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A precise measurement of the atomic mass dependence of dimuon production induced by 800 GeV protons incident on targets of ^2H, C, Ca, Fe, and W is reported. The relative Drell-Yan yield per nucleon, $R = Y_A/Y_{^2H}$, is sensitive to modifications of the antiquark sea in nuclei. No effect is seen for the range of target-quark momentum fraction, $0.1 < x_t < 0.3$. For $x_t < 0.1$ the ratio is slightly less than unity for the heavy nuclei. These results are compared with the predictions of EMC models. 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'.

INTRODUCTION

It was almost a decade ago when the European Muon Collaboration reported[1] their findings that the F_2 structure functions in heavy nucleus differ from those in deuterium. This so called EMC effect was confirmed in other lepton Deep Inelastic Scattering(DIS) experiments using electron, muon, and neutrino beams[2-4]. Despite extensive theoretical efforts, the interpretation of the EMC effects remains controversial. To shed more light on the origin of the EMC effects, it is clearly desirable to have more experimental inputs. Some of the important questions to be addressed are; 1) Can one observe nuclear effects in other processes which are also sensitive to the parton distributions? 2) Can one identify the nuclear effects caused by the quark (or antiquark) distribution alone? 3) What happens to the gluon distributions in nuclei?

Lepton-pair production in high energy hadron-nucleus collision provides an independent means to probe the quark, antiquark, and gluon distributions in nuclei[5]. Two distinct processes dominate the lepton-pair production at high energies - the Drell-Yan(DY) process and the quarkonium ($J/\Psi, \Upsilon$) production. The mechanism[6] for the DY process is quark-antiquark annihilation, hence the quark and antiquark contents in nuclei can be studied. Indeed, most of the information to date on parton distributions in hadrons are derived from the DIS and DY experiments. The mechanism for the quarkonium production is less clear, but is generally attributed to gluon-gluon fusion[7]. We recall that the J/ψ and Υ production data have been analysed[8,9] to yield information on the gluon structure functions in pion and in nucleon.

The nuclear dependence of lepton-pair production is of interest for another reason which has to do with the finding[10] in relativistic heavy-ion collisions that the J/ψ production rate in central collisions is suppressed relative to that in peripheral collisions. This phenomenon was predicted as a signature[11] of quark-gluon plasma formation. However, before arriving at such a conclusion, it is crucial to study resonance production in proton-nucleus collisions where quark-gluon plasma formation is not expected to take place.

Several experiments[12-16] to study the nuclear dependence of lepton-pair production have been reported in the literature. Unfortunately, they suffer from low statistical accuracy. Previous studies of nuclear effects on J/ψ production, performed at lower energies[8,17-19], did not have adequate statistics or mass resolution to extract information on the ψ' resonance.

In this paper we report the recent results obtained in the Fermilab experiment E772, which was designed to make an accurate A-dependence measurement of dimuon cross sections in 800 GeV proton-nucleus collisions. We will first discuss the setup and data analysis of the E772 experiment. The results on the nuclear dependence of the DY and J/ψ , ψ' productions will then be presented, followed by a summary.

THE E772 EXPERIMENT

The E605/772 spectrometer[20] was used to detect dimuons produced in 800 GeV proton-nucleus collisions. This spectrometer was designed to measure a pair of charged particles having large p_t. A 15-meter long magnet (p_t kick $\simeq$ 7 GeV), located immediately downstream of the target, bends the charged particles through its upper and lower apertures. A beam dump placed inside this magnet absorbs the uninteracted beam and also shields the downstream detectors from the neutral particles produced in the target. Most of the relatively low energy particles generated in the beam dump are swept away by the magnet or absorbed in the absorbers placed inside the magnet, keeping the singles rates on the downstream detectors at an acceptable level. This allowed up to 2×10^{12} protons per beam spill (20 sec) on a 10% interaction-length target. E772 took data for approximately 6 month during 1987-1988. A total luminosity of $3.5 * 10^{41} cm^{-2}$/nucleon was reached.

