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A MEASUREMENT OF THE DIFFERENCE BETWEEN THE SINGLE NUCLEON
CROSS SECTIONS FOR J/ψ MUOPRODUCTION IN IRON AND IN H_2, D_2 TARGETS

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Abstract

The cross sections for J/ψ production have been measured in interactions of 280 GeV μ^+ on hydrogen and deuterium (H,D) and also in interactions of 250 GeV μ^+ on iron. The single nucleon cross sections in iron are found to be larger than those in H,D. The mean ratio of the iron to H,D photoproduction cross sections in the range $60 < \nu < 200$ GeV is 1.45 ± 0.12 (statistical) ± 0.22 (systematic error). Within the framework of the photon gluon fusion model, this indicates that the gluon density per nucleon is $\sim 45\%$ larger in iron than in H,D in the range $0.026 < x < 0.085$, on a mass scale $Q_{\text{eff}}^2 \sim M_{J/\psi}^2$.

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Recently it was discovered that the nucleon structure functions F_2 measured in iron are not the same as those measured in deuterium (1,2). Many theoretical models have been proposed to explain this effect (3). In order to obtain more experimental information on the effect, results are presented on a comparison of the single nucleon cross section for inclusive J/ψ muoproduction in an iron target with those from hydrogen and deuterium targets. Inclusive J/ψ production is a particularly fruitful channel to study since it has been proposed (4) that the cross sections are proportional to the gluon density in the target.

The data were taken in the M2 muon beam at CERN at an incident muon energy of 280 GeV using a 6 metre long liquid hydrogen or deuterium target and at 250 GeV with an iron target which consisted of a sampling total absorption calorimeter (STAC). Bound and open charm production from the iron data has been fully reported elsewhere (5,6). Decay muons from J/ψ production were detected in the EMC forward spectrometer (7). The trigger for the H,D data demanded a single μ^+ originating from the target region with an angle relative to the beam direction of $\geq 0.5^\circ$. The trigger for the iron data demanded at least two muons from the target region one of which was required to have a minimum vertical opening angle of ± 13 millirads. The H,D data were obtained from 6 experimental runs, 4 with hydrogen and 2 with deuterium in the target. The usable integrated muon fluxes were 7.6×10^{11} and 5.7×10^{11} giving total luminosities of $2.0 \times 10^{37} \text{ cm}^{-2}$ and $3.4 \times 10^{37} \text{ cm}^{-2}$ for the hydrogen and deuterium data, respectively. The iron data were taken in one experimental run in which the usable integrated muon flux was 3.8×10^{11} yielding a luminosity of $3.5 \times 10^{38} \text{ cm}^{-2}$.

For many of the events the scattered muon remained in the beam region, and its momentum could not be directly measured in the spectrometer. In the analysis of the iron data reported in (5) the total energy measurement in the target calorimeter was used to derive the energy of the scattered muons for such events by applying energy conservation. As this measurement was not available for the H,D data which were obtained from conventional liquid targets the scattered muon energies were not measured for these events. Thus the scattered muon was ignored in this analysis as these events were a large fraction of the total sample. The measurements presented are the total muon cross sections for J/ψ production and the muon differential cross sections, $d\sigma/dE_{J/\psi}$, where $E_{J/\psi}$ is the total energy of the J/ψ . The values of the photoproduction cross sections at $Q^2=0$ were then derived from the measured values of $d\sigma/dE_{J/\psi}$. The iron data were reanalysed using exactly the same methods as a consistency check.

Dimuon events were selected for further analysis if they were consistent with having produced the trigger directly and formed a good vertex inside the target volume. In order to reduce background both muons were required to have a momentum greater than 15 GeV/c. Fig. 1 gives the dimuon mass spectra which show clear peaks at the J/ψ mass for each target. The mass resolution for the iron data is much broader than that for H,D due to the multiple Coulomb scattering in the calorimeter target. Mass spectra were produced in each bin in $E_{J/\psi}$. To obtain the number of events per bin the background under the J/ψ peak in H,D (~10%) was subtracted using the average of two control regions on each side of the peak. The background corrections for the iron data were obtained, as in (5), by fitting a smooth background function plus a gaussian to the mass spectrum for each energy bin. The total number of J/ψ events in the reanalysis of the iron data presented here was 1212 ± 50 . The total numbers of J/ψ events from hydrogen and deuterium was 110 ± 11 and 225 ± 16 , respectively.

