Chapter 3

Experimental Study of Charmonium

3.1 Why charmonium?

One might rightly ask why it is charmonium, and not another quark-antiquark system, which one should study in order to understand the strong interaction. It is a well-known experimental fact that light quark mesons, *e.g.* the $\phi(s\bar{s})$, or the $\rho(u\bar{u}, d\bar{d})$, are far more prolifically produced than charmonium, regardless of the production mechanism. In general, the cross sections for the production of quarkonia decrease rapidly with their mass. Thus, from the point of view of statistical precision alone, light quark mesons would be the preferred subject of study. However, statistics is not the only criterion which we must consider.

In a light quark meson, the constituent quarks are quite relativistic. It is estimated that $(\langle v^2/c^2\rangle \simeq 1.0(u\bar{d}), \simeq 0.85(u\bar{s}), \simeq 0.7(s\bar{s}))$ As such, these systems are poorly described by a non-relativistic formulation of the strong interaction.

In addition, it is well-known that the coupling constant of QCD, $\alpha_s(q)$, grows to rather large values (~ 0.5) at the small momentum scales (q) characteristic of light quark systems. The QCD interaction, which is perturbative at high q, becomes dominated by non-perturbative effects at low q. Thus, predictions for light quark systems become very unreliable.

A third problem arises because of the near equality of the u, d and s quark masses. Aside from the few mesons below ~ 1 GeV, mesons composed of (u, d, s) quarks and antiquarks are nine times as numerous (as a single flavor $q\bar{q}$), they acquire very similar masses, and the large decay widths (typically 100 to 500 MeV). Their spectra become extremely dense and overlapping. Spectroscopy of such states becomes quite difficult, and often requires computationally-intensive partial wave analyses to make even the simplest identifications. These complications would suggest avoiding the light quark systems.

In contrast, both the relativistic and non-perturbative effects are smaller for charmonium than for light quark mesons; average charm quark velocities are $\langle v^2/c^2 \rangle \simeq 0.25$, and the coupling constant $\alpha_s(m_c) \simeq 0.3$. Production cross sections for charmonium resonances are reasonably large. Further, the charmonium spectrum is characterized by well-spaced states, with narrow widths - so that they are well resolved. Spectroscopy of charmonium is thus clean and can be made very precise.

Precision spectroscopy of such simple two-body systems as charmonium is a good tool with which to examine the physics of the underlying strong interaction, just as the study of the hydrogen atom and positronium have contributed greatly to the understanding of the electromagnetic interaction which binds them. Besides providing insight into the QCD interaction, the spectroscopy of the charmonium system may also be expected to shed light on the nature and properties of the charm quark.

3.2 Discovery of Charmonium

In 1974, two groups, one at the Brookhaven National Laboratory, and the other at the Stanford Linear Accelerator Center, simultaneously announced the discovery of a resonance with a mass of $\sim$ 3.1 GeV and a surprisingly narrow width of $\sim$ 100 keV. (See Fig. 3.1) The group at BNL, led by Sam Ting, was studying the production of dilepton pairs in proton-Beryllium collisions; they called the state they observed "J". [24] The SLAC group, led by Burton Richter, was measuring the hadronic cross section in e^+e^- annihilation in the vicinity of 3 GeV, they called the state they found "ψ". [25] Though a number of imaginative interpretations for this state, J/ψ, were offered, [26] it became clear very soon that it had a 'natural' explanation in terms of a new quark and its antiquark partner. The 'charm' quark anticipated by Bjorken, Glashow, Iliopoulos and Maiani had arrived.

Ting and Richter subsequently shared the 1976 Nobel Prize in Physics for this momentous discovery. It is perhaps not hyperbolic to say that the discovery of bound charm brought the quark model from its existence merely as a mathematical tool to account for the classification of hadrons according to SU(3) symmetry, to its recognition as a legitimate model of hadron structure.

