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NEW PARTICLES OR "WHY I BELIEVE IN QUARKS"

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1. - INTRODUCTION

One of the most striking events in the last three years has been the discovery of the new particles. By new particles I mean the J/ψ , ψ' , X 's and also the charmed bosons. There are other new particles like the heavy lepton τ or the "baryonium states" or the candidate for charmed baryon that I shall leave aside. The reason I became interested in this particular group of particles is :

- (i) that it is difficult not to be excited by such discoveries even if your field of interest is miles away, namely rigorous bounds on scattering amplitudes and at the other extreme rigorous inequalities on non-relativistic systems ;
- (ii) that it appears that the members of the J/ψ family can be described as a non-relativistic system of a charmed quark-antiquark pair with great success (of course, the non-relativistic Schrödinger equation can result from the deduction of a relativistic equation), with, of course, a few exceptions ; I realized that this is a sufficiently simple situation to allow to investigate by rigorous methods, within the framework of the Schrödinger equation, the sensitivity of the spectrum and decay mechanisms to the details of the interaction, and try to get, through a few theorems, some insight on how much model dependent are the results ; on the other hand, I shall not touch at all fundamental questions like the confinement of quarks ; I think that for these models it makes absolutely no difference whether quarks are exactly confined or approximately confined escaping after 10^{20} years ;
- (iii) that Prof. N. Zichichi gave me the order to lecture about new particles instead of working on uninteresting problem of mathematical physics ;
- (iv) that I have taught before on the subject of new particles as shown in the Table, which comes from lectures given in Paris in 1958.

My plan will be the following. First I shall try to describe in a minimal way the experimental situation concerning the members of the J/ψ family and in particular discuss the attribution of quantum numbers. You will see that it is not yet possible to make all attributions without theoretical prejudice. In particular this is what happens for the X 's (3550, 3510, 3450, 3410 and 2850 GeV). I shall discuss what can be done experimentally to improve the situation, a thing which seems to me very essential if one wants to consolidate a theoretical model which, after all, has not a very strong basis.

I shall discuss briefly "open charm" and also possible higher states well above the charm production threshold.

Then I shall try to review some of the existing models and present to you a few theorems which help to understand the level scheme and the widths of the new particles.

Finally let me say that I find it very difficult to present all references on the subject. I admire for instance Bjorn Wiik and G. Wolf for the very thorough job they have made in this respect in Les Houches last year lectures ¹⁾, but please do not expect that of me. Other useful general references are Vera Lüth's lectures ²⁾, and J.D. Jackson's talk at the Budapest Conference ³⁾, and also the experimental talks of Litke, Goldhaber and Timm at the same Conference ⁴⁾.

2. - THE J/ψ , ψ' FAMILY AND THEIR DAUGHTERS

2.1. - J/ψ and ψ'

The J/ψ and ψ' are very narrow resonances produced in e^+e^- collisions at 3095 and 3685 MeV, respectively. Their total width is estimated by the following method : one assumes that the cross-section has a Breit-Wigner form. Integrating over energies after subtraction of the background one finds the production width which is Γ_e , independently of the energy resolution of the machine :

$$\Gamma_e = \frac{M^2}{2\pi^2(2J+1)} \int \sigma_{\text{Total}}(E') dE'$$

Similarly the ratio $\Gamma_e/\Gamma_{\text{tot}}$ can be obtained by

$$\frac{\Gamma_e}{\Gamma_{\text{total}}} = \frac{\int \sigma_{\mu^+\mu^-}(E') dE'}{\int \sigma_T(E') dE'}$$

where $\sigma_{\mu^+\mu^-}$ represent the cross-section for producing a muon pair (assuming that the e^+e^- width is equal to the $\mu^+\mu^-$ width).

After elimination of background and radiative effects, one finds

	$\Gamma_e = \Gamma_\mu$	Γ_{tot}
J/ψ	$4.8 \pm 0.6 \text{ keV}$	$69 \pm 1.5 \text{ keV}$
ψ'	$2.1 \pm 0.3 \text{ keV}$	$228 \pm 56 \text{ keV}$

In composite models the leptonic width is proportional to the square of the quark-antiquark wave function at the origin. We shall come back on that question in Section 4 : the comparison of the two widths gives some indications on the potential.

We want now to know the quantum numbers of the J/ψ and ψ' . In both cases it is possible to show that the resonant amplitude in $e^+e^- \rightarrow \mu^+\mu^-$ interferes with the Bhabha term, destructively below the resonance energy, constructively above. This shows that J/ψ and ψ' have the same quantum numbers as the photon $J^{PC} = 1^{--}$.

Next we come to isospin, G parity and SU_3 classification. When one looks superficially at the pionic decay modes of the J/ψ , one sees that it produces both odd and even number of pions. However, odd numbers are dominant. Even numbers can be accounted for by a second order electromagnetic effect, i.e., production of a virtual photon by the resonance followed by hadron production. This mechanism is confirmed by measuring the ratio $\sigma(n \text{ pions})/\sigma_{\mu^+\mu^-}$ on and off the resonance and showing that for n even this ratio does not change, while it changes a lot for n odd. The conclusion is that G parity is conserved in purely hadronic decays of the J/ψ and is odd. From the relation $G = C(-1)^I$ we deduce that isospin is even. But the decay $J/\psi \rightarrow p\bar{p}$, with a probability of $0.22 \pm 0.02\%$ is too large to be explained by QED effects, and is only compatible with $I=0$ or $I=1$, and hence $I=0$. Another proof is given by looking at the $\pi\rho$ decays of ψ/J . One finds that $\sigma(\pi^+\rho^- + \pi^-\rho^+) \simeq 2\sigma(\pi_0\rho_0)$, in agreement with $I=0$. Finally there is the question of the SU_3 classification of J/ψ . One uses the fact that it is forbidden for an SU_3 singlet with odd charge conjugation to decay into two members of the same SU_3 multiplet (and also into two objects belonging to multiplets whose neutral components have the same charge conjugation)⁵⁾. One observes that the decays to $K^+K^-, K^0\bar{K}^0$ are at least 20 times less abundant than the decays to $K^+K^{*-}, K^0\bar{K}^{*0}, K^{*0}K^{*0*}$. Another confirmation of the singlet assignment comes from comparing $p\bar{p}$ and $\Lambda\bar{\Lambda}$ which should have equal rates except for phase space. The same holds for $\pi^-\rho^+$ and K^-K^{*+} . Data indicate that the maximum amount of octet component is in amplitude 12%.

