The ψ-resonances

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THE ψ-RESONANCES

by

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PREFACE

The work presented in this thesis was carried out in the Department of Mathematics, University of Durham, under the supervision of Professor E.J. Squires. The author expresses her highest appreciation and sincere gratitude to Professor Squires for continuous guidance, encouragement and help.

CONTENTS

ABSTRACT

The main idea of this thesis is to review the ψ- resonances. The past two years since the discovery of ψ- particles at SPEAR and BNL have been the most exhilarating of particle physics in many years. In the following pages we try to summarize the great amount of information which has been gathered in this short period.

In Chapter one, we summarize the experimental data about the ψ- particles, i.e. their masses, lifetimes and decay modes. We have also presented a summary of the known spectrum of the ψ- family.

In Chapter two, we review briefly SU(3) group and quark model. Then we discuss the need for the extension of SU(3) group to SU(4), and finally we consider the classification of elementary particles in SU(4) group and the introduction of charmed particles.

In Chapter three, the idea of interpretation of ψ- particles as bound states of charmed quarks and antiquarks ($c\bar{c}$) has been presented.

In Chapter four, some other interpretations, which have been advanced for the new resonances, are discussed. Two sections are devoted to the phenomenology of ψ- particles in Han-Nambu colour scheme and in Harari's model and some other models such as the weak boson interpretation and the Iwasaki's model are discussed briefly in this chapter.

CHAPTER ONE

EXPERIMENTAL OBSERVATION OF ψ-PARTICLES

This Chapter involves the experimental data about the ψ-particles. In section (1.1) the quantum numbers and decay modes of $\psi(3.1)$ will be discussed. Section (1.2) is devoted to the properties of $\psi'(3.7)$. In section (1.3) the structure in the vicinity of 4.1 will be discussed, and finally in section (1.4) the observed particles related to the ψ family will be considered.

1.1 - Experimental Observation of $\psi(3.1)$ -

In November 1974, Aubert et al,[1] reported the observation of a heavy particle (which they called J), with mass M=3.1 Gev. and width approximately zero in the reaction

$$p + Be \longrightarrow e^+ e^- + \text{anything}$$

The experiment was performed at the Brookhaven National Laboratory 30 Gev. alternating gradient synchrotron. In independent experiments at the same time, a SLAC-LBL[2] group has observed sharp resonant peaks around 3.1 Gev. (they suggested naming this structure $\psi(3.1)$ and we shall use this notation from now on) in the colliding beam processes:

$$e^+ e^- \longrightarrow \text{hadrons}$$
$$e^+ e^- \longrightarrow \mu^+ \mu^- \text{ and } e^+ e^-$$

at SPEAR. The observation of this resonance was also confirmed by DESY people[3] later on. Mass spectrum showing the existence of ψ as reported by Aubert et al is shown in Fig (1). Fig (2a) shows the cross section for reaction $e^+ e^- \rightarrow \psi \rightarrow$ hadrons as measured at SPEAR and Fig (2b) and (2c) show the cross section for $e^+ + e^- \longrightarrow \mu^+ \mu^-$ and $e^+ e^-$ respectively, versus energy in the angular range $|\cos\theta| < 0.6$, where θ is the angle between the outgoing positive lepton and the incident positron. The mass of ψ as determined at the various laboratories is summarized in

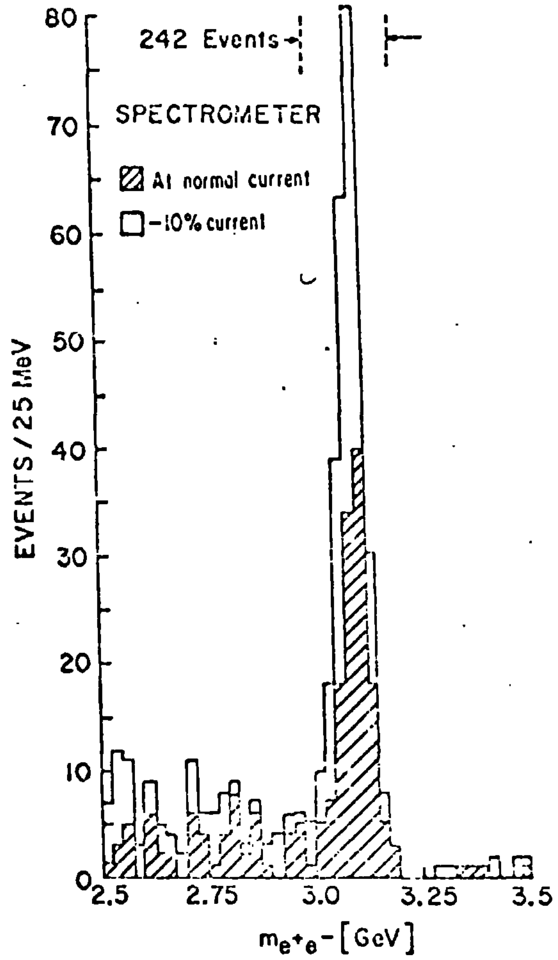


Fig. 1-Mass spectrum showing the existence of ψ. Results from two spectrumeter settings are plotted showing that the peak is independent of spectrometer currents.

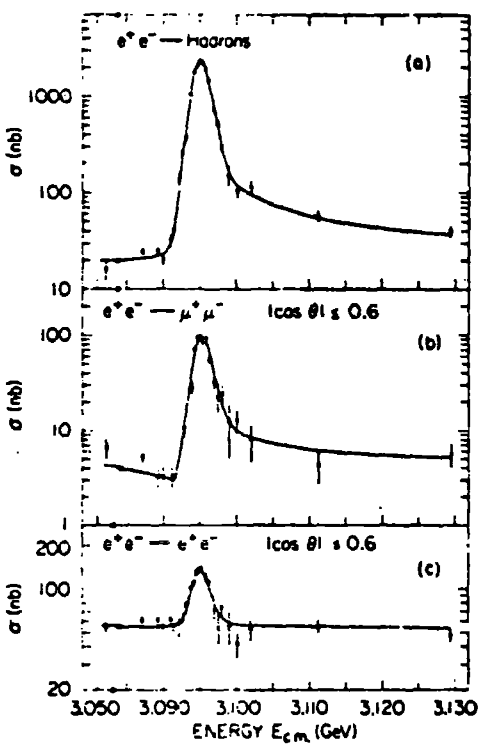


Fig .2 Cross sections in the region of the ψ

table 1. The total area under the resonance (the integrated cross-section), which is the only parameter that does not depend on the machine resolution and it is also related to the partial widths as will be seen later, is defined as:

$$\Sigma = \int \sigma(E)\, dE$$

where σ is the resonant cross-section. This integrated cross section for the ψ after corrections for the effect of initial state radiation (these are the effects caused by the emission of a photon by the incident e^+ or e^-) as measured at SPEAR is :

$$\Sigma_\psi = \int \sigma_\psi(E)\, dE = 10400 \pm 1500 \ \text{nb}\cdot\text{Mev} \qquad (1)$$

Results from ADONE[4] for Σ_ψ are about 30% lower than (1):

$$\int_{3097}^{3111} \sigma(E)\, dE = 6.7 \pm 2.4 \ \text{nb}\cdot\text{Gev}$$

LABORATORY	MASS (Mev)
SLAC (SPEAR)[2]	3095 ± 4
DESY (DORIS)[3]	3090 ± 31
FRASCATI (ADONE)[4]	3100 (error not given)

Table (1) - Mass of ψ - particle.

Total and Leptonic Width of the ψ -

The data of Fig 2 are used to determine the mass M, and the partial widths Γ_{ee} , $\Gamma_{\mu\mu}$, and Γ_h to electrons, muons, and hadrons respectively. Assuming that the total width is $\Gamma = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_h$ and using a Breit - Wigner shape for the ψ , then the cross-section for the reaction $e^+ e^- \rightarrow \psi \rightarrow f$ can be described by the Breit - Wigner formula:

$$\sigma_{\psi,f} = \frac{\pi(2J+1)}{s} \cdot \frac{4M^2\Gamma_{ee}\Gamma_f}{(s-M^2)^2 + M^2\Gamma^2} \qquad (2)$$

where Γ_f is the partial width to the channel f, and J is the spin of ψ. We know from the properties of the ψ that Γ is very small in comparison to M, so we can expand equation (2) in $\sqrt{s} - M = E - M$ to obtain;

$$\sigma_{\psi,f} = \frac{\pi(2J+1)}{M^2} \frac{\Gamma_{ee}\Gamma_f}{(E-M)^2+\Gamma^2/4} \qquad (3)$$

In order to obtain a simple relation between the partial width and the observed cross section we integrate over energy;

$$\Sigma_{\psi,f} = \int \sigma_{\psi,f}(E)dE = \frac{2\pi^2(2J+1)}{M^2} \frac{\Gamma_{ee}\Gamma_f}{\Gamma} \qquad (4)$$

Using $J = 1$, which will be discussed in the quantum numbers of ψ, we can obtain:

$$\Gamma_{ee} = \frac{M^2}{6\pi^2}\Sigma_{\psi,all}$$

and

$$\Gamma = \frac{\Sigma_{\psi,all}}{\Sigma_{\psi,ee}}\Gamma_{ee}$$

Such relations are used to determined the ψ widths, the results as determined at SPEAR[(5)] are shown in table 2. Γ_{ee} and $\Gamma_{\mu\mu}$ are in good agreement, as expected from μ - e Universality, and the width of the ψ about 70 Kev is about a factor of a thousand smaller than the width one might expect for a normal hadron resonance of this mass and this is what makes this particle so remarkable.

Γ_{ee}	4.8 ± 0.6 Kev
$\Gamma_{\mu\mu}$	4.8 ± 0.6 "
Γ_{had}	59 ± 14 "
Γ	69 ± 15 "
Γ_{ee}/Γ	0.069 ± 0.009
Γ_{had}/Γ	0.86 ± 0.02
$\Gamma_{\mu\mu}/\Gamma_{ee}$	1.00 ± 0.05

Table (2) - widths and branching ratios of the ψ.

Quantum Numbers of the ψ -

If we accept the traditional belief that the electron has only electromagnetic and weak interactions, the only known particle which can couple to $e^+ e^-$ system is the photon. And since ψ is produced in $e^+ e^-$ annihilation, our first guess is that, it is presumably a vector state which couple to $e^+ e^-$ pairs through a virtual photon intermediate state and so it has the same quantum numbers as the photon $J^{PC} = 1^{--}$.

The determination of the quantum numbers J^{PC} for ψ is made by a study of interference between resonance and quantum electrodynamic (QED) amplitudes and by examination of angular distribution of leptons for ψ decays. Interference is most easily studied in the $\mu^+\mu^-$ channel because a resonant amplitude sharing the quantum numbers of the photon should show strong interference with the known S-channel QED amplitude, while the interference in the $e^+ e^- \longrightarrow e^+ e^-$ is much smaller than the μ - channel. So we consider the interference between two reactions:

$$e^+ e^- \longrightarrow \mu^+\mu^- \qquad (5)$$

and

$$e^+ e^- \longrightarrow \psi \longrightarrow \mu^+\mu^- \qquad (6)$$

The amplitude for reaction (5) is:

$$A(e^+e^- \longrightarrow \mu^+\mu^-) = \left(\frac{3\pi}{E^2}\right)^{1/2} \left(-\frac{2}{3}\alpha\right)$$

and the amplitude for reaction (6) is described by a simple Breit-Wigner formula:

$$A(e^+e^- \longrightarrow \psi \longrightarrow \mu^+\mu^-) = \left(\frac{(2J+1)\pi}{E^2}\right)^{1/2} \frac{\Gamma_{ee}}{M-E-i\Gamma/2} \qquad (7)$$

Assuming $J = 1$ for the ψ, cross-section will have the following form:

$$\frac{d\sigma}{d\theta} = \frac{9\pi}{8E^2}\left(1+\cos^2\theta\right)\left|-\frac{2}{3}\alpha + \frac{\Gamma_{ee}}{M-E-i\Gamma/2}\right|^2 \qquad (8)$$

Fig (3) shows the sum of the amplitudes which contribute into eq.(8). The ratio of $\mu^+\mu^-$ to $e^+ e^-$ yields is used to exhibite interference effects. This ratio for the detected angular range $|\cos\theta| < 0.6$ is shown in Fig (4) and also the curves representing no interference, i.e. $J = 0$, and maximum interference, i.e., a pure $J^{PC} = 1^{--}$ state are shown. The data agree with maximum interference prediction. The angular distribution of e pair and μ pairs are shown in Fig (5). The muon pairs and electron pairs after subtraction of the QED

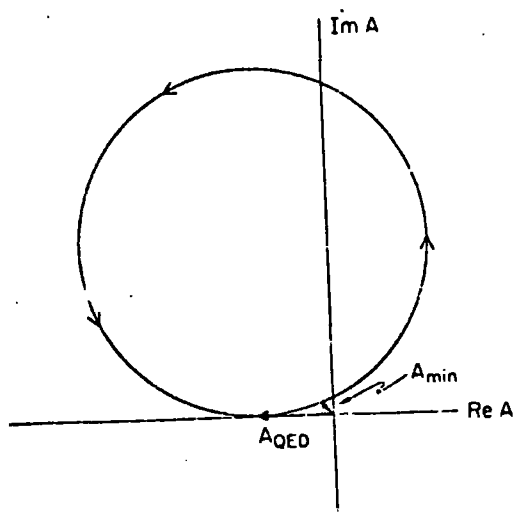


Fig 3- Schematic drawing of the amplitude for production of μ pairs in the ψ region, assuming ψ has the same quantum numbers as the photon. A_{QED} is the amplitude for direct production of μ pairs far below and far above the resonant energy. A_{min} is the amplitude at the point of maximum distructive interference below the resonant energy.

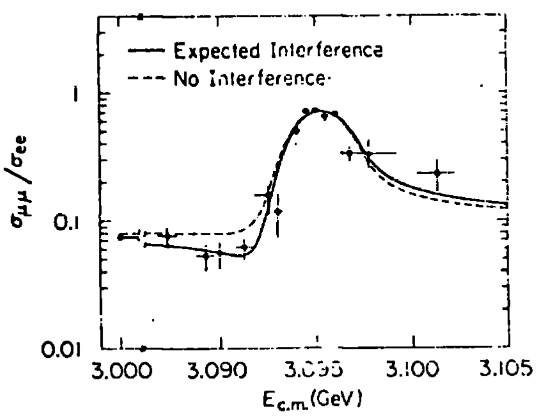


Fig 4 - The ratio of μ pair yield to e pair yield in the region for the ψ for $|\cos\theta| \leq 0.6$. The dashed line gives the expected ratio for no interference while the solid line gives the expected ratio for full interference.

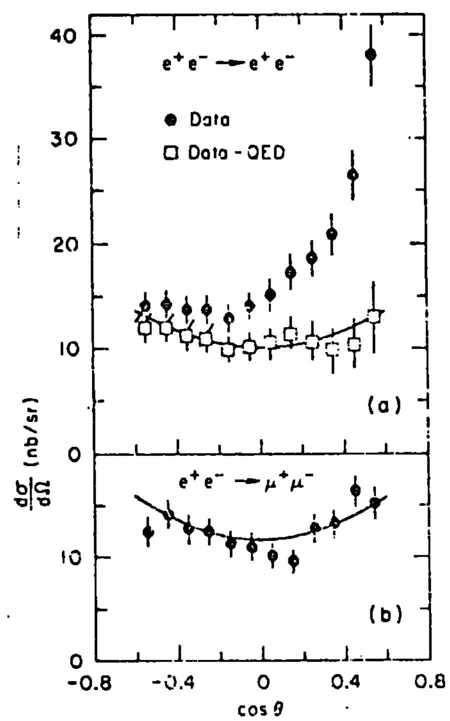


Fig 5 - a) The angular distribution of electron pairs for the energy range 3.0944 to 3.0956 Gev. The open squares show the result of subtracting the expected contribution from the direct production and scattering of elrctron pairs.

b) The angular distribution of muon pairs for the same energy region. The lines represent $1+\cos^2\theta$.

distributions are consistent with the angular distributions $(1 + \cos^2\theta)$ expected for a simple 1^{--} state. This is sufficient to confirm the $J^{PC} = 1^{--}$ assignment for the ψ.

Hadronic Decays of $\psi(3.1)$ -

The isospin of ψ can be determined by observing whether it decays into even or odd numbers of pions. Assuming one photon exchange leads to restrictions on the final state as follows:

a- Since parity is conserved in electromagnetic interactions, the final state parity should be P= -1.

b- Since photon couples only to I = o or I = 1 state, the final state isotopic spin can be zero or 1.

c- The final state charge conjugation number is -1.

d- When the final state contains only pions, using $G = C\,(-1)^I$ and C = -1 leads to two important results; firstly odd number of pions for I = o, and secondly even number of pions for I = 1. These restrictions together with the fact that ψ decays into both even and odd number of pions lead to a violation of isospin.

The direct decay of ψ into hadrons is shown graphically in Fig (6a), while Fig (6b) shows its decay into hadrons via an intermediate photon, and Fig (6c) shows the decay of ψ into muon pairs. In Fig (6b), the final state should be the same as the non-resonant final state produced in $e^+ e^-$ annihilation at the same energy and need not conserve isospin and can be different from the states produced in Fig (6a). We can determine the contribution of (6b) in the total width, because the ratio between (b) and (c) must be the same as it would be if the ψ was not present in the diagram, i.e., about:

$$R = \frac{\sigma_{had}}{\sigma_{\mu^+\mu^-}} \sim 2.5$$

So using the data in table (2), $\frac{\Gamma_{\mu^+\mu^-}}{\Gamma} \sim 0.07$

then $\frac{\Gamma_b}{\Gamma} \sim 0.07 \times R \sim 0.18$

and using $\Gamma = \Gamma_a + \Gamma_b + \Gamma_{\mu\mu} + \Gamma_{ee}$

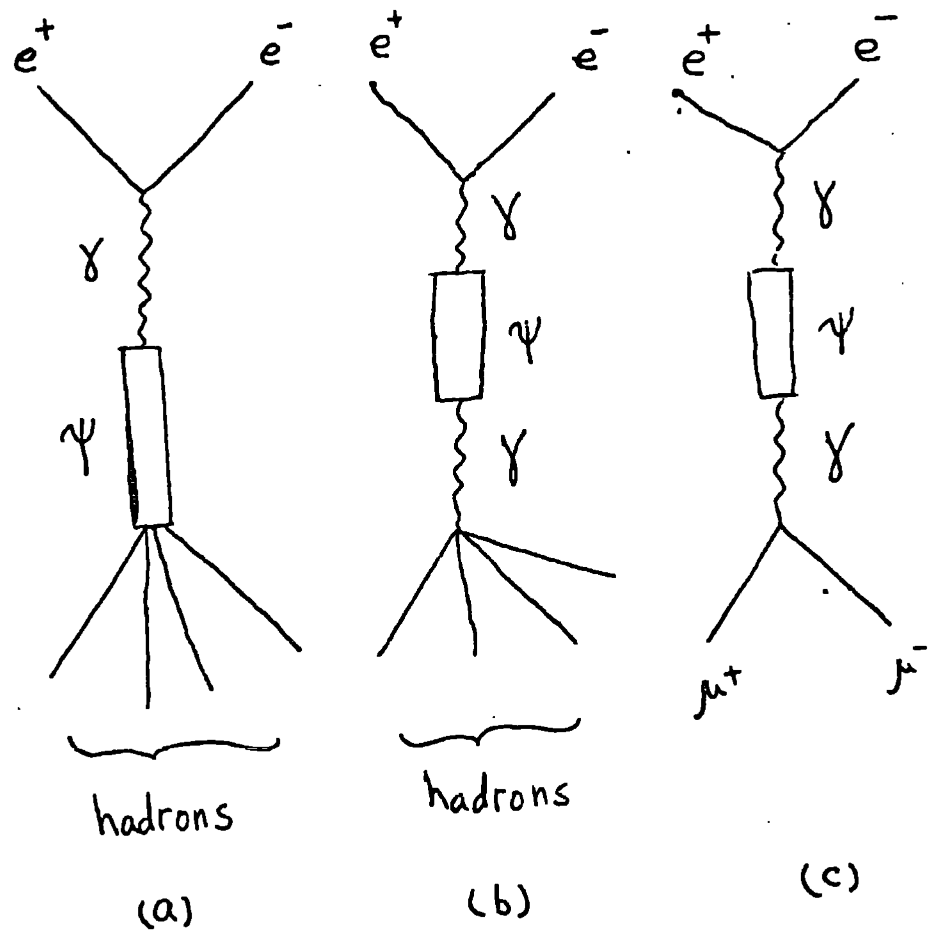


Fig 6- Feynman diagrams for (a) the direct ψ decay to hadrons, (b) the ψ decay to hadrons via an intermediate photon , and (c) the ψ decay to μ pairs.

we deduce $\frac{\Gamma_a}{\Gamma} \sim 0.68$

Thus we conclude that if ψ couples to photon, (a) contributes 68%, and (b) 18% and the leptonic modes 14% to the width of the ψ.

To test this hypothesis, the comparison of the ratio of all pion state cross sections to muon pair cross sections on and off resonance are shown in table (3), where the data at 3.0 Gev are used as off-resonance sample. The result is that all of the even number of pion production (G even, I odd) are due to the intermediate photon decay (Fig 6b), while most of the odd pion production comes from the direct ψ decay (Fig 6a), and it seems that ψ decays directly into a pure $I^G = o^-$ state.

Fig (7) shows the invariant mass squared recoiling against four charged pions at 3.0 Gev and the ψ. The difference between the two case is quite remarkable, at 3.0 Gev no structure can be seen, while at the ψ, a π^c peak is visible.

Various decay modes of the ψ which have been identified or searched for in the SLAC - LBL[6] magnetic detector with the relative branching ratios are shown in table 4.

1.2 - Experimental observation of $\psi'(3.7)$ -

The discovery of $\psi(3.1)$, the very narrow resonant state coupled to leptons and hadrons, raised the question of the existence of other narrow resonances also coupled to leptons and hadrons. Therefore a systematic search began and within 10 days of the discovery of ψ, the SLAC - LBL group at SPEAR[7] found another resonance in the process $e^+ e^- \longrightarrow$ hadrons (we shall refer to this resonance as ψ'). The mass of ψ' as determined at SPEAR and DORIS is shown in table (5), and Fig (8) shows the total cross-section for the reaction:

$$e^+ e^- \longrightarrow \psi' \longrightarrow \text{hadrons}$$

State	$\dfrac{\sigma^{\psi}_{n\pi}}{\sigma^{\psi}_{\mu\mu}} \Big/ \dfrac{\sigma^{3.0}_{n\pi}}{\sigma^{3.0}_{\mu\mu}}$
$2\pi^+ 2\pi^-$	0.82 ± 0.22
$2\pi^+ 2\pi^- \pi^0$	> 5.2
$3\pi^+ 3\pi^-$	1.10 ± 0.54
$3\pi^+ 3\pi^- \pi^0$	> 4.5

Table 3 -comparison of all pion state production to μ pair production at 3.0 Gev and the ψ.

