CHARMONIUM PRODUCTION IN FERMILAB E789

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Abstract

Using a sample of greater than \(10^5 \ J/\psi \rightarrow \mu^+ \mu^-\) decays, Fermilab experiment 789 has studied production of \(J/\psi\) and \(\psi'\) in 800 GeV proton-nucleon collisions. Differential cross sections and nuclear dependences have been measured for charmonium as well as for charm and beauty production. While charm and beauty production are consistent with perturbative QCD calculations, charmonium cross sections exceed the predictions of the color-singlet model by large factors, suggesting that additional mechanisms such as color-octet production may play important roles. Nuclear dependences of production cross sections may offer a new tool for the detailed understanding of charmonium production.

1. Introduction

Fermilab experiment 789 is a study of two-prong decays of beauty and charm which took data during the 1990/1 fixed-target run. E789 has published the most precise measurement of the charm production cross section and its \(A\) dependence in 800 GeV proton collisions, as well as novel measurements at very forward \(x_F\) of the \(J/\psi\) production cross section and its \(A\) dependence using our beam dump (or a beryllium insert just upstream of the beam dump) as the target. More recent results include the only measurement to date of the cross section for beauty production in proton collisions at fixed-target energy observed via the process \(b \rightarrow J/\psi + X\), \(J/\psi \rightarrow \mu^+ \mu^-\), and high-statistics studies of \(J/\psi\) and \(\psi'\) production.


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2. Apparatus Description

The E789 apparatus (shown schematically in Fig. 1) has been described in detail elsewhere\cite{4,6}; we summarize briefly here. It is based on the pre-existing E605/772 spectrometer\cite{6} upgraded for this run by the addition of two silicon-microstrip vertex telescopes (Fig. 2), one above and one below the beam, replacement of the Station-1 MWPCs with drift chambers, and a tenfold increase in data-recording capacity (to 50 MB/spill). Wire-like targets were used to localize the primary-interaction vertex in $y$ and $z$, so that only the decay vertex need be reconstructed.

![Figure 1: Plan (x-z) view of E789 apparatus.](image1)

![Figure 2: Elevation view of E789 vertex telescopes; note that the target dimensions indicated correspond to the beauty running, and thinner targets were used for the charm running.](image2)

The spectrometer features two large analysis magnets, SM12 and SM3, which deflect charged particles in opposite directions in $y$. A water-cooled copper beam dump suspended within SM12 absorbs non-interacting beam protons as well as secondaries emitted within $\approx\pm20$ mrad of the beam in $y$. Shielding within and around SM12 absorbs neutral secondaries. This geometry limits the pair acceptance to $\approx1\%$ but allows operation at high interaction rates. The vertex telescopes and the 23 planes of scintillation-counter hodoscopes and drift chambers at Stations 1, 2, and 3 measure the tracks of charged particles passing above or below the beam dump. The SM3 magnet serves to remeasure charged-particle momenta and thus to confirm the target origin of tracks, allowing the copious background of muons created within the
beam dump to be rejected. Particles are identified by electromagnetic and hadronic calorimeters, scintillation-phototube and proportional-tube muon detectors, and a ring-imaging Cherenkov counter. In most events only two oppositely-charged particle tracks traversing the spectrometer are fully reconstructed, one passing through each vertex telescope.

Data were taken separately in charm and beauty spectrometer settings. In the charm running we were able to operate the spectrometer at interaction rates up to 5 MHz, using an on-line vertex trigger processor to reject >80% of hadron pairs from the target. The higher SM12 current used in the beauty setting allowed $J/\psi$ and $\psi'$ data to be taken at a 50 MHz interaction rate, with no on-line vertex cut needed.

3. Charm and Charmonium Production Cross Sections

We have measured differential cross sections for charm and charmonium production. Charm data were taken using gold and beryllium targets at SM12 currents of 900 and 1000 amperes. Fig. 3 shows the observed hadron-pair mass distributions (under the $K^-\pi^+$ and $\pi^-K^+$ assumptions) for the various E789 charm data samples, using two different decay-vertex cuts. Clear $D^0(\bar{D}^0)$ signals stand out above the dihadron background. The looser vertex cuts ($\tau/\sigma_\tau > 7.2$) were found to optimize the statistical significance of the signal and were used in the cross-section and $A$-dependence analyses.

Figure 3: Left: dihadron mass spectra for the E789 charm data samples for two different decay-vertex cuts. Right: dimuon mass spectrum for E789 beauty data sample.

