ONIA SPECTROSCOPY BY DIRECT CHANNEL PRODUCTION

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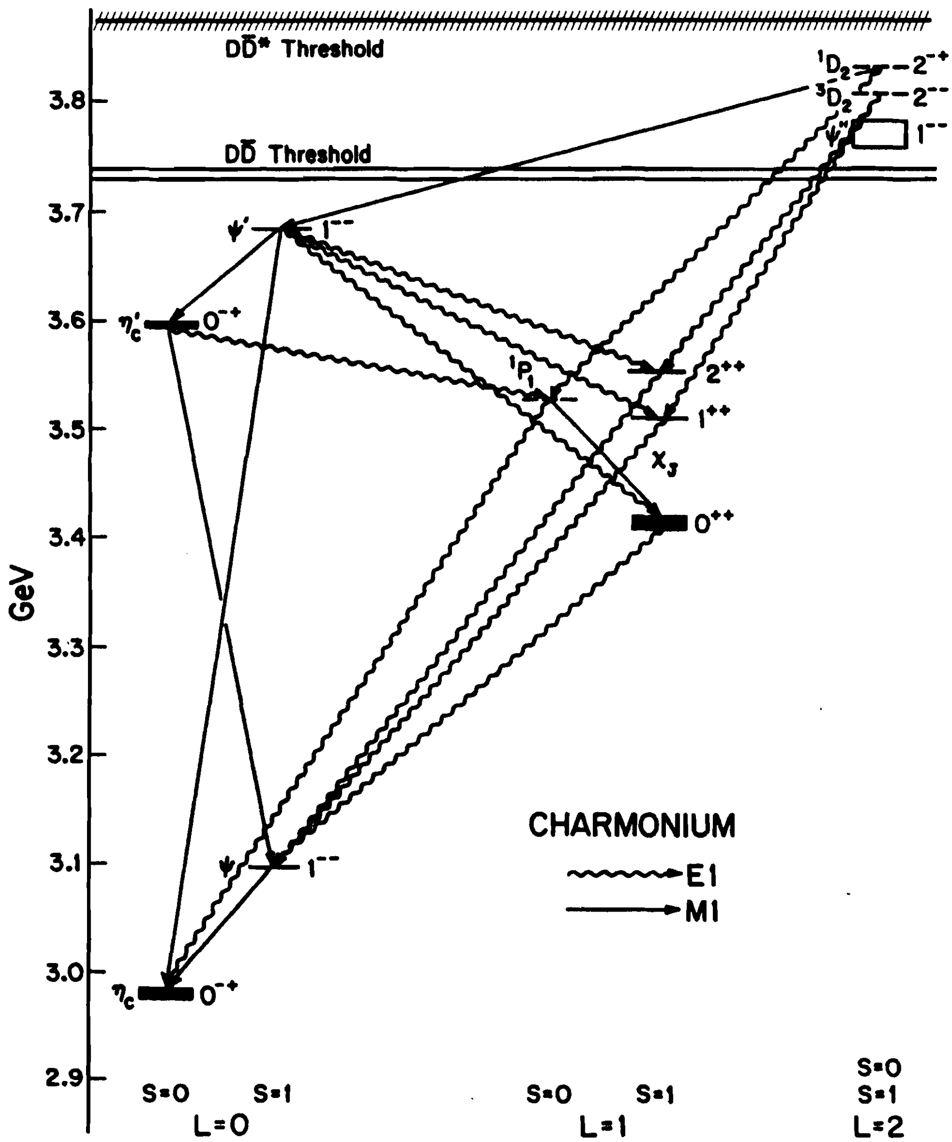

Fig. 1 Charmonium level diagram showing photon transitions. Total widths of the $c\bar{c}$ states are roughly indicated by the thickness of the level.

