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NEW PARTICLE SPECTROSCOPY AND DECAYS*

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I. INTRODUCTION

In the year since the last meeting in this series, great progress has been made in the spectroscopy of the new particles and their decays. Much of this progress is either directly the result of experiment or at least has been very much stimulated by the astonishing results presented to us one after another by our experimental colleagues. In one way, what has happened is exemplified by the contrast between what was known about the 4-GeV region in $e^+e^- \rightarrow$ hadrons a year ago[1] (Figure 1) and the data[2] which were shown this morning (Figure 2).

To my mind, the most shattering of the developments in the past year are the events[3] of the form, $e^+e^- \rightarrow e^{\pm} + \mu^{\mp} + (\geq 2$ unobserved particles), inasmuch as they are consistent with, or even point toward, a pair produced, charged heavy lepton as their origin. However, as there is no dramatic movement either experimentally or theoretically on this subject in the past few months, I will lay this topic aside for the remainder of this talk with only the remark that no conventional explanation of these events has been found and everything remains consistent with their being due to a plain, ordinary, garden-variety heavy lepton!

Instead, I should like to discuss where we stand phenomenologically on the spectroscopy and decays of new hadrons, both those possibly carrying a new quantum number ("charmed particles") and those without it. Such a discussion is important for a number of reasons. First, it teaches us about the nature of the new particles themselves: are they hadrons and exhibit a hadronic spectroscopy, do some of them carry a new quantum number, is there more than one new quark, etc? Second, we learn about the existence of other new states by studying the decay modes of the known states, as has happened already with the states below the ψ' reached from it by gamma ray emission. Also, although I will not discuss it today, there are hints that there may be things to be learned even about the "old" spectroscopy by studying decays of the new particles. Third, we can study the transformation properties of the new states under isospin or SU(3) if these symmetries are preserved in their decays and thereby transmitted to the final state hadrons. Finally, there is much to learn about dynamics, ranging from the "Zweig rule" and the calculation of masses and transition amplitudes in the (non-relativistic?) quark model, to Adler zeros and the usefulness of vector dominance.

In a number of places I will emphasize difficulties or problems in our understanding as well as gaps in the information available to us. Indeed, in looking back at the talk I gave last year[4] it turns out rather surprisingly to be the case that several of the most important problem areas are the same, which troubles me somewhat. So if this afternoon's session is in "psychotherapy," I'm afraid the audience will have to play doctor while I'm the patient. The emphasis on extant problems is simply because by understanding their solution we will all make considerable progress. That way, we can hope that the doctor-patient roles can be largely reversed at the next conference.

II. THE SPECTROSCOPY OF THE ψ's AND THEIR RELATIVES

It is very useful to have a model of the new particles in the back of one's mind as a reference point when discussing their spectroscopy and decays. For such a model we take the hypothesis that in addition to the u, d, and s quarks and corresponding antiquarks, which are supposed to be the basic constituents of hadrons, there is one (or more) new quark, c. This quark(s) is assumed to carry a new quantum number(s), with the generic name charm,[5] which is to be conserved in strong and electromagnetic interactions. Until the last section of this talk wherein charmed particles and their decays are discussed, the specific charm quantum number of Glashow _et al._[6] will have no distinctive role to play _vis-à-vis_ any other new quantum number conserved in strong and electromagnetic processes.

The ψ, ψ', ... are taken to be $c\bar{c}$ bound states or resonances. Such states with a mass less than about 4 GeV cannot decay into a pair of charmed particles for kinematic reasons, and hence only have "ordinary" mesons and baryons among their hadronic decay products. Since the quarks in the $c\bar{c}$ state then do not appear within the final hadrons, such decays are forbidden by the "Zweig rule"[7] and the corresponding widths are very much suppressed (by a factor $\sim 10^4$) from those of an ordinary hadron with such a mass.

Spectroscopically, one expects a set of SU(3) singlet (and therefore SU(2) singlet) $c\bar{c}$ states, given that the charmed quark is itself an SU(3) singlet. The lowest mass such states would have zero orbital angular momentum (L) between the quark and antiquark, and hence be $J^{PC} = 0^{-+}$ and 1^{--} states. The L = 1 states, 0^{++}, 1^{++}, 2^{++} and 1^{+-} should lie several hundred MeV higher. Following this would be the L = 2 states (1^{--}, 2^{--}, 3^{--} and 2^{-+}) and/or radially excited L = 0 states.

For comparison, the presently known spectroscopy is shown in Fig. 3. The existence of the state of lowest known mass, X(2.8), has been reinforced by the new data[8] presented here from DESY.[9] Although all we know is that $J \neq 1$ and $C = +$, it is conventional in the $c\bar{c}$ scheme to assign this state $J^{PC} = 0^{-+}$ quantum numbers so that it is the quark spin S = 0 ground state partner of the $\psi(3.095)$ ($\equiv \psi$) with S = 1.

Between the ψ and ψ' ($\equiv \psi(3.684)$) are the C = + states,[9] $\chi(3.41)$, $P_c(3.51)$ and $\chi(3.53)$. All are found in decays of the ψ' involving emission of a gamma ray. The $\chi(3.41)$ and $P_c(3.51)$ have widths consistent with experimental resolution; moreover, the dominant electromagnetic decay of P_c into $\gamma\psi$ points to a narrow width. On the other hand, $\chi(3.53)$ is observed (in hadronic decay modes) to be wider than resolution and to have a central mass value different from the P_c. One then infers the $\chi(3.53)$ is more than one state (if they are narrow) and economy in the proliferation of states then suggests that the P_c be identified with one of these states at the lower end of the mass range subsumed in the χ(3.53). The other(s) must lie at somewhat higher mass to give the impression of a broader state. There are then at least three C = + states between the ψ and ψ'.

Above the ψ' (3.684) is the broader structure "ψ(4.1)" and the ψ(4.414), discussed[2] this morning. Considering the leptonic width of the ψ(4.414), which is proportional to the area under the resonance bump in a plot of $\sigma(e^+e^- \rightarrow$ hadrons) vs E_{cm}, and the sensitivity of previous scans for resonances, one concludes that objects like the ψ(4.414) could exist at almost any mass and have escaped detection up to now. The apparent structure within the "ψ(4.1)", particularly the jump in the cross section by ~ 50% over ~ 20 MeV in E_{cm} near 4 GeV, strongly suggests that several objects like the ψ(4.414) are to be found in this region. We probably have entered a new regime of "mini-structure" — i.e., bumps whose area is one-twentieth or less than that of the ψ. In particular, further resonances with leptonic widths comparable to that of ψ(4.414), although likely with larger total widths, seem a foregone conclusion above ~ 4.6 GeV.

The present spectrum of states is consistent with the spectrum expected from one new quark bound to its antiquark. In particular, the X(2.8) and ψ(3.095) are the L = 0 states, while the χ's and P_c are good candidates for the C = +, L = 1 states as indicated in Fig. 3.

