9

The J/ψ, the τ, and charm

New forms of matter, 1974–1976

In November 1974, Burton Richter at SLAC and Samuel Ting at Brookhaven were leading two very different experiments, one studying e^+e^- annihilation, the other the e^+e^- pairs produced in proton–beryllium collisions. Their simultaneous discovery of a new resonance with a mass of 3.1 GeV so profoundly altered particle physics that the period is often referred to as the "November Revolution." Word of the discoveries spread throughout the high energy physics community on November 11 and soon much of its research was directed towards the new particles.

Ting led a group from MIT and Brookhaven measuring the rate of production of e^+e^- pairs in collisions of protons on a beryllium target. The experiment was able to measure quite accurately the invariant mass of the e^+e^- pair. This made the experiment much more sensitive than an earlier one at Brookhaven led by Leon Lederman. That experiment differed in that $\mu^+\mu^-$ pairs were observed rather than e^+e^- pairs. Both these experiments investigated the Drell–Yan process whose motivation lay in the quark–parton model.

The Drell–Yan process is the production of e^+e^- or $\mu^+\mu^-$ pairs in hadronic collisions. Within the parton model, this can be understood as the annihilation of a quark from one hadron with an antiquark from the other to form a virtual photon. The virtual photon materializes some fraction of the time as a charged-lepton pair.

The e-pair and μ-pair approaches to measuring lepton-pair production each have advantages and disadvantages. Because high-energy muons are more penetrating than high-energy hadrons, muon pairs can be studied by placing absorbing material directly behind the interaction region. The absorbing material stops the strongly interacting π s, K s, and protons, but not the muons. This technique permits a very high counting rate since the muons can be separated from the hadrons over a large solid angle if enough absorber is available. The momenta of the muons can be determined by measuring their ranges. Together with the angle between the muons, this yields the invariant mass of the pair. Of course, the muons are subject to multiple Coulomb scattering in the absorber, so the resolution of the technique is limited by this effect. The spectrum observed by Lederman's group fell with increasing invariant mass of the lepton pair. There was, however, a shoulder in the spectrum between 3 and 4 GeV that attracted some notice, but whose real significance was obscured by the inadequate resolution.

By contrast, electrons can be separated from hadrons by the nature of the showers they cause or by measuring directly their velocity (using Čerenkov counters), which is much nearer the speed of light than that of a hadron of comparable momentum. The Čerenkov-counter approach is very effective in rejecting hadrons, but can be implemented easily only over a small solid angle. As a result, the counting rate is reduced. Ting's experiment used two magnetic spectrometers to measure separately the e^+ and e^-. The beryllium target was selected to minimize multiple Coulomb scattering. The achieved resolution was about 20 MeV for the e^+e^- pair, a great improvement over the earlier μ-pair experiment. The electrons and positrons were, in fact, identified using Čerenkov counters, time-of-flight information, and pulse height measurements.

In the early 1970s Richter, together with his co-workers, fulfilled his long-time ambition of constructing an e^+e^- ring, SPEAR, at SLAC to study collisions in the 2.5 to 7.5 GeV center-of-mass energy region. Lower energy machines had already been built at Novosibirsk, Orsay, Frascati, and Cambridge, Mass. Richter himself had worked as early as 1958 with Gerard O'Neill and others on the pioneering e^-e^- colliding-ring experiments at Stanford.

To exploit the new ring, SPEAR, the SLAC team, led by Richter and Martin Perl, and their LBL collaborators, led by William Chinowsky, Gerson Goldhaber, and George Trilling built a multipurpose large-solid-angle magnetic detector, the SLAC-LBL Mark I. The heart of this detector was a cylindrical magnetostrictive spark chamber inside a solenoidal magnet of 4.6 kG. This was surrounded by time-of-flight counters for particle velocity measurements, shower counters for photon detection and electron identification, and by proportional counters embedded in iron absorber slabs for muon identification.

What could the Mark I Collaboration expect to find in e^+e^- annihilations? In the quark-parton model, since interactions between the quarks are ignored, the process $e^+e^- \to q\overline{q}$ is precisely analogous to $e^+e^- \to \mu^+\mu^-$, except that the charge of the quarks is either $2/3$ or $-1/3$ and that the quarks come in three colors, as more fully discussed in Chapter 10. Thus the ratio of the cross section for annihilation into hadrons to the cross section for the annihilation into muon pairs should simply be three times the sum of the squares of the charges of the quarks. This ratio, conventionally called R, was in 1974 expected to be $3[(-1/3)^2+(2/3)^2+(-1/3)^2] = 2$ counting the u, d, and s quarks. In fact, measurements made at the Cambridge Electron Accelerator (CEA) found that R was not constant in the center-of-mass region to be studied at SPEAR, but instead seemed to grow to a rather large value, perhaps 6. The first results from the Mark I detector confirmed this puzzling result.

In 1974, Ting, Ulrich Becker, Min Chen and co-workers were taking data with their pair spectrometer at the Brookhaven AGS. By October of that year they found an e^+e^- spectrum consistent with expectations, except for a possible peak at 3.1 GeV. In view of the as-yet-untested nature of their new equipment, they proceeded to check and recheck this effect under a variety of experimental conditions and to collect more data.

During this same period, the Mark I experiment continued measurements of the annihilation cross section into hadrons with an energy scan with steps of 200 MeV. Since no abrupt structure was anticipated, these steps seemed small enough. The data confirming and extending the CEA results were presented at the London Conference in June 1974.