The 800 GeV proton beam, 8 mm wide by $\leq$ 2 mm high at the target, was monitored by position sensitive RF cavities and ion chambers; position stability was typically better than 1 mm. Beam intensity was monitored by two secondary-emission detectors and a quarter-wave RF cavity. Two four-element scintillator telescopes viewing the target at 90° monitored the luminosity, the beam duty factor, and the data acquisition livetime.

The dimuon yields were measured for five targets, ^2H, C, Ca, Fe, and W. Care was taken to achieve a very accurate target-to-target relative normalization. Long-term monitor drifts were cancelled by regularly interchanging the solid targets with the ^2H target every few minutes. The solid targets consisted of 7.28 cm diameter disks[21] distributed over a length of 50 cm, the length of the liquid deuterium cell. Target thicknesses, ranging from 6%(W) to 15%(^2H) of an interaction length, were chosen to equalise rates in the spectrometer. Elemental assays of the targets and beam attenuation were included in the luminosity calculation.

The electronic trigger consisted of a pair of triple hodoscope coincidences having the topology of a $\mu^+\mu^-$ pair from the target. This trigger reduced the primary background of low p_T muons from the target and beam dump. Typically 50 events per second were recorded of which ~ 1 was a valid dimuon event from the target. Electronic livetime was kept above 98%.

Track reconstruction was performed on a Fermilab Advanced Computing Project parallel processor. Track reconstruction efficiency averaged $\sim 91\%$; the inefficiency was proportional to the instantaneous luminosity. Target-to-target rate dependent corrections in reconstruction efficiency were applied. A small contamination ($\sim 3\%$) of random muon coincidences was subtracted by studying like-sign muon pairs. Target-out backgrounds were measured and found to be negligible.

One million muon pairs were tracked through a complete Monte Carlo simulation of the spectrometer to study the acceptance. The acceptance for the solid targets was slightly larger than that with the liquid deuterium cell; this correction (0.9%) was applied to the data .

The systematic error in the ratio of yields from the solid targets versus deuterium is dominated by the uncertainty in the rate dependence (1.5%), acceptance (0.4%), deuterium thickness (0.4%), and beam attenuation (0.3%). All other contributions are negligible. This results in a total estimated systematic error in the ratios of less than 2%.

A-DEPENDENCE OF THE DRELL-YAN CROSS SECTIONS

Proton-induced DY production, for fractional longitudinal momentum (Feynmann x), $x_F \geq 0.2$, is dominated by the quark-antiquark annihilation subprocess

$$q_p + \bar{q}_t \to l^+ l^-,$$

where p and t indicate the beam proton and target nucleon, respectively. Acceptance corrected mass spectra from the three spectrometer settings are shown for the ^2H target in Fig. 1. Also shown is a calculation of the DY cross section in the leading-log approximation($q(x) \to q(x, M^2)$) which was normalized