However, at a minimum, the dynamics of the $c\bar{c}$ system must be complicated to understand the "mini-structure" in the 4-GeV region. Simple non-relativistic potentials would seem inadequate, given the number of states which are very likely present there. A number of proposals[10] to explain this situation by involving more complicated quark configurations have already been made. Alternately, one may invoke the existence of another new quark, somewhat heavier than the c quark, and with its bound states with the corresponding antiquark having a small admixture of $c\bar{c}$ so as to permit decay into pairs of charmed particles with an almost "normal" hadronic width.

Aside from the 4- GeV region, it is possible that a second new quark exists and its corresponding spectroscopy is accessible to present experiments. In particular, if this quark had charge - 1/3 while that bound in the ψ' s has charge +2/3, the corresponding lowest mass vector meson might have gone undetected[11] in the SPEAR scan[12] for narrow resonances provided its mass was above ~ 5 GeV. The fragility of the present situation with respect to consistency with what is expected from only one new quark is to be noted in general. The existence of other narrow states below X(2. 8), the existence of other than just the specific L = 1 states and the pseudoscalar partner of the ψ' between 3. 1 and 3. 7 GeV, or the existence of further very narrow states above ~ 4 GeV would immediately call for the introduction of more new quarks or, depending on the character of the hypothetical additional states, even the possible abandonment of the whole picture.

III. ψ(3. 095) DECAYS

The ψ(3. 095) has $J^{PC} = 1^{--}$ and has both decays through one photon and "direct" decays. Decays proceeding through one photon[13] into e^+e^- and $\mu^+\mu^-$ each comprise ~ 7% of the total width, and imply the existence of $\psi \rightarrow \gamma_V \rightarrow$ hadrons with a branching ratio of $R_{\text{off-resonance}} \times 7\% \simeq 17\%$. From study of a number of exclusive decay channels, there is strong evidence that the ψ acts as G = - , I = 0 object in its direct decays.[14]

The totaling-up of all the observed or inferred decays of the ψ involving hadrons (plus possible gamma rays) has changed little since the summer.[15] The arithmetic goes as follows (in percent of the ψ decays involving hadrons):

$\psi \rightarrow$	$3\pi, 5\pi, 7\pi, \ldots$	20-30%	direct decays
$\rightarrow$	$K\bar{K} + \pi$'s	20-30%	direct decays
$\rightarrow$	$N\bar{N} + \pi$'s	5-10%	direct decays
$\rightarrow$	$\gamma_V \rightarrow$ hadrons	20%	
$\rightarrow$	$\gamma + X(2.8)$	2-10%	
		67-100%	

Still to be included are some modes containing γ's, η's, etc. The upper limit on the photon decay into the X(2.8) is a relatively conservative one based on the absence of monochromatic gamma rays,[16] while the lower number assumes that the decay $X \rightarrow p\bar{p}$ is real with such a mode being at most 1% of all $X \rightarrow$ hadron decays in any reasonable model. In any case, what is to be learned from this exercise is not that we understand where 100.00% of ψ decays go: One cannot rule out another 10 or 20% mode or modes involving multineutrals a large part of the time (e.g., $\eta' \omega$). Rather, one learns that a fairly healthy fraction is accounted for as rather inauspicious direct decays into hadrons and that major ($\sim$ 40%, corresponding to $\Gamma \sim 25$ keV) unconventional modes are not possible.

Another area where little has changed since this past summer is the question of the SU(3) character of the ψ. If composed of SU(3) singlet quarks, the ψ should be a singlet. If SU(3) is conserved in the direct decay process, then an examination of relative decay rates into specific channels will reflect on the character of the ψ itself. In particular,[17] $\psi \rightarrow KK^*$ and K^*K^{**} are observed,[18] while decays into K_SK_L (or K^+K^-), K^*K^*, $K^{**}K^{**}$, and KK^{**} are not, which is just the way an SU(3) singlet state should behave. In other words, where there are zeroes in the SU(3) Clebsch table for decays of an SU(3) singlet into two mesons, one finds no evidence for such channels in ψ decays. A different test involves the ratio of rates for two allowed processes. Here the one measured example is $\Gamma(\psi \to \pi^+\rho^-)/\Gamma(\psi \to K^+K^{*-})$, which is found to be $\sim 2\frac{1}{2}$ rather than unity as expected for a singlet. Note that this failure is not attributable to contamination[19] of the direct decays by $\psi \to \gamma_V \to \pi^+\rho^-$ and $\psi \to \gamma_V \to K^+K^{*-}$, for the ratio is still unity when these processes are included as well, if SU(3) holds for the relevant photon-hadron vertex. At the moment then, the situation is confused. It is possible that we will have to face $\sim 50\%$ violations of SU(3) in the amplitudes to various channels — presumably induced by SU(3) violation in the decay process if we wish to continue to believe the ψ is an SU(3) singlet. However, with the recent tripling of the data more accurate versions of previous tests as well as new tests in other channels will become possible. Perhaps we should wait for these results on both the ψ and ψ', before coming to a definite conclusion about SU(3) for the new particles and their decays.

IV. ψ(3.684) DECAYS

A major development in decays of the new particles over the past year has been the discovery of the gamma ray decays of the ψ' into C = + intermediate states.[9] A relatively minor consequence of this is that the "anything" in $\psi' \to \psi$ + anything is now completely consistent with being accounted for[20] by $\pi^+\pi^-$, $\pi^0\pi^0$, η and $\gamma\gamma$. The $\pi\pi\psi$ and $\eta\psi$ modes demand that the ψ and ψ' have the same isospin and G parity. Aside from being squeezed out by the known modes, other specific channels like $\psi' \to \pi^0\psi$, which are allowed in some models, now have very stringent upper limits placed upon them.[20]

The more accurate measurement of the branching ratio for $\psi' \to \eta\psi$ of $4.3 \pm 0.8\%$ now available[20] permits one to quantitatively check another aspect of the dynamics, that of vector dominance involving the ψ and ψ'. For example, ψ - dominance of the photon in $\psi' \to \eta\gamma$ leads one to expect[21]

$$\Gamma(\psi' \to \eta\gamma)/\Gamma(\psi' \to \eta\psi) \simeq 0.5 .$$

However, employing the upper bound from DESY[9] on $\psi' \to \eta\gamma$, one finds

$$\Gamma(\psi' \to \eta\gamma)/\Gamma(\psi' \to \eta\psi) \lesssim 0.14\%/4.3\% \approx 0.03 ,$$

so that the theoretical prediction is too large by over an order of magnitude. In a completely analogous way, ψ' dominance of the photon in $\psi \to \eta\gamma$ leads to a predicted[21] width for this process of roughly 1 keV. This is too large by an order of magnitude: experiment gives a value[9] of $\sim$ 0.1 keV.

