e^+e^- ANNIHILATION, THE NEW PARTICLES,
AND CHARM

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INTRODUCTION

These notes contain nothing that is not well known to many people. The attempt to give due reference to theoretical papers on the subject was hopeless, and I apologize to people who are not referred to appropriately. The inclusion of something in these notes without acknowledgement does not imply that nobody else thought of it, or even that the author did think of it. It will probably all be irrelevant in a few weeks anyway.

At the time of writing, the prejudice of the author is that some form of "charm" may be the least unlikely explanation for the new phenomena. This prejudice is reflected in the notes, which treat "colour" and other models for the new particles rather slightly.

1. THE NEW PARTICLES^{1,2)}

In this first lecture we start by listing some of the experimental facts and rumours about the new particles, then make a general phenomenological analysis of widths, branching ratios and so on. We finish by introducing and discussing some of the theoretical explanations proposed for them.

1.1 Experimental facts

Much of the information mentioned here is probably inaccurate and apocryphal, and many of the quoted numbers should not be taken seriously. However, at the moment just a qualitative picture of what is happening is all that is required.

1.1.1 e^+e^- annihilation

Three distinct structures have been seen in this reaction -- two very narrow peaks at 3095 ± 4 MeV ^{2,3)} and 3684 ± 4 MeV ^{4,5)} and a broader (200-300 MeV) enhancement at about 4.1 GeV ⁶⁾. They seem to have the following properties⁷⁾:

$$\Gamma(3.1 \rightarrow e^+e^-) \approx 5.2 \text{ keV} \approx \Gamma(3.1 \rightarrow \mu^+\mu^-) \quad (1.1)$$

$$\frac{\Gamma(3.1 \rightarrow e^+e^-)}{\Gamma(3.1 \rightarrow \text{any})} \approx 6.88, \quad \Gamma(3.1 \rightarrow \text{any}) \approx 77 \text{ keV}$$

to within 20%.

The angular distribution of the leptons in decays of the 3.1 have no visible forward-backward asymmetry^{*)} and are consistent with $1 + \cos^2 \theta$, indicating that the 3.1 decays do not violate parity and that it is either vector 1^- or axial 1^+ .

*) Results of a Frascati experiment showing such an asymmetry have not been confirmed by other laboratories.

Also, statistically significant negative interference has been seen at SPEAR in the $e^+e^- \rightarrow \mu^+\mu^-$ channel below the peak -- as expected from a 1^- state interfering with the 1γ exchange. There is a vast wealth of information⁷⁾ on the hadronic decays of the 3.1: an important decay is $2\pi^+2\pi^-$ + missing neutral, probably a π^0 . Specific mesonic decay modes such as $\rho\pi$, $\rho\pi\pi\pi$, $\omega\pi^+\pi^-$, $\pi\pi K\bar{K}$, $K^*K\pi$, $K^{**}K\pi$ have apparently been identified at SPEAR. Very few $2\pi^+2\pi^-$ decays have been seen. In fact,

$$\frac{\Gamma(3.1 \rightarrow 2\pi^+2\pi^-)}{\Gamma(3.1 \rightarrow \mu^+\mu^-)} \approx \frac{\sigma(e^+e^- \rightarrow 2\pi^+2\pi^-)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \quad (1.2)$$

outside the peak, suggesting that all $2\pi^+2\pi^-$ decays could come from 1γ intermediate states as in Fig. 1. The five-pion decays are, however, too copious to come from this source, and apparently come from the direct coupling of Fig. 2. Quite generally, since

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \approx 2.5$$

from data outside the peak, it seems that if the 3.1 couples to leptons via the photon and we can neglect interference effects, then

$$\Gamma(3.1 \rightarrow \begin{matrix} \rightarrow \text{hadrons} \\ \gamma \rightarrow \mu^+\mu^- \\ \rightarrow e^+e^- \end{matrix}) \approx 23 \text{ keV} \quad (1.3)$$

leaving 0(50) keV for the direct decays of $3.1 \rightarrow \text{hadrons}$ in the absence of interference. In the decays the final states $p\bar{p}$ and $\Lambda\bar{\Lambda}$ have been seen, though it is not excluded that they may also be accompanied by low momentum γ -rays. These modes have rates both 0(100-200) eV. The decays $3.1 \rightarrow \pi^+\pi^-$, K^+K^- have apparently not yet been seen, and the DASP experiment at DESY gives upper bounds of 130 eV for each of these modes. From looking at energetic collinear photons produced in the decay, there is no evidence⁸⁾ for a $\gamma\gamma$ decay mode (forbidden if the 3.1 has spin = 1). From DESY data on almost collinear energetic photons, there are the following upper limits on neutral decay modes:

$$\frac{\Gamma(3.1 \rightarrow \pi^0\gamma)}{\Gamma(3.1 \rightarrow e^+e^-)} \leq 0.08, \quad \frac{\Gamma(3.1 \rightarrow X\gamma)}{\Gamma(3.1 \rightarrow e^+e^-)} \times \frac{\Gamma(X \rightarrow \gamma\gamma)}{\Gamma(X \rightarrow \text{any})} \leq 0.2 \quad (1.4)$$

where X is any state with mass ≥ 2.6 GeV ^{*)}. The inclusive $K^\pm$ and p spectra in the decay seem to be large for $x = 2E/E_{cm}$ large, with $K^\pm/\pi^\pm \approx 0.4$ for $x \geq 0.4$ and $\bar{p}/\frac{1}{2}\pi^\pm \approx 0.3$ for $x \geq 0.7$.

As for the 3.7, it seems ⁷⁾ to have

$$\Gamma(3.7 \rightarrow e^+e^-) \approx 2.2 \text{ keV} \approx \Gamma(3.7 \rightarrow \mu^+\mu^-) \quad (1.5)$$

$$\frac{\Gamma(3.7 \rightarrow 3.1 \pi^+\pi^-)}{\Gamma(3.7 \rightarrow \text{any})} \approx 30\%, \quad 200 \text{ keV} < \Gamma(3.7 \rightarrow \text{any}) < 800 \text{ keV} \quad (1.6)$$

The total width is uncertain because $3.7 \rightarrow 3.1 + \text{neutrals}$ decays would produce $\ell^+\ell^-$ pairs from the 3.1 decay which could be confused with those from the direct 3.7 decay. The angular distributions of the products in the $3.7 \rightarrow 3.1 \pi^+\pi^-$ decay are exactly as expected from a decay of one 1^- state to another 1^- state by emission of a 0^+ dipion state such as the $\epsilon(600)$. One would then expect $\Gamma(3.7 \rightarrow 3.1 \pi^0\pi^0) \approx \frac{1}{2}\Gamma(3.7 \rightarrow 3.1 \pi^+\pi^-)$: experimentally, it seems ⁷⁾ that this relation is not exactly correct. Thus cascade decays such as

$$\begin{aligned} 3.7 &\rightarrow X + \gamma \\ &\quad \searrow \\ &\quad 3.1 + \gamma \end{aligned} \quad (1.7)$$

or other decays such as $3.7 \rightarrow 3.1\eta$ may be present. Decays $3.7 \rightarrow X\gamma$ with the emission of a γ having an energy of a few hundred MeV have not yet been seen: systematic searches are now starting.

As for the 4.1 structure, it seems to have a width of $\sim (200-300)$ MeV: integrating over the peak would give $\Gamma(4.1 \rightarrow e^+e^-) = O(\text{few}) \text{ keV}$. Its decay shows no obvious features ⁷⁾, there being apparently no evidence for $4.1 \rightarrow 3.7 \pi\pi$, $3.1 \pi\pi$ or $\pi^\pm Z^\mp$ with $m_Z \geq 3$ GeV.

*) SPEAR data on the decays $3.7 \rightarrow 3.1 \pi^+\pi^-$ indicate that the decays $\Gamma(3.1 \rightarrow \text{all neutrals})$ are a small fraction of its total width. This has been assumed in deriving the numbers (1.1) from the experimental data on the 3.1.

1.1.2 Hadronic collisions

So far only the 3.1 has been seen in purely hadronic reactions. It was seen¹⁾ in $p + \text{Be} \rightarrow 3.1 (\rightarrow \mu^+\mu^-) + \text{anything}$ at an energy of 29 GeV with a cross-section difficult to estimate because of the unknown inclusive distribution in p_T and $p_{||}$, but probably corresponding to $\sigma(p + p \rightarrow 3.1 + \text{anything}) \approx 10^{-34 \pm 1} \text{ cm}^2$. The process $p + \text{Be} \rightarrow 3.7 (\rightarrow \mu^+\mu^-) + \text{anything}$ is at least 10^{-2} times smaller at this energy⁹⁾: a very much smaller rate is of course to be expected because of the small leptonic branching ratio of the 3.7. The $p + \text{Be} \rightarrow 3.1 + \text{anything}$ signal apparently disappears at $\sim 20 \text{ GeV}$ ⁷⁾, and the previous experiment which saw a shoulder in the $p + \text{U} \rightarrow \mu^+\mu^- + \text{anything}$ distribution is apparently consistent¹⁰⁾ with a cross-section $O(10^{-34}) \text{ cm}^2$ at 29 GeV. A more recent¹¹⁾ experiment, $n + \text{Be} \rightarrow (\mu^+\mu^-) + \text{anything}$, with an average neutron energy of 250 GeV sees a 3.1 signal possibly of the order of 10^3 larger^{*}). The 3.1's produced have apparently larger $\langle p_T \rangle$ than do the ρ^0 's produced in the same experiment, and seem to be produced centrally in $x = 2p_{||}/E_{\text{cm}}$.

1.1.3 Photoproduction

The initial results on photoproduction of the 3.1 were negative, with upper limits of $\sim 1 \text{ nb}$ at $E_\gamma \approx 11 \text{ GeV}$ ¹²⁾ **) and $\sim 29 \text{ nb}$ at $\langle E_\gamma \rangle \approx 18 \text{ GeV}$ ¹³⁾. But it has now been seen at Fermilab in $\gamma + \text{Be} \rightarrow (\mu^+\mu^-) + \text{anything}$ with a cross-section/nucleon = $O(20) \text{ nb}$ at $E_\gamma \geq 80 \text{ GeV}$ ¹⁴⁾. The cross-section has a forward peak, including a very sharp inner peak consistent with e^{+0t} corresponding to coherent scattering off the entire nucleus. As will be discussed later, this observation suggests very strongly that the 3.1 is coupled to the photon, and scatters diffractively just like a normal hadron at high enough energies as shown in Fig. 3. New experiments at $\langle E_\gamma \rangle \sim 18 \text{ GeV}$ are apparently¹⁵⁾ also seeing $\gamma + N \rightarrow 3.1 + \text{anything}$, at a rate smaller by about an order of magnitude than the Fermilab value. Fermilab and SLAC also apparently see $\gamma + N \rightarrow 3.7 + \text{anything}$ at a considerably smaller rate.

1.2 Phenomenological analysis¹⁶⁾

We now move on to a phenomenological discussion of the above experimental facts, and a comparison with other particles and processes. It is clear that the 3.1 and 3.7 particles' widths are very small. The leptonic widths are however comparable with those of strong vector mesons: $\Gamma(\phi \rightarrow e^+e^-) \sim 1.3 \text{ keV}$,

*) Further analysis of the CERN-Columbia-Rockefeller-Saclay experiment on $pp \rightarrow (e^+e^-) + \text{anything}$ at the CERN Intersecting Storage Rings (ISR) also gives a cross-section much bigger than that of MIT-BNL.

**) Rumour has it that this group has now found some events.

$\Gamma(\omega \rightarrow e^+e^-) \sim 0.76 \text{ keV}$. If we parametrize the 3.1 couplings to leptons by phenomenological axial and vector couplings $g_A^\mu, g_A^e; g_V^\mu, g_V^e$, then we find

$$g_A^{\mu^2} + g_V^{\mu^2} \approx g_A^{e^2} + g_V^{e^2} \approx 0.6 \times 10^{-4} \quad (1.8)$$

If we suppose that this coupling proceeds via 1γ exchange, then we have $g_A^\mu = g_A^e = 0$, and if the γ -3.1 coupling is $em^2/2\gamma_{3.1}$ as in Fig. 1, then

$$\frac{1}{\delta_{3.1}^2} \approx \frac{1}{2.6} \quad (\text{cf. } \frac{1}{\delta_\phi^2} \approx \frac{1}{2.5}) \quad (1.9)$$

The corresponding numbers to formulae (1.8) and (1.9) for the 3.7 are a factor of 2-3 lower, and by way of comparison

$$\frac{1/\delta_\rho^2}{1/\delta_{\rho'}^2} \approx O(3)$$

if we take ρ' to be the state at $\sim 1600 \text{ MeV}$.

How much are the hadronic decays suppressed relative to the decay width of a normal hadron? For comparison we may note

$$\Gamma(\phi \rightarrow \text{any}) \approx 4.2 \text{ MeV}, \quad \Gamma(\omega \rightarrow \text{any}) \approx 10 \text{ MeV}$$

Experience with known states, and with dual and statistical models, might suggest¹⁶⁾ a width of ~ 50 to 500 MeV for a meson with mass 3 GeV . Hence the suppression of $\Gamma(3.1 \rightarrow \text{anything})$ is by a factor of 10^3 to 10^4 , that of $\Gamma(3.7 \rightarrow \text{anything})$ by a factor of 10^2 to 10^3 . On the other hand, the 4.1 structure has a characteristic hadronic width.

There has been much discussion and comparison with the suppression of the ϕ coupling to non-strange hadrons. This latter we can estimate in various ways:

$$\frac{g_{\phi p\pi}^2}{g_{\omega p\pi}^2} \approx \frac{1}{100}, \quad \frac{\sigma(\pi^- p \rightarrow \phi n)}{\sigma(\pi^- p \rightarrow \omega n)} \approx \frac{1}{60}, \quad \frac{\sigma(\pi^- p \rightarrow \phi n)}{\sigma(\pi^- p \rightarrow \omega n)} \approx \frac{1}{300} \quad (1.10)$$

Thus the ϕ coupling to non-strange hadrons seems to be suppressed by a factor of $O(10^2)$. This is usually "explained" by assuming that disconnected quark diagrams such as that of Fig. 4 for $\phi \rightarrow 3\pi$ decay are essentially zero. One other similarity to the ω and ϕ should be noted: the predominance of 3, 5, and 7π decay modes and

the apparent absence of direct 4π decays suggest that the concept of G parity makes sense for the 3.1, and that it has $G = -1$.

Simple radiative decays of the 3.1 must also be strongly suppressed. For example, for the radiative decay to a pseudoscalar P,

$$\frac{\Gamma(3.1 \rightarrow P\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)} = \left(\frac{g_{3.1P\gamma}}{g_{\omega\pi^0\gamma}} \right)^2 \left(\frac{m_{3.1}}{m_\omega} \right)^3 \left(\frac{m_{3.1}^2 - m_P^2}{m_\omega^2 - m_\pi^2} \right) \quad (1.11)$$

If $m_P \ll 3.1$, we can use the known rate $\Gamma(\omega \rightarrow \pi^0\gamma) \approx 0.87$ keV to get

$$\Gamma(3.1 \rightarrow P\gamma) \approx \left(\frac{g_{3.1P\gamma}}{g_{\omega\pi^0\gamma}} \right)^2 \times 15 \text{ MeV} \quad (1.12)$$

Since experimentally $\Gamma(3.1 \rightarrow \pi^0\gamma) < 0.4$ keV, we must have

$$\left(\frac{g_{3.1\pi^0\gamma}}{g_{\omega\pi^0\gamma}} \right)^2 \leq 0.3 \times 10^{-4} ! \quad (1.13)$$

How about the comparison between e^+e^- and hadronic experiments? We can define two ratios R_H and R_L by

$R_H = \frac{\text{production of } 3.1 \text{ from } p\bar{p}}{\text{decay of } 3.1 \text{ into } \gamma l^+ l^-}$, $R_L = \frac{\text{production of } 3.1 \text{ from } e^+e^-}{\text{decay of } 3.1 \text{ into } \gamma e^+e^-}$

If the production and decay mechanisms of the 3.1 were the same, then we would expect $R_H \approx R_L$. The comparison has been made¹⁶⁾ for the BNL and e^+e^- experiments. We have

$$R_H = \frac{\text{number of events in peak of Ref. 1}}{\text{number of events/MeV in background}} \quad (1.14)$$

$$= \frac{242}{5/25} = 1200 \text{ MeV},$$

while from the SPEAR data

$$R_L = \frac{\int \sigma_{3.1}(E) dE}{\sigma_{\text{background}}} \approx 300 \text{ MeV} \quad (1.14')$$

yielding $R_H/R_L \approx 4$. We conclude that production of the 3.1 in the BNL and the decay $3.1 \rightarrow \text{anything}$ could well go via similar dynamics. On the other hand, the much larger (by $\sim 10^3$) cross-section seen at Fermilab in $n + \text{Be} \rightarrow 3.1 + \text{anything}$ at $E \gtrsim 250$ GeV suggests that the 3.1 coupling to hadrons is no longer suppressed at such energies.