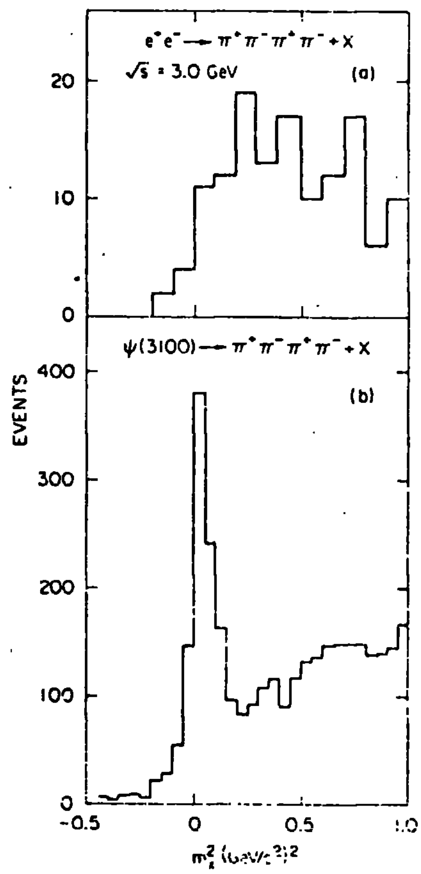


Fig 7 - The invariant mass squared recoiling against four charged pions at (a) 3Gev and (b) the ψ.

Mode	Branching Ratio (%)	No. of Events Observed	Comments
e^+e^-	6.9 ± 0.9	ca 2000	
$\mu^+\mu^-$	6.9 ± 0.9	ca 2000	
$\rho\pi$	1.3 ± 0.3	153 ± 13	$> 70\%$ of $\pi^+\pi^-\pi^0$
$2\pi^+ 2\pi^-$	0.4 ± 0.1	76 ± 9	
$2\pi^+ 2\pi^- \pi^0$	4.0 ± 1.0	675 ± 40	$\begin{cases} 20\%\ \omega\pi^+\pi^- \\ 30\%\ \rho\pi\pi\pi \end{cases}$
$3\pi^+ 3\pi^-$	0.4 ± 0.2	32 ± 7	
$3\pi^+ 3\pi^- \pi^0$	2.9 ± 0.7	181 ± 26	
$4\pi^+ 4\pi^- \pi^0$	0.9 ± 0.3	13 ± 4	
$\pi^+\pi^- K^+K^-$	0.4 ± 0.2	83 ± 18	$\begin{cases} \text{not including} \\ K^*(892)\ \bar{K}^*(1420) \end{cases}$
$2\pi^+ 2\pi^- K^+K^-$	0.3 ± 0.1		
$K_S K_L$	< 0.02	≤ 1	90% C.L.
$K^0 \bar{K}^{0*}(892)$	0.24 ± 0.05	57 ± 12	
$K^{\pm} K^{\mp*}(892)$	0.31 ± 0.07	87 ± 19	
$K^0 \bar{K}^{0*}(1420)$	< 0.19	≤ 3	90% C.L.
$K^{\pm} K^{\mp*}(1420)$	< 0.19	≤ 3	90% C.L.
$K^{*0}(892)\bar{K}^{*0}(892)$	< 0.06	≤ 3	90% C.L.
$K^{*0}(1420)\bar{K}^{*0}(1420)$	< 0.18	≤ 3	90% C.L.
$K^{*0}(892)\bar{K}^{*0}(1420)$	0.37 ± 0.10	30 ± 7	
$p\bar{p}$	0.21 ± 0.04	105 ± 11	$\begin{cases} \text{assuming} \\ f(\theta) \sim 1+\cos^2\theta \end{cases}$
$\Lambda\bar{\Lambda}$	0.16 ± 0.08	19 ± 5	
$\left.\begin{matrix} p\bar{p}\pi^0 \\ \bar{n}p\pi^- \\ \bar{p}n\pi^+ \end{matrix}\right\}$	0.37 ± 0.19	87 ± 30	

Table 4 Decay modes of the ψ

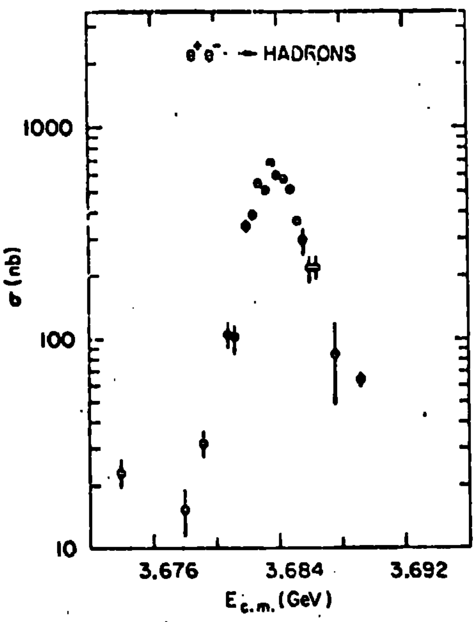


Fig 8 - The total cross-section for $e^+e^- \to$ hadrons in the region of ψ'.

Lab	$m_{\psi'}$ (Mev)
SLAC (SPEAR)[7]	3684 ± 5
DESY (DORIS)[3]	3680 ± 37

Table5 - Mass of ψ particle

Γ_{ee}	2.2 ± 0.3 Kev
$\Gamma_{\mu\mu}$	$\Gamma_{ee} = \Gamma_{\mu\mu}$ assumed
Γ_h	220 ± 56 Kev
Γ	225 ± 56 Kev
Γ_{ee}/Γ	0.0097 ± 0.0016
Γ_h/Γ	0.981 ± 0.003
$\Gamma_{\mu\mu}/\Gamma_{ee}$	0.89 ± 0.16

Table 6 - Widths of the ψ'

as measured at SPEAR and the integrated cross section is

$$\Sigma_{\psi'} = \int \sigma_{\psi'}(E)\,dE = 3700 \pm 900 \text{ nb MeV}$$

ψ' was not seen in the reaction

$$P + Be \longrightarrow \mu^+\mu^- + \text{anything}$$

at Brookhaven.

The Quantum numbers and decay width of the ψ' -

Since ψ' is produced in e^+ e^- annihilation, our first guess is again that it has the same quantum numbers of the photon, i.e., $J^{PC} = 1^{--}$. The confirmation of this guess can be obtained by the study of interference effects in the same way as was done for the ψ.

The total and partial widths of ψ' can be determined in the same way as was done for the ψ. Since the branching ratio into leptons is much smaller than the non-resonant e^+ e^- scattering, the $\mu - e$ Universality has to be used, i.e., $\Gamma_{ee} = \Gamma_{\mu\mu}$. The properties of ψ' as determined at SPEAR are shown in table 6. The width of ψ' is much larger than that of ψ, but it is still much less than would be expected for a hadron in this mass range.

$\psi' \to \psi$ Decay -

In studying the decay products of ψ', approximately one-half of its decays lead to ψ and in a majority of these decays, ψ is accompanied by two pions;

$$\psi' \longrightarrow \psi\,\pi^+\pi^-$$

In two different ways the presence of ψ among the decay products of ψ' can be seen. In the first way, the reaction

$$\psi' \to \psi + \text{anything} \longrightarrow \mu^+\mu^- + \text{anything} \qquad (9)$$

is considered. Fig (9) shows the invariant mass spectrum of the two oppositely charged particles of highest momenta for every ψ' decay. Two distinguished peaks are visible in Fig (9), one

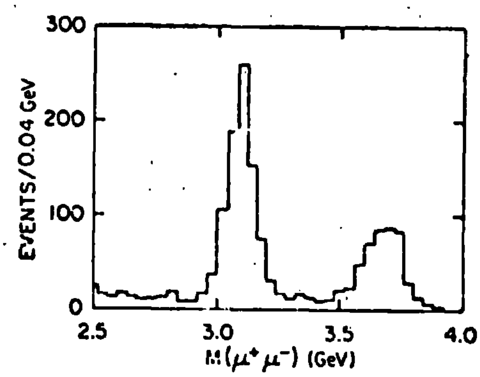


Fig 9 - The distribution of $\mu^+\mu^-$ invariant mass for the highest momentum oppositely charged particle pair from each ψ' event. Electron pairs are excluded.

around 3.7 due to the muon pairs production with the full beam energy; i.e., ψ' decays to μ pairs plus the direct production of muon pairs, and another peak is around 3.1 which represents decay of ψ to muon pairs and therefore confirms the decay mode (9). The result for branching ratio of reaction (9) is:

$$\frac{\Gamma(\psi' \to \psi + \text{anything})}{\Gamma(\psi' \to \text{all})} = 0.57 \pm 0.08 \qquad (10)$$

The value of 0.54 ± 0.10 has been reported by DORIS for this branching ratio.

The second way of observing ψ in the decay products of ψ' is through the reaction:

$$\psi' \longrightarrow \psi + \pi^+ + \pi^- \qquad (11)$$

Fig (10) shows the spectrum of missing masses recoiling against all combinations of $\pi^+\pi^-$. There is a clear enhancement at the missing mass of 3095 ± 5 Mev due to the ψ, which confirms the decay mode (11). The result for the branching ratio of this reaction is

$$\frac{\Gamma(\psi' \to \psi + \pi^+ + \pi^-)}{\Gamma(\psi' \to \text{all})} = 0.32 \pm 0.04 \qquad (12)$$

Fig (11) shows the Computer reconstruction of the decay

$$\psi' \longrightarrow \underbrace{\psi}_{\longrightarrow e^+e^-}\pi^+\pi^-$$

From equations (10) and (12) we get:

$$\frac{\Gamma(\psi' \to \psi + \pi^+ + \pi^-)}{\Gamma(\psi' \to \psi + \text{anything})} = 0.56 \pm 0.03 \qquad (13)$$

which shows that more than half of the ψ' decay to ψ occurs mainly with emission of $\pi^+\pi^-$. Using Fig (9), the branching ratio

$$\frac{\Gamma(\psi' \to \psi + \text{neutrals})}{\Gamma(\psi' \to \psi + \text{anything})} = 0.44 \pm 0.03 \qquad (14)$$

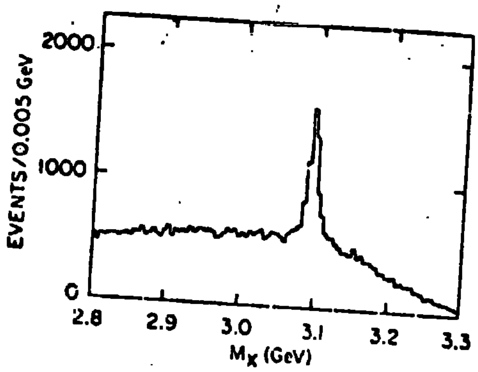


Fig 10- The distribution of missing mass recoiling against all pairs of oppositely charged particles at ψ'.

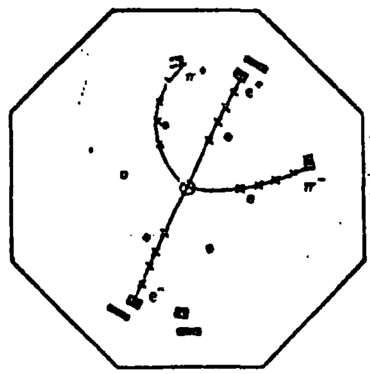


Fig 11 - A computer reconstruction of the decay $\psi' \rightarrow \psi\pi\pi$ where $\psi \rightarrow e^+e^-$ from the SLAC-LBL magnetic detector at SPEAR. The event is seen in the x-y projection where z is the beam and magnetic field direction.

can be determined from the $\mu^+\mu^-$ events in the ψ peak. Equations (13) and (14) show that the data are consistent with the hypothesis that ψ' decay to ψ is accompanied mainly by $\pi^+\pi^-$ or neutrals.

Observing the decay mode (11) make us to expect the mode $\psi' \to \psi\pi^\circ\pi^0$

If $\psi' \longrightarrow \psi$ decay proceeds entirely via the reaction

$$\psi' \to \psi\pi\pi$$

which the $\pi\pi$ system is in a state of definite isospin, we can calculate the equation (13) by using the Clebsch-Gordan coefficients:

$$\psi(J,M) = \sum_{m_1,m_2} C(J,M;j_1,m_1,j_2,m_2)\,\phi(j_1,m_1)\,\chi(j_2,m_2) \qquad (15)$$

First we forget about the difference between the π^c and $\pi^\pm$ masses. Since ψ has zero isospin, according to the decay $\psi' \longrightarrow \psi\pi\pi$, ψ' can have isospin zero, one, or two. For each case we expand the ψ' state in $\pi\pi$ states according to equation (15) and by using it we can calculate the values of the branching ratio in (13). For I = o;

$$|\psi'\rangle = |0,0\rangle = \frac{1}{\sqrt{3}}|\pi^+\pi^-\rangle + \frac{1}{\sqrt{3}}|\pi^-\pi^+\rangle - \frac{1}{\sqrt{3}}|\pi^\circ\pi^0\rangle$$

then

$$\sigma(\psi' \to \psi\pi^+\pi^-) \sim 2\times\left(\frac{1}{\sqrt{3}}\right)^2 = \frac{2}{3}$$

and

$$\sigma(\psi' \to \psi\pi^\circ\pi^\circ) \sim \left(\frac{1}{\sqrt{3}}\right)^2 = \frac{1}{3}$$

and

$$\sigma(\psi' \to \psi + \text{anything}) = \sigma(\psi' \to \psi\pi^+\pi^-) + \sigma(\psi' \to \psi\pi^\circ\pi^\circ)$$
$$\sim \frac{2}{3} + \frac{1}{3} = 1$$

and then

$$\frac{\Gamma(\psi' \to \psi\pi^+\pi^-)}{\Gamma(\psi' \to \psi + \text{anything})} = \frac{2/3}{1} = \frac{2}{3}$$

Similarly for I = 1:

$$|\psi'\rangle = |1,0\rangle = \frac{1}{\sqrt{2}}|\pi^+\pi^-\rangle - \frac{1}{\sqrt{2}}|\pi^-\pi^+\rangle$$

Then

$$\sigma(\psi' \to \psi\pi^+\pi^-) \sim \frac{1}{2} \times 2 = 1$$

$$\sigma(\psi' \to \psi\pi^0\pi^0) = 0$$

and

$$\frac{\Gamma(\psi' \to \psi\pi^+\pi^-)}{\Gamma(\psi' \to \psi + \text{anything})} = 1$$

And finally for I = 2;

$$|\psi'\rangle = |2,0\rangle = \frac{1}{\sqrt{6}}|\pi^+\pi^-\rangle + \frac{1}{\sqrt{6}}|\pi^-\pi^+\rangle + \sqrt{\tfrac{2}{3}}|\pi^0\pi^0\rangle$$

and

$$\frac{\Gamma(\psi' \to \psi\pi^+\pi^-)}{\Gamma(\psi' \to \psi + \text{anything})} = \frac{1/3}{1/3 + 2/3} = \frac{1}{3}$$

So finally we can write;

$$\frac{\Gamma(\psi' \to \psi\pi^+\pi^-)}{\Gamma(\psi' \to \psi + \text{anything})} = \begin{cases} \frac{2}{3} & \text{For } I = 0 \\ 1 & \text{"} \quad I = 1 \\ 1/3 & \text{"} \quad I = 2 \end{cases} \tag{16}$$

If we consider the mass difference between $\pi^{\pm}$ and π^0 in the above calculations, the values of the branching ratio will differ slightly from those in equation (16) and we will have the following equation instead:

$$\frac{\Gamma(\psi' \to \psi\pi^+\pi^-)}{\Gamma(\psi' \to \psi + \text{anything})} = \begin{cases} 0.66 & \text{For } I = 0 \\ 1 & \text{"} \quad I = 1 \\ 0.32 & \text{"} \quad I = 2 \end{cases} \tag{17}$$

Now, we compare equations (13) and (17) to decide about the isospin of ψ', clearly isospin zero is prefered. We can also calculate the branching ratio;

$$\frac{\Gamma(\psi' \to \psi + \text{neutrals})}{\Gamma(\psi' \to \psi + \text{anything})} = \begin{cases} 1 - 0.66 = 0.37 & \text{For } I = 0 \\ 1 - 1 = 0 & \text{"} \quad I = 1 \\ 1 - 0.32 = 0.68 & \text{"} \quad I = 2 \end{cases} \tag{18}$$

Comparing equations (14) and (18) also confirms the choice of I = o for ψ', and the difference between the two equations for I = o shows that there are other

$\psi' \to \psi + \text{neutrals}$

than just $\psi \pi^0 \pi^0$ with branching ratios $\lesssim$ 10% of the total. To look for such modes, we consider the missing mass distribution for reaction

$$\psi' \to \psi + X, \quad \psi \to \mu^+ \mu^-$$

in Fig (12). There is no peak at low mass indicating a decay of ψ' into a single low mass particle, such as a γ or π^0, so there is no evidence for modes like $\psi' \to \psi \gamma$ or $\psi' \to \psi \pi^0$, and they must have very small branching ratio if they exist at all. Among other candidates are the decay mode $\psi' \to \psi \eta$. Fig (13) shows the subtraction of 3/2 of the $\psi' \to \psi \pi^+ \pi^-$ spectrum from the $\psi' \to \psi + \text{anything}$ spectrum. There is a peak around a mass squared of 0.3 $(\text{Gev}/\text{C}^2)^2$ which confirms the decay mode $\psi' \to \psi \eta$ with branching ratio;

$$\frac{\Gamma(\psi' \to \psi \eta)}{\Gamma(\psi' \to \text{all})} = 0.04 \pm 0.02$$

The only other mode with reasonable quantum numbers is $\psi' \to \psi \gamma \gamma$ which could occur directly or through an intermediate state; $\psi' \to \gamma \chi \to \gamma \gamma \psi$

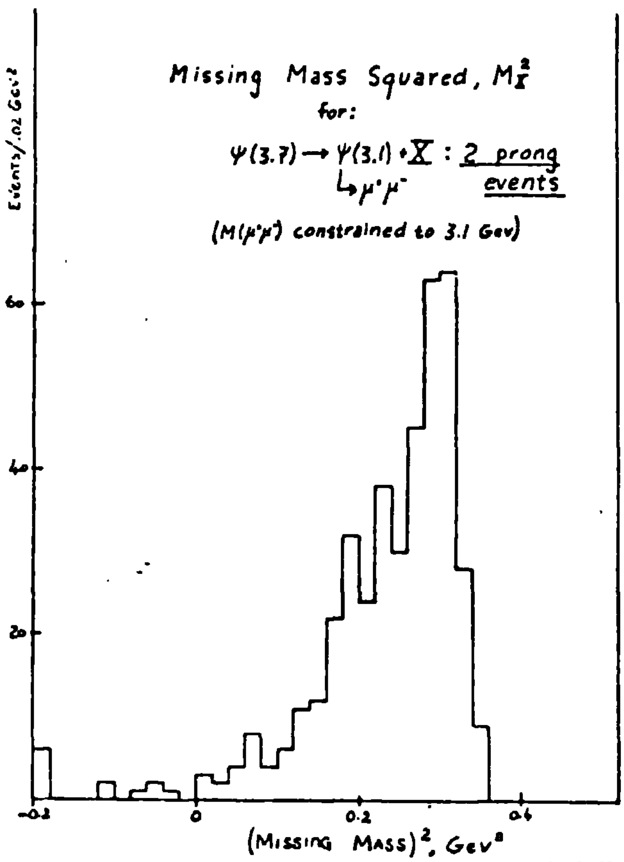


Fig. 12 Missing mass distribution for reaction

$\psi' \to \psi + X$
$\hookrightarrow \mu^+\mu^-$

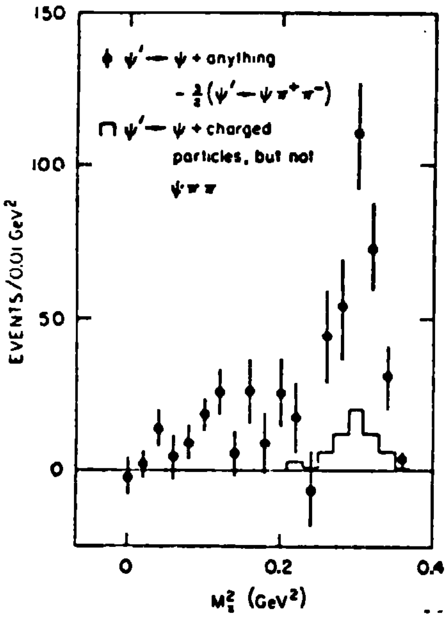


Fig. 13 – The missing mass squared to the ψ corresponding to
$\psi' \longrightarrow \psi + \text{anything} - 3/2\,(\psi' \longrightarrow \psi\pi^+\pi^-)$.
The solid line indicates the missing mass squared spectrum of events in which the ψ and an additional charged particle are detected, but the detected particles are not kinematically compatible with $\psi' \longrightarrow \psi\pi^+\pi^-$

The observation of such resonances has been reported by SPEAR, DASP, and DESY people and they will be discussed in section (1.4) in detail.

Other ψ' Decays -

No decays to ordinary hadrons have been identified for ψ' in contrast to the ψ which has many decay channels to ordinary hadrons as mentioned in table (4). Adding up the $\psi' \rightarrow \psi$ - decays with 57%, the $\psi' \rightarrow \gamma \rightarrow$ anything (including $e^+ e^-$, $\mu^+ \mu^-$, and hadrons) with 5%, and $\psi' \rightarrow \gamma + \chi \rightarrow$ hadron with 10 - 20%, and we make the limit 10% for the direct hadronic decays (which is obtained from the estimation that for any specific hadronic decay the measured partial width for the ψ' is about a factor 3 smaller than for the ψ), then there remain 10 - 20% of all decays of the ψ' which are still missing.