Direct exclusive production of heavy onia will provide a rich new source of information on these states. The recent R704 experiment[1] at CERN has shown the feasibility of producing and detecting a variety of $c\bar{c}$ states by exclusive $\bar{p}p$ annihilation. The E760 experiment[2] at Fermilab will extend this technique to new states and improve existing data. The proposed Fermilab $\bar{p}$ facility would bring great additional improvements in the energy resolution, luminosity and detector possibilities which will further enlarge the experimental range. We will try here to indicate first why the study of heavy quark bound states is interesting and fundamental and then why $\bar{p}p$ formation experiments are useful. Our main emphasis will be on charmonium which is by far the most accessible in $\bar{p}$ experiments. The sharp charmonium states and radiative transitions are shown in Fig. 1.

The Virtues of Heavy Quarks

Heavy quark bound state spectroscopy involves an interplay between perturbative and non-perturbative QCD. What makes this system unique is that we have an excellent zeroth order model for the non-perturbative part: the non-relativistic potential model. The potential model provides wavefunctions which together with QED and perturbative QCD makes possible realistic calculations of radiative transitions and leptonic or hadronic annihilation.

The potential interaction between the quark and antiquark is motivated in form by perturbative QCD and the string model. Much recent progress has been made in a more fundamental calculation of the static potential[3] and the spin interaction[4] by use of Monte Carlo lattice gauge (MCLG) techniques. A Born–Oppenheimer type approximation considerably aids in the evaluation of the heavy quark potential. A recent large lattice evaluation of the static potential[3] is shown in Fig. 2. There is a real expectation that the complete potential including spin dependence will be known in the near future. Unfortunately these MCLG calculations so far have been done in the quenched approximation in which light quark vacuum polarization is neglected. The resulting potential although