How about $\Gamma(3.7 \rightarrow 3.1 \pi^+ \pi^-)$? According to formula (1.6) this = 0(200) keV. If we discuss generally the decay of a vector state V' into a lower mass vector state V emitting two charged pions via an interaction $g_{V'V\pi\pi} V' V \pi^+ \pi^-$, then

$$\Gamma(3.7 \rightarrow 3.1 \pi^+ \pi^-) \approx 14 \left(\frac{g_{3.7,3.1\pi\pi}^2}{4\pi} \right) \text{ keV}$$

whereas

$$\Gamma(e' \rightarrow e \pi^+ \pi^-) \approx 0.25 \left(\frac{g_{e'e\pi\pi}^2}{4\pi} \right) \text{ MeV}$$

Using

$$\Gamma(e' \rightarrow e \pi^+ \pi^-) \approx 200 \text{ MeV}$$

we find

$$\left(\frac{g_{3.7,3.1\pi\pi}^2}{g_{e'e\pi\pi}^2} \right) \approx \frac{200}{14} \times \frac{0.25}{200} \approx 2 \times 10^{-2} \quad (1.15)$$

We conclude that the $3.7 \rightarrow 3.1 \pi^+ \pi^-$ decay is suppressed relative to a comparable hadronic width by $\sim 10^{-2}$ *).

Finally, we discuss the photoproduction experiments. The cross-section at small t quoted for the Fermilab experiment is so large that it is explicable only if the 3.1 couples directly to the photon and is being produced diffractively.

If we assume 3.1 vector meson dominance of the photon, then

$$\left. \begin{aligned} \sigma_{\text{diff}}(\gamma N \rightarrow 3.1 N) &\approx \frac{\alpha}{4} \left(\frac{g_{3.1}^2}{4\pi} \right)^{-1} \sigma_{\text{diff}}(3.1 N \rightarrow 3.1 N) \\ \sigma_{\text{diff}}(3.1 N \rightarrow 3.1 N) &\approx \frac{1}{16\pi B} \sigma_{\text{tot}}^2(3.1 N) \end{aligned} \right\} \quad (1.16)$$

where B is the slope of the diffraction peak in 3.1N scattering. From their value of $\sigma_{\text{diff}}(\gamma N \rightarrow 3.1 N)$, the Fermilab group find $\sigma_{\text{tot}}(3.1 N) \approx 1 \text{ mb}$. This cross-section can only be hadronic, but it is suppressed at high energies:

$$\frac{\sigma_{\text{tot}}(3.1 N)}{\sigma_{\text{tot}}(\phi N)} = O\left(\frac{1}{10}\right) \quad (1.17)$$

*) Similar ratios are obtained by assuming that the $(\pi^+ \pi^-)$ state is an s-wave resonance ϵ .

The latest SLAC and Rochester-Cornell data would correspond to a value of $\sigma_{\text{tot}}(3.1 \text{ N})$ about three times smaller at $E_\gamma \lesssim 20 \text{ GeV}$.

1.3 Theoretical models

The theoretical response to the new particles has been copious, but far from conclusive. Probably well over 100 papers have appeared in the last two months, and it has only been possible to look at a fraction of them¹⁶⁾. Accordingly, we will review the range of possibilities only long enough to motivate my own prejudice as to the interpretation of the new phenomena. One of the criteria used is Occam's razor^{*)}: explanations should ideally give a unified understanding of the 3.1, the 3.7, and hopefully the 4.1 enhancement and the large e^+e^- total cross-section. They should also be consistent with the developed phenomenology of deep inelastic processes, and should ideally have been invented for other reasons before the new particles came along. Suggestions can be classified as follows:

1.3.1 Non-hadronic models

Many people¹⁶⁾ jumped on equation (1.8) and noticed that

$$\frac{g_A^2 + g_V^2}{m_{3.1}^2} \approx 0.6 \times 10^{-5} / m_p^2 \quad (1.18)$$

suggesting a relation to the neutral currents in weak interactions. Notice that for a W boson in a theory of charged weak currents

$$\frac{g_A^2 + g_V^2}{m_W^2} \approx 1.5 \times 10^{-5} / m_p^2 \quad (1.19)$$

Using the 3.1 as a neutral vector boson gave predictions for neutral current rates in leptonic and semileptonic weak interactions qualitatively in agreement with low-energy experiments. But:

- i) What is the 3.7? If it is another weak boson, why is the $3.7 \rightarrow 3.1 \pi\pi$ coupling so large? Even supposing we accept¹⁷⁾ strong pairwise interactions of W bosons with hadrons,
- ii) there are apparently¹⁸⁾ no propagator effects with characteristic masses $\sim (3-4) \text{ GeV}$ seen in the Fermilab neutral current data. Also

*) "Entities should not be unnecessarily multiplied" (Websters Third New International Dictionary). I am deeply indebted to C.H. Llewellyn Smith for this reference.

- iii) It is difficult, if not impossible, to understand the large photoproduction rate.

Discarding weak bosons (including Higgs scalars on account of their spin), some people were led to postulate new medium-strength interactions, possibly violating parity, or time reversal, or charge conjugation, or some combination of these. We assassinate these models with a deft flick of Occam's razor, and move on to the next sub-section.

1.3.2 Hadronic models

It may be possible to understand the new objects as conventional hadrons. We prefer to think not, and go on to consider models involving new hadronic degrees of freedom. There are two obvious ways of extending SU(3), the usual symmetry group of strong interactions. One is $SU(3) \rightarrow SU(3) \times G$, where G is some new symmetry, which can be called "colour". The other is $SU(3) \rightarrow SU(N)$: $N \geq 4$, which can be called "charm". The best-known example of the first scheme is the Han-Nambu¹⁹⁾ colour scheme [$G = SU(3)$]; another is the Tati²⁰⁾ scheme [$G = SO(3)$]. The best-known example of the second scheme is traditional charm²¹⁾ (a particular model with $N = 4$), but other possibilities are open (fancy, gentleness, ... $N = 5, 6, \dots$)*). We will again use Occam's razor to slash the possibilities down to Han-Nambu colour -- previously proposed in order to understand the particle spectra, quark binding, and the $\pi^0 \rightarrow 2\gamma$ decay; and SU(4) charm -- previously proposed as the simplest way of constructing calculable weak interaction theories. However, many of our remarks about suppression of radiative decays, production in deep inelastic scattering, the dual diagram selection rules, etc., will apply to all "colour" or "charm" schemes.

Han-Nambu colour

In this scheme²²⁾ the "colour" group is SU(3): the ordinary fractionally charged p , n , λ quarks are each replaced by three integrally charged quarks as in Fig. 5. The familiar electromagnetic current $J_\mu^{\text{em}} = I_\mu^3 + \frac{1}{2}Y_\mu$ belonging to an 8 representation of SU(3) now becomes

$$J_\mu^{\text{em}} = \underbrace{\left(I_\mu^3 + \frac{Y_\mu}{2} \right)}_{\text{(uncoloured)}} + \underbrace{\left(\tilde{I}_\mu^3 + \frac{\tilde{Y}_\mu}{2} \right)}_{\text{(coloured)}} \quad (1.20)$$

where $\tilde{I}$ and $\tilde{Y}$ are the isospin and hypercharge of the new SU(3). The uncoloured

*) Other schemes are of course possible, e.g. new heavy quarks which are strongly coupled to each other via vector gluons, but not to the familiar quarks. This would again have a symmetry $SU(3) \times G$, but realized very differently from "colour".

and coloured pieces of J_{μ}^{em} belong to $(\underline{8}, \underline{1})$ and $(\underline{1}, \underline{8})$ representations of $SU(3) \times SU(3)$ colour respectively. Ordinary hadrons are supposed to be colour singlets [mesons in $(\underline{8}, \underline{1})$ and $(\underline{1}, \underline{1})$ representations, etc.]

The proposal is that the 3.1 and 3.7 are colour octet states. There are at least four ways of assigning them.

- I) Both 3.1 and 3.7 are in the same $(\underline{1}, \underline{8})$ representation, and are $\tilde{\rho}^0$ and $\tilde{\omega}_8$. $\tilde{I} = 1$ and 0 octet states. In this case, colour symmetry-breaking is very bad: $\Delta m^2/m^2 \sim 40\%$, and it is not clear why colour is conserved so well as to suppress the hadronic decays by $O(10^4)$. For example, you might expect the traditional $(\underline{8}, \underline{1})$ vector mesons to acquire large "coloured" components. Such a large breaking of colour symmetry is not impossible theoretically. At the very least, colour symmetry must be broken electromagnetically, e.g. by mass differences. Weak interactions may also violate colour symmetry, and gauge theories suggest this may be the same order of magnitude as that of electromagnetic breaking. A larger breaking from some semi-strong interaction is also possible.
- II) The 3.1 and 3.7 are in different $(\underline{1}, \underline{8})$ representations -- one probably a radial excitation of the other. In this case there is no reason to suppress the hadronic $3.7 \rightarrow 3.1 \pi\pi$ decays as required by formula (1.15).
- III) The most natural colour scheme is that the 3.1 and 3.7 are in $(\underline{1}, \underline{8})$ and $(\underline{8}, \underline{8})$ representations, and are ideally mixed so that the 3.1 has only non-strange quarks, the 3.7 only strange quarks. In this case we can postulate that colour symmetry is broken only in the electromagnetic direction. As the photon is both a U-spin and $\tilde{U}$ -spin scalar, only U- and $\tilde{U}$ -spin scalar states can couple directly to it. In particular only one combination of $\tilde{\phi}^0$ and $\tilde{\omega}$ is coupled to the photon, and 3.1 and 3.7 are the only states in e^+e^- annihilation before the advent of radial excitations^{*)}. Quark model universality would then give the couplings

$$\gamma_{\rho}^{-2} : \gamma_{\omega}^{-2} : \gamma_{\phi}^{-2} : \gamma_{3.1}^{-2} : \gamma_{3.7}^{-2} = 9 : 1 : 2 : 8 : 4 \quad (1.21)$$

and the ratio $\Gamma(3.7 \rightarrow e^+e^-)/\Gamma(3.1 \rightarrow e^+e^-)$ comes out about right. The ratio $\Gamma(3.1 \rightarrow e^+e^-)/\Gamma(\phi \rightarrow e^+e^-)$ is within the expected range of accuracy, given the large mass differences, and it is historically unclear whether symmetry predictions should apply to γ_V^{-1} or to $m_V^p \gamma_V^{-1}$ for some power $p \neq 0$. Because the 3.7 is strange and the 3.1 non-strange, the usual quark diagram selection rule suppresses $3.7 \rightarrow 3.1 \pi\pi$ decay because the simplest diagram of Fig. 6 is forbidden. The suppression

*) If the colour breaking violates $\tilde{U}$ -spin as in some weak interaction models, then there should be four coloured vector states in e^+e^- .

of $3.1 \rightarrow \text{hadrons}$ is understood from colour symmetry, but the suppression of $3.1 \rightarrow \gamma + \text{hadrons}$ is not. Naively one would expect no suppression relative to $\omega \rightarrow \pi^0 \gamma$, a decay rate for $3.1 \rightarrow X\gamma$ of $O(10)$ MeV from Eq. (1.9), and a total decay rate $3.1 \rightarrow \gamma + \text{hadrons}$ of $O(10-100)$ MeV. There are arguments for suppressing these decays to some extent: small overlap of $(q\bar{q})$ bound state radial wave functions, coloured vector meson dominance of the photon; but these seem unlikely to suppress the rates by the necessary factor of $\gtrsim 100$. A problem with colour schemes is that they predict a vast spectrum of other coloured states (pseudoscalars, scalars, ...) which should have masses naively expected to start around the mass of the lowest vector state, i.e. ~ 3 GeV, and could be produced together with ordinary hadrons in e^+e^- annihilation above $q^2 = 10$ or in strong decays of the 3.7. Experimentally, there is a threshold around $q^2 \approx 15$, but there is no news yet of new states in the strong decays of the 3.7 or of the 4.1. Perhaps the coloured vector mesons have especially low masses because of scheme.

IV) The coloured vector mesons mix with coloured vector gluons. This might be a way of making the coloured vector states the lightest. However, there is still a problem: if the 4.1 is identified as a radially excited coloured state, then it should have strong decays into lower coloured states and ordinary hadrons, e.g. $4.1 \rightarrow 3.1 \pi\pi$, and rumour has it that such decays are not yet seen.

The colour scheme also has a problem not associated with e^+e^- annihilation: Why do the deep inelastic electroproduction structure functions not rise far above those of SLAC at Fermilab energies²³⁾ because of the excitation of coloured states? Calculations²⁴⁾ suggest this rise should be $O(100)\%$. We return to this point in Lecture 3.

While there is nothing conclusive, the general trend of the data seems against the above schemes^{*)} as possibilities, and in the next lecture we move on to discuss charm.

2. THE HIDDEN CHARM HYPOTHESIS

Many years ago²¹⁾ it was proposed to add a fourth "charmed" quark c to the conventional p , n , λ in order to build attractive and eventually renormalizable theories of weak and electromagnetic interactions. We will discuss this structure in more detail in Lecture 4. Much of what we say now could apply to other "charm" schemes, but we consider for definiteness the usual model in which the charmed quark has $Q = 2/3$, $B = 1/3$, $I = 0$, $S = 0$, and a new quantum number $C = 1$, the conventional quarks having $C = 0$. The resulting quantum number diagram for quarks is given in Fig. 7. The old and new quarks provide a basic $SU(4)$ symmetry for hadrons. As shown in Fig. 8, each nonet of mesons made of p , n , and λ quarks is

*) It may be possible to avoid these problems with strong colour symmetry-breaking chosen in a special way (N. Marinescu and B. Stech, and F.E. Close and J. Weyers, private communications).

now replaced by a 16-plet, the new mesons being $c\bar{p}$, $c\bar{n}$ (usually called D), $c\bar{\lambda}$ (usually called F), the antiparticles of these, and a "hidden charm" $c\bar{c}$ state (usually called η_c , ϕ_c , f_c , ...). In general the $c\bar{c}$ states can mix with the $\lambda\bar{\lambda}$ and $1/\sqrt{2} (p\bar{p} + n\bar{n})$ states.

The hypothesis¹⁶⁾ is that the 3.1 is essentially a pure $c\bar{c}$ state. The 3.7 is then regarded as a radial excitation or daughter state (cf. the ρ - ρ' pair). The 4.1 structure is seen as a second recurrence, broadened because it is sitting above the threshold for producing charmed meson pairs $D\bar{D}$, $F\bar{F}$, etc.²⁵⁾. The large $e^+e^- \rightarrow$ hadrons cross-section above $E_{cm} = 4$ is to be due to charmed particle production^{*)}. The big problem of this model is of course the very narrow widths of the 3.1 and 3.7. The usual explanation is to use quark diagrams²⁶⁾. Normal allowed decays such as $\phi \rightarrow K^+K^-$, $4.1 \rightarrow D\bar{D}$, correspond to connected diagrams. Disallowed decays, such as $\phi \rightarrow 3\pi$, $3.1 \rightarrow 3\pi$, $K\bar{K}$, etc., correspond to disconnected diagrams as in Fig. 4. Such diagrams are supposed to be zero as a first approximation, forbidding 3.1 and 3.7 decays to ordinary hadrons and $3.7 \rightarrow 3.1 +$ ordinary hadrons in lowest order. However, as we saw in Lecture 1, the suppression of disallowed ϕ decays is $O(10^2)$, whereas the suppression of disallowed 3.1 decays is $O(10^3 \text{ to } 10^4)$. We will discuss later whether this improvement in the quark diagram selection rule can be made plausible.

2.1 Charm spectroscopy

The diagram in SU(4) space for a typical meson 16-plet is shown in Fig. 8. To calculate the masses of these states, we try as a first approximation²¹⁾ the lowest order SU(4) breaking in quadratic mass formulae. As in gauge theories, the strong interactions are supposed to be SU(4) invariant apart from quark mass terms:

$$d\mathcal{L}_{\text{break}} = m_p \bar{p}p + m_n \bar{n}n + m_\lambda \bar{\lambda}\lambda + m_c \bar{c}c \quad (2.1)$$

$$= m_0 (u_0 + r u_8 + r' R u_{15}) \quad (2.2)$$

where $u_\alpha = \bar{q}\lambda_\alpha q$ with the λ_α SU(4) generalizations of the usual SU(3) matrices, e.g.

$$\lambda_{15} = \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -3 \end{pmatrix}$$

*) Other options are open. At one extreme the 3.7 state could lie just above the $D\bar{D}$ threshold, with decays suppressed by phase space. At the other extreme, the 4.1 could be a mixture of $c\bar{c}$ and uncharmed quarks, the $D\bar{D}$ threshold could lie above it, and the 4.1 could decay just into familiar hadrons.

