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J/ψ AND ψ' PRODUCTION WITH 800 GeV PROTONS

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The yields of J/ψ and ψ' vector meson states have been measured for 800 GeV protons incident on deuterium, carbon, calcium, iron and tungsten targets. A depletion of the yield per nucleon from heavy nuclei is observed for both J/ψ and ψ' production. This depletion exhibits a strong dependence on x_F and p_t.

1. INTRODUCTION

The recent observation[1] of the suppression of J/ψ suppression in relativistic heavy-ion central collisions, predicted as a signature of quark-gluon plasma formation,[2] has generated renewed interest in the subject of hadron-induced J/ψ production.[3-7] In general, hadronic production of heavy quarks (c and b) from nuclear targets holds much interest for Nuclear Physics. At high energies ($\geq$ 100 GeV) the dominant production diagram is gluon fusion, $gg \rightarrow Q\overline{Q}$. Hence nuclear effects on the gluon structure function may be observable in measurements of the A dependence of charm and beauty production. The quarkonium resonances, J/ψ and Υ, have easily detectable experimental signals and can be used to analyze the dynamics of reaction processes; examples are co-mover interactions,[4-7] nuclear dependence of fragmentation functions, and color transparency.[4,8] On the theoretical side, because the masses of c and b quarks are large compared to Λ_{QCD}, calculations based on perturbative QCD may be applied with some validity.[9,10]

We report here the results of Fermilab E772, a precesion study of the A- dependence of proton-induced dimuon production at 800 GeV. The original goals of E772 were twofold:

1. To precisely measure the A-dependence of the nuclear antiquark sea via the proton induced Drell-Yan (DY) process, and
2. To determine the A-dependence of the gluon structure function from a study of quarkonium prodution.

We have been successful in achieving our first goal. The A-dependence of the antiquark structure function has been described in detail in a recent letter.[11] Studies of the A-dependence of quarkonium production, the principle subject of this paper have not, however, led to the fulfillment of the second goal. The reasons for this have to do with several major issues which are raised by the present data, and which we believe will not be clearly resolved without further experimental data on heavy quark production. Fortunately, the experimental sequel to E772, Fermilab E789 should provide much of these data in the near future. Among the anticipated results which compliments those reported here are studies of the J/ψ and ψ' resonances in the central region and the first precision A-dependence measurements of charmed-meson production.

Although the data from E772 include the first A-dependence studies of the Υ family of resonances, these data are not yet at the stage of final analysis and will not be discussed in this manuscript. We will focus on the results for the J/ψ and ψ' resonances.

2. THE EXPERIMENT

The E772 proposal was presented to the Fermilab Physics Advisory Committee in April of 1986 and approved in June, 1986. Construction of E772 starting from the E605 spectrometer began in August, 1986 and was completed in May, 1987. The spectrometer is optimized to measure, with high resolution, the mass of a pair of oppositely charged particles having large transverse momentum.[12]

The most important objective of E772 was to achieve a very accurate target-to-target relative normalization error while recording a much larger number of dimuon events than previous experiments. In order to accomplish this, the magnetic fields of the three dipole magnets of the spectrometer were configured to optimize acceptance for different regions of dimuon mass. Three configurations were chosen which maximized the yield at invariant masses of 4.5, 6, and 8.5 GeV respectively. A key element in reducing errors due to long-term drifts and changes in efficiency was the regular, rapid interchange of targets. During stable running conditions a cycle of two or three targets, one always being ^2H, were alternately inserted into the beam for periods of $\approx$ 15 min.

The spectrometer was used in the closed-aperture configuration, permiting the use of a very high-intensity primary 800 GeV proton beam. Maximum intensities per 20 sec. spill varied from $2 * 10^{12}$ protons for the high-mass setting to $0.5 * 10^{12}$ for the low-mass setting. A total luminosity of $3.5 * 10^{41} cm^{-2}/nucleon$ was recorded. Total systematic error in the heavy-target/deuterium ratios is less than 2%.