Of course, one is extrapolating a very long way from the photon to the ψ and ψ' mass shell, and there are other heavy vector mesons[22] which contribute to each amplitude which haven't been taken into account. But this is precisely the point: the failure of these most naive calculations should be taken as a warning against relying on the same exercise done on other amplitudes. A particular case in point is the extraction of $\sigma_T(\psi N)$ from $d\sigma/dt\,(\gamma N \to \psi N)$ by assuming the photoproduction amplitude is mostly imaginary (diffractive) and then using ψ - dominance of the photon. There is no a priori reason for vector dominance to work much better here than in the two cases discussed above. Fortunately, a measurement of $\sigma_T(\psi N)$ independent of any vector dominance assumption is possible by studying the A dependence of the cross section on nuclei. This is now in progress.[23]

Some new developments have occurred with respect to "direct" decays of the ψ' into ordinary hadrons. Enough such decays have been seen[18] so that a pattern is beginning to emerge with respect to the same decays of the ψ: it is that $\Gamma(\psi' \to \text{hadronic channel}) = (\frac{1}{2} \text{ to } \frac{1}{5}) \times \Gamma(\psi \to \text{hadronic channel})$ for each of the "direct decay" channels so far found. If the pattern is general then we would have

$$\Gamma(\psi' \to \text{hadrons})\Big|_{\substack{\text{direct}\\ \text{decays}}} = \left(\frac{1}{2} \text{ to } \frac{1}{5}\right) \Gamma(\psi \to \text{hadrons})\Big|_{\substack{\text{direct}\\ \text{decays}}} .$$

This is of some importance for it checks against another pair of measured widths

$$\Gamma(\psi' \to e^+e^-) \simeq \frac{1}{2.3}\, \Gamma(\psi \to e^+e^-) .$$

In the charmonium picture both the e^+e^- decay and the "direct" decay are proportional to the square of the wave function of the state at the origin, $|f(0)|^2$. The consistency of the two independent measurements[24] of the ratio of the square of the ψ and ψ' wave functions at the origin provides some encouragement to this picture of "direct" and e^+e^- decays.

We are now in a position to add up the known or inferred decay modes of the ψ' involving hadrons:

$\psi' \to \psi$ + anything	$\sim$ 57%
$\to \gamma_V \to$ hadrons	3%
$\to$ "direct" hadrons	$\lesssim$ 10%
$\to \gamma + \chi$, $\chi \to$ hadrons	5-10%
	75-80%

The 10% number for direct decays comes from taking <u>all</u> ψ decays other than those proceeding through one photon and scaling them by the ratio of the square of the ψ' and ψ wave functions at the origin, as measured in their e^+e^- decays. It is therefore presumably an upper limit. The estimate of 5-10% for gamma ray decays ending in <u>known</u> χ states decaying into hadrons is based on scaling up the observed $\chi \to$ hadron modes to guess their total direct hadronic decays.

The remaining 20-25% of unaccounted for ψ' modes containing hadrons is a serious discrepancy, unlike the case for the superficially similar analysis for the ψ. For in this case it is not "ordinary" direct decays which have not been explicitly reconstructed which might fill the void: such direct decays are already rather liberally accounted for in the 10% figure obtained by scaling down all possible "direct" ψ decays to the ψ' by the ratio of their leptonic widths.

The discrepancy can also not be entirely due to the decay $\psi' \to \omega + X(2.8)$, as we heard this morning.[2] Furthermore, if we assume the $\chi(3.41)$ is the 0^{++} p-wave state, with the others lying above 3.50 GeV, we can use the upper bound[25] on $\psi' \to \gamma + \chi(3.41)$ to bound the size of the remaining transitions to the 1^{++} and 2^{++} states. Even taken altogether they cannot fill up the gap of unaccounted for ψ' decays. Similarly, the bounds[25] on any single monochromatic photon transition prevent the decay of the ψ' into its pseudoscalar partner (if not already seen as a χ or P_c state) by gamma ray emission from accounting for the total discrepancy.

However, it is still in the range of possibility that the problem will be solved by each of several (of the above?) channels eating up several percent of the ψ' decays, leaving any remaining discrepancy within the statistical errors on the data. Another, relatively conventional, possibility is that some important modes which exist for both the ψ and ψ' do not scale as we have done for all "direct decays." An explicit example is provided by assuming that the η and/or η' have a small $c\bar{c}$ component, as has been proposed by several authors.[26] The new round of ψ and ψ' decay experiments at SPEAR may give us a clue as to the direction in which the answer lies.

V. χ, P_c, X, ... DECAYS

In their hadronic decays as so far observed, the χ's behave as would be expected for C = G = + states: formed by emission of one photon from the ψ', decay channels with even numbers of pions are observed. Some particular decay modes which are already accessible are of special importance for the determination of quantum numbers. Decay of a C = + object into two pseudoscalars implies J is even and therefore parity P = +. If both $\pi^+\pi^-$ and K^+K^- are present, as indicated[9] for the (3.41), then I = 0, for the $\pi^+\pi^-$ system may have I = 0 or 2 while K^+K^- has I = 0 or 1. The assignment of the χ(3.41) to $I^G = 0^+$ and $J^{PC} = (\text{even})^{++}$ is probably the most important observation on the intermediate states between the ψ and ψ' up to this point, inasmuch as it both rules out a pseudoscalar state and is just what is expected for the L = 1, 0^{++} or 2^{++} $c\bar{c}$ states.

Observation of decays like πA_2, $K\bar{K}\pi$, etc. are likely to be of use in the future since they immediately rule out the assignment $J^P = 0^+$. And of course, $\gamma\gamma$, as observed[9] for the X(2.8), rules out J = 1.

Below the ψ', the three L = 1 states 0^{++}, 1^{++}, 2^{++} should be found arising from monochromatic gamma ray decays of the ψ'. The 0^{++} state lies lowest in most models and so is assumed to be the χ(3.41). The formation, and some possible decays of the 2^{++} state, which might be contained in the χ(3.53), are shown in Fig. 4. The decay of such a state into X(2.8) could well be competitive with the direct decay into ordinary hadrons.

A fourth C = + state should be found between ψ and ψ': the pseudoscalar partner of the ψ'. Some possibilities for formation and decay of the pseudoscalar states are shown in Fig. 5. Again the transition from the heavier to lighter pseudoscalar may be non-negligible in comparison to other decay modes of the upper 0^{-+} state. In the charmonium model direct decays into hadrons are supposed to have widths in the multi-MeV range[27] and hence would likely dominate the remaining modes shown in Fig. 5.

Above the ψ' it is possible that there are further very narrow states until one gets to the threshold for decay into a pair of charmed hadrons. This might be as high as 3.9 GeV, in which case other L = 2 or even L = 3 states of the $c\bar{c}$ system would have widths like the ψ and ψ'.