The parameters r and R describe the relative magnitudes of quark masses: r is the same as the Gell-Mann Oakes Renner²⁷⁾ parameter c , probably $\approx -\sqrt{2}$, and $R = m_c - m_p/m_\lambda - m_p$. The breaking of $SU(4)$ comes just from a $\underline{15}$ -plet in lowest order; hence in describing mass splittings for a meson $\underline{16} = \underline{1} + \underline{15}$ -plet we need, in addition to R , four parameters corresponding to

$$\underline{1} \times \underline{1} = \underline{1}, \quad \underline{1} \times \underline{15} = \underline{15}, \quad \underline{15} \times \underline{1} = \underline{15}, \quad \underline{15} \times \underline{15} \ni \underline{15}$$

We introduce these via an effective mass term

$$\Delta \mathcal{L}_{\text{break}} = A(T_F M)^2 + B T_F (M^2) + C T_F (M \Delta M) + D T_F (M) T_F (\Delta M) \quad (2.3)$$

where M is the meson $\underline{16}$ -plet written in matrix form. The parameter B gives the average meson mass²; A splits singlet and $\underline{15}$ -plet masses; C splits the $\underline{15}$ -plet masses; and D gives singlet- $\underline{15}$ -plet mixing. For the vector mesons a fit to the $SU(3)$ nonet implies

$$B \approx 0, \quad D \approx 0,$$

so that the states separate essentially according to their quark content. We then have

$$m_{D^*}^2 - m_\phi^2 \approx m_{F^*}^2 - m_{K^*}^2 \approx \frac{1}{2} (m_{\phi_c}^2 - m_\rho^2) \approx R (m_{K^*}^2 - m_\rho^2) \quad (2.4)$$

For the pseudoscalar mesons the situation is more complicated, but irrespective of the singlet- $\underline{15}$ -plet mixing parameters we have

$$m_D^2 - m_\pi^2 \approx m_F^2 - m_K^2 \approx R (m_K^2 - m_\pi^2) \quad (2.5)$$

implying, if $m_D \approx 2$ GeV, that $m_F - m_D \approx 60$ MeV. However, the status of the $I = 0$ states is unsatisfactory: the apparent octet structure of the lowest pseudoscalars forces a choice of A, B, C, D which gives substantial $c\bar{c}$ content to the $X(958)$. If this were true, then the decay $3.1 \rightarrow X\gamma$ would no longer be forbidden by the quark diagram rule, and the width of the 3.1 would be disastrously large. We return to this problem later: in the meantime we assume the validity of (2.4) and (2.5). Identifying the 3.1 with ϕ_c we see from Eq. (2.4) that $m_{D^*}, m_{F^*} \approx 1/\sqrt{2} m_{\phi_c}$, and we expect the pseudoscalars to be somewhat lighter. Therefore m_D, m_F, m_{D^*} , and m_{F^*} are all around 2.2 GeV. The position of the apparent threshold in $e^+e^- \rightarrow \text{hadrons}$ is slightly overestimated, suggesting that the mass formula may only work to $O(10)\%$. However, it seems reasonable that the 3.7 may still be below charm threshold and should be narrow.

We can guess other things about the spectrum by analogy with uncharmed spectroscopy. Thus we might expect Regge trajectories approximately linear in $(\text{mass})^2$: if we identify the 3.7 with the ϕ'_c , then it seems experimentally that if we identify ρ' with the 1600 state:

$$M_{\phi'_c}^2 - m_{\phi_c}^2 \approx 2(M_{\rho'}^2 - m_{\rho'}^2)$$

Since the $\rho'(1600)$ is approximately degenerate with the g meson with spin 3, we might expect a similar structure for hidden charmed mesons, with an exchange-degenerate vector/tensor meson trajectory with slope $\sim \frac{1}{2} \text{ GeV}^{-2}$:

$$\alpha_{\phi_c, f_c}(m^2) \approx -3.8 + \frac{1}{2} m^2 \quad (2.6)$$

yielding a hidden charmed tensor meson f_c with mass 3.4 to 3.5 GeV. Applying the mass formula (2.4) to charmed meson trajectories, we get $\alpha'_D \approx \alpha'_F \approx \alpha'_{D^*} \approx \alpha'_{F^*} \approx 1/\sqrt{2}$ and

$$\alpha_D(m^2) \approx -2.8 + \frac{1}{\sqrt{2}} m^2 \quad (2.7)$$

if $m_D \approx 2 \text{ GeV}$ *).

In SU(6) and the real world

$$M_K^2 - m_\pi^2 \approx M_{K^*}^2 - m_\rho^2 \approx M_{\phi}^2 - m_{K^*}^2 \quad (2.8)$$

If we extend this to SU(8) and charmed mesons,

$$m_D^2 - m_\pi^2 \approx m_{D^*}^2 - m_\rho^2 \approx m_{\phi_c}^2 - m_{D^*}^2 \approx m_{F^*}^2 - m_K^2 \quad (2.9)$$

Then for $m_D \sim 2 \text{ GeV}$ we get $m_{D^*} - m_D \approx 120 \text{ MeV}$. Bearing in mind the differences (2.6) and (2.7) in trajectory slopes this estimate may easily be wrong by a factor of 2. If we further assume that the $c\bar{c}$ pseudoscalar η_c is essentially pure, and that from ideal mixing and SU(8)

$$M_{\phi_c}^2 - m_{\eta_c}^2 \approx M_{\rho}^2 - m_\pi^2 \quad (2.10)$$

*) Identifying ρ' with the possible $\omega\pi$ state at 1200 MeV would give a different structure: the tensor f_c would be approximately degenerate with the 3.7, the hidden charmed trajectory would be $\alpha_{\phi_c, f_c}(m^2) \approx -1.4 + \frac{1}{4} m^2$, and there would be corresponding modifications to equation (2.7) and the subsequent discussion.

which may also easily be wrong by a factor of 2, then $m_{\phi_c} - m_{\eta_c} \approx 90$ MeV and $m_{\eta_c} \approx 3000$ MeV. The observed masses of SU(3) axial mesons might lead us to expect for the axial vectors D_A , F_A , and A_c^* :

$$m_{D_A}^2 - m_{D^*}^2 \approx m_{D^*}^2 - m_{D_c}^2, \quad m_{A_c} \approx 3.3 \text{ GeV} \quad (2.11)$$

and analogy with the SU(3) scalars suggests

$$m_{D_A} \gtrsim m_{D_s} \gtrsim m_{D^*} \quad (2.12)$$

$$m_{A_c} \gtrsim m_{\epsilon_c} \gtrsim m_{D_c}$$

for the scalars D_s , F_s , and ϵ_c . The resulting very rough particle spectra^{**)} are given in the tables^{***)}:

Meson	Quark content	Spin-parity	Mass (MeV)	
D	$c\bar{p}, c\bar{n}$	0^-	$m_D = 0(2000)$	Charmed mesons
F	$c\bar{\lambda}$	0^-	$m_D + 60?$	
D*	$c\bar{p}, c\bar{n}$	1^-	$m_D + 120?$	
F*	$c\bar{\lambda}$	1^-	$m_D + 180?$	
D_s	$c\bar{p}, c\bar{n}$	0^+	$m_D^* = m_D + 150??$	
F_s	$c\bar{\lambda}$	0^+	$m_F^* = m_D + 200??$	
η_c	$c\bar{c}$	0^-	3000?	Hidden charmed mesons
ϕ_c	$c\bar{c}$	1^-	3100	
ϵ_c	$c\bar{c}$	0^+	3200??	
A_c	$c\bar{c}$	1^+	3300?	
f_c	$c\bar{c}$	2^+	3500?	
g_c	$c\bar{c}$	3^-	3700?	
ϕ_c	$c\bar{c}$	1^-	3700	

*) There are two of each, with charge conjugation $\pm$.

**) Charmed baryons are expected to be more massive (see Ref. 25) and we will not discuss them here.

***) Similar spectra arise in the dynamical schemes discussed later in this Lecture.

2.2 Electromagnetic decays

The most obvious electromagnetic decays of the ϕ_c are $\phi_c \rightarrow e^+e^-$, $\phi_c \rightarrow \mu^+\mu^-$. Quark model universality and SU(4) symmetry predict γ -vector meson couplings:

$$\delta_e^{-2} : \delta_\omega^{-2} : \delta_\phi^{-2} : \delta_{\phi_c}^{-2} = 9 : 1 : 2 : 8 \quad (2.13)$$

We saw in Lecture 1 that from the observed decay widths $\gamma_\phi \approx \gamma_{\phi_c}$, so that the γ - ϕ_c coupling is weaker than in the SU(4) symmetry limit, not a disaster in view of the large mass breaking of SU(4) and the uncertainty in what mass factors to include in broken symmetry calculations. We have already noticed that

$$\delta_{\phi_c'}^2 / \delta_{\phi_c}^2 = O(2-3) = \delta_{e'}^2 / \delta_e^2$$

if ρ' is the 1600 MeV state.

The abundance of hidden charmed states below the ϕ_c' mass suggests that the 3.7 may have an abundance of radiative decay cascades: $\phi_c' \rightarrow f_c \gamma$, $f_c \rightarrow \phi_c \gamma$, and so on. The calculation of these is very model-dependent; however, we can give a very rough estimate of

$$\frac{\Gamma(\phi_c \rightarrow \eta_c \gamma)}{\Gamma(\omega \rightarrow \pi^0 \gamma)} = \left(\frac{g_{\phi_c \eta_c \gamma}}{g_{\omega \pi^0 \gamma}} \right)^2 \left(\frac{m_{\phi_c}^2 - m_{\eta_c}^2}{m_\omega^2 - m_\pi^2} \right) \left(\frac{m_\omega}{m_{\phi_c}} \right)^3 \quad (2.14)$$

assuming $g_{\phi_c \eta_c \gamma} \approx g_{\omega \pi^0 \gamma}$ and from formula (2.10)

$$m_{\phi_c}^2 - m_{\eta_c}^2 \approx m_\omega^2 - m_\pi^2$$

we get

$$\Gamma(\phi_c \rightarrow \eta_c \gamma) = O(10) \text{ keV} \quad (2.15)$$

A way of calculating the ratio $g_{\phi_c \eta_c \gamma} / g_{\omega \pi^0 \gamma}$ is given by the axial vector anomaly²⁵⁾ estimates of the pseudoscalar $\frac{1}{f} \gamma \gamma$ decays which work well for $\pi^0 \rightarrow \gamma \gamma$ and $\eta \rightarrow \gamma \gamma$. The anomaly yields

$$\frac{g_{\eta_c \gamma \gamma}}{g_{\pi^0 \gamma \gamma}} = \frac{f_\pi}{f_{\eta_c}} \times \frac{4\sqrt{2}}{3} \quad (2.16)$$

where f_π and f_{η_c} are defined by

$$\langle 0 | A_\mu^\pi | \pi(p) \rangle = -i p_\mu f_\pi, \quad \langle 0 | A_\mu^{\eta_c} | \eta_c(p) \rangle = -i p_\mu f_{\eta_c}$$

A_μ^c being the charmed axial current. Dominating the photons by hidden charmed vector mesons gives

$$\frac{g_{\phi_c \gamma \gamma}}{g_{\omega \pi \pi}} = \frac{4\sqrt{2}}{3} \frac{f_\pi}{f_{\eta_c}} \frac{\delta\phi_c}{\delta\omega} \approx \frac{f_\pi}{f_{\eta_c}} \quad (2.17)$$

if we take γ_ϕ and γ_ω from experiment. Just as γ_ϕ^{-1} is smaller than expected from naïve SU(4), and $f_\pi \neq f_K$, it may well be that $f_\pi \neq f_{\eta_c}$. But, if we use Eq. (2.16) and $f_\pi \approx f_{\eta_c}$, then we find $\Gamma(\eta_c \rightarrow \gamma\gamma) \sim 300$ keV: this may well be an overestimate. A similar calculation can be made of the $\epsilon_c \gamma\gamma$ coupling using the canonical trace anomaly²⁸⁾. It yields

$$\frac{\Gamma(\epsilon_c \rightarrow \gamma\gamma)}{\Gamma(\epsilon \rightarrow \gamma\gamma)} = \left(\frac{f_\epsilon}{f_{\epsilon_c}}\right)^2 \left(\frac{R_c}{R}\right)^2 \left(\frac{m_{\epsilon_c}}{m_\epsilon}\right)^3 \quad (2.18)$$

where $R_c/R = 2/3$ is the charmed quark/non-charmed quark ratio in $e^+e^- \rightarrow$ hadrons, and

$$\langle 0 | \theta_\mu^\mu | \epsilon \rangle = f_\epsilon m_\epsilon^2, \quad \langle 0 | \theta_\mu^\mu | \epsilon_c \rangle = f_{\epsilon_c} m_{\epsilon_c}^2$$

where θ_μ^μ is the trace of the energy momentum tensor. Putting in the very preliminary experimental estimate²⁹⁾ $\Gamma(\epsilon \rightarrow 2\gamma) \approx 10$ keV and $f_\epsilon = f_{\epsilon_c}$, we get $\Gamma(\epsilon_c \rightarrow 2\gamma) = 0(500)$ keV.

2.3 Dynamical schemes

In Sections 2.1 and 2.2 we saw how very naive considerations built up a picture of the spectrum of charmed particles, and gave a limited picture of electromagnetic decays. Many people have gone further than this and tried to construct dynamical schemes based on asymptotically free gauge theories which give particle spectra, radiative decay widths, and try to explain the amazing success of the quark diagram suppression rule. A common ingredient is that because from Eq. (2.5)

$$R = \frac{m_c - m_p}{m_\lambda - m_p} = \frac{m_D^2 - m_\pi^2}{m_K^2 - m_\pi^2} = O(20) \quad (2.19)$$

then if the strange quark mass $m_\lambda = 0(100-300)$ MeV as we expect, then the charmed quark mass must be in the GeV range.

The first scheme, the "charmonium" picture of Appelquist and Politzer³⁰⁾, proposed that since the ϕ_c has a large mass, the associated gauge theory running coupling constant $\alpha_s(q^2)$ should be much smaller than, for example, at the ϕ mass. They then proposed a picture in which the ϕ_c is an "orthocharmonium" state

(cf. orthopositronium) which decays by the emission of three coloured gluons which transmogrify into hadrons, or a photon which gives e^+e^- , $\mu^+\mu^-$, as indicated in Fig. 9.

To calculate the decays

$$\Gamma(3.1 \rightarrow \text{hadrons}) = |M_H|^2 |\psi(0)|^2, \quad \Gamma(3.1 \rightarrow l^+l^-) = |M_L|^2 |\psi(0)|^2 \quad (2.20)$$

where $\psi(0)$ is the orthocharmonium wave function at the origin, and M_H and M_L are hadronic and leptonic decay matrix elements. Independently of the wave function they have

$$\frac{\Gamma(3.1 \rightarrow e^+e^-)}{\Gamma(3.1 \rightarrow \text{hadrons})} = \frac{|M_L|^2}{|M_H|^2} = \frac{\frac{2}{9} \alpha^2}{\frac{2}{9\pi} (\pi^2 - 9) \frac{5}{18} \alpha_s^3} \quad (2.21)$$

Taking this ratio as $\sim 1/10$ from experiment gives $\alpha_s \approx 1/5$ to $1/4$. This is a reasonable value in the context of asymptotic freedom, and fits reasonably with the total $e^+e^- \rightarrow \text{hadrons}$ cross-section for which the asymptotic freedom formula is

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 2 \left(1 + \frac{\alpha_s}{\pi} + \dots \right) \quad (2.22)$$

giving $R \approx 2$ in the background just outside the resonance peak. We can go further and try to use the orthopositronium wave function at the origin in the formulae (2.20). Then we have

$$\left. \begin{aligned} \Gamma(3.1 \rightarrow e^+e^-) &= \frac{2}{9} \alpha^2 \left(\frac{4}{3} \alpha_s \right)^3 m_c \\ \Gamma(3.1 \rightarrow \text{hadrons}) &= \frac{2}{9\pi} (\pi^2 - 9) \frac{5}{18} \alpha_s^3 \left(\frac{4}{3} \alpha_s \right)^3 m_c \end{aligned} \right\} \quad (2.23)$$

Taking $m_c = 2 \text{ GeV}$ and $\alpha_s \leq 1/4$ gives $\Gamma_L \leq 1 \text{ keV}$ and $\Gamma_H \leq 20 \text{ keV}$: certainly in the right ball-park. The scheme can be extended to the η_c ("paracharmonium") and predicts

$$\frac{\Gamma(\phi_c \rightarrow \text{hadrons})}{\Gamma(\eta_c \rightarrow \text{hadrons})} = \frac{5}{6} \frac{2}{9\pi} (\pi^2 - 9) \alpha_s = O(0.01) \quad (2.24)$$

yielding a $\Gamma(\eta_c \rightarrow \text{hadrons})$ of the order of 5-10 MeV. The η_c state is wider in this scheme because it can decay by emitting only two gluons as shown in Fig. 9c.

The $\eta_c - \phi_c$ mass splitting can also be calculated using hyperfine splitting, getting 0(10) MeV.