The data seemed to show a constant cross section rather than the $1/s$ behavior anticipated. (In the quark-parton model, there is no dimensionful constant, so the total cross section should vary as $1/s$ on dimensional grounds.) In addition, the value at center-of-mass energy 3.2 GeV appeared to be a little high. It was decided in June 1974 to check this by taking additional data at 3.1 and 3.3 GeV. Further irregularities at 3.1 GeV made it imperative in early November, 1974, before a cross section paper could be published, to remeasure this region. Scanning this region in very small energy steps revealed an enormous, narrow resonance. The increase in the cross section noticed at 3.2 GeV was the due to the tail of the resonance and the anomalies at 3.1 GeV were caused by variations in the precise energy of the beam near the lower edge of the resonance, where the cross section was rising rapidly.

By Monday, November 11 (at which time the first draft of the ψ paper was already written) Richter learned from Sam Ting (who too had a draft of a paper announcing the new particle) about the MIT-BNL results on the resonance (named J by Ting), and *vice versa.* Clearly, both experiments had observed the same resonance. Word quickly reached Frascati, where Giorgio Bellettini and co-workers managed to push the storage ring beyond the designed maximum of 3 GeV and confirmed the discovery. Papers reporting the results at Brookhaven, SLAC, and Frascati all appeared in the same issue of *Physical Review Letters* **(Refs. 9.1, 9.2**, 9.3).

That the resonance was extremely narrow was apparent from the e^+e^- data, which showed an experimental width of 2 MeV. This was not the intrinsic width, but the result of the spread in energy of the electron and positron beams due to synchrotron radiation in the SPEAR ring. Additionally, the shape was spread asymmetrically by radiative corrections. If the natural width is much less than the beam spread, the area under the cross section curve

$$Area = \int dE \; \sigma$$

is nearly the same as it would be in the absence of the beam spread and radiative corrections. The intrinsic resonance cross section is of the usual Breit–Wigner form given in Chapter 5

$$\sigma = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{\pi}{p_{cm}^2} \frac{\Gamma_{in}\Gamma_{out}}{(E-E_0)^2 + \Gamma_{tot}^2/4}$$

where the incident particles have spin $S_1, S_2 = 1/2$ and momentum $p_{cm} \approx M_\psi/2 = E_0/2$. If the observed cross section is that for annihilation into hadrons, then $\Gamma_{out} = \Gamma_{had}$, the partial width for the resonance to decay into hadrons, while $\Gamma_{in} = \Gamma_{ee}$ is the electronic width. Assuming that the observed resonance has spin $J = 1$, we find by integrating the above,

$$Area = \frac{6\pi^2\Gamma_{ee}\Gamma_{had}}{M_\psi^2\Gamma_{tot}}$$

The area under of the resonance curve measured at SPEAR is about 10 nb GeV. If we assume $\Gamma_{had} \approx \Gamma_{tot}$ and use the measured mass, $M_\psi = 3.1$ GeV, we find $\Gamma_{ee} \approx 4.2$ keV. The accepted value is 4.7 keV. Subsequent measurements of the branching ratio into electron pairs ($\approx 7\%$) led to a determination of the total width of between 60 and 70 keV, an astonishingly small value for a particle with a mass of 3 GeV.

Spurred by these results and theoretical predictions of a series of excited states like those in atomic physics, the SLAC–LBL Mark I group began a methodical search for other narrow states. It turned out to be feasible to modify the machine operation of SPEAR so that the energy could be stepped up by 1 MeV every minute. Ten days after the first discovery, a second narrow resonance was found **(Ref. 9.4)**. The search continued, but no comparable resonances were found up to the maximum SPEAR energy of 7.4 GeV. The next such discovery had to wait until Lederman's group, this time at Fermilab and with much-improved resolution, continued their study of muon pairs into the 10 GeV region, as discussed in Chapter 11.

The discovery of the $\psi(3096)$ and its partner, ψ' or $\psi(3685)$ was the beginning of a period of intense spectroscopic work, which still continues. The spin and parity of the ψ s were established to be $J^P = 1^-$ by observing the interference between the ψ and the virtual photon intermediate states in $e^+e^- \to \mu^+\mu^-$. The G-parity was found to be odd when the predominance of states with odd numbers of pions was demonstrated. Since C was known to be odd from the photon interference, the isospin had to be even and was shown to be nearly certainly $I = 0$. Two remarkable decays were observed quite soon after, $\psi' \to \psi\pi\pi$ and $\psi' \to \psi\eta$. Figure 9.30 shows a particularly clean $\psi' \to \psi\pi\pi$ decay with $\psi \to e^+e^-$.

Prior to the announcement of the ψ, Tom Appelquist and David Politzer were investigating theoretically the binding of a charmed and an anticharmed quark, which is described later in the chapter. They found that QCD predicted that there would be a series of bound states with very small widths, analogous to the e^+e^- bound states known as positronium. The $c\bar{c}$ bound states immediately became the leading explanation for the ψ and this interpretation was strengthened

Figure 9.30: An example of the decay $\psi' \to \psi\pi^+\pi^-$ observed by the SLAC–LBL Mark I Collaboration. The crosses indicate spark chamber hits. The outer dark rectangles show hits in the time-of-flight counters. Ref. 9.5.

by the discovery of the ψ'. The ψ was seen as the lowest s-wave state with total spin equal to one. In spectroscopic notation it was the 1^3S_1. The ψ' was the next lowest spin-triplet, the s-wave state 2^3S_1.

The analogy between the $c\overline{c}$ bound states and positronium was striking. The two lowest energy states of positronium are the ${}^3S_1$ and the ${}^1S_0$. The former has $C = -1$ and the latter $C = +1$. It is this difference that first enabled Martin Deutsch to find experimental evidence for positronium in 1951. Because the triplet state has odd charge conjugation, it cannot decay into two photons like the charge-conjugation-even singlet state. As a consequence it decays into three photons and has a much longer lifetime. With detailed lifetime studies, Deutsch was able to find evidence for a long-lived species. QCD required that the triplet state of $c\overline{c}$ decay into three gluons, the quanta that bind the quarks together, while the singlet state could decay into two gluons. Again, this meant that the triplet state should be longer lived, that is, should have a narrow width.

