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Polarization of Charmonium in πN Collisions

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Abstract. Measurements of the polarization of J/ψ produced in pion-nucleus collisions are in disagreement with leading twist QCD prediction where J/ψ is observed to have negligible polarization whereas theory predicts substantial polarization. We argue that this discrepancy cannot be due to poorly known structure functions nor the relative production rates of J/ψ and χ_J. The disagreement between theory and experiment suggests important higher twist corrections, as has earlier been surmised from the anomalous non-factorized nuclear A-dependence of the J/ψ cross section.

INTRODUCTION

One of the most sensitive tests of the QCD mechanisms for the production of heavy quarkonium is the polarization of the J/ψ in hadron collisions. In fact, there are serious disagreements between leading twist QCD prediction [2] and experimental data [3] on the production cross section of 'direct' J/ψ and χ_1. We would like to advocate that polarization of J/ψ provides strong constraints on the production mechanisms of J/ψ and thus can pinpoint the origin of these disagreements.

In this paper we will present results on the theoretical calculation of the polarization of J/ψ in πN collisions. The detailed analysis will be published in a later paper[1]. We found that the polarization of J/ψ provides important constraints on the nature of the production mechanisms and urge that polarization measurement of J/ψ should be included in the design of future charm production experiment.

PRODUCTION RATES OF ψ AND χ_J STATES

In leading twist QCD, the production of the J/ψ at low transverse momentum occurs both 'directly' from the gluon fusion subprocess $gg \to J/\psi + g$ and indirectly via the production and decay of χ_1 and χ_2 states. These states have sizable decay branching fractions $\chi_{1,2} \to J/\psi + \gamma$ of 27% and 13%, respectively.

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In this model, we assume that the non-perturbative physics, which is described by the wave function at the origin in cases of production of J/ψ and ψ', is separable from the perturbative hard subprocess, *i.e.*, factorization holds. As the wave function at the origin can be related to the leptonic decay amplitude, the ratio of ψ' to direct J/ψ production can be expressed in terms of the ratio of their leptonic decay width. More precisely, taking into account of the phase space factor,

$$\frac{\sigma(\psi')}{\sigma_{dir}(J/\psi)} \simeq \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \frac{M^3_{J/\psi}}{M^3_{\psi'}} \simeq 0.24 \pm 0.03 \tag{1}$$

where $\sigma_{dir}(J/\psi)$ is the cross section for direct production of the J/ψ. The ratio (1) should hold for all beams and targets, independently of the size of the higher twist corrections in producing the point-like $c\bar{c}$ state. The energy should be large enough for the bound state to form outside the target. The available data is indeed compatible with (1). In particular, the E705 values [4] with different projectiles are all consistent with 0.24.

The anomalous nuclear target A-dependence observed for the J/ψ is also seen for the ψ' [9], so that the ratio (1) is indeed independent of A. Therefore, at high energies, the quarkonium bound state forms long after the production of the $c\bar{c}$ pair and the formation process is well described by the non-relativistic wavefunction at the origin.

In leading twist and to leading order in α_s, J/ψ production can be computed from the convolution of hard subprocess cross section $gg \to J/\psi g$, $gg \to \chi_j$, *etc.*, with the parton distribution functions in the beam and target. Higher order corrections in α_s, and relativistic corrections to the charmonium bound states, are unlikely to change our qualitative conclusions at moderate x_F. Contributions from direct J/ψ production, as well as from indirect production via χ_1 and χ_2 decays, will be included. Due to the small branching fraction $\chi_0 \to J/\psi + \gamma$ of 0.7%, the contribution from χ_0 to J/ψ production is expected (and observed) to be negligible. Decays from the radially excited 2^3S_1 state, $\psi' \to J/\psi + X$, contribute to the total J/ψ rate at the few per cent level and will be ignored here.

In Table 1 we compare the χ_2 production cross section, and the relative rates of direct J/ψ and χ_1 production, with the data of E705 and WA11 on $\pi^- N$ collisions at $E_{lab} = 300$ GeV and 185 GeV [4]. The χ_2 production rate in QCD agrees with the data within a 'K-factor' of order 2 to 3. This is within the theoretical uncertainties arising from the J/ψ and χ wavefunctions, higher order corrections, structure functions, and the renormalization scale. A similar factor is found between the lowest-order QCD calculation and the data on lepton pair production [10] On the other hand, Table 1 shows a considerable discrepancy between the calculated and measured relative production rates of direct J/ψ and χ_1, compared to χ_2 production. A *priori* we would expect the K-factors to be roughly similar for all three processes. We conclude that leading twist QCD appears to be in conflict with the data on direct J/ψ and χ_1 production. Although in Table 1 we have only compared our calculation with the

	$\sigma(\chi_2)$ [nb]	$\sigma_{dir}(J/\psi)/\sigma(\chi_2)$	$\sigma(\chi_1)/\sigma(\chi_2)$
Experiment	$188 \pm 30 \pm 21$	$0.54 \pm 0.11 \pm 0.10$	$0.70 \pm 0.15 \pm 0.12$
Theory	72	0.19	0.069

Table 1: Production cross sections for χ_1, χ_2 and directly produced J/ψ in $\pi^- N$ collisions. The data from Ref. [4, 5] include measurements at 185 and 300 GeV. The theoretical calculation is at 300 GeV.