The detailed spectrum of charmonium states with major decays indicated is

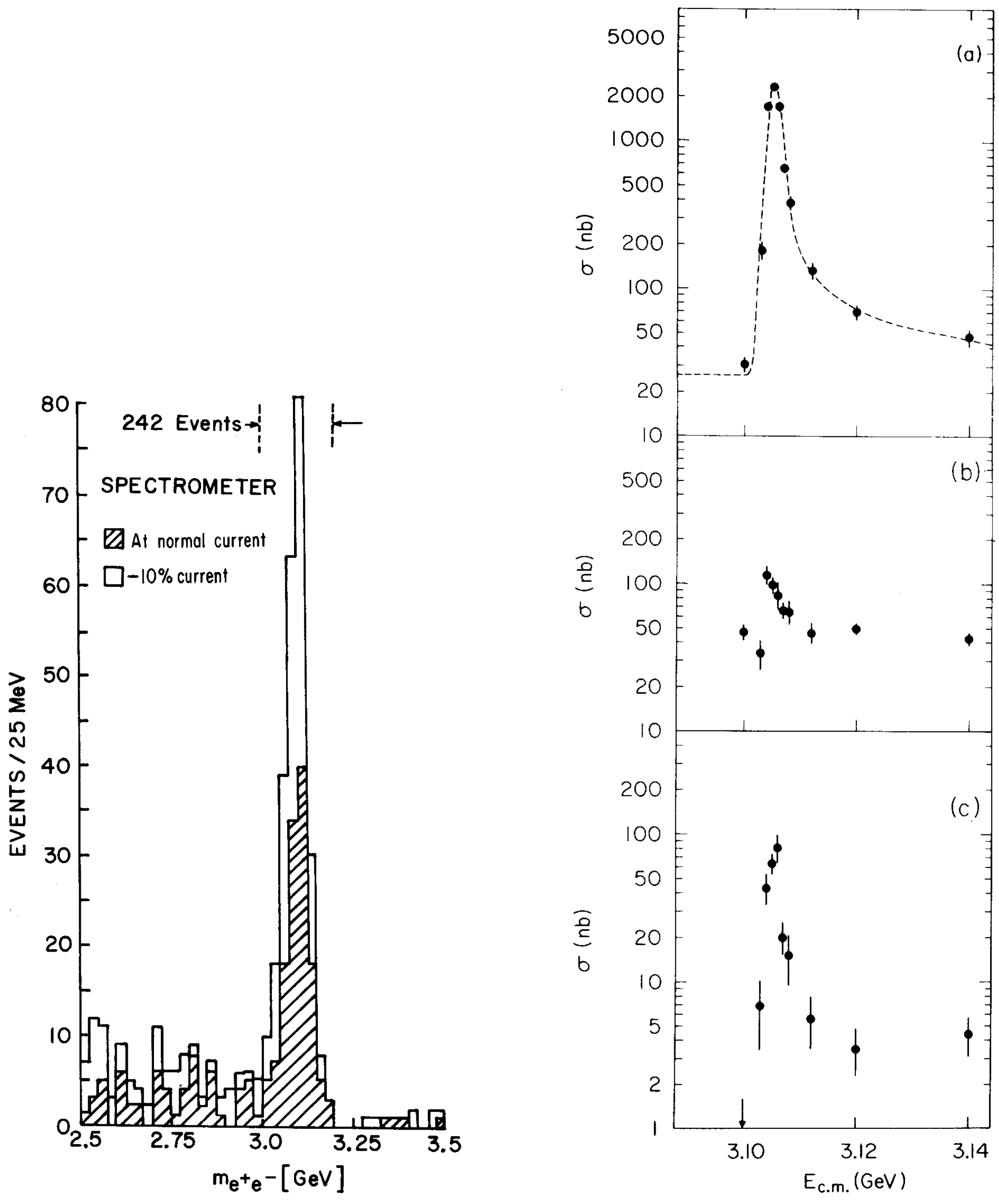

Figure 3.1: Spectra demonstrating the first experimental evidence in 1974 for the resonance known as J/ψ, from (left) the BNL experiment [24] and (right) the SLAC experiment. [25]

shown in Fig. 3.2. Charmonium has been studied primarily by e^+e^- annihilation, and more recently by $\bar{p}p$ annihilation. We describe each of these techniques in this chapter.

3.3 Charmonium Production in e^+e^- collisions

Aside from the J/ψ discovery experiment in p-Be collisions at Brookhaven, charmonium was studied almost exclusively at electron-positron colliders. All bound states of charmonium (below the open charm threshold at ~ 3.7 GeV) were either observed or claimed to have been observed. Not all were well studied, however, for various reasons.

The best studied of the charmonium states were the J/ψ and ψ' - the vector states ($J^{PC} = 1^{--}$). These are the only states which can be directly formed in the annihilation of e^+e^-, since e^+e^- annihilation is mediated by a virtual photon, whose quantum numbers are $J^{PC} = 1^{--}$. (See Fig. 3.3) Because these states were formed directly, their masses and widths could be measured with (good) precision, which depended only upon the precision in the knowledge of the electron/positron beam parameters.