The acceptance of the apparatus was calculated by Monte Carlo methods. Events were generated and weighted using the best fit parameterisations of the photon-gluon fusion model (8) which gave a good representation of the data reported in (5). Decay muons from the J/ψ were tracked through the forward spectrometer simulating the effects of chamber and hodoscope inefficiencies, multiple Coulomb scattering and measurement errors. Each generated event was accepted if it fulfilled the trigger requirement and would have been detected in the forward spectrometer. Radiative corrections were included in the Monte Carlo using the equivalent radiator approximation. Other radiative corrections which could affect the iron data were estimated to be negligible. For example, Bethe-Heitler production of J/ψ was estimated from the calculations of Ganapathi and Smith (9) and found to be $< 0.1\%$. Higher order processes such as two photon exchange which are more difficult to calculate are small in deep inelastic muon scattering on iron (10). They should also be small in J/ψ production because of the large energy transfer required to produce the J/ψ .

The total muon-nucleon cross sections for J/ψ production in the hydrogen, deuterium and iron targets were 0.49 ± 0.05 , $0.62 \pm .05$ and $0.88 \pm .04$ nbarns, respectively, where the errors are statistical only. Applying the correction for coherent production in iron, as in (5), reduces the single nucleon cross section to $0.74 \pm .03$ nbarn. The smaller coherence corrections in deuterium (~4%) were neglected. To compare the cross sections for nucleons in iron to those in hydrogen and deuterium the iron cross section must be corrected for the difference in

incident muon energy between the iron data (250 GeV) and the H,D data (280 GeV). This correction arises from the changes in the virtual photon flux between the two energies and from kinematic effects. The correction factor is dependent on ν , the virtual photon energy, and varies from 1.05 at $\nu = 70$ GeV to 1.20 at $\nu = 190$ GeV with a mean value of 1.08 when averaged over ν . These corrections were calculated from the Monte Carlo model for the process. After making this correction the total muon cross section per nucleon in iron becomes $0.80 \pm .03$ nbarns at an incident muon energy of 280 GeV.

The single nucleon cross section in iron is larger than those in hydrogen and deuterium. The muon cross section in deuterium is also somewhat larger than that in hydrogen by two standard deviations which is assumed to be a statistical fluctuation. To make a comparison between free or quasi-free nucleons and bound nucleons, the hydrogen and deuterium data have been combined to give a mean cross section per nucleon of $0.55 \pm .04$ nbarn. The ratio of the single nucleon cross section in iron to that in H,D is $1.45 \pm .12$ (statistical) $\pm .22$ (systematic) at 280 GeV incident muon energy. The branching ratio for $J/\psi \rightarrow \mu^+ \mu^-$ has been assumed to be 0.07 throughout this work.

In comparing the iron data with the H,D data systematic errors arise as follows. The normalisation uncertainty between the two samples is $\pm 10\%$. Further systematic errors arise due to unknown nuclear effects. For example, the number of J/ψ obtained on iron should be increased by an estimated 8% if all the J/ψ which interact in the nuclear matter, taking the worst possible case, are destroyed when leaving the iron nucleus. This estimate was made assuming a total J/ψ scattering cross section of 2 millibarns (5). Systematic error also arises from the corrections for coherent production in iron. These coherence corrections could not plausibly be changed by more than 50% which would lead to an overall error on the single nucleon cross section in iron of 10%. Combining these errors in quadrature leads to an overall systematic error of $+16\%$ -14% on the ratio of the single nucleon cross section in iron to those in H,D. It should be noted that a major systematic error in (5) arose from the unknown angular distribution of the decay muon in the J/ψ rest frame. This error cancels when comparing H,D and iron data assuming that the angular distribution is the same for each target.

Fig. 2 shows the energy distribution of the J/ψ , $d\sigma/dE_{J/\psi}$, obtained for both the iron (250 GeV) and the combined H,D data (280 GeV) where corrections for coherence in iron have been made exactly as in (5) and the smaller coherence corrections in deuterium (~4%) again neglected. The iron differential cross sections are systematically larger than the H,D.

