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Recent Discoveries in High Energy Physics

by

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The past years have brought many unexpected and exciting discoveries. Some, which were made at CERN and the Fermi NAL, provided some new aspects for the strong interaction (examples are: the abundance of large transverse momenta in p-p collisions, correlations between particles produced in high energy collisions, the scaling behaviour of the momentum spectra of produced particles etc). The most exciting results, however, came recently from experiments with leptons (i.e. electrons, muons and neutrinos) either in the initial or final state. Since my time is limited I shall have to restrict myself to these latter discoveries and I shall report on the newly discovered particles and the so-called "neutral currents".

The Discovery of the J and ψ Particles

In 1974 S. Ting[1)] and collaborators bombarded a Be-target with 30 GeV protons at Brookhaven. Among the produced particles they looked for e^+e^--pairs and measured the momentum of each particle. From these one can calculate the relativistic invariant mass of the pair. If the pair is directly produced one

expects a more less uniform distribution of invariant masses, whereas if the pair originates from the decay of a particle one expects a sharp peak in the mass distribution at the mass of the particle. The result is shown in Fig.1. A sharp peak was observed at a mass of 3.1 GeV with a width of about 20 MeV which is entirely due to the instrumental resolution. The BNL group attributed the name J to this particle.

The advantage of this experiment was that a whole range or particle masses could be scanned simultaneously. The measurements was very difficult, however, since the production cross section is quite small and hence the detectors had to be able to cope with very high beam intensities and they had to be very selective in order to find the few e^+e^--pairs among a huge background of other particles.

If this new particle decays like $J \rightarrow e^+e^-$ it should be possible to produce it by the reverse reaction. This indeed was done for the first time at the e^+e^- storage ring SPEAR[2] at Stanford which had sufficient energy per beam to produce the particle in e^+e^- annihilation. The Stanford group which claims to have detected the new particle independent of the BNL group named it ψ . Within days this particle was found also at DORIS[3,4] in Hamburg which in November 1974 had

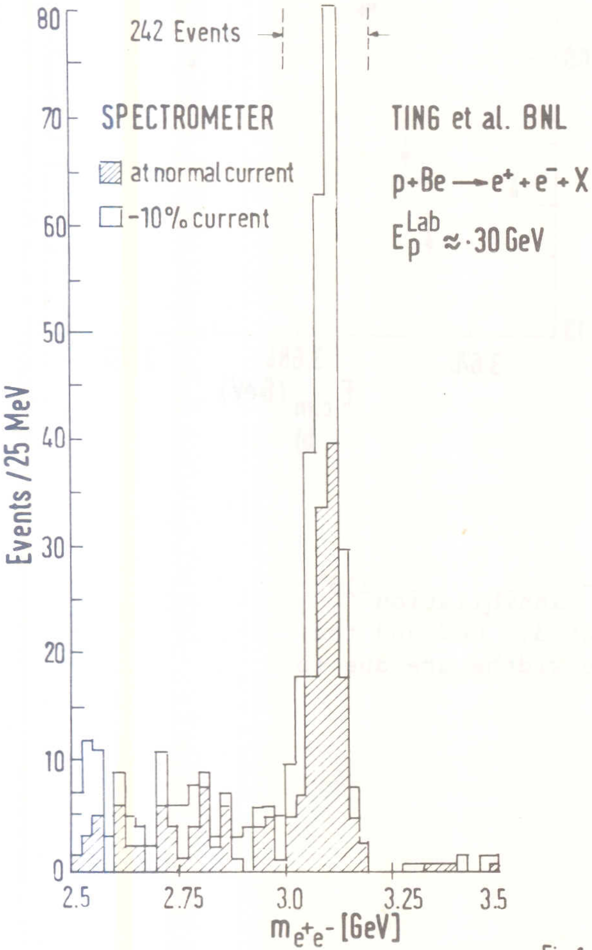

Fig.1

Fig.1:
Distribution of invariant mass of e^+e^--pairs produced in the reaction[1] $p + Be \rightarrow e^+e^- + x$ at 30 GeV showing the J particle with mass of 3.1 GeV.

just started its experimental programme and at ADONE[5)] in Frascati which had a maximum beam energy of 1.5 GeV but could be pushed a little bit beyond it to produce the 3.1 GeV-particle.

In electron storage rings the energy of the stored particles can be controlled to an accuracy of about 1 MeV. By changing the energy of the two beams one can run across the production resonance of the particle and thus determine precisely its mass and its width (Fig.2).

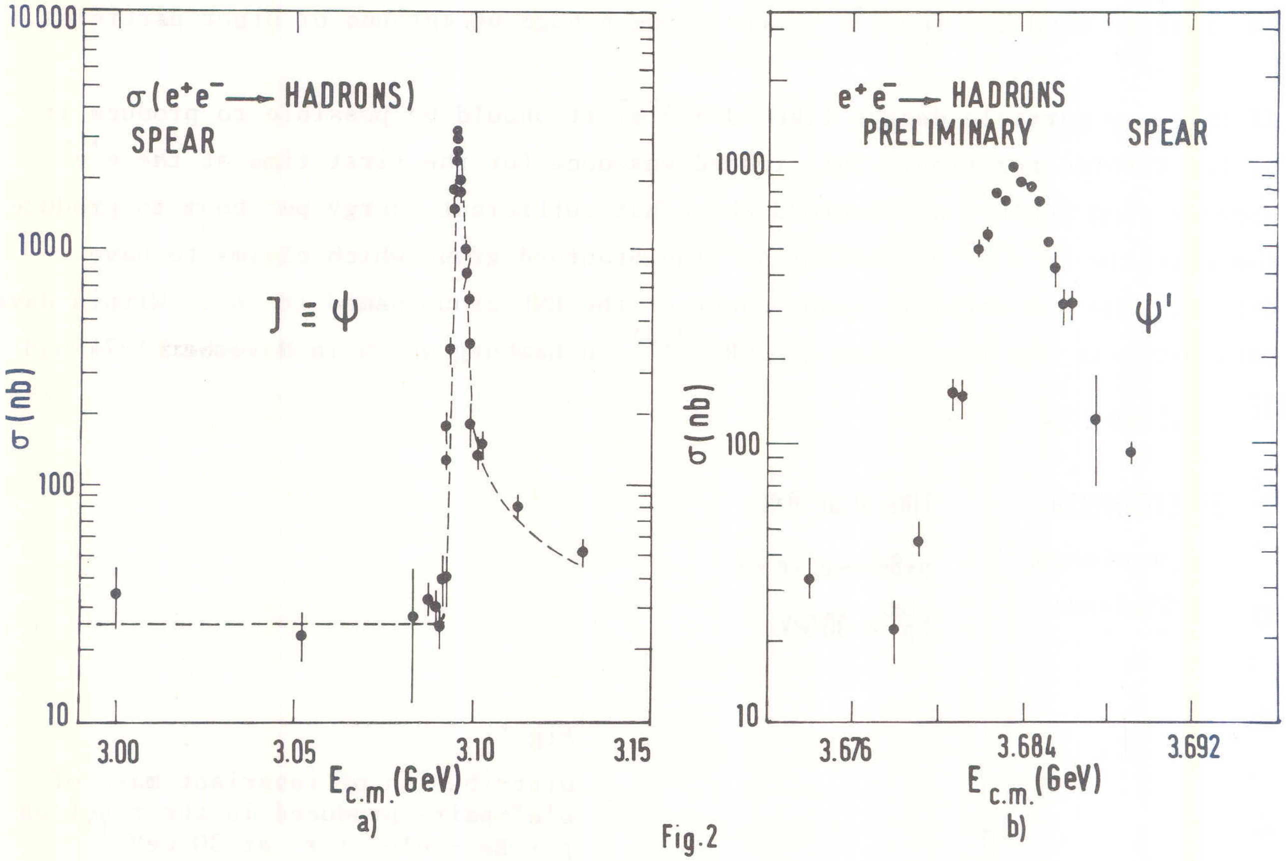

Fig.2:

Production of hadrons in e^+e^--annihilation[2)6)] showing the J/ψ resonance at 3.1 GeV and the ψ' resonance at 3.7 GeV. The widths are due to the stored beams.

Surprisingly the measured width is still determined by the experimental resolution. Assuming that the particle is produced and decays like an ordinary Breit-Wigner resonance and measuring its decay into hadrons and leptons separately (Fig.3) it is possible to extract the true width from the measured width. The result is a total width Γ = (69 ± 15) keV. This extremely small width was, of course, the reason why this particle had not been found earlier with e^+e^--storage rings. Nobody expected at these high energies phenomena that would change so sharply with energy and hence in the first SPEAR experiments step widths of about 100 MeV were chosen to investigate the total cross section as function of energy.