1.3 - Experimental Observation of ψ'' (4.1) -

After the discovery of the ψ (3.1), a systematic search for other narrow resonances in $e^+ e^-$ annihilation began. In the first run of this search ψ' (3.7) was discovered. The search continued, and in the experiment performed at Stanford Linear accelerator centre, data were taken at centre of mass energies between 2.4 and 5.0 Gev.[8] Aside from the very narrow resonances ψ and ψ', the cross section varies between 32 and 17 nb over this region with structure in the vicinity of 4.1 Gev (we shall refer to it as ψ''). The experimental results from SLAC - LBL are shown in table (7), and Fig (14a) shows the total hadronic cross section versus centre of mass energy and the ratio R of σ_T to the theoretical muon pair production cross section versus Ec.m. is shown in Fig (14b). Aside from the narrow resonances indicated in Fig (14a), the cross-section falls smoothly with centre of mass energy from 2.4 to 3.8 Gev, where it rises sharply, peaking near 4.1 Gev before falling again. In Fig (14b),

Center-of-Mass Energy $E_{c.m.}$ (GeV)	Integrated Luminosity L $(nb)^{-1}$	Average Detection Efficiency ϵ	Mean Charged Multiplicity $\langle n_{ch} \rangle$	Net Radiative Correction σ_{meas}/σ_T	Total Cross Section σ_T (nb)
2.4	26.1	0.40 ± 0.02	3.31 ± 0.12	1.02	31.8 ± 3.6
2.6	14.1	0.37 ± 0.03	3.18 ± 0.15	1.02	32.5 ± 4.4
2.8	14.9	0.33 ± 0.03	3.37 ± 0.18	1.02	29.4 ± 4.1
3.0	152.0	0.43 ± 0.01	3.55 ± 0.04	1.02	23.3 ± 2.0
3.1	16.7	0.40 ± 0.04	3.51 ± 0.21	1.02	22.5 ± 3.4
3.2	50.8	0.43 ± 0.02	3.89 ± 0.12	1.29	21.4 ± 2.3
3.3	22.7	0.47 ± 0.03	3.84 ± 0.19	1.17	18.9 ± 2.6
3.4	25.4	0.51 ± 0.03	3.93 ± 0.19	1.12	18.7 ± 2.4
3.6	33.4	0.52 ± 0.03	4.00 ± 0.17	1.07	19.1 ± 2.2
3.8	421.9	0.50 ± 0.01	3.87 ± 0.05	1.21	19.7 ± 1.7
4.0	18.3	0.52 ± 0.04	3.90 ± 0.20	1.03	24.5 ± 3.3
4.1	26.5	0.50 ± 0.03	4.04 ± 0.17	0.90	31.8 ± 3.6
4.2	70.5	0.51 ± 0.02	4.00 ± 0.10	1.02	28.1 ± 2.7
4.3	31.3	0.50 ± 0.03	4.02 ± 0.18	1.06	23.6 ± 2.8
4.4	21.3	0.58 ± 0.04	4.40 ± 0.24	1.08	19.6 ± 2.5
4.6	38.7	0.63 ± 0.04	4.62 ± 0.23	1.08	15.3 ± 1.9
4.8	767.2	0.58 ± 0.01	4.31 ± 0.04	1.05	18.2 ± 1.5
5.0	198.0	0.57 ± 0.02	4.32 ± 0.09	1.04	17.7 ± 1.5

Table 7 - Table of experimental quantities relating to the measurement of the total hadronic cross-section for the centre of mass energies covered in this experiment

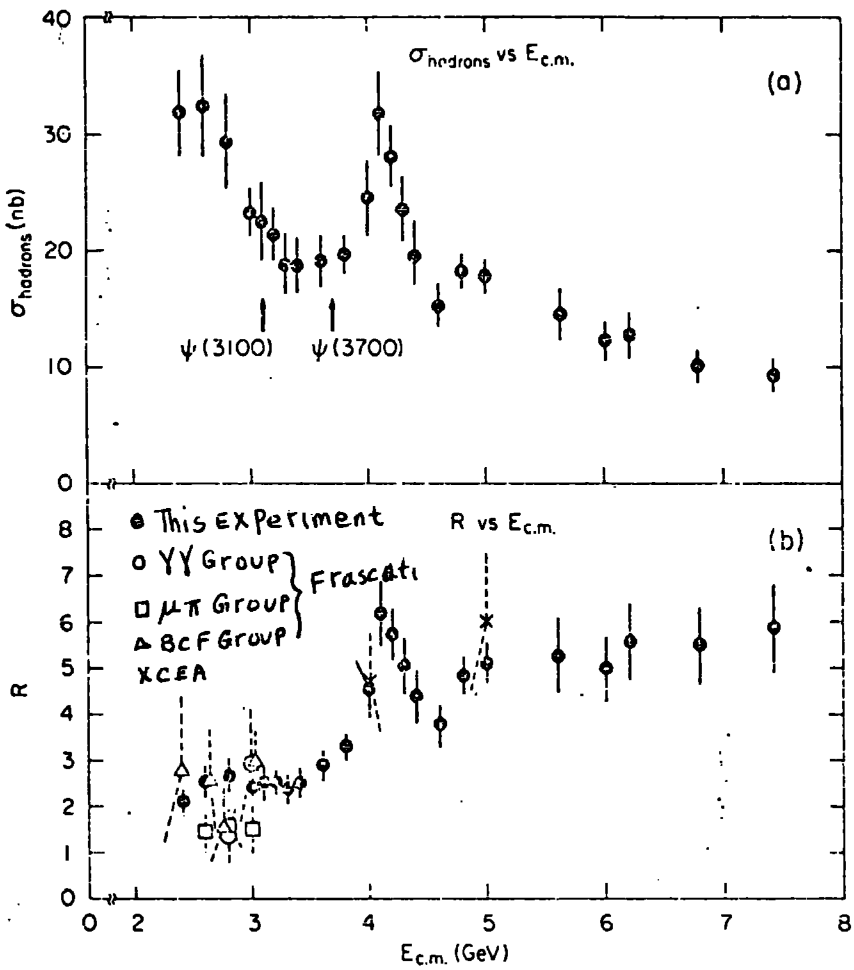


Fig 14 - a) Total hadronic cross-section σ_T versus $E_{c.m.}$ from this experiment. The position of Ψ and Ψ' are indicated, their cross-sections and radiative tails are not included in σ_T .

b) Ratio R of σ_T to the theoretical muon pair production cross-section versus $E_{c.m.}$.

R is approximately constant at a value of 2.5 from 2.4 to about 3.8 Gev, rises dramatically between 3.8 and 4.1 Gev, and at 5 Gev it has a value of about twice that of its value at 2.4 Gev. The enhancement shown in Fig (14) suggests either a broad resonance in σ_T centred at 4.1 Gev, or a new threshold phenomena related to the increase in R, or both.

While the present uncertainties in σ_T do not permit to distinguish between these possibilities, we can estimate parameters describing this structure. Assuming it to be a single resonance (Although there are arguments that it is most likely not a single state[9] and it is difficult to tell the number of states), we find a peak at 4.15 Gev, having a total width of 250 - 300 Mev, and rising from a level of about 18 nb outside the peak to about 32 nb at the top. The integrated total cross-section corresponding to the peak is about 5500 nb. Mev, a value comparable to that of the ψ and ψ' . Furthermore, assuming this resonance to have spin 1 like ψ and ψ', we find a partial width to electrons of roughly 4 Kev. The partial width to electrons is comparable with those of ψ and ψ' (approximately 5 and 2 Kev respectively), while its total width is much greater. No enhancement in the cross section for lepton pairs is observed near 4.1 Gev as expected, because this resonance would have small branching ratio to leptons.

1.4 - The Observation of Other Particles Related to the ψ - Family -

After the discovery of ψ , ψ', and ψ'', search for other resonances continued and some other particles were found which we briefly present them in the following:

a- The relatively small ψ''' bump around 4.45 reported by E. Eichten et al in August 1975. Later more precise data published showing the resonance having mass (4414 $\pm$ 7) Mev and full width (33 $\pm$ 10) Mev and partial width to electron pairs equal to (0.44 ± 0.14) Kev. Fig (15) shows the R versus Ec.m. including more recent data.

b- Looking for radiative transitions of $\psi'(3.7)$, SLAC people found a resonance at 3.415 (they called it χ) which can decay to $4\pi^{\pm}$, $6\pi^{\pm}$, $\pi^+\pi^-K^+K^-$ and $\pi^+\pi^-$ or K^+K^-.

$$\psi'(3.7) \longrightarrow \chi\gamma, \quad \chi \longrightarrow 4\pi^{\pm}, 6\pi^{\pm}, \pi^+\pi^-K^+K^-, \pi^+\pi^- \text{ or } K^+K^-$$

c- The same group found another resonance $\chi(3.51)$ which can decay to $4\pi^{\pm}$, $6\pi^{\pm}$, and $\pi^+\pi^-K^+K^-$. This resonance was observed by DESY[10] people also, and they referred to it as P_c. The branching ratio products for the decay sequence $\psi' \to \gamma\chi$, $\chi \to \gamma\psi$ is reported to be $(3.7 \pm 1.1)\%$

d- In the same sort of radiative decays two other χ states have been observed namely $\chi(3.45)$, and $\chi(3.55)$ with the branching ratio products equal to $(1.2 \pm 0.6)\%$. Fig (16) shows the observation of χ states and table (8) shows the summary of the hadronic decay modes of the χ states with the relative branching ratio. In Fig (17) the $\chi(3.41)$, and $\chi(3.5)$ peaks in the mass plots of $4\pi^{\pm}$, $6\pi^{\pm}$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-$ or K^+K^- are shown.

e- Looking for radiative decay of $\psi(3.1)$, DESY people observed another resonance $\chi(2.85)$ in the reaction

$$\psi \longrightarrow \chi(2.85)\gamma, \quad \chi(2.85) \longrightarrow \gamma\gamma$$

and later it was confirmed by DASP people.

f- There is a report of multihadronic final states produced in e^+e^- annihilation[11] showing the observation of a state with mass 1865 ± 15 Mev/C^2 which decays to $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$ This state is suggested to be a charmed particle and it will be discussed in charm particles production in chapter 3.

Some properties of the new particles are summarized in table (9).

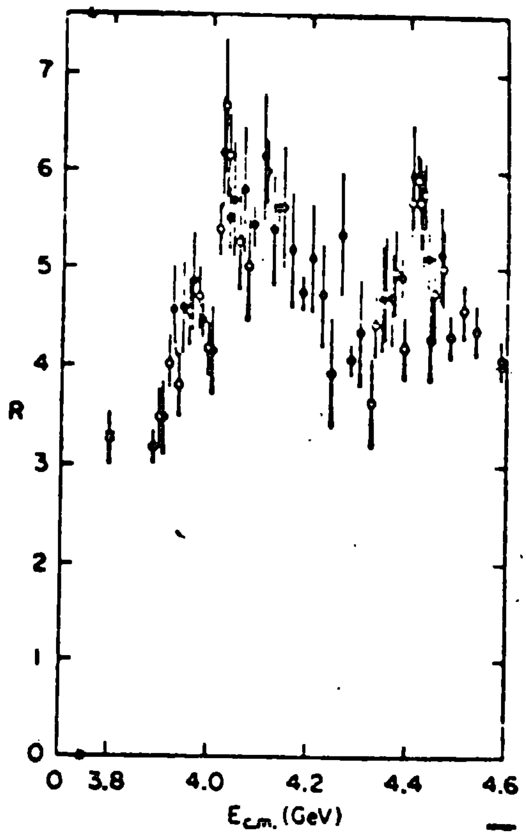


Fig. 15 — R versus C.M. energy including more recent data

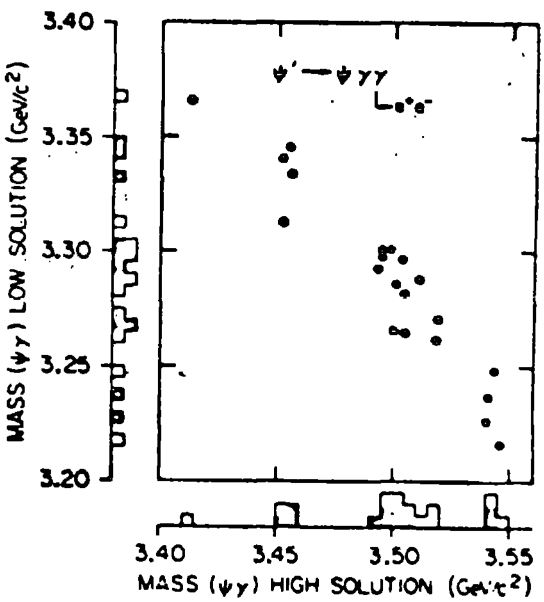


Fig. 16 — Scatter plot of the two solutions for the mass of intermediate states in decays $\psi' \to \psi\gamma\gamma$

Table 8 Summary of the hadronic decay modes of the χ states.

State	Decay mode f	$BR(\psi' \to \gamma\chi) \times BR(\chi \to f)$	$BR(\chi \to f)$	Coefficient a in $(1 + a \cos^2 \theta)$
$\chi(3415)$	$\pi^+\pi^-\pi^+\pi^-$	$(3.2 \pm 0.6) \times 10^{-3}$	0.05 ± 0.02	1.4 ± 0.4
	$\pi^+\pi^-K^+K^-$	$(2.7 \pm 0.7) \times 10^{-3}$	0.04 ± 0.02	
	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(1.4 \pm 0.5) \times 10^{-3}$	0.02 ± 0.01	
	$\pi^+\pi^-$	$(0.7 \pm 0.2) \times 10^{-3}$	0.01 ± 0.005	
	K^+K^-	$(0.7 \pm 0.2) \times 10^{-3}$	0.01 ± 0.005	
$\chi(3500)$	$\pi^+\pi^-\pi^+\pi^-$	$(1.1 \pm 0.4) \times 10^{-3}$		0.25 ± 0.5
	$\pi^+\pi^-K^+K^-$	$(0.6 \pm 0.3) \times 10^{-3}$		
	$\pi^+\pi^- + K^+K^-$	$< (0.15 \times 10^{-3})$		
$\chi(3500) + \chi(3550)$	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(2.5 \pm 0.8) \times 10^{-3}$		
$\chi(3550)$	$\pi^+\pi^-\pi^+\pi^-$	$(1.6 \pm 0.4) \times 10^{-3}$		0.2 ± 0.4
	$\pi^+\pi^-K^+K^-$	$(1.4 \pm 0.4) \times 10^{-3}$		
	$\pi^+\pi^- + K^+K^-$	$(0.23 \pm 0.12) \times 10^{-3}$		
$\chi(3450)$*	$\pi^+\pi^-\pi^+\pi^-$	$< 4 \times 10^{-4}$		
	$\pi^+\pi^-K^+K^-$	$< 5 \times 10^{-4}$		
	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$< 7 \times 10^{-4}$		
	$\pi^+\pi^- + K^+K^-$	$< 3 \times 10^{-4}$		

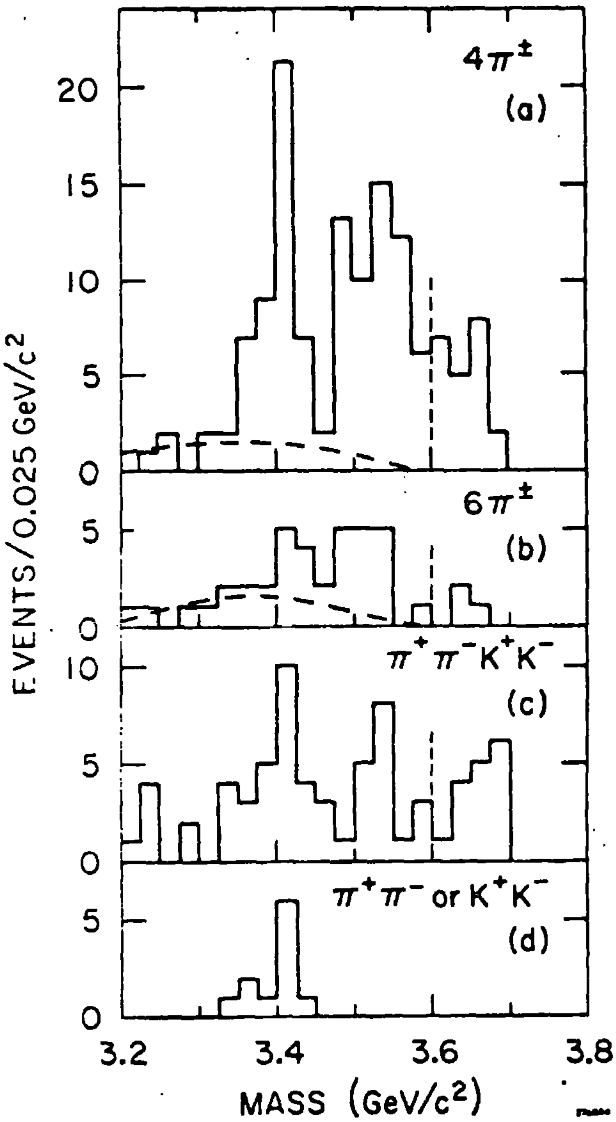


Fig. 17 — The number of events versus the mass of

a) $4\pi^{\pm}$ b) $6\pi^{\pm}$ c) $\pi^{+}\pi^{-}K^{+}K^{-}$

d) $\pi^{+}\pi^{-}$ or $K^{+}K^{-}$ For The Processes:

$\psi' \longrightarrow \gamma\, \chi$

$\hookrightarrow 4\pi^{\pm}$

$6\pi^{\pm}$

$\pi^{+}\pi^{-}K^{+}K^{-}$

$\pi^{+}\pi^{-}$ or $K^{+}K^{-}$

Name	Mass	Width	J^P	C	Decay Modes
$\psi = J$	3095	70 keV	1^-	-	$e^+e^-, \mu^+\mu^-$, hadrons (via γ) Many hadronic modes (G=-1, I=0) $\gamma + \chi(2800)$
ψ'	3684	225 keV	1^-	-	$e^+e^-, \mu^+\mu^-$, Hadrons (via γ) $\gamma + P_c(3510)$, $\gamma + \chi(3410)$ $\pi\pi\psi, \eta\psi$
ψ''	~4100	100-200 MeV	1^-	-	?
ψ'''	~4450	50-80 MeV	1^-	-	?
$\chi(=\eta_c?)$	~2800	?	?	+	$\gamma\gamma, p\bar{p}$
χ	3410	narrow	$P=(-1)^J$	+	$4\pi, 6\pi, \pi\pi K\bar{K}, \pi\pi$ or $K\bar{K}$ $\gamma\psi(?)$
$P_c(=\chi?)$	3510 (or 3260?)	narrow	?	+	$\gamma\psi$
$\chi'(=P_c?)$	3530	wide or two narrow states?	?	+	$4\pi, 6\pi, \pi\pi K\bar{K}$ $\gamma\psi(?)$

Table 9 - A short particle data table for the ψ-family.

CHAPTER TWO

SYMMETRY GROUPS AND ELEMENTARY PARTICLE PHYSICS

This chapter is devoted to the description of symmetry groups in elementary particle physics. In section (2.1) the group SU(3) and quark model are described. In section (2.2) the SU(4) group and the classification of elementary particles in SU(4) group are discussed. In section (2.3) charm spectroscopy and the idea of charmed particles are introduced.

2.1 - SU(3) and Quark Model -

In the study of the elementary particles, the symmetry groups have an important role, because we do not have a satisfactory dynamical theory to describe the interactions of the elementary particles. But despite this lack of detailed knowledge of dynamics, much information can be obtained by studying the symmetry properties of elementary particle interactions.

First attempts to introduce a symmetry group is back to the years since 1936, when Breit and his collaborators postulated that nuclear forces were charge independent. Then the symmetry under rotations in the space of isospin as an approximate symmetry of the strongly interacting particles were proposed. This led to the fact that particles could be grouped into multiplets, each member of which had approximately the same mass, but different charge and each multiplet is labelled by the eigenvalue of isospin $I^2 = i\ (i + 1)$ where i can take on integer or half integer values. Each member of a multiplet differs in the eigenvalue of I_3 which is associated with electric charge. The basic postulate is that the proton and neutron are represented by a two-component column vector:

$$|P\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad , \text{and} \quad |N\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Transformations between P and N states are then effected by the Hermitian operators I_1, I_2 and I_3. A general transformation, for which these operators are the infinitesmal generators, can be written as:

$$U = \exp\left(i \sum_{J=1}^{3} \alpha_J I_J\right)$$

where α_1, α_2 and α_3 are parameters. The set of such transformations form a group SU(2). The generators are (2 x 2) Hermitian matrices as follows:

$$I_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad I_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad I_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

where the diagonal one, I_3, is identified with the additive quantum number I_3.

However, after the discovery of hyperons and the introduction of hypercharge, physicists began to enlarge the SU(2) group to a larger approximate symmetry. Then in 1961, Gell Mann(12) and Ne'eman(13) independently proposed a classification of the strongly interacting particles into the 8-dimensional representation of SU(3). The resulting symmetry scheme has had considerable success in providing a phenomenological framework for describing experimental data on elementary particles.

The group SU(3), which is the generalization of the isospin group is accomplished simply by considering the group of Unitary Unimodular transformations on three basic three-component column vectors u, d, and s;

$$u \equiv q(1) \equiv \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad d \equiv q(2) \equiv \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \quad s \equiv q(3) \equiv \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Then a general three component spinor can be written as:

$$q \equiv \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

which transforms according to

$$q' = Q \cdot q$$

where Q can be expressed in terms of the generators of the group

$$Q = \exp\left(i \sum_{j=1}^{8} \alpha_j F_j\right)$$

where the generators of the group are: $F_j = \frac{1}{2}\lambda_j$

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \qquad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \qquad \lambda_8 = \frac{1}{\sqrt{3}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

where λ_3, and λ_8 are two generators which can be simultaneously diagonalized and they can be identified with the additive quantum numbers I_3 third component of isospin, and y hypercharge respectively.