In order to compare with data from other experiments, the values of the photoproduction cross sections for J/ψ , $\sigma_Y(Q^2=0, \nu)$, were extracted from the measured values of $d\sigma/dE_{J/\psi}$ (Fig. 2) using the following procedure:

1) As the z distribution (where $z = E_{J/\psi}/\nu$) peaks strongly at $z = 1$ (5) the energy of the J/ψ is, on average, slightly less than ν . Thus $d\sigma/d\nu = k(E_{J/\psi}) d\sigma/dE_{J/\psi}$, where $k(E_{J/\psi})$ is a correction factor which unfolds the z distribution from the energy distribution and varies from between 1.0 at $\nu = 70$ GeV to 1.15 at $\nu = 190$ GeV. The correction factor was determined from the Monte Carlo model for the process based on the iron data reported in reference (5). It is assumed that the z distribution in iron has the same shape as that in H,D which implies that the values of $k(E_{J/\psi})$ are the same for H,D and iron targets. A downstream calorimeter (7) was used for part of the hydrogen data to check the shape of the z distribution from H,D. The measured z distribution was consistent with that from iron reported in (5). Taking extreme z shapes in the Monte Carlo model showed that the systematic error in computing $k(E_{J/\psi})$ was small at $\nu = 70$ GeV and rose to $\pm 6\%$ at $\nu = 190$ GeV.

2) The photoproduction cross section, $\sigma_Y(Q^2=0, \nu)$, was then computed from the values of $d\sigma/d\nu$ as follows,

$$\frac{d\sigma}{d\nu} = \int \frac{d^2\sigma}{dQ^2 d\nu} dQ^2 = \int_{Q^2_{\min}}^{Q^2_{\max}} \Gamma_t(Q^2, \nu) \sigma_Y(Q^2, \nu) dQ^2$$

where $\Gamma_t(Q^2, \nu)$ is the virtual photon flux according to the Hand convention (11), σ_Y is the virtual photoproduction cross section of J/ψ and $Q^2_{\min}$ and $Q^2_{\max}$ are the values at kinematic limits. The Q^2 variation was assumed to follow the form

$$\sigma_Y(Q^2, \nu) = \frac{\sigma_Y(Q^2=0, \nu)}{[1 + \frac{Q^2}{M^2}]^2}$$

which gave a good fit to the data in (5). $\sigma_Y(Q^2=0, \nu)$ was factored out of the integral in each ν bin and the integral evaluated numerically. Dividing the measured value of $d\sigma/d\nu$ by the calculated integral gives $\sigma_Y(Q^2=0, \nu)$. The results were insensitive to the propagator mass, M , and the value used was the mean of those given in (5) i.e. $M = 2.9$ GeV.

When this procedure was applied to the measured values of $d\sigma/dE_{J/\psi}$ from iron the values of $\sigma_Y(Q^2=0, \nu)$ obtained agreed, to within 10%, with those reported in (5). The latter were derived by direct extrapolation to $Q^2=0$ using the observed Q^2 distribution where Q^2 and ν were directly measured from the detected scattered muons. This shows that the above procedure to extract $\sigma_Y(Q^2=0, \nu)$ from $d\sigma/dE_{J/\psi}$ is accurate to about 10% and allows a comparison to be made between the data presented here and other experiments.

Fig. 3 shows the values of $\sigma_Y(Q^2=0, \nu)$ for H,D plotted as a function of ν using this procedure together with the results of other experiments. The straight line shows the fit to the data of Binkley et al (12) on H,D which has a quoted normalisation error of $\pm 15\%$. This is in good agreement with the data presented here and also with the photoproduction data of (13). Fig. 3 also shows that the EMC muoproduction measurements of $\sigma_Y(Q^2=0, \nu)$ (5) for iron agree with those of the BFP group (14). Thus the available measurements on H,D all agree and those on iron also agree with each other. However, the iron cross sections are clearly larger than the H,D cross sections (15). The larger iron cross sections are also apparent in Fig. 2 from this experiment alone.