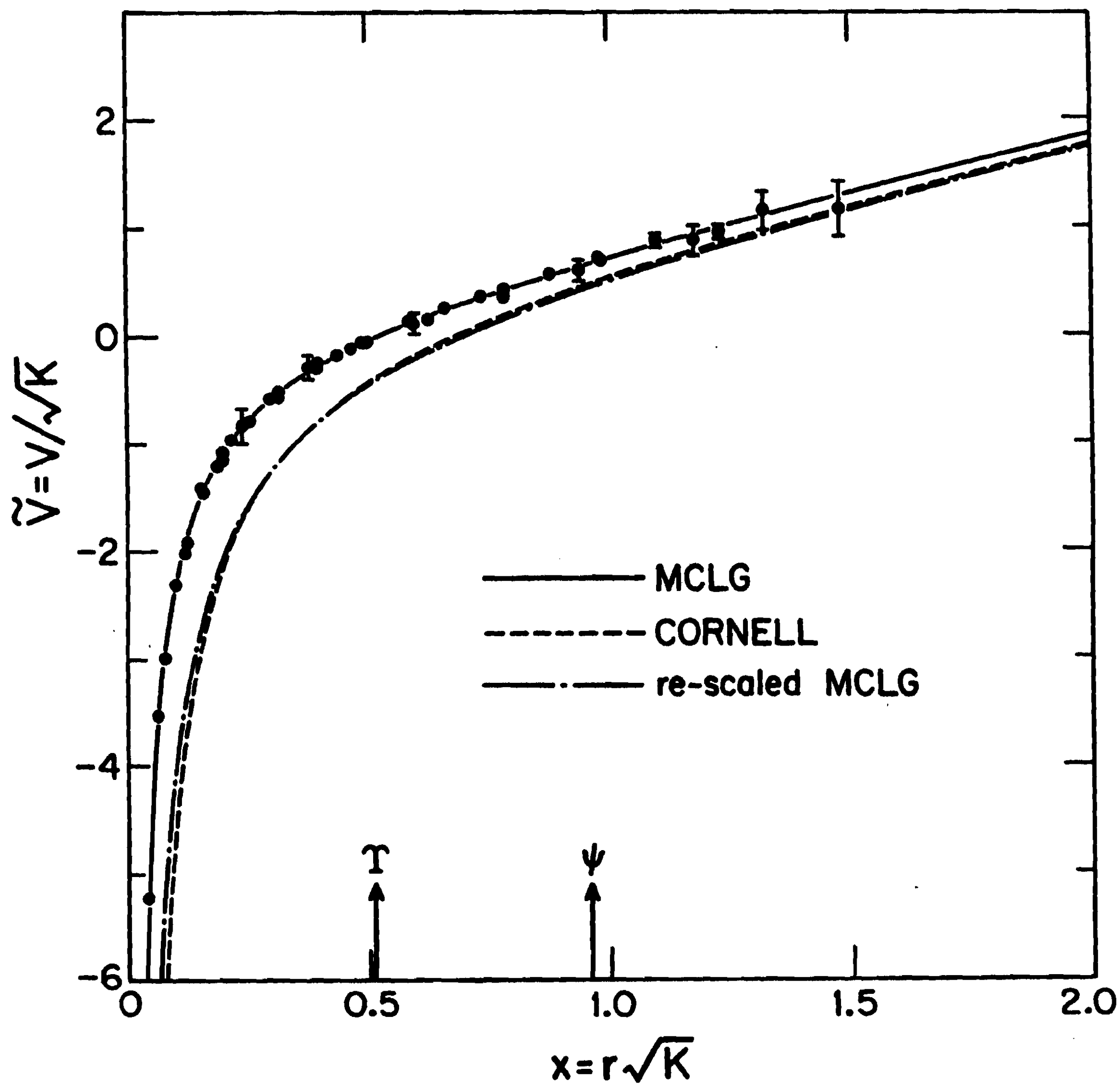

Fig. 2 Monte Carlo heavy quark potential. The string tension K is an arbitrary parameter in QCD so the result is presented in terms of a dimensionless potential plotted in terms of a dimensionless distance x.

qualitatively correct is not yet phenomenologically correct.[5] There is reason to believe though that quark vacuum polarization effects will improve agreement with experiment.[6]

The number of sharp onia states increases as the square root of quark mass. Strangonium just misses having a sharp $^3S_1$ state, charmonium has two sharp states and upsillonium has three. The existence of these states with OZI forbidden decays provides an interesting arena for testing the quark model and QCD predictions. The existence of $c\bar{c}$, $b\bar{b}$ and possibly $t\bar{t}$ spectroscopies governed by the same dynamics is a powerful tool to understand a wide range of strong interaction physics. Some schematic transitions and annihilations are shown in Fig. 3.

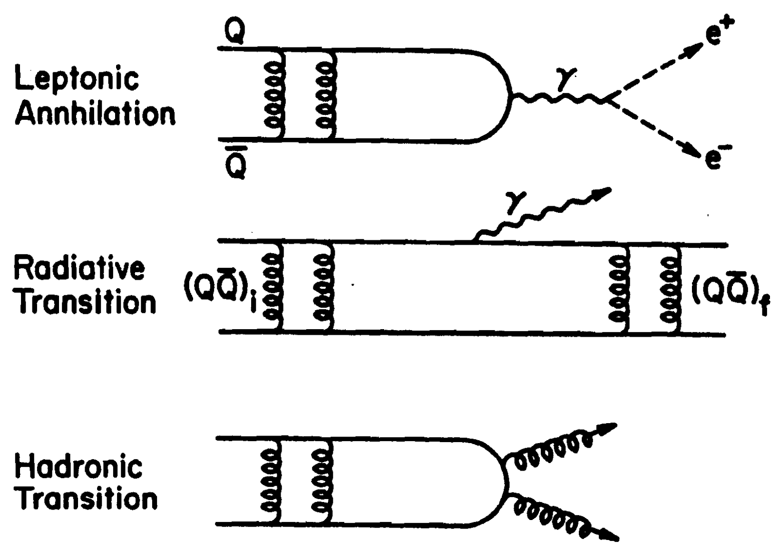

Fig. 3 Transitions in onia states which can be calculated once the wavefunctions of the states are known.

Why $p\bar{p}$ Production?

