The A-Dependence of J/ψ and ψ' Production at 800 GeV/c

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Abstract

The yield of J/ψ and ψ' vector meson states has 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. Within experimental errors the depletion is the same for the J/ψ and the ψ'.

The recent observation[1] 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, 4, 5, 6, 7]. In order to elucidate the origin of J/ψ suppression, it is desirable to examine the characteristics of hadronic J/ψ production in heavy versus light nuclei, which may mirror certain aspects of conditions encountered in central versus peripheral collisions in heavy-ion interactions. Since existing theoretical models predict that gluon-gluon fusion is the dominant mechanism for hadron-induced quarkonium production at 800 GeV[8, 9], measurement of the nuclear dependence of J/ψ production might also reveal possible modification of the gluon distribution in nuclei[10].

We report here, from Fermilab experiment 772, the first A-dependence measurements of J/ψ and ψ' production in 800 GeV proton-nucleus collisions. Previous studies of nuclear effects on J/ψ production, performed at lower energies[11, 12, 13, 14], did not have adequate statistics or mass resolution to extract information on the ψ' resonance.

The E605/772 spectrometer[15] at Fermilab was used to measure dimuons produced in 800 GeV proton-nucleus collisions. A $5.2\,m$ thick absorber composed of copper, graphite, and polyethylene, located at the exit aperture of the $15\,m$ spectrometer magnet, absorbed low-energy backgrounds and allowed incident proton intensities of up to 10^{11} protons per second to interact with targets of $\sim$10 g/cm^2 thickness. Solid nuclear targets (C, Ca, Fe, W) and a liquid deuterium target were interchanged frequently during the experiment. A detailed Monte-Carlo calculation was performed to correct for the small acceptance variations among different targets. This procedure, together with many beam intensity and electronic lifetime monitors, yielded a systematic uncertainty on the ratios of yields from the various targets of $\sim 2\%$. Only statistical errors are shown in the figures. Further detail on the measurements may be found in reference 16.

The data correspond to $\sim 8 * 10^{15}$ incident protons on target yielding $\sim 10^5$ $J/\psi s$ and $\sim 1.2 * 10^4$ $\psi' s$. The mass resolution of ~150 MeV at a mass of 3 GeV gives excellent separation between the J/ψ and ψ' peaks (Fig.1 insert). To extract the peak areas the spectrum was fitted with a combination of asymmetric gaussian peaks plus a polynomial to represent the Drell-Yan (DY) continuum. Nuclear dependence of the DY continuum has been presented elsewhere[16].

Figure 1 shows the heavy nucleus to deuterium ratio per nucleon, R, integrated over x-Feynman (x_F) and transverse momentum (p_t) for the J/ψ , ψ' , and the DY continuum ($4 \leq M_{\mu\mu} \leq 9$ and $M_{\mu\mu} \geq 11 GeV$) versus A. Mean values of the kinematic variables for the J/ψ and ψ' resonances, averaged over the spectrometer acceptance, are $< x_F >\sim 0.27$ and $< p_t >\sim 0.7$ GeV. In contrast to the DY data, which give a value of R very close to unity, a large depletion of the J/ψ and ψ' yields is found in the nuclear targets. A significant new result seen in Fig. 1 is that the depletion is the same within errors for the J/ψ and ψ'. To describe the A-dependence of the J/ψ , ψ' depletion, We use the usual parametrization;

$$\sigma_A = \sigma_N * A^{\alpha}. \tag{1}$$

The curve in Fig. 1 corresponds to the best fit with $\alpha = 0.92$. The $\sim 2\%$ normalization error translates into an approximately constant systematic error in α of ~ 0.008. The validity of Eq. 1 for J/ψ production has not been well tested, since previous experiments typically measured only two targets. Katsanevas et al.[14] noted that the form A^α fails to describe their data, when combined with earlier NA3[13] data. Fig.1 shows that A^α gives an adequate, though not excellent, description of the present data.

Figure 2 shows R for the J/ψ as a function of x_F and p_t. The J/ψ depletion in heavy targets is most pronounced at larger values of x_F and at smaller values of p_t. This statement also applies to $R(x_F; p_t)$ for the ψ'. The observed x_F and p_t dependence is in qualitative agreement with previous proton-induced J/ψ production data[13, 14], as well as the pion and antiproton induced J/ψ production data[13, 14].