Unfortunately, such states will be very difficult to detect experimentally, aside perhaps from the 1^{--} state with L = 2 which could couple to e^+e^- with enough strength to be seen as a bump in the total cross section. One possible way to try to find some of these states is by looking for

$$e^+e^- \rightarrow \psi + (C = +)$$

at center-of-mass energies above ~ 7 GeV. The ψ is readily detectable in the e^+e^- or $\mu^+\mu^-$ mode, but the absence[28] of an inclusive ψ signal down to a level of ~ 1% of the total cross section means that such processes are quite rare, at best.

The C = -1 states might be accessible by studying

$$\psi(4.?) \rightarrow (\pi\pi \text{ or } \eta) + (C = -1) ,$$

where $\psi(4.?)$ is one of the bumps in the 4 GeV region. Since several of these bumps have apparent widths of 20-40 MeV, and since $\psi' \rightarrow \pi\pi\psi$ has a partial width of ~ 100 keV, it might be possible that such decays occur at the 1% branching ratio level for a given $\psi(4.?)$. This method is also applicable to finding the quark spin singlet, p-wave state with $J^{PC} = 1^{+-}$ which presumably lies between the ψ and ψ', near the other L = 1 states. However, it cannot be formed by gamma emission from the ψ' because of charge conjugation invariance, while phase space presumably stops the formation by emission of $\pi\pi$ from the ψ'. If some of the other L = 1 states with C = + lie above it they can decay into it by emitting a gamma ray as indicated in Fig. 6. As also shown there, such a state could have a number of interesting competitive modes of decay.

VI. CHARMED PARTICLES

Particles containing only one new quark (antiquark) carry 1(- 1) unit of charm. The lowest mass such particle (meson?) should lie between 1.84 GeV and 1.95 GeV. The lower limit arises from the narrow width of the ψ', while the upper limit is based on the rapid rises and falls in R starting at 3.9 GeV, presumably due to non-narrow $c\bar{c}$ resonances decaying into pairs of charmed particles with ordinary hadronic widths.

Further evidence of the existence of hadrons carrying a new quantum number comes from the dimuon events induced by neutrinos[29, 30] together with the Gargamelle[31] and Fermilab[32] bubble chamber events of the form

$$\nu_\mu N \rightarrow \mu^- + e^+ + (\mathrm{Vee})^0 + \ldots .$$

It is difficult to find any explanation for such events other than that a new heavy hadron is being produced which decays weakly (i. e. semi-leptonically), but "promptly" enough that the positron appears to originate at the interaction vertex. With a non-negligible branching ratio for weak decays, the new hadrons must be forbidden from decaying strongly or electromagnetically by posessing a quantum number conserved in these interactions. If the semileptonic branching ratio of such a particle is ~ 10%, the present data on, e.g., $e^+e^- \rightarrow \mu + K_S + \ldots$, are not yet sensitive enough[28] to see such a signal for charm production unambiguously, even if final states containing charmed particles are a fair fraction of all events above ~ 4 GeV in E_{cm}.

The critical place to look for evidence of charm production in e^+e^- annihilation is the 4 GeV region. Indeed, much more important than exactly how many states like the $\psi(4.414)$ exist, is the use they can be put to in delineating the properties of charmed particles. For if such resonances are $c\bar{c}$ states with widths of 20-40 MeV because they are decaying into pairs of charmed particles (+ other hadrons), then any change in $< n_{ch} >$, $< K_S >$, $< \gamma >$, $< \mu >$, etc., etc., off and on a bump in R is assignable to the effects due to (pairwise) charm production and subsequent weak decay.

Since, e.g., R changes by ~ 50% in 20 MeV in E_{cm} near 4.03 GeV, such an analysis is independent of the existence of any other new (or old) physics which varies slowly with energy, such as the existence of pair produced heavy leptons in the same energy region. Note that (Fig. 2) off the bumps in the 4 GeV region $R \simeq 4$, so that if a charged heavy lepton does exist with $M_L \simeq 1.8$ GeV, there is less than about one unit of R available for charmed particle production after taking away the "old physics" ($R \simeq 2.5$) and the heavy lepton ($R \simeq 1$) contributions.

In some ways we have come almost full circle since the conference[4] one year ago with regard to searches for charmed particles in e^+e^- annihilation. At the time of the last conference in this series searches[33] for bumps in invariant mass plots of two and three body systems produced in e^+e^- annihilation at E_{cm} = 4.8 GeV showed no statistically significant evidence for charmed particles decaying non-leptonically. One way out of this was to assume that the lowest mass charmed particle typically decayed into relatively high multiplicity states. However, this could not be, for the observed charged multiplicity on entering the 4 GeV region, where R approximately doubled, showed no great jump and was

~ 4. Since one had two charmed particles in every "new physics" event, this created a "multiplicity crunch."

By mid-summer the crunch was relieved by the possible existence of a heavy lepton with a threshold not far from that of charm. The multiplicity crunch, as well as other crises for charm production, were diluted by the possible presence of another new particle which could decay into low multiplicity channels, allowing the charmed particles to balance this with high multiplicities. Furthermore, only 1/4 of the cross section at 4.8 GeV need then be due to charm, rather than the $\sim 1/2$ assumed before: the limits on branching ratios into specific channels rise accordingly.

But now it is possible to look at the charged multiplicity on and off the bumps in the 4 GeV region. The data[34] show little or no change on passing through these bumps! The crunch would seem to be back — a reasonable estimate[35] of the number of charged particles per charmed particle decay is $\lesssim 2.3$.

As can also be seen from previous data, the average momentum per charged particle must be less for final state hadrons resulting from the charmed quark contribution to R than from that from ordinary quarks. This follows already from the observation that the inclusive single particle distribution only changes for $x = 2p/E_{cm} \lesssim 0.5$ on crossing 4 GeV. Thus $< x >$ is less for <u>any</u> of the "new" physics than for the "old" physics in that region. If we assume each particle, charged or neutral, has the same average momentum, then a drop in the mean charged particle momentum means a jump of the <u>total</u> multiplicity. Thus it may be that charm is characterized by a greater total multiplicity than ordinary physics at the same e^+e^- energy, and if the charged multiplicity shows no increase[36], this increased multiplicity shows up in the neutrals.

Whether this possible change is because of neutrinos, or from π^0's and/or γ's from $D^* \rightarrow D$ transitions[37] we do not know. But at the rate experimental progress is being made, I do not think this problem will survive until yet another conference. There is hope for proper "psychotherapy" by then.

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16. See the photon spectra in A. D. Liberman, Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energy, W. T. Kirk, editor (Stanford Linear Accelerator Center, Stanford, 1976), p. 55.

17. Here $K^* \equiv K^*(890)$, a member of the nonet of vector mesons, while $K^{**} \equiv K^*(1420)$, a member of the nonet of tensor mesons.

18. The experimental situation is reviewed in G. S. Abrams, Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energy, W. T. Kirk, editor (Stanford Linear Accelerator Center, Stanford, 1976), p. 25.