Almost all present data on heavy quark bound states comes from e^+e^- colliders. The advantage of this type of experiment is that the final states can be analyzed exhaustively. The disadvantage is that only $J^{PC} = 1^{--}$ states can be formed directly and that all other states must be reached by photon or other emission.

Direct production from antiproton–proton annihilation suffers from a large hadronic background that requires clear signatures for the decay products. The new aspect is that any $Q\bar{Q}$ state can be directly produced, making possible observation of predicted sharp states which have not yet been seen. A cooled $\bar{p}$ beam can provide a very well-defined $\bar{p}$ incident momentum, conceivably to a few tens of keV. This initial state resolution allows direct measurement of the total widths of the sharp states by sweeping through their formation cross sections. These measured widths can be compared to QCD predictions.

By direct formation of a sharp state the radiative decay angular correlations can also be more directly measured. As we will discuss these radiative decay multipoles probe details of the quark model not considered previously.

Finally, the annihilation process into an onia state has intrinsic interest. Exclusive QCD calculations,[7] although still in their infancy, show considerable promise. The calculations of exclusive formation of charmonia states[8] are in reasonable agreement with the recent R704 experiment[1] although crude approximation are made, such as neglecting the light quark constituent masses. A representative annihilation diagram is shown in Fig. 4. The gluons shown are hard and the soft gluon exchanges factorize into the various wavefunctions.

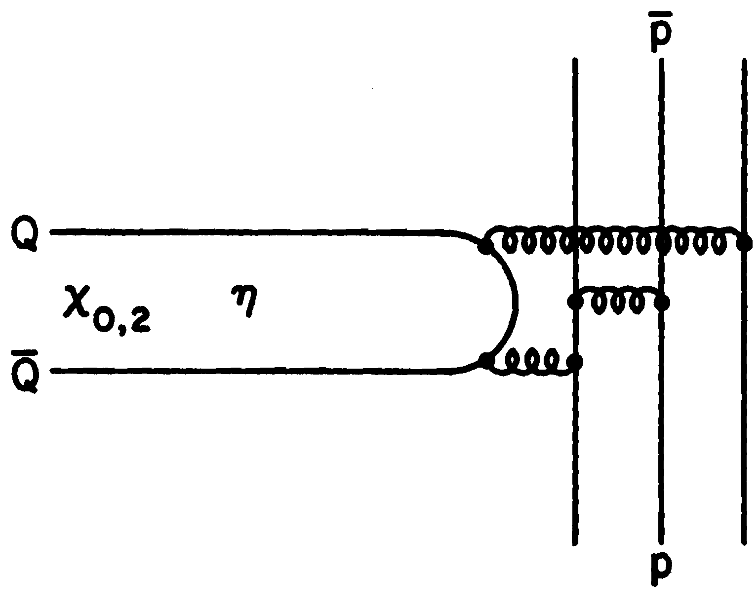

Fig. 4 Exclusive two gluonQCD diagram for $\bar{p}p \to Q\bar{Q}$ formation.

Two comments might be made on the present exclusive production calculations. First, the branching ratio decreases rapidly with the heavy quark mass

$$Br(p\bar{p} \to Q\bar{Q}) \sim m_Q^{-8}$$

and hence

$$\frac{Br\left[(p\bar{p} \to (b\bar{b})_{J^{PC}}\right]}{Br\left[(p\bar{p} \to (c\bar{c})_{J^{PC}}\right]} = \left(\frac{m_c}{m_b}\right)^8 \sim 10^{-4} \qquad (1)$$

Thus $b\bar{b}$ states are very rarely produced from $p\bar{p}$ annihilation compared to $c\bar{c}$ states of the same quantum numbers and so are even more difficult to extract from the background. These form factor effects are so far theoretical and would be interesting to check.

