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Charmonium Hadro-Production
at HERA-B.

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1 Introduction

The charmonium system and its production in hadronic collisions has recently attracted considerable attention from both theoretical and experimental sides due to two different problems, namely, understanding of the production mechanism and the influence of the nucleus on production rates.

The production mechanism includes the creation of a $c\bar{c}$ pair in the interaction of gluons and/or quarks and the formation of a charmonium state from an unbound pair. The first step is calculated in pQCD. However the process of formation of the bound state is not understood. Three different models compete to describe production of heavy quarkonium: the Color Singlet Model (*CSM*)[1], non relativistic QCD (*NRQCD*)[2] and the Color Evaporation Model (*CEM*)[3]. To distinguish between the models new measurements are required, such as the production rates of all charmonium states below $D\bar{D}$ threshold as a function of transverse momentum p_T , the Feynman variable x_F ¹, and the polarization.

The production rate is also influenced by the presence of the nucleus. The (anti)nuclear shadowing[4], energy loss[5], or an intrinsic charm component[6] affect initial parton density distributions. Those effects influence also other processes, e.g. Drell-Yan production. The absorption of the produced $c\bar{c}$ by the nucleus[7], comovers[8], or energy loss by the $c\bar{c}$ pair[9] have been claimed to be responsible for the observed charmonium suppression.

It has been suggested that the change in the production rate of charmonium due to the presence of the nucleus factorizes with the production mechanism and can be expressed by the function

$$\sigma_{pA} = \sigma_{pN} \cdot A^\alpha, \quad (1)$$

where σ_{pN} is the production cross section of a given state in proton-nucleon interactions and A is the atomic mass of the nucleus. The parameter α represents the combination of different nuclear effects. To distinguish between models one could study the dependence of α on x_F [10]. As was shown in [11] the χ_c states are more sensitive to nuclear effects than J/ψ or ψ' .

Measurements of the hadro-production of different charmonium states are available only for J/ψ and ψ' and only in the positive x_F region. Measurements of the fraction of J/ψ produced via χ_c states are very limited. No measurement of the nuclear dependence of χ_c production is available.

¹ x_F is the longitudinal momentum fraction $x_F = p_z/p_z^{\max}$ in the c.m. system.

2 Detector

HERA-B is a fixed target experiment located at the HERA proton storage ring at DESY (Hamburg). The energy of the proton beam is 920 GeV which gives the energy in the c.m. frame $\sqrt{s} = 41.6$ GeV. The target consists of 8 wires of different materials, namely C, Al, Ti, W. During operation, the wires are inserted into the halo of the beam. Good resolution of reconstructed vertices allows for separation of the primary interactions between the different wires. The interaction rate varies in the range 5-20 MHz. At 5 MHz interaction rate one event contains in average 0.5 primary interactions distributed according to Poissonian statistics.

Figure 1: The HERA-B detector.

The detector scheme is presented in Fig.1. The tracker consists of 3 parts : a silicon vertex detector, micro strip gas chambers (the inner tracker) and honeycomb drift chambers (the outer tracker). The 2.2 Tm magnet is positioned in the middle of the spectrometer and gives a 0.64 GeV/c transverse momentum kick to the charged particles. Particle identification devices include a ring imaging Cherenkov counter (RICH), an electromagnetic calorimeter and a muon system. A detailed description of the detector can be found elsewhere[12].

The detector covers a large pseudo-rapidity interval $\eta \in [2, 5]$, corresponding to the $x_F^{J/\psi}$ interval $[-0.4, 0.3]$. During the year 2000 run the inner part of the tracker was not in use and therefore the coverage of detector was restricted to $x_F^{J/\psi} \in [-0.4, 0.1]$.

The detector allows complete event reconstruction including the neutral particles γ and π^0 . Therefore, HERA-B can search for excited charmonium states such as $\chi_{c0}, \eta'_{c0} \rightarrow J/\psi + \gamma$, $\psi' \rightarrow J/\psi + \pi\pi$, $h_c(1P_1) \rightarrow J/\psi + \pi^0$.

The cross section for J/ψ production is small compare to the inelastic cross section $\sigma_{J/\psi}/\sigma_{in} = 3 \cdot 10^{-5}$. HERA-B uses a J/ψ oriented trigger which selects lepton pairs e^+e^- , $\mu^+\mu^-$ with a high invariant mass. Tracks with hits in at least three muon superlayers are

classified as muon tracks. The transverse momentum of muons is required to be greater than 0.7 GeV/c. For the electron trigger the transverse energy deposited in the calorimeter by each candidate is required to be greater than 1 GeV/c. HERA-B also makes use of triggers of other kinds (e.g. hard photon or single lepton triggers) which are not discussed in this article.

3 Analysis

The year 2000 data were collected in parallel with commissioning of the detector. Only the carbon and titanium wires were used. The collected sample consists of about $16 \cdot 10^6$ events with varying trigger conditions. Among them we have reconstructed approximately 4000 $J/\psi \rightarrow \mu^+\mu^-$ decays and $10^5 J/\psi \rightarrow e^+e^-$. The detailed analysis of the events included a precise calculation of track parameters, a common vertex constraint, and particle identification. The muon identification included data from the muon system, RICH, and tracker. Electron identification was based on the calorimeter and tracker information. To reduce background from hadrons, the presence of a bremsstrahlung cluster in the direction of the track in front of the magnet was required for at least one of the 2 electron candidates.