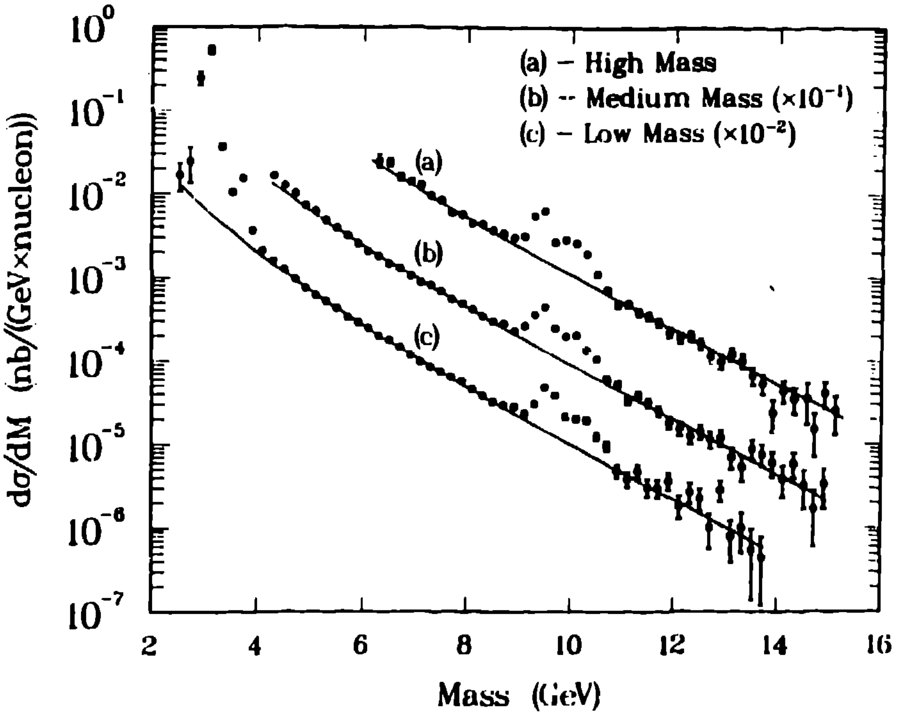

Fig. 1. Acceptance corrected mass spectra at the three spectrometer settings for the ^2H target. The solid curves are calculations of the Drell-Yan cross section, normalized to the data, using the structure functions of Eichten et al.[22]

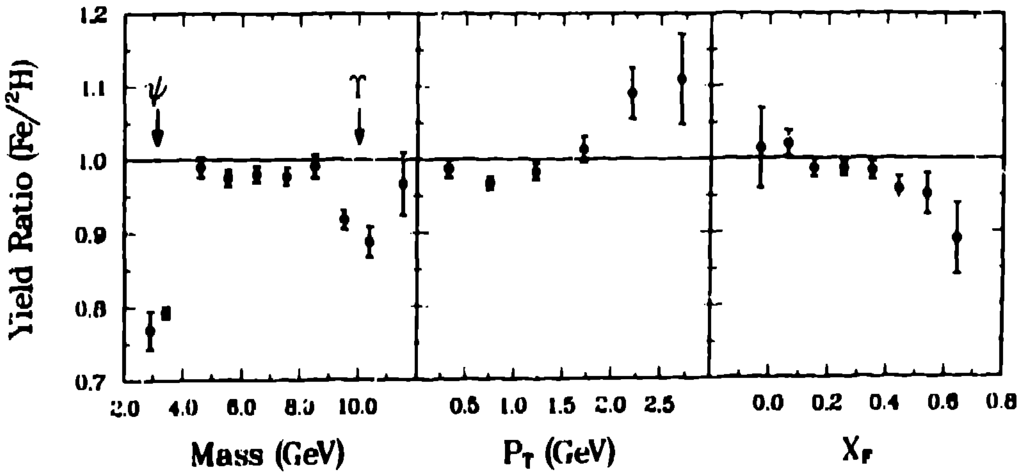

Fig. 2. Ratios of the dimuon yield per nucleon for $Fe/^2H$ versus dimuon mass, p_T, and x_F. The p_T and x_F ratios were cut on the pure continuum mass region, $4 \leq M \leq 9$ GeV and $M \geq 11$ GeV.

to the data. The calculation, which employed the structure functions (set 1) of Eichten et al.,[22] gives an excellent account of the shape of the DY continuum. Figure 2 shows the $Fe/^2H$ ratio as a function of dimuon mass, x_F, and transverse momentum. It is evident that the mass regions dominated by quarkonium resonances ($M \leq 4$ GeV and $9 \leq M \leq 11$ GeV) have very different A dependences than the DY continuum; the A dependence of J/ψ and ψ' production will be described in the next section. The dependence on transverse momentum is similar to that seen by NA10[23] at 280 GeV, but significantly less than that observed at 140 GeV.

Figure 3 shows the ratios of Drell-Yan yield per nucleon for each heavy target versus ^2H, $Y_A/Y_{^2H}$, as a function of x_t for muon pairs with positive x_F. Mean values of x_F and transverse momentum are 0.26 and 0.95 GeV/c, respectively . The x_t ratios are based on mass regions free of contribution from decay of the quarkonium states, specifically, $4 \leq M \leq 9\ GeV$ and $M \geq 11\ GeV$. With these cuts the above calculation predicts that the fraction of the accepted DY events due to $q_p\bar{q}_t$ annhilation is ~ 0.95 at $x_t = 0.05$ and ~ 0.75 at $x_t = 0.3$.