In the case of the ψ' the situation is quite analogous. First of all $1/3$ of the decays goes to $J/\psi \pi^+\pi^-$ and $1/6$ to $J/\psi \pi^0\pi^0$. This indicates that : i) G parity is odd ; ii) $I=0$ from the comparison of $\pi^+\pi^-$ and $\pi^0\pi^0$ rates. This is also confirmed by the observation of $J/\psi + \eta$ decay, and of $p\bar{p}$ decay. Concerning the SU_3 assignment all one can say is the following. If it is a singlet the decay to K^+K^- is forbidden and is observed to be less than 5×10^{-5} . However, we have no data on the $\bar{K}K^*$ modes for comparison. But for $p\bar{p}$ (allowed by singlet) we observe $2.3 \pm 0.7 \times 10^{-4}$. So it seems reasonable to take ψ' to be a singlet part. Then, of course, one has to explain the $\psi' \rightarrow J/\psi + \eta$ decay by the singlet admixture of the η .

2.2. - The X states

It is difficult at this stage to keep completely away from theoretical considerations. In spite of my desire to remain neutral for the time being with respect to the theoretical interpretation of the new particles I have to mention that before the X states were discovered, two groups ^{6),7)} had predicted theoretically the existence of intermediate states between the ψ' and the J/ψ , in a model in which these particles are bound states of charm-anticharm quarks. In fact the prediction of charm-anticharm S states was made by L. Maiani at this school in 1970 ⁸⁾ and later by Applequist and Politzer ⁹⁾. The reason why a charm-anticharm pair has been chosen rather than any other particle-antiparticle system is the narrowness of the J/ψ and ψ' states. By the Okubo-Zweig-Izuka rule the $J/\psi \psi'$, if made of quark-antiquark, have their decays into ordinary hadrons strongly suppressed,

because quark diagrams are unavoidably disconnected. Do not ask me the justification of this rule.

The predictions, made mostly with a potential $V = -\frac{4\alpha_s}{3r} + A + Br$, are as follows.

One has singlet and triplet states depending on how you combine the spins of the quarks. The charge conjugation is given by

$$C = (-1)^{L+S},$$

parity is given by

$$P = -(-1)^L.$$

We get then this picture with the indication of J^{PC} :

We shall discuss later the relative position of the levels, but let me say that with the type of potential that was used the $L=1$ levels were predicted to lie between the ψ' and the J/ψ .

Intermediate states have indeed been observed in several ways :

- i) monochromatic peaks in the inclusive photon decay spectrum of the ψ' ;
- ii) two photons followed by leptonic decay of ψ ;
- iii) one photon plus hadrons.

In i) and iii) decays of the ψ' to three states + one photon have been observed, the energies of the states being 3.41 GeV, 3.50 GeV, 3.55 GeV. In ii) an additional state was found. In fact there was an ambiguity to resolve : in the decay $\psi' \rightarrow \gamma + X$, $X \rightarrow \gamma + \psi/J$, which γ is emitted first ? This has been answered because since the X is in motion the second γ is not monoenergetic. The states found are 3.41, 3.45, 3.50, 3.55 GeV. The 3.45 state, considered as doubtful for some time, partly because of low statistics, partly because of its absence of decay into hadrons, has been recently confirmed by PLUTO.

Here the attribution of J^{PC} quantum numbers is much more difficult, that is if one does not want to appeal to theoretical prejudice. One can of course safely say that $C=+1$, since $\psi' \rightarrow X + \gamma$, and $X \rightarrow \gamma + \psi$, for all four states.

Information on spins and parity can be obtained by looking at single and double γ ray distributions and also hadron decay and correlations between the first γ and hadronic decay. Another easy attribution for the states 3410, 3510, 3550 is the attribution of G parity : it is seen that only even number of pions appear in pionic decay and so

$$G = +1 .$$

From $C = +1$ and from the formula

$$G = C (-1)^I$$

we see that the isospin of these three states (if it is meaningful !) has to be even. However, in the decay $\psi' \rightarrow \gamma + X$ we have $|\Delta I| \leq 1$ to lowest order in electromagnetic interactions and therefore, since $I = 0$ for ψ' we attribute $I = 0$ to 3410, 3510, 3550. However, we must be careful, because we have no guarantee that isospin is conserved in the decay. Fortunately charge conjugation is good enough. If a state with $C = +1$ decays into $\pi^+\pi^-$ or K^+K^- we conclude that :

- i) it has natural spin parity 0^{+1-2+} , etc.;
- ii) however $C = +1$ eliminates odd angular momenta so only $0^{++}, 2^{++}, 4^{++}$, etc. are allowed.