In the nonrelativistic approximation, we can describe the $c\overline{c}$ system by a wave function, $\phi(r)$, satisfying a Schrödinger equation for some appropriate potential. The partial width, $\Gamma(\psi \to e^+e^-)$, is related to the wave function at zero separation, $\phi(0)$. The relation is obtained from the general prescription for a reaction rate, $\Gamma = \sigma\rho v$, where Γ is the reaction rate, σ the cross section, v is the relative velocity of the colliding particles and ρ is the target density. In this application $\rho = |\phi(0)|^2$. For the cross section we use the low energy limit of the process $c\overline{c} \to e^+e^-$,

$$\sigma = 3 \times \frac{2\pi\alpha^2 e_q^2}{\beta s}$$

where α is the fine-structure constant ($\approx 1/137$), β is the velocity of the quark or antiquark in the center-of-mass frame, s is the center-of-mass energy squared ($\approx M_\psi^2$), and e_q is the charge of the quark measured in units of the proton's charge. A factor of 3 has been included to account for the three colors. The above cross section is averaged over the quark spins. The ψ is in fact a spin-triplet. The spin-singlet state has $C = +1$ and cannot annihilate through a virtual photon into e^+e^-. Since the cross section in the spin-singlet state is zero, the cross section in the spin-triplet state is actually 4/3 times the spin-averaged cross section. Noting that the relative velocity, v, is 2β, we have

$$\begin{aligned}\Gamma(\psi \to e^+e^-) &= \frac{4}{3} \times 3 \times \frac{2\pi\alpha^2 e_q^2}{\beta M_\psi^2} \cdot 2\beta|\phi(0)|^2 \\ &= \frac{16\pi\alpha^2 e_q^2}{M_\psi^2}|\phi(0)|^2\end{aligned}$$

The nonrelativistic model predicted that between the s-wave ψ and ψ' there would be a set of p-wave states. The spin-triplet states, ${}^3P$, would have total angular momentum J =2, 1, or 0. The spin-singlet state, ${}^1P$, would have total angular momentum $J = 1$. For a fermion–antifermion system the charge conjugation quantum number is $C = (-1)^{L+S}$, while the parity is $P = (-1)^{L+1}$. Thus the ${}^3P_{2,1,0}$ states would have $J^{PC} = 2^{++}, 1^{++}, 0^{++}$, while the ${}^1P_1$ state would have $J^{PC} = 1^{+-}$. The ψ' was expected to decay radiatively to the C-even states, which are now denoted χ (thus $\psi' \to \gamma\chi$). Such a transition was first observed at the PETRA storage ring at DESY in Hamburg by the Double Arm Spectrometer (DASP) group **(Ref. 9.6)**. Evidence for all three χ states was then observed by the SLAC–LBL group with the Mark I detector, both by measuring the two photons in $\psi' \to \chi\gamma$, $\chi \to \psi\gamma$ and by detecting the first photon and a subsequent hadronic decay of the χ that was fully reconstructed.

The complete unraveling of these states took several years and was culminated in the definitive work of the Crystal Ball Collaboration, led by Elliott Bloom (**Ref 9.7**). Their detector was designed to provide high spatial and energy resolution for photons using 672 NaI crystals. A particularly difficult problem was the detection of the anticipated s-wave, spin singlet states, 1^1S_0 and 2^1S_0 (denoted η_c and η_c') that were expected to lie just below the corresponding spin-triplet states, 1^3S_1 and 2^3S_1. Since these states have $C = +1$ and $J = 0$, they cannot be produced directly by e^+e^- annihilation through a virtual photon. Instead, they must be observed in the same way as the χ states, through radiative decays of the ψ and ψ'. The transitions are suppressed by kinematical and dynamical factors. They were identified only after a long effort.

In the simplest nonrelativistic model for the interaction between the charmed and anticharmed quarks, the potential is taken to be spin independent. In this approximation, the four p-states are degenerate, with identical radial wave functions. The $E1$ transitions, $\psi' \rightarrow \gamma\chi$ thus would occur with rates proportional to the statistical weights of the final states, ${}^3P_{0,1,2}$, i.e., $1:3:5$. In fact, as a result of spin-dependent forces, the splittings between the p-states are significant, so a better approximation is obtained by noting that the $E1$ rates are proportional to ω^3, where ω is the photon energy in the ψ' rest frame,

$$\omega = \frac{M_{\psi'}^2 - M_\chi^2}{2M_{\psi'}}$$

If, for the masses of the ψ', χ_2, χ_1, χ_0 we take the measured values, 3.686, 3.556, 3.510, and 3.415 GeV, respectively, we find $\omega_2 = 0.128$ GeV, $\omega_1 = 0.172$ GeV, and $\omega_0 = 0.261$ GeV and the ratios

$$5 \times (0.128)^3 : 3 \times (0.172)^3 : 1 \times (0.261)^3 = 1 : 1.46 : 1.70$$

The 1988 edition of the *Review of Particle Properties* gives branching ratios for $\psi' \rightarrow \gamma\chi_{2,1,0}$ of $7.8 \pm 0.8\%, 8.7 \pm 0.8\%$, and $9.3 \pm 0.8\%$, in fair agreement with the above estimates.