There are some theoretical questions about this model. Quark binding is supposed to be an infrared phenomenon, and the infrared behaviour of gauge theories is supposed to be very different from Coulomb QED. In particular, why should one use the Coulomb formulae (2.23)? And if one does use the formulae, why should the quark-gluon coupling constant used in the decay be the asymptotically free one? The gluons in the binding and decay are almost real and not highly virtual. Another problem³⁰⁾ is that in a Coulomb potential if the first two vector states have masses 3.1 and 3.7 GeV, then the continuum starts at 3.9 GeV. However, the basic idea that strong interactions become weaker at large (mass)² is very interesting.

People have tried to go further by generalizing the Coulomb potential. Gauge theories suggest that at large distances the quark-antiquark potential $\propto |\underline{r}|$. Some people^{31,32)} take a potential of the form

$$V(\underline{r}) = \frac{A}{|\underline{r}|} + B|\underline{r}| \quad (2.25)$$

and insert it into a non-relativistic Schrödinger equation to calculate energy levels. Fitting A, B, and m_c to get the 3.1 and 3.7 vector states they find values of m_c justifying *a posteriori* the use of a non-relativistic wave equation. If the radii $\langle r \rangle$ of these states are calculated they are found to be of the order of a fermi, and our doubts about the use of the short distance form of the gauge theory are strengthened. Many predictions can be made about the spectrum using the potential (2.25): additional vector states with masses $\simeq 4.2$ GeV, 4.6 GeV, and so on are predicted, together with a congregation of 0^+ , 1^+ , and 2^+ levels between 3.4 and 3.5 GeV. It is also possible to calculate the cascade radiative decays in such a model. The 3.7 is expected to have a radiative decay width of the order of (200-300) keV, and similarly for the 0^+ , 1^+ , and 2^+ states.

Another more intuitive approach is taken by the Harvard group³²⁾ who have a branching ratio for radiative decays of the 3.7 of order $1/3$, and predict that the 0^+ , 1^+ , and 2^+ states should decay dominantly into $3.1 + \gamma$. It was remarked in Lecture 1 that probably not all the 3.7 decays into the 3.1 go via the emission of two pions. But it remains to be seen what else is going on.

One point of interest is the $3.7 \rightarrow \eta_c \gamma$ decay: this distinctive channel is present in some schemes but strongly suppressed in others. In any case radiative decays should be a rich area of experimental study.

Although the dynamical calculations to date confirm the naïve picture of Section 2.1 in general terms, specific details do not yet seem reliable, there being several differences between the schemes of Refs. 31 and 32.

2.4 A simple mixing scheme

In this section we discuss a simple-minded attempt³³⁾ to understand the magnitudes of various couplings of the 3.1 and 3.7. We recall from Lecture 1 the estimates of various suppressions:

$$\left. \begin{aligned} \frac{\Gamma(3.1 \rightarrow \text{hadrons})}{\Gamma(\text{typical hadron})} &= O(10^{-3} \text{ to } 10^{-4}), \quad \frac{\Gamma(3.1 \rightarrow \pi^0 \gamma)}{\Gamma(\text{typical radiative decay})} \leq O(10^{-4}) \\ \frac{\sigma(pp \rightarrow 3.1 + a_{00})|_{29 \text{ GeV}}}{\sigma(pp \rightarrow 3.1 + a_{00})|_{250 \text{ GeV}}} &= O(10^{-3}), \quad \left(\frac{g_{3.1 \pi \pi}}{g_{\rho^0 \pi \pi}} \right)^2 = O(10^{-2}) \\ \frac{\sigma_{\text{tot}}(3.1N)}{\sigma_{\text{tot}}(\bar{\nu}N)} &\approx O(10^{-1}), \quad \frac{\sigma(\bar{\nu}N \rightarrow 3.1N)|_{18 \text{ GeV}}}{\sigma(\bar{\nu}N \rightarrow 3.1N)|_{80 \text{ GeV}}} \approx O(10^{-1}) \end{aligned} \right\} (2.26)$$

By way of comparison, the suppressions of cross-sections and rates involving ϕ were $O(10^{-2})$. Can we understand simply these various numbers? The lowest order quark diagrams, such as those of Fig. 4, are taken as being disallowed. The first allowed diagrams are single loops like that for $\phi_c \rightarrow K^+ K^-$ decay shown in Fig. 10a. We can rewrite this suggestively by twisting the loop to get Fig. 10b. We now make a duality transformation on the part of the diagram to the right of the twists, similar to those which identify the resonance and Regge contributions to elastic scattering amplitudes. We then obtain Fig. 11. That the two diagrams of Figs. 10 and 11 are the same is a dynamical assumption. If it is true, then we see that all couplings of $c\bar{c}$ states to states made up of uncharmed quarks take place via an intermediate resonant $\lambda\bar{\lambda}$ or $1/\sqrt{2} (p\bar{p} + n\bar{n})$ state, such as ϕ or ω in the case of ϕ_c .

Let us now make the assumption that in order of magnitude the transitions $(c\bar{c}) \leftrightarrow (\lambda\bar{\lambda})$, $(\lambda\bar{\lambda}) \leftrightarrow (p\bar{p} + n\bar{n})$, and $(c\bar{c}) \leftrightarrow 1/\sqrt{2} (p\bar{p} + n\bar{n})$ are more or less SU(4) symmetric. Possible models for this mixing are the dual model diagram of Fig. 11, the field theoreticians' diagram of Fig. 12a, and the hadron phenomenologists' Fig. 12b. (Notice that we are using the gluon intermediate state differently from

Appelquist and Politzer²⁹⁾: our gluons do not metamorphose directly into final-state physical particles.) We further assume that only the lowest vector meson states contribute^{*)}. We can now represent the scheme via a (mass)² matrix

$$\begin{pmatrix} C+\epsilon & \epsilon & \epsilon \\ \epsilon & \Lambda+\epsilon & \epsilon \\ \epsilon & \epsilon & N+\epsilon \end{pmatrix} \quad (2.27)$$

where the matrix is written in a pure $(c\bar{c})$, $(\lambda\bar{\lambda})$, $(N\bar{N}) \equiv 1/\sqrt{2} (p\bar{p} + n\bar{n})$ basis, and C , Λ , N are the (mass)² of the unmixed states, so that in units of GeV^2 , $C \approx 10$, $\Lambda \approx 1$, $N \approx \frac{1}{2}$ for the vector mesons. The quantities ϵ are supposed to be equal only in order of magnitude. Let us suppose that ϵ is small in the case of vector mesons. Then diagonalizing the matrix (2.27) we get eigenvectors

$$\left. \begin{aligned} (c\bar{c}) &+ \frac{\epsilon}{C-\Lambda} (\lambda\bar{\lambda}) + \frac{\epsilon}{C-N} (N\bar{N}) \\ \frac{\epsilon}{\Lambda-C} (c\bar{c}) &+ (\lambda\bar{\lambda}) + \frac{\epsilon}{\Lambda-N} (N\bar{N}) \\ \frac{\epsilon}{N-C} (c\bar{c}) &+ \frac{\epsilon}{N-\Lambda} (\lambda\bar{\lambda}) + \epsilon (N\bar{N}) \end{aligned} \right\} \quad (2.28)$$

with eigenvalues respectively

$$C+\epsilon, \quad \Lambda+\epsilon, \quad N+\epsilon \quad (2.29)$$

If we look at the $SU(3)$ subsector of (2.28) and (2.29) we see that the ω mass shift is $O(\epsilon)$. Assuming the ρ and unmixed ω were degenerate we get

$$\epsilon \approx O(m_\omega^2 - m_\rho^2) \approx O\left(\frac{1}{30}\right) \quad (2.30)$$

in units of GeV^2 . We can also estimate ϵ from the observed suppression of $\phi \rightarrow \rho\pi$, which in lowest order takes place only via mixing. We find

$$\frac{g_{\phi\rho\pi}}{g_{\omega\rho\pi}} = O\left(\frac{\epsilon}{\Lambda-N}\right)$$

*) This might be due, for example, to the small overlap of radial wave functions in Fig. 12a, or to the observed suppression of $\rho' \rightarrow 2\pi$ decay, where 2π is expected to be an important contribution to Fig. 12b.

giving

$$\epsilon = O\left(\frac{1}{20}\right) \quad (2.31)$$

The estimates (2.30) and (2.31) agree in order of magnitude, which is all we need: henceforward we take $\epsilon = O(1/10)$ for the vector meson system.

Going to the ϕ_c , we see from formulae (2.28) that its admixture of $(\lambda\bar{\lambda})$ and $(N\bar{N})$ is $O[\epsilon/(C - \Lambda)] = O(\epsilon/10) = O(1/100)$ ^{*}). Disallowed amplitudes involving the ϕ_c are suppressed by $O(10^{-2})$, and rates and cross-sections by $O(10^{-4})$. This is consistent with the suppression (2.26) of $3.1 \rightarrow \text{hadrons}$ and $3.1 \rightarrow \pi^0\gamma$. Presumably the production of ϕ_c will also be suppressed by $O(10^{-4})$ if there are no charmed particles in the final state corresponding to the disallowed diagrams (Fig. 13a) and the allowed diagrams (Fig. 13b). Indeed it is persistently rumoured to be well known that in the case of the ϕ :

$$\frac{\sigma(pp \rightarrow \phi + \text{non-strange hadrons})}{\sigma(pp \rightarrow \phi + \text{anything})} = O(10^{-1} \text{ to } 10^{-2})$$

From the mass formulae, the MIT-BNL experiment is below the threshold for associated production of ϕ_c and charmed particles, whereas the Fermilab experiment is above. Hence we might expect a rise of 10^2 to 10^4 in the cross-section. Furthermore, at least 99% of the final states at the higher energy should contain charmed particle pairs! Thus a clean way of looking for charm in hadronic collisions may be to trigger on production of the 3.1 state. Later on we will discuss ϕ_c photoproduction using Regge analogues of the twisted loops of Figs. 10 and 11.

We can extend the scheme to other meson multiplets: in general the ϵ parameter of formulae (2.26) may vary between multiplets, and be of order 1 in some cases. Consider, for example, the pseudoscalars: from the complete absence of ideal mixing at the SU(3) level we conclude $\epsilon_{0-} = O(1)$. But even then $\epsilon/(C - \Lambda)$, $\epsilon/(C - N) = O(1/10)$, the X(958) contains only $O(10^{-1})$ $(c\bar{c})$ pairs, and similarly the η_c is ideally mixed to $O(10^{-1})$. In particular its total hadronic decay width is just suppressed by $O(10^{-2})$ and its decay width should be $O(\text{few})$ MeV. The amplitude for $\phi_c \rightarrow X\gamma$ should then be suppressed by $O(1/10)$ because of the mixing of the X in Fig. 14a, and $\Gamma(\phi_c \rightarrow X\gamma)$ by $O(10^{-2})$. The resulting decay rate is still rather large, but may be reduced by the necessity of ϕ_c dominating the final state γ or some other breaking of SU(4). It is clear, though, that in this scheme we expect $\Gamma(\phi_c \rightarrow X\gamma) \gg \Gamma(\phi_c \rightarrow \pi^0\gamma)$ ^{**}). Further, because the η_c has $O(1/10)$ $(\lambda\bar{\lambda})$ and $(N\bar{N})$ pairs, we expect its production rate below the associated charmed particle production threshold to be suppressed only by $O(10^{-2})$, and so perhaps

^{*}) Because C/Λ and C/N are smaller for daughter states, these could in principle be less ideally mixed.

^{**}) As for $\Gamma(\phi_c \rightarrow \eta\gamma)$, usual analyses suggest that η is 0(10%) SU(3) singlet, of which some unknown fraction is now expected to be $c\bar{c}$. A suppression of $\Gamma(\phi_c \rightarrow \eta\gamma)$ to a rate between that of $\Gamma(\phi_c \rightarrow \pi^0\gamma)$ and $\Gamma(\phi_c \rightarrow X\gamma)$ might seem not unreasonable.

$$\frac{\sigma(pp \rightarrow \eta_c + \text{any})}{\sigma(pp \rightarrow \phi_c + \text{any})} \gg 1$$

at low energies.

A similar analysis applies to the scalar multiplet, which is also apparently nowhere near ideally mixed at the SU(3) level, implying similar predictions for the ε_c width, production rate, and so on. It also predicts that the amplitude for $3.7 \rightarrow 3.1 \pi^+ \pi^-$, assumed to proceed via $3.7 \rightarrow 3.1 \varepsilon$, should only be suppressed by $O(10^{-1})$ because of the ε impurity in Fig. 14b, so that $\Gamma(3.7 \rightarrow 3.1 \pi^+ \pi^-)$ is suppressed by $O(10^{-2})$ as seen experimentally [formulae (2.26)].

The same basic idea can also be applied to $\sigma_{\text{total}}(\phi_c N)$. At high energies this proceeds via Pomeron exchange, which in the dual model has the lowest order contribution shown in Fig. 15a. Making a double duality transformation above and below the twists gives Fig. 15b. The Pomeron propagator in the angular momentum plane then contains a factor $1/J - \alpha_P(0)$ with $\alpha_P(0) \approx 1$ from the loop, and $1/J - \alpha_T(0)$ from the stalks connecting it to the external particles where α_T is the appropriate leading tensor meson trajectory. The Pomeron couplings are supposed otherwise to be SU(4) symmetric. This scheme then gives for the ratios of residues of the Pomeron pole in vector meson-nucleon scattering:

$$\left. \begin{aligned} \sigma_{\text{total}}(\pi N) : \sigma_{\text{total}}(\phi N) : \sigma_{\text{total}}(\phi_c N) \\ = \frac{1}{1-\alpha_f(0)} : \frac{1}{1-\alpha_{f'}(0)} : \frac{1}{1-\alpha_{f_c}(0)} \approx 2 : 1 : \frac{1}{5} \end{aligned} \right\} \quad (2.32)$$

if we believe the trajectory (2.6). This estimate works very well³⁴⁾ for the ratios of πN , KN , and ϕN cross-sections giving $\sigma_{\text{total}}(\pi N) : \sigma_{\text{total}}(KN) : \sigma_{\text{total}}(\phi N) = 2 : 3/2 : 1$, to be compared with $\sigma_{\text{total}}(\pi N) \approx 23$ mb, $\sigma_{\text{total}}(KN) \approx 17$ mb, $\sigma_{\text{total}}(\phi N) \approx 13$ mb. It is also not grossly inconsistent with preliminary data on $\sigma_{\text{total}}(\phi_c N)$. It is worth noting that in Fig. 15 the Pomeron in $\phi_c N$ scattering is the shadow of charmed particle production^{*)}, and that the threshold for production of $D + \bar{D} + N$ in the intermediate state is $E \sim 12$ GeV. Hence it is not surprising that the photoproduction cross-section should increase less rapidly than the cross-section for $pp \rightarrow \phi_c + \text{anything}$ between 18 and 80 GeV.

*) The lowest order dual Pomeron of Fig. 15 is probably hopelessly naïve, but a similar thing happens in the multiperipheral model. We return to this point in Lecture 4.

Thus this simple mixing scheme is consistent with the observed suppressions (2.26). At any rate, the narrow widths of the 3.1 and the 3.7 may not be completely unthinkable.

3. e^+e^- ANNIHILATION

We now move on to a discussion of the $e^+e^- \rightarrow \text{hadrons}$ data and review possible models. Perhaps we will justify the prejudice that the approximate constancy of the total cross-section reflects the crossing of the charmed particle threshold.

3.1 Naïve theoretical expectations

Before the advent of the data from CEA³⁵⁾ and SPEAR³⁶⁾, the expectation of theoreticians was that the $e^+e^- \rightarrow \text{hadrons}$ cross-section should scale. The reason was that deep inelastic electroproduction and neutrino production data had suggested that current interactions at large $|q^2|$ had no intrinsic scale. Since a cross-section has the dimensions of (length)² or (momentum)⁻², this led to the prediction^{*)}

$$\sigma(e^+e^- \rightarrow \text{hadrons}) \propto \frac{1}{q^2} \quad (3.1)$$

Applying the same arguments to the inclusive cross-section gave

$$q^2 \frac{d\sigma}{dx} (e^+e^- \rightarrow \pi + \text{any}) \rightarrow f(x) : x = \frac{2E}{\sqrt{q^2}} \quad (3.2)$$

so that $(1/\sigma)(d\sigma/dx)$ should be independent of q^2 . These predictions were all asymptotic, but experience with deep inelastic scattering, where scaling set in for $|q^2| > 1-2 \text{ GeV}^2$, suggested that data in the CEA-SPEAR I range should exhibit the scaling (3.1) and (3.2). The most popular model for scaling was the parton model, with the photon coupling to point-like objects at large q^2 , giving

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \sum_{\text{partons}} Q^2 \quad (3.3)$$

corresponding to the diagram in Fig. 16a.

*) The reaction was assumed to proceed predominantly via one-photon exchange.

Deep inelastic data suggested the partons were quarks: spectroscopy, quark binding arguments and the $\pi^0 \rightarrow 2\gamma$ decay rate suggested the Gell-Mann/Zweig colour model, with three identical quarks of each type p, n, λ , and $R = 2$. The inclusive hadronic cross-section then came from partons decaying into a "cigar" in momentum space oriented along the parton-antiparton separation axis and with limited transverse momenta, as shown in Fig. 17.