No nuclear dependence of the antiquark ratio is observed over the range $x_t > 0.1$. A slight, but experimentally significant depression of the ratio is seen in the heavier targets for $x_t < 0.1$. Figure 3 compares present data for $W/^2H$ to the F_2 ratio $Sn/^2H$ from the EMC group.[4] The lepton scattering data exhibit a more pronounced shadowing at small x_t. It is clearly of interest to know whether this difference can be understood in terms of current models of shadowing.[24] It is worth noting that $Q^2 \geq 16\ GeV^2$ for our data, which is significantly larger than in DIS.

Many of the theoretical attempts to calculate the EMC effect fall into three general categories: pion-excess models, quark-cluster models and rescaling models. These models can also be used to predict the nuclear dependence of DY dimuon production. The acceptance of the E772 spectrometer was taken into account in each of the following calculations.

The pion-excess model in its earliest forms[25,26] predicted a rise in the $F_2^{Fe}/F_2^{^2H}$ ratio at small x_t as well as a depletion for $x_t \geq 0.2$. The small enhancement in the pion cloud surrounding a bound nucleon arises from a conjectured attractive p-wave $\pi - N$ interaction in nuclear matter. The strength

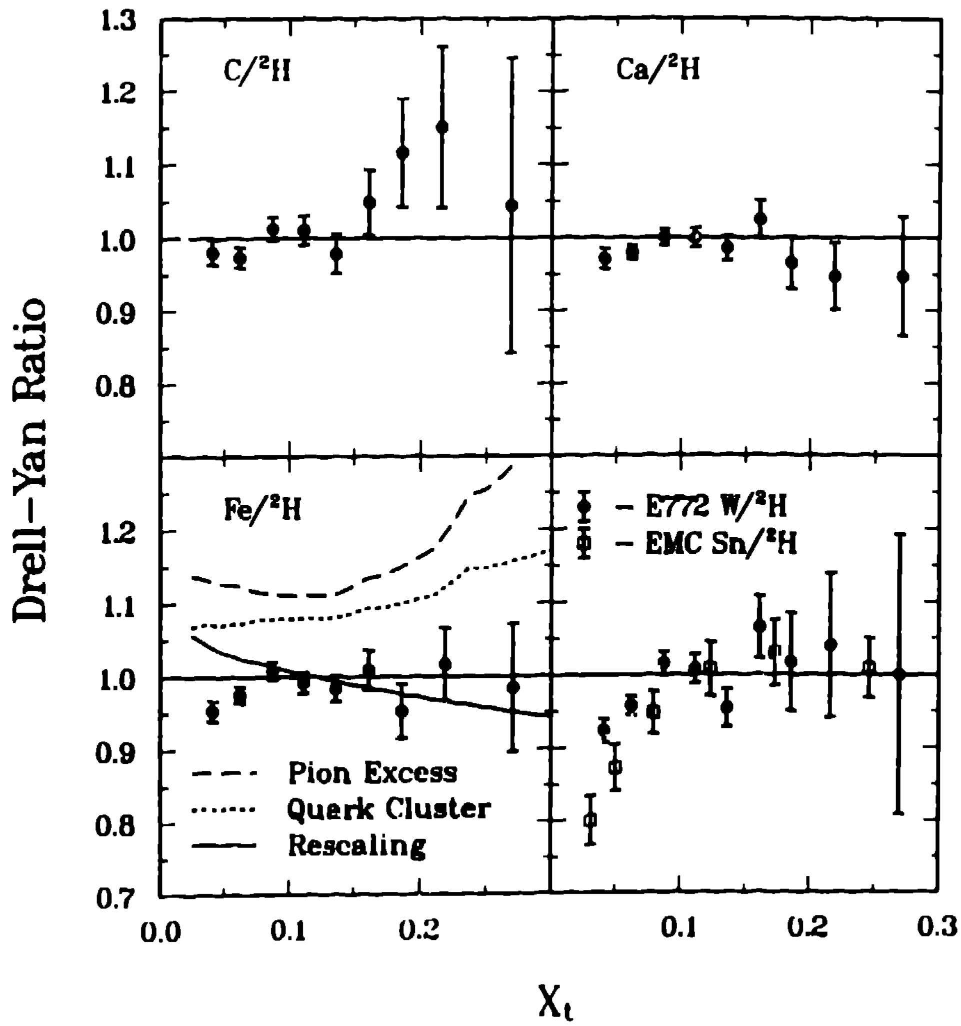

Fig. 3. Ratios of the Drell-Yan dimuon yield per nucleon, $Y_A/Y_{^2H}$ for positive x_F. The curves shown for $Fe/^2H$ are predictions of various models of the EMC effect. Also shown are the DIS data for $Sn/^2H$ from the EMC group.[4]