The 3410 and 3550 states are seen to decay into $\pi^+\pi^-$ and K^+K^- and therefore they have $J_{\text{even}}, P = C = +1$.

The state 3510 does not decay into $\pi^+\pi^-$ or K^+K^- . This is not a very severe restriction. As far as I can see, it excludes $0^{++}, 2^{++}, 4^{++}$, etc., but no more.

The second restriction comes from the angular distribution of the γ 's. The simplest thing to do which has been done experimentally is to look at the angular distribution of the first γ from $\psi' \rightarrow \gamma + X$. Only one prediction is model independent : if a X has spin 0 the angular distribution of the γ with respect to the beam is

$$1 + \cos^2\theta$$

However, finding that the distribution is so does not prove that it is spin 0. What is found in a fit $1 + \alpha \cos^2\theta$ is

3414	$\alpha = 1.4 \pm 0.4$
3508	$\alpha = 0.25 \pm 0.5$ or -1 ± 0.5
3552	$\alpha = 0.22 \pm 0.4$
3454	? ? .

The conclusion is

$$\boxed{3508 \text{ and } 3552 \text{ have } J \neq 0}.$$

Hence

$$\boxed{J^{PC}(3552) = 2^{++}, 4^{++}, \text{ etc.}}.$$

This is as far as we can go being completely rigorous. Let us notice, however, that on the basis of general positivity requirements we have $\alpha \leq 1$. If one finds that α is exactly equal to unity it will be only by a dynamical accident (vanishing of the amplitude for producing a helicity one χ) that a spin $J \neq 0$ could simulate a spin 0 and therefore it is likely that 3414 has spin 0^{++} .

If you simplify the rules of the game by deciding that you want to identify the four states with the four states $0^{++} 1^{++} 2^{++} 0^{-+}$ predicted by the charmonium model, you find, following Chanowitz and Gilman ¹⁰⁾

$$\begin{array}{l} 2^{++} \leftarrow 3552 \\ 0^{++} \leftarrow 3414 \\ 1^{++} \leftarrow 3508 \end{array} \left. \begin{array}{l} \leftarrow \text{even } J^{++} \\ \leftarrow \end{array} \right\} \boxed{\text{Spin} \neq 0}$$

The left-over has to be

$$0^{-+} \leftarrow 3450.$$

For the first three states this kind of assignment is consistent with the widths predicted for an electric dipole transition $(2J+1)k^3 \times \text{const.}$ where k is the photon momentum, knowing that the space wave functions of the three states, in a composite model, are the same.

However, my personal opinion is that we should not be contented with this situation and that every effort should be made to obtain a model-independent determination of the spins of these four states. Sooner or later we shall know the angular distribution of $\psi' \rightarrow 3450 + \gamma$ and this might exclude the 0^{-+} assignment in favour of a proposal of Harari ¹¹⁾ to make this a D state, with $J=2$, or consolidate $J=0$, with, however, the possibility of accidental vanishing of an amplitude which would mimic $J=0$.

It has been suggested by various people ¹²⁾ to study correlations, either in the chain

$$\psi' \rightarrow \gamma \chi \xrightarrow{\quad} \gamma \psi/\psi \xrightarrow{\quad} \mu^+ \mu^-$$

or

$$\psi' \rightarrow \gamma \chi \xrightarrow{\quad} 2 \text{ spin } 0 \text{ mesons.}$$

The second procedure, when it can be applied (i.e., for 3414 and 3552) is the most advantageous one because it minimizes the number of amplitudes since the final particles have spin 0. This is what has been pointed out by Kabir and Hey in particular.

They obtain an expression for the correlation function

$$W_2(\theta_\gamma, \theta_M, \phi_M)$$

where θ_γ and θ_M are the angles of the γ and the meson with the beam and ϕ_M is the relative azimuthal angle. These are complicated expressions depending on $J+1$ parameters which are the $J+1$ amplitudes for producing a χ with helicity $0, 1, \dots, J$. Irrespective of the value of these parameters the spin is fixed by the (perfect !) knowledge of W_2 .

In the case of $\gamma\gamma$ correlations the situation is not as nice. In that case Kabir and Hey show that "accidents" can occur producing a completely isotropic angular distribution of the second photon for fixed direction of the first photon and simulating therefore $J=0$, even though the spin is 1 or 2. However, Kabir and Hey, limiting themselves to $J \leq 2$ show that the difficult cases can be resolved by looking at the lepton pair of the final ψ decay. If, for instance, the distribution of the second γ is isotropic the correlation function between the first γ and the muon pair, averaged over azimuthal angles takes the form

$$(1 + A_1 \cos^2 \theta_1)(1 + A_\mu \cos^2 \theta_\mu)$$

$$\begin{array}{ll} \text{if } J_\chi = 0 & A_\mu = 1 \\ J_\chi = 1 & A_\mu = -3/5 \\ J_\chi = 2 & A_\mu = -1/7 \end{array}$$

Therefore, with sufficient statistics a determination of the spins of the χ 's, free from theoretical prejudice, is possible.

Finally let us indicate ¹³⁾ that a spin J larger than 2 would unavoidably show a characteristic pattern in $\gamma\gamma$ correlations (without study of the lepton pair).