Subsequently a second sharp resonance at an energy of 3.7 GeV was found at SPEAR[6] (Fig.2b) which was called ψ' and a rather wide peak was observed at about 4.2 GeV (Fig.5). The properties of these particles have been studied extensively at SPEAR and DORIS and an enormous amount of experimental material has been gathered within a few months. Some relevant results are summarized

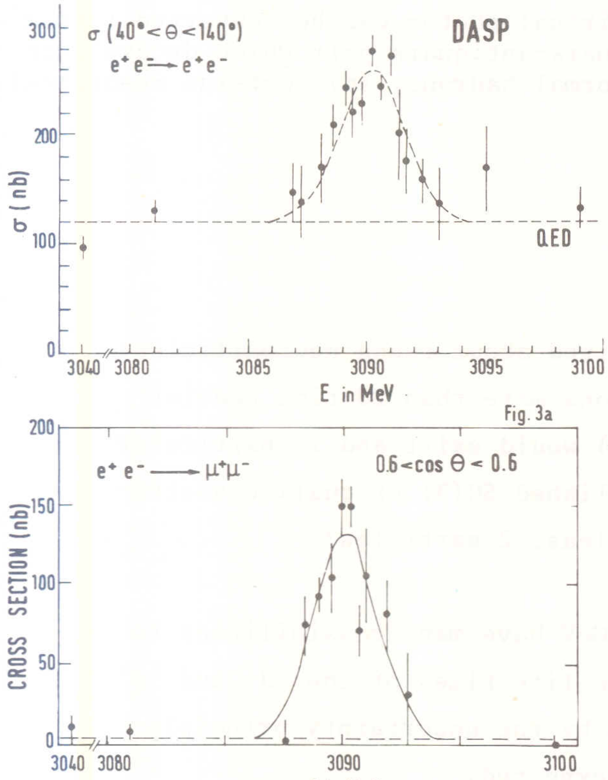

Fig. 3a

Fig.3b

Fig.3:

The decay of the J/ψ particle into lepton pairs. The resonance decays are superimposed on a non-resonant distribution associated to normal Q.E.D. processes[4].

in Table 1. From these it can be infered that the J and ψ' are bosons and that they have the same quantum numbers as the photon (spin 1, parity -). (Table 1 and 2).

This is in agreement with the idea basic to all electromagnetic interactions that the production and decay of the particle goes at least partially via an intermediate photon (Fig.4). The quantitative analysis shows, however, that there exists also an appreciable direct coupling. It is also important to note that the ψ' (3.7 GeV) decays predominantly into J (3.1 GeV) which indicates a close relationship between J/ψ and ψ' . The information on the peak at 4.2 GeV is still somewhat scarce. It seems that it does not decay frequently into J or ψ' . The nature of this resonance has not been clarified yet.

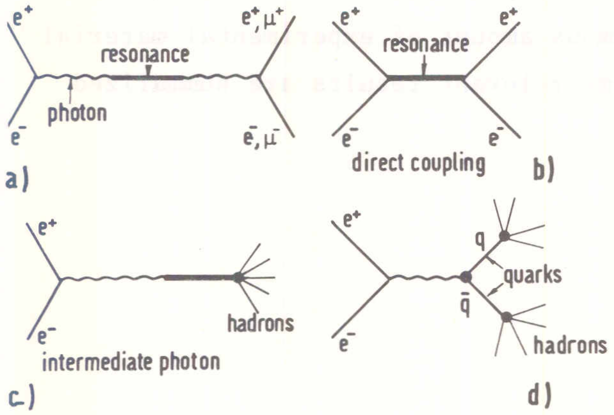

Fig.4:

Different graphs for particle production in e^+e^--annihilation. a) and c) production of a resonance via a virtual photon into lepton pairs (a), or directly into hadrons (c). The resonance can also be produced directly (b). The virtual photon can be converted into a quark-antiquark pair which decays into normal hadrons, (d) (outside resonance).

Let me summarize why physicists got so excited about these new particles:

1) It had not been expected that bosons more than 20 time heavier than the lightest boson (the pion) would exist and in particular they do not fit in the well established SU(3) or quark classification scheme. Why are there at least 2 particles?

2) Bosons with masses larger than 3 GeV have many possibilities to decay into lighter particles. The life times of the J and ψ' as deduced from their total width by the uncertainty principle are about 1000 times longer than expected.

3) A new law of nature is necessary to understand the extremely long life times and some of the decay properties, if the new particles are hadrons.

Pointlike Constituents of Elementary Particles

Before I discuss possible explanations of the new particles let me mention some other interesting results which have been known already before the discovery of the J and ψ particles and which have some bearing on their interpretation.

In 1973 some indications were obtained at the Cambridge Electron Accelerator that the cross section for e^+e^--annihilation had an anomalous behaviour above c.m. energies of 2 GeV. If the annihilation into hadrons is compared to the annihilation into pointlike particles (e.g. $e^+e^- \rightarrow \mu^+ + \mu^-$) one expects that $R = \sigma(e^+ + e^- \rightarrow \text{hadrons})/\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-) \lesssim 1$. This is because the coupling of the intermediate photon to hadrons is reduced by destructive interference from the different parts of the hadron. Indeed for hadrons with a finite radius one expects R to approach 0 if the energy gets very large. If, however, the hadrons contain pointlike constituents (partons, quarks) R should approach asymptotically a constant limit. For example it can be assumed that the intermediate photon converts into a quark-antiquark pair (Fig.4d) and the quarks subsequently decay into normal particles. The photon-quark coupling strength is given by the electric charges of the quarks Q_i and one finds that $R \rightarrow \sum Q_i^2$. In particular for the 3 well-known quarks with their charges of (-1/3, -1/3, 2/3) one expected $R \rightarrow 2/3$. The experimental results shown in Fig.5 clearly demonstrate that R neither goes to zero nor approaches 2/3 but tends to rise even at the highest energies accessible at present. The proper interpretation is still lacking and is probably connected to the existence of the new particles. The behaviour of R indicates, however, that i) the hadrons contain pointlike constituents, ii) there must be more charged constituents than the 3 known quarks.

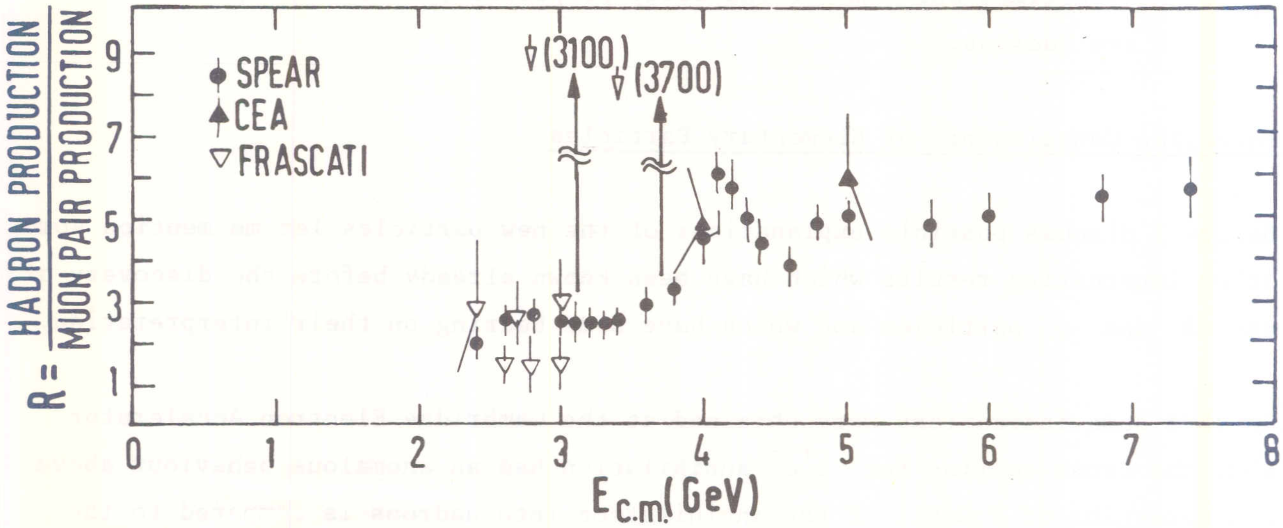

Fig.5:

Production cross section $e^+e^- \to$ hadrons normalized to the "pointlike" cross section $e^+e^- \to \mu^+\mu^-$ as function of the total energy. Dashed line: expected asymptotic value for 3 ordinary quarks. Line widths of 3.1 and 3.7 GeV resonance is too small to be displayed.

Possible Explanations of the New Particles

In the six months following the detection of the J and ψ particles several hundred theoretical papers were written. This shows the tremendous interest that this discovery has attracted but it also gives some measure of the difficulties to find an interpretation for these very sharp resonances.

