A6, C6)
$\psi \rightarrow \chi(0^-) + \gamma$	Allowed	(B13)	Allowed	(C9)
Number of narrow states	Any number, but only below $D\bar{D}$ threshold	(B8)	At most two. One of the two much wider (~ 10:1) than the other.	(C8)
Additional predicted particles	Charmed mesons (D^+, D^o, F^+; $D^-, \bar{D}^o, F^-$; etc.) and baryons	(B14)	A full color octet (ψ^+, ψ^-, etc.) Many colored mesons and baryons.	(C10)
$\dfrac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$	$R = 3\frac{1}{3}$ at high s	(B17)	$R = 4$ at high s	(C13)