One could also ask oneself if the polarization of the e^+e^- beam, which is parallel to the magnetic field and occurs only in certain circumstances, could be used. By a theorem of Bjorken ¹⁴⁾ the answer is negative. In the ultra-relativistic case the only thing the virtual photon remembers is that its linear polarization is perpendicular to the beam. So the unpolarized cross-section for a beam along the z axis, for any exclusive process is :

$$\sigma_u^z = \frac{1}{2}(\sigma_x + \sigma_y)$$

where σ_x and σ_y correspond to linear polarizations of the photon along the x and y axes. From this formula we get

$$\sigma_x = \sigma_u^z + \sigma_u^y - \sigma_u^x .$$

σ_x corresponds precisely to electrons and positrons polarized up and down along the magnetic field. So the polarization of the beam introduces a new azimuthal dependence but gives no new information at least for a 4π detector. It can help in practice because two cones are excluded from the detecting apparatus.

Now we come to another χ state which lies below the J/ψ and has been observed at DORIS ^{4c)}. In the $e^+e^- \rightarrow 3\gamma$ spectrum a peak is observed at 2850 MeV in the $\gamma\gamma$ system after subtraction of the contributions of $\pi\gamma$ and $\eta'\gamma$. Though this state has not been observed at SLAC, evidence for its existence is accumulating at DESY. Naturally the classical arguments of Yang apply to this state which decays like $\chi \rightarrow \gamma\gamma$, and therefore it has $J \neq 1$, and $C = +1$. It is tempting to attribute the quantum numbers 0^{-+} to this state but not yet fully justified.

Finally a new state ^{4a)} has been observed very recently at SPEAR, produced directly in e^+e^- collisions at 3772 GeV, with a width of 28 ± 5 MeV, and a leptonic width of 370 ± 100 eV. This state was not seen before because

it is in the radiative tail of the ψ' . As we shall see this is slightly above the charm-anticharm production threshold and indeed this new state is seen to decay in $D\bar{D}$. This state could be interpreted as 1^{--} (photon quantum numbers) possibly a $L=2$ state in a composite model.

3. - THE CHARM SECTOR 4a), 4b)

New states have been observed around 1870 GeV. In fact they have been looked for very actively before they have been discovered, for two reasons.

i) The Glashow-Iliopoulos-Maiani mechanism for suppressing strangeness changing neutral currents requires the existence of charmed particles. In terms of quarks it requires the existence of a fourth quark :

	B	S	Q	Y	C
u	1/3	0	2/3	1/3	0
d	1/3	0	-1/3	1/3	0
s	1/3	-1	-1/3	-2/3	0
c	1/3	0	2/3	-2/3	+1

ii) The second reason is that it is extremely tempting to regard the ψ and χ states are bound states of pairs of new quarks. The small width of the ψ' indicate that the threshold for the production of charmed-anticharmed mesons should be close to or above 3700 MeV.

In the quark model the three charmed mesons are the

$$D^+(c\bar{d}) \quad D^0(c\bar{u}) \quad F^+(c\bar{s}).$$

The structure of the weak charged current in the GIM is

$$j^+ = \cos\theta (\bar{u}d + \bar{c}s) + \sin\theta (\bar{u}s - \bar{c}d),$$

where θ is the Cabibbo angle.

This leads to the selection rule

$$\Delta Q = \Delta S = \Delta C \quad \Delta I = 0$$

for the favoured transitions, while transitions

$$\Delta Q = \Delta C \quad \Delta S = 0,$$

are suppressed and

$$\Delta Q = \Delta C = -\Delta S$$

is strictly forbidden.

So one expects

$$D^0 \rightarrow K^- \pi^+, \quad D^+ \rightarrow K^- \pi^+ \pi^+,$$

while

$$D^0 \rightarrow \pi^+ \pi^-, \quad D^+ \rightarrow \pi^- \pi^+ \pi^+,$$

is suppressed, and

$$D^0 \rightarrow K^+ \pi^-, \quad D^+ \rightarrow K^+ \pi^+ \pi^-$$

is forbidden. It is worth noticing that in the "old physics" a state like $K^- \pi^+ \pi^+$ which has at least isospin $\frac{3}{2}$ is "exotic", i.e., could not be made of a quark-antiquark pair, while $K^+ \pi^+ \pi^-$ is not exotic. So the D^+ decays will have a very clear signature, and could not be mistaken with the decay of a new excited K. On the contrary the decay of the F^+ ($c\bar{s}$) has not an easy signature. It could decay into a strangeness system like $\eta + n\pi$ or $K\bar{K} + n\pi$'s.

What has been observed is the following.

i) States near 1.86 GeV

- neutrals decaying into $K^\pm \pi^\mp, K^\pm \pi^\pm \pi^\mp$ with mass at 1864 ± 2 MeV, width < 40 MeV. I do not want to describe the tricks of the analysis in which one difficulty is the imperfect separation between K's and π 's.; the initial e^+e^- production energy was 4.03 GeV but new data have been obtained around 3.77 GeV.
- charged particles decaying into $K^+ \pi^- \pi^-, K^- \pi^+ \pi^+$ but not $K^+ \pi^+ \pi^-$ or $K^- \pi^- \pi^+$, with mass 1869 ± 2 , with < 40 MeV; it is natural to identify these states with $D^0 \bar{D}^0, D^+ D^-$. Notice the purely "exotic" decay of the charged D's which clearly excludes excited K^* 's.

- ii) At 4.03 GeV e^+e^- energy one observes peaks in the recoil spectrum of the D^0 and D^- from which one can infer the existence of D^{0*} , mass 2003 MeV $\Gamma < 40$ MeV, with decay $D^{0*} \rightarrow \pi^0 D^0$ and γD^0 and D^{*+} at 2010 MeV with $D^{*+} \rightarrow \pi^+ D^0$. There are other peaks but it has been shown that these can be accounted for by kinematical reflections and are caused by the very small Q value of $D^* \rightarrow \pi D$. Decays into $\bar{D}^* D^*$ have been observed as well.