The distribution of hadrons in any particular event should then resemble that in a typical high-energy hadronic collision with a central plateau and so on, but with an angular distribution

$$\frac{d\sigma}{d(\cos\theta)} \propto (1 + \cos^2\theta) \quad (3.4)$$

resulting from the spin $\frac{1}{2}$ of the partons. The model also expects

$$\frac{d\sigma}{dx}(\pi^+) = \frac{d\sigma}{dx}(\pi^-) = \frac{d\sigma}{dx}(\pi^0) \quad (3.5)$$

and that pions should be the dominant species of particle produced: hence the charged energy fraction $E_{ch}/E_{tot} \approx \frac{2}{3}$. The data of Frascati³⁷⁾ in the range $2 < q^2 < 10$ suggested that R was indeed $O(2)$ and had the expected charged/neutral energy ratio. But the CEA and SPEAR data completely contradicted the naïve expectations (3.1) to (3.4) in the range $10 < q^2 < 25$.

3.2 The CEA³⁵⁾ and SPEAR³⁶⁾ data

An almost complete summary of these, with the exception of the latest SPEAR data on R , is given in the Proceedings of last year's London Conference³⁶⁾. Let us just summarize the main points:

- i) QED works for leptons with cut-off orders of magnitude larger than the q^2 accessible in $e^+e^- \rightarrow$ hadrons. Hence weird happenings in $e^+e^- \rightarrow$ hadrons cannot be blamed on QED.
- ii) The e^+e^- cross-section is large: expressed in terms of R ; it rises from ~ 2.5 at $q^2 \approx 10$ to ~ 5 at $q^2 \approx 25$, with a (200-300) MeV wide peak at $q^2 \approx 20$ rising to $R \approx 6$.
- iii) For $x = 2E/\sqrt{q^2} \gtrsim 0.5$, the inclusive charged hadronic distribution is small, and consistent with $q^2 d\sigma/dx$ scaling. For $x \lesssim 0.5$, the distribution is large and rises rapidly with q^2 : scaling of $(1/\sigma)(d\sigma/dx)$ is nowhere a good approximation. The average charged particle momentum is roughly constant at ~ 500 MeV.

- iv) The angular distribution of charged tracks is consistent with isotropy for $10 \leq q^2 \leq 25$, for $|\cos \theta| \leq 0.6$.
- v) The mean charged particle multiplicity rises relatively slowly with q^2 , with $\langle n_{ch} \rangle \approx 4$, and shows no obvious structure.
- vi) As a result of (iii) and (v) the fraction E_{ch}/E_{tot} of the total energy carried by charged particles is relatively small, falling to around 0.5 at $q^2 \approx 25$ -- the "energy crisis".
- vii) At low momenta $\langle n_{\pi^\pm} \rangle : \langle n_{K^\pm} \rangle : \langle n_p \rangle \approx 100 : 10 : 1$. As the momentum is increased, $n_{K^\pm}/n_{\pi^\pm}$ increases and is of the order of $1/3$ for $x \gtrsim 0.5$ at $\sqrt{q^2} = 4.8$.

3.3 Possible theoretical explanations

There are four possible mechanisms for trying to explain the experimental data:

a) The "hadronic" events may not in fact be due to the production of hadrons alone, the most likely possibility being the production by the one-photon mechanism of a heavy lepton-antilepton pair which then decay leptonically or semi-leptonically as shown in Fig. 18. This mechanism seems to be ruled out by the scarcity of (μe) coincidences seen at SPEAR, which are all consistent with other sources.

b) Hadrons or leptons may be produced by the two-photon mechanism of Fig. 19. However, by looking at the $e^\pm$ passing through tagging counters near the beam pipes, it was possible to estimate these as small, and the published data should have $\leq 6\%$ contamination from 2γ processes.

c) The hadrons may indeed be produced by the one-photon mechanism, but the simple quark parton model has to be modified. We will discuss this possibility in a moment.

d) The hadrons may be produced by some "no-photon" mechanism, e.g. by a direct or crossed channel weak interaction. We shall return later to this possibility.

3.4 One-photon mechanisms

Approaches in the context of one-photon exchange can be grouped into parton and non-parton models. Parton models may either

- a) keep the same quark partons, but postulate a very slow approach to scaling, or
- b) keep the same quark partons, but give them interactions or form factors violating scaling, or
- c) add in new partons, e.g. colour or charm.

First let us discuss²⁴⁾ the approach to scaling in the parton model. If one took the naive parton model literally, and calculated Fig. 16a in the usual way, then the approach to a constant R would be $O(q^{-4})$ for spin $\frac{1}{2}$ partons. In more sophisticated covariant parton models the approach is slower, as $(q^2)^{-p}$ with $p < 1$. The slowest approach is that found in an asymptotically free gauge theory. For three-coloured Gell-Mann/Zweig quarks

$$R = 2 \left(1 + \frac{\alpha_s}{\pi} + \dots \right) \quad (3.6)$$

where $\alpha_s \approx 4\pi/[9 \ln(q^2/\mu^2)]$ with μ an *a priori* unknown mass parameter. The α_s correction terms in (3.6) correspond to the gluon exchange graphs of Fig. 16b, with an effective gluon coupling α_s . Choosing μ^2 to lie in the typical hadronic range $\frac{1}{2} < \mu^2 < 2$ yields values of R which are ≤ 3 for $q^2 \geq 5$, as shown in Fig. 20. In fact the data on R for $2.6 \leq \sqrt{q^2} \leq 3.4$ are clearly just in the range expected on the basis of asymptotic freedom.

Many people have suggested other reasons for a slow approach to scaling in e^+e^- . For example:

- i) There are strong direct channel resonances with $q^2 > 0$ (ρ , ω , ϕ , ρ' , ...) and scaling can only be expected for q^2 much greater than these values, and hence slower than for $q^2 < 0$;
- ii) Only one partial wave contributes to e^+e^- annihilation, this has fewer states than the partial waves in electroproduction, and hence the statistical conspiracy necessary for scaling may be slower in turning up;
- iii) There may be threshold effects for the production of massive conventional particles, e.g. $B\bar{B}$, which may delay scaling.

A counter-example to the first two arguments is given²⁴⁾ by a simple dual model. Following a long tradition³⁸⁾ we construct a phenomenological current model by replacing external currents by fictitious "leptons" as shown in Fig. 21, taking usual moving trajectories in the hadron-hadron channels, and fixed singularities in the lepton-lepton and lepton-hadron channels. This method has been applied³⁸⁾ in order to get amplitudes for deep inelastic scattering. Applied to e^+e^- annihilation we have a dual four-point function with a fixed lepton-lepton trajectory $\alpha = K$ and a moving lepton-antilepton trajectory $\alpha \approx \frac{1}{2} + \alpha' q^2$ giving direct channel vector meson poles. This is proportional to

$$\frac{\Gamma(-\frac{1}{2} - \alpha' q^2)}{\Gamma(-K - \frac{1}{2} - \alpha' q^2)} \approx (-\alpha' q^2)^K \left(1 + \frac{K(K+2)}{2\alpha' q^2} + \dots \right) \quad (3.7)$$

if we use (3.7) as a model for the vacuum polarization $\Pi(q^2)$ and recall that $\sigma(q^2) \propto 1/q^2 \text{ Im } \Pi(q^2)$ then

$$\frac{R(q^2)}{R(\infty)} = 1 + O\left(\frac{1}{\alpha' q^2}\right) + \dots \quad (3.8)$$

with α' a normal trajectory slope $\approx 1 \text{ GeV}^{-2}$. Strict belief in the formula (3.8) would entail $K = 0$, but this may be pushing things too far. Thus we have a rapid approach to scaling independent of whether $q^2 > 0$ or $q^2 < 0$ despite all the direct channel poles and the presence of just one partial wave.

As for the $B\bar{B}$ threshold possibility, SPEAR³⁶⁾ data indicate that in regions where they have been separated $\langle n_p \rangle / \langle n_{\pi^+} \rangle \approx 0(1)\%$ essentially independently of energy, so $B\bar{B}$ production seems unlikely to be a large source of scaling violations.

But what of the inclusive distribution $q^2 d\sigma/dx d(\cos \Theta)$? The dilemma is that at values of q^2 where R may scale, the inclusive distribution $q^2 d\sigma/dx$ does not scale, and the particles are isotropic rather than having a $(1 + \cos^2 \Theta)$ angular distribution. This may not be too serious: for scaling at fixed x near 1 it is presumably necessary that the missing (mass)² m_X^2 be large, bigger than 3 corresponding to $m_X \approx m_g$, for example. Since $m_X^2 \approx (1 - x) q^2$, we see that for scaling for $q^2 \approx 9$ we need $x \lesssim 2/3$. Experimentally $q^2 d\sigma/dx$ nevertheless does scale for large x -- but even if $q^2 d\sigma/dx$ does scale, then the double differential cross-section $d\sigma/dx d(\cos \Theta)$ is probably more sensitive to non-scaling terms, and may well not be $\propto (1 + \cos^2 \Theta)$. Other kinematic effects are present in the parton model at small x : because²⁴⁾ of the finite width of the hadronic cigar, the inclusive distribution gets substantial corrections at small x :

$$q^2 x \frac{d\sigma}{dx} \approx f_0(x) + \frac{1}{x^2 q^2} f_1(x) + O\left(\frac{1}{x^4 q^4}\right) \quad (3.9)$$

where both $f_0(x)$ and $f_1(x)$ are regular as $x \rightarrow 0$. These $1/x^2 q^2$ terms also violate the expected $(1 + \cos^2 \Theta)$ angular distribution. These effects may be substantial at small x , particularly if $\langle p_T \rangle \approx$ twice the average value of p_T seen in hadronic reactions, as suggested by theoretical models of the "shrinking photon" supposed to cause broadening of p_T and t distributions in deep inelastic electroproduction compared with photoproduction.

We conclude that without some sophistry it is probable that parton models should approximately scale in σ_{tot} for $q^2 \approx 10$, but not necessarily exhibit parton-like features in the inclusive distributions. In this case the rise in R above $q^2 \approx 12$ would come either from giving partons structure, or from postulating new types of partons whose threshold is being passed in the CEA-SPEAR I energy range.

Various authors³⁹⁾ have proposed that partons may have structure with electromagnetic form factors

$$\bar{p}(k+q) \left[\gamma_\mu F(q^2) + \sigma_{\mu\nu} q^\nu G(q^2) \right] p(k) \quad (3.10)$$

either with $F'(0) \neq 0$ giving an electric charge radius, or with $G(0) \neq 0$ giving a magnetic moment. The familiar parton model diagrams are drawn for electroproduction and annihilation as in Fig. 16a. A simple parton charge radius is not able to fit the scaling in deep inelastic and the lack of scaling in e^+e^- simultaneously as it has for the deep inelastic structure function $F_2(x)$, and the annihilation ratio R :

$$F_2(x) \rightarrow F_2(x) (1 - 2a|q^2|) \quad , \quad R \rightarrow R (1 + 2a q^2) \quad (3.11)$$

for the same parameter a . It is possible to reconcile approximate scaling in electroproduction and violations in annihilation by combining charge radii and magnetic moments, but such schemes seem somewhat *ad hoc*. Also, a simple multiplicative violation of scaling as in (3.11) is not a good model for the apparent small scaling violations in electroproduction. Kogut⁴⁰⁾ has suggested, on the other hand, that the renormalization group effective coupling constant α_s may tend to zero for a range in q^2 , as in asymptotic freedom (3.6), but that then as yet unknown dynamics drive it away again as q^2 increases, and the correction terms of Fig. 16b in (3.6) start growing. Some of the same remarks about lack of motivation apply to this idea as to the parton form factors.

What of non-parton analysis of $e^+e^- \rightarrow$ hadrons in the one-photon approximation? The most interesting of these are probably the various statistical, thermodynamic, and hydrodynamic approaches. Characteristically, these models do not predict the behaviour with energy of the total cross-section, but make predictions for the normalized inclusive distribution $(1/\sigma)(d\sigma/dx)$ and the multiplicity. The main features are:

Statistical⁴¹⁾ models -- final-state hadrons populate uniformly all available N -particle phase space (relativistic or non-relativistic).

Thermodynamic⁴¹⁾ models -- the spectrum of hadronic states is bootstrapped by requiring the level density of each system to be the same as its constituents, and all exclusive states contribute with equal statistical weight to the inclusive cross-section.

Hydrodynamic⁴²⁾ models -- a blob of very hot and dense pre-matter is formed by the virtual photon in a small volume and then expands and cools according to some hydrodynamical equation of state. When the density falls to typical hadronic values, the matter condenses out into normal hadrons, mainly pions. Opinions differ about the appropriate initial volume and the right equation of state.

Common features of all these models are

$$\frac{1}{\sigma_{tot}} \frac{d\sigma}{dx} \quad \downarrow \quad \text{at large } x, \quad \uparrow \quad \text{at small } x \text{ as } q^2 \quad \uparrow \quad (3.12)$$

$$\langle n_{ch} \rangle \approx (q^2)^p \quad : \quad 0 < p < \frac{1}{2} \quad (3.13)$$

and

$$E_{\pi^+} = E_{\pi^0} = E_{\pi^-} \quad (3.14)$$

The first two of these predictions agree qualitatively with the data: prediction (3.13) falls foul of the "energy crisis". Forgetting this for the moment, we may draw the lesson that at present energies in e^+e^- machines the phase space available to the hadrons may be too small for characteristic parton structure to show up, and qualitative considerations may work well. We should remember⁴³⁾ that at $S \approx 25$ in purely hadronic reactions the inclusive pion distribution is essentially isotropic in the centre of mass and rising rapidly near $x = 0$, while the total cross-section is already comfortably constant.

3.5 No-photon mechanisms

Motivated by the apparent absence of a swasivious one-photon explanation for the large $e^+e^- \rightarrow$ hadrons cross-section, various people discussed new interactions to explain the data. These could be characterized either by extra exchanges in the s-channel such as an intermediate vector boson W ⁴⁴⁾ or a scalar Higgs meson Φ (Fig. 22a) or⁴⁵⁾ by the exchange in the cross-channel of a "hadrolepton" X (Fig. 22b). If the W , Φ , or X mass is sufficiently large, then all these interactions can be Fierz-transformed and written using a phenomenological Lagrangian

$$\mathcal{L}_{eff} = \sum_i g_i (\bar{\psi} \gamma_i \psi) (\bar{q} \gamma_i q) \quad (3.15)$$

where the γ_i are the usual tensors S , P , V , A , and T . An amusing aspect⁴⁵⁾ of such schemes is that the non-vector contributions depend in general on the transverse polarization of the colliding beams: for scalars and pseudoscalars

$$\sigma_{pol.}^{S,P} = (1 \mp p^2) \sigma_{unpol.}^{S,P} \quad (3.16)$$

where p is the transverse beam polarization. Theoretically the beams in e^+e^- rings should become transverse polarized while they are circulating, though this has

apparently not yet been established by the machine people. They apparently see no time-dependence of the cross-section as would be implied by formula (3.16).

It is also very difficult in the W boson case⁴⁵⁾ to reconcile the magnitudes of W couplings necessary to fit the observed violation of scaling in $e^+e^- \rightarrow \text{hadrons}$ with the known success of scaling in deep inelastic scattering and the magnitude of purely leptonic weak neutral currents. In general such models must be careful not to contradict other data as well, such as the data on $\mu^\pm$ production and $e^\pm$ electroproduction cross-section differences which are known experimentally to be very small. We refer to Pati and Salam⁴⁶⁾ for details.

All the new interactions proposed for the $e^+e^- \rightarrow \text{hadrons}$ data, while based on pre-existing theoretical ideas, are much larger than had been expected. Hence we administer them a *coup de grâce* with Occam's razor, and return to less unconventional models.

3.6 Models with new partons

In Section 3.4 we argued that a simple quark parton model fitted $\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})$ as well as could be expected for $q^2 \leq 12$, and that the violations of parton model predictions for the inclusive distribution should not be worried about too seriously. On the other hand, we argued in Section 3.4 also that simple quark partons could not fit the rise in R from $q^2 = 12$ to $q^2 = 25$, and motivated later in Sections 3.4 and 3.5 the prejudice that there was no good alternative to the simple quark parton scheme for e^+e^- annihilation. Accordingly we now consider adding new degrees of freedom to the quark scheme.

In Lecture 1 we distinguished two possible ways of extending the symmetry group SU(3): $SU(3) \rightarrow SU(3) \times G$ or generalized "colour", and $SU(3) \rightarrow SU(N)$, $N \geq 4$ or generalized "charm". Which of these is more natural in the light of the e^+e^- and electroproduction data?

