HEAVY QUARK STATES

THE IDEA OF QUARK ATOMS FOUND HAPPY APPLICATION AFTER THE DISCOVERY OF THE J/ψ PARTICLE IN 1974. THIS PARTICLE IS CONSIDERED AS A $c\bar{c}$ PAIR WHERE c = CHARMED QUARK, WITH $M_c \sim 1600$ MeV AS DISCUSSED BELOW. THE MASS SPLITTINGS BETWEEN THE VARIOUS EXCITED STATES OF THE $c\bar{c}$ ATOM ARE MUCH LESS THAN 1600 MeV, WHICH ALLOWS THE NON-RELATIVISTIC CONCEPT OF AN ATOM TO BE A SUITABLE DESCRIPTION.

1. DISCOVERY OF THE J/ψ PARTICLE

ALREADY IN 1964 BJORKEN AND GLASHOW [PHYS. LETT 11, 255 (1964)] SPECULATED ON THE POSSIBILITY OF A 4TH QUARK FLAVOR WHICH THEY NAMED CHARM. BUT IN THE SEARCH FOR CHARM MOST ATTENTION WAS GIVEN TO POSSIBLE MESONS OF THE FORM $c\bar{u}$, WHICH CARRY NON-ZERO CHARM FLAVOR, AND HENCE HAVE A NEW QUANTUM NUMBER.

ON ANOTHER FRONT, VARIOUS GROUPS WERE STUDYING THE PRODUCTION OF VECTOR MESONS. HIGH MASS VECTOR MESONS WERE TYPICALLY EXPECTED TO BE EXCITED STATES OF THE ρ, ω AND ϕ MESONS. THEY WOULD DECAY QUICKLY VIA STRONG INTERACTION, LEADING TO LARGE WIDTHS, Γ, OF THE RESONANCE CURVES.

HENCE THE DISCOVERY OF A NARROW VECTOR MESON RESONANCE OF MASS 3.1 GeV IN 1974 WAS A STUNNING EVENT TO BOTH THE THEORETICAL AND EXPERIMENTAL COMMUNITIES ALIKE.

[THIS IS THE ONLY SUCH REMARKABLE DISCOVERY IN HIGH ENERGY PHYSICS WHICH OCCURRED DURING MY CAREER OF 1967 ONWARDS. PERHAPS THE EARLIER DAYS WERE HEADIER, WITH THE DRAMATIC DISCOVERIES OF THE μ-MESON, STRANGENESS, THE Δ RESONANCE, P AND CP VIOLATION – ALL UNANTICIPATED BY THE BULK OF THE COMMUNITY.]

FIRST EVIDENCE CAME IN THE REACTION $p + Be \to e^+e^- + X$ [AUBERT ET AL, P.R.L. 33, 1404 (1974). TOP RIGHT FIGURE ON p 271] THE GROUP LEADER, TING, HESITATED TO PUBLISH THIS DRAMATIC RESULT UNTIL HE HAD RUMORS OF CONFIRMATION FROM THE RICHTER GROUP AT SLAC, THEREBY LOSING HIS CLAIM TO BE THE SOLE DISCOVERER. IT IS ALSO NOTABLE THAT THE J/ψ HAD BEEN SEEN BUT NOT RECOGNIZED IN AN EARLIER EXPERIMENT [CHRISTENSON ET AL P.R.L. 25, 1523 (1970). TOP LEFT FIGURE ON p 271]

A VERY NARROW RESONANCE WAS 'SIMULTANEOUSLY' OBSERVED IN THE REACTIONS $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, OR HADRONS [AUGUSTIN ET AL, P.R.L. 33 1406 (1974), BOTTOM RIGHT FIGURE ON p 271]

ITALIAN GROUPS AT FRASCATI LABORATORY HAD BEEN STUDYING e^+e^- COLLISIONS FOR SEVERAL YEARS, BUT NEVER LOOKED AT C.M. ENERGIES HIGHER THAN 3.0 GeV. WITHIN 1 DAY OF HEARING OF THE ABOVE RESULTS THEY WERE ABLE TO CONFIRM THEM, BY RAISING THEIR BEAM ENERGY 3%! [BACCI ET AL, P.R.L. 33, 1408 (1974)]

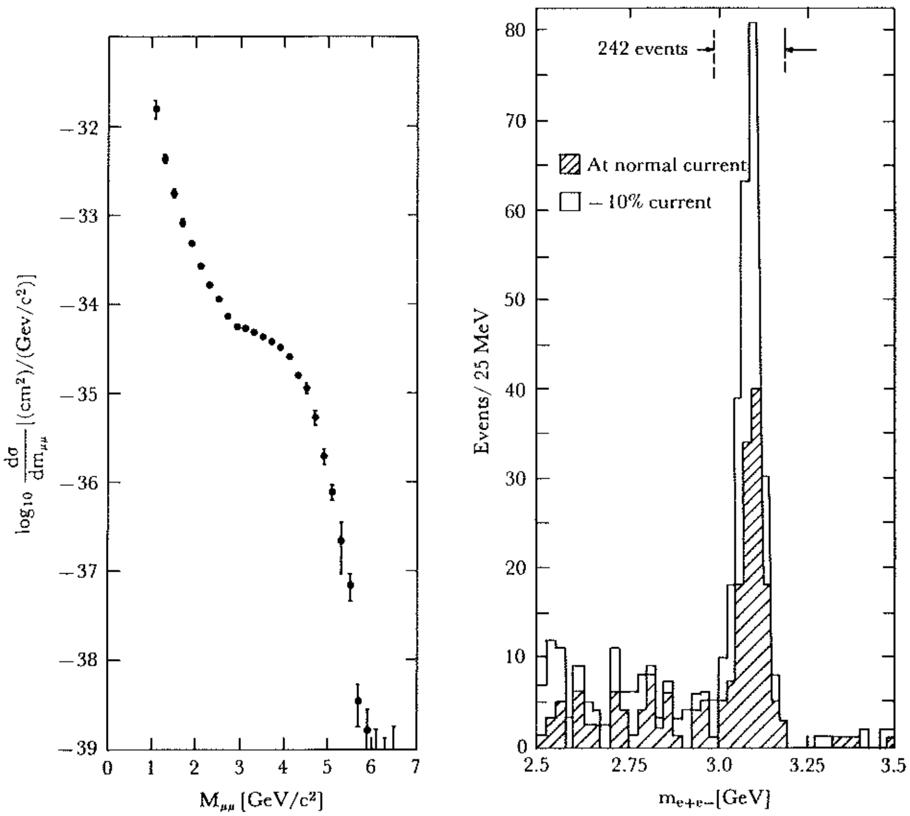


Figure 1. The effect of good resolution. Left: $pU \to \mu\mu X$, Right: $pBe \to eeX$ [7,8]

WHILE THE PROTON BEAM EXPERIMENTS HAVE PROVED USEFUL IN MAKING THE INITIAL DISCOVERIES OF NARROW RESONANCES [Υ IN 1977, Z^0 IN 1983] ALMOST ALL SUBSEQUENT ANALYSIS OF THESE STATES HAS BEEN DONE BY e^+e^- COLLIDING BEAM EXPERIMENTS. THE e^+e^- COLLIDING BEAM TECHNIQUE WAS THUS TRANSFORMED FROM A CURIOSITY INTO ONE OF THE MAINSTAYS OF HIGH ENERGY PHYSICS.

FOR EXAMPLE, THE SLAC GROUP LOCATED A SECOND NARROW RESONANCE, THE $\psi'(3686)$ ABOUT 1 WEEK AFTER THEIR DISCOVERY OF THE $\psi(3097)$ [ABRAMS ET AL. PRL. 33, 1452 (1974). THE C.M. ENERGY AVAILABLE AT THE BROOKHAVEN AGS IS INSUFFICIENT FOR NOTICEABLE PRODUCTION OF THE ψ'.]

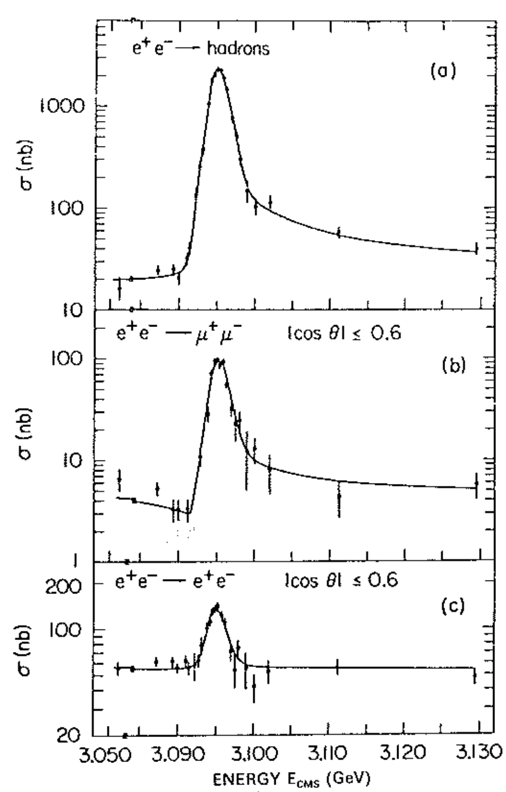
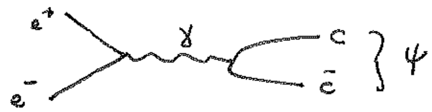


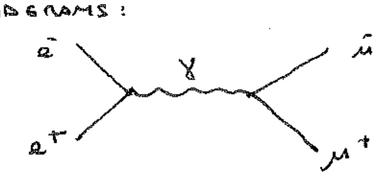
Fig. 5.10 Results of Augustin *et al.* (1974) showing the observation of the ψ/J resonance of mass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC.

2. Spin and Parity of the ψ and ψ'

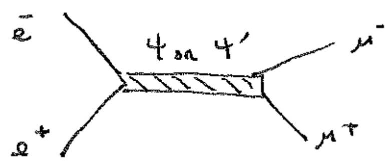
From our previous discussion of vector meson production in e^+e^- collisions (p. 187) it is natural to conclude that $J^P = 1^-$ for the ψ and ψ', supposing the production diagram is



It is amusing that the question can be addressed experimentally, by observing the reaction $e^+e^- \to \mu^+\mu^-$ near the ψ and ψ' resonances. We can have 2 diagrams:



CONTINUUM



RESONANCE

As $E_e \sim 1.5$ GeV, helicity conservation holds to excellent approximation in the 1st diagram. Thus the virtual photon has $S_z = \pm 1 \Rightarrow$ transverse $\Rightarrow J^P = 1^-$. In the 2nd diagram we assume nothing about the coupling of the ψ to e^+e^- or $\mu^+\mu^-$.