of this interaction is often characterized by the Landau-Migdal parameter g'_0; typical values found in the literature range around $g'_0 \sim 0.6 - 0.7$. Figure 3 compares the results of a calculation[27] (using the structure functions of Ref. 22) with $g'_0 = 0.6$ to the present $Fe/^2H$ DY data; it is completely inconsistent with the data. The pion-excess model of Ref. 26, which uses a different pion distribution function, predicts a similar enhancement in the antiquark content of nuclei, in disagreement with our data.

Quark-cluster models view the nucleus as composed of a combination of ordinary nucleons plus some fraction of multiquark ($6q$, $9q$, and higher) clusters formed by the overlap of nucleons. The uncertainties in these models come from the essentially unknown structure functions of multiquark clusters. In the model of Carlson and Havens[28], for example, the parton structure functions were parameterized according to constituent counting rules. The gluon momentum fraction for the $6q$ cluster was constrained to be the same as for the free nucleon. This results in a significant enhancement of the sea even for a modest 15% $6q$-cluster fraction. The calculated DY ratio (Fig. 3) is in significant disagreement with the present data. An alternate but plausible assumption,[29] that the momentum fraction sea/glue in $6q$-clusters is the same as it is for nucleons, leads to a smaller enhancement of the DY ratio. However such a calcula' is still in disagreement with our data.

The rescaling model assumes that nuclear binding results in a phenomenon similar to the scaling violation associated with gluon emission.[30] Comparisons to the present DY data are made on the basis of the scale change of structure functions $f(x_t, Q^2) \to f(x_t, \xi Q^2)$, where $\xi \sim 2$ over the Q^2 range of our data. The calculation, shown in Fig. 3, yields a scaling violation similar to DIS. It approximately fits the DY data, except in the range $x_t < 0.1$ where the approximations made in this model are known to break down.

A-DEPENDENCE OF J/ψ and ψ' PRODUCTION

Figure 4 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 continuum versus A. The mass resolution of ~150 MeV at a mass of 3 GeV gives excellent separation between the J/ψ and ψ' peaks (Fig. 4 insert). To extract the peak areas the spectrum was fitted with a combination of asymmetric gaussian peaks plus a polynomial

