PRODUCTION OF CHARMONIUM IN 250 GeV μ^+ -IRON INTERACTIONS

The European Muon Collaboration

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ABSTRACT

The production of J/ψ and ψ' has been measured in 250 GeV muon iron interactions. The measured total cross-sections are $\sigma(\mu N \rightarrow \mu J/\psi X) = 0.74 \pm 0.14 \text{ nb}$ and $\sigma(\mu N \rightarrow \mu \psi' X) = 0.16 \pm 0.07 \text{ nb}$. An upper limit on the cross-section times branching ratio for T production of $\text{BR} \cdot \sigma(\mu N \rightarrow \mu TX) < 5.2 \times 10^{-38} \text{ cm}^2$ (at 90% confidence level) is obtained. About half the J/ψ cross-section is found to have $Z > 0.95$ (where $Z = E(J/\psi)/v$). The first order photon gluon fusion model agrees well with the measured Q^2 and v dependence of the J/ψ data and is used to extract the gluon momentum distribution. However, higher order QCD effects are needed to explain the Z distribution of the J/ψ and the observed broadening of the P_t^2 distribution with decreasing Z . The decay angular distributions of the J/ψ are found to be flat in the s -channel frame, but there is evidence for polarisation in the t -channel frame.

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1. Introduction

J/ψ production has been measured in μ^+ iron interactions at 250 GeV, with an effective luminosity of $3.5 \times 10^{38} \text{ cm}^{-2}$. The J/ψ events were observed through the decay to $\mu^+\mu^-$ with all three final state muons detected. Previous results on J/ψ muoproduction from this experiment at 280 GeV have already been reported [1,2]. The new results presented here are from another experimental run with 5 times the luminosity of the 280 GeV data allowing the J/ψ virtual photoproduction cross-sections to be presented in terms of all the independent kinematic variables. The higher statistics have enabled a measurement of the ψ' production cross-section and an upper limit to be placed on T production.

The production of heavy quark systems is interesting as the large quark mass implies a short distance scale. Thus it provides an ideal testing ground for hard QCD processes. The investigation of the virtual photoproduction of J/ψ allows these studies to be made for charmed quarks. Studies for the corresponding production of open charm are discussed in the following paper [3].

2. Theoretical Models

The theoretical models for this process fall into three categories, namely, photon gluon fusion models, vector meson dominance models and quark anti-quark fusion models.

2.1 Photon gluon fusion models

The lowest order QCD process for charm photo-production is photon-gluon fusion (PGF). This process has been discussed and calculated for real photons by many authors [4-10], and more recently calculated for virtual photons [11-13]. A review of this work is given by Phillips [14]. The cross section for $\gamma g \rightarrow c\bar{c}$ (fig. 1) is calculated using perturbative QCD and then related to $\gamma N \rightarrow c\bar{c}$ by using the gluon distribution $G(\eta)$ of the nucleon where η is the fraction of the nucleon momentum carried by the gluon. Final state interactions, at least the emission or exchange of soft gluons, must take

place in order that the $c\bar{c}$ and the recoil nucleon system are colour singlets in the final state. However, this point is usually neglected in these first order calculations. Only a fraction of the $c\bar{c}$ states result in J/ψ production. Conventionally, the total bound $c\bar{c}$ cross-section up to open charm ($D\bar{D}$) threshold in the $\gamma\gamma$ rest frame is calculated; it is then assumed that the contribution to J/ψ production is a constant fraction, F , of this. A way of estimating F is to use the local duality argument of Fritzsche [15], that all bound $c\bar{c}$ states would be formed with equal probability, leading to $F = 1/7$. However, measurements of the $\psi'/(J/\psi)$ production ratio discussed below show that this postulate is too naive.

The simple PGF model predicts the variation of the cross-section with the virtual photon variables but makes no predictions for the differential momentum spectra of the J/ψ produced. However it is assumed that the J/ψ will be produced with nearly all the energy of the photon. The model has recently been used to give predictions of the dependence of the cross-section on the azimuthal angle between the J/ψ production plane and the lepton scattering plane [17].

Following the experimental observation of a large cross-section for events with energy transferred to other hadrons [2], several developments of PGF involving higher order QCD processes have been proposed [18-26]. In these models it is possible to make predictions of the cross-section and its dependence on the virtual photon variables, (Q^2, ν) , the differential momentum of the J/ψ , (Z, P_t) , and the dependence on the angle of the production plane relative to the lepton scattering plane. Duke and Owens [19,20,23] have made a calculation of the complete set of second order QCD diagrams. This model still requires the factor, F , to relate the $c\bar{c}$ states produced below $D\bar{D}$ threshold to J/ψ production. They find that $F = 1/4.5$ gives agreement with available data [1,2]. In the model of Berger and Jones [18] the $c\bar{c}$ state emits a hard gluon and so forms the colour singlet state necessary for J/ψ production. In addition the formation of the J/ψ from the $c\bar{c}$ state is calculated directly by using an explicit wave-function for the J/ψ , thus avoiding the factor F discussed above. Recent developments of this model have been made to calculate the polarization of the J/ψ [24,25], and the azimuthal angle dependence between the lepton scattering plane and the J/ψ production plane [26].

2.2 Vector meson dominance models.

The traditional model for photoproduction of vector mesons has been vector meson dominance, VMD [27,28], fig. 2. In this model the photon is assumed to couple to the J/ψ which then scatters as a hadron off the nucleon. For virtual photons the process is damped with Q^2 according to the mass scale of the vector meson produced. The J/ψ -photon coupling measured in e^+e^- annihilation may be used to derive the J/ψ nucleon cross-section using this model.

The vector meson dominance model is normally applied to diffractive photoproduction. In diffractive photoproduction of light vector mesons s-channel helicity conservation, SCHC, has been observed for ρ and ω at small values of t [29] and for ϕ over a wide range of t [30]. It is therefore of interest to see if this behaviour is reproduced for heavy quark vector mesons.

2.3 Quark anti-quark fusion model.

A further model for inelastic J/ψ production is $c\bar{c}$ fusion [31,32] shown in fig. 3. This model is similar to that used for hadronic charm production. A $\bar{c}(c)$ quark in the nucleon and a bound state J/ψ is formed. The charm content of the photon is thought to be well known [33] and various nucleon charm quark distributions have been used [34-37]. Predictions have been made for the Feynman x dependence of the cross-section which give a rather flat dependence for positive Feynman x . This result follows from the large Bjorken x behaviour of the photon structure function. In contrast, if the nucleon intrinsic charm distribution of Brodsky et al. [37] is used, a large enhancement at low Feynman x , corresponding to low J/ψ momentum, is predicted. However, there are uncertainties in the $c\bar{c}$ fusion model; two calculations of the same cross-section using the same nucleon charm quark distribution differ by a factor three [31,32].