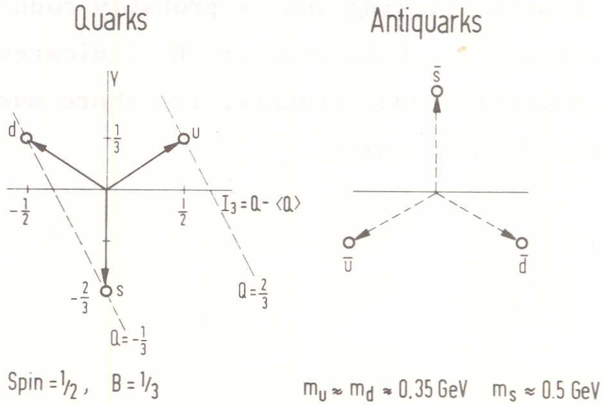

Fig.6:

Representation of ordinary quarks. I_3 third component of isospin, Y hypercharge (strangeness). Q electric charge, B baryon number.

At the beginning the possibility was considered that the J and ψ' are particles of the weak interaction which would explain their long half lives. However, in the meantime it could be shown by several experiments that the J and ψ' are subject to the strong interaction and hence they are hadrons, in particular bosons, because of their spin 1.

Knowing the coupling strength of the nuclear forces and the possible decay channels into lighter particles one estimates that the decay width of a hadron with a mass above 3 GeV should be $\Gamma \approx 40$ to 200 MeV whereas the measured width of the J/ψ and ψ' are about 1000 times smaller.

Some models which tried to explain these reduced decay probabilities by special assumptions in the frame of conventional theories failed in explaining some of the other decay properties. What survived so far are models in which a new quantum number is introduced and a new selection rule or symmetry principle inhibits the decay. In terms of subelementary constituents, i.e. quarks, a new quantum number implies that the number of 3 quarks has to be increased. Models with 4, 6, 9 and even more quarks have been suggested. In the following I want to discuss the "charm model" which is based on 4 quarks. The reason is that it is the simplest and according to my personal bias the most attractive model. During the last months all the models have gone through periods of success and difficulty depending on the publication of experimental results. It is by no means yet clear which of the models presently under discussion will turn out to be correct, if any. However, I believe that the most important qualitative features which I am going to describe to you now, will be incorporated in one way or the other in a future theory.

May I remind you that in the usual quark model 3 subelementary units, the u, d and s quark, are the building bricks of all elementary particles. The 3 quarks have spin 1/2 and baryon number 1/3. They are distinguished by their electric charges represented by the third component of isospin I_3 (u = up and d = down quark) and the hypercharge Y which is closely related to the strangeness quantum number (s = strange quark) (see Fig.6). Mesons can be obtained by combining a quark with an antiquark and baryons by combining 3 quarks (e.g. p = Uud, n = udd). Subsequently I shall discuss only mesons. All possible combinations of 3 quarks with 3 antiquarks are obtained if the triangle representing the antiquarks is superimposed on the 3 edges of the quark triangle (Fig.7). One obtains a particle multiplet, a nonet. The 3 particles at the center are combinations of a quark and its own antiquark. Having the same quantum numbers their wave functions can be mixed. Hence the physical particles can be mixtures of the pure states. This complicates somewhat the interpretation of the experiments.

The $\bar{q}q$-system of a meson is an object like a hydrogen atom or better like positronium. In particular the spins of the 2 quarks can be parallel ("ortho-quarkonium") or antiparallel ("para-quarkonium") and hence a nonet with $J^P = 1^-$ and another one with 0^- is expected. Indeed all the pseudoscalar and vector mesons found in nature exactly fit into that scheme (Fig.8).

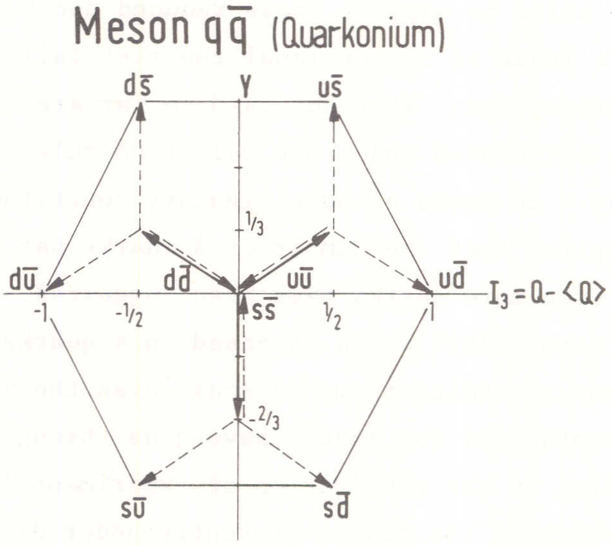

Fig.7:

Nonet of possible states obtained by quark-antiquark combinations (Quarkonium). Full arrows: quarks, dashed arrows: antiquarks.

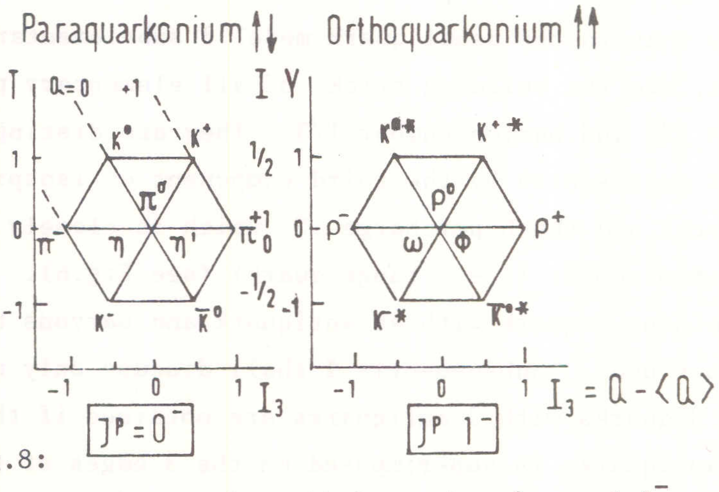

Fig.8:

0^--nonet with antiparallel quark spins and 1^--nonet with parallel spins as compared to particles found in nature.

The great success of the quark model is based on the fact that all of the several hundred known elementary particles fit into this classification scheme and indeed some unknown particles could be predicted.

The new J/ψ and ψ' particles, however, do not fit into the 3 quark model. In order to incorporate them the existence of a fourth quark with $I_3 = Y = 0$ but with the new quantum number charm $C = +1$ has been proposed in the frame of the charm model7) (Fig.9).

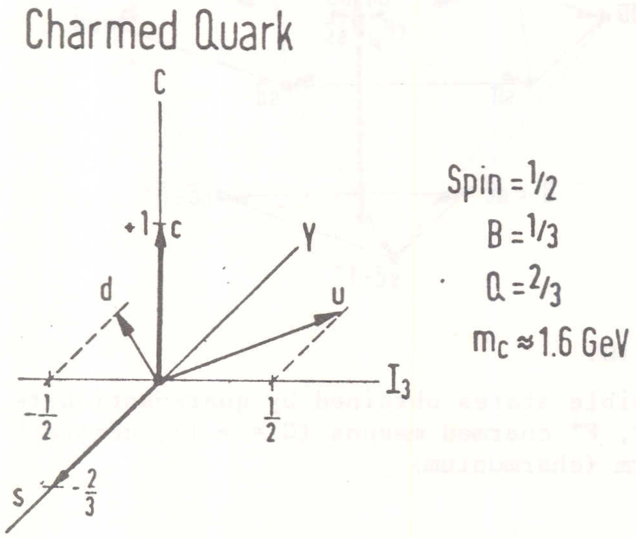

Fig.9:

Presentation of 4 quarks in charm model. Charm quantum number C.

If now the four quarks are combined with the four antiquarks one obtains a 3-dimensional structure (Fig.10). There are three new particles D^+, D^0 and F^+ which are composed of a charmed and an ordinary quark and they have therefore the charm number $C = +1$ (and their antiparticles have $C = -1$). In addition there is one more particle composed of the charm quark and its antiquark ("charmonium") having $C = +1 - 1 = 0$ ("hidden charm"). This state with parallel spins (orthocharmonium) is identified with the new particle J/ψ. The second new particle ψ' is interpreted as the first radially excited state of orthocharmonium. This explains, among other things, why the ψ' decays preferentially into the "ground state" J/ψ.

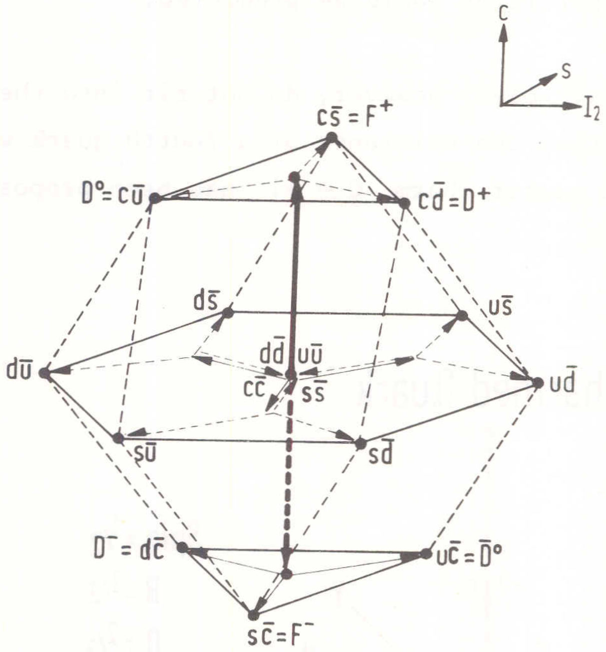

Fig.10:

Possible states obtained by quark-antiquark combinations. $D^{o,+}$, F^+ charmed mesons (C = + 1), $c\bar{c}$-state with hidden charm (charmonium).