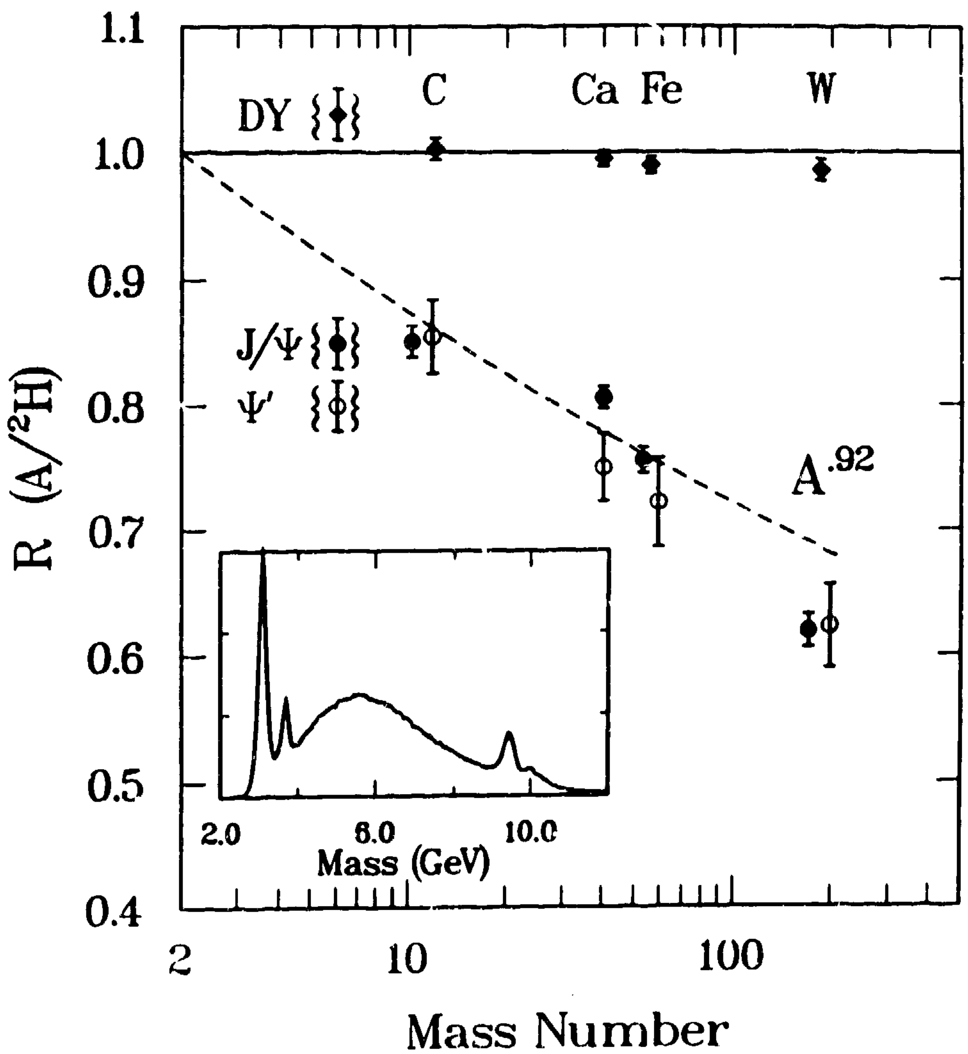

Fig. 4. The ratios of heavy nucleus to deuterium integrated yields for the J/ψ and ψ' resonances and the Drell-Yan continuum. The insert shows the raw (no acceptance correction) dimuon invariant mass spectrum.

to represent the Drell-Yan continuum. 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. 4 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. 4 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.[19] noted that the form A^{α} fails to describe their data, when combined with earlier NA3 data[8]. Fig. 4 shows that A^{α} gives an adequate, though not excellent, description of the present data.

Figure 5 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, as well as the pion and antiproton induced J/ψ production data[8,19].

In Fig. 6 we show α for the J/ψ versus x_F, x_2, and p_t, as determined by fits to R for all targets. Also shown are $\alpha(x_F)$ and $\alpha(x_2)$ for 200 GeV proton production of the J/ψ from NA3[8]. Comparison of the two data sets shows that $\alpha(x_F)$ depends little on beam energy.

In the simplest gluon-gluon fusion model[7], 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. Here it is assumed that x_1 and x_2 are related to the observed quantities m and x_F through the relations