To consider the SU(3) multiplets, we begin with the simplest nontrivial one, the triplet which has the following quantum numbers:

$$u = |I_3, Y\rangle = |\tfrac{1}{2}, \tfrac{1}{3}\rangle$$

$$d = |I_3, Y\rangle = |-\tfrac{1}{2}, \tfrac{1}{3}\rangle$$

$$s = |I_3, Y\rangle = |0, -\tfrac{2}{3}\rangle$$

and the corresponding weight diagram is shown in Fig (18). There is also another independent triplet (3^*), which is dual to the fundamental triplet (3), with the corresponding weight diagram as shown in Fig (19). Other SU(3) multiplets can be obtained from the combinations of 3 and 3^*;

$$3 \otimes 3^* = 1 \oplus 8$$

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$

Then the $\frac{1}{2}^+$ baryons and pseudoscalar mesons can be displayed into SU(3) octets which are shown in Fig (20). Actually the existence of the η meson was not known in 1961; it was predicted by this classification which is called the eightfold way. The members of the multiplets so formed are not degenerate in mass and the mass splitting is roughly equal to m_π as compared to the isospin splitting of a few Mev. For example the masses of P and N differ by 1.3 Mev, while the (P $-\Lambda$) mass difference is 177 Mev, and if this mass splitting is linearly related to the strength of the symmetry breaking interaction, then the SU(3) breaking interaction should be 100 times stronger than the SU(2) breaking electromagnetic interaction

Another great triumph of SU(3) has to do with the $\frac{3}{2}^+$ baryon resonances, these are grouped into the 10-dimensional representation of SU(3), i.e., a decuplet as is shown in Fig (21) The Ω was predicted as the tenth member of the multiplet of N^{*++}, N^{*+}, N^{*o}, N^{*-}, Y^{*+}, Y^{*o}, Y^{*-}, Ξ^{*o}, and Ξ^{*-}. A search at the Brookhaven Laboratory in 1964 confirmed the existence of Ω with the same properties predicted by the eightfold way.

After the eightfold way had been established, Gell-Mann[14] and Zweig[15] independently suggested that corresponding to the fundamental triplet of SU(3) there should exist a fundamental triplet of particles u, d, and s. These particles, named quark

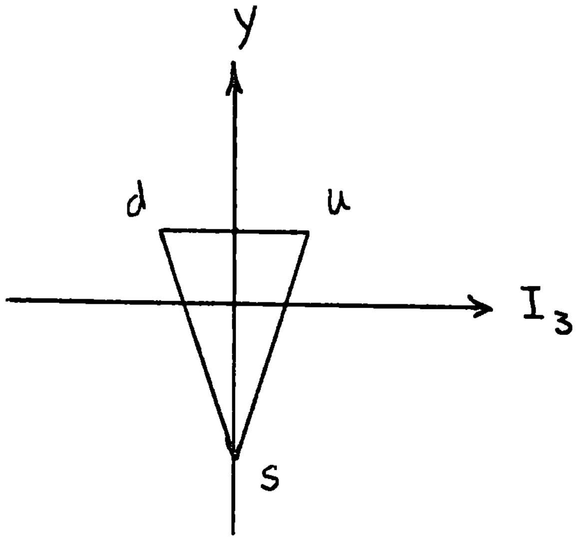


Fig 1·8- Fundamental triplet of SU(3)

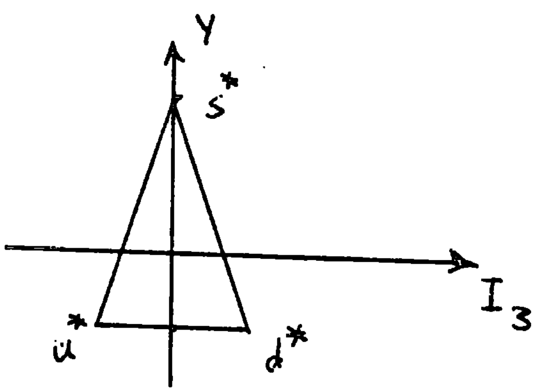


Fig 1·9 - Weight diagram of 3*

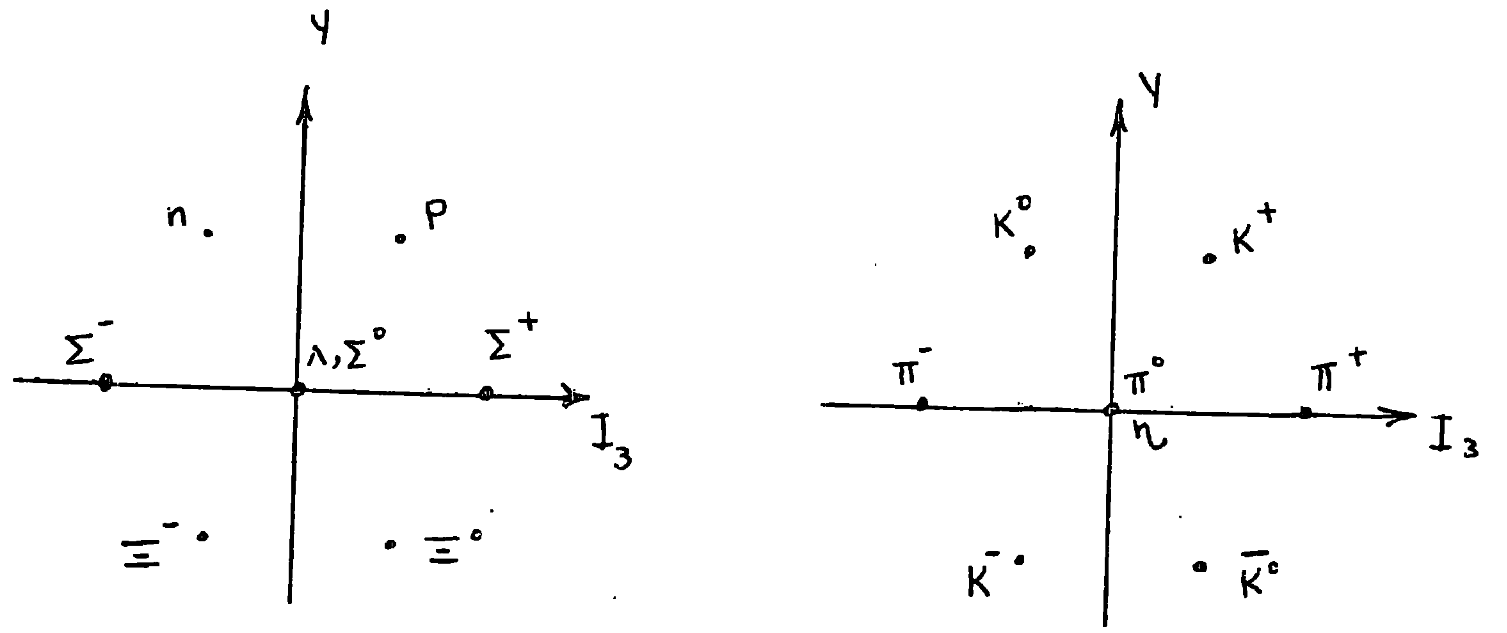


Fig 2c- The baryon and pseudo-scalar meson octets

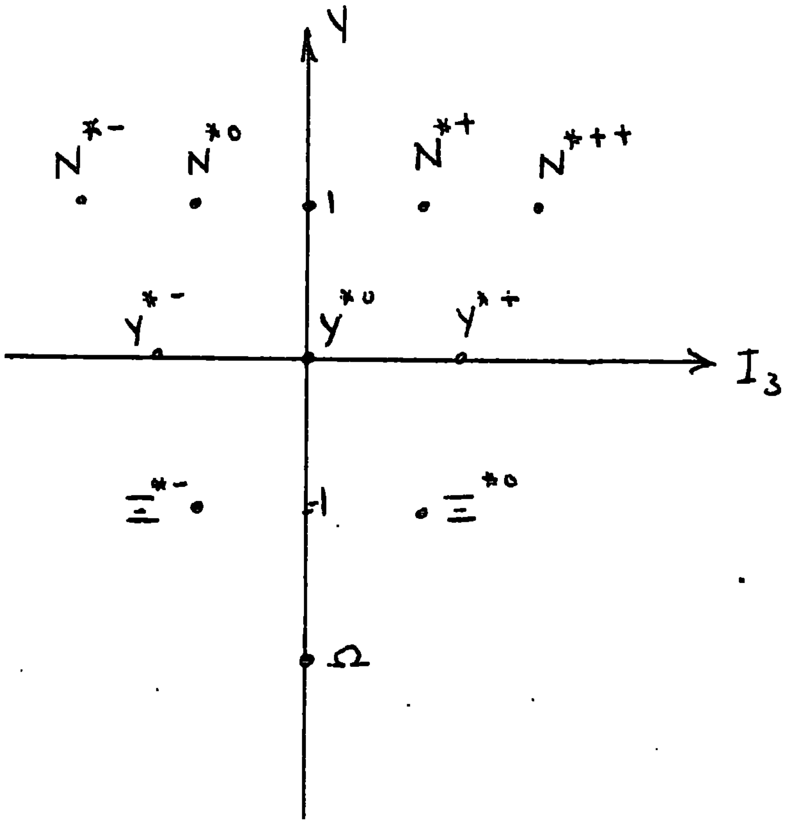


Fig 21 - The baryon resonances decuplet

by Gell-Mann, and ace by Zweig, are to be the building blocks which compose all of the mesons and baryons. Two of these particles should form an isospin doublet, while the third one should have I = o and they must have the usual triplet hypercharge and presumably ordinary spin one-half. Antiquarks which have all additive quantum numbers reversed correspond to 3^*. Then we can suppose that the mesons are bound states of quark-antiquark pair, while baryons are three-quark bound states. This predicts singlet and octet mesons, and singlet, octet and decuplet baryons, exactly as observed. So here we have an explanation of the eightfold way. But this also gives the quarks fractional baryon number and charge (table 10) which are certainly something new and so far fractionally charged particles have not been found. Nevertheless, quarks are convenient for illustrating the mathematical structure of the SU(3) symmetry.

However, the application of SU(3) considerations to weak interactions leads to unnecessary high rates of strangeness-changing neutral currents and to large value of $K_S^o - K_L^o$ mass difference. These facts together with the discovery of new ψ and χ states which can not be accommodated in SU(3) multiplets may mean that the successful SU(3) symmetry scheme should be enlarged to SU(4).

2.2 - SU(4) and Strong Interactions -

The SU(4) symmetry for strong interaction was first proposed in the basis of hadron-lepton symmetry (by Bjorken and Glashow[16]), since the extra quark completes the symmetry between quarks and the four leptons e, ν_e, μ and ν_μ. Later SU(4) symmetry was suggested from the gauge theoretical point of view by Glashow, Iliopoulos and Maini[17]. Since using SU(3) as the symmetry group to make a renormalizable unified gauge theory of weak interactions leads to unacceptably high rates for

	spin	B	I	I_3	Q	Y
U	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$
d	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$
S	$\frac{1}{2}$	$\frac{1}{3}$	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$

Table 10 - The quantum numbers of quarks

semileptonic transitions like

$$K^{\circ} \rightarrow \mu^{+}\mu^{-} \quad , K^{+} \rightarrow \pi^{+} \nu\bar{\nu} \ . \ \text{etc.}$$

that involve a neutral $|\Delta S| = 1$ hadronic current, and to large value of the $K_L - K_S$ mass difference which arises from a second order weak interaction $\Delta S = 2$, $K^0 \rightarrow \bar{K}^0$ transition. So the gauge theories are incompatible with SU(3) as the first symmetry, and we must consider a group of higher order with SU(3) as a subgroup. Then this larger group will introduce new quantum numbers and new hadrons. The simplest possibility is to consider the group SU(4) which adds a fourth charmed quark C to the conventional u, d, and s, and introduces a new quantum number called charm (c), with the conventional quarks having c = o, while the fourth one has C = 1.

Accepting SU(4) as the basis of a gauge theory with the general charged (V - A) type hadronic current:

$$W_{\mu} = \bar{q}\, V \gamma_{\mu} (1 + \gamma_5)\, q$$

where q is the quark column vector (c, u, d, s) and the matrix V is of the form:

$$V = \left(\begin{array}{cc|cc} 0 & 0 & \multicolumn{2}{c}{\multirow{2}{*}{U}} \\ 0 & 0 & & \\ \hline 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right)$$

with

$$U = \begin{pmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{pmatrix}$$

Then the corresponding neutral current

$$W_o = \frac{1}{8}\left[W, W^{+} \right]$$

contains no $|\Delta S| = 1$ term. It is also required to suppose that the strong interaction is approximately SU(4) invariant, then the above mentioned processes are depressed by a factor $G\,(\delta M)^2$ where δM is the scale of SU(4) breaking. With the choice

$$\delta M = M_c - M_u \sim 2-3 \ \text{Gev}$$

theory reaches the experimental limits for these processes and thus the problem of neutral strangeness changing transitions is solved and we can say that the charm hypothesis is a device to solve the problem of the decay $K^\circ \rightarrow \mu^+\mu^-$. We discuss some of the properties of SU(4) group in some detail in what follows.

The generators of the group SU(4) are as follows:

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \lambda_2 = \begin{pmatrix} 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_3 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_5 = \begin{pmatrix} 0 & 0 & -i & 0 \\ 0 & 0 & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_9 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \qquad \lambda_{10} = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ i & 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_{11} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \qquad \lambda_{12} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \end{pmatrix}$$

$$\lambda_{13} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \qquad \lambda_{14} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{pmatrix}$$

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

where λ_3, λ_8 and λ_{15} are the three generators which can be simultaneously diagonalized. Therefore we have at our disposal three additive conserved quantum numbers, I_3 third component of isospin, Y hypercharge, and c a new quantum number called charm, corresponding to these generators.

The fundamental quartet of the group contains, in addition to the three conventional u, d and s quarks, a fourth quark c with the same charge as the u- quark. The quantum numbers of these four quarks are shown in table (11). (There are different

	I	I_3	S	Y	C	B	Q
u	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{3}$	0	$\frac{1}{3}$	$2/3$
d	$\frac{1}{2}$	$-\frac{1}{2}$	0	$\frac{1}{3}$	0	$\frac{1}{3}$	$-1/3$
s	0	0	-1	$-\frac{2}{3}$	0	$\frac{1}{3}$	$-1/3$
c	0	0	0	$-2/3$	1	$\frac{1}{3}$	$2/3$

Table 11 - Quantum numbers of the fundamental quartet of SU(4)

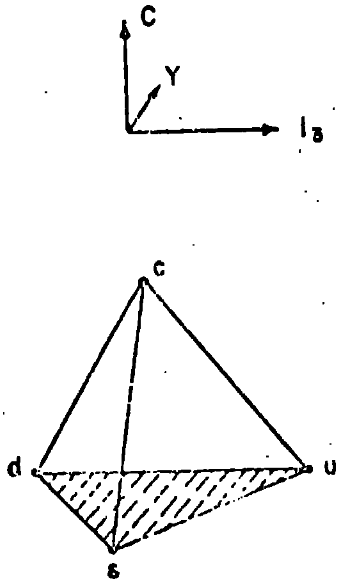


Fig 12- Fundamental quartet of SU(4).

conventions used by different authors,[18] but we will follow the Gaillard etal's convention [19].) The quantum number c is an additive quantum number like hypercharge Y. The Gell - Mann-Nishijima formula is $Q = I_3 + \frac{1}{2}(B + S + C)$
and hypercharge and strangeness are connected by:

$$Y = S + B - C$$

To assign hadrons in the SU(4) representations, we must look for the lowest representations of the group, although there is no a priori reason why the particles and resonances observed in nature should belong to the lowest representations, this is an appealing guiding idea. So we must look at the possible particle assignments restricting ourselves to the lower representations. The decomposition of the products of lower dimensional representations of SU(4) are shown in table (12), and their contents in SU(3) submultiplets in table (13). We see from table (13) that besides the uncharmed c = o SU(3) submultiplets, there appear charmed SU(3) submultiplets. The corresponding particles would be stable with respect to decay into uncharmed particles.

2.3 - Charm Spectroscopy -

Now we try to assign baryons and mesons to SU(4) representations. In the case of baryons, the SU(3) octet of spin $\frac{1}{2}$ baryons is enlarged to a <u>20</u> - plet, since besides the states containing only the conventional u, d and s quarks which form the known octet of $(\frac{1}{2}^+)$ baryons, there are other states which carry one or two charmed quarks. There are nine baryon states containing one charmed quark which six of them are symmetric in the remaining two ordinary quarks while three others are antisymmetric. There are also three baryon states with two charmed quarks which make a triplet of $(\frac{1}{2}^+)$ baryons with c = 2. So there are altogether 20 states of $(\frac{1}{2}^+)$ baryons

4	$\bar{4}$	6	10	$\overline{10}$	15	20	$\overline{20}$	$20'$	$\overline{20}'$	$20''$	
$6+10$	$1+15$	$\bar{4}+20'$	$20+20'$	$\bar{4}+\overline{36}$	$4+\overline{20}'+36$	$35+45$	$\overline{10}+\overline{70}$	$15+20''+45$	$6+\overline{10}+64$	$\overline{20}'+60$	4
		$1+15+20''$	$15+45$	$\overline{15}+\overline{45}$	$6+10+\overline{10}+64$	$36+84'$	$\overline{36}+\overline{84}'$	$4+\overline{20}'+36+60$	$\bar{4}+20'+\overline{36}+\overline{60}$	$6+50+64$	6
			$20''+35+45$	$1+15+84$	$6+10+64+70$	$56+60+84'$	$\bar{4}+\overline{36}+160$	$\overline{20}'+36+60+84'$	$\bar{4}+20'+\overline{36}+140''$	$\overline{10}+64+126$	10
					$1+15+15+20''+45+\overline{45}+84$	$20+20'+\overline{120}+\overline{140}''$	$\overline{20}+\overline{20}'+\overline{120}+\overline{140}''$	$\bar{4}+20+20+\overline{20}'+\overline{36}+\overline{60}+140''$	$4+\overline{20}+\overline{20}'+\overline{20}'+36+60+140''$	$15+20''+45+\overline{45}+175$	15
						$50+84''+126+140$	$1+15+84+300$	$64+70+126+140$	$15+45+84+256$	$\overline{36}+140''+224$	20
								$6+10+\overline{10}+50+64+64+70+126$	$1+15+15+20''+\overline{45}+45+84+175$	$\bar{4}+20'+\overline{36}+\overline{60}+140'+140''$	$20'$
										$1+15+20''+84+105+175$	$20''$

Table 12 – Product decompositions of representations in SU(4).

Rep. of SU_4	4		6		10			15			20				$20'$			$20''$		
Submultiplets of SU_3	3	1	$\bar{3}$	3	6	3	1	3	$1+8$	$\bar{3}$	10	6	3	1	8	$\bar{3}+3$	3	$\bar{6}$	8	6

Table 13 – Lowest representations of SU(4) with their contents in SU(3) sub-multiplets.

which form an irreducible representation 20 of SU(4). These states are listed in table (14), and the corresponding weight diagram in the three dimensional plot of I_3, Y and C is shown in Fig (23). Similarly the SU(3) decuplet of spin $3/2$ baryons changes to another 20 - plet and the corresponding weight diagram is shown in Fig (24).

For the mesons, each nonet (octet + singlet) of mesons made of u, d and s quarks is replaced by a 16 - plet, which the new mesons are : an isodoublet c $\bar{u}$ and c $\bar{d}$ (usually called D), c $\bar{s}$ (usually called F), the antiparticles of these, and a hidden charm c $\bar{c}$ state (usually called η_c, ϕ_c, f_c, ...). It should be noted that six of these new mesons carry the charm quantum number C = $\pm$ 1, the exception is c $\bar{c}$ which has c = o and that is the reason for calling it a hidden charm state.
To write down the quark contents of the meson states it is useful to consider a matrix array by labelling the rows by the quark symbols and the columns by antiquark symbols, then for the pseudoscalar mesons:

$$
P = \begin{array}{c} \\ (\bar{u}) \\ (\bar{d}) \\ (\bar{s}) \\ (\bar{c}) \end{array}
\begin{array}{c}
\begin{array}{cccc} (u) & (d) & (s) & (c) \end{array} \\
\begin{pmatrix}
\left(\frac{\sqrt{2}}{2}\pi^{\circ}+\frac{\sqrt{6}}{6}\eta+\frac{1}{2}\eta'+\frac{\sqrt{12}}{12}\eta'_c\right) & \pi^- & K^- & D^{\circ} \\
\pi^+ & \left(-\frac{\sqrt{2}}{2}\pi^{\circ}+\frac{\sqrt{6}}{6}\eta+\frac{1}{2}\eta'+\frac{\sqrt{12}}{12}\eta'_c\right) & \bar{K}^{\circ} & D^+ \\
K^+ & K^{\circ} & \left(\frac{1}{2}\eta'-\frac{\sqrt{6}}{3}\eta+\frac{\sqrt{12}}{12}\eta'_c\right) & F^+ \\
\bar{D}^{\circ} & D^- & F^- & \left(\frac{1}{2}\eta'-\frac{\sqrt{12}}{4}\eta'_c\right)
\end{pmatrix}
\end{array}
$$

The list of the charmed pseudoscalar mesons and their quantum numbers are shown in table (15) and the corresponding weight diagram is shown in Fig (25). Similarly the vector mesons make another 16 - plet, and again we can make a matrix array

Charm Q·N	lable	Quark Content	Isospin	strangeness
$C=1$	C_1^{++}	cuu		
$C=1$	C_1^{+}	$c(ud)_{sym.}$	$I=1, I_3=\begin{cases}1\\0\\-1\end{cases}$	0
$C=1$	C_1^{0}	cdd		
$C=1$	C_0^{+}	$c(ud)_{anti.}$	$I=0$	0
$C=1$	S^{+}	$c(su)_{sym.}$		
$C=1$	S^{0}	$c(sd)_{sym.}$	$I=\frac{1}{2}, I_3=\begin{cases}1/2\\-1/2\end{cases}$	-1
$C=1$	A^{+}	$c(su)_{anti.}$	$I=\frac{1}{2}, I_3=\begin{cases}1/2\\-1/2\end{cases}$	-1
$C=1$	A^{0}	$c(sd)_{anti.}$		
$C=1$	T^{0}	css	$I=0$	-2
$C=2$	X_u^{++}	ccu		
$C=2$	X_d^{+}	ccd	$I=\frac{1}{2}, I_3=\begin{cases}1/2\\-1/2\end{cases}$	0
$C=2$	X_s^{+}	ccs	$I=0$	-1