Now one has to attribute quantum numbers. The small mass difference $D^0 D^+$ makes us put it in an isospin doublet. The spin is tentatively taken to be zero because a spin 1 would in general show decay correlations which are not seen.

The decay $D^{*0} \rightarrow \gamma + D^0$ shows that not both D^0 and D^0 have spin 0. Spin 0 is favoured for D^0 by the angular distribution in $e^+e^- \rightarrow 3.772 \rightarrow D^0 \bar{D}^0$ ¹⁵⁾, hence we are tempted to attribute spin 1 to D^{*0} . If according to the theoretical prejudice D^0 is 0^- D^{*0} is 1^+ because of the existence of the strong decay $D^{*0} \rightarrow D + \pi$.

The question of parity violation

The decay $D^+ \rightarrow K_{\text{short}}^0 \pi^+$ very recently observed, indicates that if parity is conserved D^+ belongs to the natural spin-parity sequence 0^+ 1^- 2^+ , etc. However, the decay $D^+ \rightarrow K^- \pi^+ \pi^+$ is also observed and one can repeat exactly the same exercise that was carried 22 years ago comparing the decays $\rho \rightarrow \pi^+ \pi^-$, $\tau \rightarrow \pi^+ \pi^- \pi^0$.

Notice first that in $D^+ \rightarrow K^- \pi^+ \pi^+$ the subsystem $\pi^+ \pi^+$ is only allowed to have natural spin-parity $0^+, 1^-, 2^+$. If D^+ has spin 0 (favoured by production data) the relative angular momentum of $K^- (\pi^+ \pi^+)$ is equal to the spin of $(\pi^+ \pi^+)$ and hence D^+ should have parity $-$. For higher spins one can compare with the distributions calculated by Zemach which give the minimal structure for a given assignment. The conclusion is that the distribution of momenta of the K 's is uniform and $1^-, 2^+$, etc., are excluded. We are left with spin 0, for which there is an inconsistency i.e., 0^+ from two-body decay, 0^- for three-body decay. Parity is therefore violated.

Pushing the analogy with the $\Theta - \tau$ puzzle we can ask ourselves if there is mixing of the $D^0 \bar{D}^0$ like in the $K^0 \bar{K}^0$ system. More exactly, is the mixing so fast that produced D^0 's decay in $K^+\pi^-$ as well as in $K^-\pi^+$? The test consists in looking at the decay products of $e^+e^- \rightarrow D^0 \bar{D}^0$. In the absence of mixing we should observe only $K^+K^-\pi^+\pi^-$. For 100% mixing we should observe $e^+e^- \rightarrow D_s^0 \bar{D}_s^0$ where D_s is the short-lived combination (notice that $e^+e^- \rightarrow \text{one virtual photon} \rightarrow D_s^0 \bar{D}_L^0$ is forbidden by CP conservation), and events with final states $K^+K^-\pi^+\pi^-$ should be as frequent as $K^+K^-\pi^+\pi^-$. Experiment by the SLAC-LBL group indicates that the mixing is less than 16%.

The unfavoured decays

We have now upper limits on $D^0 \rightarrow \pi^+\pi^- / D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^+K^- / D^0 \rightarrow \pi^+K^-$ of 7% compatible with the value of the Cabibbo angle ^{4b)}.

- iii) Evidence for the existence of the F meson has been obtained at DORIS. One assumes that F is produced as $e^+e^- \rightarrow F^{*-} F^+$, $F^+ \rightarrow \eta\pi^+$. One tries to look for the production of η 's (from the F decay) accompanied by a soft γ (energy < 140 MeV). At 4.4 GeV production energy a clear signal is detected. For more details you can see the lecture by Björn Wiik ¹⁶⁾. The masses are 2.03 ± 0.06 for the F and 2.14 for the F^* .

4. - A THEORETICAL DISCUSSION OF THE J/ψ PARTICLES

It is out of question to make a complete presentation on the whole literature on the subject. Following the example of many others, I shall unavoidably concentrate on the aspects to which I have contributed.

The interpretations in which these various states are colour states have been essentially universally abandoned. Everybody seems to agree that the J/ψ particles are bound states of a charmed quark and a charmed antiquark. Where people differ is on what these quarks are : are they physical particles interacting via a potential which lets them escape so slowly that they are very difficult to observe ?, are they permanently confined by infra-red gluons which can possibly be simulated by a bag with surface and volume energy, or by strings ?, are they "mathematical" objects ? I shall not at all try to answer these questions about which people fight

with great verbal energy and which sometimes are pure questions of semantics : I do not see a great difference between mathematical quarks and permanently confined quarks. There is only one fact on which I think everybody will agree : it is that we need quarks to explain many phenomena in high energy physics. The most spectacular case is that of the new particles, but there are many other things such as the absence of exotic states, the values of the hyperon nucleon cross-sections (1% check by Steinberger of the Lipkin sum rules) the ratio close to $\frac{3}{2}$ for $NN/\pi N$, total cross-sections, etc.

Once you agree that the "new particles" (1975-76) are made of a quark-antiquark pair you have to decide what is responsible for the binding. There you can start at various levels, from a fundamental point of view to a purely phenomenological point of view. The fashionable point of view consists in saying that quarks are bound by coloured gluons, but all you can do is to compute the single gluon exchange which produces a kind of relativistic Coulomb potential in which you can even decide that the coupling constant dies logarithmically for $r \rightarrow 0$ because of asymptotic freedom ; here at least one has a relatively clear prescription for the choice of the vector character of the potential, and this is relevant when one goes to the non-relativistic reduction to know what will be the spin effects accompanying the "Coulomb" force. However, nobody knows how to compute the "confining" force, its spin dependent effects, etc. So depending on what you assume in your relativistic equation as interaction you get different results in its non-relativistic reduction.