Consider first a generalized "colour" scheme, in which each conventional quark q^a is "spectrum analysed" into N coloured quarks q_i^a . They have the advantage that a lot of "coloured" hadronic decays are radiative, which may be useful for the "energy crisis". If we denote the usual threefold quark index by a, and the N-fold colour index by i, then

$$\sum_{i=1}^N (Q_i^a)^2 = \sum_{i=1}^N (Q_i^a - Q^a)^2 + 2Q^a \sum_{i=1}^N (Q_i^a - Q^a) + N(Q^a)^2 \quad (3.17)$$

and in these models $\sum_{i=1}^N Q_i^a = NQ^a$, so that the second term in equation (3.17) vanishes.

Below "colour" threshold $R = N \sum_a (Q^a)^2$ and formula (3.17) shows that it rises to $\sum_{a,i} (Q_i^a)^2 > N \sum_a Q^a{}^2$ above the "colour" threshold. But by the same token, the deep inelastic electroproduction cross-section

$$\propto N \sum_a (Q^a)^2 F^a(x) \quad (3.18)$$

[where $F^a(x)$ is the distribution of quarks of type a with fraction $x = q^2/2v$ of the target's longitudinal momentum] will also rise, becoming

$$\sum_{a,i} (Q_i^a)^2 F_i^a(x) = \sum_{a,i} (Q_i^a)^2 F^a(x) > N \sum_a (Q^a)^2 F^a(x) \quad (3.19)$$

[We assumed the target was colour symmetric so that the $F_i^a(x)$ were equal for fixed a but varying i .] In general this increase is $O(100)\%$ for all values of x . For example, in the Han-Nambu model¹⁹⁾ $G = SU(3)$ is the colour group, and conventional distributions of p and n quarks in the proton and neutron give the following²⁴⁾ rises in F_2^{ep} and F_2^{en} :

	Rise in F_2^{ep} (%)	Rise in F_2^{en} (%)
$x \approx 1$	50	200
$x \approx 1/3$	67	100
$x \approx 0$	100	100

These increases should presumably appear in electroproduction at values of v and q^2 comparable to the 20 GeV² where e^+e^- scaling is violated. These effects are not apparently seen in the Fermilab⁴⁷⁾ muon electroproduction data. What about a generalized "charm" scheme in which we add in new quarks $q^{a'}$? There is no natural resolution of the energy crisis. However, these quarks are expected to show up in the proton and neutron only at small $x \lesssim 0.1$, the so-called "sea" where valence (p and n) and non-valence ($\bar{p}$, $\bar{n}$, λ , $\bar{\lambda}$) quarks are supposed to be roughly equally abundant. In this case electroproduction data should only rise at small x if at all, which is consistent with experiment (we return to this point in Lecture 4). The main features of the above remarks are of course independent of the particular "colour" or "charm" scheme.

In Fig. 20 we have compared the SPEAR I data with simple quark model predictions ($R = 2, 3\frac{1}{3}, 4$ for Gell-Mann/Zweig, charmed, and Han-Nambu, respectively), the asymptotic freedom version of the Gell-Mann/Zweig model

$$R = 2 \left(1 + \frac{4}{9 \ln(q^2/\mu_1^2)} + \dots \right) \quad (3.20)$$

where $\frac{1}{2} < \mu_1^2 < 2$, and the asymptotic freedom version of the conventional four-quark charm scheme

$$R = \frac{10}{3} \left(1 + \frac{12}{25 \ln(q^2/\mu_2^2)} + \dots \right) \quad (3.21)$$

with $1 < \mu_2^2 < 4$. Both the schemes are of the order of magnitude of the present data -- detailed comparison is meaningless in the apparently resonance-dominated region of q^2 seen at present.

In conclusion, the $e^+e^- \rightarrow \text{hadrons}$ data at present energies may prefer "colour" over "charm", principally because of the "energy crisis", but not conclusively. The apparent absence of a "colour" threshold in electroproduction at comparable q^2 strongly favours "charm" schemes though. However, if it should turn out that there is a further increase in R at $q^2 > 25$, a simple $SU(4)$ charm scheme would probably be untenable. Whether it should be further "charmed" or "coloured" would probably be reflected in the electroproduction cross-sections for $|q^2| > 25$. It is worth noting that Han-Nambu with charm gives $R = 6$. Anyway, we hope that the detailed study of the conventional charm scheme and of how to see charmed particles experimentally, has now been adequately justified.

4. SEEING CHARM

We saw in the previous lectures that "hidden charm" was not excluded as an explanation of the new narrow resonances. Many of the considerations made were qualitative and did not depend on the details of the "charm" scheme, such as the quantum numbers and weak interactions of the new charmed quark. In this section we specialize to the conventional $SU(4)$ charm scheme, as it appears, for example, in the Weinberg-Salam⁴⁸⁾ model of weak interactions, and speculate how it may show up in various experimental situations.

4.1 The decays of charmed particles

The absence so far of heavy leptons and the presence of neutral currents suggest that if you want to make a renormalizable unified gauge theory of weak interactions, then the simplest possibility is the Weinberg-Salam model⁴⁸⁾. Indeed this model is not yet inconsistent with published data on neutral and charged currents

in purely leptonic and semileptonic processes^{*)}. If the absence of strangeness-changing neutral currents is to be accommodated in this scheme, then the simplest possibility is to introduce a fourth charmed quark with quantum numbers $Q = 2/3$, $B = 1/3$, $I = 0$, $S = 0$, and $C = 1$, where ordinary quarks have $C = 0$. In this scheme the hadronic charged current is

$$\begin{aligned} J_{\mu}^{ch} = & \bar{p} \gamma_{\mu} (1 - \gamma_5) (u \cos \theta_c + \lambda \sin \theta_c) \\ & + \bar{c} \gamma_{\mu} (1 - \gamma_5) (-u \sin \theta_c + \lambda \cos \theta_c) \end{aligned} \quad \left. \vphantom{\begin{aligned} J_{\mu}^{ch} = & \bar{p} \gamma_{\mu} (1 - \gamma_5) (u \cos \theta_c + \lambda \sin \theta_c) \\ & + \bar{c} \gamma_{\mu} (1 - \gamma_5) (-u \sin \theta_c + \lambda \cos \theta_c) \end{aligned}} \right\} (4.1)$$

where θ_c is the usual Cabibbo angle. The Weinberg-Salam model with charm is the simplest one that has no known defects except the presence of undetermined angles and other parameters. The optimist may hope they will be specified in the next generation of unified field theories⁴⁹⁾. For the moment we assume the validity of (4.1) and pursue²¹⁾ its implications for the decay modes of charmed particles. We will assume, as suggested in Lecture 2, that the lightest charmed particles are pseudoscalars. It is not obvious that this is true, and papers exist⁵⁰⁾ discussing what happens if the lightest particles are vectors. The expected mass splittings are such that the decay $D^* \rightarrow D\pi$, $F^* \rightarrow F\pi\pi$ may well be kinematically forbidden, so that the vectors would decay into pseudoscalars predominantly radiatively.

Let us now look at the decays of the pseudoscalars D and F, much of the analysis being taken from Gaillard, Lee and Rosner²¹⁾.

4.1.1 Leptonic decays

The hadronic charm-charging current (4.1) gives a selection rule for leptonic and semileptonic decay amplitudes:

$$\left. \begin{aligned} \Delta C = \Delta Q = \Delta S = 1, \quad \Delta I = 0 & \propto \cos \theta_c \\ \Delta C = \Delta Q = 1, \quad \Delta S = 0, \quad \Delta I = \frac{1}{2} & \propto \sin \theta_c \end{aligned} \right\} (4.2)$$

Hence the dominant leptonic decay rates are

$$\left. \begin{aligned} D^0 & \rightarrow "K^- " + \text{leptons} \\ D^+ & \rightarrow "K^0 " + \text{leptons} \\ F^+ & \rightarrow "\eta " + \text{leptons} \end{aligned} \right\} \propto \cos^2 \theta_c \quad (4.3)$$

*) This remark remains true of the new data presented at the Paris neutrino conference of March 18-20, 1975.

where " $\bar{K}^0$ ", etc., indicate hadronic final states with the SU(3) quantum numbers of $\bar{K}^0$, etc., but quite possibly multiparticle states with different spin-parity.

The simplest decays are two-body ones akin to $\Pi_{\ell 2}$ and $K_{\ell 2}$ decays. Defining²¹⁾ f_D and f_F analogously to the f_π of Lecture 2:

$$\left. \begin{aligned} \langle 0 | J_\mu^c | D^+(k) \rangle &= i f_D \sin \theta_c k_\mu \\ \langle 0 | J_\mu^c | F^+(k) \rangle &= -i f_F \cos \theta_c k_\mu \end{aligned} \right\} \quad (4.4)$$

then SU(4) symmetry would predict

$$f_D \approx f_F \approx f_K \approx f_\pi$$

which is probably not a good approximation. Experimentally $f_K/f_\pi \approx 1.2$: also, we saw in Lecture 2 that the vector-photon coupling $1/\gamma_{\phi_c}$ was smaller than the SU(4) prediction by a factor of ~ 2 . Pressing on regardless, we get

$$\frac{\Gamma(D^+ \rightarrow \mu^+ \nu)}{\Gamma(K^+ \rightarrow \mu^+ \nu)} \approx \frac{m_D}{m_K}, \quad \frac{\Gamma(F^+ \rightarrow \mu^+ \nu)}{\Gamma(K^+ \rightarrow \mu^+ \nu)} \approx \frac{m_F}{m_K} \cot^2 \theta_c \quad (4.5)$$

Taking $\Gamma(K^+ \rightarrow \mu^+ \nu) \approx 0.5 \times 10^8 \text{ sec}^{-1}$ and $m_F \approx m_D \approx 4m_K$, we get

$$\left. \begin{aligned} \Gamma(D^+ \rightarrow \mu^+ \nu) &\approx 2 \times 10^8 \text{ sec}^{-1} \\ \Gamma(F^+ \rightarrow \mu^+ \nu) &\approx 4 \times 10^9 \text{ sec}^{-1} \end{aligned} \right\} \quad (4.6)$$

Notice that the (ev) decays are suppressed by the usual helicity arguments.

The dominant leptonic decays are expected to be multibody; Gaillard, Lee and Rosner²¹⁾ give a cute estimate of the inclusive semileptonic decay rate. They regard the decay as resulting from a fundamental process

$$c \rightarrow \bar{\lambda} + L^+ + \nu \quad \text{or} \quad c \rightarrow u + \bar{\lambda}^+ + \nu$$

followed by a dressing of the final-state quarks into hadronic matter as shown in Fig. 23a. The sum over final states should then have a rate given by the elementary process whose rate has the same formula as that for the μ decay:

$$\Gamma_{\text{total}}(c \rightarrow l + \nu + \text{hadrons}) = \frac{G_F^2 m_c^5}{192 \pi^3} \quad (4.7)$$

Taking the charmed quark mass $m_c \approx 1.5$ GeV gives a total rate

$$\Gamma_{\text{total}} (\text{charm} \rightarrow l + \nu + \text{hadrons}) \approx 10^{12} \text{ sec}^{-1} \quad (4.8)$$

Estimates of the specific $D_{\ell 3}$ and $F_{\ell 3}$ decays are consistent with this estimate, giving a few $\times 10^{11} \text{ sec}^{-1}$, and these may be an appreciable fraction of the total, even if not dominant. Notice that there are no helicity arguments to suppress $(e + \nu) + \text{hadrons}$ decays relative to $(\mu + \nu) + \text{hadrons}$.

The dominant decays of charmed particles are expected to be non-leptonic. Discarding γ matrices the effective current-current weak Lagrangian can be written

$$\mathcal{L}_{\text{eff}} \approx G_F \left\{ (\bar{e} \lambda p \bar{n}) \cos^2 \theta_c + (\bar{e} \lambda p \bar{\lambda} - \bar{e} n p \bar{n}) \sin \theta_c \cos \theta_c \right. \\ \left. - (\bar{e} n p \bar{\lambda}) \sin^2 \theta_c + \text{herm. conj.} \right\} \quad (4.9)$$

The dominant decays have amplitudes with

$$\left. \begin{aligned} \Delta C &= \Delta S && \propto \cos^2 \theta_c \\ |\Delta C| &= 1, \Delta S = 0 && \propto \cos \theta_c \sin \theta_c \end{aligned} \right\} \quad (4.10)$$

Hence the dominant non-leptonic decay rates are

$$\left. \begin{aligned} D^0 \rightarrow " \bar{K}^0 " , D^+ \rightarrow "(\bar{K} n \pi)^+ , F^+ \rightarrow " \pi^+ " &\propto \cos^4 \theta_c \\ \text{and} \\ D^0 \rightarrow " \pi^0 , " \gamma " ; D^+ \rightarrow " \pi^+ " , F^+ \rightarrow " K^+ " &\propto \cos^2 \theta_c \sin^2 \theta_c \end{aligned} \right\} \quad (4.11)$$

To estimate the total non-leptonic decay rate we again use the Gaillard, Lee and Rosner²¹⁾ estimate that the rate is given essentially by the elementary process $c \rightarrow \lambda + p + \bar{n}$ shown in Fig. 23b, which yields

$$\Gamma_{\text{total}} (\text{charm} \rightarrow \text{hadrons}) \approx \frac{1}{196 \pi^3} (G_F A \cos^2 \theta_c)^2 m_c^5 \quad (4.12)$$

where A is a typical factor for the enhancement of non-leptonic decays, estimated from strange particle decays to be $O(\sin^{-1} \theta_c)$. We then get for $m_c \approx 1.5$ GeV

$$\Gamma_{\text{total}} (\text{charm} \rightarrow \text{hadrons}) \approx 20 \left(\frac{m_c}{m_\mu} \right)^5 \Gamma(\mu \rightarrow e \nu \bar{\nu}) = O(10^{13}) \text{ sec}^{-1} \quad (4.13)$$

Estimates of the specific $D^0 \rightarrow K^- \pi^+$ mode are consistent with this inclusive estimate, giving at most a few $\times 10^{12} \text{ sec}^{-1}$ for this mode. Comparing the inclusive estimates (4.8) and (4.13) we get an estimate

$$\frac{\Gamma(\text{leptonic})}{\Gamma(\text{nonleptonic})} \approx O\left(\frac{1}{20}\right)$$

This is very uncertain -- there seems to be a general impression that it may be an overestimate -- but a leptonic branching ratio of the order of 1 to 10% seems reasonable.

We used above a non-leptonic enhancement factor A; phenomenologically strange non-leptonic decays with $|\Delta I| = \frac{1}{2}$ are enhanced relative to $|\Delta I| = \frac{3}{2}$ transitions and leptonic decays by a factor of $O(20)$ in the rate.

Data on SU(3) weak decays are consistent with a general octet dominance rule, and the question arises of finding the appropriate generalization of this rule to SU(4) decays. Asymptotically free gauge theories of the strong interactions give such a prescription^{21,51)} based on the differences in the anomalous dimensions of SU(4) tensor operators. The conclusion is that the dominant piece of $\mathcal{L}_{\text{eff}}$ for SU(4) decays should belong to a 20 representation of SU(4). Decomposed into SU(3) representations this has a $\Delta C = 0$ octet part, and $\Delta C = +1, -1$ parts belonging to 6 and $\bar{6}$ representations of SU(3). The suppressed $\Delta C = +1, -1$ parts belong to 15 and 15 representations of SU(3).

This scheme then makes predictions about the relative abundances of different decays of D^0 , D^+ , and F^+ . For the two-pseudoscalar $\cos^4 \theta_C$ decays they are^{50,51)}

$$\begin{aligned} \Gamma(D^0 \rightarrow \pi^+ K^-) &= 2 \Gamma(D^0 \rightarrow \bar{K}^0 \pi^0) \\ &= 6 \Gamma(D^0 \rightarrow \bar{K}^0 \eta) = \Gamma(F^+ \rightarrow \bar{K}^0 K^+) = \frac{3}{2} \Gamma(F^+ \rightarrow \pi^+ \eta) \end{aligned} \quad (4.14)$$

Other decay modes are suppressed either because they are proportional to $\cos^2 \theta_C \sin^2 \theta_C$ or $\sin^4 \theta_C$, or because they go via the 15 and $\bar{15}$ SU(3) representations. We note that there are no enhanced two-body $D^\pm$ decay modes: hence their important two-body modes may come from $\cos^2 \theta_C \sin^2 \theta_C$ terms in $\mathcal{L}_{\text{eff}}$ or from 15 and $\bar{15}$ contributions. For the $\cos^2 \theta_C \sin^2 \theta_C$ modes we have^{50,51)}

$$\Gamma(D^+ \rightarrow \bar{K}^0 K^+) = \frac{3}{2} \Gamma(D^+ \rightarrow \eta \pi^+) \quad (4.15)$$

which may be competitive with the unenhanced mode $D^+ \rightarrow \bar{K}^0 \pi^+$. Note however there are still enhanced $\cos^4 \theta_C$ multibody decay modes which may well be dominant.