2.4 A summary of the models

Each of the three models described above pictures the photon-nucleon interaction in a different way. The PGF model involves photon interactions and nucleon structure. VMD involves the hadronic component of the photon and $Q\bar{Q}$ fusion involves the quark structure of the photon. Attempts have been made to reconcile the vector meson dominance model with photon-gluon fusion by regarding the Pomeron or exchanged particle as a colour singlet assembly of partons that form the $c\bar{c}$ and balance colour [38,39]. The predictions of these three models are compared with the results presented in this paper to test their validity. Where possible the parameters of each model are determined from the data.

3. Experiment

The experiment was performed in the M2 muon beam at the CERN SPS using the EMC forward spectrometer which is described in some detail elsewhere [40]. Positive muons of 250 GeV energy were incident on a target consisting of a 3.75 meter long iron-scintillator sampling total absorption calorimeter (STAC), containing 2 cm thick iron plates interspersed with 0.7 cm thick scintillator sheets. The calorimeter target allowed the energy of the hadron showers produced by muon interactions to be measured with a resolution $\sigma/E = 0.56 E^{-0.4}$ (E in GeV) as determined from single arm muon scattering data taken during this experiment. The momentum of each incident muon was determined to an accuracy of ± 0.7 GeV/c and the angle to ± 0.2 mrad by scintillator hodoscopes placed in a spectrometer stage in the beam line and hodoscopes upstream from the target respectively. The beam momentum measurement was checked and found to be accurate to $\pm 0.3\%$ by comparing the momenta of muons measured in both the EMC forward spectrometer and in the beam spectrometer stage. The total spread in momentum of the beam was 8% FWHM and the beam diameter was 4.0 cms FWHM at the target.

Fig. 4 shows a diagram of the EMC spectrometer. Particles leaving the target were detected and momentum analysed in the drift chambers labelled W1-W5 and the multiwire proportional chambers, labelled P0-P3 in fig. 4. Particle tracks which traversed the 2.5 m thick magnetised iron absorber were reconstructed in drift chamber W6-W7 and were assigned to be muons. Each of the

drift chambers and proportional chambers P1-P3 contained a dead region through which the beam passed. Secondary particles which remained in the beam region were detected in the small proportional chambers, P0.

The experiment was triggered by the scintillator hodoscopes H1-H4 shown in fig. 4. The multimMuon trigger used for this experiment demanded at least two particles passing through the iron absorber, both of which satisfied a broadly smeared lower momentum cut extending down to 10 GeV/c. In addition, to avoid triggers from the copious electromagnetic tridents, one of the particles was required to have a minimum vertical angle of ± 13 mrad. These requirements were met by forming coincidences between selected hodoscope elements. A target pointing requirement eliminated most of the unwanted triggers from the beam halo. The remainder were rejected by the veto hodoscopes V1-V3 shown in fig. 4.

The beam intensity was monitored by a random trigger. Knowing the sensitive time and the rate of this random trigger and counting the number of reconstructed muons in coincidence with it, the incident beam flux was measured to an accuracy of $\pm 1\%$ [41]. The total number of reconstructed incident muons for the data presented here was 3.8×10^{11} corresponding to a total useful luminosity of $3.5 \times 10^{38} \text{ cm}^{-2}$.

The scattered muon from J/ψ events tends to emerge at small angles to the beam direction and for about 70% of the events one of the μ^+ remained in the beam region of the apparatus and was not detected in the normal forward spectrometer system. These small angle muons were detected in the two proportional chambers P0A and P0B and reconstructed using the vertex position found from the other tracks in the event. To avoid backgrounds from random hits in P0, tracks were only accepted with at least 3 hits from the 4 planes in each projection. This requirement reduced the reconstruction efficiency to 69%, with a background of $< 5\%$ arising from random hits. The momenta of such small angle tracks were not measured directly but calculated assuming energy balance in the overall event. This assumption was checked for the 30% of events with all three outgoing tracks momentum analysed and found to be correct within the expected resolution.

4. Definitions

For events with $\mu^+ \mu^+ \mu^-$ in the final state there is no certain way of selecting the scattered μ^+ and the following prescription was adopted. The scattered muon was taken to be the faster μ^+ if the ratio of the μ^+ momenta was greater than 1.5, otherwise the smaller angle μ^+ was selected. Monte-Carlo studies showed that the scattered μ^+ was misidentified in 8% of the events using this criterion. The method also optimised the signal to background ratio although it gave a small loss of J/ψ events which was corrected for in the Monte-Carlo simulation. This selection begins to fail for very energetic J/ψ thus limiting the range of v for which data may be presented. At lower v corrections for this effect were made in the acceptance calculations.

Once the above assignment has been made the kinematics of the event can be determined. As in most lepton scattering reactions the process is assumed to proceed via the exchange of a virtual photon emitted by the scattered μ . The virtual photon is then assumed to interact with the nucleon and the J/ψ is produced in this interaction. There is no transverse polarisation of the incident muon or target nucleon so the process is completely described by seven variables which were chosen as follows:

- v - the energy of the virtual photon in laboratory frame = $E - E'$ where E is the incident muon energy and E' is the scattered muon energy.
- $-Q^2$ - the four-momentum transfer squared of the virtual photon = $(P - P')^2$ where P and P' are 4 vectors of the incident and scattered muon respectively.
- Z - the fraction of the energy of the virtual photon carried by the J/ψ as measured in the laboratory frame.
- P_t - the transverse momentum of the J/ψ relative to the virtual photon direction.
- θ_D - the polar angle of the decay μ^+ measured in the Helicity (Hel) or Gottfried-Jackson (G-J) frame. These frames are defined in the J/ψ rest frame and have their z -direction opposite to the recoil hadron momentum and along the incident photon respectively.

- ϕ_D - the azimuthal decay angle measured between the plane containing the decay μ^+ and the z-axis and the plane containing the incident nucleon and the z-axis, where the z-axis is defined in either the G-J or Hel frames.
- ϕ_P - the angle of the J/ ψ production plane to the lepton scattering plane.
- $\phi_{D-P} = \phi_D - \phi_P$.

5. Data

From the total sample of 41571 reconstructed $\mu^+ \mu^+ \mu^-$ candidates, events were selected which had all tracks above 10 GeV. Fig. 5 shows the reconstructed mass of the decay $\mu^+ \mu^-$ for the 39948 surviving events. There is a clear signal for J/ ψ production around 3.1 GeV above a background due to QED tridents [3] which is falling with increasing mass. A fit was made to this distribution using a gaussian function for the J/ ψ and a parameterisation of the background according to the Weibull distribution [42]. The fit yielded a total of 1746 ± 48 J/ ψ , a fitted mass of 3.082 ± 0.007 GeV and a gaussian standard deviation of 0.206 GeV.