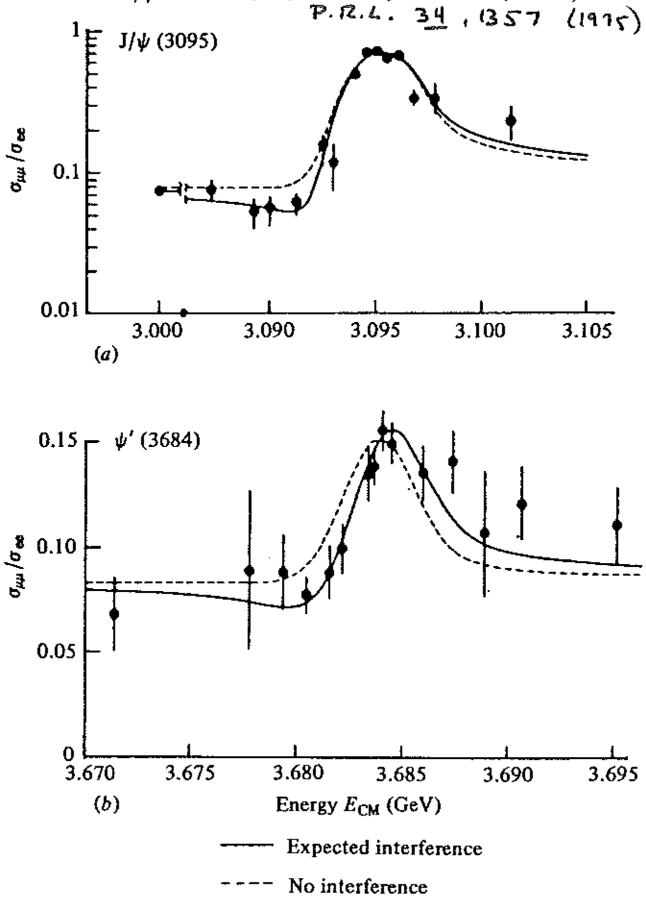
But if $J^P = 1^-$ rather than 0^+ or 2^+, etc, for the ψ, the 2 diagrams can interfere. This leads to visible effects in the cross section slightly off resonance. In particular, there should be a dip in the cross section for E_{CM} slightly less than M_ψ.

For $E_{CM} > M_\psi$ there is a complication. Often the e^+ or e^- radiates a real photon before the annihilation,

This makes the C.M. energy of the annihilation process less than $2E_{beam}$. Hence the resonance peak is smeared out on the side of large E_{CM} (nominal), producing the so-called 'radiative tail'.

The evidence favors $J^P = 1^-$.

Fig. 9.8. Ratio of lepton pair cross-sections $\sigma_{\mu\mu}/\sigma_{ee}$ in the vicinity of the J/ψ and the ψ'. (From Boyarski *et al.*, 1975.)
P.R.L. 34, 1357 (1975)



[ANOTHER TECHNICALITY. THE PLOT SHOWS $\sigma_{\mu\mu}/\sigma_{ee}$. BY σ_{ee} THEY MEAN THE CROSS SECTION FOR BHABHA SCATTERING (p. 109) WHICH IS USED TO KEEP TRACK OF THE BEAM FLUX. BY MONITORING THE BHABHA SCATTERING AT SMALL ANGLES, THERE IS ALMOST NO 'CONTAMINATION' DUE TO ψ PRODUCTION IN THIS METHOD OF NORMALIZATION.]

3. WIDTH OF THE ψ AND ψ'

THE WIDTH OF THE ψ RESONANCE CURVE IN THE e^+e^- REACTION (p 271) IS ALMOST EXACTLY THAT OF THE KNOWN SPREAD OF THE e^+ AND e^- BEAM ENERGIES ($\sim \pm 1$ MeV). HENCE WE INFER THAT THE TRUE RESONANCE WIDTH IS MUCH SMALLER THAN 1 MeV.

THE DECAY WIDTHS $\Gamma_{\psi \to \text{hadrons}}$, $\Gamma_{\psi \to e^+e^-}$ AND $\Gamma_{\psi \to \mu^+\mu^-}$ CAN BE OBTAINED BY INTEGRATING OVER THE RESONANCE CURVES. A QUICK INSPECTION OF THE DATA SUGGESTS $\Gamma_{e^+e^-} \sim \Gamma_{\mu^+\mu^-} \sim \frac{1}{20}\Gamma_{\text{hadrons}}$

FOR A MORE DETAILED ANALYSIS WE RECALL THE RESULTS OF p 210

$$\sigma(E)_{e^+e^- \to \text{spin 1 resonance} \to f} = \frac{3\pi}{4K^2} \frac{\Gamma_{e^+e^-}\Gamma_f}{(E-E_R)^2 + \Gamma_t^2/4} \qquad (K \approx E_{cm}/2)$$

FIRST WE SUPPOSE THAT IF THE BEAM ENERGY IS NOMINALLY E_0, THERE IS AN ACTUAL SPREAD IN TRUE BEAM ENERGY E, DESCRIBED BY $P(E, E_0)\,dE$. P IS NEARLY GAUSSIAN. $\int P(E,E_0)\,dE \equiv 1$

THE OBSERVED CROSS SECTION AT A GIVEN NOMINAL BEAM ENERGY IS

$$\sigma(E_0) = \int P(E, E_0)\,dE \; \frac{3\pi}{E^2} \frac{\Gamma_{e^+e^-}\Gamma_f}{(E-E_R)^2 + \Gamma_t^2/4}$$

THIS IS GREATLY SIMPLIFIED IF WE INTEGRATE OVER NOMINAL BEAM ENERGY:

$$\int \sigma(E_0)\,dE_0 = \frac{6\pi}{E_R^2} \frac{\Gamma_{e^+e^-}\Gamma_f}{\Gamma_t}$$

WE HAVE DEFINED $\Gamma_t \equiv \Gamma_{e^+e^-} + \Gamma_{\mu^+\mu^-} + \Gamma_{\text{hadrons}}$

FOR THE ψ, THE DATA GIVE $\int \sigma_{\text{hadrons}} \sim 10\,\mu b$; $\int \sigma_{e^+e^-} = \int \sigma_{\mu^+\mu^-} \sim 800\,nb$

WHICH LEADS TO $\Gamma_t = 63 \pm 9$ keV

$$\Gamma_{\psi \to e^+e^-} = \Gamma_{\psi \to \mu^+\mu^-} = 4.7 \pm 0.8 \text{ keV}$$

AND $\frac{\Gamma_{e^+e^-}}{\Gamma_t} = 7\%$

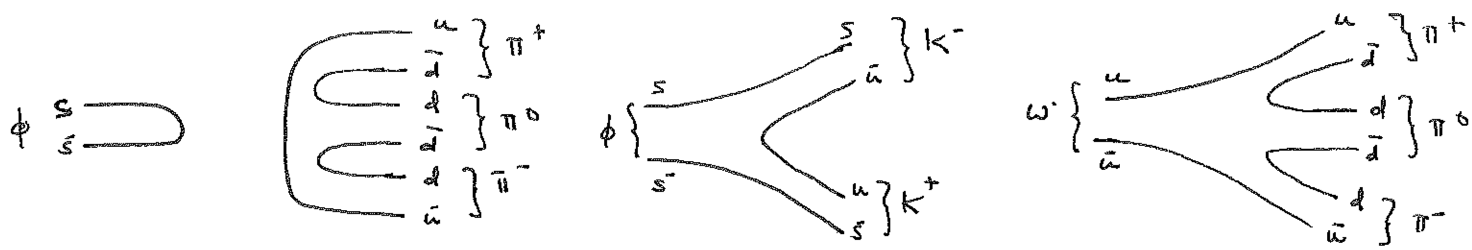
FOR THE ψ': $\Gamma_{\psi' \to \text{anything}} = \Gamma_t = 215 \pm 40$ keV

$$\Gamma_{\psi' \to e^+e^-} = \Gamma_{\psi' \to \mu^+\mu^-} = 1.8 \pm 0.2 \text{ keV} \qquad \frac{\Gamma_{e^+e^-}}{\Gamma_t} \sim 1\%$$

4. The Zweig Rule

The biggest surprise of the J/ψ particle was its extremely narrow width, $\Gamma_t \sim 63$ keV. This suggested to some people that the J/ψ might be a bound state of Ω^- and $\bar{\Omega}^+$, noting a near coincidence of the masses! However the interpretation of the ψ as a $c\bar{c}$ quark atom was made more plausible by the resurrection of the Zweig rule (also called the OZI rule, after Okubo-Zweig-Iizuka). This rule was invented about 1964 to explain the relatively slow decay rate $\phi \to 3\pi$ compared to $\phi \to 2K$ or $\omega \to 3\pi$.
[The reader may recall that on p 198 we gave another explanation why $\phi \to 3\pi$ is suppressed.]

The proponents ask us to draw the decay process in terms of quarks!

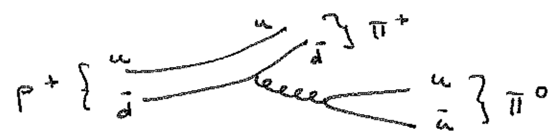


Then the rule is that diagrams are suppressed in which some quark lines are completely 'disconnected' from the others.

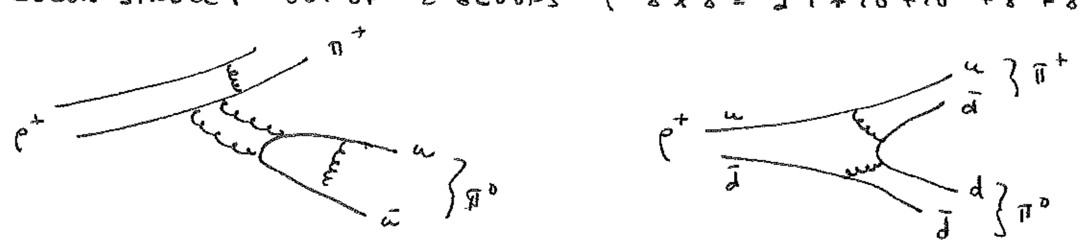
This is the case for the decay $\phi \to 3\pi$ sketched above, but not for the other 2. However this rule seems somewhat ad hoc, and it was not taken too seriously in the 60's.

Nowadays we can give greater justification for the Zweig rule in terms of the model of colored quarks and gluons.

In principle the production of a $q\bar{q}$ pair can take place via single gluon exchange. An example might be the decay $\rho^+ \to \pi^+\pi^0$. We might draw

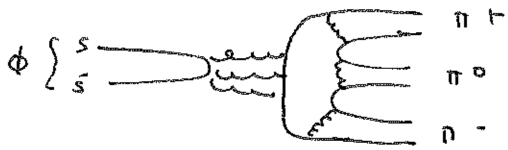


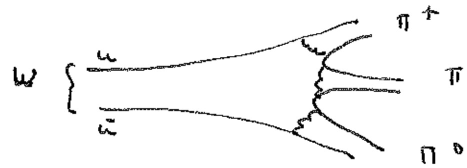
But if the $q\bar{q}$ pair is to emerge as a real particle this is not actually possible. The reason is that real particles are all color singlets - and a state produced by a single gluon will belong to a color octet. To produce a real particle at least 2 gluons must be exchanged, as we can form a color singlet out of 2 gluons ($8 \times 8 = 27 + 10 + 10^* + 8 + 8 + 1$ in SU(3))



The left diagram is possible, but it has more gluons exchanged than the righthand diagram, and so is suppressed.

In some cases 3 gluons must be exchanged. If the $q\bar{q}$ state has negative charge conjugation it cannot be produced via 2 gluons which will have $C = +1$. The ϕ and J/ψ have $C = -1$ and so their $s\bar{s}$ or $c\bar{c}$ quarks can only annihilate to 3 gluons.