It is unclear how many of the D^0 and F^+ decay modes should also be multibody. Gaillard, Lee and Rosner²¹⁾ used a simple algebra/phase-space model to estimate that for D^0 's and F^+ 's with masses ~ 2 GeV

$$\begin{aligned} \Gamma(2\text{body}) : \Gamma(3\text{body}) : \Gamma(4\text{body}) : \Gamma(5\text{body}) \\ \approx 51\% : 38\% : 9\% : 1\% \end{aligned} \quad (4.16)$$

However, this may well overestimate the two-body decays. It seems to be a phenomenological fact that no matter how you prepare a hadron "blob" with a given mass, final-state interactions have a universal effect, and the multiplicity of final decay products is about the same. For example, the charged multiplicities in $e^+e^- \rightarrow$ hadrons and $p\bar{p} \rightarrow$ mesons are essentially identical, and $\langle n_{ch} \rangle \simeq 3$ for systems with mass ~ 2 GeV. Thus we might expect for non-leptonic decays of D and F with masses 2 GeV $\langle n_{ch} \rangle$ also ~ 3 and $\langle n_{total} \rangle \sim 4$ to 5. Because of this large multiplicity, the total K/ π ratio in charmed particle decays might not be greater than $1/4$. In this case the dominant decays would be messy multibody ones, and it might be difficult to see significant enhancements in mass plots for experimentally simpler channels such as $K^\pm \pi^\mp$. However, these decays would be very spectacular in emulsions: very short tracks producing many-pointed stars.

4.2 The production of charmed particles

In this section we discuss how charmed particles may be produced in various different types of experimental situations. The discussion of the previous section suggests that while it may be easy to see that something is going on, it may not be easy to verify that it is charm. As we shall see, there are plenty of suggestions that something is happening!

4.2.1 e^+e^- annihilation

According to the charm scheme, essentially all the increase above $\sqrt{q^2} = 4$ GeV of

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

above the naive quark value 2 is due to the production of charmed particles. Because of the near degeneracy of the masses $m_D \approx m_F \approx m_{D^*} \approx m_{F^*} \approx m_{D_s} \approx m_{F_s}$, etc.,

we can expect a very dramatic threshold effect due to the opening up of many channels. Also, naïve extrapolation of $m_{3.7}^2 - m_{3.1}^2$ yields a new state (radial excitation in the quark language or lower daughter in the dual language) with a mass ~ 4.1 to 4.2 , which will further enhance the threshold effect. This state should have a typical hadronic decay width and decay mainly into the available charmed meson pairs^{*)}.

The data are not inconsistent with this possibility, but the storage rings have not yet seen any sign of a charmed particle. Rumour⁷⁾ has it that in the data at $\sqrt{q^2} = 4.8$ GeV the following channels have been examined for suspicious bumps in effective mass plots:

$$K^0 \pi^\pm, \pi^+ \pi^-, K^0 \pi^+ \pi^- \quad \text{and} \quad \pi^+ \pi^+ \pi^-$$

and that nothing has been seen with a mass around 2 GeV. How serious would this be for charm if the rumour were correct? Reference back to Section 4.1 shows that neither of the above two-body channels is expected to be populated by the dominant enhanced charmed meson decays. On the other hand, the $(K^0 \pi^+ \pi^-)$ and $(\pi^+ \pi^+ \pi^-)$ channels should be populated by D^0 and F^+ decays, respectively, but with unknown branching ratios which could well be small. What is the branching ratio of $\bar{n}p \rightarrow \pi^+ \pi^+ \pi^-$ near 2 GeV? The most distinctive two-body decay favoured by the arguments of Section 4.2 is $D^0 \rightarrow K^- \pi^+$. Unfortunately, a simple kinematical calculation shows that if a pair of charmed mesons with masses 2 to 2.1 GeV each are produced in an $e^+ e^-$ collision, then at a centre-of-mass energy of 4.8 GeV, 80 to 100% of the $K^\pm$ produced in their two-body decays have momenta > 600 MeV, beyond the centre-of-mass momenta for which the SPEAR magnetic detector can discriminate $K^\pm$ from $\pi^\pm$. Therefore the prospects of seeing lots of charm in the near future may be little better than the amount seen so far.

There is one problem, namely the apparent excess of neutral energy or "energy crisis"⁵²⁾, which seems to have no natural resolution in the charm scheme. Radiative transitions between charmed mesons (e.g. $D^* \rightarrow D\gamma$) should only emit relatively low energy γ -rays if the mass formulae of Lecture 2 are to be believed. Above charm threshold the quark diagram rules suggest that relatively few "hidden charmed" states should be produced -- so no high-energy γ -rays from that source. Simple estimates with the preferred two-body decay modes (4.14) and (4.15) reveal little tendency for the neutral energy to be much more than the canonical $1/3$. Also, as we said in Lecture 3, charm probably has to go back to the drawing board if R continues to rise above 5 for $\sqrt{q^2} > 5$ GeV.

*) Remember, however, the cautionary footnote on p. 12.

4.2.2 Neutrino production

This is one place that a large production of charmed particles might be expected; the motivation for introducing charm required that their weak couplings be comparable to those of uncharmed particles. Here we will concentrate on deep inelastic experiments. Gaillard, Lee and Rosner²¹⁾ give a discussion of quasi-elastic experiments. Let us recall the main formulae of the quark parton model for deep inelastic scattering. The nucleons are supposed to contain constituents with momentum distributions $p(x)$, $n(x)$, $\bar{\lambda}(x)$, etc., where $x = |q^2|/2\nu$ is the fraction of the nucleons' longitudinal momentum carried by the quark partons p , n , $\bar{\lambda}$, etc. Scattering of leptons off antipartons or antileptons off partons is proportional to $(1-y)^2$, where $y = E_h/E_\nu$, and scattering of leptons off partons or antileptons off antipartons is independent of y . Assuming the Weinberg-Salam model with charm (4.1) and setting $\theta_c = 0$, we get double differential cross-sections off heavy nuclei:

$$\left. \begin{aligned} \frac{d^2\sigma^\nu}{dx dy} &\approx \frac{G_F^2 m_N E_\nu}{\pi} \left[(n+\lambda) + (1-y)^2 (\bar{p}+\bar{c}) \right] \\ \text{and} \quad \frac{d^2\sigma^{\bar{\nu}}}{dx dy} &\approx \frac{G_F^2 m_N E_\nu}{\pi} \left[(\bar{n}+\bar{\lambda}) + (1-y)^2 (p+c) \right] \end{aligned} \right\} \quad (4.17)$$

where we have (optimistically) included a contribution from charmed partons. The constituents are divided into two classes: "valence" partons (p and n for the proton and neutron), which are expected to be copious; and "sea" partons (λ , c , $\bar{p}$, $\bar{n}$, $\bar{\lambda}$, and $\bar{c}$ for the proton and neutron), which are expected to be less important and to cluster around $x \approx 0$. It is expected that $p/\bar{p}$, $n/\bar{n}$, $\lambda/\bar{\lambda}$, and $c/\bar{c} \rightarrow 1$ as $x \rightarrow 0$, and $SU(3)$ or even $SU(4)$ symmetry may be restored there.

We see from equation (4.17) ^{*)} that at high energies

$$\frac{\sigma_{\text{total}}^{\bar{\nu}}}{\sigma_{\text{total}}^{\nu}} \approx \frac{Q/3 + \bar{Q}}{Q + \bar{Q}/3} \quad (4.18)$$

where Q and $\bar{Q}$ are the x integrals of the parton and antiparton distributions.

Experimentally the ratio (4.18) is close to $1/3$, and suggests $\bar{Q}/Q < 10\%$.

Gargamelle data⁴⁸⁾ taken literally would yield $\bar{Q}/Q = 6 \pm 2\%$ and suggest that the antiparton distributions are very small above $x \approx 0.1$.

Presumably the charm degree of freedom is not being excited in the Gargamelle experiments, and the contributions of λ , $\bar{\lambda}$, c , and $\bar{c}$ are negligible at these low energies. Also, in scattering off heavy nuclei with almost equal numbers of neutrons $n \approx p$. Hence for Gargamelle

*) Since $\theta_c \neq 0$, there are contributions $\propto \sin^2 \theta_c \approx 0.05$ to the production of charmed^c particles arising from ν scattering off "valence" n partons or $\bar{\nu}$ scattering off "sea" $\bar{n}$ partons. These may be difficult to see, except that the former may be a source of dimuon events (see the second footnote on page 42).

$$\left. \begin{aligned} \frac{d^2\sigma^{\nu}}{dx dy} &\approx \frac{G_F^2 m_\nu E_\nu}{\pi} [p + (1-y)^2 \bar{p}] \\ \text{and} \quad \frac{d^2\sigma^{\bar{\nu}}}{dx dy} &\approx \frac{G_F^2 m_\nu E_\nu}{\pi} [\bar{p} + (1-y)^2 p] \end{aligned} \right\} \quad (4.19)$$

Hence the Gargamelle data on $\bar{Q}/Q$ suggest

$$\int dx \bar{p}(x) \approx \frac{6}{100} \int dx p(x) \quad (4.20)$$

Now we proceed to FNAL energies. Comparing (4.17) to (4.19) we see that the increases in the cross-sections due to exciting the charm degree of freedom are proportional to

$$\left. \begin{aligned} \lambda(x) + (1-y)^2 \bar{c}(x) &\quad \text{for } \nu \\ \bar{\lambda}(x) + (1-y)^2 c(x) &\quad \text{for } \bar{\nu} \end{aligned} \right\} \quad (4.21)$$

Hence the absolute increases in the ν and $\bar{\nu}$ cross-sections are the same, but the fractional increase in the $\bar{\nu}$ cross-section is almost three times larger, just because $\sigma_{\bar{\nu}}/\sigma_\nu \sim 1/3$ at low energies. If we suppose that SU(3) symmetry is good for "sea" parton distributions, then

$$\lambda(x) = \bar{\lambda}(x) \approx \bar{p}(x) \quad \text{etc.}$$

Let us also assume SU(4) symmetry is badly violated so that $c(x) \ll \lambda(x)$, etc. Then the increases in both the $\bar{\nu}$ and ν cross-sections are essentially independent of y , and

$$\frac{\Delta\sigma^{\bar{\nu}}}{\sigma^{\bar{\nu}}} \approx \frac{\int dx \lambda(x)}{\int dx [\bar{p}(x) + \frac{1}{3} p(x)]} \approx \frac{0.06}{0.39} \approx 0(15\%) \quad (4.22)$$

whereas

$$\frac{\Delta\sigma^{\nu}}{\sigma^{\nu}} \approx \frac{\int dx \bar{\lambda}(x)}{\int dx [p(x) + \frac{1}{3} \bar{p}(x)]} \approx \frac{0.06}{1.02} \approx 0(6\%)$$

What does this increase in the cross-section correspond to? According to the Weinberg-Salam model with $\Theta_C \approx 0$, the charged current interacting with the λ or $\bar{\lambda}$ quark produces a c or $\bar{c}$ quark in the final state, and hence charmed particles in the final state. These particles presumably travel predominantly in the forward direction and have a branching ratio into μ + anything of the order of (1-10)%.

The Harvard-Pennsylvania-Wisconsin-Fermilab group has recently published two papers^{53,54)} on deep inelastic neutrino scattering which claim to see such effects. In one of them⁵³⁾ they find an increase in the inclusive differential $\bar{\nu}$ cross-section $d^2\sigma/\text{d}x\text{d}y$ above $E_{\bar{\nu}} = 30$ GeV which is confined to $x \lesssim 0.1$, essentially independent of y and of the order of 14%. They also say that a similar effect in the ν data of the order of 5% cannot be excluded. It is possible to have questions about cuts on the experimental data and so on, but it may not be coincidental that the theoretical and experimental figures are so similar. There is, however, a problem: at small x the formula (4.17) indicates that the ν and $\bar{\nu}$ cross-sections should be equal, whereas experimentally their ratio seems to be ≈ 2 ⁵⁵⁾.

The other paper⁵⁴⁾ by the same group reports the observation of events of the type

$$\nu \text{ or } \bar{\nu} + \text{nucleus} \rightarrow \mu^+ \mu^- + \text{anything} \quad (4.23)$$

with a partial cross-section of the order of a few parts per thousand. This observation is of the type expected on the basis of charm -- the forward-moving charmed hadron should decay into a lepton of the opposite charge from that of the muon associated with the incoming ν or $\bar{\nu}$. However, it may still be wondered whether the data could be contaminated by the decay products of fast forward-moving pions or kaons. Since the ratio of π^+/π^- in the forward direction in ν scattering is experimentally much greater than 1 (and similarly for π^-/π^+ in $\bar{\nu}$ scattering), this contamination would also produce pairs of muons of opposite signs^{*)}. For the moment we do not regard either of the H-P-W-Fermilab papers as strong evidence for charm -- but they may be indicative^{**)} .

4.2.3 Electroproduction

If the nucleon contains some charmed partons, then they presumably would not contribute to the inclusive electroproduction cross-section at low energies, but would show up later, probably at Fermilab energies. As discussed in Lecture 3, any charmed partons should be lurking at low $x \lesssim 0.1$, and their distribution is probably less than that of uncharmed "sea" partons. If we suppose $c(x)/p(x) \approx r_c$ as $x \rightarrow 0$, then the corresponding fractional rise in the electroproduction cross-section is

$$\frac{\frac{4}{9} (c + \bar{c})}{\frac{4}{9} (p + \bar{p}) + \frac{1}{9} (u + \bar{u} + d + \bar{d})} = \frac{2}{3} r_c \quad (4.24)$$

*) The CERN Theory Boson Workshop¹⁶⁾ estimated the contamination of $(\mu^+ \mu^-)$ pairs due to weak production of the 3.1 : it was very sensitive to the Weinberg angle, but $\leq 10^{-4}$ and hence not significant.

**) In a seminar at CERN, B.Barish has reported the observation of events like (4.23) in the Caltech experiment at Fermilab, at least some of which are very difficult to explain as being due to π or K decays. Some of these have $x \gtrsim 0.1$, and may be due to the mechanism discussed in the footnote on p. 40.

It appears⁴⁷⁾ that in an experiment at Fermilab the deep inelastic muon electro-production scales when 56 GeV and 150 GeV data are compared, but that for $x \leq 0.1$ the cross-section at both energies is $\sim 20\%$ higher than that extrapolated from the SLAC cross-section. There could of course be other explanations for this -- for example, the "non-charmed" part of the cross-section may well not have scaled near $x \approx 0$ at SLAC energies -- but it is not impossible that this increase may reflect charmed particle effects.

4.2.4 Photoproduction

We discussed in Lecture 1 the photoproduction of the 3.1 state, and how this corresponded to a total cross-section $\sigma_{\text{tot}}(3.1 N) \approx 1$ mb. In Lecture 2 a model was suggested according to which this cross-section would correspond to the "conventional" dual Pomeron graph of Fig. 15, in which it is apparent from cutting down the dotted line that this cross-section comes mainly from the production of charmed particles in the intermediate state^{*)}. If we now make the usual model in which

$$\sigma_{\text{total}}(\gamma N) = \sum_{\substack{\text{vector} \\ \text{mesons } V}} \frac{|\langle \gamma | V \rangle|^2}{m_V^4} \sigma_{\text{total}}(VN) \quad (4.25)$$

then the contribution of $\phi_c = 3.1$ to this total is approximately

$$\frac{\sigma_{\text{total}}(\phi_c N)}{\frac{4}{3} \sigma_{\text{total}}(pN)} \times \frac{1/\delta_{\phi_c}^2}{1/\delta_p^2} \approx \left(\frac{4}{3} \times 20\right)^{-1} \times \frac{2}{9} \approx 1/120 \quad (4.26)$$

Hence $O(1 \mu\text{b})$ of the asymptotic photoproduction cross-section could be due to charmed particles. A similar estimate gives a fraction of about $1/12$ for associated production of strange particles, which seems to be consistent with experiment⁵⁶⁾.

4.2.5 Hadronic collisions

The first task is to estimate the total inclusive cross-section for the production of charmed particles. The inclusive charged π cross-section is $O(300)$ mb at ISR energies (recall that each inelastic event produces of the order of 10 charged pions): the charged kaon inclusive cross-section is one or two orders of magnitude less, and in qualitative agreement with the prediction of the thermodynamical model that the production rate of a particle of mass m is proportional to $e^{-m/T}$ with $T \approx m_\pi$. This model also predicts a p_T distribution at high energies

*) This model for the Pomeron is probably hopelessly naïve; at infinite energies charmed particle yields in γN and πN collisions should be similar. But also in multiperipheral models one would expect $\sigma(\gamma N \rightarrow 3.1 N)$ to be the shadow of charmed particle production in the photon fragmentation region, and the bulk of $\sigma_{\text{tot}}(3.1 N)$ to contain charmed particles.

of the form $e^{-p_T/T}$, which is known to be valid for $p_T \lesssim 1$ GeV, but to break down for $p_T > 1$ GeV, and is probably replaced by some sort of power law. Let us assume without justification that the thermodynamical predictions for large p_T and heavy mass production are violated in the same way. We then get

$$\frac{\sigma_{\text{inclusive}}(m)}{\sigma_{\text{inclusive}}(\pi)} \approx \frac{\sigma_{\text{inclusive}}^{\pi}(p_T)}{\sigma_{\text{inclusive}}^{\pi}(p_T=0)} \quad (4.27)$$

In the case of charm it is unclear whether we should take $p_T = m_D$ or $2m_D$ on the right-hand side because charmed particles have to be produced in pairs.