This interpretation opens a new field of charmonium spectroscopy which will be discussed in more detail below. One of the results is that the binding energy in the $c\bar{c}$-system is small so that the mass of the charmed quark is roughly half of the J-mass, i.e. $m(c) \simeq 1.6$ GeV. From the ordinary quarkonium system one can infere masses for the ordinary quarks of the order 0.3 to 0.5 GeV and hence the charmed quark is much heavier.

Using this knowledge one can estimate the masses of the charmed D- and F-particles. Being composed of a charmed and an ordinary quark one expects masses of about (1.6 + 0.4) GeV $\simeq$ 2 GeV. Many searches for these charm particles have been performed in the last months, but so far their existence could not be established.

The reason for introducing a new quantum number was not only to explain how the new particles can be fittet into the quark scheme+), but in particular to

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+) paranthetically it should be mentioned that the introduction of a fourth quark corresponds to an extension of the SU(3) symmetry to SU(4).

explain their narrow decay widths. How this can be achieved is shown qualitatively in Fig.11. In these so-called duality diagrams each quark is symbolized by a line and an antiquark by an opposite line. From the decay of ordinary hadrons a rule has been established ("Zweig rule") which says that decays corresponding to duality diagrams with unconnected quark loops (e.g. Fig.11b and c) are strongly hindered whereas diagrams with throughgoing lines (Fig.11a) are allowed. If we apply this empirical rule to the ψ particle we find that the allowed decays according to Fig.11a are forbidden by energy conservation. This is because the decay products are two particles with charm each having a mass of about 2 GeV. Since the masses of J and ψ' are 3.1 and 3.7 GeV, respectively, they cannot decay into 2 charmed mesons.

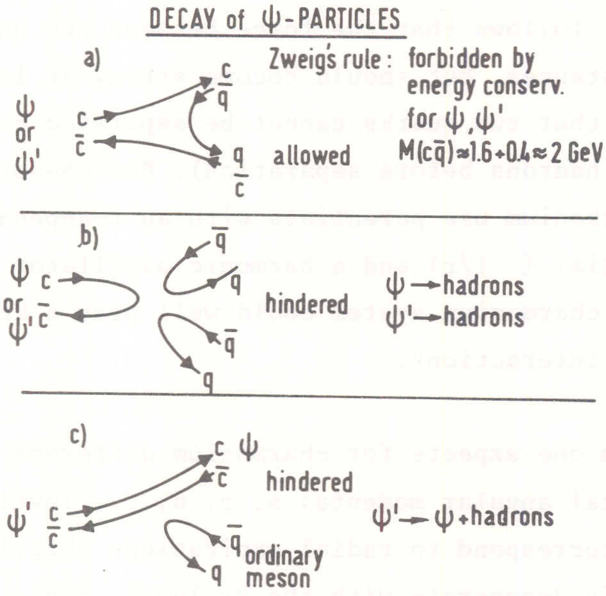


Fig.11:

Duality diagrams for ψ-decays. Each line represents a quark or antiquark.

What remains are decays according to the diagrams Fig.11b and c with ordinary mesons as final products. Since these diagrams have unconnected loops the decay are hindered, resulting in the very narrow width of the new particles. Diagram Fig.11c also explains the decay $\psi' \to \psi$ + hadrons with the charmed quarks staying together but giving off energy in the form of essentially pions. It should be mentioned that the Zweig rule which applies to all hadrons, not only to the new particles, is not yet understood, reflecting our poor knowledge of the dynamics of strong interaction.

Charmonium Spectroscopy and the P_c- and X-particles

The quark-antiquark state of a meson is a hydrogen-atom like system and hence one might hope to get a wealth of information from its level scheme. For ordinary mesons the quantitative treatment is difficult, however, since ordinary quarks have a low mass (~ 0.4 GeV) and therefore relativistic effects are important. For charmonium on the otherhand the classical non-relativistic procedure should be quite adequate since the mass of the charmed quark is rather large (~ 1.6 GeV). The good old Schroedinger equation becomes honourable again except that the force that binds the two quarks is not known. From field theoretical arguments it follows that the force between two quarks should be rather weak at small distances, but should become strong at larger distances. (This might be a reason that two quarks cannot be separated but that they are converted into ordinary hadrons before separation). Phenomenological fits to the level scheme of quarkonium use potentials with an r-dependence which is between a Coulomb-potential (~ 1/r) and a harmonic oscillator (~ r^2). For the reasons given above the charmonium system could well play a key role in the investigation of strong interactions.

As for the hydrogen atom one expects for charmonium different sequences of levels according to their orbital angular momenta: s, p, d, ... levels. The levels above the lowest level correspond to radial excitations (Fig.12). For a Coulomb potential the 1p state is degenerate with the 2s level. Since the quark potential is supposed to be somewhat stronger the 1p should be lower than the 2s-state and hence the position of the 1p level gives valuable information on the potential.

Again analogously to the H-atom one has to introduce hyperfine splitting and spin orbit splitting of the levels since the quarks have spin 1/2. The levels with opposite spin orientation (S = 0) are expected to be somewhat lower than those with parallel spin (S = 1) (see Fig.12). The LS-coupling splits the p-states with S = 1 into 3 states with J = 0^+, 1^+, 2^+.

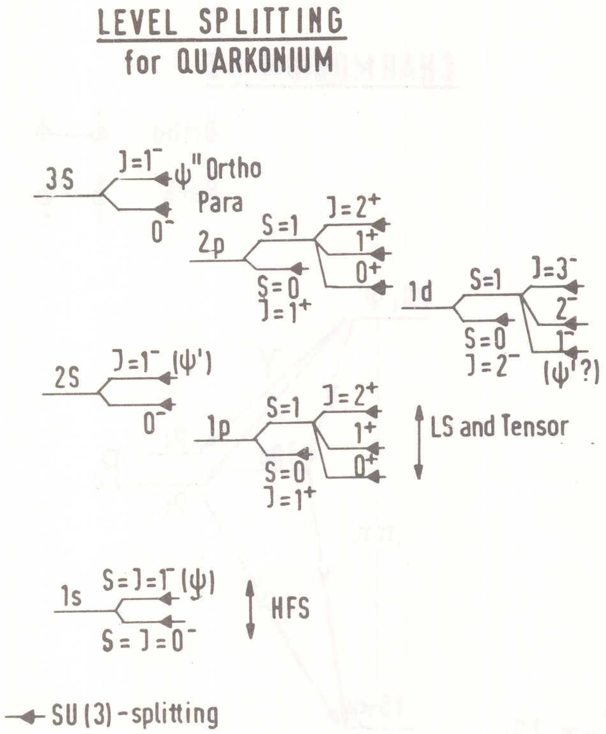


Fig.12:

Schematic level scheme of charmonium with HFS and LS level splitting.

The predictions for the magnitude of the HFS as well as the LS splitting vary between 50 MeV to several hundred MeV according to different models. Finally each level is split because SU(3) symmetry holds only approximately and hence the particles in one multiplet have different masses. However the charmonium states are SU(3)-singletts which avoids this complication. This is an additional reason why the charmonium system seems specially adequate to unravel the level scheme of the quark-quark forces.

Between the various levels transitions are possible, again in complete analogy with the hydrogen atom. Of course the proper selection rules must be observed. For electromagnetic transitions parity conservation has the consequence that the orbital angular momentum must change by one unit. The strongest transitions are shown in Fig.13. The transition $\psi' \to \psi + \pi\pi$ induced by the strong interaction is, however, the strongest since the suppression by the Zweig rule is not as effective to reduce this transition probability to the magnitude of electromagnetic transitions.