What I want to argue is that it is as well to start non-relativistically from the very beginning, or if you want, to justify laziness, precisely because of our ignorance, and, also, because it happens that the spectrum is fitted by a relatively high quark mass, about 1.6 GeV, and that quarks are indeed not moving too fast.

The standard model proposed first by Applequist, Politzer and Glashow ⁶⁾ and Eichten, Lane, Kinoshita, Gottfried and Yan ⁷⁾ has a central potential of the form $V = -\frac{4}{3}(\alpha_s/r) + A + Br$. This potential produces a sequence of levels (using the hydrogen notation) :

which splits into singlet and triplet states. We have indicated J^{PC} of the various states using

$$\begin{cases} P = -(-1)^L \\ C = (-1)^{L+S} \end{cases}$$

The spectrum appears to be in qualitative and, almost quantitative, agreement with the data. The most spectacular prediction is that of the three P states. I was the witness of a talk given by Kurt Gottfried in Dijon before the discovery of the $C=+1$ states. He said that the model would be definitely ruined if it was confirmed that these states were absent. Another spectacular prediction by various groups ^{17),18)} is that of the triplet $3D$, 1^{--} state at 3.77 GeV which has just been recently discovered, which we shall call ψ'' . One could argue that the agreement is too good. It is true that there is an element of luck. However, what is significant is that within 10 MeV of the ψ' a new state, which can be directly produced by one photon in e^+e^- collisions, is observed (see below a discussion of the production mechanism).

The prediction of the pseudoscalars is also a success, assuming that 3454 and 2830 are really that (this attribution may be destroyed by a study of the angular distribution) but the singlet-triplet mass splitting is much larger (~ 300 MeV) than what can be predicted by taking a simple-minded

relativistic interaction and carrying the non-relativistic reduction ¹⁸⁾⁻²⁰⁾. However, let us remember that the true interaction is not known. Another problem, with the "pseudoscalars" is the magnitude of the transition $V \rightarrow \gamma + P$. If the central potential is dominant or if the spin-spin interaction is concentrated at the origin (as it is in atomic physics) the magnetic dipole transition is favoured because the space-wave functions of the two states are almost identical. So what is needed is a large, extended spin-spin force. Forces of that type have been considered by Schnitzer ¹⁹⁾.

Following a question by Harry Lipkin, let me make a personal remark on the question of the splitting by terms of the type $\vec{\sigma}_1 \cdot \vec{\sigma}_2$. Usually a term $(\vec{\sigma}_1 \cdot \vec{\sigma}_2) \delta^3(\vec{r})$ appears in the Schrödinger equation. This term is only well defined in perturbation theory. An approximation to $\delta^3(\vec{r})$ will be

$$V = \frac{3}{4\pi} R^{-3} V_0 \text{ for } r < R \quad V = 0 \text{ for } r > R ;$$

the delta function corresponds to the limit $R \rightarrow 0$. However, perturbation theory is only applicable for $R^3 V_0 \times R^2 \ll 1$, i.e., $V_0 R^{-1} \ll 1$. So R cannot be made arbitrarily small. In atomic physics there is no problem because we have a natural cut-off due to the extension of the nucleons. Here not. Taking R very small is only allowed if one solves exactly the Schrödinger equation. Then one finds : i) that in the triplet states the interaction produces a negligible energy shift ; ii) that in the singlet state large shifts can be produced and the wave function is radically changed so that the favoured magnetic transition between 3S and 1S is reduced while the orthogonality between the 1S and 3S is destroyed, making a magnetic dipole transition possible.

With these restrictions the model is a success. There are in fact other successes such as the transition rates $\psi' \rightarrow X$ to the supposedly P triplet states. Another success to be discussed later is the description of the state at 4.028 GeV (for which, however, alternative interpretations have been proposed, such as molecular charmonium).

Let us notice also that the non-observation of the singlet P state is relatively well understood. It cannot be produced directly in e^+e^- collisions because it has the wrong parity. It cannot be produced by photon cascade from a state directly produced in e^+e^- collisions such as ψ' or ψ'' . A detailed analysis of its possible production on decay has been made by Renard ²¹⁾.

Before going to the higher states, we want to discuss the sensitivity of the model to details. In the purely central approximation, the level sequence appears to be very stable.

What Harald Grosse and I have proved ^{22),23)} is this : if

$$V = -\frac{4}{3} \frac{\alpha_s}{r} + V_c \quad (V_c = \text{confining potential}).$$

Theorem I

If

$$\left(\frac{d}{dr}\right)^3 r^2 V_c > 0,$$

and

$$\lim_{r \rightarrow 0} 2r V_c + r^2 \frac{dV_c}{dr} = 0, \quad (*)$$

$$E_{1S} < E_{2P} < E_{2S},$$

and as well

$$E_{2P} < E_{3D} < E_{3P},$$

i.e., the X states with $C=+1$ lie between the S states. Remember that for a pure Coulomb potential $E_{2P} = E_{2S}$. For a pure harmonic oscillator $E_{2P} = \frac{1}{2}(E_{2S} + E_{1S})$ (here I keep the hydrogen notation).