It was during the exciting period of investigation of the ψ, ψ', and χ states that Martin Perl and co-workers of the SLAC–LBL group made a discovery nearly as dramatic as that of the ψ. Carefully sifting through 35,000 events, they found 24 with a μ and an opposite sign e, and no additional hadrons or photons. They interpreted these events as the pair production of a new lepton, τ, followed by its leptonic decay **(Ref. 9.8)**. The leptonic decays were $\tau \rightarrow e\nu\nu$ and $\tau \rightarrow \mu\nu\nu$. Figure 9.31 shows results obtained by the DASP Collaboration, using a double arm spectrometer, and by the DESY-Heidelberg Collaboration at the DORIS storage ring at DESY. Figure 9.32 show results from DELCO, the Direct Electron Counter at SPEAR. These established the spin and mass of the τ.

The decay $\tau \rightarrow e\nu\nu$ is exactly analogous to the decay $\mu \rightarrow e\nu\nu$. In both cases we can ignore the mass of the final state leptons. The decay rate for the μ is proportional to the square of the Fermi constant, G_F^2, which has dimension $[\text{mass}]^{-4}$. The decay rate for the μ must then be proportional to m_μ^5. We conclude that

$$\Gamma(\tau \rightarrow e\nu\overline{\nu}) = (m_\tau/m_\mu)^5 \Gamma(\mu \rightarrow e\nu\overline{\nu}) = 6 \times 10^{11}\ \text{s}^{-1}$$

The measured lifetime of the τ is about 3.0×10^{-13} s and the branching ratio into $e\nu\nu$ is near 18%. Combining these gives a partial rate for $\tau \rightarrow e\nu\nu$ of roughly $6 \times 10^{11}\ \text{s}^{-1}$, in good agreement with the expectation.

Within a very short time, two new fundamental fermions had been discovered. The interpretation of the ψ as a bound state of a charmed quark and an charmed antiquark was backed by strong circumstantial evidence. What was

Figure 9.31: Left: The cross section from e^+e^- annihilation into candidates for τ leptons, as a function of center-of-mass energy, as measured by the DASP Collaboration. The threshold was determined to be very near 2×1800 MeV, that is, below the $\psi(3685)$ (Ref. 9.9). Right: Similar results from the DESY-Heidelberg group which give 1787^{+10}_{-18} MeV for the mass of the τ. The curves shown are for a spin-1/2 particle [W. Bartel *et al.*, *Phys. Lett.* **B77**, 331 (1978)].

Figure 9.32: The production of anomalous two-prong events as a function of the center-of-mass energy, as determined by DELCO. These candidates for τ s yielded a threshold of 3564^{+4}_{-14} MeV, *i.e.* a mass of 1782^{+2}_{-7}. The threshold behavior confirmed the spin-1/2 assignment. (Ref. 9.10)

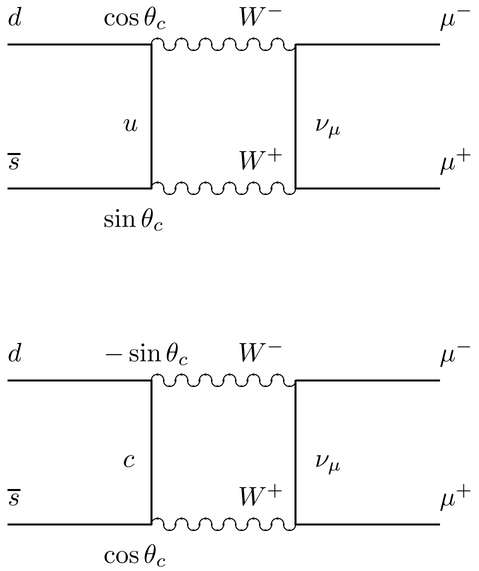

Figure 9.33: Two contributions to the decay $K_L^0 \rightarrow \mu^+\mu^-$ showing the factors present at the quark vertices. If only the upper contribution were present, the decay rate would be far in excess of the observed rate. The second contribution cancels most of the first. The cancellation would be exact if the c quark and u quark had the same mass. This cancellation is an example of the Glashow–Iliopoulos–Maiani mechanism.

lacking was proof that its constituents were indeed the charmed quarks first proposed by Bjorken and Glashow. As Glashow, Iliopoulos, and Maiani showed in 1970, charmed quarks were the simplest way to explain the absence of neutral strangeness-changing weak currents.

Until 1973 only weak currents that change charge had been observed. For example, in μ decay, the μ turns into ν_μ, and its charge changes by one unit. The neutral weak current, which can cause reactions like $\nu p \rightarrow \nu p$, as discussed in Chapter 12, does not change strangeness. If strangeness could be changed by a neutral current, then the decays $K^0 \rightarrow \mu^+\mu^-$ and $K^+ \rightarrow \pi^+e^+e^-$ would be possible. However, very stringent limits existed on these decays and others requiring strangeness-changing neutral weak currents. So restrictive were these limits that even second order weak processes would violate them in the usual Cabibbo scheme of weak interactions. Glashow, Iliopoulos, and Maiani showed that if in addition to the charged weak current changing an s quark into a u quark, there were another changing an s quark into a c quark, there would be a cancellation of the second order terms.

Consider the decay $K_L^0 \rightarrow \mu^+\mu^-$ for which the rate was known to be extremely small. The decay can proceed through the diagrams shown in Figure 9.33. Aside from other factors, the first diagram is proportional to $\sin\theta_C$ from the usW vertex and to $\cos\theta_C$ from the udW vertex. Here, W stands for the carrier of the weak interaction mentioned in Chapter 6 and discussed at length in Chapter 12.