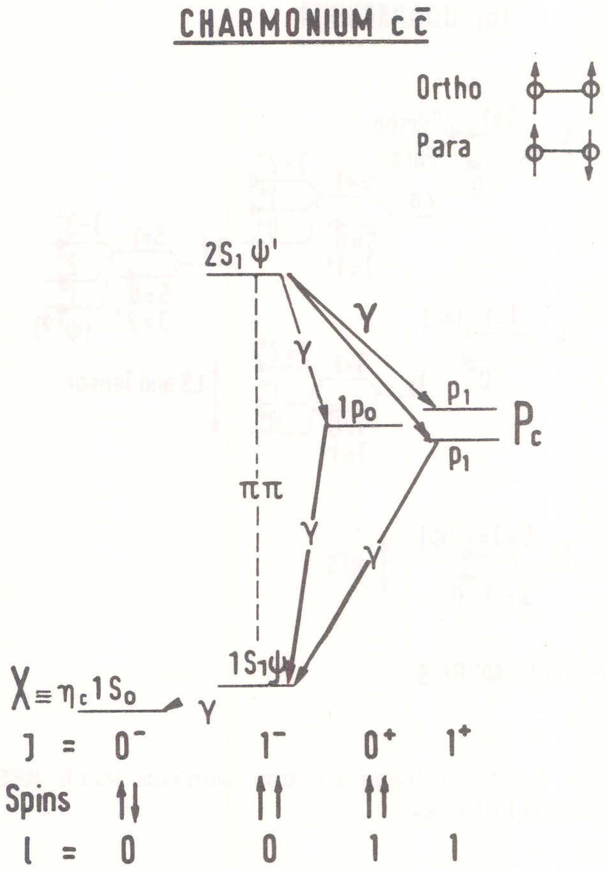


Fig.13:
The most important radiative transitions expected
for the charmonium system.

Not only the charm model but some of the other models introducing new kinds of quarks predict states between the ψ' and ψ . In particular some versions of the so-called colour model predict states about 200 MeV below the ψ' (3.7 GeV). These states have quantum numbers different from the photon and can therefore not be produced directly in e^+e^--annihilation, but by the decay of the ψ'.

During the last half year an intensive search for monoenergetic γ-lines in the region of 200 and 400 MeV was carried out. Originally nothing was found, on the contrary a disappointingly low limit for the radiative decays of the ψ' could be established. Also the decay of the J/ψ into the paracharmonium state $1S_0$

(usually called η_c) by the emission of a photon could not be detected. Since also the charmed mesons D and F were not found it seemed for some time that all the models with extra quarks were in trouble and theoriests were somewhat worried.

This pessimism was converted into optimism, "the veil has been lifted" as a journalist wrote, when several weeks ago the decay $\psi(3.7)' \rightarrow \psi(3.1) + \gamma + \gamma$ was detected by the DASP-group[8)] (double arm spectrometer) at DESY, proving the existence of an intermediate state which was named P_c .

The energies of the γ-lines were found to be 160 and 420 MeV corresponding to a P_c-mass of 3.52 or 3.26 GeV depending on the sequence in which the photons are emitted. This result has been confirmed recently by a DESY-Heidelberg collaboration working in the second interaction region of DORIS. Consequently what has been observed is the $\gamma - \gamma$ cascade shown in Fig.13 and very likely P_c is one of the P-states predicted. In the meantime two states have been identified also at SPEAR by their decays into hadrons at 3.53 and 3.41 GeV. The first could be identical with P_c .

If these states are identified with the P-states one could draw the conclusion that the quark potential has indeed a stronger r-dependence than the Coulomb potential and secondly the LS splitting would be of the order of 100 MeV. This is surprisingly large. Maybe history is repeating itself since a large LS splitting in nuclei was originally met with scepticism.

A few days ago I was informed that both groups working at the two intersection regions at DORIS have found evidence for the decay of $\psi(3.1) \rightarrow X(\rightarrow \gamma\gamma) + \gamma$ and with a mass $M(X) \simeq 2.8$ GeV. This could be the expected decay of paracharmonium (J = 1) into orthocharmonium $\eta_c(J = 0)$ by flipping the spins. If this interpretation is right it would imply a rather large (~ 300 MeV) HFS-splitting.

We are right now going through a very exciting time and things are changing almost daily. Hence I have to warn you that some of the results I reported are still preliminary and might be modified. However, at present it seems that the predictions of the charm model are verified one after the other. What is still missing is the detection of the charmed mesons D and F , but there are even some weak indications for them. It must be mentioned, however, that some versions of "colour model" seem to be compatible with the data and certainly much more experimental information is required before the whole question can be settled.

The Neutral Current of the Weak Interaction

Let me turn now to a different subject which seems at a first glance disconnected from the new particles but a very interesting relation will become evident in a moment.

The interaction between two electrons can be described by the exchange of a virtual photon. In a similar way the weak interaction between 4 fermions can be associated to the exchange of an "intermediate boson" W (Fig.14). There are two differences. The range of the interaction R is (by the uncertainty principle) determined by the mass M_B of the boson: $R \sim h/M_B c$. The infinite range of the Coulomb force is associated with the vanishing mass of the photon whereas the very short range ($\lesssim 10^{-17}$ cm) of the weak interaction implies a high boson mass ($\gtrsim 30$ GeV). This high mass is probably the reason why the intermediate boson has not been found so far.

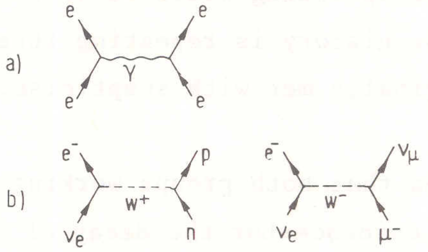


Fig.14:

Comparison of electromagnetic and weak processes. The interaction is transmitted by a virtual photon (a, electron-electron interaction) and by an intermediate charged boson W± (b, neutron decay; c, muon decay).

The second essential difference is that the photon does not carry electric charge whereas W does. In an ordinary weak process the incoming lepton changes its charge (Fig.14).

In spite of these differences theorists have tried since almost 20 years to find a unified field theory for the electromagnetic and weak interaction based on the principle of "gauge invariance", in which an additional symmetry is assumed to exist between the two interactions. Quite a number of theories have been proposed but almost all require that the weak boson can be charged as well as neutral 9) 10). The neutral weak boson Z^o is in a way a brother of the photon.

If the Z^o and the associated "neutral currents" exist, some processes should be observed which are not possible by an exchange of charged W. The most straight forward process is the elastic $e-\nu_e$-scattering, not easy to measure, however. Another process is the inelastic ν-scattering from protons with the proton breaking up in several hadrons (Fig.15).

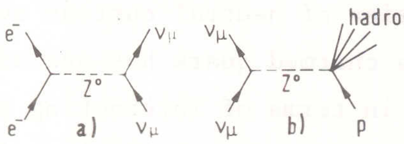


Fig.15:

Graphs for weak processes with neutral current a) electron-neutrino scattering, b) inelastic neutrino-proton scattering with exchange of neutral boson Z^o.

For quite some time an experimental search for neutral weak currents appeared to be out of the question, since for easily detectable processes the exchange of a photon is competing. Only with the help of neutrino beams the separation of the electric and weak neutral current became possible. In 1973 processes as shown by the diagrams of Fig.15 were observed in the heavy liquid bubble chamber Gargamelle at CERN 11) and later also in electronic experiments at the Fermi NAL 12).

This discovery opens the possibility for a unified theory. However, immediately a difficulty arose. Weak processes in which a strange particle is converted into a non-strange hadron with the participation of Z^o should be allowed (Fig.16). But experiments showed that these processes are about 10^5 times less likely to take place than expected.

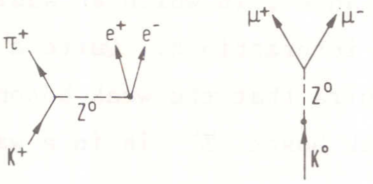


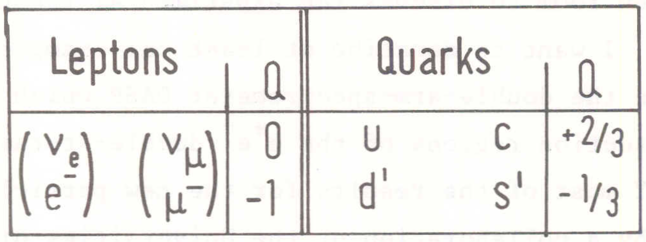
Fig.16:

Processes with neutral currents and change of strange particle K into ordinary particles. These decays should be allowed, but are strongly hindered in nature.

To remedy this difficulty it had been proposed that instead of describing the hadrons by 3 quarks a fourth quark with a new charge, called charm, should be introduced. This hypothesis was brought forward in 1970 (before the new particles had been found !!), but did not meet with great enthusiasm. Nevertheless, besides explaining the suppression of neutral current events with a change of strangeness the hypothesis of a charmed quark has one additional virtue. The weak interaction is formulated in terms of interacting pairs of particles. It is evident that 3 quarks cannot be grouped easily in pairs. Since it had been found that the d- and s-quarks, which have the same electrical charge (see Fig.6) participate in the weak interaction only as a mixture the pair (u, d') was used to describe the weak interaction of hadrons. The mixing angle θ with $d' = d \times \cos\theta + s \times \sin\theta$ was determined from experimental decay rates as $\theta = 0.26$ which implies that the strange quark is coupled only weakly because of $\sin\theta$ is small. There remains a strong asymmetry for the three quarks.