Simply counting the number of exchanged gluons, we estimate

$$\frac{\Gamma_{\phi\to 3\pi}}{\Gamma_{\omega\to 3\pi}} \sim \alpha_s^3 \qquad \text{DATA: } \frac{\Gamma_{\phi\to 3\pi}}{\Gamma_{\omega\to 3\pi}} = \frac{.6\text{ MeV}}{9\text{ MeV}} \sim \frac{1}{15}$$

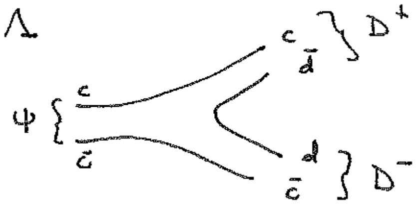
$\Rightarrow \alpha_s \sim 0.4$, which is not too far from the value inferred from our previous studies of ρ, ω & ϕ decays, p. 252.

The Zweig rule also explains the observed results that

$$\sigma_{\pi^- p\to\phi n} << \sigma_{\pi^- p\to\omega n}$$

while $\sigma_{K^- p\to\phi\Lambda} \sim \sigma_{K^- p\to\omega\Lambda}$

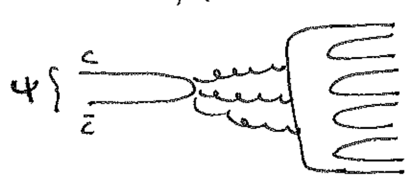
Returning to ψ decay, the diagram



is Zweig allowed.

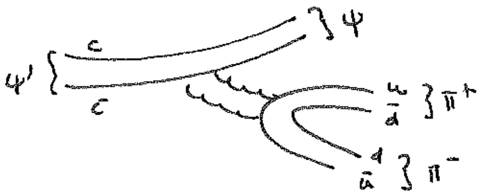
But it turns out that $M_\psi < 2M_D$ $\quad$ [$D^+ \equiv c\bar{d}$ = lightest charmed meson]

The dominant observed decay of the ψ is to 5π or 7π [This implies $G_\psi = -1 \Rightarrow I_\psi = 0$] Such decays can only happen via disconnected diagrams, and so are suppressed! Hence the decay width of the ψ is narrow.



The ψ' width is larger than that of the ψ, but it is still fairly narrow. The dominant decay mode is $\psi' \to \psi + 2\pi$, which happens 50% of the time.

Again the decay diagram is disconnected



The 2π can be in an L = 0 state ⇒ C = +1 ⇒ only 2 gluon exchange.

We then estimate $\dfrac{\Gamma_\psi}{\Gamma_{\psi'}} \sim \alpha_s$

DATA: $\dfrac{\Gamma_{\psi \to \text{hadrons}}}{\Gamma_{\psi' \to \text{hadrons}}} \sim \dfrac{53\text{ keV}}{210\text{ keV}} \sim \dfrac{1}{4}$

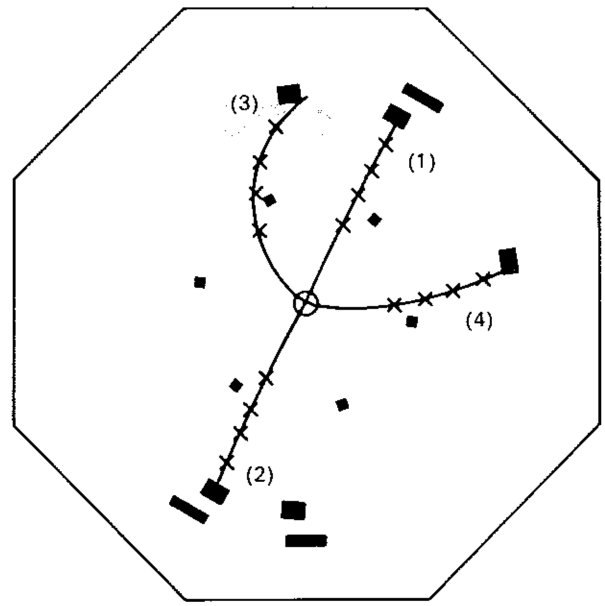


Fig. 5.13 Example of the decay $\psi'(3.7) \to \psi(3.1) + \pi^+ + \pi^-$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^+ + e^-$. Tracks (3) and (4) are due to the relatively low-energy (150-MeV) pions, and (1) and (2) to the 1.5-GeV electrons. The magnetic field and the SPEAR beam pipe are normal to the plane of the figure. The trajectory shown for each particle is the best fit through the sparks, indicated by crosses. [From G. S. Abrams *et al., Phys. Rev. Letters* **34**, 1181 (1975).]

5. The Charmonium Family

The $c\bar{c}$ quark atom picture was been rather successful in categorizing the observed family of neutral mesons closely related to the ψ and ψ'.

The observed spectrum of states is very reminiscent of atomic physics. There are candidates for states with non-zero orbital angular momentum, the χ states & ψ(3767); states of radial excitation, ψ(3686), ψ(4414); as well as one observed spin singlet state, $\eta_c(2980)$.

The name charmonium of course comes from the analogy of these $c\bar{c}$ states with the positronium family of e^+e^- bound states.

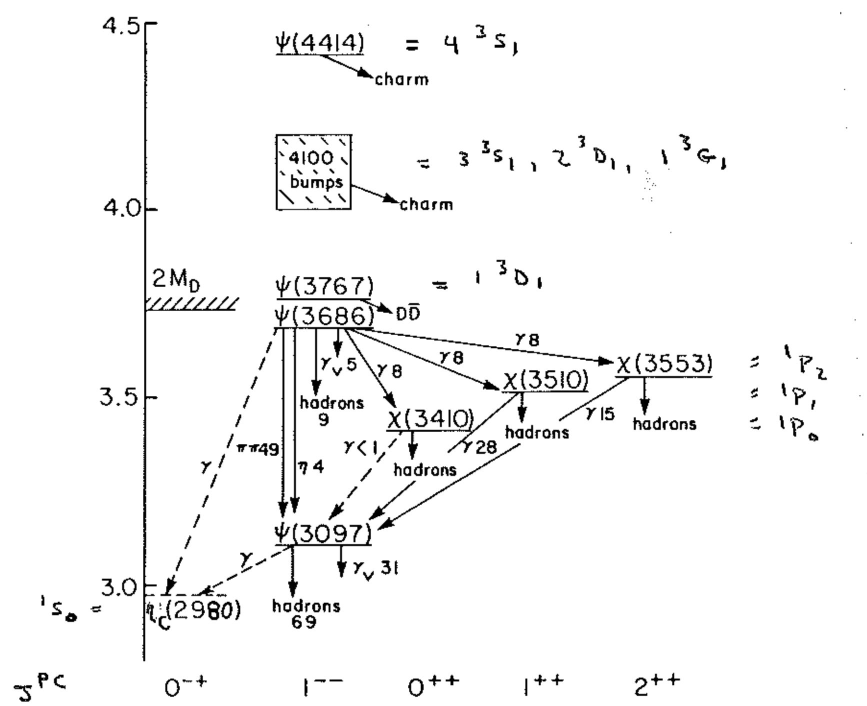


Fig. 30. Bound states of a charmed quark and charmed antiquark (charmonium). Decay modes and branching ratios (in percent) are shown.

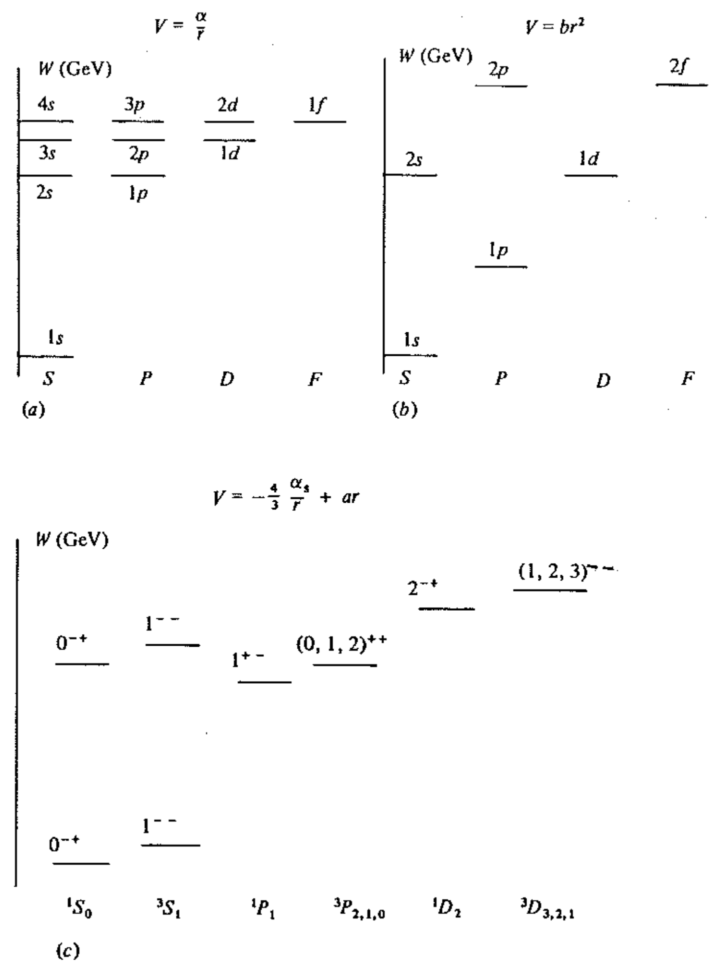
THE OBSERVED CHARMONIUM MASS SPECTRUM IS NOT WELL FIT BY SUCH SIMPLE ASSUMPTIONS AS A COULOMB, OR HARMONIC OSCILLATOR QUARK-QUARK POTENTIAL.

GUIDED BY ARGUMENTS OF GLUON EXCHANGE AND QUARK CONFINEMENT, AS SKETCHED IN LECTURES 12 AND 14, PEOPLE HAVE CONSIDERED THE COMBINED POTENTIAL

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + Kr$$

THE FIRST TERM IS DUE TO GLUON EXCHANGE AND IS THOUGHT TO GOVERN THE STRONG INTERACTION AT DISTANCES $\lesssim$ 0.1 FERMI. THE SECOND TERM IS A GUESS AT THE FORM OF THE CONFINING POTENTIAL, WHICH DOMINATES BEHAVIOR AT $r \sim 1$ FERMI.

THE OBSERVED $c\bar{c}$ MASS SPECTRUM CAN BE FAIRLY WELL FITTED WITH THE ABOVE POTENTIAL ON TAKING $\alpha_s \sim 0.4$ AND $K \sim 0.2\ \mathrm{GeV}^{-2}$



BOTH VALUES ARE ROUGHLY CONSISTENT WITH PREVIOUS ESTIMATES OF THESE QUANTITIES.

WE NOW CONSIDER A FEW DETAILS OF THE CHARMONIUM SPECTRUM.

6. $\psi(3097) - \eta_c(2980)$ MASS DIFFERENCE

THE $\psi(3097)$ AND THE $\eta_c(2980)$ ARE THE LOWEST MASS $^3S_1$ AND $^1S_0$ $c\bar{c}$ MESONS. ON PP 266-268 WE GAVE A VIEW OF THE MASS DIFFERENCE BETWEEN SUCH STATES, BASED ON THE COLOR MAGNETIC DIPOLE INTERACTION.