19. S. Rudaz, Cornell preprint CLNS-324, 1975 (unpublished). Recall also that $\psi \to \pi\rho$ is known (Ref. 14) to be overwhelmingly "direct" rather than electromagnetic in origin.

20. W. Tanenbaum et al., SLAC-PUB-1696, 1975 (unpublished).

21. In the usual spirit of vector dominance for a process on the photon-mass-

shell, one uses the $\gamma-\psi$ coupling as measured on the ψ-mass-shell in $\psi \to e^+e^-$. Similarly, for ψ' vector dominance, one employs $\psi' \to e^+e^-$.

22. The contributions from the "light" ρ, ω, and ϕ are negligible. Note that the additional heavy vector meson contributions which were omitted would have to cancel the calculated contributions from the ψ or ψ' almost completely to reproduce the experimental data.

23. SLAC-Wisconsin collaboration (private communication).

24. Technically, in the charmonium picture there is an additional dependence on the strong interaction (gluon-quark) coupling constant for the "direct" hadronic decays. However, as this change is only logarithmic, the coupling only changes slightly between 3.1 and 3.7 GeV.

25. See A. Liberman, Ref. 16, and G. J. Feldman, invited talk at the Palermo Conference, June 23-28, 1975 and SLAC-PUB-1624, 1975 (unpublished).

26. H. Harari, Weizmann Institute preprint WIS-75/39, 1975 (unpublished). See also in this connection C. Rosenzweig, University of Pittsburgh preprint PITT-156, 1975 (unpublished) and Chan Hong-Mo et al., Rutherford Laboratory preprints RL-75-177 and RL-75-192, 1975 (unpublished).

27. See, for example, T. Appelquist and H. D. Politzer, Phys. Rev. Letters 34, 43 (1975).

28. G. J. Feldman, invited talk at the Irvine Conference, December, 1975 (unpublished).

29. A. Benvenuti et al., Phys. Rev. Letters 34, 419 (1975).

30. B. Barish in Proceedings of La Physique du Neutrino a Haute Energie (Ecole Polytechnique, Paris, 1975), p. 131.

31. Gargamelle collaboration, CERN preprint, 1975 (unpublished), and H. Deden et al., Phys. Letters 58B, 361 (1975).

32. J. von Krogh et al., University of Wisconsin preprint, 1975 (unpublished).

33. A. M. Boyarski et al., Phys. Rev. Letters 35, 196 (1975).

34. See R. F. Schwitters, Ref. 12.

35. This comes from calculating the largest possible multiplicity due to a "bump" and assuming it all arises from the weak decays of two charmed particles. Since "ordinary" pions, etas, etc. will generally be produced in the same event as charmed particles, this number is certainly an upper limit, given our assumptions.

36. Inasmuch as any change in the total multiplicity is small, and a small change in the charged multiplicity on a bump in R cannot be ruled out yet, the increase in neutrals must be considered as very tentative.

37. See, for example, S. Nussinov, Institute for Advanced Study preprint COO 2220-54, 1975 (unpublished).

FIGURE CAPTIONS

Figure 1: Values of $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ near $E_{cm} = 4$ GeV as of one year ago.[1]

Figure 2: Values of R near $E_{cm} = 4$ GeV presented[2] to this conference.

Figure 3: Known spectroscopy of the ψ's and related states.

Figure 4: Formation and some possible decays of a $c\bar{c}$, $J^{PC} = 2^{++}$ state.

Figure 5: Some possibilities for formation and decay of pseudoscalar partners of the ψ and ψ'.

Figure 6: Some possibilities for formation and decay of a $J^{PC} = 1^{+-}$ $c\bar{c}$ state between ψ and ψ'.