Further cuts were made to purify the sample. All events were checked for consistency with having caused the trigger. This eliminated events, produced by triggers from δ rays or electromagnetic showers, for which the efficiency would have been difficult to calculate. The interaction vertex was selected to be in the upstream 2.8 m of the target calorimeter leaving ~ 5 collision lengths of active target to absorb and measure the hadronic shower energy. For J/ ψ events v was restricted to be between 60 and 200 GeV. The above selections removed regions of poor acceptance and also removed some background. The final sample is shown by the shaded histogram in fig. 5. It contains 907 ± 36 J/ ψ events with a signal to background ratio of 5:1.

To study the variation of the J/ ψ production cross-section the data were binned according to their kinematic variables. The mass plot of the data in each bin was fitted in the same way as for the total mass plot. The mass and observed width of the reconstructed J/ ψ was found to be independent of the kinematic variables and was therefore fixed in the final fits.

6. Acceptance Calculations

To obtain cross-sections from the sample of measured events, the acceptance of the apparatus was calculated using a Monte Carlo simulation. The photon-gluon fusion model as given by Weiler [43] was used to describe the (Q^2, ν) dependence of the process. The (Z, p_t^2) distribution of J/ψ 's was chosen by an iterative procedure to yield accepted distributions similar to those seen in the data. The production ϕ_p angular distribution and the J/ψ decay angular distributions were taken to be flat, consistent with those observed in the data. For $Z > 0.95$ a coherent nuclear enhancement was included as $A^2 \exp(135t)^*$, where t is the four-momentum transfer squared between the virtual photon and the J/ψ , (t is related to the p_t^2 of the J/ψ , $p_t^2 \approx -t + t_{\min}$). Events were generated according to the above model at vertices in the target using the observed distributions of incident beam tracks. The scattered muon and the J/ψ decay muons were tracked through the forward spectrometer system. The effects of multiple scattering, energy loss, chamber efficiencies, trigger and reconstruction conditions were included, and the incoming and outgoing muons were allowed to radiate bremsstrahlung photons in the iron target. In addition, the effects of internal radiation were included using the equivalent radiator approximation of Mo and Tsai [44]. Finally, if the acceptance conditions were satisfied, the event parameters were recalculated using the reconstructed tracks. The re-definition of the scattered μ^+ , as described above, was made at this stage.

The resolution of the system found by the Monte Carlo study gave a width for the simulated J/ψ mass peak consistent with that observed in the data. The resolution was such that the very steep p_t^2 distribution expected at small t due to a coherent enhancement could not be measured directly.

7. Higher Mass Resonances

A search for the production of ψ' and T has been made. A fit was made to the mass spectrum of fig. 5 including a second gaussian to allow for a shoulder of ψ' events. The $\psi'-J/\psi$ mass difference was fixed and their

* As discussed in ref. [1]

mass resolutions set equal. The ratio of $\psi'/(J/\psi)$ events was measured to be 0.025 ± 0.011 which, allowing for the difference in branching ratios [60], gives a production ratio of 0.22 ± 0.010 . Data taken from other experimental runs using H2 and D2 targets [59] support this result. Fig. 6 shows the muon pair mass spectrum from these runs indicating ψ' production. A fit to this spectrum yields a production ratio of 0.22 ± 0.12 . Both these results are consistent with the reported value of 0.19 ± 0.06 from a photo-production experiment [16]. This low value of $\psi'/(J/\psi)$ production ratio indicates that relatively few J/ψ 's are produced as daughters of higher mass charmonium states and that the assumptions of Fritzsche are probably wrong [15]. Consequently this effect has been neglected in the analysis of J/ψ production.

The single event with a mass of 10.1 GeV in fig. 5 is a candidate for T or T' production. The extrapolated background from the fit to the mass distribution predicts 0.14 events in the T region (mass 9.1 - 10.3 GeV). The background in the mass spectrum of fig. 5 has been shown to be mainly explained by QED trident production [3]. The calculated yield of trident events in the T mass region is 0.2 events consistent with the value obtained from the above extrapolation. Furthermore the observed event has no deposited shower energy and the background from such elastic tridents is calculated to be only ~ 0.1 events. The acceptance for T production has been calculated to be 12% using a model similar to that for J/ψ production described above. If this event is interpreted as arising from T decay then the production cross-section times leptonic branching ratio (BR) is

$$BR \cdot \sigma(\mu^+ N \rightarrow \mu^+ T_X) = 2.5 \pm 2.5 \times 10^{-38} \text{ cm}^2 \text{ at } 250 \text{ GeV}.$$

Expressing this as an upper limit at 90% confidence level yields

$$BR \cdot \sigma(\mu^+ N \rightarrow \mu^+ T_X) < 5.2 \times 10^{-38} \text{ cm}^2.$$

This result is consistent with the recently reported upper limit at 280 GeV by the BCDMS collaboration [58] of $1.3 \times 10^{-38} \text{ cm}^2$ and indicates that the true cross-section must be close to their upper limit.

8. Cross-sections for J/ψ Photoproduction

The J/ψ production cross-sections were evaluated in two regions of Z , namely, a high Z region $Z > 0.95$ (diffractive production) and a low Z region $Z < 0.95$ taking the branching ratio for $J/\psi \rightarrow \mu^+\mu^-$ to be 7% [60]. Corrections for coherent nuclear production were applied to the high Z region only. Table 1 shows the cross-sections for virtual photoproduction as a function of Q^2 and ν calculated from the observed muon differential cross-sections using the virtual photon flux convention of Hand [45]. In the high Z region the cross sections are given both with and without corrections for coherent production as described in the next section.

The Q^2 dependence of the cross-section is shown in fig. 7 for two ranges of ν ; 60 - 120 GeV and 120 - 200 GeV. This Q^2 dependence was fitted to the mass propagator form $(1 + Q^2/M^2)^{-2}$. For high Z the fit yielded $M = 2.9 \pm 0.3$ GeV and $M = 3.6 \pm 0.4$ GeV for $\langle \nu \rangle = 90$ GeV and $\langle \nu \rangle = 160$ GeV respectively. Corresponding fits for low Z gave $M = 2.3 \pm 0.2$ GeV and $M = 2.7 \pm 0.3$ GeV. The fitted values of M as a function of ν for the two Z ranges are shown in fig. 8. The values of M are in the range expected from the VMD value of the J/ψ mass (3.1 GeV) at high Z and the values obtained by fitting the PGF models of Weiler [43] and Duke and Owens [20] of around 2.7 GeV. There is also a tendency for the low Z data to have a smaller propagator mass as was observed previously [1,2].