FOR EXAMPLE, WE ESTIMATED $M_\phi = 2M_s + \frac{2b}{M_s^2} \sim 1032\ \mathrm{MeV}$ (P 268)

IF A $^1S_0$ $s\bar{s}$ STATE EXISTED, OUR FORMALISM WOULD INDICATE

$$M_{^1S_0} = 2M_s - \frac{4b}{M_s^2} \sim 834\ \mathrm{MeV}$$

OR $\Delta M(^3S_1 - {}^1S_0) = 8b/M_s^2 = 264\ \mathrm{MeV}$

AS A SIMPLE ESTIMATE OF C QUARK MASS, WE TAKE $M_c \sim 3M_s \sim 1500\ \mathrm{MeV}$

THEN FOR THE $c\bar{c}$ SYSTEM, $\Delta M(^3S_1 - {}^1S_0) = \frac{8b}{M_c^2} \sim 30\ \mathrm{MeV}$ (IF b UNCHANGED)

THE DATA INDICATE $\Delta M \sim 117\ \mathrm{MeV}$!

WE RECALL THE DEFINITION OF PARAMETER $b = \frac{8}{9}\pi\,\alpha_s\,|\psi(0)|^2$

POSSIBLY α_s AND/OR $|\psi(0)|^2$ HAVE CHANGED FOR THE $c\bar{c}$ SYSTEM.

$|\psi(0)|^2$ CAN BE SEPARATED FROM α_s BY CONSIDERING THE DECAYS $^3S_1 \to e^+e^-$.

ON p 252 WE SAW THAT $\Gamma_{V\to e^+e^-} \sim \frac{Q^2|\psi(0)|^2}{M_V^2}$

SO WE ESTIMATE $$\frac{|\psi(0)|^2_\psi}{|\psi(0)|^2_\phi} = \frac{M_\psi^2}{M_\phi^2}\,\frac{\Gamma_{\psi\to e^+e^-}}{\Gamma_{\phi\to e^+e^-}}\,\frac{Q_s^2}{Q_c^2} \sim 8.8 \qquad \text{IF } Q_c = 2/3$$

TO EXPLAIN THE OBSERVED $\psi - \eta_c$ MASS DIFFERENCE, WE THEN INFER

$$\frac{\alpha_s|_\psi}{\alpha_s|_\phi} = \frac{117\,\text{MeV}}{30\,\text{MeV}}\,\frac{|\psi(0)|^2_\phi}{|\psi(0)|^2_\psi} \sim \frac{4}{8.8} \sim 0.45$$

ROUGHLY CONSISTENT WITH $\alpha_s|_\psi \sim 0.3 \qquad \alpha_s|_\phi \sim 0.6$

THIS DECREASE OF THE APPARENT VALUE OF THE STRONG COUPLING CONSTANT α_s WITH INCREASING MASS IS INTERPRETED AS EVIDENCE FOR <u>ASYMPTOTIC FREEDOM</u> OF THE STRONG INTERACTION. THIS CONCEPT WAS MENTIONED BRIEFLY ON p 38, AND IS A KEY, IF NOT SELF EVIDENT FEATURE, OF THE THEORY OF COLORED QUARKS AND GLUONS (QCD).

7. ψ AND η_c DECAYS

WE GIVE FURTHER CONSIDERATION TO THE WIDTHS OF VARIOUS ψ AND η_c DECAYS.

OUR THINKING ABOUT THE DECAY $\psi \to$ HADRONS IS GUIDED BY THE ZWEIG RULE: ALL HADRONIC DECAYS TAKE PLACE VIA 3 GLUON EXCHANGE IN THIS PARTICULAR CASE

ASSUMING THE 3 GLUONS CONVERT TO SOME HADRONIC FINAL STATE WITH 100% PROBABILITY, WE MAY ESTIMATE THIS DECAY RATE, IN ANALOGY WITH THAT OF POSITRONIUM

$$\Gamma_{\psi\to 3\,\text{gluons}\to\text{hadrons}} = \frac{160}{81}(\pi^2-9)\,\alpha_s^3\,\frac{|\psi(0)|^2}{M_\psi^2}$$

WE INCLUDE THE NON TRIVIAL NUMERICAL FACTORS IN ORDER TO MAKE FURTHER NUMERICAL COMPARISONS.

LIKEWISE, AS RECENTLY NOTED, WE MAY ESTIMATE

$$\Gamma_{\psi\to e^+e^-} = 16\pi\,\alpha^2\,Q_c^2\,\frac{|\psi(0)|^2}{M_\psi^2}$$

[THIS IS A FACTOR OF 3 LARGER THAN OUR ESTIMATE OF p 252, BECAUSE WE NOW BELIEVE QUARKS COME IN 3 COLORS ⇒ AMPL: $c\bar{c}\to e^+e^-$ IS $3/\sqrt{3}$ LARGER ...]

THEN
$$\frac{\Gamma_{\psi \to 3G \to \text{HADRONS}}}{\Gamma_{\psi \to e^+e^-}} = \frac{10(\pi^2-9)}{81\pi}\frac{\alpha_s^3}{\alpha^2 Q_c^2} \sim 1440\,\alpha_s^3 \qquad \text{IF } Q_c = 2/3$$

DATA:
$$\frac{\Gamma_{\psi \to \text{HADRONS}}}{\Gamma_{\psi \to e^+e^-}} = \frac{53\text{ keV}}{4.7\text{ keV}} \sim 11 \quad \Rightarrow \quad \alpha_s = 0.2$$

AGAIN, α_s AS OBSERVED AT 3 GeV APPEARS SMALLER THAN THE α_s INFERRED FOR ρ, ω AND ϕ.

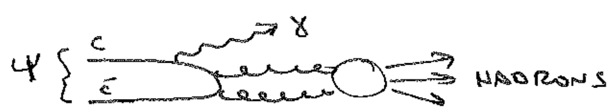
WE CAN MAKE A DIFFERENT COMPARISON BETWEEN $\psi'(3686)$ AND $\psi(3097)$ DECAYS THAN THAT GIVEN ON p 276. THIS TIME WE ONLY CONSIDER DECAYS TO 'ORDINARY' HADRONS, i.e. THOSE CONTAINING u, d OR s QUARKS. THREE GLUONS MUST BE EXCHANGED, AND SO WE CAN USE THE EXPRESSIONS ON p 278 TO WRITE

$$\frac{\Gamma_{\psi' \to \text{ORDINARY HADRONS}}}{\Gamma_{\psi \to \text{HADRONS}}} = \frac{M_\psi^2}{M_{\psi'}^2}\frac{|\psi(0)|^2_{\psi'}}{|\psi(0)|^2_{\psi}} = \frac{\Gamma_{\psi' \to e^+e^-}}{\Gamma_{\psi \to e^+e^-}}$$

DATA:
$$\frac{\Gamma_{\psi' \to 2(\pi^+\pi^-)\pi^0}}{\Gamma_{\psi \to 2(\pi^+\pi^-)\pi^0}} = \frac{.75\text{ keV}}{2.3\text{ keV}} \sim .33 \qquad\qquad \frac{1.9\text{ keV}}{4.7\text{ keV}} \sim 0.4$$

WE OBTAIN ANOTHER ROUGH CONSISTENCY CHECK OF OUR ATOMIC MODEL.

AN INTERESTING DECAY POSSIBILITY IS $\psi \to \gamma + 2$ GLUONS



THE $^3S_1$ $c\bar{c}$ STATE CAN BECOME A $^1S_0$ BY EMISSION OF AN M1 PHOTON. THEN THE $^1S_0$ CAN ANNIHILATE VIA 2 GLUON EMISSION, WHICH PRODUCES THE OBSERVED HADRONS. IT IS CLAIMED THAT

$$\Gamma_{\psi \to \gamma + 2\text{ GLUONS}} = \frac{128}{9}\,\alpha Q_c^2\,\alpha_s^2(\pi^2-9)\frac{|\psi(0)|^2}{M_\psi^2}$$

IF SO,
$$\frac{\Gamma_{\psi \to \gamma + \text{HADRONS}}}{\Gamma_{\psi \to \text{HADRONS}}} = \frac{36}{5}\frac{\alpha Q_c^2}{\alpha_s} \qquad \text{REFERRING TO p 278}$$

WITH $Q_c = 2/3$ AND $\alpha_s \sim 0.2$ THE RATIO IS ESTIMATED AS $\sim 12\%$

EXPERIMENTALLY THE SITUATION IS CONFUSED BY THE PRESENCE OF $\pi^0 \to \gamma\gamma$ DECAYS, WHICH GIVE PHOTONS BY ANOTHER MECHANISM. IT IS KNOWN THAT
$$\frac{\Gamma_{\psi \to \text{ANY } \gamma + \text{HADRONS}}}{\Gamma_{\psi \to \text{HADRONS}}} \sim 20\%$$

WHILE ABOUT 10% OF ALL HADRONIC FINAL STATES OF ψ DECAY CONTAIN π^0's. SO OUR MODEL MAY INDEED BE ABOUT RIGHT.

A SPECIFIC DECAY OF THE ψ OF POSSIBLE INTEREST IS $\psi \to \eta_c + \gamma$. WITH THE η_c AS A $^1S_0$ STATE, THIS IS AN M1 TRANSITION. AS ON p 250 WE ESTIMATE

$$\Gamma_{\psi \to \eta_c + \gamma} = \frac{k^3}{3\pi} \langle f|i\rangle^2 (2\mu_c)^2 = \frac{4\alpha Q_c^2 k^3}{3 M_c^2} \langle f|i\rangle^2$$

THE SIMPLE ASSUMPTION IS THAT THE ψ AND η_c DIFFER ONLY IN THEIR SPIN CONFIGURATION, SO THE OVERLAP INTEGRAL $\langle f|i\rangle = 1$. THEN WITH $k \sim 117$ MeV, $Q_c = 2/3$ AND $M_c \sim 1500$ MeV,

$$\Gamma_{\psi \to \eta_c + \gamma} \sim 3 \text{ keV}$$

EXPERIMENTALLY THIS TRANSITION HAS BARELY BEEN OBSERVED: $\Gamma_{\psi \to \eta_c + \gamma} \sim .7 \pm .3$ keV

THE SOURCE OF THE DISCREPANCY IS NOT WELL UNDERSTOOD.

A RELATED TRANSITION IS $\psi' \to \eta_c + \gamma$. AGAIN THIS DEPENDS ON THE OVERLAP INTEGRAL $\langle f|i\rangle$. IF $\psi'(3686)$ IS INDEED A RADIAL EXCITATION OF THE ψ, THEN $\langle \psi'|\psi\rangle = 0$. AND IF THE η_c AND ψ HAVE THE SAME RADIAL WAVEFUNCTIONS AS ASSUMED ABOVE, THEN $\langle \psi'|\eta_c\rangle = 0$ ALSO i.e. THE TRANSITION IS FORBIDDEN. HOWEVER EXPERIMENTALLY IT IS OBSERVED, WITH $\Gamma_{\psi' \to \eta_c + \gamma} = .6 \pm .2$ keV.

THESE LAST 2 RESULTS SHOW SOME DIFFICULTIES FOR THE NON-RELATIVISTIC $c\bar{c}$ ATOM MODEL.

