ESTIMATING INCLUSIVE ψ AND $\psi\eta_c$ PRODUCTION IN e^+e^- ANNIHILATION

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The reaction $e^+e^- \to \psi + X$ provides (i) a test of perturbative QCD, and (ii) a way to study even C states (such as η_c, χ, Higgs) recoiling against the ψ. Estimates of the cross section using QCD, a simple non-perturbative model, and a calculation of the contribution from two-body final states, suggest small but not unmeasurable cross sections. If $m_{\eta_c} \approx m_\psi$, this may be a good way to find the η_c.

Introduction. At present there is little experimental evidence for even charge conjugation states in the ψ region [1] ‡1. Possible interesting states are η_c, η_c', the χ states, pseudoscalar or scalar Higgs bosons, glue ball states, $c\bar{c}q\bar{q}$ mesons. Some of these may be near the ψ in mass, and difficult to study in ψ and ψ' decays. Inclusive ψ production can provide a way to sort out this problem. Below we estimate rates for $e^+e^- \to \psi + X$, where X is a resonance or a multiparticle state ‡2. We find the rates may be large enough for experimental study.

The following points should be noted:

(i) Present detectors can be expected to have a missing mass resolution of order 60 MeV under optimum conditions, and detectors with higher magnetic fields could improve this by a factor of two or so. Even at higher energies 200 MeV resolution should be attainable. This should be satisfactory to observe several individual states in a ≈ 700 MeV range around the ψ.

(ii) Several η_c-like states could mix if they were close in mass. If this were so for, say η_c, a pseudoscalar Higgs, and a four-quark state $c\bar{c}q\bar{q}$, then as they all would have large $c\bar{c}$ components mixing would be likely. This mixing could have a dramatic effect on estimates of the mass of η_c, of $\eta_c \to \gamma\gamma$, and M1 radiative transitions. Only by learning which states are present, in an experiment such as the one under discussion, could one hope to calculate such quantities reliably.

(iii) Once an inclusive signal is observed, one can study the recoil states separately by mass, production angular distributions and energy dependence, and decay mode. The combination of these would allow one to identify each observed state.

A model for estimating $e^+e^- \to \psi + X$ is provided by perturbative quantum chromodynamics (QCD), which successfully describes the hadronic production of heavy vector mesons [3] such as ψ and Υ. Here the lowest order ($O(\alpha_s^2)$) mechanisms for the production of $Q\bar{Q}$ states are $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$ (q = u, d, s, Q = c, b, ... , g = gluon), and these provide a satisfactory description of the measured ψ and Υ cross

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‡1 Preliminary analysis of part of the new data from the Crystal Ball at Spear gives little support to previous evidence for the existence of η_c (private communication, Crystal Ball collaboration).

‡2 Iwasaki [2] has suggested looking for η_c with inclusive ψ production, but has not estimated rates.

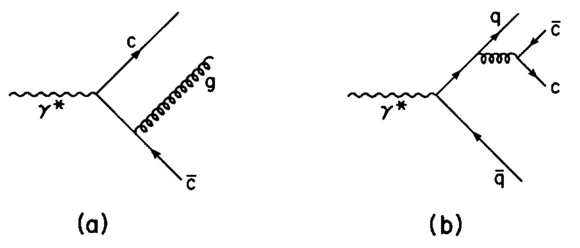

Fig. 1. QCD diagrams for $c\bar{c}$ production, (a) $O(\alpha_s)$, (b) $O(\alpha_s^2)$. Crossed diagrams are not shown.

sections, and constitute a qualitative test of QCD.

The inclusive production of ψ in e^+e^- annihilation is potentially a cleaner calculation, not clouded by the particularly uncertain gluon densities. Following a familiar route we calculate the QCD cross sections to $O(\alpha_s^2)$. The diagrams are shown in fig. 1a and 1b, respectively.

It is possible, however, that non-perturbative effects play a large role. To get some idea of how big they might be, we make a simple model, shown in fig. 2. A $c\bar{c}$ pair is produced by the virtual photon, and a ψ couples to one of the charmed quarks via a $\psi c\bar{c}$ vertex, which, for sake of argument, we take to be pointlike. It would be interesting if experimentally one can distinguish between mechanisms, especially in view of the relative sizes of the cross sections as explained later.

First we make the QCD estimates as we outlined earlier. Then, for comparison, we make an estimate of the cross section from specific two-body final states, such as $\psi\eta_c$, using couplings estimated from charmonium calculations. Last, we present our conclusions.

Estimates. The QCD calculation proceeds along familiar lines. From the $O(\alpha_s)$ and $O(\alpha_s^2)$ diagrams shown in fig. 1, we obtain the cross section $d\sigma^{c\bar{c}}/dM_{c\bar{c}}$ for $c\bar{c}$ production where $M_{c\bar{c}}$ is the invariant mass of the two quark state. To extract the ψ cross section, we integrate up to the naked charm threshold, i.e., $2m_c \lesssim M_{c\bar{c}} \lesssim 2m_D$ ($m_c \approx 1.5$ GeV has been chosen as the mass of the charmed quark as is usual in these calculations, m_D = 1.86 of the mass of the D meson), and divide by a factor f to account for the number of possible $c\bar{c}$ states in that mass range; $f \approx 4$–8 is probably reasonable. Embarrassing excess color is deemed to be removed by soft gluon emission, and disposed of by summing over it.