However, the cross-section for $p + p \rightarrow 3.1 + \text{anything}$ seen at Fermilab seems to be $0(1/10)$ μb corresponding to choosing $p_T \approx 3$ in the formula (4.27), even though according to Lecture 2 (see Fig. 13) the majority of the final states in 3.1 production should also contain charmed-anticharmed particle pairs. Hence $0(1/10)$ μb should be a lower bound on the charmed particle cross-section. Taking (4.27) with $p_T \approx m_D \approx 2$ GeV and using ISR inclusive data⁵⁷⁾ on large p_T phenomena we get

$$\frac{\sigma_{\text{inclusive}}(m=2)}{\sigma_{\text{inclusive}}(\pi)} \approx 10^{-4\frac{1}{2}} \quad (4.28)$$

corresponding to

$$\sigma_{\text{inclusive}}(m=2) \approx 10 \mu\text{b} \quad (4.29)$$

This may well be an overestimate, but charmed particle cross-sections of $0(1)$ μb in hadronic collisions seem not impossible.

What are the prospects of enhancing the proportion of charmed particle events by using a selective trigger on the multiparticle events? One way would be to trigger on a 3.1 particle, as mentioned above. A second possibility²¹⁾ is to look for events with a μ or e coming from the decay of one charmed particle and a K coming from the decay of the other one. However, if the preferred decay modes of charmed particles are multibody with a K/π ratio $\approx 1/4$, these events may not be very distinctive. Another possibility²¹⁾ is to look for $(\mu - e)$ coincidences generated by leptonic decays of both the charmed particles. This may also be difficult if the leptonic branching ratio is only $0(1)\%$. A better chance may come from looking at large p_T events. The cross-section there is very low, but the D/π ratio may be $0(1)$, as is known to be the case for the K/π ratio.

There are already indications that new things are happening at large p_T : the inclusive electron and muon distributions at large p_T have $e/\pi \approx \mu/\pi \approx 10^{-4}$ ⁵⁸⁾. Is it possible they could come from the decays of charmed particles? If we use⁵⁹⁾ the formula

$$E \frac{d\sigma}{d^3p} \propto (m^2 + p_T^2)^{-4} \quad (4.30)$$

which is qualitatively valid for familiar hadrons in the central region then the decays $D \rightarrow K\ell\nu$ *) give

$$\left(\frac{\ell}{\pi}\right) \approx B \left(\frac{D}{\pi}\right) \left(\frac{1}{300} \leftrightarrow \frac{1}{120}\right) \quad (4.31)$$

where B is the branching ratio. With $(D/\pi) = O(1)$ and $B \sim \text{few } \%$, the formula (4.31) can just succeed in reproducing the observed lepton spectrum. *A priori*, there are other possible sources. For example, the decays $3.1 \rightarrow \ell^+\ell^-$ give

$$\left(\frac{\ell}{\pi}\right) \approx B \left(\frac{3.1}{\pi}\right) \left(\frac{1}{10} \leftrightarrow \frac{1}{6}\right)$$

In this case B is known to be 7×10^{-2} , so that a ratio $(3.1/\pi) \sim O(1)\%$ would suffice to give the lepton spectrum. With the assumed p_T distribution (4.30) there is no problem with a peak in the p_T distribution of the produced leptons. However, if the 3.1 were the source of the leptons, the ISR-CCRS group believe they should have seen more (e^+e^-) pairs in their experiment. Furthermore, the familiar ϕ cannot be the source of the large (ℓ/π) ratio as data on $(K\bar{K})$ pairs at large p_T indicate that $(\phi/\pi) \leq 20\%$.

Hence it seems that at the moment no possible source of high p_T leptons is known which is less implausible than charmed particles.

4.3 Conclusions

We have seen how the new narrow resonances and other structures observed in $e^+e^- \rightarrow \text{hadrons}$ could be understood in terms of charm. We have also discussed the properties of charmed particles, how they should decay, and how they should be produced in various different reactions. As was remarked in the introduction, the author's prejudice is that some form of "charm" is the least unreasonable model for the new resonances and other phenomena. However, it is not at all obvious that the conventional SU(4) charm model is the right one, and it has various experimental problems, such as:

*) $D_{\ell 2}$ and $F_{\ell 2}$ decays should have too small a branching ratio to be relevant, and would not produce electrons.

Why have no charmed particles yet been seen at SPEAR or DORIS? If they have a large two-body branching rate, why are they not seen in mass plots, and why does the ratio of strange particle production not increase very much? If their dominant decay modes are multibody, why does $\langle n_{ch} \rangle$ not rise abruptly at $\sqrt{q^2} = 4$ GeV? What about the "energy crisis"? What happens to R for $\sqrt{q^2} > 5$ GeV?

Is charm really consistent with the Fermilab deep inelastic neutrino production data? The ν and $\bar{\nu}$ cross-sections at small x seem unequal, contrary to simple charmed parton model expectations from Eq. (4.21), and this is related to an apparent charge symmetry violation⁶⁰⁾. One may also wonder whether charmed particles would give quite so many dimuon events, particularly at x not near 0 as reported by the Caltech Group at Fermilab.

The experimental indications discussed above have all been indirectly related to the possible existence of charmed particles. Now there are some more direct experimental claims⁶¹⁾ for their existence. Only time will tell whether these swallows will turn into a summer.

REFERENCES AND FOOTNOTES

- 1) J.J. Aubert et al., Phys. Rev. Letters 33, 1404 (1974);,
and preprint submitted to Nuclear Phys. B.
- 2) J.-E. Augustin et al., Phys. Rev. Letters 33, 1406 (1974).
- 3) C. Bacci et al., Phys. Rev. Letters 33, 1408 (1974).
- 4) G.S. Abrams et al., Phys. Rev. Letters 33, 1453 (1974).
- 5) L. Criegee et al., Phys. Letters 53B, 480 (1975).
- 6) J.-E. Augustin et al., SLAC-PUB-1520 (1975).
- 7) This and much other information is derived from seminars at CERN, reports of seminars at SLAC, letters to Israel from H. Harari, newspaper reports and rumours. The most complete written source so far seems to be:
F.J. Gilman, SLAC-PUB-1537-Talk presented at Coral Gables (1975).
- 8) W. Braunschweig et al., Phys. Letters 53B, 491 (1975).
R.L. Ford et al., Stanford University preprint HEPL 748 (1975).
- 9) J.J. Aubert et al., Phys. Rev. Letters 33, 1624 (1974).
- 10) L.M. Lederman, unpublished note of 11.30 a.m., 6 December, 1974
- 11) B. Knapp et al., Photoproduction of narrow resonances, Fermilab preprint (1975).
- 12) D.E. Andrews et al., Phys. Rev. Letters 34, 233 (1975).
- 13) J.F. Martin et al., Phys. Rev. Letters 34, 288 (1975).
- 14) B. Knapp et al., Dimuon production by neutrons, Fermilab preprint (1975).
- 15) Rumour confirmed by F.J. Gilman, Ref. 7.
- 16) For reviews see: H. Harari, SLAC-PUB-1514 (1974);
CERN Theory Boson Workshop, CERN TH 1964 (1974);
I. Bars et al., SLAC-PUB-1522 (1974);
J.D. Jackson, unpublished notes.
Similar studies have been made by many other individuals and groups. My apologies to everyone not referred to, but it is impossible to be fair and complete.
- 17) R.E. Marshak and R.N. Mohapatra, Phys. Rev. Letters 34, 426 (1975).
- 18) Seminar at CERN by C. Rubbia, December 1974.
- 19) M.Y. Han and Y. Nambu, Phys. Rev. B 139, 1006 (1965).
Y. Nambu and M.Y. Han, Phys. Rev. D 10, 674 (1974).
- 20) T. Tati, Progr. Theor. Phys. 35, 973 (1966).
- 21) For a review and references see, M.K. Gaillard, B.W. Lee and J.L. Rosner, Fermilab preprint 74/86-THY (1974).
- 22) See many papers: for example, I. Bars and R.D. Peccei, Stanford University preprint ITP-484 (1975).
I thank David Broadhurst and Roger Cashmore for talking and writing to me about colour.
- 23) We will return to this point in later lectures.
- 24) J. Ellis, CERN TH 1880 (1974); also Ref. 16.
- 25) Many calculations of this have been made. It could, however, be either a virtual bound state just below threshold, or a very impure ($c\bar{c}$) state decaying into ordinary hadrons.
- 26) The origin of these is lost in the mists of time.

- 27) M. Gell-Mann, R.J. Oakes and B. Renner, Phys. Rev. 175, 2195 (1968).
- 28) R.J. Crewther, Phys. Rev. Letters 28, 1421 (1972).
M.S. Chanowitz and J. Ellis, Phys. Letters 40B, 387 (1972), and Phys. Rev. D 7, 2490 (1973).
- 29) S. Orito et al., Phys. Letters 48B, 380 (1974).
- 30) T. Appelquist and H.D. Politzer, Phys. Rev. Letters 34, 43 (1975).
R.J. Harrington, S.Y. Park and A. Yildiz, Phys. Rev. Letters 34, 168 (1975).
- 31) E. Eichten et al., Phys. Rev. Letters 34, 369 (1975).
- 32) T. Appelquist, A. Rujula, H.D. Politzer and S.L. Glashow, Phys. Rev. Letters 34, 365 (1975).
- 33) Similar ideas have been discussed by: S. Kitakado, S. Orito and T.F. Walsh, DESY preprint 74/54 (1974).
C. Montonen, M. Roos and N. Törnquist, Helsinki preprint 30-74 (1974).
and by M. Gourdin, G. Preparata and others.
- 34) R. Carlitz, M.B. Green and A. Zee, Phys. Rev. Letters 26, 1515 (1971) and Phys. Rev. D 4, 3439 (1971).
For the recent application, see, for example, R.C. Brower and J. Primack, U.C. Santa Cruz preprint 74/103 (1974) and
C.E. Carlson and P.G.O. Freund, Enrico Fermi Institute preprint 74/60 (1974).
- 35) A. Litke et al., Phys. Rev. Letters 30, 1189 (1973).
G. Tarnopolsky et al., Phys. Rev. Letters 32, 432 (1974).
- 36) B. Richter, Proc. 17th Internat. Conf. on High-Energy Physics, London, 1974 (Rutherford Laboratory, UK, 1974) p. IV-37;
J.-E. Augustin et al., Ref. 6.
- 37) See, for example, the results quoted by F.J. Gilman, Ref. 7, from a talk by G. Salvini.
- 38) References can be traced from M.A. González and J.H. Weis, Phys. Letters 49B, 351 (1974).
- 39) M.S. Chanowitz and S.D. Drell, Phys. Rev. Letters 30, 807 (1973) and Phys. Rev. D 9, 2078 (1974).
M. Pavković, Phys. Letters 46B, 435 (1973).
G.B. West and P. Zerwas, SLAC-PUB-1420 (1974).
- 40) J. Kogut, Cornell preprint CLNS-219 (1974).
- 41) See, for example, J. Engels, K. Schilling and H. Satz, Nuovo Cimento 17A, 535 (1973).
- 42) See, for example, F. Cooper, G. Frye and E. Schonberg, Phys. Rev. Letters 32, 862 (1974), and references therein.
- 43) J. Erwin et al., Phys. Rev. Letters 27, 1534 (1971).
- 44) See, for example, C.H. Llewellyn Smith and D.V. Nanopoulos, Nuclear Phys. B878, 205 (1974).
- 45) T. Goldman and P. Vinciarelli, Phys. Rev. Letters 33, 246 (1974).
- 46) J.C. Pati and A. Salam, ICTP preprint IC/74/81 (1974), and references therein.
- 47) D.J. Fox et al., Phys. Rev. Letters 33, 1504 (1974).
K.W. Chen, talk given at the Fermilab Muon Physics Workshop, January 1975.
- 48) S. Weinberg, Phys. Rev. Letters 19, 1264 (1967).
A. Salam, Proc. 8th Nobel Symposium, Stockholm, 1968 (Amquist and Wiksell, Stockholm, 1968), p. 367.
- 49) See, for example, H. Georgi and S.L. Glashow, Phys. Rev. Letters 32, 438 (1974).

- 50) R.L. Kingsley, S.B. Treiman, F. Wilczek and A. Zee, Weak decays of charmed hadrons, Princeton University preprint (1975).
- 51) G. Altarelli, N. Cabibbo and L. Maiani, Ecole Normale Supérieure preprint PTENS 74/5 (1974).
- 52) C.H. Llewellyn Smith, talk given at the 9th Rencontre de Moriond, CERN TH 1849 (1974).
- 53) A. Benvenuti et al., Invariant mass distributions as evidence for new particle production by high-energy antineutrinos, Fermilab preprint (1975).
- 54) A. Benvenuti et al., Phys. Rev. Letters 34, 419 (1975).
- 55) V. Barger, T. Weiler and R.J.N. Phillips, Wisconsin preprint COO-881-441 (1975).
- 56) H. Meyer, Proc. 6th Internat. Symposium on Electron and Photon Interactions at High Energies, Bonn, 1973 (eds. H. Rollnik and W. Pfeil) (North-Holland Publ. Co., Amsterdam, 1974), p. 175.
- 57) M. Frisch, Proc. 17th Internat. Conf. on High-Energy Physics, London 1974 (Rutherford Laboratory, UK, 1974), p. V-8.
- 58) Ibid., p. V-41.
- 59) J.M. Gaillard, M.K. Gaillard and R. Savit, private communication.
- 60) B. Aubert et al., Phys. Rev. Letters 33, 984 (1974).
- 61) K. Nu , E. Mikumo and Y. Maeda, Prog. Theor. Phys. 46, 1644 (1971);
K. Hoshino et al., Nagoya Univ. preprint DPNU-3 (1975);
E.G. Cazzoli et al., BNL preprint NG-308 (1975).

Figure captions

- Fig. 1 : Coupling of 3.1 to hadrons via the photon.
- Fig. 2 : Direct coupling of 3.1 to hadrons.
- Fig. 3 : Diffractive diagram supposed responsible for the photoproduction of the 3.1.
- Fig. 4 : Disallowed quark diagram for $\phi \rightarrow 3\pi$ decay.
- Fig. 5 : The Han-Nambu colour scheme. Marked on the figure are the quark charges and the colours (Red, Yellow and Blue) of primary coloured quarks.
- Fig. 6 : Disallowed quark diagram for $3.7 \rightarrow 3.1 \pi\pi$ decay. In the colour scheme III $q = \lambda$; in the charm scheme $q = c$.
- Fig. 7 : Quantum number diagram for the conventional charm scheme. The numbers are the quark charges.
- Fig. 8 : Quantum number diagram for the pseudoscalar mesons in the usual charm scheme. Similar 16-plets are expected for mesons with other spin parities. The $I = 0$, $Y = 0$, $C = 0$ states can in general mix strongly.
- Fig. 9 : The "charmonium" picture for (a) the hadronic decays, (b) the photonic coupling of the 3.1 state, and (c) the hadronic decays of η_c "paracharmonium".
- Fig. 10 : (a) The single-loop diagram allowed for $\phi_c \rightarrow K^+ K^-$ decay.
(b) The same diagram twisted.
- Fig. 11 : The single-loop diagram after a duality transformation.
- Fig. 12 : Diagrams expected to give vector meson mixing (a) in a quark gluon picture, (b) in a phenomenological hadronic approach.
- Fig. 13 : Typical (a) disallowed and (b) allowed quark diagrams for ϕ_c production in nucleon-nucleon collisions.
- Fig. 14 : The diagrams (a) for $\phi_c \rightarrow X\gamma$, (b) for $\phi'_c \rightarrow \phi_c \varepsilon$ decay, including mass mixing for the pseudoscalar X and the scalar ε .
- Fig. 15 : (a) A dual Pomeron contribution to $\phi_c p$ scattering.
(b) The same diagram after a double duality transformation.
- Fig. 16 : (a) The simple parton model for $\sigma_{\text{tot}}(e^+ e^- \rightarrow \gamma \rightarrow \text{hadrons})$.
(b) Modifications to this model found in renormalization group models including asymptotic freedom.

- Fig. 17 : The parton model for the final state in e^+e^- annihilation.
- Fig. 18 : Heavy lepton pair production via one-photon exchange where (a) both happen to decay semileptonically, (b) both happen to decay purely leptonically.
- Fig. 19 : The two-photon mechanism for producing hadrons.
- Fig. 20 : Comparison of the data on
- $$R = \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$
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- Fig. 21 : A simple dual current model. For e^+e^- annihilation we calculate graphs like this with no external hadrons.
- Fig. 22 : No-photon models for $e^+e^- \rightarrow \text{hadrons}$.
- Fig. 23 : Diagrams for (a) inclusive semileptonic decays, (b) inclusive non-leptonic decays of charmed mesons.

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