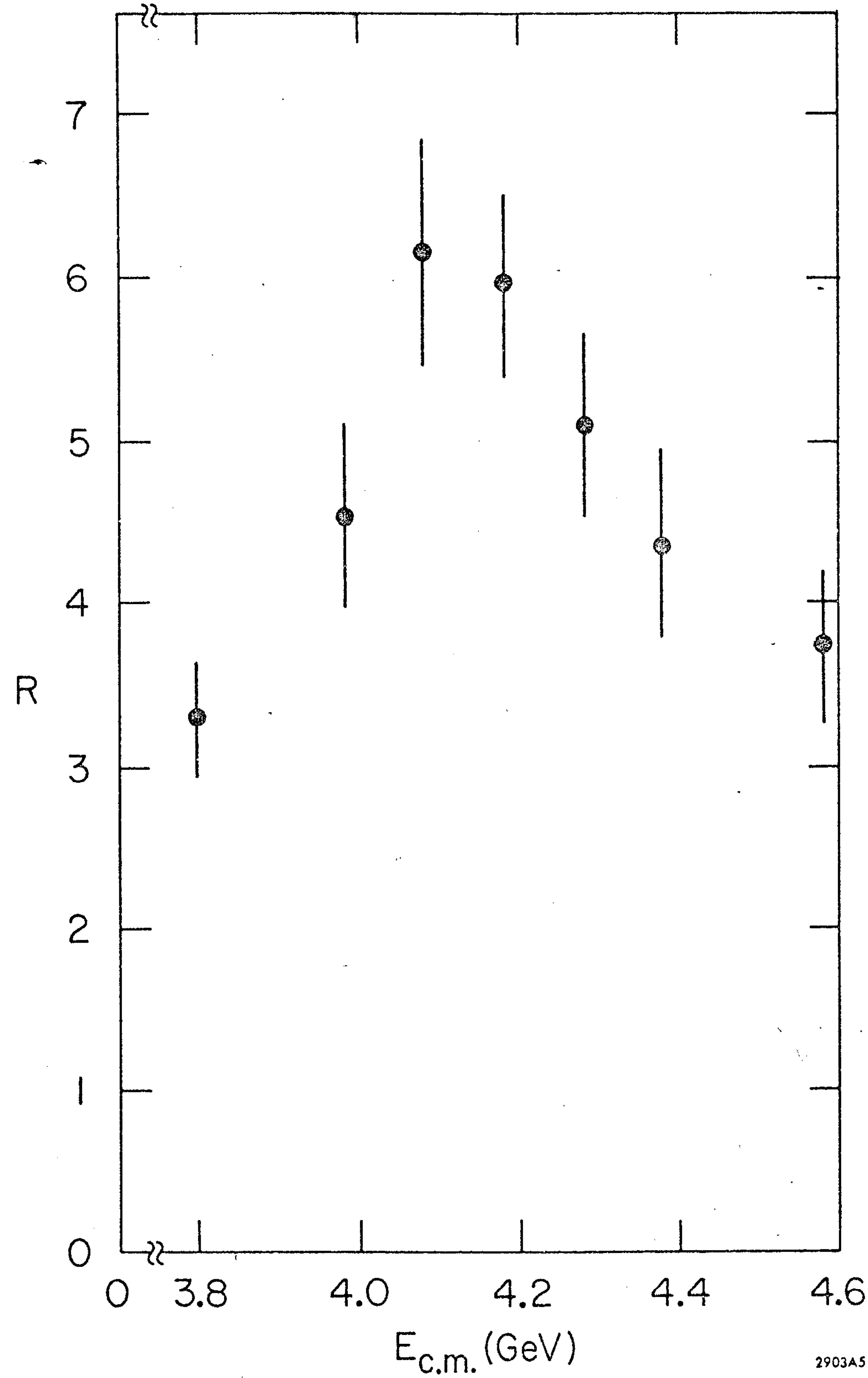

Fig. 1

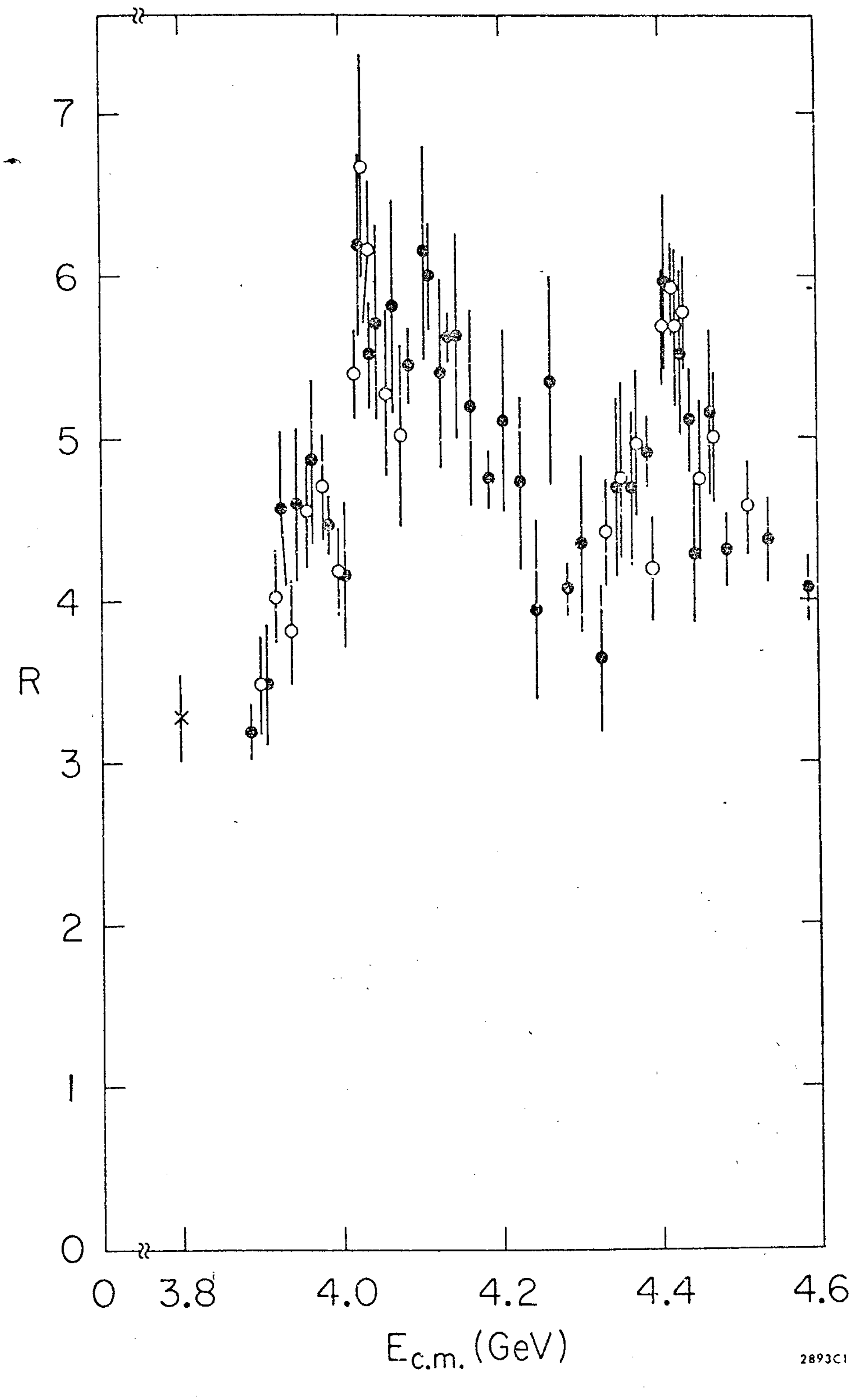

Fig. 2

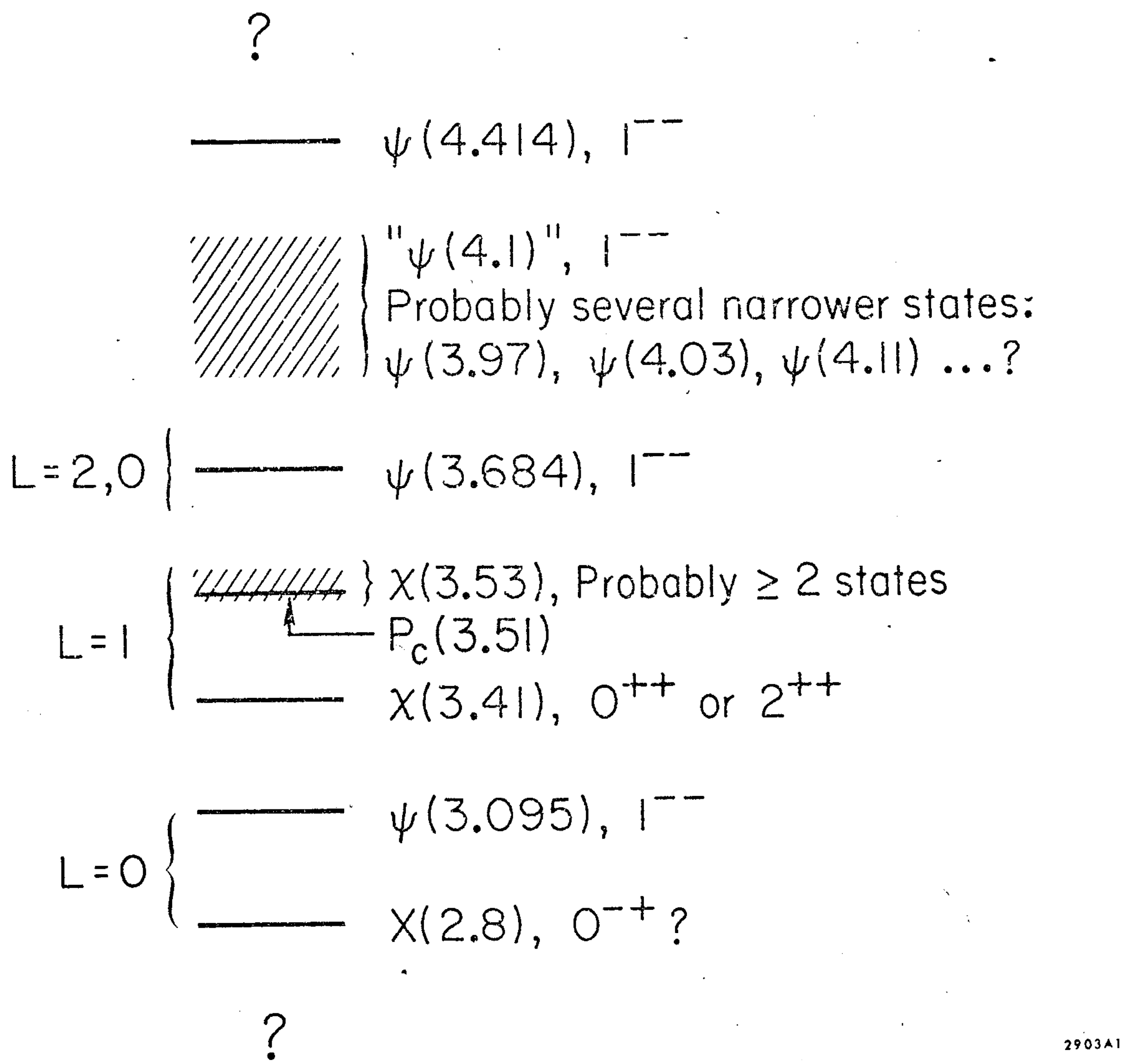
?
ψ(4.414), 1⁻⁻
"ψ(4.1)", 1⁻⁻
Probably several narrower states:
ψ(3.97), ψ(4.03), ψ(4.11) ...?
L=2,0
ψ(3.684), 1⁻⁻
χ(3.53), Probably ≥ 2 states
L=1
Pc(3.51)
χ(3.41), 0⁺⁺ or 2⁺⁺
ψ(3.095), 1⁻⁻
L=0
X(2.8), 0⁻⁺?
?
2903A1