A second result of these exclusive QCD formation calculations[7] is that if the light quark masses are neglected compared to the momentum carried by the gluon such processes as $\bar{p}p \to \chi_0$, η_c or $^1P_1$ are not allowed while $\bar{p}p \to \chi_1$, χ_2 or ψ can take place. For charmonium the relevant momentum transfer is some fraction of m_c which can be camparable to the light quark constituent mass. In any case the observed branching ratios of η_c and ψ into $\bar{p}p$ are comparable indicating that c quarks are not massive enough for helicity selection rules to apply. We can conclude that all $c\bar{c}$ states should be accessible by $\bar{p}p$ formation.

Hadron Widths

We mentioned earlier the particular advantage presented by $\bar{p}p$ formation combined with a highly momentum selected beam. Total width measurements can be made for the η_c, η_c', χ_0 and χ_2 states with a momentum resolution of one part in 10^4 and with one part in 10^5 the very sharp state widths (ψ, ψ', ${}^1\mathrm{P}_1$ and others) can be measured. The hadronic width is then found by $\Gamma_{\mathrm{had}} = \Gamma_{\mathrm{tot}}[1-Br(\mathrm{radiative})]$ where the radiative branching ratio is either already known experimentally or can be adequately estimated from theory.

For the wider, two gluon decay, widths (see Fig. 3) the lowest order QCD predictions are[9]

$$\Gamma_{\eta}^{\mathrm{had}} = \frac{8\alpha_s^2}{3M^2}\,|R_s(0)|^2 \tag{2a}$$

$$\Gamma_{\chi_0}^{\mathrm{had}} = \frac{96\alpha_s^2}{M^4}\,|R_p'(0)|^2 \tag{2b}$$

$$\Gamma_{\chi_2}^{\mathrm{had}} = \frac{4}{15}\,\Gamma_{\chi_0}^{\mathrm{had}} \tag{2c}$$

where M is the state mass and $R_s(0)$ and $R_p'(0)$ are, respectively, the radial s-wave wave function and the derivative of the p-wave wavefunction at the origin.

At present there are few accurate measurements of hadronic decay widths which can be compared with the predictions of Eqs. (2). There are however some suggestive results mostly from e^+e^- experiments which for the most part are in agreement with predictions. From the photon energy spectrum from $\psi \rightarrow \eta_c \gamma$ the width[10] $\Gamma(\eta_c \rightarrow \text{all}) = 11.5 \pm 4.5$ MeV can be extracted. The theoretical[11] prediction from Eq. (2a) is in good agreement.

More indirectly, if the radiative branching ratio is measured and if we believe the theoretical radiative transition width the hadronic width can then be found. From e^+e^- formation of Υ' and Υ'' the χ_{2b} and χ'_{2b} hadronic widths are found[11] to be in good agreement with the predictions of Eq. (2c).

The hadronic width of the χ_{2c} is an interesting case since the width can be found either by the radiative branching ratio and the theoretical radiative rate, as mentioned in the preceding paragraph, or from the R704 $\bar{p}p$ formation experiment. Both give $\Gamma(\chi_2 \rightarrow \text{hadrons}) \simeq 2$ MeV. The theoretical prediction[11] from Eq. (2c) using the non-relativistic wavefunction is a much smaller value of about 0.5 MeV. Relativistic corrections[11] increase the prediction but retardation effects are crucial. It is important to more accurately measure such widths as a probe of relativistic quark dynamics.

Angular Distributions and Multipoles

It has proven difficult,[12] even with millions of events, to determine the radiative multipole decay structure of $c\bar{c}$ states formed from e^+e^- collisions. The reason is that a double radiative cascade is usually involved. For example, if we wish to study $\chi_2 \rightarrow \psi\gamma$ decay we always have to simultaneously analyze $\psi' \rightarrow \chi_2\gamma$. With direct $\bar{p}p$ produciton we can avoid this problem almost entirely. The only price we have to pay is that most $c\bar{c}$ states can be produced from helicity ± 1 or 0 whereas the e^+e^- state annihilates into a photon only with helicity ± 1.