Photoproduction of J/ψ can be described by the photon gluon fusion model (8). In this model the inelastic events are ascribed to the emission of hard secondary gluons from the charmed quarks. This has been shown to give a good representation of the data for very inelastic production (16) and so these cross sections can be considered to be proportional to the gluon density in the target. The quasi-elastic and elastic cross sections are thought to arise from soft secondary gluon emission and so these cross sections will also depend on the target gluon density. We make the assumption that the total inclusive J/ψ production cross section is proportional to the gluon density per nucleon in the target and, following (4), that the fraction of the momentum of the nucleon carried by the gluon is

$$x \sim \frac{M_{J/\psi}^2}{2M_N v} \quad (1)$$

where $M_{J/\psi}$ and M_N are the J/ψ and nucleon masses, respectively. As shown above the photoproduction cross section $\sigma_Y(Q^2=0, v)$ is proportional to $d\sigma/dE_{J/\psi}$. Thus the ratio of the gluon densities is given by

$$\begin{aligned} \rho &= \left[\frac{G(x, Q^2)_{Fe}}{G(x, Q^2)_{H,D}} \right] Q_{eff}^2 \sim M_{J/\psi}^2 \\ &= \frac{\sigma_Y(Q^2=0, v)_{Fe}}{\sigma_Y(Q^2=0, v)_{H,D}} = \frac{(d\sigma/dE_{J/\psi})_{Fe}}{(d\sigma/dE_{J/\psi})_{H,D}} \quad (2) \end{aligned}$$

where $G(x, Q^2)$ is the gluon density per nucleon at an effective $Q_{eff}^2 \sim M_{J/\psi}^2$

The ratio of the gluon densities, ρ , was obtained from equation (2) using the measured values of $d\sigma/dE_{J/\psi}$, shown in Fig. 2, (i.e. from this experiment alone) after correction for the incident muon energy difference described above. Fig. 4 shows this ratio plotted as a function of x , where x is calculated according to equation (1). The errors are statistical and the systematic errors apply to the overall normalisation of the data. The mass scale associated with these values of the gluon density is $Q_{eff}^2 \sim M_{J/\psi}^2 \sim 10 \text{ GeV}^2$ (17). The ratio has a tendency to fall with x but it could also be constant within the errors. The mean value of the ratio in the range $.026 < x < .085$ is 1.45 ± 0.12 (statistical) ± 0.22 (systematic). Thus, within the assumptions detailed above, the gluon density per bound nucleon in iron is found to be $\sim 45\%$ larger than that in free or quasi-free nucleons in H,D in this x range at $Q_{eff}^2 \sim M_{J/\psi}^2$. The effect of this increase on the integral gluon momentum fraction is small over such a narrow range of x , assuming that the gluon distributions in iron and H,D are similar elsewhere in x .

In conclusion the cross sections for virtual photoproduction of J/ψ per bound nucleon measured from an iron target are larger than those from free or quasi-free nucleons in hydrogen and deuterium. Within the framework of the photon gluon fusion model this implies that the ratio of the gluon densities per bound nucleon in iron to that of free nucleons in the range $.025 < x < .075$, is 1.45 ± 0.12 (statistical) ± 0.22 (systematic) at $Q_{eff}^2 \sim M_{J/\psi}^2$.

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The straight line fit shown on fig. 3 of this paper is the fit given in fig. 3 of the paper by Binkley et al corrected for the branching ratio of $J/\psi \rightarrow \mu^+ \mu^-$ (0.07). The cross sections presented by Binkley et al included 95% of the J/ψ events but excluded the remaining 5% which had an extra particle in their magnetic spectrometer (M. Binkley, private communication).
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Figure Captions

- Fig. 1 Dimuon mass spectra a) from the H,D target, b) from the iron target.
- Fig. 2 The differential cross sections for inclusive muoproduction of J/ψ , $d\sigma/dE_{J/\psi}$ from H,D at 280 GeV and from iron at 250 GeV incident muon energy, measured in this experiment.
- Fig. 3 $\sigma_Y(Q^2=0, \nu)$ ($\gamma N \rightarrow J/\psi X$) as a function of the incident photon energy, ν , from H,D (this experiment, (12) and (13)) and from iron targets (5,14).
- Fig. 4 The ratio, ρ , of the gluon density in iron to that in H,D as a function of $x = M_{J/\psi}^2 / 2M_N \nu$ at $Q_{\text{eff}}^2 \sim M_{J/\psi}^2$.

FIG. 1

FIG. 2

FIG. 3