The picture is appreciably changed with 4 quarks. Now a second quark pair (c, s') with $s' = + s \times \cos\theta - d \times \sin\theta$ can interact with 2 lepton pairs (Fig.17). There is full symmetry between lepton and quark pairs, also with respect to the electric charge in so far as the charge difference between upper and lower particles in a pair is one unit. Strong and weak interaction differ in that leptons have integer, quarks third integer charges and the d- and s-quarks are rotated by an angle θ.

Of course, it cannot be excluded that additional (lepton, neutrino) and quark pairs exist.



Leptons		Q	Quarks		Q
ν_e	ν_μ	0	u	c	+2/3
e^-	μ^-	-1	d'	s'	-1/3

Fig.17:

The displayed pairs of leptons and quarks suffice to describe all the interactions of known weak processes. A symmetry exists between the two leptons and the two quark pairs (including the charmed quark). The d and s quarks are rotated by the angle θ: $d' = d \times \cos\theta + s \times \sin\theta$; $s = s \times \cos\theta - d \times \sin\theta$.

These ideas which were met with great scepticism at the beginning appear in a completely different light after the discovery of the J/ψ, ψ' and recently the P_c and X particles.

Conclusion

New experimental possibilities like higher energies, powerful neutrino beams and last not least e^+e^- storage rings have lead during the last years to a number of surprising discoveries.

The detection of the new particles has opened the door for a new branch of hadron physics and a better understanding of the symmetries governing the structure of elementary particles might ensue.

The discovery of neutral currents in weak interaction might provide a basis for a theory unifying the electromagnetic and weak interaction.

The concept of a charmed quark or any other extension of the 3 classical quarks will give new insights about the subelementary units of matter and perhaps yield links between the weak and strong interactions.

Of course, many detailed but also fundamental problems remain. Are quarks real particles or mathematical symbols for certain symmetries? Such "philosophical questions" are certainly very interesting but for me as an experimental physicist it is already very exciting and gratifying that unpredicted new facts have been found and that relations between phenomena have been established, which had been completely disconnected before.

Appendix

There had not been room to discuss the experimental techniques which enabled the new discoveries. I want to describe at least one example of a typical experiment and I have chosen the double-arm-spectrometer DASP which has been installed at one of the intersection regions of the e^+e^- double-storage-ring-system DORIS at Hamburg. At DESY most of the results for the new particles were obtained with this instrument by a collaboration of the Universities of Aachen, Hamburg, Tokyo, the Max-Planck Institut München and DESY.

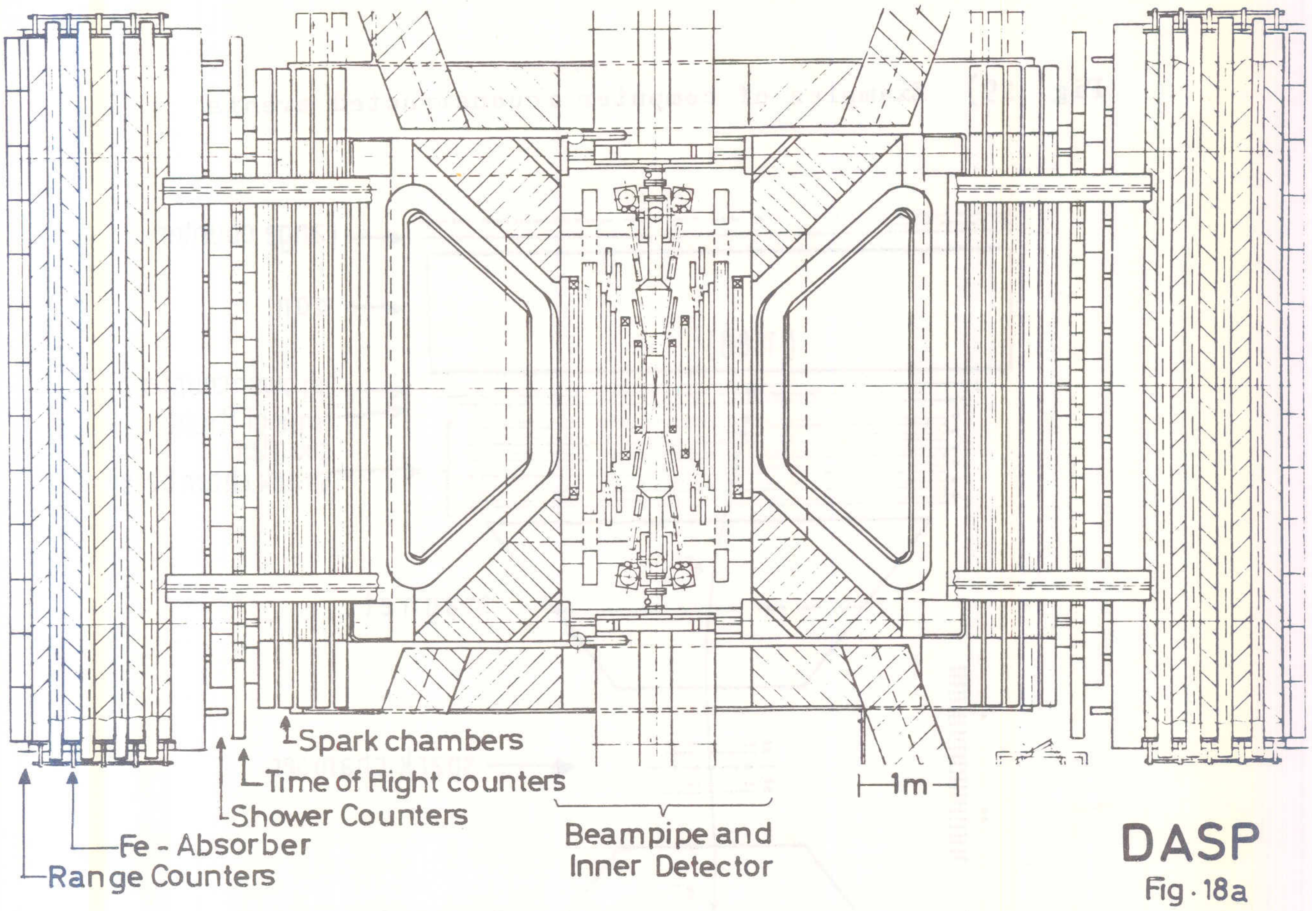
Fig.18a shows the top view and Fig.18b a cross section perpendicular to the intersecting electron and positron beams. On both sides of the intersection two identical magnets with a total weight of about 500 tons are installed producing vertical fields. Spark chambers in front and behind the magnets permit a precise momentum measurement of charged particles. Combining a time of flight measurement with the momentum determination one can identify particles up to momenta of about 1.5 GeV/c.

Muons are recognized by their penetration through a thick steel absorber.

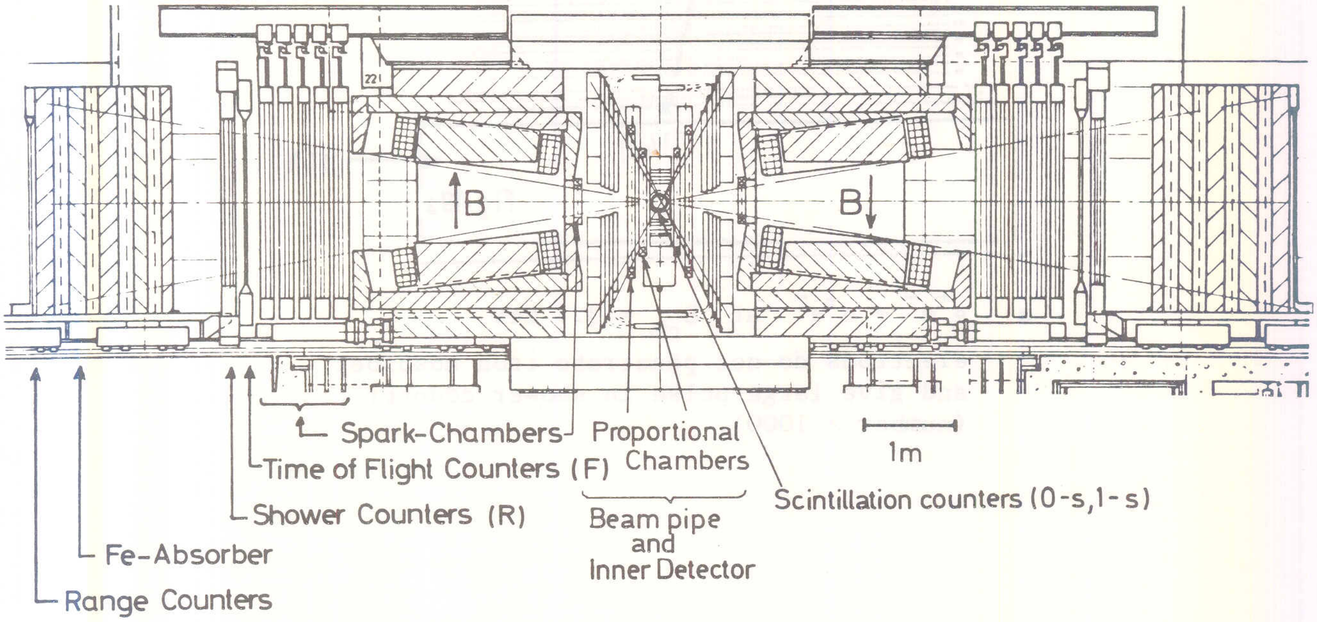
Precise momentum measurement and particle identification is achieved for a comparatively small solid angle. Close around the vacuum tube an inner detector has been set up which consists of a combination of scintillation and proportional counters and telescopes for electromagnetic showers. These permit the detection of charged and neutral particles (in particular photons) over about 80% of the total solid angle. A very good angular resolution and a moderate energy determination is achieved.