The normalized joint angular distribution[13,14] for the process

$$\bar{p}p \rightarrow \chi_2 \rightarrow \psi\gamma \quad \llcorner\!\!\rightarrow e^+e^- \tag{3}$$

is a good example of how such an analysis proceeds. The production and decay angles are defined in Figure 5.

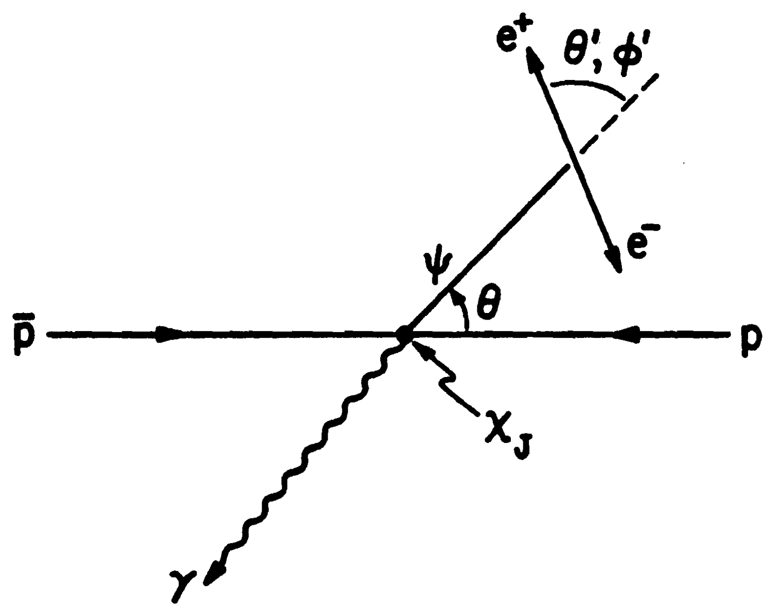

Fig. 5 Production angle θ and decay angles θ', ϕ for the process of Eq. (3).

This joint angular distribution involves eleven observables $\{K_i\}$ each of which is expressed in terms of not more than three real numbers:

$$\begin{aligned}\frac{64\pi^2}{15}\hat{W}(\theta,\theta',\phi') = K_1 &+ K_2\cos^2\theta + K_3\cos^4\theta \\ &+ (K_4 + K_5\cos^2\theta + K_6\cos^4\theta)\cos^2\theta' \\ &+ (K_7 + K_8\cos^2\theta + K_9\cos^4\theta)\sin^2\theta'\cos 2\phi' \\ &+ (K_{10} + K_{11}\cos^2\theta)\sin 2\theta\sin 2\theta'\cos\theta'\end{aligned} \tag{4}$$

The three parameters are the ratio of helicity zero to helicity one annihilation cross section, and the two multipole ratios a_2/a_1 and a_3/a_1 corresponding to the magnetic quadrupole and electric octupole transition amplitudes relative to the dominant electric dipole. Other radiative transitions[14] are likewise, although more simply in most cases, related to the angular distribution terms.

The multipoles for heavy quark radiative transitions are directly related to the constituent structure. For the above transition the magnetic quardrupole and electric octupole amplitudes (relative to the electric dipole) are

$$a_2 \simeq -0.11\ (1+\kappa); \qquad a_3 = 0 \tag{5}$$

where κ is the anomolous magnetic moment of the charm quark. Relativistic wavefunction corrections cancel and recoil and hadronic (open channel) corrections are expected to be small. The angular distributions are sensitive to the anomolous moment and therefore provide an interesting test of possible composite structure of heavy quarks.

Conclusions

Heavy quark bound state formation from antiprotons is proven technique since the original R704 experiment. A vigorous program of direct channel $\bar{p}p$ production of charmonia states will test our ideas of heavy quark dynamics in many new ways. Fundamental calculation of the production process, the total widths and the decay angular distribvutions will shed much light on such questions as exclusive QCD techniques, relativistic corrections, radiative QCD corrections, the nature of the confining interaction, new sharp states, flavor dependence, quark compositeness and the admixture of gluonic states.

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