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Quasielastic J/ψ muoproduction from hydrogen, deuterium, carbon and tin

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Abstract

Quasielastic production of J/ψ mesons has been measured in muon interactions with hydrogen, deuterium, carbon and tin targets at incident muon energies of 200 and 280 GeV. The hydrogen and deuterium data were used to study the transverse momentum distribution of the J/ψ's. These data have been analysed together with previously published ρ^0 data in the framework of the vector meson dominance model. The radii of the J/ψ and the ρ^0 as well as the total J/ψ-N and ρ^0-N cross sections were deduced. From the tin and carbon data the ratio of the quasielastic J/ψ production cross sections, $R_{qe}(\mathrm{Sn/C})$, has been extracted and found to be less than unity. In the Glauber approach this suppression can be related to the J/ψ absorption probability in nuclei. The suppression is also compared to those predicted by various colour transparency models.

1. Introduction

In this paper we present measurements of quasielastic J/ψ muoproduction, i.e. $\mu N \to \mu' J/\psi N$ on hydrogen, deuterium, carbon and tin at incident energies of 200 and 280 GeV. This analysis is a continuation of that presented in previous papers on inelastic J/ψ muoproduction from hydrogen and deuterium [1] and inelastic and coherent production from carbon and tin [2].

At high energies quasielastic J/ψ production is usually described by the coupling of a virtual photon to a $c\bar{c}$-system, which then forms a J/ψ meson. The quasielastic interaction is necessary to put the virtual $c\bar{c}$-system on mass shell. The time to form a J/ψ has not been measured. It is therefore a priori not known whether the quasielastic interaction involves a J/ψ meson or an embrionic $c\bar{c}$-system. If the formation time is long, it is not a J/ψ but rather an expanding $c\bar{c}$-system which interacts elastically with a nucleon. If the corresponding formation length is larger than the nuclear radius, it is possible to study the intranuclear interactions of the $c\bar{c}$-system. In particular, one can test some of the recent QCD inspired models of colour transparency [3–5]. If the formation time is short, one could describe the process in terms of the interaction between the J/ψ and a nucleon. A particular example is the well known vector meson dominance model (VMD) in which it is assumed that a virtual J/ψ scatters elastically off a nucleon [6]. In this case the intranuclear interaction is related to the total J/ψ-N cross section [7].

In the present work the data from the hydrogen and deuterium targets are used to study the transverse momentum distribution of photoproduced J/ψ's. Such a study has also been made for quasielastic ρ^0 production and has been published in Ref. [8]. In the VMD model, these distributions are related to those of elastic hadron-nucleon scattering. Therefore, we compared the distributions of the transverse momentum of photoproduced J/ψ and ρ^0 mesons to that of elastically scattered pions. From this comparison we obtained information on the radii of the J/ψ and ρ^0 and the total J/ψ-N and ρ^0-N cross sections.

The data from the tin and carbon targets were used to study the intranuclear interactions. In the VMD model we can make another estimate of the total

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Table 1
Kinematic variables

$-Q^2 = q^2$	invariant mass squared of the virtual photon
$\nu = E - E'$	energy of the virtual photon in the laboratory frame
$z = E_{J/\psi}/\nu$	fractional energy of the J/ψ in the laboratory frame
p_T^2	the transverse momentum squared of the J/ψ with respect to the photon direction

Table 2
Cuts applied in the event selection

Variable	Range
ν ($E = 200$ GeV)	40 -180 GeV
ν ($E = 280$ GeV)	60 -240 GeV
p_T^2 (H, D)	0 0 -10 $(\mathrm{GeV}/c)^2$
p_T^2 (C, Sn)	0 4 -10 $(\mathrm{GeV}/c)^2$
z (H, D)	0 97- 1 05
z (C, Sn)	0 9 - 1 1
$M_{\mu^+\mu^-}$ (H, D)	2.9 - 3 3 GeV/c^2
$M_{\mu^+\mu^-}$ (C, Sn)	2 7 - 3 5 GeV/c^2

J/ψ-N cross section by comparing the ratio of the quasielastic J/ψ production cross sections $R_{qe}(\mathrm{Sn/C})$ [2] to the absorption probabilities of the J/ψ inside the two nuclei [7]. The result of this comparison may be influenced by the finite formation time of the J/ψ. The influence of the formation of the J/ψ is treated in the models of colour transparency (CT) [3-5,9].