Fig. 9 and Table 1(d) show the real photon cross-sections ($Q^2 = 0$) which were extracted for each ν bin by refitting the Q^2 distribution using the mean value of the propagator mass M for the two Z ranges. The curves in Fig. 9 show the PGF calculations of Weiler (43) using first order QCD, and Duke and Owens (20) using second order QCD both with $F = 1/6.5$. The calculations by Berger and Jones (18) of the colour singlet model were a factor 5 below the data. They were repeated by Baier and Rückl (24) who showed that the normalisation in this model is very sensitive to the assumed value of the charmed quark mass, M_c . Their calculation for $M_c = 1.25$ GeV is shown in Fig. 9 (dashed curve).

An alternative but equivalent way of presenting the data in table 1 is to calculate that part of the nucleon structure function F_2 corresponding to J/ψ production, assuming that the longitudinal part of the cross-section is zero.

This is shown in Fig. 10. The contribution of charm production to F_2 is discussed fully in ref. [3].

The gluon momentum distribution $G(\eta)$ may be extracted (43,46) from the data using the PGF model. For fixed ν the contribution to the cross-section is from a fixed range of fractional gluon momentum η . Thus the $G(\eta)$ can be deduced from the ν dependence of the measured cross-sections. Fig. 11 shows the distribution $G(\eta)$ obtained from these data combined with lower energy photo-production data (47-50). The cross-sections for all Z , corrected for coherence, have been used in order to compare with the low energy photoproduction data which contain an indeterminate fraction of inelastic events. A gluon distribution of the form $3(1-\eta)^5/\eta$ gives a good representation of the data as it stands. Adding a reasonable inelastic contribution to the low energy data is unlikely to change the exponent of the $(1-\eta)$ term in the gluon distribution by a significant amount. More comprehensive fits to the PGF model are described later.

The J/ψ nucleon elastic and inelastic scattering cross-sections can be deduced from the measured photon cross-sections at $Q^2 = 0$ using the VMD model assuming that these correspond to the high Z ($Z > 0.95$) and low Z ($Z < 0.95$) regions respectively. In this model the photon cross-sections are scaled by the γ - J/ψ coupling constant [51] yielding at $\langle \nu \rangle = 140$ GeV.

$$\sigma(J/\psi N \rightarrow J/\psi N) = 27 \pm 4 \text{ } \mu\text{b}$$

and $\sigma(J/\psi N \rightarrow J/\psi X) = 79 \pm 12 \text{ } \mu\text{b}.$

Extrapolating the observed t distribution to $t = 0$ gives $\left(\frac{d\sigma}{dt}\right)_{t=0}^{\gamma N \rightarrow J/\psi N} = 90 \pm 20 \text{ nb/GeV}^2$ with an additional systematic error (20%) arising from uncertainties in the subtraction of the coherent part. Using this value with the VMD model and the optical theorem [28] taking the real part of the forward scattering amplitude to be zero gives

$$\sigma_T(J/\psi N) = 2.2 \pm 0.7 \text{ mb},$$

where the error includes the systematic uncertainties.

9. J/ψ Momentum Distributions

There are three independent variables which describe the J/ψ production relative to the virtual photon vector. It is conventional in deep inelastic scattering to take these as Z , P_t^2 and ϕ_p as defined in section 4. Differential cross-sections are represented as a function of Z and P_t^2 , integrated over all other variables and normalised to the measured cross-section at $Q^2 = 0$, $\nu = 140$ GeV. The differential photoproduction cross-sections, $d^2\sigma/dZdP_t^2$ are given in Table 2. For $Z < 0.2$ the acceptance was too small to allow measurement, but the cross-section near this region is low and falling, indicating a negligible contribution.

Coherent scattering, as discussed above, affects only the point at highest Z and lowest P_t^2 ($Z > 0.95$ and $P_t^2 < 0.133$). In order to estimate this from the data, the (Z, P_t^2) distribution was fitted excluding this region by a form:

$$\frac{d^2\sigma}{dZdP_t^2} \propto F(Z) G(Z, P_t^2)$$

where F and G were chosen to parameterize the data. The forms of the functions F and G are given in Table 3. A reasonable fit was obtained ($\chi^2 \approx 100$ for 84 degrees of freedom). Extrapolating into the high Z and low P_t^2 region the predicted cross-section was 1432 nb/GeV^2 compared to the measured value of $2456 \pm 188 \text{ nb/GeV}^2$. This indicates a coherent enhancement which is about 72% of the non coherent part in this bin. The data were corrected for this contribution by assuming a form for the differential cross-section for photoproduction from scattering off iron of

$$\left(\frac{d\sigma}{dt}\right)^{\gamma A} = [A^2 \exp(135t) + A \exp(bt)] \left(\frac{d\sigma}{dt}\right)^{\gamma N}_{t=0}$$

Fig. 12 shows $d\sigma/dP_t^2$ versus P_t^2 for the high Z , ($Z > 0.95$) and low Z , ($Z < 0.95$) regions. The data peak at low P_t^2 but have a broader distribution in P_t^2 than for light hadron production [52]. The low Z data have a broader distribution than the high Z data. The dashed curve plotted is the second order PGF calculation of Duke and Owens [20] which is in fair agreement except at low P_t^2 . The predictions of the colour singlet model of Berger and Jones [18] have a similar shape. The data have been fitted to the sum of two exponentials. For high Z the data, corrected for coherence at low P_t^2 , can be represented by

$$\frac{d\sigma}{dP_t^2} = (89 \pm 15) \exp[(-5.2 \pm 0.6) P_t^2] + (2.3 \pm 0.9) \exp[(-0.66 \pm 0.14) P_t^2],$$

and for low Z by

$$\frac{d\sigma}{dP_t^2} = (65 \pm 10) \exp[(-4.7 \pm 0.6) P_t^2] + (4.0 \pm 0.9) \exp[(-0.58 \pm 0.07) P_t^2].$$

For $P_t^2 > 0.13 \text{ GeV}^2$ the data are, however, better represented by the form $a(P_t)^{-n}$ and were fitted to this form for each bin in Z . Fig. 13 shows the results of these fits and fig. 14 shows the fitted powers of $1/P_t$ versus Z . There is continuous change in shape of the P_t distribution with Z from about $1/P_t^2$ at $Z = 0.5$ to about $1/P_t^4$ at high Z . This indicates that the underlying processes are continuous in Z and that there is no clear change in the physics between low Z and high Z .