Table 14- charmed $1/2^{+}$ Baryon state

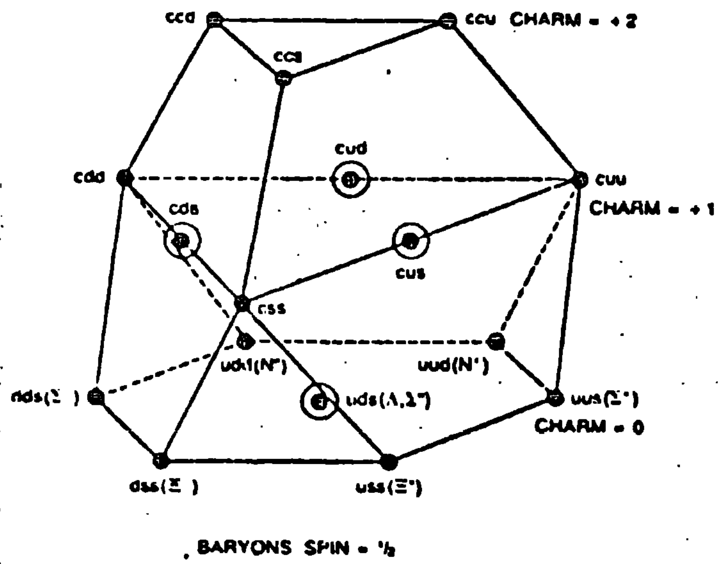


Fig.23 The weight diagram for baryon spin $\frac{1}{2}$

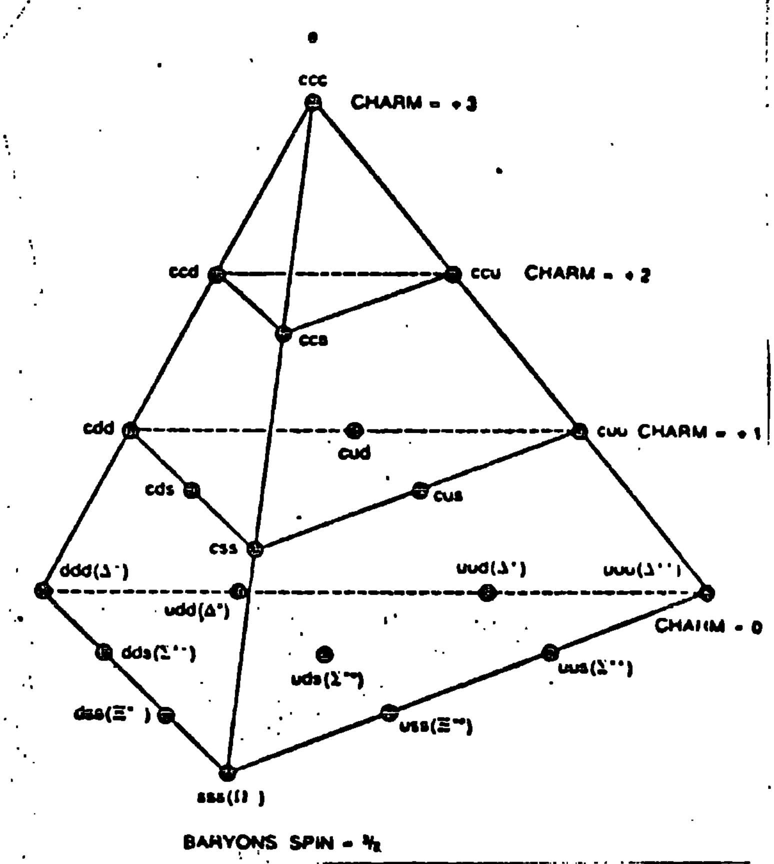


Fig. 24 The weight diagram for baryon spin $^3/_2$

Charm Q.N.	Table	Quark Content	Isospin	Strangeness
$c=1$	D^+	$c\bar{d}$	$I=\frac{1}{2}, I_3=\begin{cases}1/2\\-1/2\end{cases}$	0
$c=1$	D^0	$c\bar{u}$		
$c=1$	F^+	$c\bar{s}$	$I=0$	+1
$c=0$	$\eta \simeq (6)^{-1/2}(u\bar{u}+d\bar{d}-2s\bar{s})$		$I=0$	0
$c=0$	$\eta' \simeq \frac{1}{2}(u\bar{u}+d\bar{d}+s\bar{s}+c\bar{c})$		$I=0$	0
$c=0$	$\eta'_c \simeq (12)^{-1/2}(u\bar{u}+d\bar{d}+s\bar{s}-3c\bar{c})$		$I=0$	0
$c=-1$	$\bar{D}^0$	$\bar{c}u$	$I=\frac{1}{2}, I_3=\begin{cases}1/2\\-1/2\end{cases}$	0
$c=-1$	D^-	$\bar{c}d$		
$c=-1$	F^-	$\bar{c}s$	$I=0$	-1

Table 15-charmed 0^- mesons with their quark contents

$C=1$	D^{0+} D^{*0} F^{*+}
$C=0$	$\omega \simeq (2)^{-1/2}(u\bar{u}-d\bar{d})$ $\phi \simeq s\bar{s}$ $\phi_c \simeq c\bar{c}$
$C=-1$	$\bar{D}^{*0}$ D^{*-} F^{*-}

Table 16-charmed $\Gamma=J^P$ mesons.

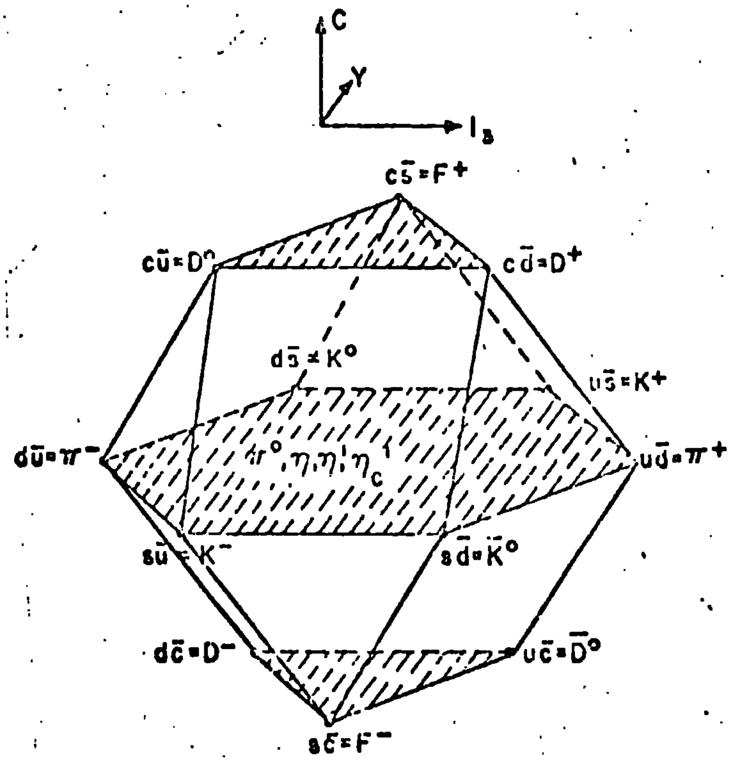


Fig 25- Weight diagram for Mesons.

to show the quark contents:

$$V = \begin{array}{c c} & \begin{array}{cccc} (u) & (d) & (s) & (c) \end{array} \\ \begin{array}{c} (\bar{u}) \\ (\bar{d}) \\ (\bar{s}) \\ (\bar{c}) \end{array} & \begin{pmatrix} (\frac{1}{\sqrt{2}}\omega+\rho^{0}) & \rho^{-} & K^{*-} & D^{*0} \\ \rho^{+} & \frac{1}{\sqrt{2}}(\omega-\rho^{0}) & \bar{K}^{*0} & D^{*+} \\ K^{*+} & K^{*0} & \phi & F^{*+} \\ \bar{D}^{*0} & D^{*-} & F^{*-} & \psi \end{pmatrix} \end{array}$$

The charmed vector mesons are listed in table (16), and the corresponding weight diagram is similar to that of the pseudoscalar mesons.

In strong interactions isospin, strangeness and charm are conserved, while in weak interactions these quantum numbers are not conserved in general.

CHAPTER THREE

ψ-PARTICLES AS $c\bar{c}$ BOUND STATES

This chapter is devoted to the interpretation of ψ particles in Charm scheme. In section (3.1) the ψ particles will be considered as $c\bar{c}$ bound states. In section (3.2) the Zweig's rule is discussed. The section (3.3) is devoted to the ψ-spectroscopy and its comparison with the charmonium predictions. In section (3.4) the transitions involving ψ particles will be discussed. In section (3.5) the missing decays of ψ' (3.7) are discussed. And finally section (3.6) is devoted to the discussion about the charmed particles.

3.1 - The ψ particles as $c\bar{c}$ bound states -[20]

To interpret the new resonances we should concentrate on hadronic models, because there are many reasons indicating that the new particles are hadrons, such as;

i - Their decays predominantly respect strong interaction symmetries like I - spin and G - parity.

ii - Their strong coupling,

$$\frac{g^2_{\psi',\psi\pi\pi}}{g^2_{\rho',\rho\pi\pi}} \simeq 10^{-2}$$

iii - $\sigma(\gamma p \to \psi(3.1) + p)$ has forward diffractive peak ten times bigger than electromagnetic.

These together with many other reasons make us to believe that they are hadrons. Since these particles have very narrow widths, we must consider models involving new hadronic degrees of freedom. There are two obvious ways of extending SU(3), the usual symmetry group of the strong interactions. One is $SU(3) \to SU(3) \times G$, where G is some new symmetry. The other is $SU(3) \longrightarrow SU(N)$, $N \geq 4$. The best known example of the first scheme is the Han - Nambu colour scheme (G = SU(3)). The best known example of the second scheme is the traditional charm model with N = 4 but other possibilities are open (fancy, gentleness,...for N = 5, 6, ...).

In this chapter we concentrate on the classification of ψ particles in charm model and the colour model in addition to some other models will be discussed in the next chapter.

In the charm model, we explore the characteristics of ψ particles with the view that;

a - The $\psi(3.1)$ is a pure $1\,{}^3S_1$ $c\bar{c}$ state, partner of ρ, ω, ϕ (it is called orthocharmonium 1 by Appelquist et al[20], in analogy with positronium).

b - The $\psi'(3.7)$ is a radially excited $2\,{}^3S_1$ $c\bar{c}$ state, possible partner of $\rho'(1600)$, (called orthocharmonium 2). The fact that much of the time ψ' decays into ψ and two pions shows that ψ' is an excited state of ψ and confirms our assumption. Also the leptonic decay width of ψ' is about half that of ψ,

$$\Gamma(\psi \to e^+e^-) \sim 4.8 \quad \text{Kev}$$

$$\Gamma(\psi' \to e^+e^-) \sim 2 \quad \text{Kev}$$

which is again another confirmation of the above assumption.

c - Finally $\psi''(4.1)$ structure is second recurrence, broadended because it is sitting above the threshold for producing charmed meson pairs $D\bar{D}$, $F\bar{F}$, etc, (Although the very recent data suggests that the structure at 4.1 region is most likely not a single state).

If this is the case, the new particles should be accompanied by a host of others carrying a nonzero charm quantum number. The charmed particles should have properties even more dramatic than those of the above states. The lowest one should decay only weakly and have lifetimes of order 10^{-13} sec. If the large $e^+ e^- \to$ hadrons cross section near 4 Gev is related to the threshold for the production of charmed particles then their masses should be between 1.84 Gev and 1.95 Gev (the lower limit is due to the narrow width of ψ' and the upper limit is given by the rise of R near 3.9 Gev).

The main objection against this interpretation is very narrow widths of the ψ and ψ' which is much below the average widths of mesons with strong or first-order electromagnetic decays. The usual explanation is the Zweig's rule which will be discussed in the next section.

3.2 - Zweig's Rule -

Zweig's rule (or more properly Okubo, Zweig and Iizeik's rule) states that a transition which can only be described by a disconnected quark diagram, in which the particles can be divided into two groups such that quark lines do not cross from one group to the other, is forbidden whereas the connected diagrams such as the diagrams corresponding to the decays

$$\phi \longrightarrow K^+K^- \quad \text{and} \quad \psi'' \longrightarrow D\bar{D}$$

are allowed. In fact the Zweig's rule was first stated to describe the relative suppression of the decay $\phi \longrightarrow 3\pi$ compared to $\phi \longrightarrow K\bar{K}$ as an imperical rule. Then it was generalized for all meson decays. It states that the two quarks in a meson state do not annihilate. To explain the rule in a simpler way, we can compare it with the fact that if we break a dipole into many pieces, each piece is still a dipole and has two poles. Fig (26) shows some examples of Zweig's rule allowed transition (connected diagram) and disallowed ones (disconnected diagram). Decays $\psi \rightarrow 3\pi, K\bar{K}$ (or generally $\psi \rightarrow$ charmless hadrons) correspond to disconnected diagrams and they are supposed to be zero as a first approximation, and the decay $\psi' \rightarrow \psi +$ ordinary hadrons is also forbidden in lowest order.

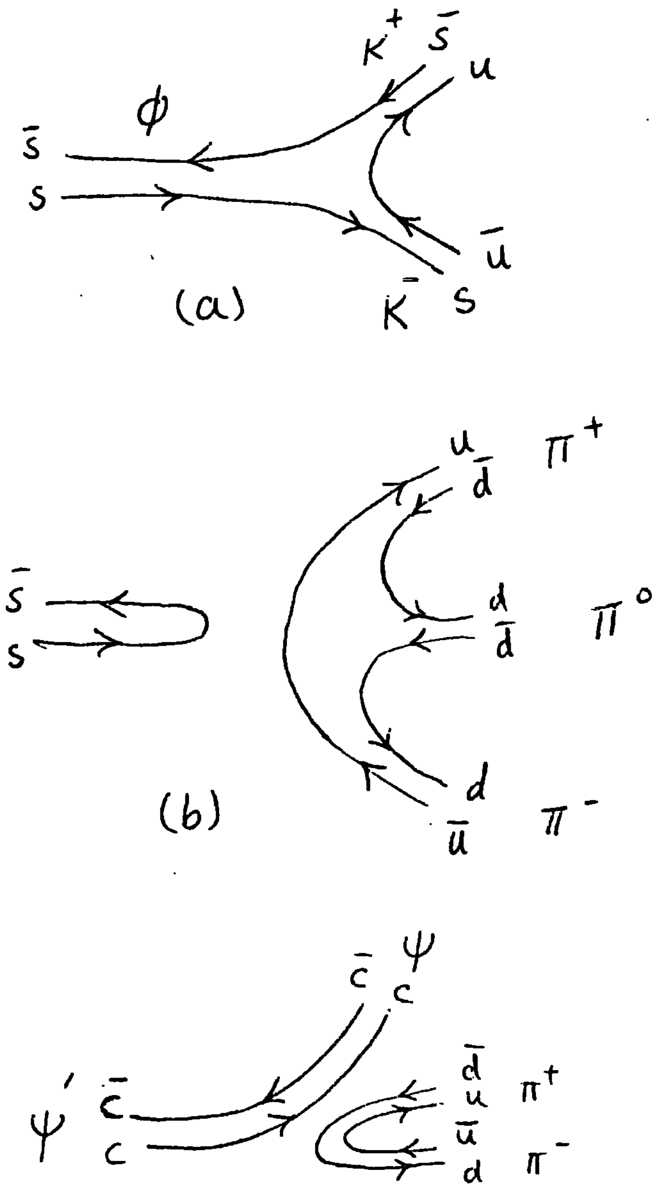


Fig. 26 - a) connected diagram for the decay $\phi \longrightarrow K^+K^-$

b) Disconnected diagram for the decay $\phi \longrightarrow 3\pi$

c) Disconnected diagram for the decay $\psi' \longrightarrow \psi\pi\pi$

However the suppression of disallowed ϕ decays is $O(10^2)$ in the rate, i.e., if we compare $\phi \to 3\pi$ with $\omega \to 3\pi$ which is allowed by the rule, we have

$$\frac{(\phi \to 3\pi)}{\text{phase space}} \Big/ \frac{(\omega \to 3\pi)}{\text{phase space}} \simeq 1/100$$

whereas the suppression of disallowed ψ decays is $O(10^3 - 10^4)$, i.e.,

$$g^2(\psi \to \text{hadrons}) / g^2(\phi \to 3\pi) \sim 1/50$$

which shows that the Zweig's rule is getting better and better when mass increases. Various explanations proposed for this extra suppression. One is based on the gluon exchange and the fact that gluon coupling decreases as the exchanged mass increases, thus it explains the suppression of the ψ coupling relative to the ϕ coupling.

It should be noted that, the Zweig's rule does not really explain anything, it is just a rule which appears to work approximately, although we really do not know why. There are various ways to understand the approximate validity of this rule. One way is to accept that it is valid in the limit of perfect SU(3) or SU(4) symmetry, then the symmetry breaking will lead to the approximate validity of this rule, i.e. ϕ is not a pure $s\bar{s}$ state and have small admixtures of $u\bar{u}$ and $d\bar{d}$ and similarly the ψ and ψ' won't be pure $c\bar{c}$ states and these admixtures other than $s\bar{s}$ and $c\bar{c}$ will cause the breaking of the Zweig's rule for ϕ and ψ decays respectively.

Another way of looking at the violation of the Zweig's rule is in the language of the topological expansion. It is supposed that the diagrams which break Zweig's rule are non-planar as it is shown in Fig (27) for the decays $\phi \to 3\pi$ and $\psi' \to \psi\pi\pi$. There are reasons to believe that non-planar corrections decrease with energy, which may explain why the rule is better for ψ than ϕ (this is called asymptotic planarity).

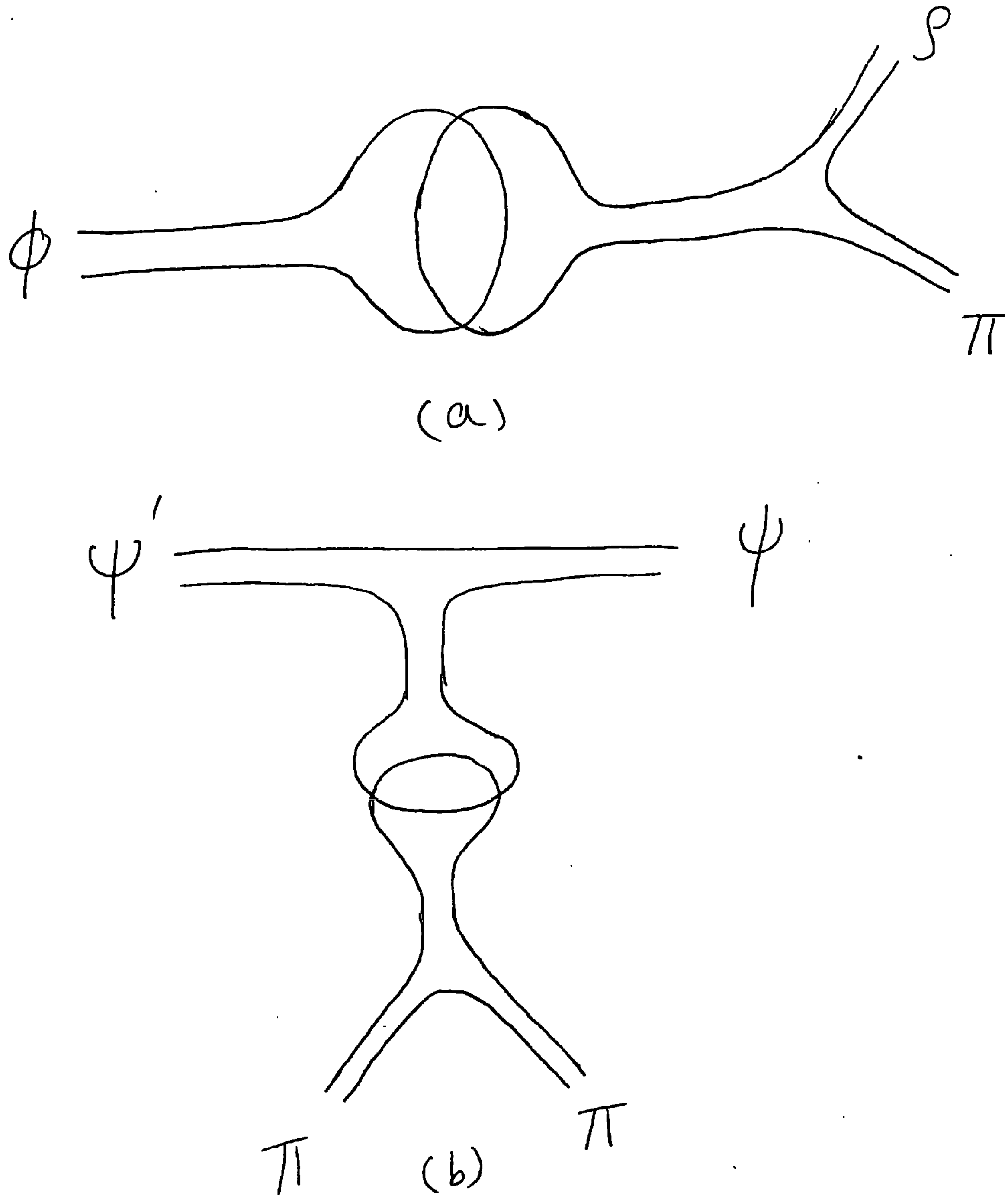


Fig. 27 - Nonplanar diagrams for the decays

a) $\phi \longrightarrow \rho\pi$

b) $\psi' \longrightarrow \psi\pi\pi$

From the above discussions we conclude that the decay of ψ into ordinary hadrons is highly suppressed. Furthermore, if the charmed particles masses are greater than or equal to 1.5 Gev, decays like $\psi \longrightarrow D\bar{D}$ would be energetically forbidden, so ψ would be very narrow.

As long as the ψ' is below charm-anticharm threshold, it will remain narrow too. This is an important difference between the ψ' and ρ' which has a number of open channels into which to decay and is consequently very broad. The very narrow width of ψ' (3.7) means that the lowest charmed particle must be above 1840 Mev in mass as mentioned in the beginning of this chapter.

3.3 - The Spectrum of Quark - Antiquark Bound States and ψ-Spectrum -

The discovery of ψ and ψ' arised the prediction of other states of charmonium with masses less than 3.7 Gev. To investigate these predictions, we consider the spectrum of $q\bar{q}$ bound states and compare it with the recent data about the ψ spectrum.

We consider the spectrum of a state $q\bar{q}$ with orbital angular momentum L, since the spin of a quark is ½. there are two possibilities S = o, 1 for each value of L. We use the familiar notation of H-atom; S,P,D,... states as are shown in table (17). In Fig (28), the so-called charmonium level scheme is shown, as predicted in December 1974[21] when only ψ and ψ' were known.