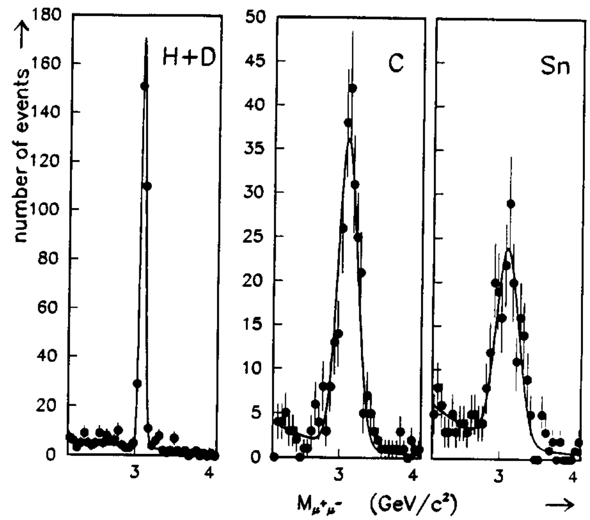

Fig. 1 Invariant mass distributions of $\mu^+\mu^-$ pairs for the combined hydrogen and deuterium data samples and for the carbon and tin data at 280 GeV after applying the cuts listed in Table 1. The smooth curves are fits to the observed distributions (see text).

2. Experiment and results on hydrogen and deuterium

The New Muon Collaboration measured deep inelastic muon scattering with a modified and upgraded version of the EMC forward spectrometer [10] using the M2 muon beam line of the CERN SPS. The data presented here were collected at incident energies of 200 and 280 GeV on carbon and tin targets and at an incident energy of 280 GeV on hydrogen and deuterium targets. The detailed description of the apparatus and of the data analysis can be found elsewhere [1,2]. The kinematic variables used in the present analysis are listed in Table 1. The cuts applied in order to exclude regions of poor acceptance and with high background are listed in Table 2 for the various data samples. The cuts on z and p_T^2 are also listed in Table 2.

Fig. 1 shows the invariant mass distributions of selected muon pairs for the combined hydrogen and deuterium data samples and for the carbon and tin data at 280 GeV. To each mass spectrum the sum of a gaussian distribution and an exponentially falling background was fitted (smooth curves in the figure). After subtracting the fitted background from the number of events in the mass intervals given in Table 2, the numbers of J/ψ events were found to be 280 ± 15 for the hydrogen and deuterium targets together at 280 GeV. For the tin and carbon targets the numbers of J/ψ events are 81 ± 10 and 86 ± 10 at 200 GeV and 177 ± 14 and 255 ± 16 at 280 GeV, respectively. The hydrogen and deuterium data were combined, since the ratio of the cross sections per nucleon for elastic J/ψ production was measured to be equal to unity within the statistical error [11,12].

For the hydrogen and deuterium data the z cut (Table 2) was determined by comparing the slope parameters b obtained from fits of the function $Ae^{-bp_T^2+cp_T^4}$ to the the p_T^2 distributions of the data from various

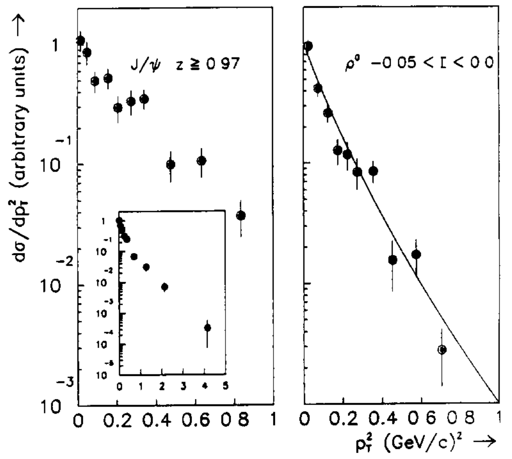

Fig. 2. The cross section as a function of p_T^2 for quasielastic J/ψ events from hydrogen and deuterium together (left) and ρ^0 events from deuterium (right) For the reaction $\gamma^* N \to \rho^0 N$ the elasticity z is related to the inelasticity I by $z \simeq 1 - I$ The curve is a fit to the p_T^2 distribution of elastic pion scattering data of Ref. [14] Inserted is the p_T^2 distribution of J/ψ events over the full measured range.