The Z distribution $d\sigma/dZ$ integrated over P_t^2 is shown in fig. 15. The data are strongly peaked at high Z but there is a significant tail down to low Z . The distribution is not consistent with being the result of higher mass charmonia decays, as has been discussed previously [2]. The low $\psi'/(J/\psi)$ production ratio discussed in section 7, further rules out this interpretation. In fig. 15, the data are compared with the predictions of the $c\bar{c}$ fusion model [31,32]. These predictions are incompatible with the data for the particular forms of the nucleon $c(x)$ used in the calculations. In particular, the intrinsic charm $c(x)$ distribution of Brodsky et al. [37] is far above the data. However the calculation in ref. [31] is for an intrinsic charm intensity, λ , of 100% whereas λ is expected to be $\sim 1\%$. The data in fig. 15 impose an upper limit on λ of 2.5% with 90% confidence. A better limit has been obtained from an analysis of open charm production from this same experiment [53].

The Z dependences at different P_t values are shown in fig. 16. The high Z peak becomes less steep as P_t increases. The data for $P_t = 1$ and 3 GeV are compared with the second-order PGF [19,20] (solid curve) and the colour singlet [18] (dashed curve) models as calculated by Duke and Owens [23]. The PGF model is in good agreement except at large P_t and high Z . The normalization of both models is not well predicted. However, the shape of the second-order QCD model is still in better agreement with the data than the shape of the colour singlet model.

10. Angular Dependence of the Production Plane (ϕ_p distribution)

The variation of the J/ψ production cross-section with ϕ_p , the angle between the lepton scattering plane and the J/ψ production plane, has been studied. This angle is poorly defined at low Q^2 or low P_t^2 and the data are only presented for $Q^2 > 0.5 \text{ GeV}^2$ and $P_t^2 > 0.5 \text{ GeV}^2$. The data for the high Z and low Z regions are shown in fig. 17, folded about $\phi_p = 0$.

The acceptance corrected data have been fitted to the form

$$\frac{d\sigma}{d\phi_p} = A (1.0 + B \cos \phi_p + C \cos 2\phi_p).$$

The results of these fits are given in Table 4 together with the predictions for the parameters B and C from the models of references 17, 20 and 26. It can be seen that the value of C disagrees with the prediction of Leveille and Weiler [17] at high Z and that of Duke and Owens [20] at low Z both by about two standard deviations. The values of B and C agree with the colour singlet model within the large errors [26].

11. J/ψ Decay Angular Distributions

The polarisation of the produced J/ψ relative to the virtual photon helicity has been studied using the $J/\psi \rightarrow \mu^+ \mu^-$ decay angle distribution. The data were binned in $\cos \theta_D$ and ϕ_{D-P} , (defined in section 4) using both the Gottfried-Jackson (G-J) and Helicity (Hel) reference frames. The distributions were folded in $\cos \theta_D$ about zero and in ϕ_{D-P} about zero and $\pi/2$. The data were again separated into high and low Z regions as defined above. For each sample a further selection for events at low Q^2/P_t^2 ($Q^2 < 0.5$ or $P_t^2 < 0.5 \text{ GeV}^2$) or high Q^2/P_t^2 ($Q^2 > 0.5$ and $P_t^2 > 0.5 \text{ GeV}^2$) was made. At low Q^2 or P_t^2 the ϕ dependence is less well determined because of poor resolution, but the $\cos \theta_D$ dependence is still well determined.

Helicity conservation in the s-channel (SCHC) or t-channel (TCHC) and natural parity exchange (NPE) [54,55] restricts the general form for the angular decay distribution $W(\theta_D, \phi_{D-P})$. After folding in ϕ_{D-P} this general form is

$$W(\theta_D, \phi_{D-P}) = A(1 + \cos^2 \theta_D + 2\epsilon R \sin^2 \theta_D + B \sin^2 \theta_D \cos 2\phi_{D-P}),$$

where B is minus the virtual photon polarisation ϵ , i.e., $B \sim -0.7$ for this experiment. In order to test whether this form describes the data $R (= \sigma_L/\sigma_T)$ has been set to zero and a fit made to the data with B as a free parameter. The effect of resolution smearing in the ϕ_{D-P} distributions has been estimated in Monte Carlo studies. At low P_t^2 ($\leq 0.5 \text{ GeV}^2$) or low Q^2 ($\leq 0.5 \text{ GeV}^2$) the ϕ_{D-P} asymmetry is reduced by a factor 3 and at larger P_t^2 or Q^2 by a factor 1.5. In addition the overall acceptance for the SCHC/NPE decay model is about 16% lower than for the flat decay model. This difference is fairly independent of the other variables. (Q^2 , ν) and (P_t^2 , Z).

The SCHC form has been fitted to the data in both G-J and Hel frames with B as a free parameter. Only data with $\cos \theta_D \leq 0.75$ were included due to poor acceptance for $\cos \theta_D > 0.75$. The results of these fits are given in Table 5. For VMD elastic scattering the high Z sample should be considered. For both frames B is consistent with zero. At high Q^2 and P_t^2 in the Helicity frame B is consistent with the SCHC/NPE prediction. However a similar χ^2 is obtained from a simple fit $W(\theta_D, \phi_{D-P}) = 1 + C \cos^2 \theta_D$ with no ϕ_{D-P} dependence (given in Table 5). The Berkeley-Fermilab-Princeton experiment [56], BFP, has reported good agreement with SCHC/NPE. However the BFP result is based on their observation of a $\cos 2\phi_{D-P}$ dependence but with no strong dependence on $\cos \theta_D$. Indeed their data prefer a $\cos 2\phi_{D-P}$ dependence alone rather than the SCHC/NPE form (A χ^2 of 36 compared with 47 for the same number of degrees of freedom). This is surprising as $\cos \theta_D$ is the better measured quantity and the ϕ_{D-P} distribution depends heavily on smearing corrections.

Fig. 18 shows the data versus $\cos \theta_D$ and ϕ_{D-P} after integrating over the other variable. Also shown is the $\cos \theta_D$ distribution for $Z \leq 0.7$ following Baier and Ruckl [24]. The $\cos \theta_D$ dependence has been fitted to the form $1 + D \cos^2 \theta_D$ while the ϕ_{D-P} dependence was fitted to the form $1 + E \cos 2\phi_{D-P}$. The results of the fits are shown in fig. 18 and the fitted values given in Table 6. There is no evidence for a ϕ_{D-P} dependence in the data even after allowing for smearing effects. This is in conflict with the BFP results. The $\cos \theta_D$ dependence is consistent with flat in the s-channel frame. However in the t-channel a significant positive value of D is observed essentially at all Z . This implies that the J/ψ s are produced preferentially polarised with their spins along the virtual photon direction.