3. RESULTS FOR THE J/ψ AND ψ'

Figure 1 insert shows the dimuon mass spectrum, uncorrected for spectrometer acceptance. The data correspond to $\sim$4 x 10^{16} incident protons and $\sim$2 x 10^5 dimuon events. The resolution of $\sim$150 MeV at a mass of 3 GeV gives excellent separation between the J/ψ and ψ' peaks. To extract the peak yields the spectrum was fitted with a combination of asymmetric gaussians plus a polynomial to represent the Drell-Yan (DY) continuum. Nuclear dependence of the DY continuum has been presented elsewhere E772.[11]

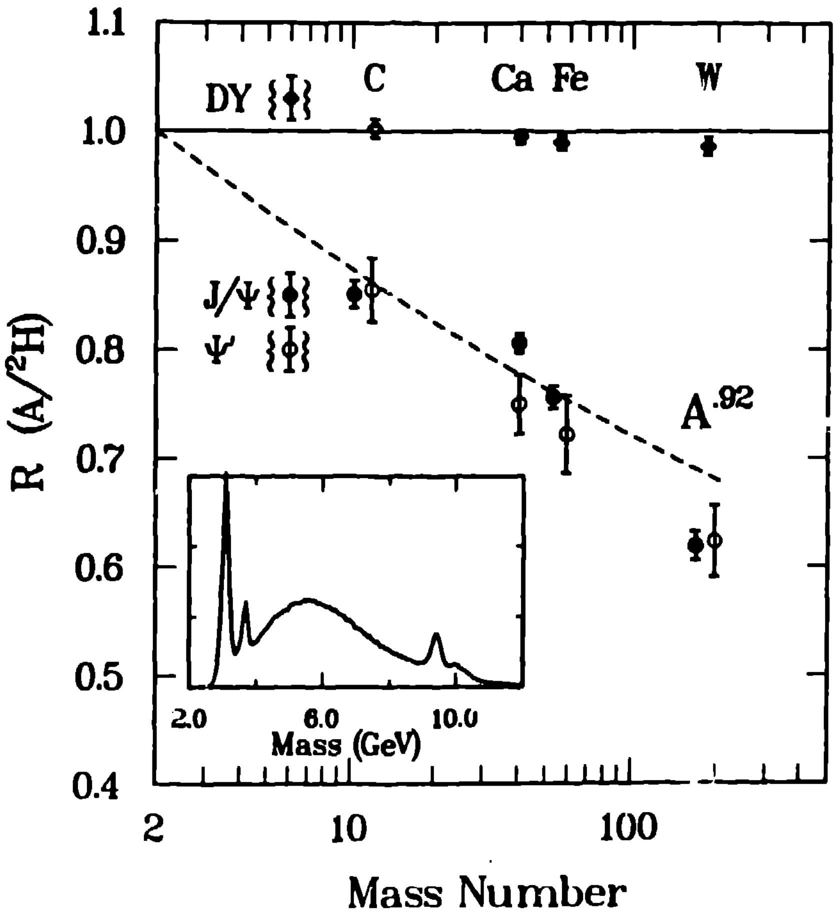

Fig. 1. The ratios of heavy nucleus to deuterium integrated yields for the J/ψ and ψ' resonances and the Drell-Yan continuum. The insert shows the raw (no acceptance correction) dimuon invariant mass spectrum.

Figure 1 shows the heavy nucleus to deuterium ratio per nucleon, R, integrated over x_F and p_t for the J/ψ, ψ', and the DY ($4 \leq M_{\mu\mu} \leq 9$ and $M_{\mu\mu} \geq 11 GeV$) continuum versus A. Figure 2 shows R for the J/ψ as a function of x-Feynman (x_F) and transverse momentum (p_t). In Fig. 3 we show α for the J/ψ versus x_2 (Bjorken-x for the target parton), and p_t, as determined by fits to R for all four heavy targets. Also shown is $\alpha(x_2; x_F)$ from 200 GeV proton production of the J/ψ from NA3,[13] and $\alpha(p_t)$ for the DY continuum from E772. We use the usual definition;

$$\sigma_A = \sigma_N * A^{\alpha}.$$

Katsanevas et al.[14] (Fermilab E537) suggest that this form fails to describe their data, when combined with the NA3 data extrapolated to a lower energy. We also find that A^{α} is not a good representation of the integrated ratio. However for individual x_F or p_t bins it is adequate within the present statistical errors.

