THE STATUS OF CHARMONIUM PRODUCTION IN
PHOTON-PHOTON COLLISIONS

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In this talk I briefly review the status of Charmonium production in photon-photon
collisions. I would like to mention that although the preliminary data were obtained
in experiment, theoretical calculation is not in a compatible status, that is the
result of dominant contributing process is still not available.

1 A Brief Overview of Onium Production Theory and Models

Quarkonium is a bound state of heavy quark and its antiquark mediated by the
strong interaction (QCD). The quarkonia can be classified and labeled in the
conventional spectroscopic way \( n^{2S+1}L_J(J^{PC}) \), where \( n \) is the radial quantum
number; \( P \) is the parity and \( C \) is the charge conjugation; \( S, L, \) and \( J \) are
total intrinsic spin, orbital angular momentum, and total angular momentum,
respectively.

Since the discovery of \( J/\psi \) in 1974, quarkonium physics has become one
of the most fruitful areas in high energy physics. With the development of
experiment in the past two decades a great advance has been made in under-
standing of the nature of quarkonium production and decays. At the time
being, the wisdoms on quarkonium production and decays can be categorized
as following theory and models:

• Color-Singlet Model

In color-singlet model, quarkonia are interpreted as non-relativistic bound
states of \( Q \bar{Q} \) pair. It assumes that the heavy quark pair produced in high en-
ergy collision can bind to form a given quarkonium state if the \( Q \bar{Q} \) is created
with exactly the same quantum numbers possessed by the bound state. And,
the quarkonium production and decay amplitudes are supposed to be factor-
ized into short- and long-distance sectors. The former can be calculated by
using perturbative QCD; the latter, referring to non-perturbative effect, can
be absorbed into a wave function factor; i.e.,

\[
d\sigma(\psi + x) = d\sigma(c\bar{c}(3S_1) + x)|R_\psi(0)|^2.
\]

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The wave function can be either determined phenomenologically from experimental measurements of quarkonium leptonic decays or calculated from bound state potential model.

• **Color Evaporation Model**

An alternative prescription for quarkonium production is the so-called color-evaporation (duality) model. In this approach, the probability of a $Q\bar{Q}$ pair with invariant mass between $2m_c$ and $D\bar{D}$ threshold $2m_D$ (in case of Charmonium) evolving into a quarkonium state will be taken nearly independent of its color and spin states. e.g., for $J/\psi$ production, the cross section can be written as

$$\sigma(J/\psi) = \hat{\sigma}(c\bar{c}(4m_c^2 < s < 4m_D^2))f_{J/\psi},$$

where $\hat{\sigma}$ is the cross section for producing a $c\bar{c}$ pair with invariant mass below $D\bar{D}$ threshold, $f_{J/\psi}$ is a phenomenological parameter. The cross section $\hat{\sigma}(c\bar{c})$ is spin-summed and can be in both color-singlet and -octet configurations. This model has the flaw of incapable of describing the variation of production ratios for different states, though with some phenomenological success.

• **NRQCD Factorization Theory**

Non-relativistic QCD (NRQCD) provides a rigorous QCD analysis of the production and decays of heavy quarkonium, which enables one to make perturbative corrections to all orders in $\alpha_s$, and relativistic corrections as well. The key point of this novel theory is that the inventors noticed that in quarkonium production and decays several typical energy scales are well-separated,

$$(M_Qv^2)^2 \ll (M_Qv)^2 \ll M_Q^2.$$ 

With this hierarchy, the NRQCD effective Lagrangian can be expressed as

$$\mathcal{L}_{\text{NRQCD}} = \mathcal{L}_{\text{light}} + \mathcal{L}_{\text{heavy}} + \delta\mathcal{L},$$

where $\mathcal{L}_{\text{light}} + \mathcal{L}_{\text{heavy}}$ describes ordinary QCD coupled to a Schrödinger field theory for the heavy quarks and antiquarks. The relativistic effects of full QCD are reproduced through the correction term $\delta\mathcal{L}$ in the Lagrangian.

In NRQCD formalism, the inclusive production cross-section of heavy quarkonium is argued taking a factorized form

$$d\sigma(H + X) = \sum d\hat{\sigma}(c\bar{c} + X) < \mathcal{O}_H >.$$ 

Here, $d\hat{\sigma}(c\bar{c} + X)$ is the hard part calculable using perturbative QCD, $< \mathcal{O}_H >$ is the non-perturbative sector which can be expressed as vacuum matrix elements of NRQCD four quark operators. In the NRQCD Lagrangian, four-fermion operators can couple to both color-neutral states and colored states,
which makes the NRQCD distinctively different from the color-singlet hypothesis in describing the quarkonium production mechanism, i.e., the Octet mechanism may play a role in quarkonium production as well.