The result given by this diagram alone would imply a decay rate that is not suppressed relative to normal K decay, in gross violation of the experimental facts. The proposal of Glashow, Iliopoulos, and Maiani was to add a fourth quark and correspondingly a second contribution to the charged weak current, which would become, symbolically,

$$\overline{u}(\cos\theta_C d+\sin\theta_C s)+\overline{c}(-\sin\theta_C d+\cos\theta_C s)=\begin{pmatrix}\overline{u} & \overline{c}\end{pmatrix}\begin{pmatrix}\cos\theta_C & \sin\theta_C\\ -\sin\theta_C & \cos\theta_C\end{pmatrix}\begin{pmatrix}d\\ s\end{pmatrix}$$

Thus the Cabibbo angle would be simply a rotation, mixing the quarks d and s. Now when the $K_L^0 \to \mu^+\mu^-$ is calculated, there is a second diagram in which a c quark appears in place of the u quark. This amplitude has a term proportional to $-\sin\theta_C\cos\theta_C$, just cancelling the previous term. The surviving amplitude is higher order in G_F and does not conflict with experiment. The seminal quantitative treatment of this and related processes was given by M. K. Gaillard and B. W. Lee, who predicted the mass of the charmed quark to be about 1.5 - 2 GeV, in advance of the discovery of the ψ!

As is described in Chapter 12, the discovery of strangeness non-changing neutral weak currents in 1973 made much more compelling the case for a unified theory of electromagnetism and weak interactions. The charmed quark was essential to this theoretical structure and the properties of the new quark were well specified by the theory. If the ψ was a bound state of a charmed quark and a charmed antiquark, there would have to be mesons with the composition $c\overline{u}$ and $c\overline{d}$, etc., that were stable against strong decays. The weak decay of a particle containing a c quark would yield an s quark. Thus the decay of a D^+ $(= c\overline{d})$ could produce a K^- $(= s\overline{u})$ but not a K^+ $(= \overline{s}u)$.

There were a number of hints of charm already in the literature. K. Niu and collaborators working in Japan observed several cosmic ray events in emulsion in which a secondary vertex was observed 10 to 100 μm from the primary vertex. These may have been decays of a particle with a lifetime in the 10^{-12} to 10^{-13} s range, just the lifetime expected for charmed particles. Nicolas Samios and Robert Palmer and co-workers, in a neutrino exposure of a hydrogen bubble chamber at Brookhaven, observed a single event that could have been a charmed baryon. See Figure 9.34. In other neutrino experiments, events with a pair of muons in the final state had been observed (Figure 9.35). These would be expected from processes in which the incident neutrino changed into a muon through the usual charged weak current and a strange quark was transformed into a charmed quark, again by the charged weak current. For that fraction in which the charmed particle decay produced a muon, two muons would be observed in the final state, and they would have opposite charges. The evidence for a new phenomenon, perhaps charm, was accumulating.

The SLAC-LBL Mark I detector at SPEAR and the corresponding

Figure 9.34: The event obtained in a neutrino exposure of the 7-ft hydrogen bubble chamber at Brookhaven that gave evidence for a charmed baryon. The overall reaction was most likely $\nu p \rightarrow \mu^- \Lambda^0 \pi^+ \pi^+ \pi^+ \pi^-$. The most probable assignments are shown in the sketch on the right. This violates the $\Delta S = \Delta Q$ rule. Such a violation can be understood if the process were really $\nu p \rightarrow \Sigma_c^{++} \mu^-$, followed by the strong decay $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$. In the quark model $\Sigma_c^{++} = uuc$ and $\Lambda_c^+ = udc$. The decay of the Λ_c^+ to $\Lambda^0 \pi^+ \pi^+ \pi^-$ accounts for the violation of the $\Delta S = \Delta Q$ rule and is in accord with the pattern expected for charm decay. The mass of the Σ_c^{++} was measured to be 2426 ± 12 MeV. There were three possible choices for the pions to be joined to the Λ^0. Of these, one gave a mass splitting between the Σ_c^{++} and the Λ_c^+ of about 166 MeV, which agreed with the theoretical expectations [E. G. Cazzoli *et al.*, *Phys. Rev. Lett.* **34**, 1125 (1975), Figure courtesy N. Samios, Brookhaven National Laboratory].

Figure 9.35: Early evidence for charm from opposite-sign dileptons observed in neutrino experiments at Fermilab. Left, one of fourteen events observed by the Harvard-Penn-Wisconsin Collaboration [A. Benvenuti *et al.*, *Phys. Rev. Lett.* **34**, 419 (1975)]. Right, a similar event, one of eight seen by the Caltech-Fermilab Collaboration [B. C. Barish *et al.*, *Phys. Rev. Lett.* **36**, 939 (1976)]. In addition, four events containing $\mu^- e^+ K^0_S$ were observed in the 15-ft bubble chamber at Fermilab [J. von Krogh *et al.*, *Phys. Rev. Lett.* **36**, 710 (1976)] and two such events were seen in the Gargamelle bubble chamber at CERN [J. Blietschau *et al.*, *Phys. Lett.* **60B**, 207 (1976)].

PLUTO and DASP at DESY were the leading candidates to produce convincing evidence for charmed particles. The rise in the e^+e^- annihilation cross section near a center-of-mass energy of 4 GeV strongly suggested that the threshold must be in that vicinity. The narrowness of the ψ' indicated that the threshold must be above that mass since the ψ' would be expected to decay rapidly into states like $c\overline{u}$ and $u\overline{c}$ if that were kinematically possible.

Despite advance knowledge of the approximate mass of the charmed particles and their likely decay characteristics, it took nearly two years before irrefutable evidence for them was obtained. The task turned out to be quite difficult because there were many different decay modes, with each having a branching ratio of just a few percent.