The main systematic error on the normalisation of the J/ψ cross-sections is due to the uncertainty in the decay angular distributions. This is because the acceptance is poor for $\cos \theta_D > 0.75$ and the acceptance corrections can be large in this region. The results of the angular analysis show that these systematic errors are about 16%.

12. Fit to the First Order Photon Gluon Fusion Model

Fits to the first order PGF model were made to the data from this experiment together with the low energy photoproduction data [47-50]. The unknown parameters of the model are, Λ , the QCD scale parameter, F , the fraction of the total charm cross-section below $D\bar{D}$ threshold which forms J/ψ , M_c , the charm quark mass, and $G(\eta)$, the distribution of the gluon fractional momentum, η . The form for $G(\eta)$ was parameterised as $G(\eta) = \frac{(g+1)}{2} \frac{(1-\eta)^g}{h}$ which is normalised so that half the nucleon momentum is carried by gluons. The scale of the strong coupling constant α_s was taken as $(Q^2 + M_{c\bar{c}}^2)$ where $M_{c\bar{c}}$ is the invariant mass of $c\bar{c}$ system. This choice rather than $4M_c^2$ or $M_{J/\psi}^2$ does not effect the conclusions presented here.

The CERN program MINUIT [57] was used to minimise χ^2 between theory and data. An acceptable fit with $\chi^2 = 100.5$ for 73 degrees of freedom was obtained. The best fit values were $M_c = 1.3 \pm 0.1$, $g = 6.8 \pm 1.0$ for a value of $\Lambda = 0.7$ GeV and $F = 0.064$. The same fitted values and a similar χ^2 are obtained for fixed $\Lambda = 0.5$ GeV with $F = 0.093$. Essentially Λ and F are correlated variables which normalise the model to the data in any fit, and as such are not measurable from J/ψ data alone. The charm quark mass, M_c , is primarily sensitive to the Q^2 dependence of the data, however it does affect the threshold rise in v of the cross-section. As described previously $G(\eta)$ is closely related to the v dependence of the cross-section. The results of the fit are shown in fig. 19.

Fixing $M_c = 1.5$ GeV the fitted power of the glue was $g = 5.3 \pm 0.2$ with a χ^2 of 104.3 for 74 degrees of freedom. There is clearly some correlation between M_c and g in the fit. The model is better constrained if the data on open charm production are used in a combined fit. This also allows a measurement of the J/ψ fraction F . Such fits are described in the following paper [3].

Using the results of these fits to extrapolate the cross-section to all virtual photon energies the total muoproduction cross-section has been extracted. For 250 GeV muons this total cross-section is $\sigma(\mu N \rightarrow \mu J/\psi X) = 0.74 \pm 0.14$ nb where the error is mainly systematic.

13. Summary and Conclusions

Heavy quarkonium production has been measured in 250 GeV muon-iron interactions. The cross-section for muoproduction of J/ψ is 0.74 ± 0.14 nb, for ψ' is 0.16 ± 0.07 nb and for Υ decaying to $\mu^+\mu^-$ is $2.5 \pm 2.5 \times 10^{-5}$ nb or $< 5.2 \times 10^{-5}$ nb as an upper limit (90% confidence level).

The real photoproduction cross-section for J/ψ in the ν range 100 - 200 GeV is about 50 nb. The data are peaked at high Z , that is, the J/ψ carries most of the energy of the virtual photon. This may be explained in the VMD model as diffractive J/ψ production. The same effect is also expected in photon-gluon fusion models.

The simple PGF model gives a good representation of the process in ν and Q^2 , but does not predict the Z or P_t dependences. The second order calculations are in reasonable agreement in ν , Q^2 , Z and P_t . Both the first order and second order models contain a somewhat arbitrary normalisation to relate the calculated charm cross-section to the measured J/ψ cross-section. A PGF model [18] which avoids this problem by including gluon emission to form a colour singlet and a specific J/ψ wave-function gives the correct magnitude for the cross-section only if a charmed quark mass of 1.25 GeV is used. In a comparison with the Z distribution of the data at large P_t , the second order QCD model gives a better description than the colour singlet model, even if arbitrary normalisation is allowed. The $c\bar{c}$ fusion model gives predicted cross-sections above the data at small Z . This is evidence against the forms of the nucleon charm quark distributions assumed in the calculation. In particular, if the nucleon contains an intrinsic charm component as proposed to explain hadronic charm production, it must exist at a level smaller than 2.5% of the total nucleon quark content.

The production angular distributions have been studied and are consistent with being flat. The various models predict small asymmetries in these distributions but the data are unable to differentiate between the models. The decay angular distributions are consistent with being flat in the s-channel frame, but indicate a polarisation of J/ψ 's in the t-channel.

The data have been fitted to first order photon gluon fusion. If the charm quark mass M_c is allowed to vary the data prefer a value $M_c = 1.3 \pm 0.1$ GeV with a gluon distribution of the form $G(\eta) = 3.9 \frac{(1-\eta)^{6.8 \pm 1.0}}{\eta}$. An almost equally good fit was obtained with $M_c = 1.5$ GeV and $G(\eta) = 3.15 \frac{(1-\eta)^{5.3 \pm 0.2}}{\eta}$ which are consistent with conventional values.

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	$Q^2 \text{ GeV}^2 \rightarrow 0$	0.18	0.32	0.56	1.0	1.8	3.2	5.6	10.0	18.0
$\nu \text{ GeV} \rightarrow$	-0.18	-0.32	-0.56	-1.0	-1.8	-3.2	-5.6	-10.0	-18.0	-32.0
60-80	17.6 ± 3.7	13.1 ± 5.3	8.3 ± 4.3	17.6 ± 5.6	4.0 ± 2.4	3.0 ± 1.9	2.9 ± 1.8	2.3 ± 1.3	0.6 ± 0.7	0.0 ± 0.7
80-100	24.9 ± 5.1	23.7 ± 7.7	14.8 ± 5.9	12.3 ± 4.6	16.8 ± 4.9	9.9 ± 3.1	6.9 ± 2.5	5.1 ± 2.2	4.4 ± 1.8	0.6 ± 0.7
100-120	23.4 ± 4.2	11.1 ± 4.9	9.7 ± 4.3	10.6 ± 4.4	14.5 ± 4.3	12.9 ± 3.9	7.2 ± 2.9	3.3 ± 1.8	2.3 ± 1.4	4.0 ± 1.8
120-140	35.5 ± 6.4	27.1 ± 9.3	18.3 ± 6.3	16.8 ± 5.8	16.5 ± 5.1	18.3 ± 6.1	16.2 ± 4.8	7.2 ± 3.4	4.9 ± 2.5	1.3 ± 1.3
140-160	17.9 ± 5.1	21.4 ± 7.6	19.2 ± 6.5	26.7 ± 8.4	20.5 ± 6.8	10.9 ± 4.5	11.9 ± 5.0	13.5 ± 4.8	8.4 ± 3.9	3.6 ± 2.5
160-180	33.6 ± 9.6	14.6 ± 8.4	39.9 ± 14.0	16.4 ± 8.7	33.6 ± 10.7	22.6 ± 9.4	6.4 ± 4.7	10.8 ± 6.2	3.6 ± 4.0	4.4 ± 4.4
180-200	28.9 ± 10.0	13.7 ± 9.7	39.2 ± 14.9	16.3 ± 11.3	52.7 ± 20.6	40.2 ± 19.0	7.2 ± 7.2	7.5 ± 8.3	9.9 ± 9.9	0.0 ± 12.2