Theorem II

If in addition to the previous conditions we have

$$\frac{d}{dr} \frac{1}{r} \frac{d}{dr} \left[2V_c + r \frac{dV_c}{dr} \right] < 0 \quad (**)$$

we get

$$E_{2S} < E_{3D}$$

where E_{3D} represents the lowest $L=2$ level. Notice that in the case of a pure harmonic oscillator potential $E_{2S} = E_{3D}$, and precisely the left-hand side of (**) is zero.

For those who think that these two theorems are not very transparent let me indicate that they tell you that in

$$V = -\frac{4\alpha_s}{3r} + B + Cr$$

you can replace $-(4\alpha/3r)$ by any superposition

$$-\int_{-1}^0 \rho(\alpha) r^\alpha d\alpha \quad \rho(\alpha) > 0$$

In particular you can weaken the "Coulomb force" if you like to have asymptotic freedom, and take, for instance, instead of $-(\alpha_s/r)$

$$-\alpha_s \int_{-1}^0 d\alpha' r^{\alpha'} = -\alpha_s \left(\frac{1}{r} - 1\right) \left(\ln \frac{1}{r}\right)^{-1}$$

and you can replace $B + Cr$ by any superposition

$$B' + \int_0^2 \sigma(\alpha) r^\alpha d\alpha$$

Then the level sequence

$$E_{1S} < E_{2P} < E_{2S} < E_{3D} < E_{3P}$$

remains unchanged. Potentials rising faster than r^2 may exchange the order of the 2S and 3D levels.

These conditions are of course only sufficient conditions. My interpretation is that the level sequence shows great stability, as soon as one admits the idea of a confining force. Naturally one can build counter examples by constructing ad hoc potentials, but these counter examples do not seem very natural physically.

Let me say a few words on the methods of proofs of these theorems.

What plays a major rôle is : i) the nodal structure of the radial wave functions : the 1S and 3D states have no nodes, the 2S state has one node ; ii) the fact that there are extreme cases, Coulomb and harmonic potentials, for which the solutions are known ; iii) the use of continuity of the energy levels with respect to a parameter in the potential ; iv) the virial theorem which says that the kinetic energy is given by

$$\frac{1}{2} \int r \frac{dV}{dr} u^2 dr$$

while the potential energy is given by

$$\int V u^2 dr$$

Details on the proofs may be given in the discussion session.

There are, however, other quantities which depend on the wave functions and therefore, indirectly, the potential. This is the case for the leptonic width, of the 1^{--} states which, for coloured quarks reduces to

$$\Gamma_\ell = 16\pi\alpha^2 \times \frac{4}{9} \frac{|\psi(0)|^2}{M^2}$$

where M is the mass of the bound state.

The decay width of the ψ' is 2.1 keV, while that of the J/ψ is 4.8 keV. What potential will produce such a ratio ? In a harmonic oscillator potential the wave function at the origin of the 2S state is larger than that of the 1S state. This is a clear indication that a pure harmonic oscillator is not acceptable. In a purely linear potential the magnitude of the wave function at the origin is the same for all $\ell=0$ levels ²⁴⁾, for it is given by

$$4\pi|\psi(0)|^2 = |u'(0)|^2 = \int_0^\infty \frac{dV}{dr} u^2(r) dr \quad (***)$$

and since all wave functions have the same normalization and $dV/dr = \text{const.}$ all the $\psi(0)$ are equal.

Recently I have proved a more precise theorem ²⁵⁾ :

Theorem

- 1) If the full potential is a concave function of r

$$|\psi_{2s}(0)| < |\psi_{1s}(0)| ,$$

- 2) If the potential is convex

$$|\psi_{2s}(0)| > |\psi_{1s}(0)| .$$

In particular the favoured combination

$$- \frac{4}{3} \frac{\alpha_s}{r} + B + Cr$$

is concave and

$$|\psi_{2s}(0)| < |\psi_{1s}(0)| ,$$

in agreement with experiment.

We see that the leptonic widths impose an additional constraint to the potential, and that harmonic oscillator potentials may be dangerous.

One problem about lepton width is that of the ψ'' , the 3.77 resonance predicted long ago as being a D state, and recently discovered.

In a purely central potential a $L=2$ state could not be produced in the non-relativistic approximation. However, two things happen :

- i) there are relativistic corrections to the Weisskopf-Van Royen formula for the leptonic width which produce a contribution

$$\Gamma_e \sim \text{const} \times |R_2''(0)|^2$$

where R_2 is the radial wave function of the $L=2$ state ; this is not quite enough to account for the leptonic width of 0.37 keV of the ψ'' ;

- ii) there is unavoidably a coupling between the $L=0$ and $L=2$ state via tensor forces. These tensor forces have been estimated by Jackson²⁶⁾ by fitting the P state levels ; in this way one can account for the leptonic width. It is not correct to say that a dominantly D state cannot have a non-vanishing $L=0$ wave function at the origin as was stated recently in a preprint which has been withdrawn.

The problem of higher states in the charmonium spectrum

We have already spoken about the 3.77 GeV ψ'' state which is slightly above the charmed particle production threshold. The description of this state as a pure quark-antiquark pair is still reasonably good. For higher states it may be questionable in the sense that a resonance above the charm threshold can be made of the physical charmed and anticharmed particles. This is what is called by De Rujulà, Georgi and Glashow "molecular charmonium" ²⁷⁾ and which, as pointed out by David Jackson, is not very different from thinking that the ρ meson is a $L=1$ pion-pion bound state. On the other hand, it seems illogical to disregard completely the sequence of higher states produced by the quark-antiquark potential which has been so successful in the description of the lower states. With the existing potential a $L=0$ $J^{PC} = 1^{--}$ state is predicted around 4.14 GeV. This is a bit too high for the prominent peak at $E=4.028$ GeV which has been extensively used as a source of D 's and D^* .