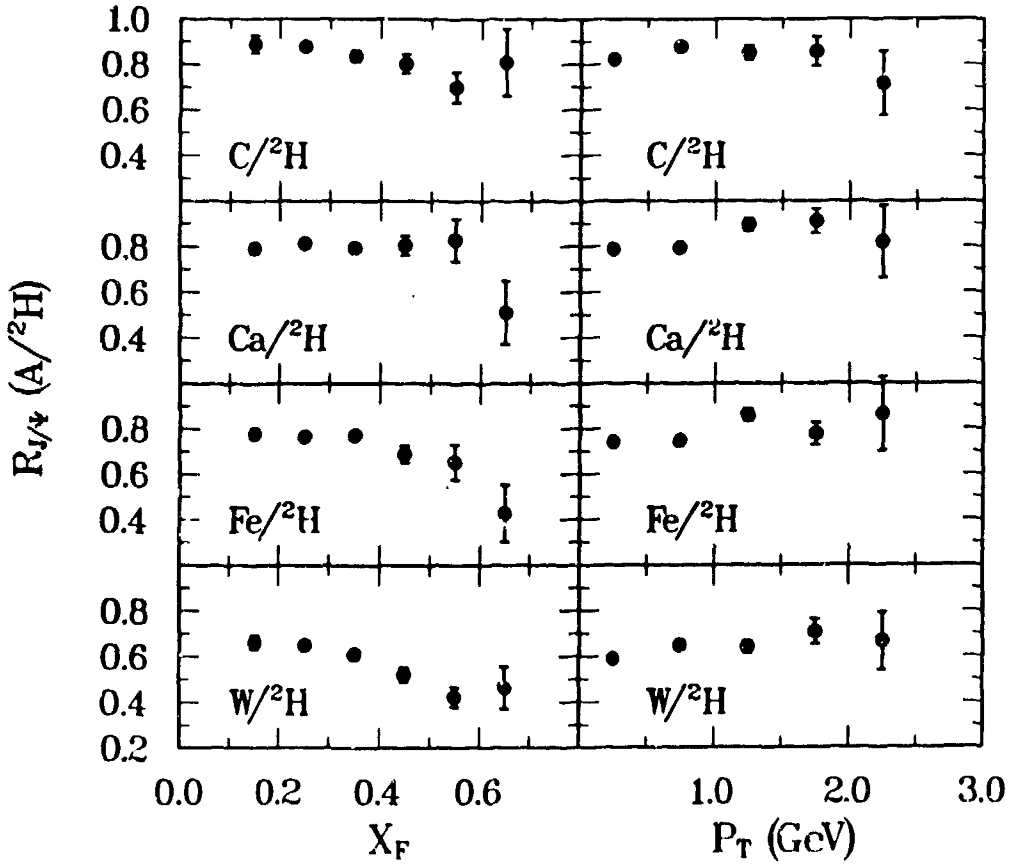

Fig. 2. The ratios of heavy nucleus to deuterium J/ψ yields versus x_F(a) and p_t(b).