The invariant mass distribution is shown in Fig.2. The main background contribution is due to random combinations of hadrons misidentified as muons or electrons. The Drell-Yan contribution is estimated to be at the level of a few percent. The fraction of charm or beauty decays with 2 muons or electrons in the final state is negligible. The mass resolution $\sigma(M_{\mu\mu}) \approx 50 \text{ MeV}/c^2$, $\sigma(M_{ee}) \approx 130 \text{ MeV}/c^2$ agrees with the expectation based on full detector simulation. The larger width of the mass in the electron channel is explained by significant loss of energy in the magnet area which was not recovered.

Figure 2: Invariant mass distribution a) e^+e^- , b) $\mu^+\mu^-$.

4 Preliminary Results

The total cross section of J/ψ production in $p-C$ interactions was measured with a sub-sample of the $J/\psi \rightarrow e^+e^-$ candidates. The obtained value is $\sigma(J/\psi)_{tot} = 403 \pm 52 \pm 103$ nb/nucleon where we assumed nuclear dependence according to equation 1 with $\alpha = 0.94$. A comparison of the HERA-B result with the measurements of other experiments is shown in Fig.3. As the data were taken in parallel to detector and trigger commissioning, the data taking conditions were relatively unstable which results in a large systematic uncertainty. The results are in agreement with measurements of experiments E771[13] and E789[14], which ran at a similar c.m. energy. The prediction of NRQCD tuned at other energies is higher than the HERA-B measurement but it is closer to the data than the CSM prediction.

Figure 3: Measured total cross section of J/ψ as a function of the c.m.s energy.

The muon channel data was used to measure the p_T, x_F spectra of J/ψ (see Fig.4). The data were fit with functions used by E789:

$$\frac{dN}{dp_T^2} = A(1 + (\frac{p_T}{P_0})^2)^{-6} \quad (2)$$

$$\frac{dN}{dx_F} = B(1 - |x_F|)^C \quad (3)$$

The shapes of the distributions are determined by parameters P_0 and C . The average transverse momentum $\langle p_T \rangle$ is of interest to study $\langle p_T \rangle$ broadening as a function of nucleus and $\sqrt{s}$ [17]. Using equation 2 it is determined as $\langle p_T \rangle = 35\pi P_0/256$. The HERA-B results are summarized in Table 1.

Figure 4: Number of J/ψ observed as a function of p_T, x_F for C and Ti data. The results of E789[14] and E866[15] are normalized to the total number of J/ψ observed by HERA-B.

Interaction	P_0	$\langle p_T \rangle$	C
p-C	2.71 ± 0.06	1.16 ± 0.03	6.24 ± 0.48
p-Ti	2.90 ± 0.09	1.25 ± 0.04	6.31 ± 0.60

Table 1: Parameters of the p_T and x_F distributions of J/ψ . (Only the statistical errors are shown.)

The nuclear dependence of J/ψ hadro-production can be extracted from the comparison of J/ψ rates for $p - C$ and $p - Ti$ collisions. Using formula 1 we estimated the parameter α to be $1.027 \pm 0.043 \pm 0.02$ where the first error is statistical and the second one is systematic. The value corresponds to the kinematic range of J/ψ shown in Fig.4. The result is in good agreement with more precise measurements of other experiments [15],[16] estimated for positive x_F region.

Fig.5 shows the χ_c signal reconstructed in the $J/\psi + \gamma$ channel for J/ψ candidates within a J/ψ invariant mass window of 2 standard deviations. The data corresponds to interactions on the carbon wire. The photons from χ_c are reconstructed in the calorimeter with an efficiency (ϵ_γ) of 22%. The signal is seen both in electron and muon samples. The shifts of the mass signals from χ_c are explained by the high occupancy of low energy clusters in the calorimeter, which increases the energy of the photon from χ_c but hardly affects energetic leptons from J/ψ . The random combinations of J/ψ and photons from different events describe the background under χ_c very well. Analysis of J/ψ sidebands does not reveal any excess in the χ_c mass region. The estimated fraction of J/ψ produced via χ_{c1} and χ_{c2} is 0.42 ± 0.12 where the major uncertainty is determined by the statistical error. A comparison of the HERA-B result with other experiments and theoretical predictions is shown in Fig.6.

Figure 5: Difference of the invariant mass of $(l^+l^-\gamma)$ and the mass of (l^+l^-) where l is electron or muon. The hatched histogram shows the invariant mass of J/ψ candidates and photons from the different events.

Figure 6: Comparison of the HERA-B results with theoretical predictions and the results of other experiments. The value of E771 is deduced from the published cross sections of $\sigma(J/\psi)_{tot}$, $\sigma(\chi_{c1})$, $\sigma(\chi_{c2})$. The references could be found at [18].

5 Outlook

During the year 2002 we aim to collect about 10^6 J/ψ in both channels. Running conditions will be more stable than in the year 2000, therefore, the systematic error in estimation of the total cross section or in the ratio of J/ψ for different wires will be significantly reduced. The statistics collected will be enough to provide a measurement of the nuclear dependence of charmonium hadro-production as a function of p_T and x_F . It will be a first measurement in the negative x_F region while the positive x_F region can be used for comparison with E866 results.

The fraction of J/ψ produced via χ_c channels is an important observable to distinguish between different models of J/ψ hadro-production and nuclear suppression. We expect to reconstruct of the order of 10^5 χ_c events which will be by far the largest sample of recorded χ_c produced in proton-nucleus interactions.

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