Fig.19 shows some examples of computer reconstructed events.

The intersecting beams of DORIS have typically currents of 200 to 300 mA electrons and positrons. The lifetime of the stored beams ranges from 10 to 20 hours and is limited by scattering from the residual gas (at pressures of several 10^{-8} Torr) and by the beam-beam interaction. The number of good events is a few per minute outside the resonance. Background from beam-gas scattering and cosmic rays has to be eliminated by a careful analysis of the events.

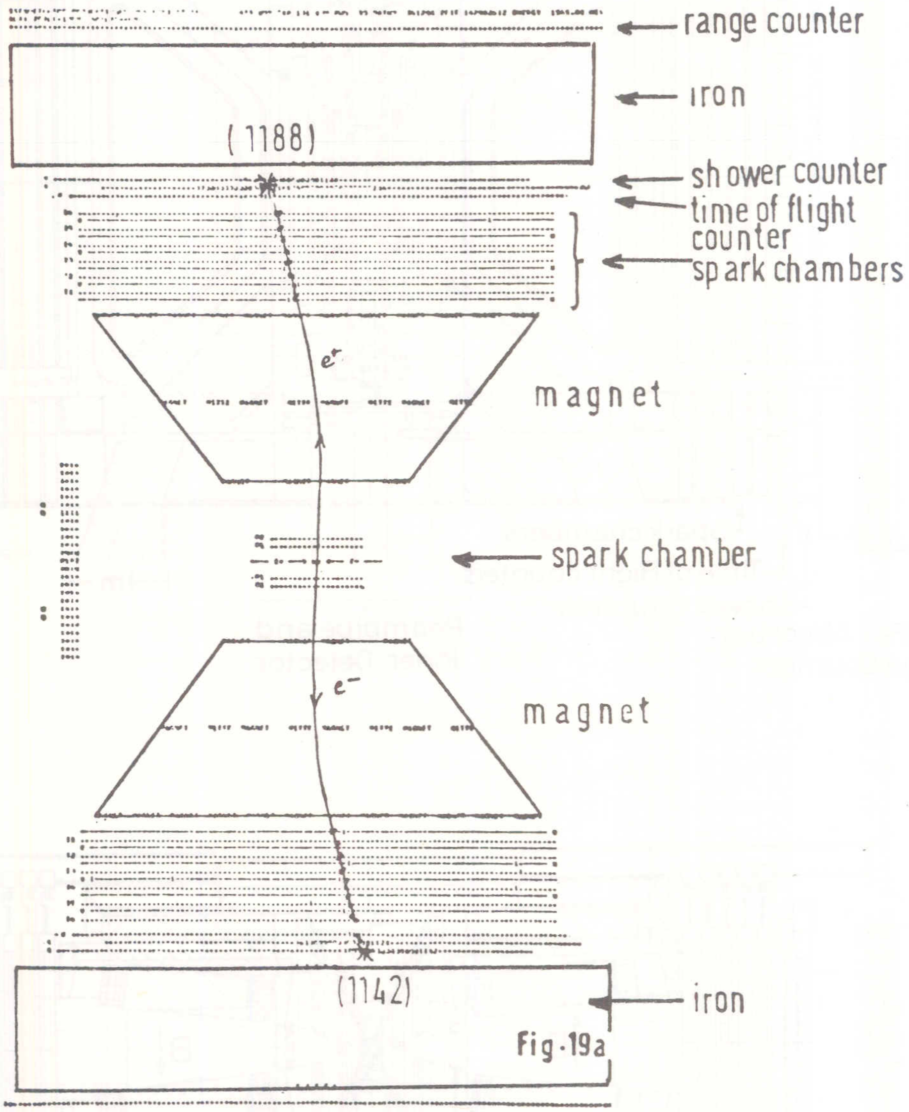


DASP
Fig. 18a



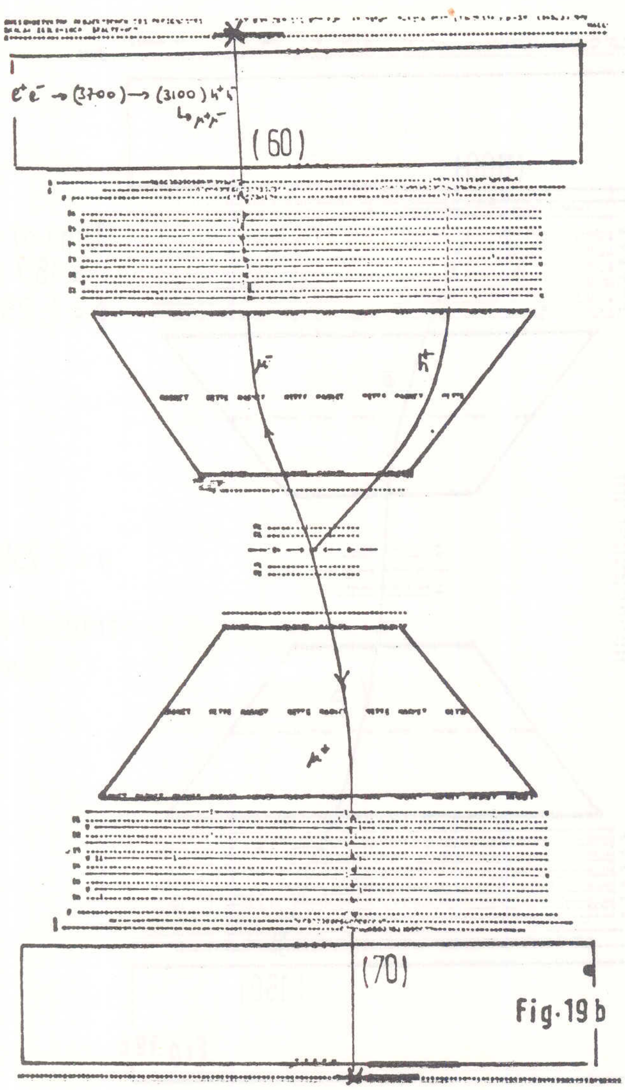
Schematic diagram of double arm spectrometer DASP
(Aachen-Hamburg-München-DESY Collaboration)
a) Top view
b) Vertical cross section

Fig. 19) Examples of computer reconstructed events



Fig·19a

a) $e^+e^- \to e^+e^-$ at $E_{cm} = 3.1$ GeV
electrons do not penetrate iron absorber
and give large pulse in shower counter
(number > 1000).



Fig·19 b

b) $e^+e^- \to \mu^+\mu^-$ + hadrons at $E_{cm} = 3.7$ GeV.

Muons go through iron and give small pulse height (number $\lesssim 100$) in shower counter. Negative hadron is not seen.
Mass of $\mu^+\mu^-$ is 3.1 GeV corresponding to decay $e^+e^- \to \psi' \to \psi$ + hadrons.