z intervals. We found that for z above 0.97 the slopes do not vary, whereas for z below 0.97 the slope parameter b gradually becomes smaller. The upper limit of $z = 1.05$ allows for the experiment's finite resolution. The results of the fit are: $b = 5.0 \pm 1.1$ $(\mathrm{GeV}/c)^{-2}$ and $c = 1.5 \pm 1.3$ $(\mathrm{GeV}/c)^{-4}$, in agreement with the results of a fit to the photoproduction data of Ref. [13]. In Fig. 2 the differential cross section is shown as a function of p_T^2, arbitrarily normalised to unity at $p_T^2 = 0$. Also shown in Fig. 2 is the corresponding distribution for quasielastic ρ^0 production [8] on deuterium at 200 GeV. The average Q^2 and ν are: $\langle Q^2 \rangle = 1.5$ GeV^2 and $\langle \nu \rangle = 150$ GeV for the J/ψ's and $\langle Q^2 \rangle = 6$ GeV^2 and $\langle \nu \rangle = 110$ GeV for the ρ^0's. From Fig. 2 it can be seen that the distribution for ρ^0's is steeper than that for J/ψ's. Fitting the same function to the ρ^0 data yields $b = 10.0 \pm 1.3$ $(\mathrm{GeV}/c)^{-2}$ and $c = 4.2 \pm 1.7$ $(\mathrm{GeV}/c)^{-4}$.

3. Analysis in the framework of VMD

At low energies (5–20 GeV), agreement was found between the transverse momentum distribution of photoproduced ρ^0's and that of elastically scattered pions. This observation supports the assumptions of VMD for the photoproduction process of ρ^0's [6]. Therefore we also show in Fig. 2 a fit to the elastic π-N scattering data at 200 GeV incident energy [14]. We find that the transverse momentum distributions of photoproduced ρ^0's and elastically scattered pions also agree at high energies ($\simeq$200 GeV). The p_T^2 distribution of elastic hadron nucleon scattering can be well described by the product of the squared form factors of both the projectile and the target hadron [15]. The observed weak dependence of the p_T^2 slope on the energy of the incident hadron is interpreted differently in various models [16]. In order to minimise this ambiguity we compared the data at the same incident energy. Assuming that in this way the energy dependence is removed, we divided our ρ^0 data by the corresponding values from a fit to the 200 GeV π data [14]. A possible Q^2 dependence of the slope of the ρ^0 data is neglected. This assumption seems valid within the statistical errors quoted in Ref. [8]. We then fitted the function $Ae^{-bp_T^2}$ to this ratio which yielded $b = -0.2 \pm 0.5$ $(\mathrm{GeV}/c)^{-2}$. From this one finds $\langle r_\rho^2 \rangle - \langle r_\pi^2 \rangle = 0.02 \pm 0.05$ fm^2 [17]. Taking the value of the pion radius from Ref. [18], $\langle r_\pi^2 \rangle^{1/2} = 0.67 \pm 0.02$ fm, we obtained $\langle r_\rho^2 \rangle^{1/2} = 0.68 \pm 0.10$ fm. Applying the same procedure to the J/ψ data yields $\langle r_{J/\psi}^2 \rangle^{1/2} = 0.2 \pm 0.1$ fm. This value should be compared to that obtained from charmonium spectroscopy data: $\langle r_{J/\psi}^2 \rangle^{1/2} = 0.22$ fm [19].

In Ref. [20] a phenomenological relation between the rms radius of a hadron and the total hadron-nucleon cross section was found: $\sigma(hN \to X) = a \times \langle r_h^2 \rangle$, with a equal to 60. Using this relation we find $\sigma(J/\psi N \to X) = 2.6 \pm 2.0$ mb and $\sigma(\rho^0 N \to X) = 28 \pm 8$ mb. The latter one is in agreement with that obtained from photoproduction of ρ^0's on nuclei [6].