In Fig. 3 we show α for the J/ψ versus x_F, x_2(defined below), and p_t, as determined by fits to R for all targets. Equation (1) describes the data quite well when binned versus x_F or p_t. Also shown are $\alpha(x_F)$ and $\alpha(x_2)$ for 200 GeV proton production of the J/ψ from NA3[13] based on two targets ,^2H and Pt. Comparison of the two data sets shows that $\alpha(x_F)$ depends little on beam energy.

In the simplest gluon-gluon fusion model[8, 9], the quarkonium cross section is given by the convolution of the process, $gg \rightarrow Q\bar{Q}$, 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

$$m^2 = x_1 x_2 s; \qquad x_f = x_1 - x_2, \tag{2}$$

where s is the center-of-mass energy squared. Strictly speaking, m in Eq. 2 can be the mass of any $c\bar{c}$ state produced by gluon fusion (or $q\bar{q}$ fusion) which subsequently decays into the J/ψ. We use the mass of the J/ψ to calculate x_2 in Fig 3. Comparison of the 800 GeV and 200 GeV results clearly indicates that the data do not scale with x_2, a parameter intrinsic to the target-parton structure function. Changing the choice of mass in Eq. (2) to 3.5 GeV shifts the 200 GeV data by $x_2 \sim 0.01$ further to the right relative to the 800 GeV data. Thus the J/ψ suppression is not a simple manifestation of the small-x_2 shadowing seen in deep-inelastic lepton scattering[18].

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 (co-movers)[3, 5, 6, 7]. The evolution of the J/ψ from the initial $c\bar{c}$ state, where the interaction cross section may be very small due to *color transparency* effects[19], to the final state of hadronic dimensions is characterized by an exponential time dependence. At present, this time dependence has not been characterized experimentally. 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 that these models predict a value of α nearer unity at large x_F for two reasons. First, the more energetic the J/ψ , the longer it stays in its (presumed) spatially small, color-transparent state. Second, for the most energetic $J/\psi s$, the density of co-movers decreases. The observation of a significant suppression in the yield of the J/ψ at large x_F implies that attenuation cannot be the complete explanation of the A-dependence of 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]. There it is found that α is substantially less than unity. Presumably open-charm channels should not suffer attenuating reactions in the same way as $c\overline{c}$ states. The suppression of open charm production may be connected to the well-known suppression of strangeness production[22, 23] at large x_F.

One model[4] is apparently able to qualitatively reproduce the x_F dependence of α. The authors of this model postulate intrinsic $c\overline{c}$ 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.

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[24]. Direct interpretation of this difference is complicated by the fact that the J/ψ is probably produced in part by decays from χ_c states which have radii comparable to the ψ' . Nevertheless, the present data indicate no dependence on final hadronic size.

Finally, we turn to the p_t dependence of α. Figure 3 shows that the increase in α at large p_t is somewhat greater for the J/ψ than for the DY continuum. This has been anticipated by models[25, 26] which describe the p_t dependence of hadronic J/ψ production 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 analyses of the NA38[1] 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.

In summary, we have observed that production of the J/ψ and ψ' resonances with 800 GeV protons is stongly suppressed in heavy nuclei. The A-dependence is well described by the simple expression, A^{α}, with a value of α which depends on x_F and p_t. Comparison of the present data with the previous 200 GeV data shows that α scales well with x_F, but not with x_2. Two popular models, small-x shadowing and hadronic attenuation, have difficulties explaining either the x_2 or the x_F dependence of existing data. It is clear that much remains to be understood about the nature of charmonium production and propagation in nuclei. In particular, it is important to have measurements of the A-dependence of J/ψ and ψ' production over a much wider kinematic range, especially at negative x_F where almost no experimental data exists. In addition to charmonium production, measurement of the A-dependence of open-charm channels, e.g. D mesons, would greatly clarify such issues as intrinsic charm in light hadrons and co-mover attenuation.

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Figure Captions

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.

Fig. 2. The ratios of heavy nucleus to deuterium yields for the J/ψ and ψ' resonances versus x_F and p_t.

Fig. 3. The parameter α for the J/ψ resonance (circles) and the Drell-Yan continuum (diamonds) as determined from fits to all four heavy target ratios. Also shown is $\alpha(x_F, x_2)$ for the 200 GeV data from NA3[13] (squares).