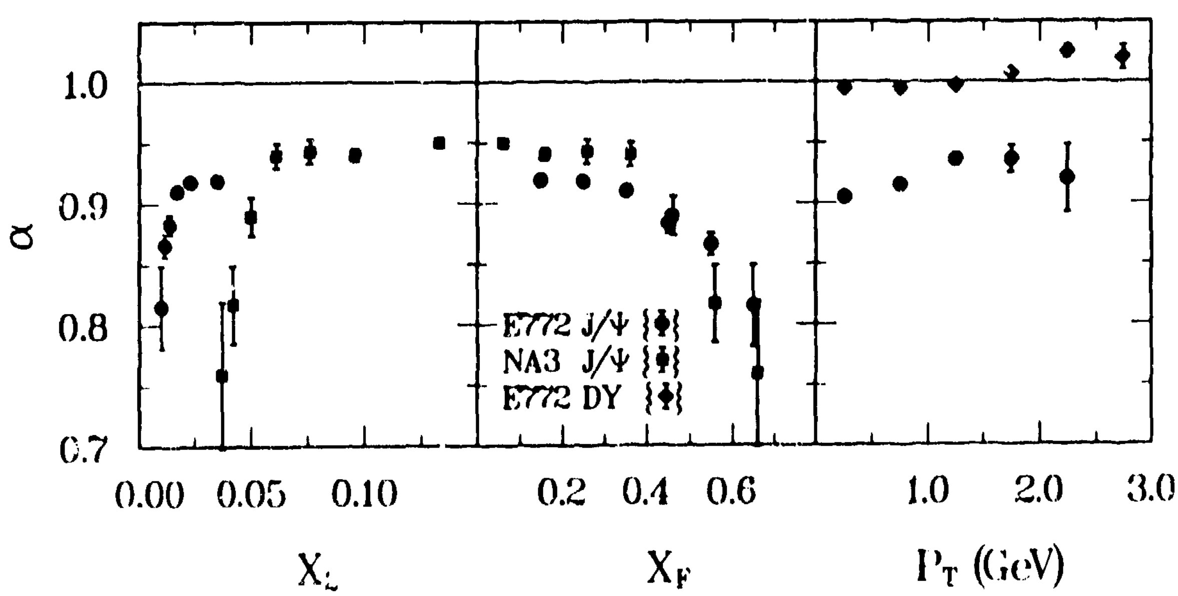

Fig. 3. (a;b) The value $\alpha(x_2; x_F)$ for the J/ψ resonance as determined from fits to all four heavy target ratios (circles). Also shown is the 200 GeV data from NA3[13] (squares). The value $\alpha(p_t)$ for the J/ψ resonance and the DY continuum.

In contrast to the DY data, which give a value of R very close to unity, a large depletion of J/ψ and ψ' yields is found in nuclear targets. A significant new result is that the depletion is the same within errors for the J/ψ and ψ'. The A dependence is most pronounced for the heaviest targets at the largest values of x_F. The observed x_F dependence is in qualitative agreement with previous proton-induced J/ψ production data.[13,14] Similar behavior was also found in pion and antiproton induced J/ψ production.[13,14]

the simplest gluon-gluon fusion model,[15,16] the quarkonium cross section is given by the convolution of the precess subprocess, $gg \to Q\bar{Q}$, with the gluon structure functions $G(x_1)$ and $G(x_2)$, where x_1 and x_2 are the Bjorken-x of the gluons in the beam and target hadrons, respectively. This simple model has been used to extract information on the gluon structure functions from J/ψ and Υ production data.[13,17] Here it is assumed that x_1 and x_2 are related to the observed quantities m and x_F through the relations;

$$m^2 = x_1 x_2 s,$$

$$x_F = x_1 - x_2,$$

where s is the center-of-mass energy squared. Strictly speaking, m can be any $c\bar{c}$ state produced in the gg fusion process which subsequently decays into J/ψ. We use the mass of the J/ψ in Fig. 3a. The present data at 800 GeV suggest a depletion of soft gluons in nuclei at small x_2, reminiscent of the shadowing effect[18] observed in deep-inelastic lepton scattering experiments. Close, Qiu and Roberts[19] predict a suppression of gluons in nuclei for $x < 0.1$ as a result of parton recombination effects. In Fig. 3a we also show $R(W/H)$ for the J/ψ from NA3.[13] These data, taken at 200 GeV/c, correspond to larger x_2 values than those of E772. If shadowing of the gluon distribution were the sole origin for J/ψ A-dependence, data at both beam energies should scale with x_2. Clearly this is not the case, indicating that mechanisms other than gluon shadowing must also be present.