2 Quarkonium Production in Photon-Photon Collisions

The NRQCD has a list of merits in describing heavy quarkonium production and decays, especially in properly regulating the singularities appeared in color-singlet model and explaining the Tevatron large-$p_T \psi'$ surplus problem based on the color-octet model. However, it is not the end of story. There still lacks of direct evidence for the octet scenario at currently running colliders. Not to mention the large-$p_T \psi'$ polarization “disaster” it encounters recently. The point is that in principle NRQCD should be a correct theory in heavy quark limit, but in practice whether it can be applied to the Charmonium system is not clear.

People believe that non-hadronic collisions may give more clear signals and predictions by experiment and theory respectively than hadronic ones, and think that the study of quarkonium production at linear colliders may be helpful in clarifying the Onium production mechanism. In recent years several new concepts on linear colliders aimed at providing collisions at the center-of-mass energy from hundreds GeV to multi-TeV with high luminosity were proposed and the feasibilities pretested, such as JLC at KEK, TESLA at DESY and CLIC at CERN, etc. Theoretically, high-intensity photon beams may be obtained by the Compton backscattering of laser light off the linac electron beams, and photon-photon collision with approximately the same luminosity as that of the $e^+ e^-$ beams. Such a photon linear collider can have high energy up to TeV order. During the past more than twenty years researches on quarkonium production at $e^+ e^-$ colliders at various energies were carried out in detail. However, studies of photon-photon scattering are very limited and have just begun (here, we focus on the direct photon-photon collision, for the resolved case see, e.g., ref. 6), though the preliminary results were obtained from LEP II data.

In $\gamma\gamma$ scattering, at leading order in $\alpha$ the $J/\psi$ is produced via the process

$$\gamma + \gamma \rightarrow J/\psi + \gamma.$$  (1)

However, since on the scale of heavy quark mass, the strong coupling constant is not too small, the process

$$\gamma + \gamma \rightarrow J/\psi^{(8)} + g$$  (2)
may compete with the pure electromagnetic process (1) through the Color-Octet mechanism. Here, $J/\psi^{(8)}$ denotes those states evolved from the Color-Octet states.

When going up one order in $\alpha_s$, one may still expect to obtain the same order of magnitude in the $J/\psi$ production rate, because in this case $J/\psi$ may be produced in color-singlet and therefore will compensate for $\alpha_s$ suppression from the non-perturbative sector relative to the octet process (2). This argument was confirmed recently by the calculation of double quarkonium, the $J/\psi$, production in direct photon-photon collision, which is a sub-category of the inclusive $J/\psi$ production process at order $\alpha^2s^2$. That is the process

$$\gamma(k_1) + \gamma(k_2) \rightarrow J/\psi(P) + J/\psi(P') \ .$$

(3)

Figure 1: Energy dependence of the cross-sections. DJ: the double $J/\psi$ process (3); CS: the color-singlet process (1); CO: the color-octet process (2).

The results for processes (1) – (3) are shown in Figure 1. Since projected linear colliders with a luminosity of hundreds of fb$^{-1}$ per year, and the integrated total cross-sections increase with the colliding energy decreasing, we may have hundreds of events being observed in one year at colliding energies 500 GeV or less. It is obvious that the color-octet process is the smallest one over the entire energy scope of LEP II to next generation of linear colliders in the three processes being concerned, though they are in the same order.

In addition it was proved in Ref. 8 that the cross-section for single $J/\psi$ production via only the fragmentation mechanism would be about one order larger than that of processes (1) – (3) at 500 GeV. That means that the process at order $\alpha^2s^2$ for single $J/\psi$ inclusive production should be the dominant one in the photon-photon collision, which unfortunately is still not studied in theory.
3 Concluding Remarks

We have given a brief review of the previously investigated works appeared in literature on $J/\psi$ production at photon colliders. It is found that at a moderate energy of next generation photon colliders, there could be hundreds of events to be detected per year with high projected luminosity. Since the production rates of $J/\psi$ via the color-octet mechanism, the electromagnetic process, and the double production are almost the same in the full scope of the colliding energy, to differentiate the color-octet mechanism from the color-singlet one in these processes, experimentally one should detect not only the $J/\psi$ but also other final states. Furthermore, without distinguishing the final states in experiment we can not make any conclusion on $J/\psi$ production mechanisms from photon-photon collision, since the dominant production process, the inclusive one at order $\alpha^2\alpha_s^2$, is left un-investigated in theory.

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