In a coulomb potential, the first P state is degenerate with second S state,

3s ———	3p ———	3d ———
2s ———	2p ———	
1s ———		

					SU(4) Content ≡ $\underline{15}+\underline{1}$		
	${}^{2S+1}L_J$	L	S	J^{PC}	SU(3) Content	$c\bar{c}$	$c\bar{u}, \bar{c}u, \ldots$
1S	${}^1S_0$	0	0	0^{-+}	π, K, η, η'	η_c	D, F
	${}^3S_1$	0	1	1^{--}	ρ, K^*, ω, ϕ	$\phi_c \equiv \psi$	D^*, F^*
2P	${}^1P_1$	1	0	1^{+-}	B ..		
	${}^3P_2$	1	1	2^{++}	A_2, K^{**}, f, f'		
	${}^3P_1$			1^{++}	A_1 ...		
	${}^3P_0$			0^{++}	δ, ε, S^*		
2S		0	0	0^{-+}		η'_c	
		0	1	1^{--}	ρ'	$\phi'_c \equiv \psi'$	
3D		2	0	2^{-+}			
		2	1	$\left\{\begin{matrix} 3^{--} \\ 2^{--} \\ 1^{--} \end{matrix}\right.$	g (ρ')?		
3P		1					
3S		0		1^{--}		ψ''	

Table 1.7 - The spectrum of quark-antiquark bound states

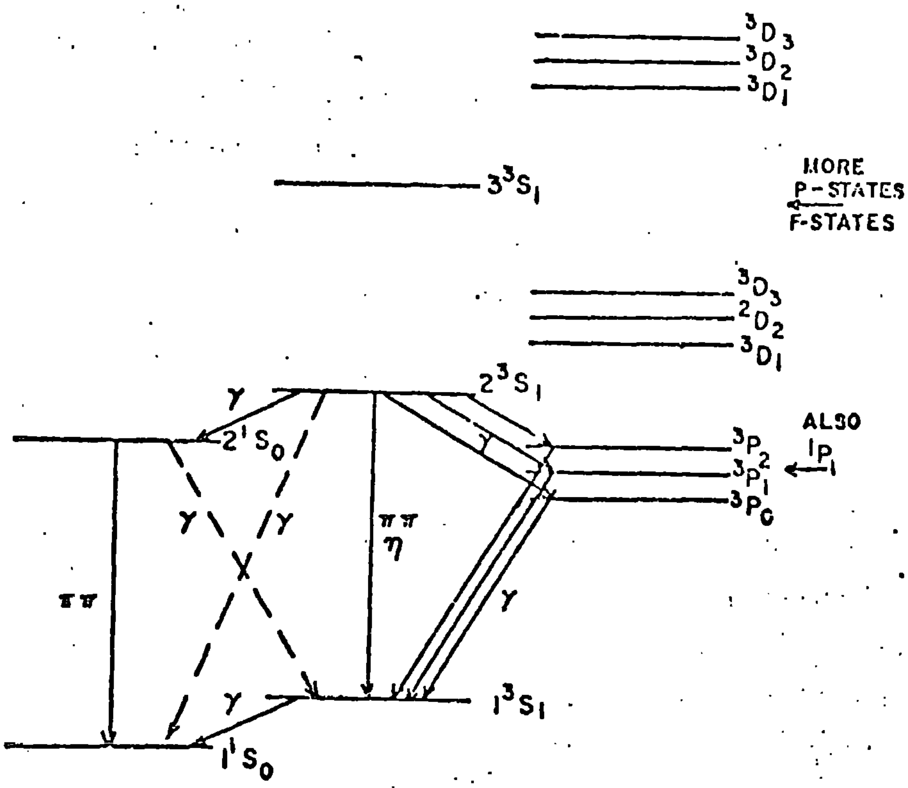
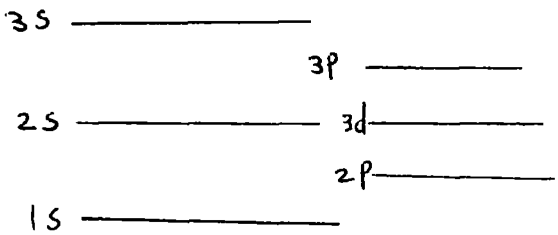


Fig 28 - The 'charmonium' level scheme.

while in a harmonic-oscillator potential, it lies halfway between the first two S states;



For the charmonium spectrum, Appelquist et al,[21] supposed an intermediate result, and with this assumption they predicted the mass region of these states. They also suggested that non of the P-states are coupled to $e^+ e^-$, but they are produced by the radiative decays of orthocharmonium 2. The experimental ψ spectrum on July 1976[9] is presented in Fig (29). The comparison of charmonium scheme with Fig (29) shows a dramatic qualitative success. There are at least three C - even states between ψ and ψ' ; $\chi(3415)$, $\chi(3500)$ and $\chi(3550)$ which are presumably related to the P - states sitting between ψ and ψ' in Fig (28). There may be a fourth state $\chi(3455)$ probably the pseudoscalar partner of ψ', in analogy with the state $\chi(2850)$ which is usually taken to be the pseudoscalar partner of the ψ .

3.4 - Qualitative Features of processes Involving ψ Particles -

a - The hadronic decays -

$\psi \rightarrow$ hadrons and $\psi' \rightarrow$ hadrons are forbidden by Zweig's rule and in fact the observed hadronic widths are much narrower than anticipated. For example, for the ψ, if we assume that it has the same suppression factor as that in ϕ decays, we would expect $\Gamma_\psi \simeq 2\text{-}4$ MeV , whereas the actual width for ψ is measured to be $\Gamma_\psi \sim 70$ KeV . This is due to the extra suppression of the Zweig's rule for ψ as was mentioned in section (3.2). The quark diagram showing the decays like $\psi \rightarrow$ hadrons are shown in the following;

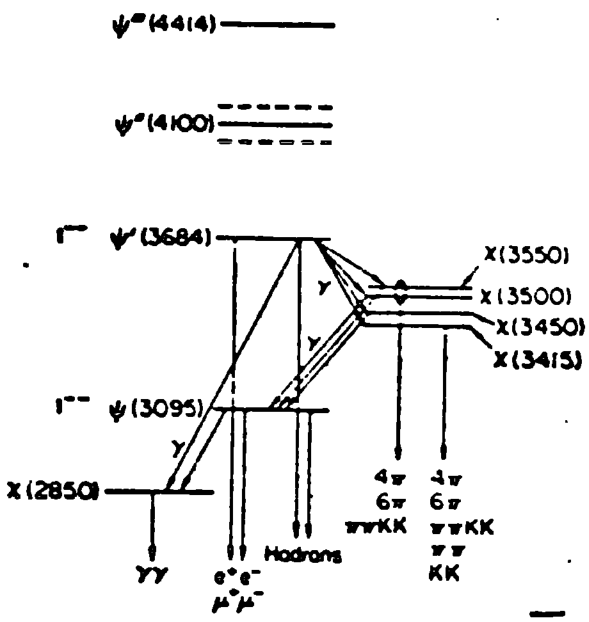
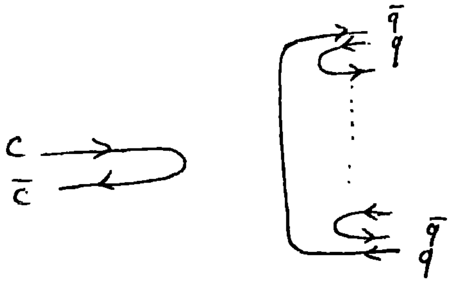


Fig. 29 – The experimental Ψ spectrum on July 1976



b - The Cascade decay -

The decay $\psi' \longrightarrow \psi\pi\pi$ is also forbidden, but the suppression is expected to be less strong. In terms of effective coupling we have:

$$g^2(\psi' \to \psi\pi\pi)/g^2(\rho' \to \rho\pi\pi) \sim (0.5-3)\times 10^{-2}$$

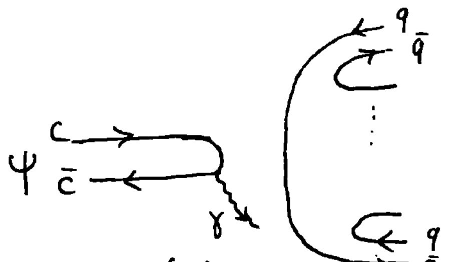
to be compared with the suppression factor;

$$g^2(\phi \to \rho\pi)/g^2(\omega \to \rho\pi) \sim 3\times 10^{-3}$$

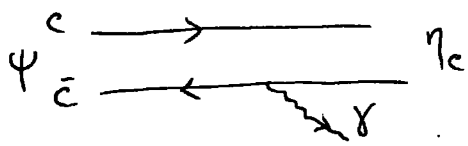
The quark diagram for the decay $\psi' \longrightarrow \psi\pi\pi$ is shown in Fig (26).

c - The radiative decays -

The decays $\psi \longrightarrow \gamma +$ hadrons and $\psi' \longrightarrow \gamma +$ hadrons are also forbidden by Zweig's rule, unless the final state hadron contains a $c\bar{c}$ component. Quark diagrams for these two cases are shown in the following figures.



(a)



(b)

The observed decays of type (a) are;

$$\Gamma(\psi \to \eta\gamma) \sim 100 \text{ ev}$$

$$\Gamma(\psi \to \eta'\gamma) \sim 1 \text{ Kev}$$

and the decays of type (b) are;

$$\psi' \to \gamma\chi \qquad (1)$$

$$\psi' \to \gamma P_c \qquad (2)$$

$$\psi \to \gamma\chi(2.8)$$

with widths of order 1 - 10 Kev. This is smaller than the width for the decays of type;

$$\phi \rightarrow \eta \gamma$$
$$\omega \rightarrow \pi \gamma \ , \ldots$$

and there is no convincing explanation for this difference. However the observation of decays (1) and (2) is a further confirmation of the charm scheme where one would expect P-wave excitations of the $c\bar{c}$ system to be between the ψ and ψ'.

d - ψ'' Decays -

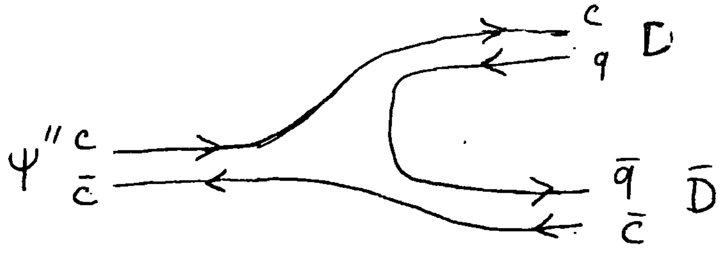
Comparing with the partial width for the cascade decay of ψ', we expect at most a total width of about 10 Mev from cascade decays of ψ'';

$$\psi'' \longrightarrow \psi + \pi\pi \, , \, K\bar{K} \, , \, \eta' \, , \, \eta$$

whereas the observed width for ψ'' is 250 - 300 Mev. This large width can be understood only if ψ'' is lying above the threshold for charmed meson pair production. Then it will decay into states such as;

$$\psi'' \longrightarrow \begin{cases} D\bar{D} \, , \, F\bar{F} \\ D^* \bar{D}^* \end{cases}$$

which are unsuppressed decays according to Zweig's rule;



3.5 - The Missing Decays of ψ' (3.7) -

According to decay modes of ψ' discussed in chapter one, we summarize the known decay modes of ψ' and their contributions in the total width in table (18). It was attempted to identify direct hadronic decays of ψ' as was done for ψ, but no direct hadronic decay with a branching ratio of more than 1% has been seen. Upper limits for the decays into $\rho^0 \pi^0$ and $\pi^+\pi^+\pi^-\pi^-\pi^0$

$\psi' \to \psi + \text{anything}$	57%	
$\psi\pi^+\pi^-$		32%
$\psi\pi^0\pi^0$		16%
$\psi\eta$		∿4%
$\psi\gamma\gamma$		∿5%
$\psi' \to \gamma + \text{anything}$	5%	
e^+e^-		1%
$\mu^+\mu^-$		1%
hadrons		3%
$\psi' \to \gamma + \chi$, $\chi \to$ hadrons		10-20%
$\psi' \to \gamma + P_c$, $P_c \to \gamma + \psi$	included in $\psi' \to \gamma\gamma\psi$	
$\psi' \to$ direct hadrons		10%

Table 8 - Known decay modes of ψ'.

of about 0.1% and 0.7% respectively have been identified by SLAC people which are much smaller than those for ψ decays in table 4 of chapter one. But, using the fact that for any specific hadronic decay the measured partial width for ψ' is about a factor of 3 smaller than for the ψ, we have estimated the limit of 10% for direct decays of ψ' in table (18). It can be seen from the table (18) that, we can only account for about (80 - 90) % of ψ' decays and the remaining (10 - 20) % of the decays are not accounted for. Among candidates for these missing decays are modes such as:

$$\psi' \longrightarrow \omega + \chi\,(2.8)$$

or $$\psi' \longrightarrow \pi^\circ \gamma\, \chi(2.8)$$

or several decay modes $\psi' \longrightarrow \gamma\chi$ with too many χ states.

3.6 - Charmed Particles -

As mentioned in the previous chapter, this model predicts some new charmed hadrons which their existence is the crucial test of this notation. So we briefly review some of their properties in what follows:

a - Decays of charmed particles -

The charmed particles could decay weakly into the usual hadrons and leptons, and for short enough lifetime could have escaped detection. If we accept the hadronic charged current to be of the form:

$$\omega_\mu^{ch} = \bar{u}\gamma_\mu(1-\gamma_5)(d\cos\theta_c + s\sin\theta_c) + \bar{c}\gamma_\mu(1-\gamma_5)(-d\sin\theta_c + s\cos\theta_c) \quad (1)$$

mentioned in chapter 2, it can be seen that among the emitted hadrons at least one strange particle should be produced. Since for example in the case of semi-leptonic and leptonic decays, the following selection rules for the decay amplitudes can be given :

from the hadronic charm changing current (1) :

$$\Delta C = \Delta Q = \Delta S = 1 , \quad \Delta I = 0 \quad \text{with Amplitude} \propto \cos\theta_c$$

and

$$\Delta C = \Delta Q = 1 , \quad \Delta S = 0 , \quad \Delta I = \tfrac{1}{2} \quad \text{with Amplitude} \propto \sin\theta_c$$

so the dominant semi-leptonic decay modes for the states $c\bar{d}$ and $c\bar{u}$ (usually called D), and $c\bar{s}$ (usually called F) are;

$$D^0 \rightarrow \text{"}K^-\text{"} + \text{leptons}$$
$$D^+ \rightarrow \text{"}\bar{K}^0\text{"} + \text{leptons}$$
$$F^+ \rightarrow \text{"}\eta\text{"} + \text{leptons}$$

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

For purely leptonic decays we consider the simple case of two body decays like $D^+ \rightarrow \mu^+\nu$ and $F^+ \rightarrow \mu^+\nu$. These are like K_{ℓ_2} decays and according to the calculations done in Ref. (19) their decay width can be calculated by using

$$\frac{\Gamma(D^+ \rightarrow \mu^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)} \simeq \frac{m_D}{m_K} ,$$

and

$$\frac{\Gamma(F^+ \rightarrow \mu^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)} \simeq \frac{m_F}{m_K} \cot^2\theta_c$$

and

$$\Gamma(K^+ \rightarrow \mu^+\nu) \simeq 0.5 \times 10^8 \ \text{Sec}^{-1} \qquad m_F = m_D = 4 m_K$$

we get;

$$\Gamma(D^+ \rightarrow \mu^+\nu) \simeq 2 \times 10^8 \ \text{Sec}^{-1}$$

and

$$\Gamma(F^+ \rightarrow \mu^+\nu) \simeq 4 \times 10^9 \ \text{Sec}^{-1}$$

The semileptonic decays of a charmed hadron is due to a semileptonic decay of c quark according to the fundamental processes;

$$c \longrightarrow s + \ell^{+} + \nu$$

and

$$c \longrightarrow d + \ell^{+} + \nu$$

while other quarks or antiquarks in the initial hadron act as spectators. Then the rate for such a decay when sum over final states would be the same as for muon decay;

$$\Gamma_{tot}(\text{charm} \rightarrow \ell\nu + \text{hadrons}) = G_F^2 \, M_c^5 \times 192\pi^3 \approx 10^{12} \text{ sec}^{-1}$$

where M_c the mass of c quark is taken to be $M_c \simeq 1.5$ Gev.

For non-leptonic decays which are due to the elementary process;

$$c \longrightarrow s + u + \bar{d}$$

with a similar estimate the total decay rate would be;

$$\Gamma_{tot}(\text{charm} \rightarrow \text{hadrons}) \approx \frac{1}{192\pi^3}\left(G_F A \cos\theta_c\right)^2 M_c^5 \approx 10^{13} \text{ sec}^{-1}$$

From the comparison of these estimates one can get;

$$\frac{\Gamma(\text{leptonic})}{\Gamma(\text{non-leptonic})} \approx O(1/20)$$

These results are not certain and the total decay rates of charmed particles may vary from the above estimates by as much as a few orders of magnitude.

It is not clear how many of the D and F decay modes should be multibody, but in Ref.(19) for D^*'s and F^*'s with mass about 2 Gev using a simple algebra leads to the following estimation:

$$\Gamma(2\,\text{body}) : \Gamma(3\,\text{body}) : \Gamma(4\,\text{body}) : \Gamma(5\,\text{body}) \approx 51\% : 38\% : 9\% : 1\%$$

which overestimates the two-body decays.

b - Production of charmed particles -

Sufficiently light charmed particles may be detected via their tracks in emulsions, and under extremely favourable circumstances perhaps also in bubble chambers. Since the shortest track that can be detected in a bubble chamber is a few milimeters, using

$\Gamma_{tot} \simeq 10^{12} \times [M(\mathrm{Gev})]^5\ \mathrm{Sec}^{-1}$ and the mean path length transversed by the particle $\ell = \gamma c \tau = \frac{\gamma c}{\Gamma}$, we can conclude that it seems unlikely to identify a charmed particle with mass greater than about 2 Gev via its track in a bubble chamber. But emulsions are sensitive to tracks about several tens of microns, so we expect to see charmed particles with masses less than about 4 Gev.

In the following subsections we discuss some of different experiments which are used to search for charmed particles.

C - Production of charmed particles in $e^+ e^-$ annihilation -

If the increase of the branching ratio,

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

above 4 Gev is related to the threshold for the production of charmed mesons, their mass should lie between 1.84 Gev and 1.95 Gev where the lower limit is estimated regarding the narrow width of $\psi'(3.684)$ while the upper limit is chosen by the rise of R near 3.9 Gev as was mentioned before. In order to search for inclusive production of charmed mesons, an experiment performed at SPEAR at 4.8 Gev[22] to look for narrow peaks in inclusive two and three body state invariant mass distributions in various modes. The results are shown in table (19) which shows no significant peaks. In another experiment done by the same group[11] recently search for narrow peaks in invariant mass plots of two, three, and four body systems were performed at energies between 3.9 and 4.60 Gev. The results are shown in Fig (30) which shows small peaks for $\pi^+\pi^-$ (near 1.74 $\frac{\mathrm{Gev}}{c^2}$)

Decay mode	Mass region (GeV/c)		
	1.5 – 1.85	1.85 – 2.4	2.4 – 4.0
$K^{\mp}\pi^{\pm}\pi^{\pm}$	0.51	0.49	0.19
$\pi^{\mp}\pi^{\pm}\pi^{\pm}$	0.48	0.38	0.18
$K_s^0\pi^{\pm}$	0.26	0.27	0.09
$K_s^0K^{\pm}$	0.54	0.33	0.09
$K^{\mp}\pi^{\pm}$	0.25	0.18	0.08
$K_s^0\pi^+\pi^-$	0.57	0.40	0.27
$\pi^+\pi^-$	0.13	0.13	0.09
K^+K^-	0.23	0.12	0.10

Table 19 - Limits on narrow width resonance production at 4.8 Gev. The upper limits are for inclusive cross section in nb and are at the 90% confidence level.

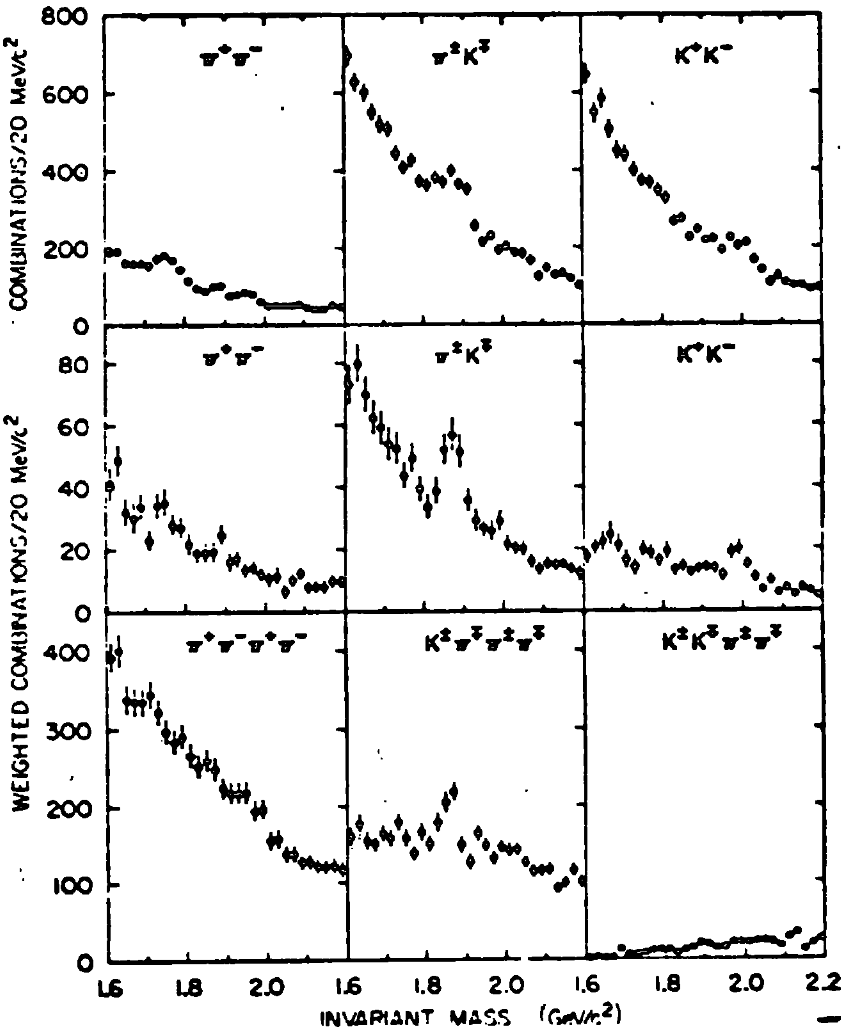


Fig. 30 - Invariant mass plot for combinations of two and three and four charged particles in $e^+ e^-$ annihilation between 3.9 - 4.6

and K^+K^-(at 1.98 $\frac{Gev}{c^2}$) but significant peaks in the invariant mass spectra of $K^{\pm}\pi^{\mp}$ and $K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$. The last two peaks are consistent with being decays of the same state with mass 1.865 $\pm$ 0.015 $\frac{Gev}{c^2}$ and width less than 40 $\frac{Mev}{c^2}$. Since this state can be produced in association with systems of higher masses, it leads to the threshold energy for its production above the $\psi'(3.684)$ but just below the broad structure in the total hadronic cross section at about 4 Gev. This is the state which is supposed to have the properties expected for a charmed meson; D^0 or D^{0*} i.e., its narrow width, the fact that it decays into states of strangeness S = $\pm$1, and its production in association with systems of even higher masses.

d - Production by strong interaction processes -

These processes will proceed in analogy with the strong production of strange hadrons in which ordinary hadronic reactions can produce strange particles in pair. Similarly we expect that charm conservation leads to reactions such as:

$$\pi^- p \longrightarrow M_c B_c$$

and

$$pp \longrightarrow N^* p$$
$$\qquad \hookrightarrow M_c B_c$$
$$\qquad\qquad \hookrightarrow M_c B$$

where M_c and B_c are charmed mesons and charmed baryons respectively with opposite charm quantum numbers. The search for processes of these kind can be performed by looking for the weakly decay of charmed particles to charged hadrons particularly those involving strange particles, to dileptons of opposite charge particularly for $\mu^{\mp}e^{\pm}$, or to a combination of hadrons (K or π) and leptons ($\ell\nu$). Some experiments of these kinds was done at CERN[23] , and no suggestive evidence have been observed.