E705 and WA11 $\pi^- N$ data, this comparison is representative of the overall situation (for a recent comprehensive review see [6]).

POLARIZATION OF THE J/ψ

The polarization of the J/ψ is determined by the angular distribution of its decay muons in the J/ψ rest frame. The angular distribution of massless muons, integrated over the azimuthal angle, has the form

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \lambda \cos^2\theta \tag{2}$$

where we take θ to be the angle between the μ^+ and the projectile direction (*i.e.*, we use the Gottfried–Jackson frame). The parameter λ can be calculated from the $c\bar{c}$ production amplitude and the electric dipole approximation of radiative χ decays.

In Fig. 1a we show the predicted value (solid curve) of the parameter λ of Eq. (2) in the GJ-frame as a function of x_F, separately for the direct J/ψ and the $\chi_{1,2} \to J/\psi + \gamma$ processes. Direct J/ψ production gives $\lambda \simeq 0.25$, whereas the production via χ_1 and χ_2 result in $\lambda \simeq -0.15$ and 1 respectively. Smearing of the beam parton's transverse momentum distribution by a Gaussian function $\exp[-(k_\perp/500 \text{ MeV})^2]$ (dashed curve) has no significant effect in λ except for the production via χ_2 which brings λ down to $\lambda \simeq 0.85$. The $\lambda(x_F)$-distribution obtained when both the direct and indirect J/ψ production processes are taken into account is shown in Fig. 1b and is compared with the Chicago–Iowa–Princeton [7] and E537 data [8] for 252 GeV πW collisions and 150 GeV $\pi^- W$ collisions respectively. Our QCD calculation gives $\lambda \simeq 0.5$ for $x_F \lesssim 0.6$, significantly different from the measured value $\lambda \simeq 0$.

The discrepancies between the calculated and measured values of λ is one further indication that the standard leading twist processes considered here are not adequate for explaining charmonium production. The J/ψ polarization is particularly sensitive to the production mechanisms and allows us to make further conclusions on the origin of the disagreements, including the above discrepancies in the relative production cross sections of J/ψ, χ_1 and χ_2. If these discrepancies arise from an incorrect relative normalization of the various subprocess contributions (*e.g.*, due to higher

Figure 1: CIP(•) and E537 (◦) data compared with theoretical prediction.

order effects), then we would expect the J/ψ polarization to agree with data when the relative rates of the subprocesses are adjusted according to the measured cross sections of direct J/ψ, χ_1 and χ_2 production The lower curve in Fig. 1b shows the effect of multiplying the partial J/ψ cross sections with the required K-factors. The smearing effect is insignificant as shown by the dashed curve. The λ parameter is still predicted incorrectly over most of the x_F range.

A similar conclusion is reached (within somewhat larger experimental errors) if we compare our calculated value for the polarization of direct J/ψ production, shown in Fig. 1a, with the measured value of λ for ψ' production. In analogy to Eq. (1), the ψ' polarization data should agree with the polarization of directly produced J/ψ's, regardless of the production mechanism. Based on the angular distribution of the muons from $\psi' \rightarrow \mu^+\mu^-$ decays in 253 GeV $\pi^- W$ collisions, Ref. [11] quotes $\lambda_{\psi'} = 0.02 \pm 0.14$ for $x_F > 0.25$, appreciably smaller than our QCD values for direct J/ψ's in Fig. 1a.

DISCUSSION

We have seen that the J/ψ and χ_1 hadroproduction cross sections in leading twist QCD are at considerable variance with the data, whereas the χ_2 cross section agrees with measurements within a reasonable K-factor of 2 to 3. On the other hand, the relative rate of ψ' and direct J/ψ production (Eq. 1), which at high energies should be independent of the production mechanism, is in agreement with experiment. It is therefore improbable that the treatment of the $c\bar{c}$ binding should require large corrections.

In a leading twist description, an incorrect normalization of the charmonium production cross sections can arise from large higher order corrections or uncertainties in the parton distributions[6]. Taking into account that the normalization may be wrong by as much as a factor of 10 and that even such a $K-$factor does not explain the polarization data of J/ψ, a more likely explanation may be that there are important higher-twist contributions to the production of the J/ψ and χ_1 as suggested in large x_F case [12, 13].

Further theoretical work is needed to establish that the data on direct J/ψ and χ_1 production indeed can be described from higher twist mechanisms. Experimentally, it is important to check whether the J/ψ's produced indirectly via χ_2 decay are transversely polarized. This would show that χ_2 production is dominantly leading twist, as we have argued. Thus, the polarization of J/ψ production from different channels provides a very sensitive discriminant of different production mechanisms.

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