WE CAN ALSO CONSIDER DECAYS OF THE η_c ITSELF. THE SIMPLEST CASES TO CALCULATE ARE $\eta_c \to \gamma\gamma$ AND $\eta_c \to 2$ GLUONS $\to$ HADRONS (CAN WE HAVE $\eta_c \to \gamma + 1$ GLUON?). POSITRONIUM TYPE CALCULATIONS YIELD

$$\Gamma_{\eta_c \to 2\gamma} = 48\pi\alpha^2 Q_c^4 \frac{|\psi(0)|^2}{M_{\eta_c}^2} \quad ; \quad \Gamma_{\eta_c \to 2G} = \frac{32}{3}\pi\alpha_s^2 \frac{|\psi(0)|^2}{M_{\eta_c}^2}$$

WE CAN THEN FORM THE RATIO

$$\frac{\Gamma_{\eta_c \to \text{hadrons}}}{\Gamma_{\psi \to \text{hadrons}}} = \frac{27\pi}{5(\pi^2-9)} \frac{1}{\alpha_s} \sim \frac{20}{\alpha_s} \sim 100 \quad \text{IF } \alpha_s \sim 0.2$$

WITH $\Gamma_{\psi \to \text{hadrons}} \sim 53$ keV WE ESTIMATE $\Gamma_{\eta_c \to \text{hadrons}} \sim 5$ MeV

DATA: $\Gamma_{\eta_c} \sim 12 \pm 5$ MeV

ANOTHER RATIO TEST IS

$$\frac{\Gamma_{\eta_c \to \gamma\gamma}}{\Gamma_{\eta_c \to \text{hadrons}}} \sim \frac{8}{9}\frac{\alpha^2}{\alpha_s^2} \sim 10^{-3} \quad \text{IF } \alpha_s = 0.2$$

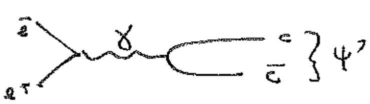
THE DECAY $\eta_c \to \gamma\gamma$ HAS NOT BEEN MEASURED YET.

8. THE χ STATES

THE 3 STATES $\chi(3415)$, $\chi(3510)$ AND $\chi(3555)$ ARE IDENTIFIED AS THE $^3P_{0,1,2}$ STATES OF CHARMONIUM. AS SUCH THE TRANSITIONS $\psi' \to \chi + \gamma$ AND $\chi \to \psi + \gamma$ CAN BE E1 TRANSITIONS WHICH ARE RELATIVELY PROMINENT. ($\psi' \to \chi$ + HADRONS IS SUPPRESSED BY THE ZWEIG RULE.) BOTH KINDS OF PHOTON TRANSITIONS SHOW UP WELL IN DATA ON $\psi' \to \gamma$ + ANYTHING COLLECTED WITH THE CRYSTAL BALL DETECTOR AT SLAC.

ESTIMATES OF THE E1 TRANSITION RATES DEPEND ON THE MATRIX ELEMENTS $\langle f | \vec{r} | i \rangle$. THESE ARE NOT TOO WELL KNOWN, AND THE EXPERIMENTAL DATA IS USUALLY INTERPRETED TO GIVE NUMERICAL VALUES OF THE MATRIX ELEMENTS, RATHER THAN VICE VERSA.

THE SPIN ASSIGNMENTS OF THE χ STATES CAN BE DETERMINED BY OBSERVING THE ANGULAR DISTRIBUTION OF THE DECAYS $\psi' \to \chi + \gamma$. IF WE ACCEPT THAT THE PRODUCTION OF THE ψ' IS VIA 1 PHOTON EXCHANGE



THEN THE ψ' HAS $J_z = \pm 1$ ONLY, FOR z = BEAM DIRECTION, BY HELICITY CONSERVATION AT THE $e^+e^-\gamma$ VERTEX. FOR A χ STATE $^3P_0$ THE REST OF THE ARGUMENT IS STRAIGHTFORWARD. THE χ-γ STATE CAN ONLY HAVE $J_{z'} = \pm 1$ ALONG THE DIRECTION OF THE γ.

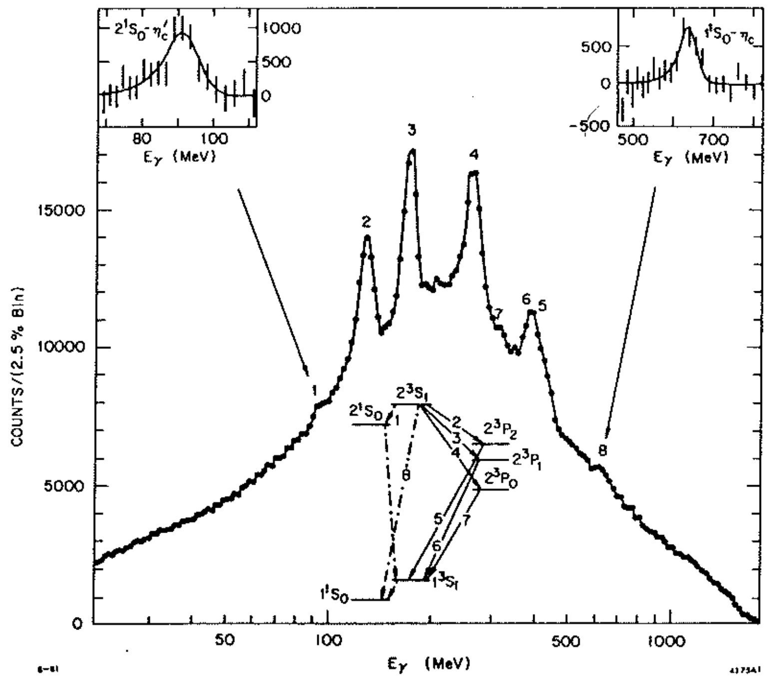


Figure 14. The inclusive γ spectrum obtained from $\approx$ 1.7M hadronic ψ' decays in the cyrstal ball detector. The lower insert shows the bound state charmonium level diagram, except for the $2^1P_1{}^{+-}$ which can only be seen as a γ transition from one of the other P states (if the energies are right) and so should be very weak. All the transitions shown in the level diagram appear as lines in the spectrum. The weaker transitions to the η_c[31] and η_c'[32] are shown in blowups of the inclusive γ spectrum in the region of the respective lines. The left upper corner contains the η_c' spectrum ,the right upper corner the η_c spectrum. For details of the measurement, including a careful discussion of this new η_c' candidate, see reference 33.

IF WE PROJECT $J_{z'} = +1$ ONTO $J_z = +1$ OR -1 USING THE SPIN 1 ROTATION MATRIX, THEN WE GET

$$\frac{d\sigma}{d\Omega} \sim 1 + \cos^2\theta$$

JUST AS FOR $e^+e^- \to \mu^+\mu^-$ ETC (p 118)

THE ARGUMENTS FOR THE $^3P_1$ AND $^3P_2$ STATES ARE A BIT SUBTLER. WE SIMPLY REMARK THAT

$$\frac{d\sigma}{d\Omega} \sim 1 - \tfrac{1}{3}\cos^2\theta \qquad \text{FOR } \psi' \to {}^3P_1 + \gamma$$

$$\frac{d\sigma}{d\Omega} \sim 1 + \tfrac{1}{13}\cos^2\theta \qquad \text{FOR } \psi' \to {}^3P_2 + \gamma$$

IN A MODEL CALCULATION, THE DATA ARE REASONABLY CONSISTENT WITH THESE DISTRIBUTIONS.

9. DISCOVERY OF THE Υ FAMILY

IN 1977 AN EXPERIMENT AT FERMILAB ON THE REACTION

$$p + \text{NUCLEUS} \to \mu^+\mu^- + \text{ANYTHING}$$

GAVE EVIDENCE FOR ENHANCEMENTS IN THE $\mu^+\mu^-$ INVARIANT MASS SPECTRUM AROUND 10 GeV [HERB ET AL, P.R.L. 39, 252 (1977)]

DESPITE FIRST APPEARANCES, THESE DATA WERE BEST FIT BY 3 NARROW RESONANCES OF MASSES 9.4, 10.0 AND 10.4. THIS WAS CONFIRMED BY PRODUCTION OF THE RESONANCES AT THE e^+e^- COLLIDING BEAMS AT CORNELL (CESR).

THESE STATES ARE INTERPRETED AS BOUND STATES OF A NEW QUARK-ANTIQUARK PAIR, WITH FLAVOR NAMED BOTTOM = b. IT IS INFERRED THAT $Q_b = -1/3$. EVIDENCE SUCH AS THE SMALL STEP IN R ABOVE THE Υ REGION (p. 260) CERTAINLY DOES NOT CONTRADICT THIS.

Fig. 9.18. Enhancement in the production cross-sections for $\mu^+\mu^-$ masses near 9.46 GeV/c^2. (From Herb *et al.*, 1977.)

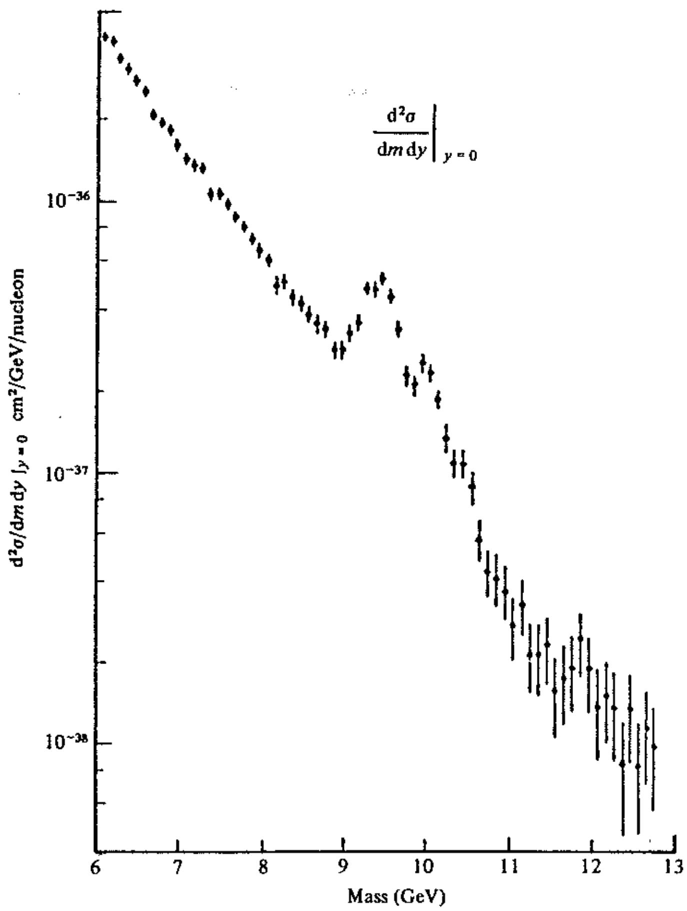
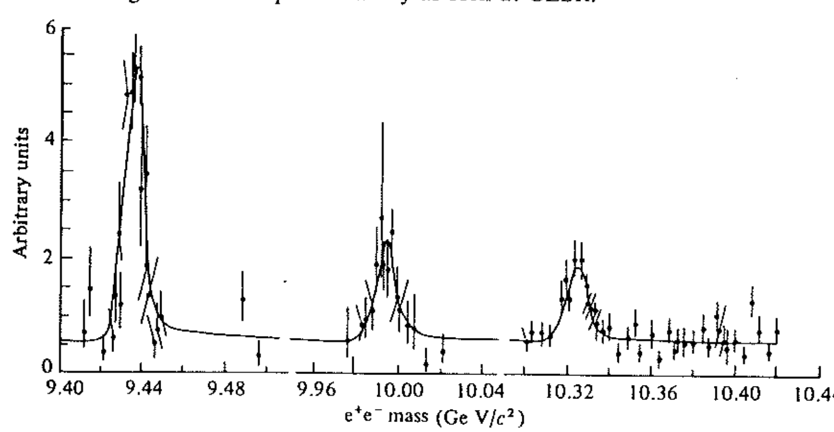


Fig. 9.20. The 'upsilon' family as seen at CESR.