The RICH detector was not optimized for the $D$ mass region and was not used in this analysis.
Our narrow range of acceptance in the longitudinal momentum of the pair (due to the beam-dump and shielding geometry) precludes a direct measurement of total cross section. We measure the $d\sigma/dx_F$ differential cross section $d\sigma/dx_F = 58 \pm 3 \pm 7 \mu b$/nucleon at $\langle x_F \rangle = 0.03$. This can be extrapolated over all $x_F$ (using the $x_F$ shape measured by previous experiments) to give a total $D\bar{D}$ cross section $\sigma = 17.7 \pm 0.9 \pm 3.4 \mu b$/nucleon. Averaging with previous measurements using 800 GeV proton beams gives $\sigma(pN \rightarrow D\bar{D} X) + \sigma(pN \rightarrow T\bar{T} X) = (20.9 \pm 3.5 \mu b$/nucleon, consistent with next-to-leading-order (NLO) QCD predictions within the broad range of theoretical uncertainty.

Fig. 3 also shows the dimuon mass distribution from the beauty running, and Figs. 4 and 5 compare our measured $J/\psi$ and $\psi'$ differential cross sections with QCD predictions. Here there is little uncertainty in the extrapolation over $x_F$, with the $x_F$ shape well determined both by these “open-aperture” data alone and in combination with our beam-dump data, as indicated in Fig. 6. As at the Tevatron Collider, $J/\psi$ and $\psi'$ production are substantially underestimated in the QCD calculation, with phenomenological “$K$ factors” of 7 and 25 (respectively) required to give agreement in magnitude between data and theory. Note that the model calculation includes only contributions from color-singlet charmonium states and neglects possible contributions from color-octet charmonium components and from postulated states above $D\bar{D}$ threshold. These discrepancies have been the subject of much attention and are discussed further in Sec. 5. We find $\sigma(p + N \rightarrow J/\psi + X) = 442 \pm 2 \pm 88 \mu b$/nucleon and $\sigma(p + N \rightarrow \psi' + X) = 75 \pm 5 \pm 22 \mu b$/nucleon. Comparison with previous results (Fig. 7) shows that the $J/\psi$ total cross section and its excitation curve are by now well determined experimentally.

4. Charm and Charmonium $A$ Dependence

Nuclear dependences of production cross sections can shed light on production mechanisms and thus are of intrinsic interest. In addition, suppression of charmonium production in nucleus-nucleus collisions has been proposed as a signature for quark-gluon-plasma formation, so it is important to study processes responsible for charmonium suppression in proton-nucleus collisions, which might present a background to a quark-gluon-plasma signal. The production of heavy quarks is naively expected to depend linearly on the atomic weight ($A$) of the target nucleus, since the dominant QCD mechanisms (gluon-gluon fusion and $q\bar{q}$ annihilation) involve hard partons. However, in Fermilab E772 we showed that charmonium production in proton-nucleus collisions in fact has a complicated dependence on $A$, parametrized as $d\sigma/dx_F \propto A^{\alpha(x_F)}$, suggesting that other processes are at work in addition to those of perturbative QCD.

The concentration of our charm sample in a narrow range of Feynman-$x$ results in the most precise determination to date of the charm-production nuclear dependence at a point in $x_F$, allowing a precise comparison to be made between open-charm and charmonium production. To augment the forward-$x_F$ $A$-dependence measurements of E772, we took additional $J/\psi$ data in E789, using a rotating wheel of beryllium, carbon, and tungsten targets placed 1.27 m downstream of the usual target position in order to increase the acceptance near $x_F = 0$. Fig. 8 shows the dimuon mass distributions thus obtained and the resulting $A$-dependence exponent $\alpha$ vs. $x_F$ for...
Figure 4: Differential cross section per nucleon vs. $p_t$ for $J/\psi$ production compared with QCD prediction (note large phenomenological “$K$” factor by which the prediction has been multiplied). Dashed curves indicate indirect (via decay from higher-mass charmonium states) and direct contributions, and solid curve their sum.

$J/\psi$ compared with that for $D^0$. We see that (at least at small $x_F$) $\alpha$ is significantly lower for charmonium than for charm: $D^0$ production depends linearly on $A$ ($\alpha = 1.02 \pm 0.03 \pm 0.02$ at $\langle x_F \rangle = 0.03$), while for the $J/\psi$, $\alpha(0.03) = 0.80 \pm 0.02$. The increased nuclear suppression at low $x_F$ of charmonium as compared to charm is consistent with models in which charmonium production is suppressed in nuclei due to dissociation by interaction with co-moving partons. Models in which the nuclear suppression of charmonium production is an initial-state effect (e.g. due to possible shadowing or nuclear modification of the gluon structure function) are disfavored, since they would predict similar nuclear dependences for $J/\psi$ and $D$ production.