In direct formation, the excitation curve of the vector state under investigation may be measured. This was done by means of a 'scan', in which the e^+ and e^- beam energies were stepped in small increments so that the center of mass energy moves across the resonance. This method was used to produce the SLAC data for the J/ψ discovery shown in Fig. 3.1(b). The mass of the resonance is simply given

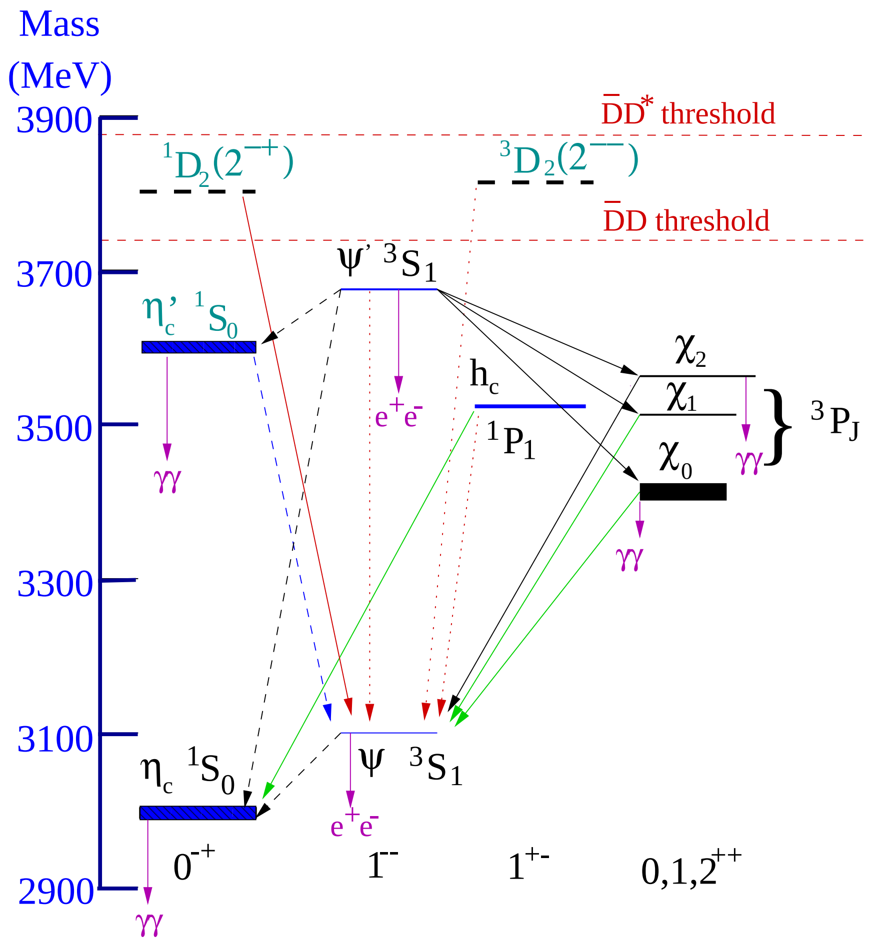

Figure 3.2: The spectrum of charmonium states. Unlabelled solid lines and dashed lines represent E1 and M1 radiative transitions, respectively. Dotted lines represent hadronic transitions.

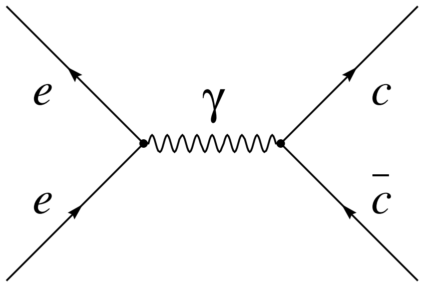

Figure 3.3: Formation of vector charmonium states via e^+e^- annihilation.

by analyzing the measured excitation function.

It was not possible to measure the widths of J/ψ and ψ', in such a direct manner. At SLAC, the e^+ and e^- beam energy spreads and initial state radiation from the e^+ and e^- beams resulted in a center of mass energy spread of ~ 2.6 MeV. The total widths of J/ψ and ψ', however, are an order of magnitude smaller. Thus their total widths had to be determined by measuring the areas under the measured excitation curves for the leptonic and hadronic decays of J/ψ and ψ'. This required knowledge of detector acceptance and efficiency for the final state particles, and corrections for distortion of the excitation curves due to initial and final state radiation (bremsstrahlung). The resulting precision in the determination of the J/ψ and ψ' widths was therefore compromised.