We also determined the total J/ψ-N cross section from the measured quasielastic production cross section using the vector meson dominance model and the optical theorem [6]. The muoproduction cross section was first converted to the virtual photoproduction cross section following the flux convention of Hand [21]. This cross section was then extrapolated to the real photon limit by fitting the propagator term $(1 + Q^2/M_0^2)^{-2}$ to the Q^2 dependence, yielding $\sigma(\gamma N \to J/\psi N) = 18 \pm 3$ (stat.) nb and $M_0 = 3.2 \pm 0.6$ GeV/c^2 at $\langle \nu \rangle = 150$ GeV. This cross section is in good agreement with the photoproduction data of Ref. [13]. Assuming VMD, the elastic J/ψ-N cross section was calculated from the photoproduction cross section by dividing the latter by the $\gamma - J/\psi$ coupling strength [6]. The forward elastic cross section is then related via the optical theorem to the total J/ψ-N cross section, yielding $\sigma(J/\psi N \rightarrow X) = 1.5 \pm 0.1(\text{stat.}) \pm 0.2(\text{syst.})$ mb. Here we neglected the real part of the elastic amplitude. The quoted systematic error arises from the uncertainty in the z cut that defines the elastic region and from the error on the leptonic width and the $\mu^+\mu^-$ branching ratio of the J/ψ.

4. Results on carbon and tin

The cuts applied to extract the quasielastic events from the carbon and tin data were slightly different from those applied to the hydrogen and deuterium data. In particular the z and p_T^2 cuts differed: $0.9 \leq z \leq 1.1$ and $p_T^2 \geq 0.4$ (GeV/c)^2 [2]. The z cut is less restrictive due to the poorer reolution of the reconstructed kinematics in these targets compared to that in hydrogen and deuterium. The lower limit on p_T^2 is necessary to remove the coherent contributions in carbon and tin [2]. The ratios of the cross sections per nucleon for tin and carbon were found to be $R_{qe}(\text{Sn/C}) = 0.94 \pm 0.14$ and $R_{qe}(\text{Sn/C}) = 0.73 \pm 0.07$ for the 200 and 280 GeV data respectively [2,12]. The measurements show that the ratio is smaller than unity. This indicates that the quasielastic cross section does not scale with the atomic number due to J/ψ absorption .

Since the hydrogen and deuterium data can be analysed in the framework of the VMD model consistently, we have applied the same model in conjunction with the Glauber approach to the analysis of the carbon and tin data. In this approach the absorption probability for the J/ψ inside a nucleus is related to the total J/ψ-N cross section. We can therefore extract $\sigma(J/\psi N \rightarrow X)$ from the measured ratios, assuming that the J/ψ production mechanism is independent of the nucleus. For this purpose we use A_{eff}, the effective number of nucleons, defined by relation $\sigma_A = A_{\text{eff}} \times \sigma_N$, where σ_A and σ_N are the cross sections for a nucleus and a nucleon respectively. Following the Glauber approach A_{eff} can be determined from the integration of the absorption probability over the nuclear density and impact parameters [7]. For quasielastic J/ψ production A_{eff} is then related to the total J/ψ-N cross section and the atomic number A by: $A_{\text{eff}} \simeq A - \sigma(J/\psi N \rightarrow X) \int d^2b T(b)^2$, where $T(b)$ is the optical thickness of the nucleus and b the impact parameter. This relation takes into account the possible absorption of the J/ψ prior to the quasielastic interaction. This can be expected at high energies due to the Lorentz boost that determines the life time of the virtual J/ψ in the laboratory system. In the low energy limit [6], the possible absorption of the J/ψ is introduced after the quasielastic interaction. The attenuation is then two times as small with the same total cross section (see e.g. Ref. [9]). In the present analysis we assumed that the data correspond to the high energy regime. We calculated the optical thicknesses for carbon and tin using the nuclear density parameters quoted in Ref. [22] and [23]. From the measured ratios $R_{qe}(\text{Sn/C}) = [A_{\text{eff}}(\text{Sn})/A_{\text{eff}}(\text{C})] \times [A(\text{C})/A(\text{Sn})]$ we obtained the values $\sigma(J/\psi N \rightarrow X) = 0.8 \pm 1.9$ mb and 3.6 ± 0.9 mb for the 200 and 280 GeV data respectively. These results are in agreement with those obtained from the photoproduction data of Ref. [24] and the hadroproduction data of Ref. [25].