However, it seems to me that the most reasonable picture which has already been proposed some time ago on a pure theoretical basis by Dashen, Healy and Muzinich ²⁸⁾ is that the confined quark-antiquark channel is coupled to the physical particle channel. Depending on the energy these channels are closed (and then their contribution to the wave function is very small) or open. In this way the two pictures are reconciled and the only risk is that there might be a slight double counting. The existence of physical channels is taken into account in the work of the Cornell group ^{17), 29)} and of the "naïve quark group" in Orsay ³⁰⁾. Then one can understand that the mechanism may lower the energy of $3S$ triplet state to 4.028 GeV. In fact the very complete calculation of the Cornell group ³¹⁾ takes also into account the effects of the closed physical channels on the "stable" particles like J/ψ and ψ' and show that these effects are important but that agreement with experiment can be obtained by "renormalizing" the parameters such as the quark masses.

Probably the greatest success of the model is the prediction by the Cornell and Orsay groups of the dominance of the $D^* \bar{D}^*$ decay of the 4.028 GeV state. If spin factors and phase space are removed one finds that the $D^* \bar{D}^*$ cross-section is 100 times too large while the $D^* \bar{D} + \bar{D}^* D$ cross-section is five times too large. Le Yaouanc et al. show that this is due to the nodal structure of the wave function in p space. They use harmonic oscillator wave functions, which, as we have seen, is objectionable but their basic conclusion is certainly unaffected by this technical simplification.

5. - THE NEXT SPECTROSCOPY

The arguments for a new heavy quark required by neutrino physics may have disappeared but the discovery of the Lederman group is there : a very clear bump in $p + Be \rightarrow \mu^+ \mu^- + \text{anything}$ has been seen at 9.5 GeV with, if interpreted as a single state, a width of 1.2 GeV. Additional statistics is required to clarify the structure. Predictions have already been made by Eichten and Gottfried. With a quark mass of 5 GeV we may have three states with a spacing of about 400 MeV which fits with the observed width ³²⁾. A more detailed study on this topic has been recently made by J. Ellis et al. ³³⁾.

NOTE ADDED AFTER THE HAMBURG CONFERENCE

With additional statistics Lederman sees clearly two peaks at 9.4 and 10.1 GeV and possibly a third one. If these two peaks are made by the same quark-antiquark pair, they cannot be explained by the same potential as charmonium because the spacing between the levels is approximately equal to the $\psi\psi'$ spacing. Quigg and Rosner notice that a potential $C \log(r/r_0)$ would produce this. Let us notice that such a potential satisfies the conditions of our theorems I and II and is concave (Theorem III). What remains to be established is whether it can admit a third bound state stable with respect to the generalized OZI rule. Anyway the third peak is not clearly established.

PARTICULES ELEMENTAIRES (Novembre 1957)

Nom	Modes de désintégration	Durée de vie (unité seconde)	
Photon	Stable		
L E P T O N S	Neutrino	Stable	
	Electron	Stable	
	Méson μ	$\mu^{\mp} \longrightarrow e^{\mp} + \nu + \bar{\nu}$ (ou $\nu + \nu$?)	$2,2 \times 10^{-6}$
Mésons π	$\pi^+ \longrightarrow \mu^+ + \nu$ $\pi^- \longrightarrow \mu^- + \bar{\nu}$ $\pi^0 \longrightarrow 2 \gamma$	$2,5 \times 10^{-8}$ $\tau < 10^{-15}$ (?)	
Mésons K	$\left\{ \begin{array}{l} \pi^{\pm} + \pi^{\pm} + \pi^{\mp} ; \pi^{\pm} + \pi^0 + \pi^0 ; \\ \pi^{\pm} + \pi^0 ; \\ \mu^{\pm} + \nu ; \\ \mu^{\pm} + \gamma + \nu ; \mu^{\pm} + \pi^0 + \nu ; \\ e^{\pm} + \gamma + \nu ; e^{\pm} + \pi^0 + \gamma . \end{array} \right\}$ $K_1^0 = \frac{K^0 + \bar{K}^0}{\sqrt{2}} \longrightarrow \pi^+ + \pi^-$ $K_2^0 = \frac{K^0 - \bar{K}^0}{\sqrt{2}} \longrightarrow e^{\pm} + \mu^{\mp} + \nu \text{ etc..}$	$1,3 \pm 0,3 \times 10^{-8}$ $0,85 \times 10^{-10}$ $\sim 10^{-8} \text{ à } 10^{-6}$	
B A R Y O N S	Nucléons	P stable $N \longrightarrow P + e^- + \bar{\nu}$ (ou ν ?)	1110 ± 220
		$\Lambda^0 \longrightarrow \begin{cases} P + \pi^- \\ N + \pi^0 \end{cases}$	3×10^{-10}
	Hypérons	$\Sigma^+ \longrightarrow \begin{cases} P + \pi^0 \\ N + \pi^+ \end{cases}$ $\Sigma^- \longrightarrow N + \pi^-$ $\Sigma^0 \longrightarrow \Lambda^0 + \gamma$	$0,8 \times 10^{-10}$ $0,8 \times 10^{-10}$ très courte
		$\Xi^- \longrightarrow \Lambda^0 + \pi^-$	1×10^{-10}

Table taken from lectures I gave at the University of Paris in 1957. Notice that the N^* , already discovered, was not considered as a particle.

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