Several models aimed at a unified description of J/ψ production in hadron- nucleus and nucleus-nucleus collisions have considered the effect of attenuation of $c\bar{c}$ states by secondary reactions of the J/ψ with some combination of the remaining nucleons of the target plus hadronic debris formed in the collision[4-7] (co-movers). The evolution from the initial $c\bar{c}$ state, where the interaction cross section may be very small due to *color transparancy* effects,[4,8] to the final state of hadronic dimensions is characterized by an exponential time dependence. At present, this time dependence is not known either experimentally or theoretically. Although attenuation models have been directed primarily toward the central production region. their extension to the present x_F range is straightforward. It is clear within the present formulations that the suppression of J/ψ production should decrease with increasing x_F for two reasons. First, the more energetic the J/ψ, the more hadronic matter it traverses in its (presumed) spatially small, color-tranparent state. Second, for the most energetic $J/\psi s$ the density of co-movers decreases. The decrease of R at large x_F implies that attenuation is not the whole story for hadronic J/ψ production. Additional evidence against the co-mover picture is found in beam-dump measurements of the A-dependence of inclusive charm production.[20,21] Here it is found that α is substantially less than unity. presumably open-charm channels should not suffer attenuating reactions in the same way as $c\bar{c}$ states.

The fact that the A-dependence of J/ψ and ψ' production is the same within errors provides an additional constraint on the hadronic attenuation picture. The radii of the J/ψ and ψ' differ by almost a factor of two in potential models.[22] Direct interpretation of this observation is complicated by the fact that the J/ψ is probably produced in part by decays from χ states which have radii comparable to the ψ'. Nevertheless these data indicate no dependence on final hadronic size. One model[3] is in qualitative accord with both the equality of the J/ψ and ψ' A-dependence and its dependence on x_F. Here the authors postulate intrinsic $c\bar{c}$ components in the wave function of the incident hadron to achieve these features. It remains to be determined whether or not the magnitude of the intrinsic charm in the proton can account for the present data.

Finally, we turn to the p_t dependence of α. Figure 3c shows that the increase in α seen at large p_t is greater for the J/ψ than for the DY continuum. This has been anticipated by models[23,24] which describe p_t dependence in terms of initial/final state partonic multiple scattering. The ratio of the J/ψ to DY p_t dependence plays an important role in understanding the significance of J/ψ production in heavy-ion collisions. Although detailed model analysis of the NA38 results are still being debated, the results seen here are in qualitative agreement with those from heavy-ion induced J/ψ production, possibly indicating a common origin.

4. FERMILAB E789

A new experiment is underway at Fermilab which has the potential to provide answers to many of the questions about heavy quark production raised by the data from E772. E789 uses the E605/E772 spectrometer in an open aperature configuration, thus permitting detection of hadron and electron, as well as muon pairs. The ring-imaging Cherenkov detector from E605 is being reactivated for hadron identification. The most important inovation in E789 is the addition of a very high resolution Silicon microvertex array. With this spectrometer one will be able to make the first high-statistics measurements of the A-dependence of D meson production. Kinematic reconstruction will be complete through observation of channnels such as $D^0 \rightarrow K^+ + \pi^-$.

Experiment 789 was approved in October 1988 by the Fermilab Physics Advisory Committee. Its original objective was the first measurement of charmless, two-prong decays of neutral b-quark hadrons, e.g. $B_d^0 \to \pi^+ + \pi^-$. Its goals have recently been extended to include the A- dependence of D production, as well as several additional studies of the J/ψ and ψ' resonances. The novel and challenging feature of E789, which sets it apart from other heavy-quark decay experiments, is the high luminosity it proposes. This is clearly crucial in an experiment which aims to measure several hundred charmless b decays during a single 6 month running period. The beauty production cross section at 800 GeV is only ~ 10 nanobarns; branching ratios for two-prong decays are expected to be no larger than $\sim 10^{-5}$. Experiment 789 achieves this capability by operating a vertex detector at much higher rates than any previous experiment, and by using a very selective trigger which includes a downstream vertex cut. At 800 GeV, B and D mesons have decay lengths of order ~ 1 cm.

E789 will begin running in the Summer of 1990 at Fermilab, with results expected beginning about a year later.

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