In the above mentioned sections, we have considered how the new narrow resonances observed in $e^+ e^- \rightarrow$ hadrons and $p + Be \rightarrow e^+ e^-$ + anything could be understood in terms of charm. We have also discussed the properties of charmed particles. It seems that this is a fair description of the new resonances although there are few problems such as:

i - For quite a long time the most serious difficulty of this description was the lack of evidence for the existence of charmed particles. But the recent experiments performed at SPEAR shows the evidence for a state expecting to be a charmed meson which means that the model can get rid of this serious problem. The observed state is supposed to be D^0 or D^{0*} and we are expecting to find its charged partners $D^{\pm}$ or $D^{\pm *}$.

ii - Another weak point of the charm model is the high value of the branching ratio R. The value $R \simeq 5.5$ was observed for energy $W \simeq 4.5$ Gev, while regarding the quantum numbers of the quarks in charm scheme as shown in table (11) we find the value:

$$R = 3\sum_{i=1}^{4} Q_i^2 = 3\left[(2/3)^2 + (-1/3)^2 + (-1/3)^2 + (2/3)^2\right] = 10/3$$

(where the factor 3 is due to colour) which is smaller than its observed value for energies above the charm threshold. The contribution of the strange quark to R is $\frac{1}{3}$, the contribution of non-strange quarks is $\frac{5}{3}$, and the contribution of the charmed quark to the value of R is $\frac{4}{3}$. So we expect the contribution of $D\bar{D}$ pair in R to be $\frac{4}{3}$ in charm scheme, but the observed increase of R at $W \simeq 4$ Gev is 2.5 - 3 which is twice the expected value in charm scheme.

iii - The known mesons (around 1600 - 1700 Mev) have average decay multiplicities $\langle n \rangle \sim 3.5-4$ (e.g. ρ' and g' mesons). Proton antiproton annihilation at rest have $\langle n \rangle \sim 5$. We estimate $\langle n \rangle \sim 4$ for an average D meson. This gives average charged multiplicity $\langle n_{ch.} \rangle \sim 2.5-2.7$ per D meson and $\langle n_{ch.} \rangle \sim 5-5.5$

for each $D\bar{D}$ pair, but experimentally the average charged multiplicity above $W \simeq 4$ Gev is 4 rather than the expected value 5 - 5.5.

iv - We expect the charmed quark couples more strongly to the strange quark than to the others, so we expect the observation of decays such as $D^{\circ} \rightarrow K^{-}\pi^{+}$ and $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}, \ldots$ and for long time this was another weak point of this model since experimentally the number of such decay modes were small. But the recent observation of $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ particles in $e^{+}e^{-}$ annihilation at SPEAR may mean that this problem is solved.

v - We expect few $e\mu$ and $\mu\nu$ decay modes, but the events of the type $e^{+}e^{-} \longrightarrow e^{\mp} + \mu^{\pm} + \text{neutrals}$ which are observed at SPEAR(24) are too much and it is called "anomalous $\mu - e$ events" in the data. There are many possibilities for the origin of these events and all are associated with the production of a pair of particles, each with an additive conserved quantum number which is zero for $e^{+}e^{-}$ system. Two examples are the production and decay of a pair of new heavy leptons and the production of a boson pair with a quantum number such as charm.

CHAPTER FOUR

SOME OTHER INTERPRETATIONS FOR ψ PARTICLES.

In this chapter we discuss some other explanations suggested to interpret the ψ resonances. From the first days of the discovery of $\psi(3.1)$ the theorists began to suggest models to interpret this new particle. Many interpretations were proposed and most of them have some problems as well as some good features.

Some authors(25) suggested that the ψ particles could be interpreted as neutral weak bosons. They supposed the gauge structure $SU(2)_L \times U(1)_Y \times U(1)_R \times U(1)_L$ where $SU(2)_L \times U(1)_Y$ is the ordinary gauge freedom in Weinberg-Salam model and $U(1)_R \times U(1)_L$ is the right-handed and left-handed Fermion number gauge. Then the symmetries act on a left-handed doublet $L = \begin{pmatrix} \mu \\ \nu \end{pmatrix}_L$ and on a right-handed singlet μ_R. The lagrangian is constructed out of L and μ_R plus ordinary gauge fields $\vec{A}_\mu$ and Z_μ plus a scalar meson $\phi_1 = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}$ Then the vector and axial vector mesons are defined by

$$X_\mu = \frac{1}{\sqrt{2}}\left(C_\mu + D_\mu\right)$$

$$Y_\mu = \frac{1}{\sqrt{2}}\left(C_\mu - D_\mu\right)$$

and ψ and ψ' are considered to be X_μ and Y_μ respectively. Actually this interpretation encounters several problems and the most serious one is the decay width of ψ' for $\psi' \to \psi + 2\pi$ which this model can not make the width for this decay greater than the leptonic decay width for ψ.

Another model was suggested by Iwasaki(26) in which $\psi(3.1)$ is assigned to a vector meson $c\bar{c}$, as in the charm scheme, while ψ' is assigned to an exotic meson $c\bar{c}(u\bar{u} + d\bar{d})$. This model predicts two resonances, $c\bar{c}(u\bar{u} - d\bar{d})$ with $I=1$ and $c\bar{c}\, s\bar{s}$ with $I=0$ between ~ 3.7 Gev and ~ 4.1 Gev, and suggests that the structure of the total cross-section at the vicinity of 4.1 Gev in $e^+ e^-$

annihilation is due to these two resonances and the threshold effect of the charmed hadron pair production. The model also predicts a resonance at about 6.2 Gev with the quark structure $c\bar{c}c\bar{c}$. The observation of a resonance at 6.0 Gev by Eartly etal[27] in high energy P-Be interactions can be a confirmation of this model, but this resonance has not been observed in $e^+ e^-$ annihilation at SPEAR. If this model was to be taken seriously, then we would, of course, need to consider the other states containing two quarks and two antiquarks, e.g. $u\bar{u}u\bar{u}$, etc. Most assignments of the "old" resonances in the quark model do not include such states. It is possible of course that these states are so broad that they have not been seen (e.g. $(u\bar{u}u\bar{u})$ can easily break up into $((u\bar{u}) + (u\bar{u}))$. The same thing does not apply in Iwasaki's model because it is not sufficiently massive. Some discussions of these type of states has been given in the MIT Bag Model.[28]

R.M. Barnett[29] proposed a model consisting of three charmed quarks (u', d', s') in addition to the three ordinary uncharmed (u,d,s) quarks and tried to construct hadrons out of these six quarks, particularly the $\psi(3.1)$ in this model is considered to be $(u'\bar{u}' + d'\bar{d}')/2$. Also the same author in another paper[30] reviewed several models with more than four quarks.

H. Fritzsch[31] has proposed a new interpretation of ψ-resonances based on five quarks (u,d,s,C,U) instead of four in the charm model. The ψ and ψ' are bound states of the two new quarks C and U; i.e. ψ is mainly a $C\bar{C}$ state and ψ' is mainly a $U\bar{U}$ state but there is a relatively small mixing φ:

$$\psi = \cos\varphi\, C\bar{C} + \sin\varphi\, U\bar{U}$$

$$\psi' = -\sin\varphi\, C\bar{C} + \cos\varphi\, U\bar{U}$$

Among other interpretations are the three-triplet models and Harari's model which we will discuss in more detail in the following sections.

4.1 - The Three-Triplet models -

The three-triplet model with double SU(3) symmetry was first proposed by M.Y. Han and Y. Nambu[32] in 1965 with a view to avoid some of the kinematical and dynamical difficulties involved in the single-triplet quark model, such as non integral electric charges, spin statistics for quark models of baryons, rate of the decay $\pi^{\circ} \longrightarrow \gamma\gamma$ etc. The concept of this model is that there are three times as many quarks as the naive SU(3) model with the corresponding quantum numbers and weight diagram shown in table (20) and Fig (31) respectively. It was supposed that the nine members of the three triplets $t_{1\alpha}, t_{2\alpha}, t_{3\alpha}$; $\alpha = 1, 2, 3$ be combined into a single multiplet;

$$T = \{ t_{i\alpha} \} \quad ; \quad i = 1, 2, 3 .$$

Then two distinct sets of SU(3) operations on T were imagined, one is the SU(3) acting on the index α for each multiplet, while the other SU(3) acts on the index i, which mixes corresponding members of different triplets. T is then a representation $(3, 3^*)$ of this group $SU(3) \times SU(3)'$. According to this model, the meson and baryon states are TT^* and TTT combinations respectively, and the $SU(3) \times SU(3)'$ contents of these 81 and 729-plets are;

$$(3,3^*) \times (3^*,3) = (8,1) + (1,1) + (1,8) + (8,8)$$

$$(3,3^*) \times (3,3^*) \times (3,3^*) = (1,1) + 2(8,1) + 2(1,8) + (1,10^*)$$

$$+ (10,1) + 2(8,10^*) + 2(10,8) + 4(8,8)$$

$$+ (10,10^*)$$

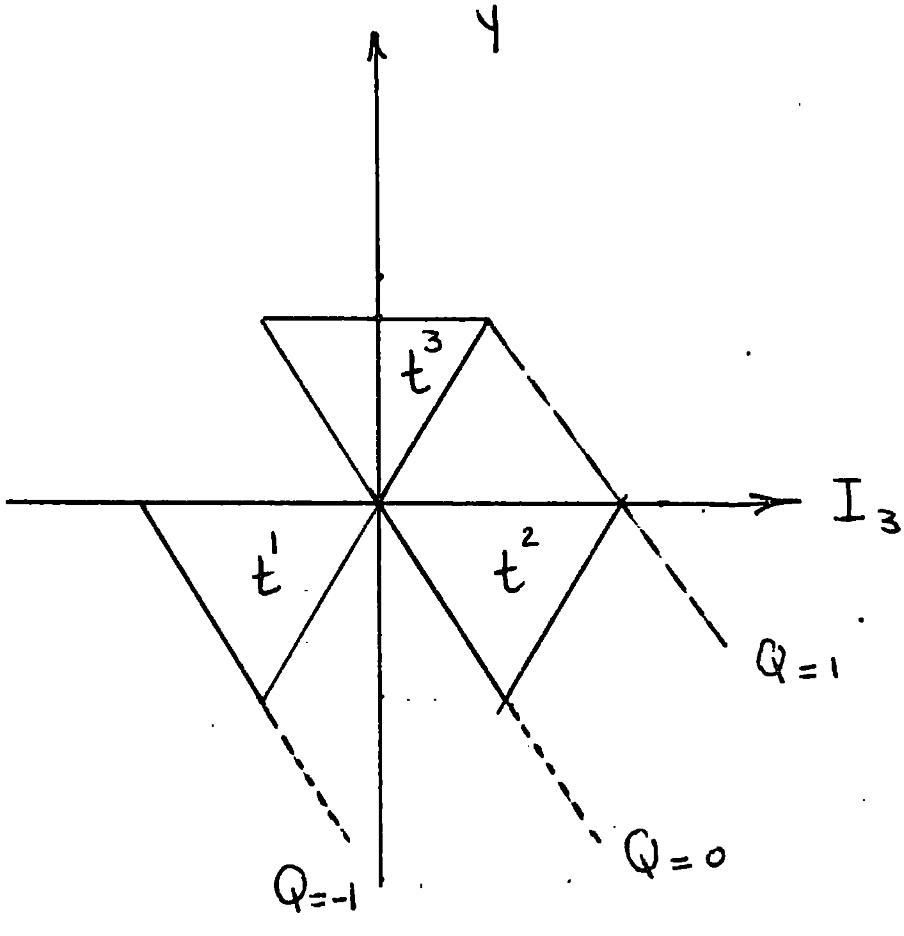


Fig 31 - The weight diagram of the three-triplet model

	t_1			t_2			t_3		
I_3	$\frac{1}{2}$	$-\frac{1}{2}$	0	0	-1	$-\frac{1}{2}$	1	0	$\frac{1}{2}$
Y	1	1	0	0	0	-1	0	0	-1
Q	1	0	0	0	-1	-1	1	0	0

Table 20 - The quantum numbers of the quarks in three triplet model

The low-lying meson and baryon states are (8,1), (1,1) and (8,1), (1,1), (10,1) respectively.

As for the baryon number assignment to the triplets, the simplest possibility would be to assign an equal baryon number, i.e. $B = \frac{1}{3}$ to them. In this case the triplets themselves would be essentially stable, and their nine members would behave like an octet plus a singlet of "heavy baryons". Another simple possibility may be B = (1,o,o) for (t_1, t_2, t_3).

Some other distinct models consisting nine quarks, with varying degrees of similarities between them, have been proposed. The paraquarks of Greenberg(33) which were proposed even before Han and Nambu model, consists of a single SU(3) triplet of parafermions of order 3, if the Green-Component fields are to be taken as independent fields, then this model contains nine quarks. The basic features of Han and Nambu three-triplet model were independently proposed by Tavkhelidze. Miyamoto has considered slightly different integrally charged three-triplets within the framework of SU(9) symmetry. Another three-triplet model was proposed by Tati in which the quarks are assigned a spin of magnitude one with the symmetry group SU(3) x So(3). Also Gell-Mann(34) has proposed the paraquark model in version in which the additional index (refred to it as Green index in Greenberg's model) is called colour. All these nine quark models will have for their respective symmetry groups either SU(3) x SU(3) or SU(3) x So(3) structure, where the first SU(3) in each case is the usual one, while the second groups SU(3) or So(3) are the ones for the symmetry of the hidden variables. It should be noted that now, in fact, most people believe that quarks do possess colour and it is proved that the idea of colour is consistent with the $c\bar{c}$ interpretation of ψ and ψ' i.e., we believe that in the charm model the four quarks appear in three colours. But what is different in this chapter is about the assignment of ψ and ψ' as colour octets in spite of the ordinary hadrons which are singlets in colour space as will be discussed later on.

In the case of colour quarks, there are a set of three indistinguishable SU(3) quarks, all their quantum numbers are to be identical except a new quantum number called colour which appears in red, yellow and blue (by convention) for different SU(3) quarks. The electric-charge assignments to the three indistinguishable sets of SU(3) quarks is:

$$(Q, Q-1, Q-1) \equiv (2/3, -1/3, -1/3)$$

where $Q = I_3 + \frac{1}{2}Y$. This model is in compatible with both the $\pi^{\circ} \rightarrow 2\gamma$ decay rates and the total $e^+e^- \rightarrow$ hadrons cross sections i.e. the $\pi^{\circ} \rightarrow 2\gamma$ decay rate becomes;

$$\Gamma(\pi^{\circ} \rightarrow \gamma\gamma) = \frac{9S\alpha^2}{32\pi^3} \left| f_A(0) \right|^2 \left(\frac{m_\pi}{f_\pi} \right)^2 m_\pi$$

with $f_A(0) = 1.23$ and

$$S = \left[\tfrac{1}{2}Q^2 + \tfrac{1}{2}(Q-1)^2 \right]^2 = \left[\tfrac{1}{2}(\tfrac{2}{3})^2 + \tfrac{1}{2}(-\tfrac{1}{3})^2 \right]^2 = \frac{25}{324}$$

then $\Gamma = 7.3$ ev which is in perfect agreement with experiment, while the nearest value calculated by Steinberger was 13.8 ev. In the asymptotic energy limit, the ratio R defined by

$$R = \frac{\sigma_{tot}(e^+e^- \longrightarrow \text{hadrons})}{\sigma_{tot}(e^+e^- \longrightarrow \mu^+\mu^-)}$$

in the parton model for spin $\frac{1}{2}$ partons is given by

$$R = \sum_i Q_i^2$$

Then the colour quark model gives R=2 which is three times those for the Gell-Mann-Zweig quarks.

$$R = 3\, R_{G.M.Z.} = 3(2/3) = 2$$

Now consider the Han-Nambu three-triplets regarding colour. There are three (red, blue and yellow) triplets which are distinguishable as it is shown in table (20), in contrast to the colour quarks introduced by Gell-Mann. The value of R in this case is R=4, which is consistent with data for energies ~ 4 to 5 Gev.

Now we construct hadrons from these new quarks. Ordinary hadrons are colour singlets. For instance a pion which is $|\pi^+\rangle = |u\bar{d}\rangle$ in the original SU(3) model, becomes in the colour model;

$$|\pi^+\rangle = \frac{1}{\sqrt{3}}|u_R\bar{d}_R + u_B\bar{d}_B + u_y\bar{d}_y\rangle$$

therefore ordinary hadrons are colourless made of the three colours, it is in this sence that colour SU(3) is a hidden symmetry. Newly discovered mesons are colour octets as will be discussed later. Constructing the photon depends on using Gell-Mann colour quarks or Han-Nambu scheme. For uncoloured quarks with the charges

u	d	s
$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

the photon may be written as:

$$\gamma \sim \frac{2}{3}u\bar{u} - \frac{1}{3}d\bar{d} - \frac{1}{3}s\bar{s}$$

so in the Gell-Mann scheme consisting three identical triplets with the charges:

	u	d	s
R	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
B	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
Y	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$

the photon may be written as:

$$\begin{aligned}\gamma_{G.M.} &\sim (\tfrac{2}{3}u_R\bar{u}_R - \tfrac{1}{3}d_R\bar{d}_R - \tfrac{1}{3}s_R\bar{s}_R) + (\tfrac{2}{3}u_y\bar{u}_y - \tfrac{1}{3}d_y\bar{d}_y - \tfrac{1}{3}s_y\bar{s}_y) \\ &\quad + (\tfrac{2}{3}u_B\bar{u}_B - \tfrac{1}{3}d_B\bar{d}_B - \tfrac{1}{3}s_B\bar{s}_B) \\ &= \underbrace{(\tfrac{2}{3}u\bar{u} - \tfrac{1}{3}d\bar{d} - \tfrac{1}{3}s\bar{s})}_{\text{u-spin singlet}}\underbrace{(R\bar{R} + B\bar{B} + Y\bar{Y})}_{\text{Colour singlet}}\end{aligned}$$

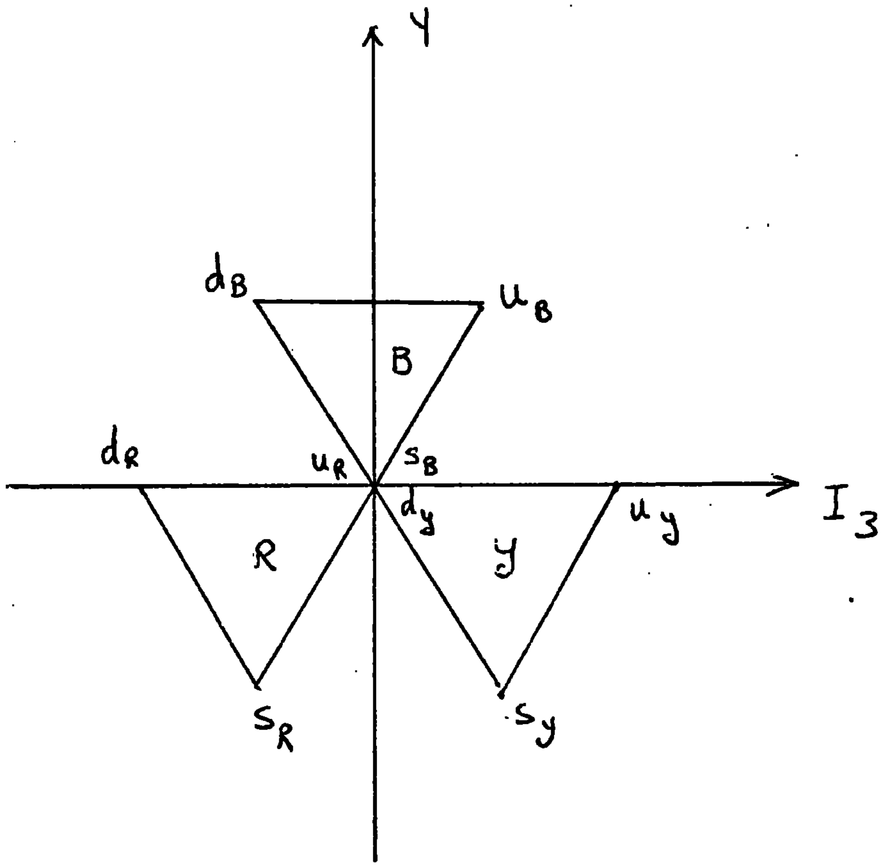


Fig 26- Three triplets in colour model

which is obvious that γ is colour singlet. In Han-Nambu model consisting three distinguishable triplets with the following charges:

	u	d	s
R	o	-1	-1
B	1	o	o
Y	1	o	o

the photon can be written as:

$$\gamma_{H.N.} \sim \bar{u}_y u_y + \bar{u}_B u_B - \bar{d}_R d_R - \bar{s}_R s_R$$

$$= \underbrace{\left(\tfrac{2}{3} u\bar{u} - \tfrac{1}{3} d\bar{d} - \tfrac{1}{3} s\bar{s}\right)}_{\underline{8}} \left(\underbrace{R\bar{R} + Y\bar{Y} + B\bar{B}}_{\underline{1}'}\right)$$

$$- \underbrace{\left(u\bar{u} + d\bar{d} + s\bar{s}\right)}_{\underline{1}} \left(\underbrace{\tfrac{2}{3} R\bar{R} - \tfrac{1}{3} B\bar{B} - \tfrac{1}{3} Y\bar{Y}}_{\underline{8}'}\right)$$

which is obvious that γ is not colour singlet here, it can excite either as colour singlet ($\underline{1}'$) or as colour octet ($\underline{8}'$)

$$\gamma_{H.N} = (\underline{8}, \underline{1}') - (\underline{1}, \underline{8}')$$

The ($\underline{8}, \underline{1}'$) part contains the familiar vector mesons (ρ, ω, ϕ) which are colour singlets, while the ($\underline{1}, \underline{8}'$) piece can excite vector mesons which are singlets of SU(3) and octets of SU(3)$'$. If colour is conserved by strong interactions, then these ($\underline{1}, \underline{8}'$) states will not decay to the ($\underline{8}, \underline{1}'$) hadrons by strong interactions and so they will be narrow. The ψ particles are assigned to be such ($\underline{1}, \underline{8}'$) states in this model.