Ultimately, the SLAC-LBL Mark I group did succeed in isolating decays like $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^-\pi^+\pi^+$ **(Ref. 9.11)**, and soon after, $D^+ \to K^-\pi^+\pi^+$ (Ref. 9.12). See Figure 9.36. Overwhelming evidence was amassed identifying these new particles with the proposed charmed particles. Their masses were large enough to forbid the decay of the ψ' into a $D\overline{D}$ pair. The par-

Figure 9.36: Invariant mass spectra for (a) $K^\mp\pi^\pm\pi^\pm$ and (b) $K^\mp\pi^+\pi^-$. Only the former figure shows a peak, in agreement with the prediction that D^+ decays to $K^-\pi^+\pi^+$, but not $K^+\pi^-\pi^+$. (Ref 9.12)

ticles came in two doublets, (D^+, D^0) and $(\overline{D}^0, D^-)$, corresponding to $c\overline{d}, c\overline{u}$ and $\overline{c}u, \overline{c}d$. The decay mode $D^+ \to K^-\pi^+\pi^+$ was seen, but $D^+ \to K^+\pi^-\pi^+$ was not. It was possible to infer decay widths of less than 2 MeV, indicating that the decays were unlikely to be strong. The D s shared some properties of the K s. They were pair-produced with a particle of equal or greater mass, indicating the existence of a quantum number conserved in strong and electromagnetic interactions. In addition, their decays were shown to violate parity. Both nonleptonic and semileptonic decays were observed. The Cabibbo mixing in the four-quark model called for decays $c \to d$, suppressed by a factor roughly $\sin^2\theta_c \approx 5\%$. These, too, were observed in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$. See Figure 9.37.

Further discoveries conformed to the charmed quark hypothesis. A set of partners about 140 MeV above the first states was found, with decays like $D^{*+} \to D^0\pi^+$ (Ref. 9.13). See Figure 9.38. These decays were strong, the analogs of $K^* \to K\pi$. Moreover, the spins of the D and D^* were consistent with the expected assignments, pseudoscalar and vector, respectively. Detailed studies of the charmed mesons were aided enormously by the discovery by the Lead Glass Wall collaboration of a resonance just above the charm threshold (Ref. 9.14), shown in Figure 9.39. The resonance, $\psi(3772)$, is primarily a d-wave bound state of $c\overline{c}$ with some mixture of $^3S_1$. The bound state decays entirely to $D\overline{D}$. The $\psi(3772)$ is thus

Figure 9.37: Examples of Cabibbo-suppressed decay modes of charmed mesons observed at the ψ''. Left: $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ as well as the Cabibbo-allowed decay to $K^\mp\pi^\pm$. The data are from the Mark II experiment [G. S. Abrams *et al.*, *Phys. Rev. Lett.* **43**, 481 (1979)]. Right: $D^+ \to \overline{K}^0 K^+$ as well as the Cabibbo-allowed mode $D^+ \to \overline{K}\pi^+$ from the Mark III experiment [R. M. Baltrusaitis *et al.*, *Phys. Rev. Lett.* **55**, 150 (1985)]. For the suppressed modes, two peaks are observed. The one near 1865 MeV is the signal while the other is due to K/π misidentification.

a D-meson "factory" and has been the basis for a continuing study of charmed mesons.

The quark model requires that in addition to charmed mesons, there must be charmed baryons, in which one or more of the first three quarks are replaced by charmed quarks. Evidence for charmed baryons accumulated from a variety of experiments including neutrino bubble chamber experiments at Brookhaven and Fermilab, a photoproduction experiment at Fermilab, a spectrometer experiment at the CERN Intersecting Storage Ring (ISR), and the work of the Mark II group at SPEAR. The lowest mass charmed baryon has the composition udc and is denoted Λ_c^+. It has been identified in decays to $\Lambda\pi^+\pi^+\pi^-, \Lambda\pi^+, pK_S^0$, and $pK^-\pi^+$. In agreement with the results for meson decays, the decay of the charmed baryon yielded negative strangeness.

Figure 9.38: Data for $D^0\pi^+$ with $D^0 \rightarrow K^-\pi^+$. The abscissa is the difference between the $D\pi$ mass and the D mass. There is a clear enhancement near 145 MeV (G. J. Feldman *et al.* Ref. 9.13). The very small Q value for the D^{*+} decay, 5.88 ± 0.07 MeV, has become an important means of identifying the presence of a D^{*+} in high energy interactions. The data for $\overline{D}^0\pi^+$, a combination with the wrong quantum numbers to be a quark–antiquark state, show no enhancement.

The strange-charmed meson with quark composition $c\overline{s}$ was even harder to find than the D. At first called the F^+ and now indicated D_s^+, it was observed by the CLEO detector at Cornell, by the ARGUS detector at DORIS (located at DESY), and by the TPC and HRS at PEP (located at SLAC). Evidence for this particle is shown in Figure 9.40. The F^* or D_s^* was also identified by TASSO at PETRA and the TPC, as well as the Mark III detector at SPEAR. It decays electromagnetically, $D_s^* \rightarrow D_s\gamma$. While the mass splitting is possibly large enough to permit $D_s^* \rightarrow D_s\pi^0$, this decay is forbidden by isospin conservation.

The lifetimes of the charmed mesons D^0, D^+, and D_s^+ as well as the charmed baryon Λ_c and the τ lepton are all in the region $10^{-13}\,$s to $10^{-12}\,$s and hence susceptible to direct measurement. The earliest measurements used photographic emulsions, with cosmic rays or beams at Fermilab or CERN providing the incident particles. This 'ancient' technique is well suited to the few micron scale dictated by the small lifetimes. Studies were also conducted using special high resolution bubble chambers at CERN and SLAC. The required resolution was also achieved with electronic detectors at e^+e^- machines with the development of high precision vertex chambers pioneered by Mark II and later by MAC and DELCO at PEP, and TASSO, CELLO, and JADE at PETRA. The latest stage of development

Figure 9.39: The $\psi(3772)$ resonance is broader than the $\psi(3096)$ and $\psi(3684)$ because it can decay into $D\overline{D}$. P. A. Rapidis *et al.*, (Ref. 9.14).

returned the focus to hadronic machines where the production rate of charmed particles far exceeds that possible at e^+e^- machines. The detection with the requisite precision is achieved with silicon microstrips. Experiments carried out at CERN and Fermilab have achieved remarkable results, which required the analysis of 10^8 events in order to isolate several thousand charm decays.