Non-vector states of charmonium (*e.g.*, $^1S_0$, $^1P_1$, ^3P_J) were only observed as products of radiative decay of ψ', and as a result they were produced much less copiously. Since their detection required the observation of several hundred MeV photons, the determination of their masses and total widths depended upon the properties of the photon detectors. The energy resolution of the best of the SLAC photon detectors, the Crystal Ball, ranged from 20 to 30 MeV for the photon energies in question. As a result, although the masses of the ^3P_J states, observed in the E1 decays of ψ', were determined to $\sim \pm 1$ MeV, it was only possible to set rather liberal limits for the widths. The study of singlet-S charmonium states (η_c and η_c') was further hampered by the fact that they could only be observed in the significantly weaker M1 radiative decay of ψ' and/or J/ψ. As a result, η_c resonance parameters were poorly determined, and the observation of η_c' was claimed, but was never confirmed. Branching ratios for the few η_c decays which were measured all had errors $\geq 30\%$. The production of the singlet-P state (h_c) in the radiative decay of ψ' is, of course, forbidden by charge conjugation, and it was not observed.

Recently, the electron-positron collider at Beijing's BEPC has been studying charmonium, but their measurements continue to have the inherent limitations of the e^+e^- annihilation method.

3.4 Charmonium Production in $\bar{p}p$ collisions

In 1984, the R704 experiment at CERN pioneeered the technique of studying charmonium resonances by forming them in $\bar{p}p$ annihilation and detecting them via their electromagnetic decays. A hydrogen gas jet target intersected the cooled, circulating antiproton beam stored in one of the ISR storage rings, and the reaction products were identified in a two-arm electromagnetic detector. Several charmonium states were investigated, but for various reasons the precision of the results was rather

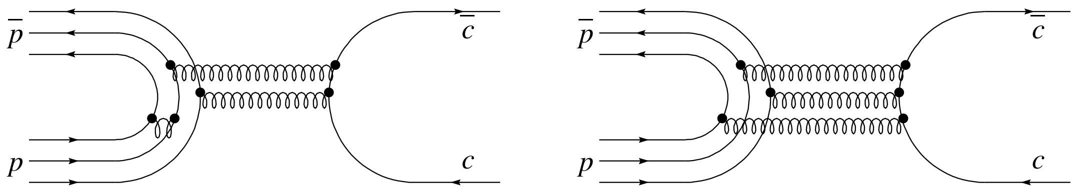

Figure 3.4: Formation of charmonium states via $\bar{p}p$ annihilation.

limited.

Fermilab Experiments E760 (1991-2) and E835 (1996-7) have used the $\bar{p}p$ annihilation technique to study charmonium spectroscopy at the Fermilab Antiproton Accumulator with a much improved beam and detector. The technique has distinct advantages over the production of charmonium states via e^+e^- annihilation.

All charmonium states can be formed directly by $\bar{p}p$ annihilation. The formation of all J^{PC} combinations is possible because the antiproton and proton annihilate into either two gluons (C = +1) or three gluons (C = -1). (See Fig. 3.4) The quantum numbers of the intermediate state may therefore take on any J^{PC}, since each of the gluons carries $J^{PC} = 1^{--}$, and there may be orbital angular momentum L among them. The fact that all states can be formed directly is a major advantage of this technique over the e^+e^- annihilation technique, because it permits the precision of the accelerator beam to directly bear on the quality of the measurements for *all* charmonium resonances.

In a $\bar{p}p$ annihilation experiment the excitation function of *any* charmonium resonance can be directly measured by stepping (or "scanning") the energy of the $\bar{p}$ beam in small increments across the resonance. The determination of the mass of any charmonium state is thus directly obtained from the excitation curve, and depends only the precision of the beam energy parameters. The $\bar{p}$ beam energy distribution can be made very small by stochastic cooling, and it can be very well measured in terms of the beam circulation frequency and the orbit length. Further, because $m_p \approx 1800 m_e$, the distortion of the excitation function caused by initial state radiation is far smaller in $\bar{p}p$ annihilation than in the e^+e^- case, This leads to direct measurements of resonance widths, which require only deconvolution of the small width of the $\bar{p}$ beam energy distribution.

Thus, the $\bar{p}p$ annihilation technique leads to much better precision in mass and width measurements for all charmonium states than was possible in the e^+e^- annihilation experiments.