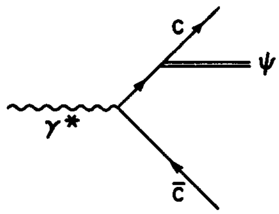

Fig. 2. Non-perturbative model.

The results of the $O(\alpha_s)$ and $O(\alpha_s^2)$ diagrams can be easily obtained from the calculations of ref. [4]. We will simply present cross sections integrated over all angles and momenta, and remark only that details of angular and momentum dependence are easily obtained also. Choosing $f = 7$, we show the resulting cross sections for $e^+e^- \to \psi + X$ as a function of center-of-mass energy in fig. 3a. The same quantities are plotted in units of the muon pair cross section (units of R) in fig. 3b. These calculations are seen to imply very small signals, provided we exclude the threshold singularity of the $O(\alpha_s)$ diagram. Indeed at threshold the $c\bar{c}$ can be produced at rest, recoiling against a gluon with zero 4-momentum, and the cross section diverges. Just how far above threshold we have to go before the answer is meaningful is a guess. If we demand that the gluon has energy greater than 1 GeV, then $\sqrt{s} \gtrsim 5$ GeV, which is not very restrictive.

We now turn to our simple non-perturbative model, shown in fig. 2, invoking a pointlike coupling $g_\psi \psi_\mu \bar{c}\gamma^\mu c$ and taking for definiteness $g_\psi^2/4\pi = 1/2$, which has been previously used for ψ production in hadronic collisions [5], and for charm photoproduction [6]. The resulting cross section and R are shown in figs. 3a and 3b. At high energies ($\sqrt{s} \gtrsim 15$ GeV) this non-perturbative estimate is quite large (a few tens of picobarns, and contributing $\Delta R \gtrsim 0.1$ and clearly dominates over the QCD estimates by approximately two orders of magnitude. This is an interesting result: if ψ production is measured at the levels suggested by this simple model, it is clear that low order perturbative QCD would have very little to say about the production mechanisms involved in e^+e^- annihilation, and we would have to reassess the use of perturbative QCD in calculating hadroproduction of heavy vector mesons and associated charm production in photoproduction and lepton reactions.

In principle totally different estimates could be ob-

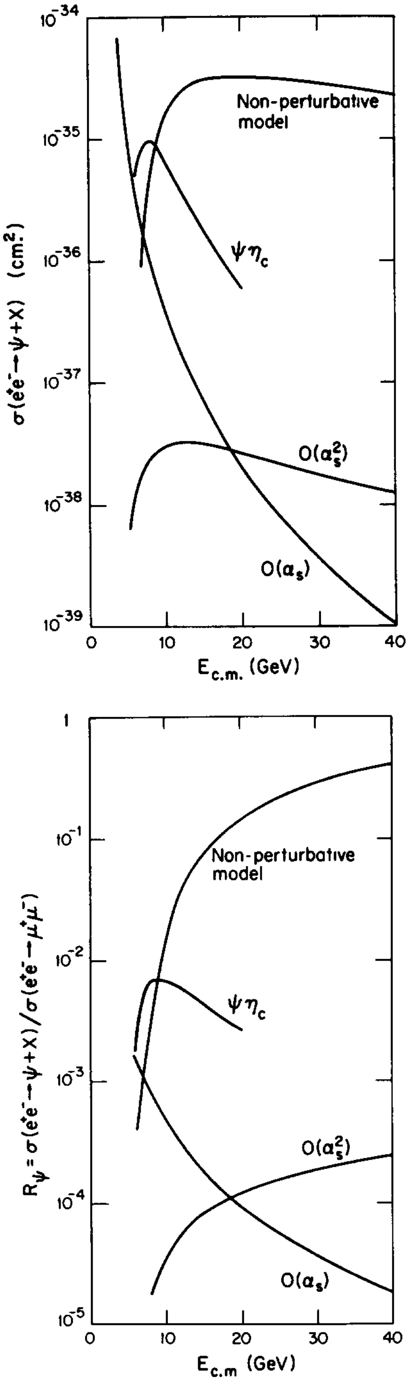

Fig. 3. (a) Estimates of $\sigma(e^+e^- \to \psi + X)$, (b) estimates of $R_\psi = \sigma(e^+e^- \to \psi + X)/\sigma(e^+e^- \to \mu^+\mu^-)$. To obtain the contribution from ψX final states, we multiply the $\psi\eta_c$ curve by about 5 (the number of X states).