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

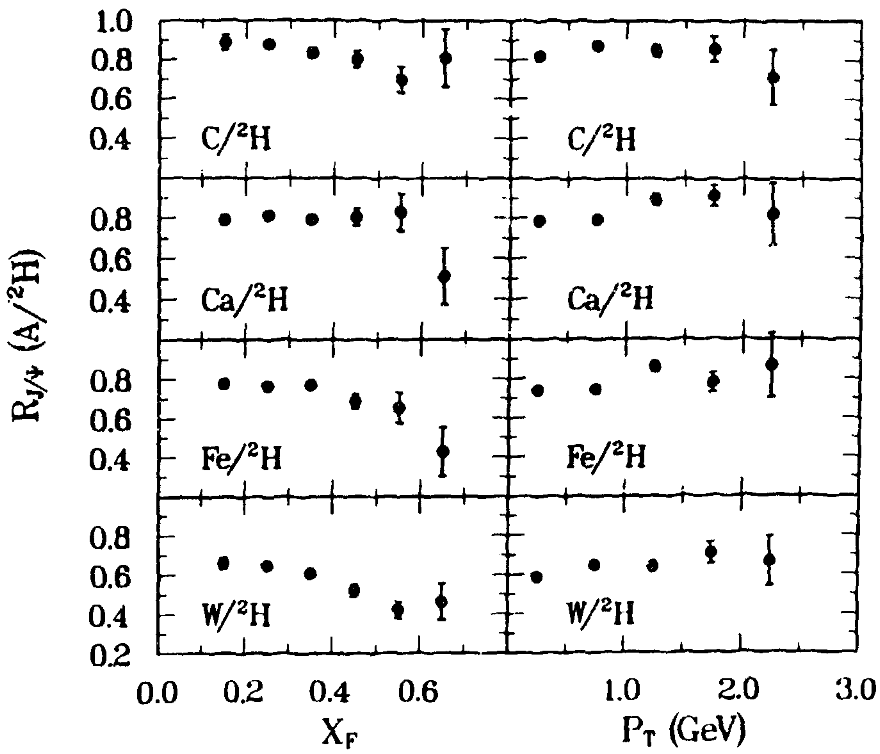

Fig. 5. The ratios of heavy nucleus to deuterium J/ψ yields versus x_F and p_t.

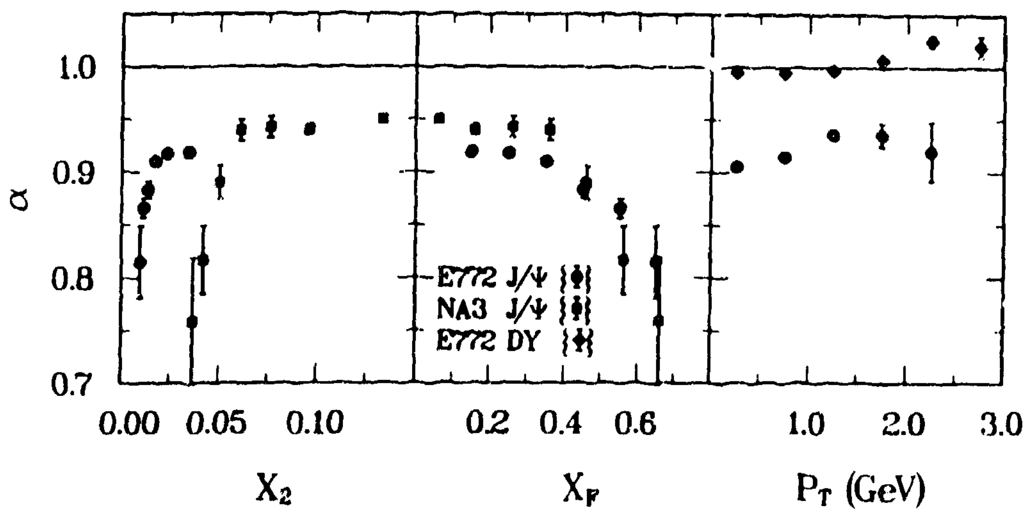

Fig. 6. The parameter α for the J/ψ resonance as determined from fits to all four heavy target ratios (circles). Also shown is $\alpha(x_F, x_2)$ for the 200 GeV data from NA3[8] (squares), and $\alpha(p_t)$ for the DY continuum (diamonds).

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 which subsequently decays into the J/ψ. We use the mass of the J/ψ to calculate x_2 in Fig 6. 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. Thus the J/ψ suppression is not a simple manifestation of the small-x_2 shadowing seen in deep-inelastic lepton scattering[4].

Several models[31-34], 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). 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[35], 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 smaller A-dependence 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[36,37]. 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 $c\bar{c}$ 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[38]. 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. One model[39] is in qualitative accord with both the equality of the J/ψ and ψ' A-dependence and the x_F dependence of R. The authors of this model 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 6 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[40,41] 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[10] 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.

SUMMARY

In summary, the E772 experiment has shown almost no nuclear dependence in the production of continuum dimuon pairs. In the context of the DY description of dimuon production this implies no modification of the antiquark sea in the range, $0.1 < x_t < 0.3$. Models of the EMC effect which postulate a significant pion excess or antiquark enhancement in multiquark clusters are apparently ruled out. The Q^2 rescaling model is consistent with the present data. A slight, but experimentally significant, depletion of the yield is seen in the heaviest targets for $x_t < 0.1$.

We have observed that production of the J/ψ and ψ' resonances with 800 GeV protons is strongly 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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