As with charmonium, one expects a large family of $b\bar{b}$ bound states. Only the $^3S_1$ and $^3P_{0,1,2}$ states have been observed so far.

Clearly there is quite a quark atomic industry underway.

Many features of the $b\bar{b}$ system can be calculated at once from the potential model used for the $c\bar{c}$ system. But now many of the model parameters are already fixed by the $c\bar{c}$ data, allowing additional checks of the hypotheses.

A prominent feature is the mass splitting between the various $^3S_1$ Υ states. These are almost the same as for the ψ states. The potential $V = -\frac{4}{3}\frac{\alpha_s}{r} + kr$ does a fairly good job of accomodating both the ψ and Υ splittings.

It is now claimed that a 5th and 6th upsilon state have been observed as broad resonances ($\Gamma_t \sim 100\ MeV$) at masses 10.85 & 11.0 GeV [Lovelock et al. P.R.L. 54, 377 (1985)]

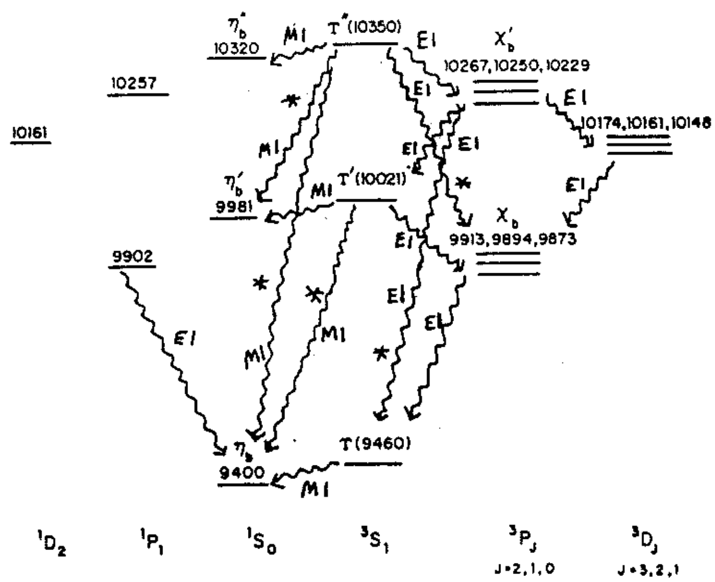


Figure 4: E1 and M1 Transitions in the b $\bar{b}$ System. Numbers above each set of states are the observed masses (in MeV) arranged in descending order of J. For states not yet observed the predicted masses (Ref. [13]) are indicated. Transitions which are particularly sensitive to relativistic corrections are indicated by a star.

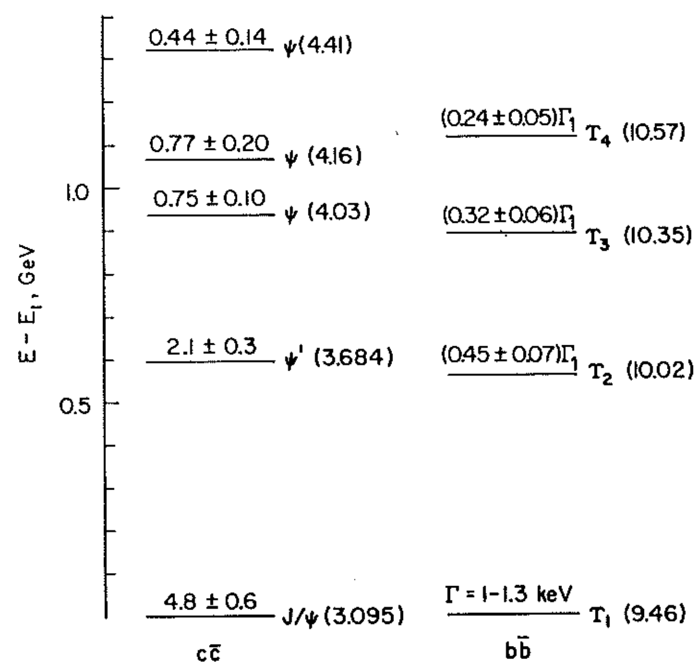


Fig. 31. Comparison of charmonium ($c\bar{c}$) and $\Upsilon(b\bar{b})$ levels.

SEVERAL OTHER POTENTIALS HAVE BEEN TRIED. THEY ALL YIELD SIMILAR RESULTS DESPITE APPARENT DIFFERENCE IN THEIR FUNCTIONAL FORM.

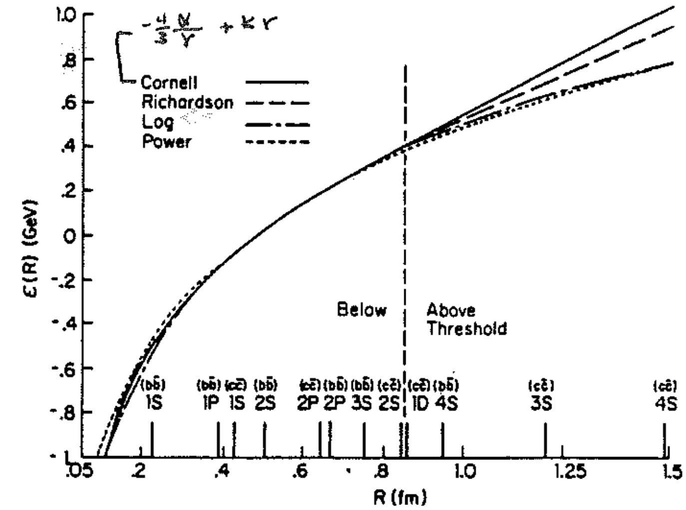


Figure 1: Phenemological Potentials for the Q $\bar{Q}$ System. The RMS radii of the observed c $\bar{c}$ and b $\bar{b}$ states are indicated by markers.

ANOTHER INTERESTING REGULARITY IS OBSERVED ON COMPARING DECAYS $V \to e^+e^-$ FOR ALL KNOWN VECTOR MESONS. WE HAVE ESTIMATED

$$\Gamma_{V\to e^+e^-} = 16\pi\alpha^2 Q_q^2 \frac{|\psi(0)|^2}{M_V^2}$$

EMPIRICALLY $\dfrac{\Gamma_{V\to e^+e^-}}{Q_q^2} \sim 10\text{–}12 \text{ keV}$

INDEPENDENT OF WHICH QUARKS ARE INVOLVED. I.E. $|\psi(0)|^2 / M_V^2 \sim$ CONSTANT.

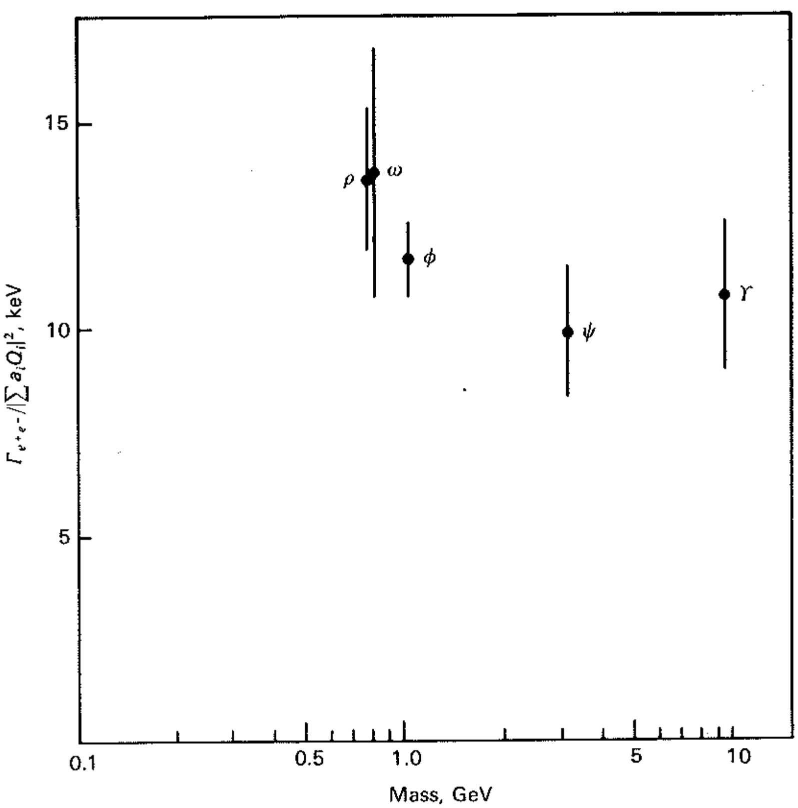


Fig. 5.17 The ratio $\Gamma_{e^+e^-}/|\sum a_i Q_i|^2$ of the leptonic width to the square of the mean quark charge, for the vector mesons $\rho = (u\bar{u} - d\bar{d})/\sqrt{2}$, $\omega = (u\bar{u} + d\bar{d})/\sqrt{2}$, $\phi = s\bar{s}$, and $\psi = c\bar{c}$. The value for $\Upsilon = b\bar{b}$ is obtained by assuming $\frac{1}{3}$ charge for the b-quark.

FOR ANOTHER SIMPLE COMPARISON, WE FOLLOW THE ARGUMENT OF PP 278-79 TO ESTIMATE

$$\frac{\Gamma_{\Upsilon\to 3G}}{\Gamma_{\Upsilon\to e^+e^-}} \sim 5800\,\alpha_s^2$$

IF $Q_b = -1/3$

EXPERIMENTALLY:

$$\frac{\Gamma_{\Upsilon\to \text{hadrons}}}{\Gamma_{\Upsilon\to e^+e^-}} \sim \frac{36 \text{ keV}}{1.2 \text{ keV}} \sim 30$$

$$\Rightarrow \alpha_s \sim 0.17$$

THIS VALUE IS PERHAPS SLIGHTLY SMALLER THAN THAT OBSERVED FOR THE ψ.

10. SEARCH FOR TOPONIUM

NUMEROLOGY SUGGESTS THAT THE MASS OF THE 6TH QUARK, FLAVOR ≡ TOP, MIGHT BE $M_t \sim 3 M_b \sim 15$ GeV. THEN $t\bar{t}$ STATES (TOPONIUM) MIGHT HAVE MASS ~30 GeV. THIS WAS ALREADY BEEN EXCLUDED BY SEARCHES IN e^+e^- STORAGE RINGS, UP TO POSSIBLE MASSES OF ABOUT 46 GeV. [FOR EXAMPLE, BEHREND ET AL. PHYS. LETT 144B, 297 (1984)]

IF THE QUARK MASS $M_t \lesssim 65$ GeV, THEN TOP MESON, $t\bar{d}$ ETC, WILL PROBABLY BE DISCOVERED IN THE DECAY $W^+ \to t\bar{b}$, FOR W^+ BOSONS PRODUCED AT THE CERN $\bar{p}p$ COLLIDING BEAM FACILITY. IF $M_t \gtrsim M_W$ IT MAY BE A WHILE BEFORE TOP IS DISCOVERED. [SEE p. 288 FOR MORE COMMENTS ON THIS.]