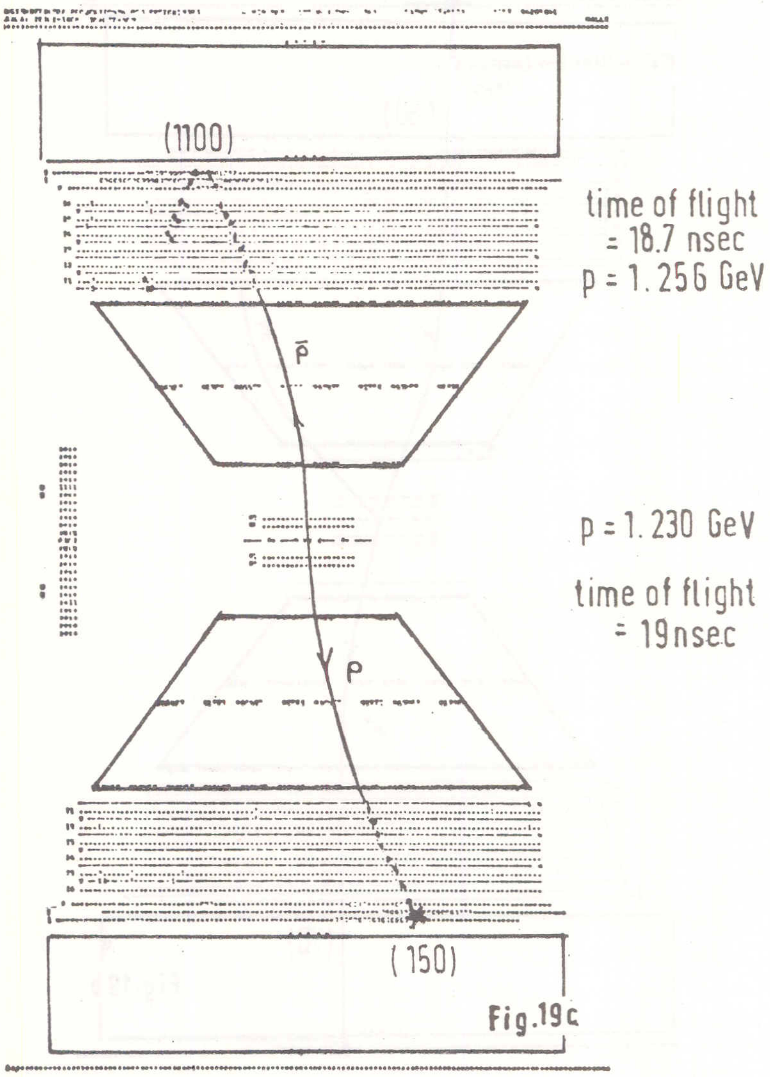
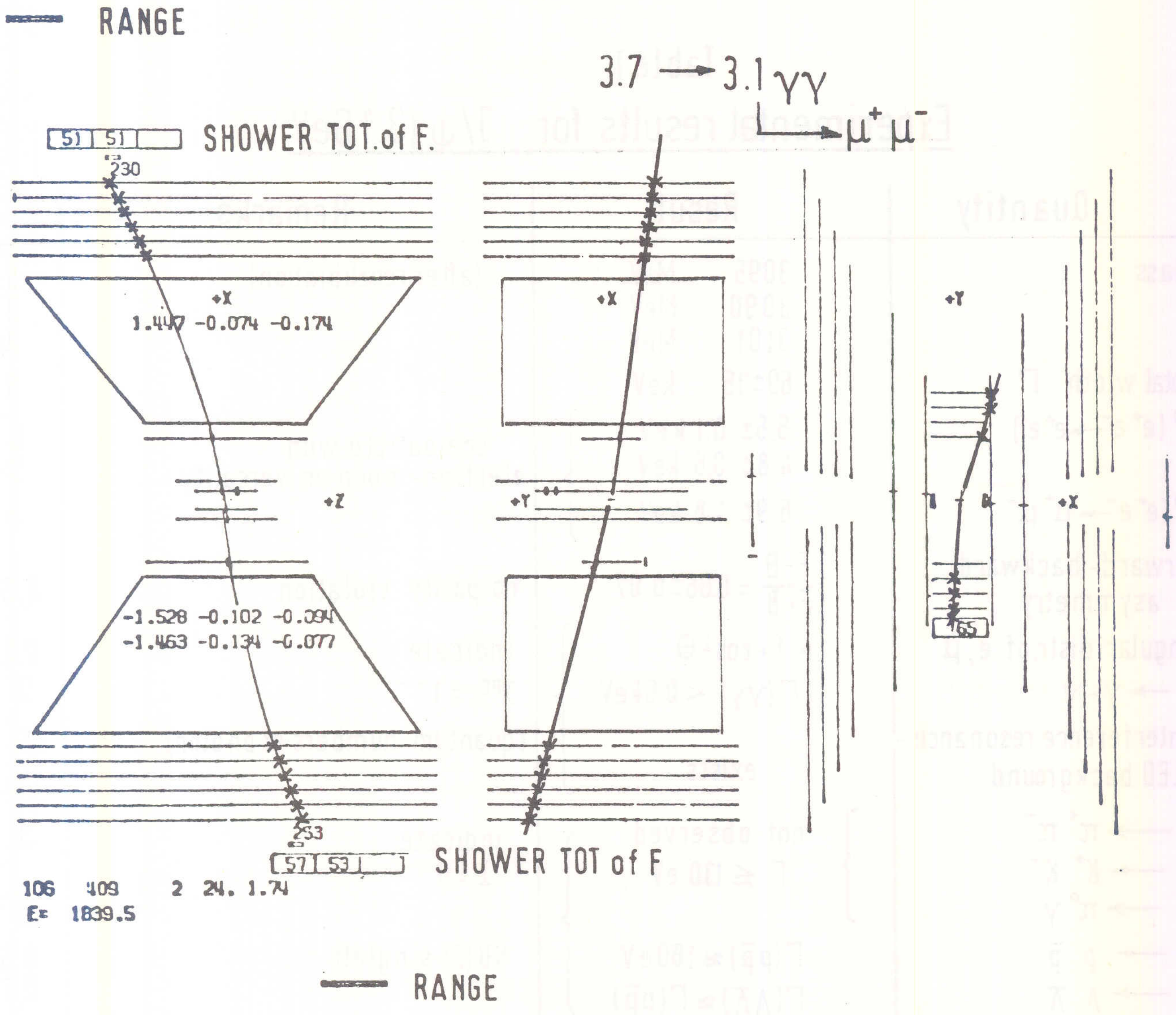


Fig.19c

c) $e^+e^- \to p\bar{p}$ at 3.1 GeV.
Hadrons do not penetrate iron, time of flight corresponds to proton mass, antiproton produces star (large pulse height, one visible track).



d) Discovery of P_c particle

Event $e^+e^- \to \mu^+\mu^- + \gamma + \gamma$ taken at 3.7 GeV total energy.

Interpreted as

$$e^+e^- \to \psi' \to P_c + \gamma$$
$$\hookrightarrow \psi(\to \mu^+\mu^-) + \gamma$$

Left: top view of magnet (x-z deflecting plane)
a well defined muon pair with mass 3.1 GeV is seen.

Middle: cross section of magnet vertical to beams (x-y plane)
muon pair is not collinear, neutral particle missing

Right: inner detector (x-y plane)
2 photons are visible (tracks start only after Pb converter)

The event is kinematically overdetermined (2C fit) allowing to calculate the photon energies from the angles.

Table 1

Experimental results for J/ψ (3.1GeV

Quantity	Result	Remarks	
Mass	3095 MeV	(after recalibration)	S
	3090 MeV		D
	3101 MeV		A
Total width Γ	69±15 keV		S
$\Gamma(e^+e^- \to e^+e^-)$	5.5± 0.1 keV	compatible with electron-muon universality	D
	4.8± 0.6 keV		S
$\Gamma(e^+e^- \to \mu^+\mu^-)$	6.9± 1.8 keV		D
forward-backward asymmetry	$\frac{F-B}{F+B} = 0.06 \pm 0.07$	no parity violation	D,S
angular distr. of e, μ	$\sim 1 + \cos^2\Theta$	indicate $J^{PC} = 1^{--}$ (quantum numbers of photon)	D,S
$J \to \gamma + \gamma$	$\Gamma(\gamma\gamma) < 0.5$ keV		D
interference resonance - QED background	exists		S
$J \to \pi^+\pi^-$	not observed $\Gamma \lesssim 130$ eV	indicate $I = 0$	D
$J \to K^+K^-$			
$J \to \pi^0\gamma$			D
$J \to p\bar{p}$	$\Gamma(p\bar{p}) \approx 180$ eV	SU(3) singlett	D,S
$J \to \Lambda\bar{\Lambda}$	$\Gamma(\Lambda\bar{\Lambda}) \approx \Gamma(p\bar{p})$		D,S
$J \to \pi^\pm\rho^\pm$	direct decay into odd number of pions, via virtual photon into even number	indicate $G = 1$	S
$J \to \pi^+\pi^-\omega$			S
$J \to K^+K^-\pi^+\pi^-$			S
$J \to \pi + X$	simular as outside resonance	no anomaly	D
$K + X$		for K	D

S = SPEAR (Stanford), D = DORIS (Hamburg), A = ADONE (Frascati)

Table 2

Experimental results for ψ' (3.7 GeV)

Quantity	Result	Remarks	
Mass	3684 MeV	(after recalibration)	S
	3680 MeV		D
Total width Γ	225 keV		S
$\Gamma(e^+e^- \to e^+e^-)$	2.2 ± 0.5 keV		S
$\psi' \to \psi + X$	(57 ± 8) % of all decays	ψ' and ψ/J particles with similar structure	S
$\psi' \to \psi + \pi^+ + \pi^-$	(56 ± 10) % of $\psi' \to \psi + X$	compatible with $I = 0$ for $\pi\pi$ system	S,D
$\psi' \to \psi + \pi^0 + \pi^0$	30 %		D
$\psi' \to \psi + \eta$	10 %		D
$\psi' \to p\bar{p}$	larger than for ψ		D
$\psi' \to \pi + X$	similar as outside resonance		D
$\psi' \to K + X$			D
$\psi' \to \psi + \gamma + \gamma$	a few % of all ψ' decays	discovery of P_c	D

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