Fig. 3

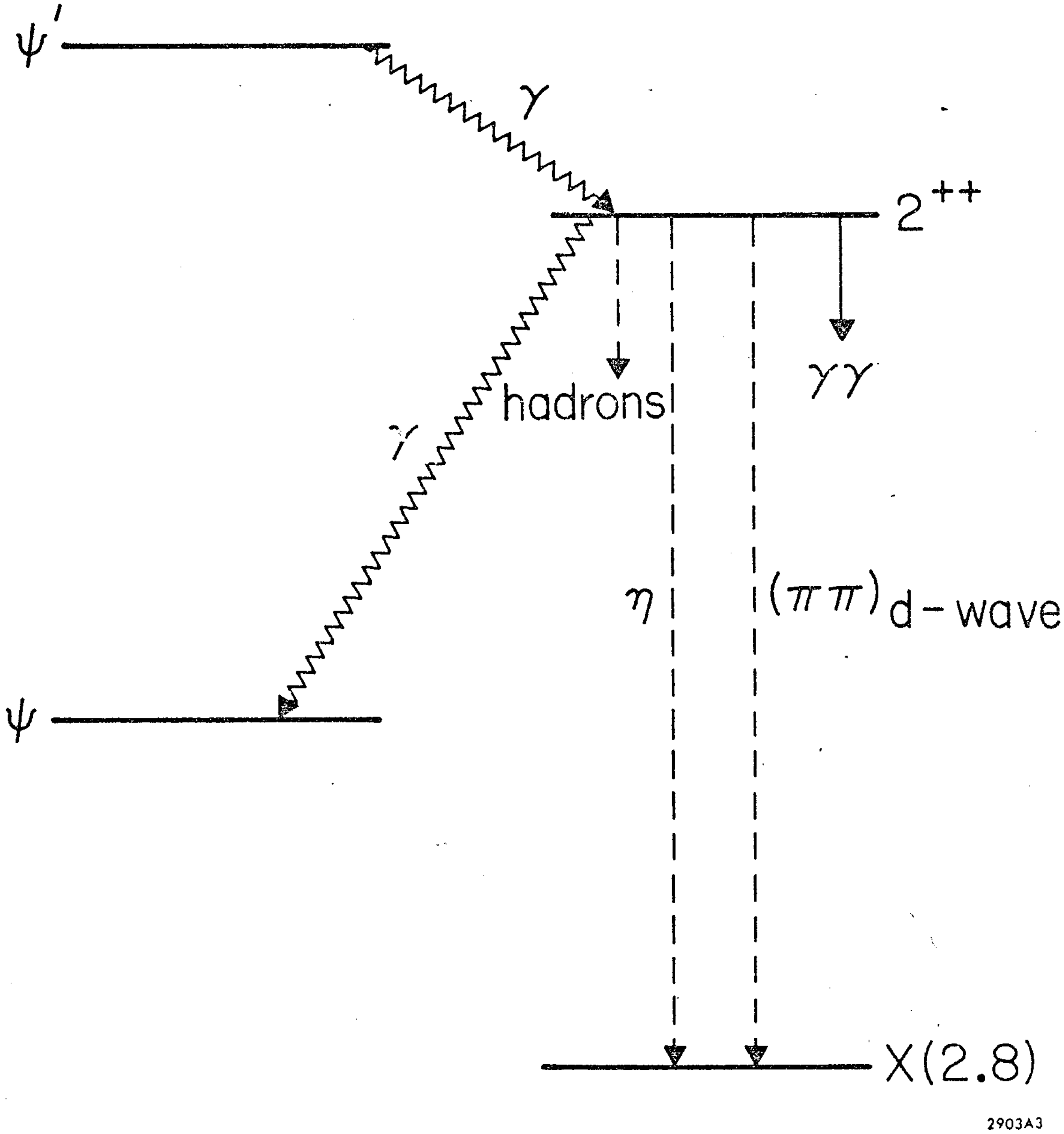

Fig. 4

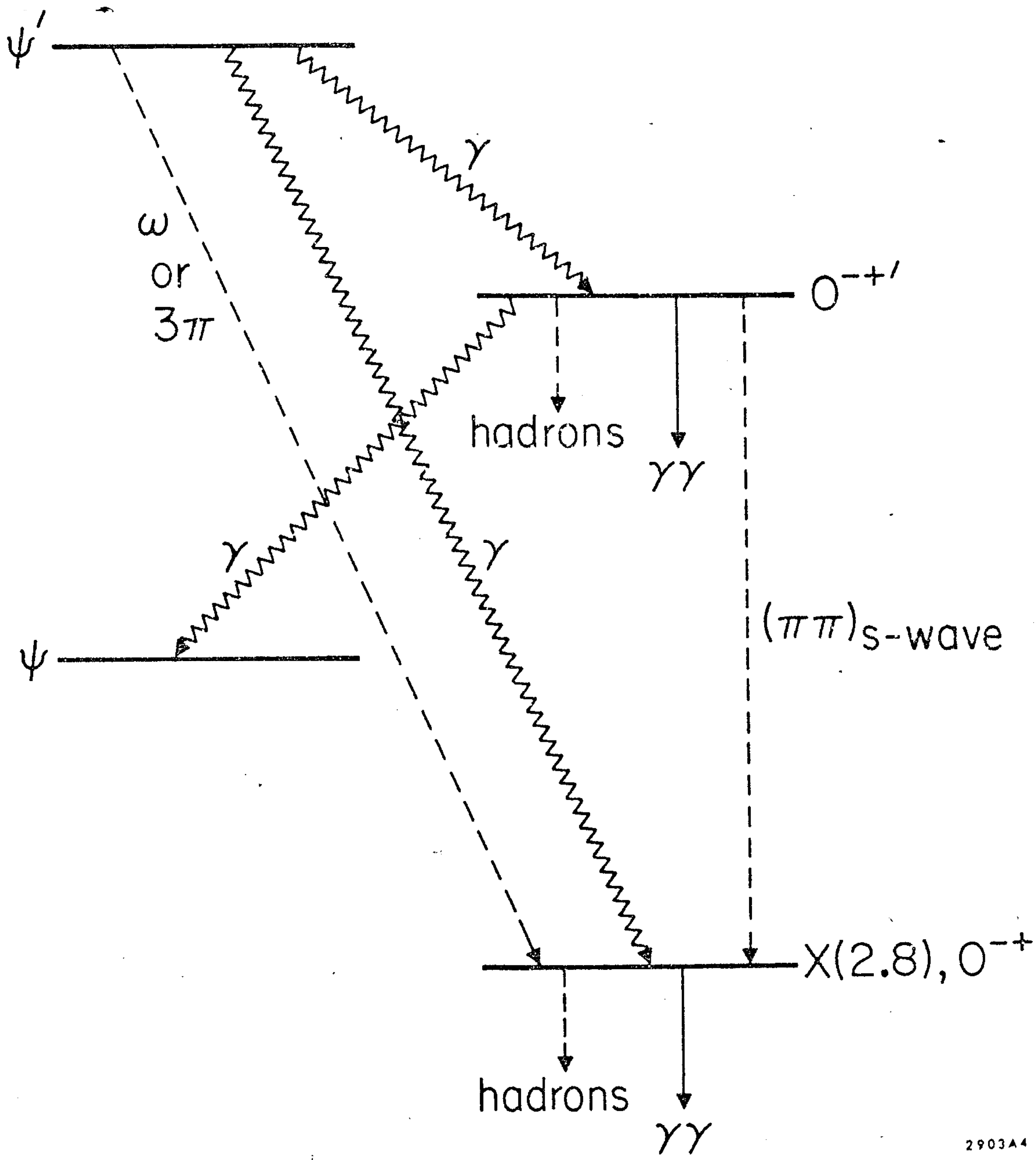

Fig. 5

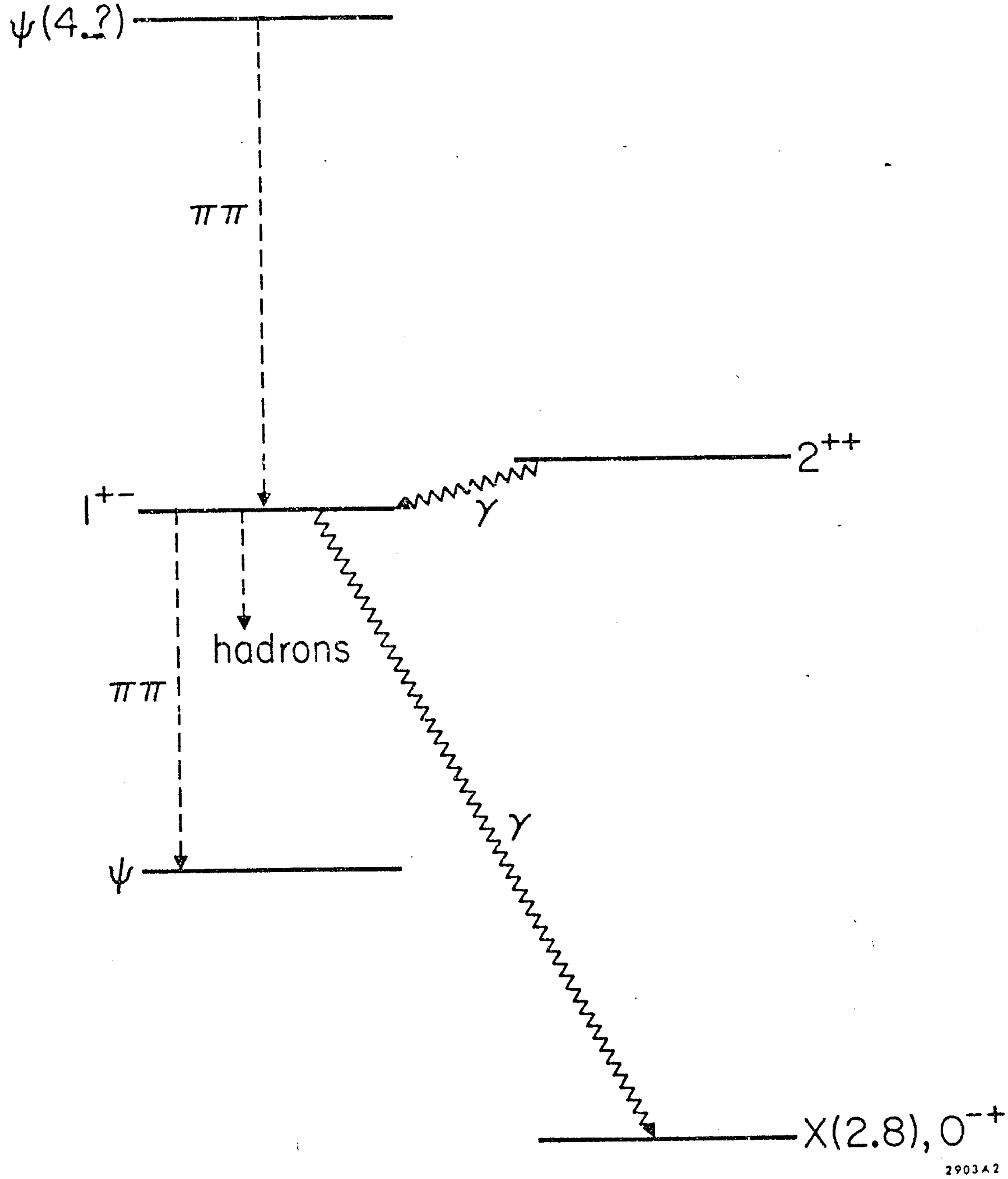

Fig. 6