Some of the lifetime measurements have relied on reconstructed vertices, others on impact parameters of individual tracks, as first employed in π^0 lifetime studies (Ref. 2.7). Figure 9.41 shows the photoproduction of a pair of charmed mesons from the SLAC Hybrid Facility Photon Collaboration. Both decay vertices are plainly visible. In the same figure a computer reconstruction of a digitized bubble chamber picture from LEBC at CERN, with an exaggerated transverse magnification, is shown. Again, pair production of charmed particles is demonstrated. Exponential decay distributions for charmed mesons obtained using a tagged photon beam at Fermilab are displayed in Figure 9.42.

The discoveries of the ψ, τ, and charm were pivotal events. They established the reality of the quark structure of matter and provided enormous circumstantial evidence for the theoretical view dubbed “The Standard Model,” to be discussed in Chapter 12. The τ pointed the way to the third generation of matter, which is discussed in Chapter 11.

Figure 9.40: On the left, observation of the decay $D_s^+ \to \phi\pi^+$ by CLEO. In (a) only events in which the K^+K^- invariant mass is consistent with the mass of the ϕ are plotted. In (b) only $K^+K^-\pi$ events not containing a ϕ are shown [A. Chen *et al.*, *Phys. Rev. Lett.*, **51**, 634 (1983)]. On the right, observation of the decay $D_s^+ \to K^{*0}K^+$ by ARGUS. In (a) only events with $K^-\pi^+$ in the K^{*0} band are shown. In (b) only events without a K^{*0} are shown [ARGUS Collaboration, *Phys. Lett.* **179B**, 398 (1986)].

Figure 9.41: Left: A bubble chamber picture of the production and decay of a charged charmed particle and a neutral charmed particle. The charged particle decays into three tracks at 0.86 mm and the neutral decays after 1.8 mm. The quantities d_{max} and d_2, the largest and second largest impact distances were used in the lifetime calculations. The incident photon beam ($E_{max} = 20$ GeV) was obtained by Compton scattering of laser light off high energy electrons at SLAC [K. Abe *et al.*, *Phys. Rev. Lett.* **48**, 1526 (1982)]. Right: A computer reconstruction of a digitized bubble chamber picture. The transverse scale is exaggerated. The production vertex is at A. A charged charmed particle decays at $C3$ and a neutral charmed particle at $V2$. The picture was obtained with LEBC (Lexan Bubble Chamber) at CERN using a 360-GeV π^- beam [M. Aguilar-Benitez *et al.*, *Zeit. Phys.* **C31**, 491 (1986)].

Figure 9.42: Proper time distributions for D^0, D^+, and D_s^+ mesons and Λ_c baryons from the Tagged Photon Spectrometer Collaboration at Fermilab, using silicon microstrip detectors [J. R. Raab *et al.*, *Phys. Rev.* **D37**, 2391 (1988), J. C. Anjos *et al.*, *Phys. Rev. Lett.* **60**, 1379 (1988)]. For the D^0, a corresponds to $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, b to $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and c to $D^0 \to K^-\pi^+$. For the D^+, the decay mode is $D^+ \to K^-\pi^+\pi^+$. For the D_s^+, a corresponds to $D_s^+ \to \phi\pi^+$ and b to $D_s^+ \to \overline{K}^{*0}K^+$, $\overline{K}^{*0} \to K^-\pi^+$. The observed lifetimes are $\tau_{D^0} = (0.422 \pm 0.008 \pm 0.010) \times 10^{-12}\,\mathrm{s}$, $\tau_{D^+} = (1.090 \pm 0.030 \pm 0.025) \times 10^{-12}\,\mathrm{s}$, $\tau_{D_s} = (0.47 \pm 0.04 \pm 0.02) \times 10^{-12}\,\mathrm{s}$ and $\tau_{\Lambda_c} = 0.22 \pm 0.03 \pm 0.02 \times 10^{-12}\,\mathrm{s}$.

EXERCISES

9.1 Estimate the lifetime of the D-meson. Do you expect the neutral and charged D's to have the same lifetime? What do the data say?

9.2 Describe the baryons containing one or more charmed quarks that extend the lowest lying multiplets, the octet and decuplet. How many of these particles have been found? Compare with *Review of Particle Properties.* What do you expect their decay modes to be?

9.3 How have the most precise measurements of the mass of the ψ been made? See Ref.(9.15).

9.4 * Calculate the branching ratio for $\tau \to \pi\nu$. See Y. S. Tsai, *Phys. Rev.* **D4**, 2821 (1971); M. L. Perl, *Ann. Rev. Nucl. Part. Sci.* **30**, 229 (1980).

9.5 * Calculate the expected widths for $\psi' \to \gamma\chi_{2,1,0}$ in terms of the s- and p-state wave functions. Evaluate the results for a harmonic oscillator potential with the charmed quark mass set to 1.5 GeV and the spring constant adjusted to give the level splitting between the ψ and ψ' correctly. Calculate the partial width for $\psi \to \gamma\eta_c$. Why is the transition $\psi' \to \gamma\eta_c$ suppressed? Compare your results with the data given in the *Review of Particle Properties.* [See the lecture by J. D. Jackson listed in the Bibliography.]