Quasielastic J/ψ production on nuclei has been advocated as a possible test of colour transparency models. In this case, the finite formation time of the J/ψ is incorporated in the production process. In particular the energy dependence of the ratio of the single nucleon cross sections from heavy and light nuclei is believed to be a possible probe of CT. Therefore we show in Fig. 3 the measured ratio $R_{qe}(\text{Sn/C})$ as a function of the photon energy ν. Also shown are the predictions of the models of Ref. [4] (dotted curve) and Ref. [9] (full curve). In these models J/ψ production is described by the coupling of a virtual photon to a $c\bar{c}$-system, which then forms a J/ψ meson. In Ref. [4] the formation time of the J/ψ is related to the time needed for a pointlike $c\bar{c}$-system to reach the size of a J/ψ. At low energies the $c\bar{c}$-system expands to a J/ψ inside the nucleus. The nuclear attenuation is then equal to that of a J/ψ. At higher energies the $c\bar{c}$-system leaves the nucleus before a J/ψ is formed. In that case a small colourless $c\bar{c}$-system is attenuated rather than a J/ψ. Therefore the nuclear attenuation is predicted to decrease with the energy. In Refs. [5,9] a size is attributed to the $c\bar{c}$-system and the formation time is related to the energy difference between the

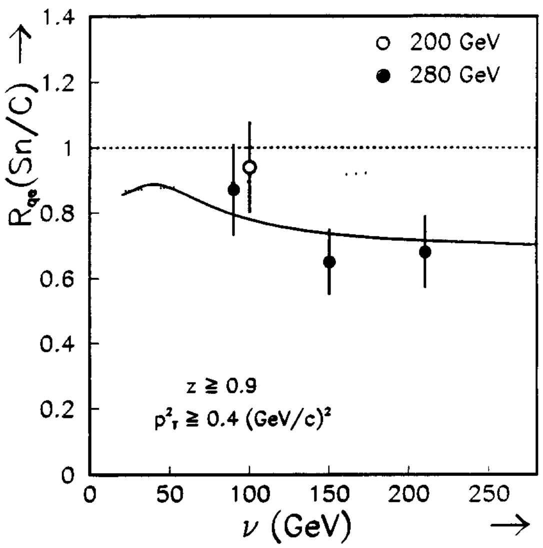

Fig. 3. The ratio of the quasielastic J/ψ production cross sections per nucleon from tin and carbon $R_{qe}(\mathrm{Sn/C})$ as a function of the energy of the photon. The dotted line is the prediction of Ref. [4] and the full line is the prediction of Ref [9].

the J/ψ and ψ'. The energy dependence then arises from the Lorentz boost that determines both the lifetime of the virtual $c\bar{c}$-system and the formation time of the J/ψ meson in the laboratory system. The nuclear attenuation calculated in Refs. [5,9] increases at higher energies, in contrast with the prediction of Refs. [3,4]. From Fig. 3 it can be seen that the prediction of Ref. [4] agrees only at lower energies, whereas the calculation of Refs. [5,9] exhibits the same qualitative behaviour as our data. This indicates that the observed suppression of J/ψ production can be related to the propagation of a $c\bar{c}$ pair through the nuclear medium. However, due to the limited statistics of our measurement we cannot distinguish between the VMD model and models including CT.

In summary, quasielastic J/ψ production from hydrogen, deuterium, carbon and tin has been studied. The p_T^2 distribution of quasielastic J/ψ production is compared to that of ρ^0 production and elastic π scattering. The radii of the J/ψ and the ρ^0 as well as the total J/ψ-N and ρ^0-N cross sections have been deduced. The suppression of J/ψ production in nuclei is analysed in the Glauber approach, providing an independent determination of the total J/ψ-N cross section. The measured energy dependence of $R_{qe}(\mathrm{Sn/C})$ is compared to the predictions of various colour transparency models.

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