Phenomenology of ψ-Particles in Han-Nambu colour scheme(35)

The long lifetime of the ψ and ψ' suggests that these particles possess a quantum number that prevents their strong decay into ordinary hadrons. A natural candidate is colour, where in the colour model the invariance group of the strong interactions is enlarged from SU(3) to SU(3) x **Gcolour** which in the Han-Nambu scheme **Gcolour** is also SU(3). The quarks in Han-Nambu model have integral charge and transform under $SU(3) \times SU(3)'$ according to the $(3,3^*)$ representation. The electromagnetic current transforms according to the $(\underline{1},\underline{8}') \oplus (\underline{8},\underline{1}')$ representation and the electric charge is given by:

$$Q = I_3 + \tfrac{1}{2}Y + I_3' + \tfrac{1}{2}Y'$$

where I' and Y' are the isospin and hypercharge of the colour $SU(3)'$ group. In this model, the ordinary hadrons are supposed to be colour singlets, while ψ and ψ' are colour octets and we postulate the exact colour symmetry for all strong interactions to make ψ and ψ' so narrow. But the colour symmetry is violated by electromagnetic and weak interactions, because of the production of the ψ via a single γ in the $e^+ e^-$ annihilation.

If we forget about the electromagnetic and weak interactions, then the masses M of Colour mesons should satisfy the Gell-Mann-Okubo mass formula;

$$M^2 = a^2 + b^2\left[I(I+1) - \tfrac{1}{4}Y^2\right] + c^2 J(J+1) \qquad (1)$$

where a^2, b^2, and c^2 are constant and J is the spin of the meson. We refer to a colour octet meson by the symbol (V,C) where V shows the characteristics of the meson in usual SU(3) and its spin-parity, and $C = (\pi, K, \bar{K}, \eta)$ represents the transformation property in the colour $SU(3)'$. For example (ω, η) refers to the colour octet neutral vector meson with transformation properties like ω and η under the SU(3) and $SU(3)'$ respectively. Then the ψ and ψ' in this notation can be interpreted as:

$$\psi(3.1) = (\omega, \eta) \equiv \omega_c$$

and

$$\psi'(3.7) = (\phi, \eta) \equiv \phi_c$$

where we have used the notation $(V, \eta_c) \equiv V_c$ for simplicity. These are not the only assignments introduced for the new resonances, for example Stech made the assignments;

$$\psi = (\omega, \rho^0)$$
$$\psi' = (\phi, \rho^0)$$

but we follow the notation in reference (35). In this picture the masses of $K_c^* \equiv (K^*, \eta)$ and $(\rho, \eta) \equiv \rho_c$ with the assumption of exact colour symmetry is calculated to be;

$$M(K_c^*) = 3.37 \text{ Gev}$$
$$M(\rho_c) = 3.07 \text{ Gev}$$

Assuming that C^2 in equation (1) is independent of the colour which means that the spin dependence of eq. (1) does not depend on colour, then the mass of colour-octet pseudoscalar mesons would be;

$$M(\eta_c) = 3.43 \text{ Gev}$$
$$M(K_c) = 3.29 \text{ Gev}$$
$$M(\pi_c) = 2.98 \text{ Gev}$$

In this picture $\omega_c^* \equiv \psi(4.1)$, $\phi_c^* = \psi(4.7)$ are the excited states of ω_c and ϕ_c respectively. M. Krammer et al [36] with similar estimates and using the masses of ψ and ψ' and the leptonic width of ψ as input have predicted the following recurrences for ψ and ψ'.

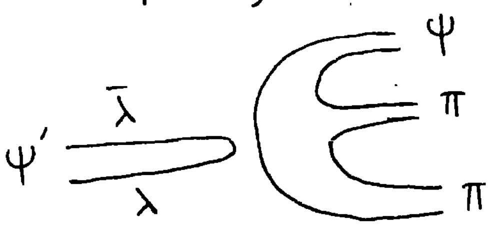
n	SU(3) x SU(3)^c	mass (Gev)
o	$(\omega, \omega_8^c) \equiv \psi(3.1)$	3.105
1	$(\omega, \omega_8^c)'$	4.18 ± 0.08
2	$(\omega, \omega_8^c)''$	5.03 ± 0.13
o	$(\phi, \omega_8^c) \equiv \psi'(3.7)$	3.695
1	$(\phi, \omega_8^c)'$	4.63 ± 0.08
2	$(\phi, \omega_8^c)''$	5.41 ± 0.13

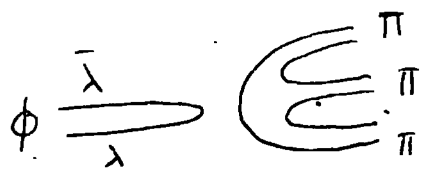
Similar calculations by D. Schildknecht give the results for the masses of the recurrences for ψ and ψ' a little different from those in the above table.

Now we briefly summarize the main features of the colour model and mention the difficulties with which we are faced:

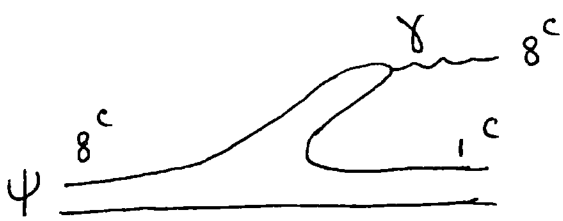
1- The process $\psi \rightarrow$ ordinary hadrons is forbidden to occur since they correspond to SU(3) colour octet-singlet transitions. Also ψ can not decay strongly into any hadron system with a coloured meson like ($\pi_c + \pi + \pi$) mode because it is forbidden energetically as it can be seen from the predicted masses for coloured mesons mentioned earlier. So ψ would **be narrow as it is seen experimentally.**

2- The decay $\psi' \longrightarrow \psi + \pi^+ + \pi^-$ is an ordinary strong decay in the colour model but it is suppressed by Zweig's rule in analogy to $\phi \longrightarrow \rho^0 \pi$





3- Radiative decays of the type $\psi \longrightarrow \gamma +$ ordinary hadrons are allowed, in contrast to the charm scheme where the hidden charm particle can not loose its hidden charm by photon emission, the coloured vector mesons can turn into a normal hadron just by radiating away its colour via a colour-octet photon



A typical radiative width such as that for $\omega \rightarrow \pi^{\circ}\gamma$ is of order 1 Mev, but for the colour case the estimated width are larger by roughly two orders of magnitude than the observed extremely narrow widths of the new particles. In references (36) and (35) some calculations have been used to reduce these estimates for radiative widths of ψ and obtain more reasonable estimations.

4- We expect only $J^{P} = 0^{-}$ neighbours of ψ and ψ' (just like ρ, ω, ϕ and $\pi, K, \ldots\ldots$) but experimentally several states are found which have not got $J^{P} = 0^{-}$ (several χ states). These problems together with the fact that the predicted states by the model haven't been observed make it unlikely to accept the ψ and ψ' being coloured states.

4.2 - A New Quark Model for Hadrons (Harari's Model)[37]

In this section we consider a new model for the spectrum of hadrons which differs from all previous schemes, but it contains some of the ideas of charm and colour models. At first, it seemed to be the most plausible model for describing the new particles because most of its predictions were in good agreement with the data. But with the recent data, it seems that this model will be in some trouble.

In this model the building blocks of hadronic states are six quarks instead of 3 or 4 or 9 in SU(3), SU(4) or three-triplet model respectively. Three of these six quarks are the usual SU(3) triplet (u, d, s), while the other three make a new SU(3) antitriplet of heavy quarks which includes an isodoublet (t,b) with electric charges ($\frac{2}{3}$, $-\frac{1}{3}$) together with an isosinglet (r) with electric charge $\frac{2}{3}$. The weight diagrams of these triplet and antitriplet are shown in Fig (33) and the corresponding quantum numbers in table (21).

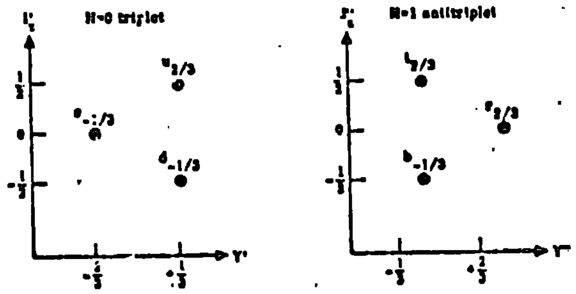


Fig.33 - The ordinary U(up), d(down),s(singlet) quarks and the proposed heavy t(top), b(bottom),r(right) quarks.

	Q	I_3	Y
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$
d	$-\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{3}$
s	$-\frac{1}{3}$	o	$-\frac{2}{3}$
t	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$
b	$-\frac{1}{3}$	$-\frac{1}{2}$	$\frac{1}{3}$
r	$\frac{2}{3}$	o	$\frac{4}{3}$

table 21 - The quantum numbers of the quarks in Harari's model.

As it is obvious from table (21), three of these six quarks (i.e. u, t, r) have $Q = \frac{2}{3}$ while the others (d, s, b) have $Q = -\frac{1}{3}$, this special choice of quarks charges will lead to the right values of R as will be seen later. The heavy quarks possess a new additive quantum number which is named heaviness by Harari. The new quarks carry the heaviness H=1, while the usual quarks have H=o. The antiquarks in this model make an H=o antitriplet together with an H= -1 SU(3) triplet. Another assumption of the model is that each of these six quarks can come in three colours, but no coloured hadrons exist.

One of the successful predictions of this model is the value of $R = \frac{\sigma(e^+e^- \longrightarrow \text{hadrons})}{\sigma(e^+e^- \longrightarrow \mu^+\mu^-)}$ It predicts that, below the threshold for the production of heavy mesons (i.e. the energy domain where the heavy quarks are not excited), the value of R would be;

$$R = 3\left[\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right] = 2$$

where the coefficient 3 is due to colour. For the values of energy above the threshold for the production of heavy mesons, this scheme predicts the following value for R;

$$R = 3\left[3\left(\frac{4}{9}\right) + 3\left(\frac{1}{9}\right)\right] = 5$$

With the assumption that the heavy mesons are produced above 4 Gev, we see that these values of R are in good agreement with the observed values of R (Fig 14 in Chapter one).

To construct the mesons out of these quarks, we must look at the combinations of (6) and $(\bar{6})$;

$6 \otimes \bar{6} = (8 + 1) \oplus (\bar{6} + 3) \oplus (6 + \bar{3}) \oplus (8 + 1)$

So for each J^P value, there are 36 meson states which appear in SU(3) multiplets as follows;

a- Those states made of ordinary quarks make the usual octet and singlet of mesons with H=o.

b- Those states containing only one heavy quark make nine heavy mesons with H=1 which appear in $(\bar{6} + 3)$ multiplets of SU(3) and nine other states with H= -1 that appear in $(6 + \bar{3})$ multiplets of SU(3). The weight diagram for these states are shown in Fig (34).

c- There are nine meson states made of a heavy quark and a heavy antiquark, so they will carry H=o. These states appear in octet and singlet. Three of these states, namely the three neutral, non-strange vector mesons, can couple directly to the photon. The states ψ, ψ' and ψ'' are assigned to be an SU(3) singlet, the I=o member of an octet, and the I=1 member of the same octet made of heavy quarks and heavy antiquarks respectively. The quark contents of ψ, ψ' and ψ'' are;

$$\psi = \frac{1}{\sqrt{3}}(t\bar{t} + b\bar{b} + r\bar{r})$$

$$\psi' = \frac{1}{\sqrt{6}}(t\bar{t} + b\bar{b} - 2r\bar{r})$$

$$\psi'' = \frac{1}{\sqrt{2}}(t\bar{t} - b\bar{b})$$

The consequences of these assignments for the ψ- particles can be summarized as follows:

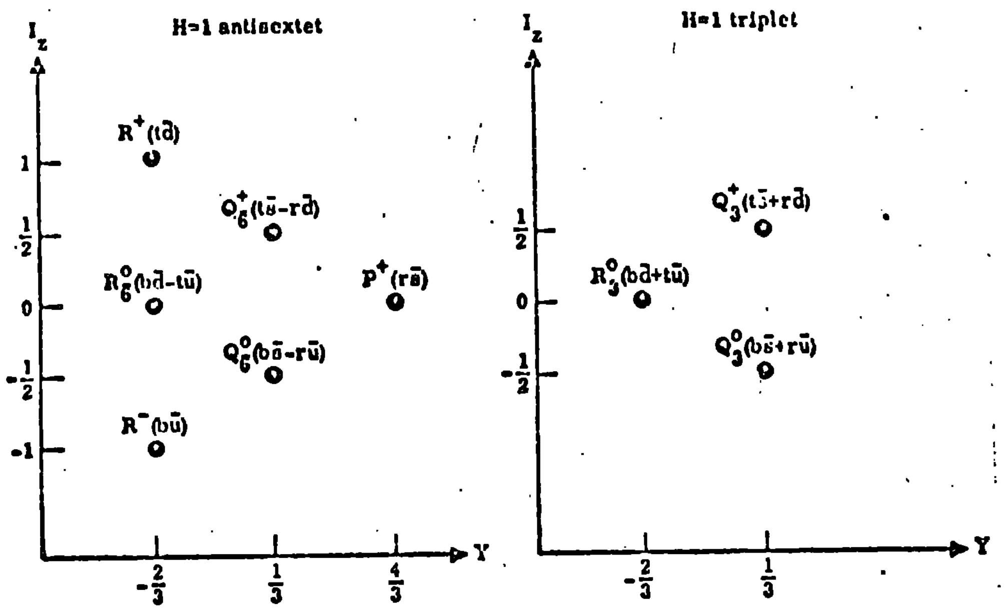


Fig 34- The predicted H=1 heavy mesons and their quark content.

1- The above identifications of ψ, ψ' and ψ'' together with the charge assignments for the t, b, and r quarks as in table (21) lead to the prediction;

$$\Gamma(\psi \rightarrow e^+e^-) : \Gamma(\psi' \rightarrow e^+e^-) : \Gamma(\psi'' \rightarrow e^+e^-) = 2:1:3$$

This is rather comparable with the corresponding experimental values

$$\Gamma(\psi \rightarrow e^+e^-) = 4.8 \text{ Kev}$$

$$\Gamma(\psi' \rightarrow e^+e^-) = 2.2 \text{ Kev}$$

$\Gamma(\psi'' \rightarrow e^+e^-) \sim 4 \text{ Kev}$ (if it is considered as a single resonance).

2- ψ (but not ψ') can not decay to $K\bar{K}$ or $K\bar{K}^*$ because it is SU(3) forbidden. The decays $\psi' \longrightarrow \psi\eta$ and $\psi' \longrightarrow \psi\pi^+\pi^-$ are allowed.

3- The masses of ψ' and ψ'' can be used to give the mass differences among the heavy quarks. For t and b quarks we can write m(t) = m(b) because of isospin conservation. For t and r quarks, we suppose that there is a linear relation between meson mass and quark masses, then from the quark contents of ψ' and ψ'' we get;

$m(t) - m(r) \sim 350$ Mev.

This means that the r quark is the lightest one among the heavy t, b, and r quarks which confirms that larger hypercharge corresponds to the lower mass (this is in fact an empirical rule for quarks and baryons).

4- The model predicts two other states around 4.1 Gev namely ψ''^+ and ψ''^-, which complete the I=1 ψ'' multiplet. This can be somewhat related to the recent suggestions that in fact the structure in the vicinity of 4.1 Gev is not a single resonance and there are more than one particle contributing to the wide bump at

4.1 Gev.

5- In this model, all P-wave ψ-particles are supposed to be above 4.1 Gev, which conflicts the prediction of charm scheme suggesting the o^{++}, 1^{++} and 2^{++} narrow mesons located somewhere between ψ and ψ'. But the discovery of $\chi(3.41)$, $\chi(3.5)$ and $\chi(3.55)$ confirms the charm prediction and this is a weak point of the Harari model.

6- As it was mentioned before, in this model, ψ, ψ', and ψ'' are 1^3S states, and the radial excited states must be much heavier and they would be very wide. The model also predicts four strange ψ-particles around 3.8 Gev having quantum numbers like K^* and $\bar{K}^*$. It is also predicted that the nonet of pseudoscalar bound states of heavy quarks and heavy antiquarks be around 3-4 Gev.

7- For the heavy mesons with $H=\pm1$, it is supposed that the lightest one is P^+ with quark contents $r\bar{s}$ and isospin $I=o$. If we accept that the rise in R is due to the production of a pair of heavy mesons, then $m(P^+)$ must be around 1800 Mev because the rise in R actually begins somewhat below the ψ' mass. The model also suggests that the lowest lying heavy mesons (with $H=\pm1$) have only weak decay and by defining the charged weak current (in the way which leads to the absence of all $|\Delta S|=1$, $|\Delta H|=1$ neutral currents), the major decay modes of the nine heavy mesons are predicted to be;

a- P^+ decays : Leptonic - $\ell^+\nu$; Semileptonic - $\phi\ell^+\nu, K^+K^-\ell^+\nu$, $K^o\bar{K}^o\ell^+\nu$, etc. nonleptonic - $\pi^+\eta$, $K^+\bar{K}^o$, $\pi^+\pi^+\pi^-$, $\pi^+\pi^o\pi^o$ $\pi^+\pi^o\eta$, etc.

b- Q^+ decays = Both Q^+_6 and Q^+_3 have decay modes similar to those for P^+. The heavier Q^+ may have radiative decay to the lighter one.

c- Q° decays = (For both $Q^{\circ}_{\bar{6}}$ and Q°_{3}): Semileptonic - $K^{-}\ell^{+}\nu$, $K^{-}\pi^{\circ}\ell^{+}\nu$, $\bar{K}^{\circ}\pi^{-}\ell^{+}\nu$, etc.; nonleptonic - $\bar{K}^{\circ}\pi^{\circ}$, $K^{-}\pi^{+}$, $K^{\circ}\eta$, $K^{-}\pi^{+}\pi^{\circ}$, $K^{-}\pi^{+}\eta$, $\bar{K}^{\circ}\pi^{+}\pi^{-}$, $\bar{K}^{\circ}\pi^{\circ}\pi^{\circ}$, etc. Again the heavier Q° can have radiative decay into the lighter one.

d- R^{+} decays = Semileptonic - $\bar{K}^{\circ}\ell^{+}\nu$, $\bar{K}^{\circ}\pi^{\circ}\ell^{+}\nu$, $K^{-}\pi^{+}\ell^{+}\nu$ etc.; nonleptonic - $\bar{K}^{\circ}\pi^{+}$, $K^{-}\pi^{+}\pi^{+}$, $\bar{K}^{\circ}\pi^{+}\pi^{\circ}$, $\bar{K}^{\circ}\pi^{+}\eta$, etc.

e- R^{O} decays - Both $R^{\circ}_{\bar{6}}$ and R°_{3} have decay modes similar to those for Q°.

f- R^{-} decays - It can not decay into H=o mesons and its leading decays will be into $R^{O}+\ell^{-}+\bar{\nu}$

g- It is stated that the heavy mesons can be discovered in $e^{+}e^{-}$ annihilation or in neutrino reactions, but their discovery as peaks in $e^{+}e^{-}$ collisions would be more difficult than for the charmed particles because they will have smaller production cross section since the same σ_{tot} should be shared among nine heavy mesons instead of three charmed ones. There is no evidence for such mesons yet and their discovery would be a crucial test of this model.

CONCLUSION

The past two years since the discovery of $\psi(3.1)$ at SPEAR and BNL have been the most exhilarating for particle physics in many years. The number of exciting new discoveries and the amount of new experimental information are incredible (at least a dozen totally new hadronic states in the mass range 1.8 Gev to 4.5 Gev have been discovered within 20 months from the discovery of the first ψ- particle, which means that every 10 days a new state has been discovered). Few theorists could resist the temptation to drop their current problems and to begin sketching out their speculations.

Besides the discovery of many new states, the experiment shows a clear threshold in R (the ratio of the total hadron cross-section to the simple QED cross-section for μ-pair production), below 3.5 Gev R is approximately constant with a value around 2.5 while above 5 Gev it is again roughly constant but at a level approximately twice that of the lower energy region. This threshold signals the beginning of a new physics as much as the new particles do. The theorists tried to construct theoretical models describing these new events. In this thesis we considered some of the theoretical models suggested to describe the new particles and tried to understand the problems associated with each case. Our conclusion is that the charm model, containing three ordinary u, d, s quarks together with a new heavy quark carrying a new quantum number charm which is conserved in strong and electromagnetic interactions, is an attractive model, although there are a few problems. The discovery of the narrow state at 1.865 Gev expecting to be a charmed meson, and more recently another candidate for charmed meson at 1.876 Gev make this model more viable.

Another model (which seemed to be a viable model for long time) called Harari's model, containing the standard light quark triplet (u, d, s) together with a heavy anti-triplet (t, b, r), appears to be in some trouble with the recent data. Non of the models containing more than six quarks seems sufficiently attractive to warrant the increase in new hadron states. So the most likely model which can explain the new states consists of 4 quarks (u, d, s, c) each appears in three colours which means that the model consists of altogether 12 quarks.

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