Table 1 - The J/ψ virtual photoproduction cross-section
 $\sigma(\gamma^*N \rightarrow J/\psi X)$ in nb versus Q^2 and ν .

a) $Z \geq 0.95$ Coherent production not subtracted.

$Q^2 \text{ GeV}^2 \rightarrow$	0	0.18	0.32	0.56	1.0	1.8	3.2	5.6	10.0	18.0
$\nu \text{ GeV} \downarrow$	-0.18	-0.32	-0.56	-1.0	-1.8	-3.2	-5.6	-10.0	-18.0	-32.0
60-80	13.3 ± 2.8	10.0 ± 4.0	6.3 ± 3.3	13.5 ± 4.3	3.2 ± 1.9	2.4 ± 1.5	2.5 ± 1.5	2.1 ± 1.2	0.6 ± 0.6	0.0 ± 0.7
80-100	17.5 ± 3.6	16.7 ± 5.4	10.5 ± 4.2	8.8 ± 3.3	12.2 ± 3.5	7.4 ± 2.3	5.4 ± 1.9	4.3 ± 1.9	4.1 ± 1.7	0.6 ± 0.6
100-120	15.8 ± 2.8	7.5 ± 3.4	6.6 ± 3.0	7.2 ± 3.0	10.1 ± 3.0	9.1 ± 2.8	5.2 ± 2.1	2.6 ± 1.4	2.0 ± 1.2	3.9 ± 1.7
120-140	23.4 ± 4.2	17.9 ± 6.1	12.1 ± 4.2	11.2 ± 3.9	11.1 ± 3.4	12.5 ± 4.2	11.4 ± 3.4	5.3 ± 2.5	4.0 ± 2.1	1.2 ± 1.2
140-160	11.6 ± 3.3	13.9 ± 4.9	12.5 ± 4.3	17.5 ± 5.5	13.4 ± 4.4	7.2 ± 3.0	8.1 ± 3.4	9.6 ± 3.5	6.5 ± 3.0	3.2 ± 2.3
160-180	21.6 ± 6.1	9.4 ± 5.4	25.7 ± 9.0	10.6 ± 5.6	21.8 ± 7.0	14.8 ± 6.2	4.2 ± 3.1	7.5 ± 4.3	2.7 ± 3.0	3.8 ± 3.8
180-200	18.4 ± 6.4	8.7 ± 6.2	25.0 ± 9.5	10.4 ± 7.2	33.9 ± 13.2	26.0 ± 12.3	4.8 ± 4.8	5.1 ± 5.7	7.2 ± 7.2	0.0 ± 10.0

Table 1 (Continued)

b) $Z > 0.95$ Coherent production subtracted.

$Q^2 \text{ GeV}^2 \rightarrow$	0	0.18	0.32	0.56	1.0	1.8	3.2	5.6	10.0	18.0
$\nu \text{ GeV} \rightarrow$	-0.18	-0.32	-0.56	-1.0	-1.8	-3.2	-5.6	-10.0	-18.0	-32.0
60-80	13.6 ± 4.7	5.4 ± 5.4	4.4 ± 4.4	3.4 ± 3.4	5.4 ± 3.8	5.0 ± 3.5	1.4 ± 1.5	0.0 ± 1.2	0.0 ± 1.1	0.0 ± 1.1
80-100	17.4 ± 3.9	24.3 ± 8.5	13.8 ± 5.9	4.6 ± 3.3	9.8 ± 4.4	7.6 ± 3.4	2.7 ± 1.8	3.5 ± 1.8	4.1 ± 1.8	2.3 ± 1.3
100-120	32.0 ± 4.9	15.4 ± 5.9	16.1 ± 6.3	13.0 ± 5.2	19.0 ± 5.3	11.2 ± 4.0	6.6 ± 3.0	4.3 ± 2.1	0.8 ± 0.9	1.7 ± 1.2
120-140	28.4 ± 5.7	23.0 ± 7.4	12.0 ± 5.7	19.7 ± 6.6	15.4 ± 5.2	17.8 ± 6.3	10.3 ± 4.7	4.4 ± 2.6	1.5 ± 1.5	0.0 ± 1.4
140-160	22.3 ± 5.8	27.2 ± 10.0	29.6 ± 8.9	24.9 ± 8.7	17.6 ± 6.5	26.4 ± 8.4	8.6 ± 4.7	3.5 ± 2.7	5.6 ± 3.4	0.0 ± 2.0
160-180	32.6 ± 8.2	25.0 ± 10.4	36.5 ± 12.1	10.9 ± 6.0	18.1 ± 6.1	10.0 ± 5.0	10.2 ± 5.6	6.7 ± 4.0	2.3 ± 2.3	0.0 ± 2.4
180-200	24.3 ± 8.6	28.6 ± 12.3	35.1 ± 12.3	26.7 ± 9.8	31.7 ± 10.1	34.1 ± 11.0	18.0 ± 7.5	14.4 ± 6.5	5.9 ± 4.2	3.1 ± 3.1

Table 1 (Continued)

c) $Z < 0.95$

ν GeV	$\sigma(Q^2=0)$ $Z > 0.95$	$\sigma(Q^2=0)$ $Z > 0.95$ coherence corrected	$\sigma(Q^2=0)$ $Z < 0.95$
60-80	16.0 ± 3.0	12.0 ± 2.1	13.0 ± 4.1
80-100	18.1 ± 2.9	12.8 ± 2.0	16.8 ± 2.9
100-120	16.8 ± 3.0	11.5 ± 2.0	28.0 ± 4.0
120-140	27.5 ± 4.5	18.0 ± 3.0	27.0 ± 3.8
140-160	20.0 ± 3.5	13.0 ± 2.5	28.8 ± 5.2
160-180	33.0 ± 6.5	21.5 ± 4.5	33.5 ± 7.0
180-200	39.0 ± 7.0	24.5 ± 4.5	35.0 ± 6.0

Table 1

d) $\sigma(\gamma^*N \rightarrow J/\psi X)$ nb extrapolated to $Q^2 = 0$ (see text).