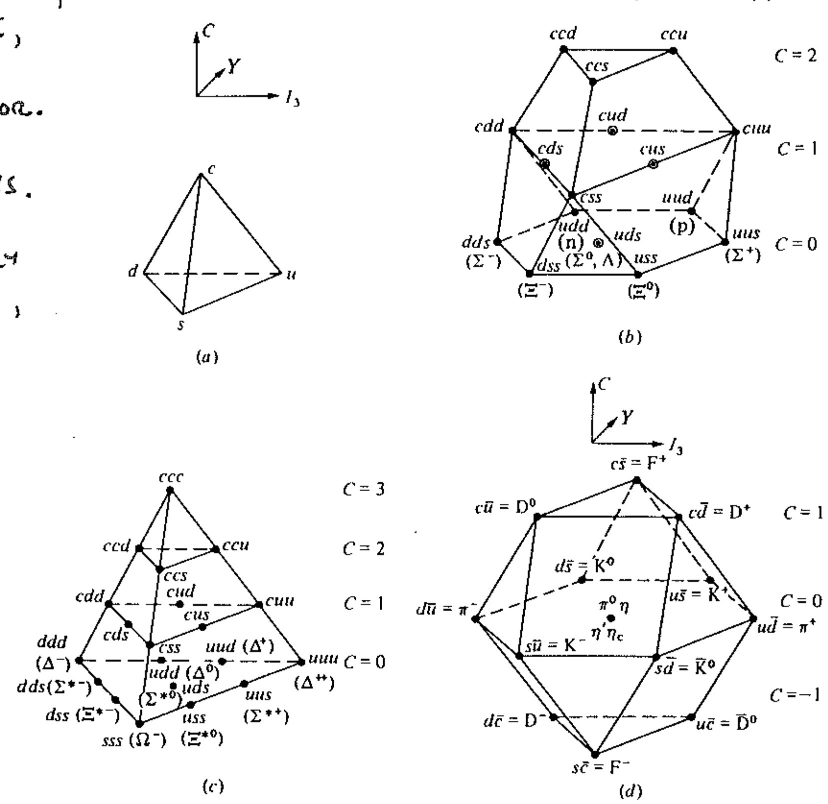
THE TOP QUARK IS DESIRED TO EXIST AND TO HAVE CHARGE 2/3 TO COMPLETE A DOUBLET WITH THE BOTTOM QUARK $\begin{pmatrix} t \\ b \end{pmatrix}$. THIS IS MORE IMPORTANT FROM THE POINT OF VIEW OF THE WEAK INTERACTION, AS HOPEFULLY DISCUSSED MORE LATER. FOR EXAMPLE, THE LOWEST MASS BOTTOM MESON, $b\bar{u}$, CAN ONLY DECAY WEAKLY. WITHOUT A TOP QUARK PARTNER, THE b DECAY IS EXPECTED TO BE EVEN WEAKER THAN IN THE DOUBLET MODEL. [GEORGI & GLASHOW, NUC. PHYS. B167, 173 (1980)]. RECENT MEASUREMENTS OF THE b MESON LIFETIME INDICATE $\tau \sim 1.5 \times 10^{-12}$ SEC, WHICH IS QUITE LONG. [FERNANDEZ ET AL, P.R.L. 51, 1022 (1983), LOCKYER ET AL. P.R.L. 51, 1316 (1983)]. PERHAPS M_t IS INDEED VERY LARGE...

11. CHARMED PARTICLES

IN CONTRAST TO THE $c\bar{c}$ STATES, THERE ARE MESONS, SUCH AS $c\bar{u}$, AND BARYONS, SUCH AS cud, WHICH CARRY NET CHARM FLAVOR. THESE CAN BE CATEGORIZED IN TERMS OF SU(4) MULTIPLETS.

HOWEVER THIS IS NOT ACTUALLY TOO USEFUL IN THAT $M_c \sim 3M_s$, WHICH SHOWS THAT SU(4) IS A BADLY BROKEN SYMMETRY.

Fig. 8.3. Representation content of mesons and baryons in *SU*(4).



IT IS PROBABLY MORE USEFUL JUST TO LOOK AT THE SU(3) SUB-MULTIPLETS WITH FIXED AMOUNTS OF CHARM.

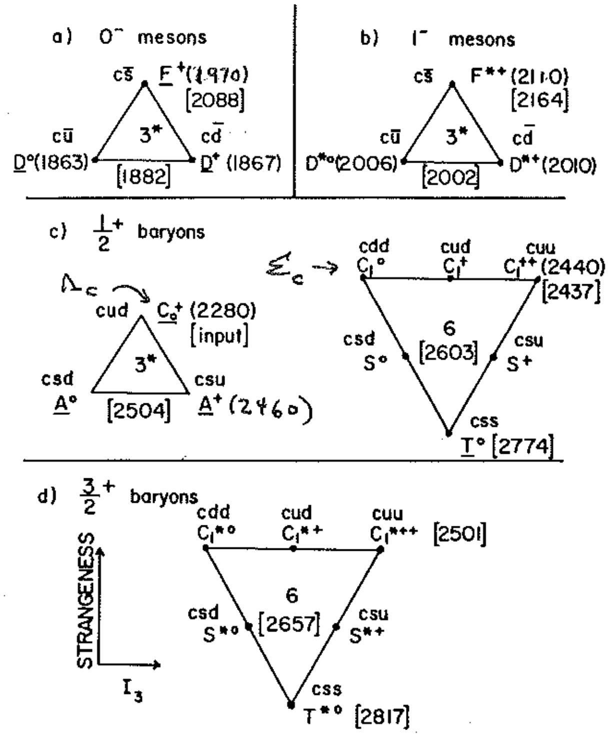
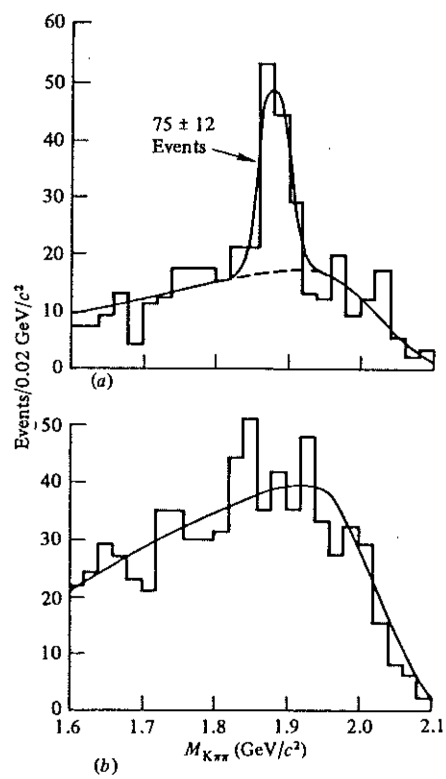


Fig. 28. L=0 mesons and baryons containing a single charmed quark. SU(3) representations are depicted in the middle of each figure. Masses in MeV/c^2 correspond to observed values (Ref. 36, values in parentheses), or predicted values (Eq. (4.1), values in brackets). Underlined states are expected to decay weakly.

CHARMED MESONS WERE FIRST OBSERVED IN e^+e^- COLLIDING BEAMS AT SLAC, BY LOOKING AT $K\pi$ AND $K\pi\pi$ INVARIANT MASS SPECTRA.
[GOLDHABER ET AL, P.R.L. 37, 255 (1976)]

Fig. 10.3. (*a*) Evidence for the decay $D^+ \to K^-\pi^+\pi^+$ and (*b*) absence of a signal for $D^+ \to K^+\pi^+\pi^-$. (From Goldhaber *et al.*, 1976.)



SHORTLY THEREAFTER THE FIRST CHARMED BARYON, THE $\Lambda_c = cud$, WAS DISCOVERED IN A PHOTOPRODUCTION EXPERIMENT AT FERMILAB

$$\gamma + \text{NUCLEUS} \to \bar{\Lambda}\,\pi\pi\pi + X$$

[KNAPP ET AL, P.R.L. 37, 882 (1976)]

IN RETROSPECT IT WAS REALIZED THAT 1 Λ_c EVENT HAD ALREADY BEEN SEEN IN A BUBBLE CHAMBER EXPERIMENT AT BNL [CAZZOLI ET AL, P.R.L. 34, 1125 (1975)].

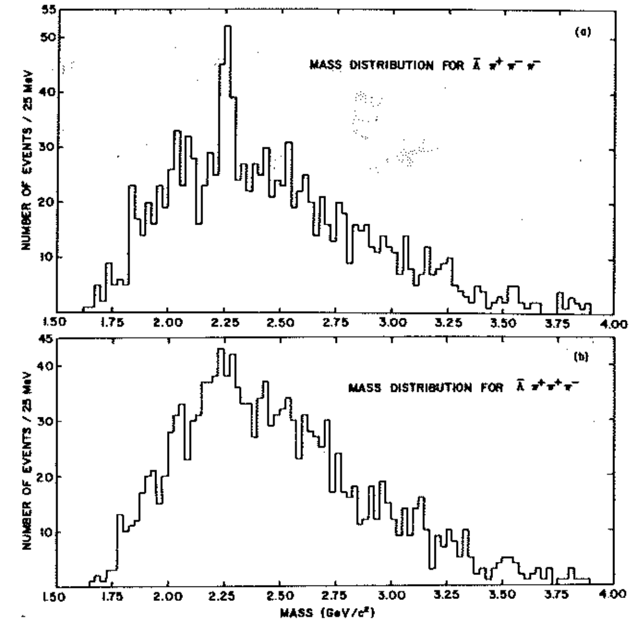


FIG. 2. Invariant-mass distributions for $\bar{\Lambda}3\pi$ combinations, separated by the total charge (a) $\bar{\Lambda}\pi^+\pi^-\pi^-$; and (b) $\bar{\Lambda}\pi^+\pi^+\pi^-$.

WE MAY READILY APPLY OUR MODEL OF MASS SPLITTINGS DUE TO THE COLOR MAGNETIC DIPOLE INTERACTION

FOR EXAMPLE, THE Λ_c AND Λ HAVE IDENTICAL QUARK CONTENT EXCEPT FOR THE SUBSTITUTION OF C FOR S IN THE Λ_c. RECALL THAT IN THE Λ THE u AND d QUARKS FORM AN $S=0$ qq PAIR (P 239). HENCE $\langle \vec{\sigma}_s \cdot \vec{\sigma}_u \rangle = \langle \vec{\sigma}_s \cdot \vec{\sigma}_d \rangle = 0$. (OF COURSE $\langle \vec{\sigma}_u \cdot \vec{\sigma}_d \rangle \neq 0$)

WE INFER THAT $M_{\Lambda_c} - M_\Lambda = M_c - M_s$, AS THERE IS NO DEPENDENCE ON THE MAGNETIC MOMENT OF THE S OR C. WITH $M_s = 483$ (P 268) AND $M_{\Lambda_c} - M_\Lambda = 1164\,\text{MeV}$ WE ESTIMATE $M_c \sim 1650\,\text{MeV}$. THIS IS PERHAPS SLIGHTLY HIGHER THAN EXPECTED FROM THE $c\bar{c}$ STATES ALONE

APPARENTLY IF YOU ARE ENERGETIC YOU CAN DEMONSTRATE THE MODEL RELATION

$$\underset{1164\,\text{MeV}}{M_{\Lambda_c} - M_\Lambda} = \underset{1179\,\text{MeV}}{\frac{3M_{D^*} + M_D}{4} - \frac{3M_{K^*} + M_K}{4}}$$

ANOTHER SIMPLE COMPARISON INVOLVES THE $D = c\bar{u}$, SPIN = 0, AND $D^* = c\bar{u}$, SPIN = 1 MESONS. THESE ARE THE ANALOGS OF THE K AND K* MESONS, SUBSTITUTING C FOR S. THE MASS DIFFERENCES $M_{D^*} - M_D$ AND $M_{K^*} - M_K$ THEN VARY AS μ_c AND μ_s

$$\Rightarrow \quad \frac{M_{D^*} - M_D}{M_{K^*} - M_K} = \frac{M_s}{M_c} \sim \frac{1}{3} \qquad \text{DATA: } \frac{2010 - 1867}{892 - 494} = .36$$

ETC.