9.6 * Show that the ψs produced in e^+e^- annihilation have their spins' components along the beam axis equal either to $+1$ or -1, but not 0. (Use the coupling of the ψ to e^+e^- : $\overline{e}\gamma_\mu e\psi^\mu$)

9.7 * What is the angular distribution of the γ's relative to the beam direction in $e^+e^- \to \psi' \to \gamma\chi_0$? What is the answer for χ_1 and χ_2 assuming that the transitions are pure $E1$? (See E. Eichten *et al.*, *Phys. Rev. Lett.* **34**, 369 (1975); G. J. Feldman and F. J. Gilman, *Phys. Rev.* **D12**, 2161 (1975); L. S. Brown and R. N. Cahn, *Phys. Rev.* **D13**, 1195 (1975).)

BIBLIOGRAPHY

e^+e^- *Annihilation: New Quarks and Leptons*, Benjamin/Cummings, Menlo Park, CA 1984, R. N. Cahn, ed. (A collection of articles from *Annual Review of Nuclear and Particle Science.*)

J. D. Jackson, "Lectures on the New Particles" in *Proc. of Summer Institute on Particle Physics, Stanford, CA, Aug. 2-13, 1976*, M. Zipf, ed.

G. J. Feldman and M. L. Perl, "Electron-Positron Annihilation above 2 GeV and the New Particles," *Phys. Rep.* **19**, *233 (1975)* and **33**, *285 (1977).*

G. H. Trilling, “The Properties of Charmed Particles,” *Phys. Rep.* **75**, *57 (1981).*

S. C. C. Ting, “Discovery of the J Particle: a Personal Recollection,” *Rev. Mod. Phys.* **44(2)**, *235 (1977).*

B. Richter, “From the Psi to Charm: the Experiments of 1975 and 1976,” *Rev. Mod. Phys.* **44(2)**, *251 (1977).*

A popular account of much of the historical material in the chapter is contained in contributions by S. C. C. Ting, G. Goldhaber, and B. Richter in *Adventures in Experimental Physics*, ϵ, B. Maglich ed., World Science Education, Princeton, N.J., 1976. See also M. Riordan *The Hunting of the Quark*, Simon & Schuster, 1987.

REFERENCES

9.1 J. J. Aubert *et al.*, “Experimental observation of a heavy particle J.” *Phys. Rev. Lett.*, **33**, 1404 (1974).

9.2 J.-E. Augustin *et al.*, “Discovery of a narrow resonance in e^+e^- annihilation.” *Phys. Rev. Lett.*, **33**, 1406 (1974).

9.3 C. Bacci *et al.*, “Preliminary result of Frascati (ADONE) on the nature of a new 3.1 GeV Particle Produced in e^+e^- Annihilation.” *Phys. Rev. Lett.*, **33**, 1408 (1974).

9.4 G. S. Abrams *et al.*, “Discovery of a Second Narrow Resonance in e^+e^- Annihilation.” *Phys. Rev. Lett.*, **33**, 1453 (1974).

9.5 G. S. Abrams *et al.*, “Decay of $\psi(3684)$ into $\psi(3095)$.” *Phys. Rev. Lett.*, **34**, 1181 (1974).

9.6 W. Braunschweig *et al.*, “Observation of the Two Photon Cascade $3.7 \rightarrow 3.1 + \gamma\gamma$ via an Intermediate State P_c.” *Phys. Lett.*, **B57**, 407 (1975).

9.7 R. Partridge *et al.*, “Observation of an η_c Candidate State with Mass 2978 ± 9 MeV.” *Phys. Rev. Lett.*, **45**, 1150 (1980).; See also E. D. Bloom and C. W. Peck, *Ann. Rev. Nucl. Part. Sci.* **30**, 229 (1983). “Physics with the Crystal Ball Detector” and J. E. Gaiser *et al.*, “Charmonium Spectroscopy from Inclusive ψ' and J/ψ Radiative Decays.” *Phys. Rev.*, **D34**, 711 (1986).

9.8 M. L. Perl *et al.*, “Evidence for Anomalous Lepton Production in e^+e^- Annihilation.” *Phys. Rev. Lett.*, **35**, 1489 (1975).

9.9 R. Brandelik *et al.*, “Measurements of Tau Decay Modes and a Precise Determination of the Mass.” *Phys. Lett.*, **73B**, 109 (1978).

9.10 W. Bacino *et al.*, "Measurement of the threshold Behavior of $\tau^+\tau^-$ Production in e^+e^- Annihilation." *Phys. Rev. Lett.*, **41**, 13 (1978).

9.11 G. Goldhaber *et al.*, "Observation in e^+e^- Annihilation of a Narrow State at 1865 Mev/c^2 Decaying to $K\pi$ and $K\pi\pi\pi$." *Phys. Rev. Lett.*, **37**, 255 (1976).

9.12 I. Peruzzi *et al.*, "Observation of a Narrow Charged State at 1876 MeV/c^2 Decaying to an Exotic Combination of $K\pi\pi$." *Phys. Rev. Lett.*, **37**, 569 (1976).

9.13 G. J. Feldman *et al.*, "Observation of the Decay $D^{*+} \rightarrow D^0\pi^+$." *Phys. Rev. Lett.*, **38**, 1313 (1977).

9.14 P. A. Rapidis *et al.*, "Observation of a Resonance in e^+e^- Annihilation Just above Charm Threshold." *Phys. Rev. Lett.*, **39**, 526 (1977).

9.15 A. A. Zholentz *et al.*, "High Precision Measurement of the ψ and ψ' Meson Masses." *Phys. Lett.*, **96B**, 214 (1980).