Effects on charmonium production at large $x_F$ due to intrinsic charm (the presence of virtual $c\bar{c}$ pairs in the nucleon sea) and initial-state parton energy loss have also been postulated. The predictions of the intrinsic-charm model have not been borne out by our data since they feature significantly larger (and more strongly $A$-dependent) cross-section contributions at the largest $x_F$ than are seen. The qualitative trend we observe at large $x_F$ (nuclear suppression increasing with $x_F$) is successfully accommodated in models which take account of parton energy loss.
traversing nuclear matter. Since gluons should interact more strongly with matter than quarks, the parton energy-loss model makes the intriguing prediction that at the highest Feynman-\(x\) (where quark-antiquark annihilation dominates over gluon-gluon fusion), the nuclear suppression should decrease.\(^{28}\) The apparent increase of \(\alpha\) at \(x_F \approx 0.8\) suggests that this may be occurring, but better statistics are needed for confirmation; these should be forthcoming from Fermilab E866, which is to take data during the 1996/7 fixed-target run.

5. **Discussion**

Production of charm\(^1\) and beauty\(^3\) quarks is in reasonable agreement with perturbative QCD calculations. On the other hand, production of charm and beauty quarkonia are observed at rates from one to two orders of magnitude higher than naively predicted. The experimental facts of enhanced quarkonium production in fixed-target experiments are not new, dating back to the mid-1970s when \(J/\psi\) hadroproduction was first observed. At that time it was realized that lowest-order production of \(c\bar{c}\) in a color-singlet state (via one intermediate virtual photon or three...
Figure 6: Differential cross section per nucleus vs. $x_F$ for $J/\psi$ production in 800 GeV $p$-Au collisions along with phenomenological fit to the form $(1 - |x_F|)^n$; we find $n = 5.0 \pm 0.2$. (Note that lowest-$x_F$ points in beam-dump sample are suspect due to large corrections.)

virtual gluons) had difficulty accounting for the large cross sections measured, and the "color evaporation" (or local-duality) mechanism achieved currency: the $c\bar{c}$ pair could be produced in a colored state and later emit a soft gluon to neutralize its color at little or no cost in probability.

Recent advances in perturbative QCD have made the predictions of the color-singlet model computable with no free parameters, allowing it to be definitively ruled out by both fixed-target and collider measurements. In the regime accessible to fixed-target experiments, questions may still remain as to the applicability of factorization and the role of intrinsic parton $k_t$. But the collider data in the previously-inaccessible regime of $p_T \gg m$ (where perturbative calculations ought to be most trustworthy) have forced theorists to consider seriously additional non-perturbative mechanisms. As a result, the leading candidate models which have emerged are the color-octet model and an updated color-evaporation model. These models, while less predictive than the color-singlet model, nevertheless make strong predictions (for example, that $J/\psi$'s should be highly polarized at high $p_T$), which can be tested in detail in upcoming experiments. In this connection we mention Fermilab E866, which should record $> 10^4 J/\psi \to \mu^+\mu^-$ decays (in closed
Figure 7: Energy dependence of total $J/\psi$ production cross section per nucleon; data from E789 and Refs. 15–22.

aperture) in the upcoming run, as well as the C0 Charm project,\(^3\) in which a sample of $\sim 10^7$ $J/\psi$ decays could be accumulated, with (due to the open geometry) most final-state particles accompanying the $J/\psi$ also measured. Thus C0 Charm holds the possibility of high-statistics measurements of $\chi_c$ (as well as $J/\psi$, $\psi'$, and open-charm) production at fixed-target energy.

Further data on $A$ dependences could also be useful. Energy loss in nuclear matter may be a means to distinguish color-singlet and color-octet charmonium states, since the color-octet state has gluonic quantum numbers and may be strongly absorbed.\(^3\) Distinguishing initial- and final-state $A$-dependence mechanisms calls for more data on the $A$ dependence of open-charm production at large $x_F$, another area in which C0 Charm could contribute.

Figure 8: Left: dimuon mass spectra for E789 $J/\psi$ $A$-dependence data samples. Right: The exponent $\alpha$ of the $A$ dependence of the production cross sections for $D^0(T\bar{D})$ and $J/\psi$ production vs. Feynman-$x$ as measured in E789; also shown are $J/\psi$ results from E772.

10. M. L. Mangano, "Quarkonium Production Codes: Documentation" (unpublished); see also Ref. 31.
15. T. Alexopoulos et al., Fermilab CONF-94/178-E.