* QUICKIE: THE DECAY $D^* \to D\pi$ IS ALLOWED, BUT $F^* \to F\pi$ IS NOT. WHY?

DECAYS OF CHARMED MESONS VIA THE WEAK INTERACTION WILL BE CONSIDERED IN LECTURE 17.

12. BOTTOM MESONS

IN THE Υ FAMILY THE STATE $\Upsilon'''(10570)$ HAS A LARGE DECAY WIDTH ~ 14 MeV. WE INFER THAT THIS IS GREATER THAN TWICE THE MASS OF THE LIGHTEST BOTTOM MESON $B = b\bar{u}$ OR $b\bar{d}$ IE $M_B \lesssim 5285$ MeV.

RECENTLY A FEW BOTTOM MESON DECAYS HAVE BEEN FULLY RECONSTRUCTED IN THE CLEO DETECTOR AT THE CORNELL e^+e^- STORAGE RING [SCIENTIFIC AMERICAN JULY 1983]. IT IS FOUND THAT $M_B \sim 5271$ MeV SO THE Υ''' IS JUST BARELY ABLE TO DECAY TO A PAIR OF B'S! [SEE BEHRENDS ET AL. P.R.L. 50, 881 (1983); CHAN, P.R.L. 51, 253 (1983) DISCUSSES MASS SPLITTINGS IN THE MANNER OF P. 244 LECTURE 13.]

13. TOP MESONS

A TENTATIVE SIGNAL FOR TOP MESONS HAS BEEN REPORTED BY THE UA1 GROUP AT THE CERN $\bar{p}p$ COLLIDER. [ARNISON ET. AL. PHYS. LETT 147B, 493 (1984)]

THEY IDENTIFY 6 EVENTS AS CONSISTENT WITH

$$W^+ \to t\,\bar{b}$$
$$\quad\quad \hookrightarrow b\,\ell\,\nu$$

THE SIGNAL IS TWO JETS FROM THE b & $\bar{b}$ DECAYS + A LEPTON. SINCE THE ν ESCAPES, THE W^+ MASS IS NOT RECONSTRUCTED.

THE UA1 GROUP ARGUES THAT THE 6 EVENTS ARE NOT TAILS OF DISTRIBUTIONS OF MORE ORDINARY PHYSICS, AND MAKE THE ROUGH ESTIMATE

$$30 < M_t < 50 \text{ GeV}.$$

WHAT DO YOU THINK?

UPDATE 1986: IN ADDITIONAL RUNNING EVENTS OF THIS TYPE NOW APPEAR AS FLUCTUATIONS OF 'ORDINARY' DECAY TOPOLOGIES!

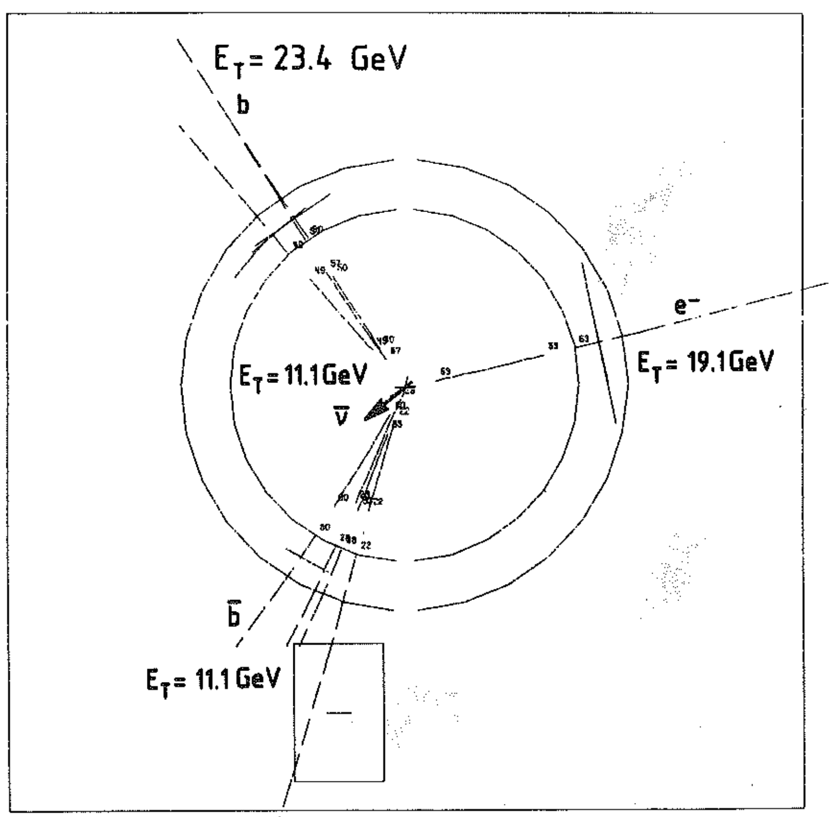
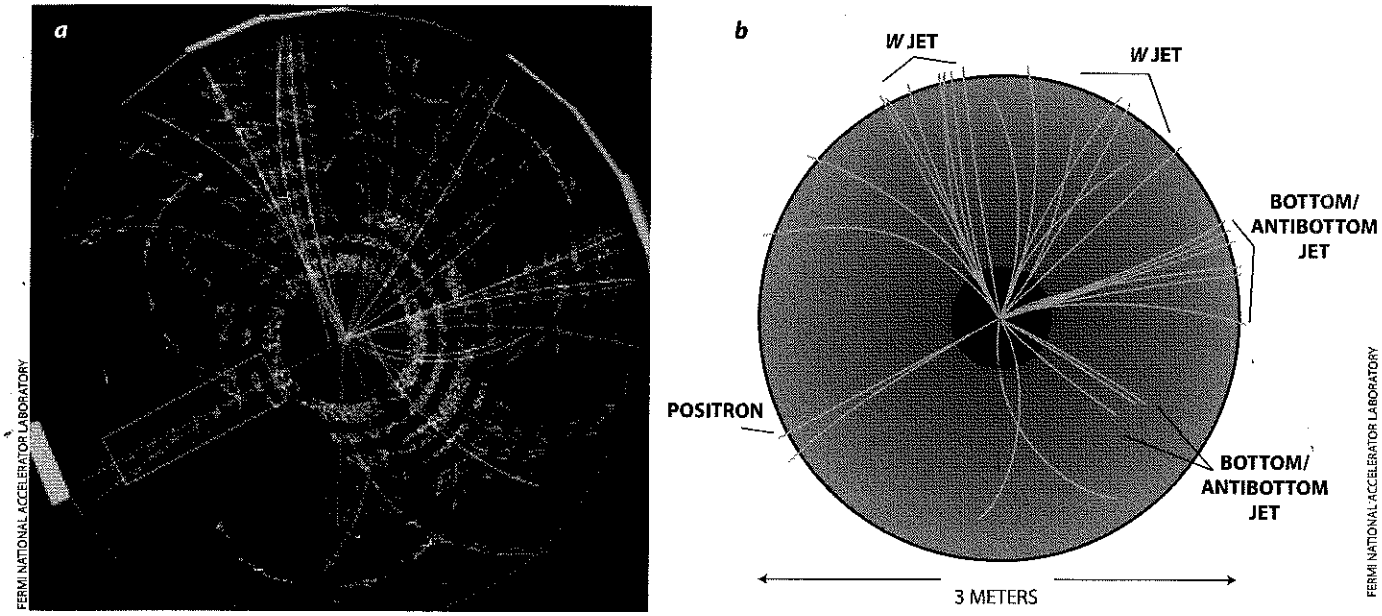


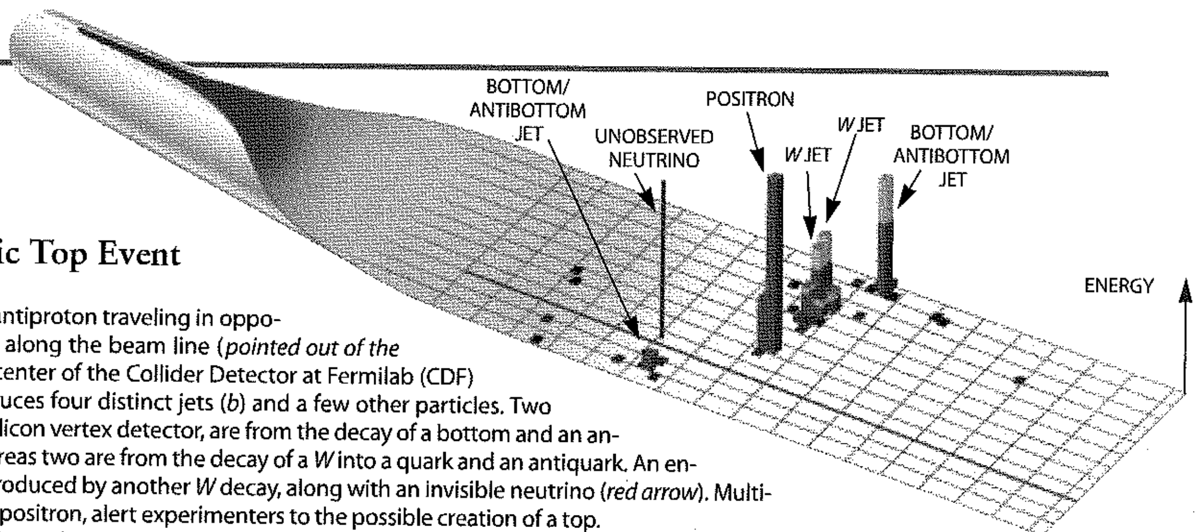
Fig. 9. As fig. 8, view looking along the beam direction.

Discovery of the Top Quark (1995)

$\bar{p}p \to t + X$
$\quad \hookrightarrow$ jets

Abe et al., PRL $\underline{74}$, 2626 (1995)
Abachi et al., PRL $\underline{74}$, 2422 (1995)





A Classic Top Event

A proton and an antiproton traveling in opposite directions along the beam line (*pointed out of the page*) collide at the center of the Collider Detector at Fermilab (CDF) (*a*). The impact produces four distinct jets (*b*) and a few other particles. Two jets, identified by a silicon vertex detector, are from the decay of a bottom and an antibottom quark, whereas two are from the decay of a *W* into a quark and an antiquark. An energetic positron is produced by another *W* decay, along with an invisible neutrino (*red arrow*). Multiple jets, along with a positron, alert experimenters to the possible creation of a top.

A magnetic field directed along the beam line curves the paths of the charged particles. The direction of curvature shows the sign of a particle's charge, and the extent reveals its momentum. Further, a calorimeter wraps around the beam line; it measures the energies of the emerging particles. It is shown unrolled (*c*). The height of a bar indicates the energy released by particles in the corresponding segment. The combination of devices allows experimenters to reconstruct the original event (*depicted on page 54*) with a high degree of confidence. —*T.M.L. and P.L.T.*

$m_t = 173 \pm 0.5$ GeV

The top quark decays so quickly that it is not meaningful to speak of top-quark mesons or baryons.

The end of the quark atom story.