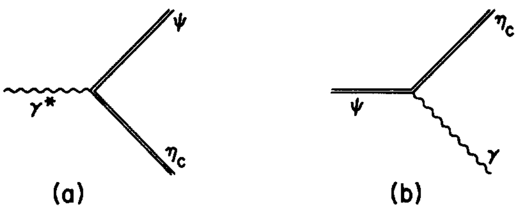

Fig. 4. (a) Diagram for virtual photon $\to \psi + \eta_c$, (b) $\psi \to \eta_c + \gamma$.

tained by considering two-body final states like $\psi\eta_c$ ... shown in fig. 4a. Such processes can be calculated with a simple model. To estimate the $\gamma^* \psi\eta_c$ coupling we proceed in two steps. Consideration of the decay $\psi \to \eta_c\gamma$ will supply the coupling of a photon to the appropriate $c\bar{c}$ system. However, in the crossed channel $\psi^* \to c\bar{c}c\bar{c}$ a heavy quark pair must be created from the vacuum, hence a suppression factor for heavy quark–antiquark production will be needed. Consider first the process shown in fig. 4b. We assume a coupling

$$V = g\epsilon^{\alpha\beta\mu\nu}\,\epsilon_\alpha^{\lambda'}(\psi)\epsilon_\beta^{\lambda}(\gamma)p_\mu(\psi)p_\nu(\gamma)$$

and calculate the width $\Gamma = g^2K_\gamma^3/12\pi$ where K is the γ momentum. A charmonium calculation [7] would give $\Gamma = 16\,K_\gamma^3/27m_c^2$. Comparison gives $g^2 = 192\pi\,\alpha/27m_c^2$, or $g^2 \approx 0.065\ \mathrm{GeV}^{-2}$ (whatever the mass of η_c). In the cross channel g^2 will have a form factor which we assume to be ψ-dominated $g^2 \to g^2m_\psi^4/(m_\psi^2 - Q^2)^2$ Using the above for $e^+e^- \to \psi\eta_c$ yields

$$(K_\psi^2 = (Q^2 - (m_\psi - m_{\eta_c})^2)(Q^2 - (m_\psi + m_{\eta_c})^2)/4Q^2):$$

$$\Delta R(\psi\eta_c) \approx \tfrac{1}{8}(g^2/e^2)Q^2(2K_\psi/\sqrt{Q^2})^3\ ,$$

which exhibits a broad peak around $\sqrt{s} = 7.5-10$ GeV and gives a cross section $\Delta R = 0.06$. To account for the suppression of heavy quark–antiquark production from the vacuum, we note that $\sigma(pp \to c\bar{c}X)/\sigma(pp\ \text{inelastic}) \approx 50\ \mu b/30\ mb \approx 1/600$. Since phase space suppression is expected to be much larger in the pp case ‡3, we estimate that the vacuum suppression in

‡3 For example, the events of Niu et al. [8] are probably charm production and correspond to a high energy cross section $\sigma(pp \to c\bar{c}X) \gtrsim$ mb, over 20 times the 50 μb estimated from beam dump experiments (see, for example, ref. [9]).Further, recently Drijard et al. [10] have reported a cross section of at least 150 μb for just D^+ inclusive production at $\sqrt{s} = 52.5$ GeV, presumably there is another factor of two for D_0 and additional χ states.

e^+e^- is ~1/50, leading to

$$\Delta R(\psi\eta_c) \approx 0.0012 \, .$$

See fig. 3a, b.

Assuming the same contribution from the other channels, η_c', χ_0, χ_1, χ_2, ... , we obtain for a total inclusive ψ production through inclusive channels,

$$\Delta R(\psi X) \gtrsim 0.006 \, .$$

We emphasize that this should be a lower bound as we have neglected multi-particle final states. It is interesting that the cross sections obtained from this estimate are similar to those found from the "non-perturbative" estimate; this might be expected from a duality argument. We note that in both cases the ψ is produced conjointly with $c\bar{c}$.

Assuming $\Delta R(\psi\eta_c) = 0.001$, and detection efficiency for ψ's of 10%, to find 10 $\psi\eta_c$ events, 100 $\psi\eta_c$ must be produced. This requires about 5×10^5 hadronic events. This is not an easy number to obtain, but it is not out of the question. Note that different beam energies could be combined if the energies and resolutions are sufficiently well known. Also, if we have been somewhat conservative in our estimates (a factor 4 or so), the predicted cross sections should be easily accessible.

Summary. We have provided estimates of four cross sections:

(1) $e^+e^- \to \psi + X$ with perturbative QCD. If perturbative estimates of heavy meson production or associated charm production are valid elsewhere, they should be even more valid here when gluon distributions in hadrons are not involved.

(2) $e^+e^- \to \psi + X$ with a possible non-perturbative contribution. This gives a much larger result than (1); if it is correct, other calculations in hadron and leptoproduction reactions must be modified.

(3) $e^+e^- \to \psi + \eta_c$ is expected to have a cross section which is small but may be large enough to find an η_c signal.

(4) $e^+e^- \to \psi + X^0$, where X^0 is any one of the large number of possible resonant states in the 2.8 GeV (or more) region, including η_c, η_c', $c\bar{c}q\bar{q}$ states, glue balls, scalar or pseudoscalar Higgs particles, χ states, and others. The difficulty of studying such states by other means may justify a large experimental effort to find them by inclusive ψ production.

The presence of an inclusive ψ signal will check our present understanding of QCD and perhaps provide us with a way to study otherwise inaccessible resonances. The absence of a signal at the expected levels would be a fairly serious problem.

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