P_t^2 (GeV) Z +	0	0.18	0.32	0.56	1.0	1.8	3.2	5.6
	-0.18	-0.32	-0.56	-1.0	-1.8	-3.2	-5.6	-10.0
0.2 -0.3	2.3 ± 2.3	5.8 ± 4.1	0.0 ± 1.4	0.0 ± 0.8	0.9 ± 0.6	0.0 ± 0.2	0.0 ± 0.1	0.0 ± 0.1
0.3 -0.4	2.3 ± 2.3	0.0 ± 2.9	0.0 ± 1.4	0.0 ± 0.8	0.9 ± 0.6	0.2 ± 0.2	0.0 ± 0.1	0.0 ± 0.1
0.4 -0.5	6.6 ± 3.9	0.0 ± 2.4	1.3 ± 1.3	1.3 ± 1.1	0.9 ± 0.6	0.2 ± 0.2	0.2 ± 0.2	0.1 ± 0.1
0.5 -0.6	2.3 ± 2.6	0.0 ± 3.3	7.7 ± 3.5	2.3 ± 1.5	1.3 ± 0.8	0.8 ± 0.4	0.1 ± 0.1	0.1 ± 0.1
0.6 -0.7	18.8 ± 7.4	17.7 ± 7.9	1.6 ± 1.6	6.6 ± 2.6	1.6 ± 0.9	1.8 ± 0.7	0.2 ± 0.2	0.2 ± 0.1
0.7 -0.8	58.2 ± 16.9	22.4 ± 9.9	10.7 ± 4.7	10.5 ± 3.6	4.1 ± 1.4	1.9 ± 0.6	0.7 ± 0.3	0.1 ± 0.1
0.8 -0.9	129.0 ± 28.0	121.1 ± 25.5	30.1 ± 9.7	18.0 ± 5.2	7.3 ± 2.0	2.3 ± 0.8	1.0 ± 0.4	0.2 ± 0.1
0.9 -0.95	510.7 ± 88.8	219.3 ± 53.8	82.1 ± 21.5	34.5 ± 9.1	11.3 ± 3.7	3.3 ± 1.5	1.4 ± 0.6	0.3 ± 0.2
0.95 -1.0	2456.1 ± 188.0	473.9 ± 67.2	219.1 ± 32.3	86.8 ± 14.9	17.6 ± 5.4	10.1 ± 2.3	2.1 ± 0.8	0.6 ± 0.3

Table 2 - The J/ ψ differential photoproduction cross-section

$$\frac{d^2\sigma}{dZdP_t^2} \quad (Q^2 = 0 \text{ GeV}^2, \nu = 140 \text{ GeV}) \quad \text{in nb/GeV}^2$$

Parameter	A	B	C
Fitted Value	53.4 ± 8.8	-10.53 ± 0.12	0.87 ± 0.065
Parameter	H	I	$\chi^2/84$ d.o.f.
Fitted Value	-1.9 ± 0.3	1.43 ± 0.3	100.5

Table 3 - Fit to (Z, P_t^2) dependence of the J/ψ photo-production cross section

$$\frac{d^2\sigma}{dZdP_t^2} = A F(Z) G(Z, P_t^2) \text{ nb/GeV}^2$$

$$\text{with } F = \exp [B(1 - Z)^C],$$

$$G = (P_t^2)^D$$

$$\text{and } D = H + I (1 - Z).$$

			Model Estimates		
Sample	Parameter	Fit value	ref. [17]	ref. [20]	ref. [26]
Z > 0.95	B	-0.11 ± 0.23	-0.3	-	-
Z > 0.95	C	0.43 ± 0.19	0.03	-	-
Z < 0.95	B	0.15 ± 0.20	-	~ 0.0	~ -0.1
Z < 0.95	C	0.11 ± 0.19	-	-0.25	~ -0.1

Table 4 - Fit to ϕ_P angular distribution for J/ψ production
of the form

$$\frac{d\sigma}{d\phi_P} = A(1 + B \cos \phi_P + C \cos 2 \phi_P) \text{ for } P_t^2 > 0.5 \text{ GeV}^2$$

and $Q^2 > 0.5 \text{ GeV}^2$

Table 5 - Fits to J/ψ decay angular distributions $W(\theta_D, \phi_{D-P})$

Sample	B	χ^2 Fit 1	C	χ^2 Fit 2
$Q^2, P_t^2 < 0.5, Z > 0.95$	-0.18 ± 0.15	7.54	0.88 ± 0.77	7.66
$Q^2, P_t^2 > 0.5, Z > 0.95$	0.11 ± 0.32	9.74	0.08 ± 1.1	9.29
$Q^2, P_t^2 < 0.5, Z < 0.95$	0.01 ± 0.17	4.74	0.50 ± 0.69	4.30
$Q^2, P_t^2 > 0.5, Z < 0.95$	-0.28 ± 0.23	14.7	-0.91 ± 0.55	8.98

a) Gottfried-Jackson Frame: fits to the forms:

$$\text{Fit 1: } W(\theta_D, \phi_{D-P}) = A (1 + \cos^2 \theta_D + B \sin^2 \theta_D \cos 2\phi_{D-P})$$

$$\text{Fit 2: } W(\theta_D, \phi_{D-P}) = A (1 + C \cos^2 \theta_D)$$

(10 degrees of freedom)

Sample	B	χ^2 Fit 1	C	χ^2 Fit 2
$Q^2, P_t^2 < 0.5, Z > 0.95$	-0.15 ± 0.16	3.37	-0.46 ± 0.72	3.74
$Q^2, P_t^2 > 0.5, Z > 0.95$	-0.40 ± 0.33	10.5	-0.20 ± 1.1	10.9
$Q^2, P_t^2 < 0.5, Z < 0.95$	0.08 ± 0.18	9.58	-0.35 ± 0.55	5.61
$Q^2, P_t^2 > 0.5, Z < 0.95$	-0.13 ± 0.24	11.4	0.0 ± 0.6	10.5

b) Helicity frame: fits to the forms:

$$\text{Fit 1: } W(\theta_D, \phi_{D-P}) = A (1 + \cos^2 \theta_D + B \sin^2 \theta_D \cos 2\phi_{D-P})$$

$$\text{Fit 2: } W(\theta_D, \phi_{D-P}) = A (1 + C \cos^2 \theta_D)$$

(10 degrees of freedom)

Table 6 - Fits to J/ψ angular decay distributions $W(\theta_D)$, $W(\phi_{D-P})$:

Fit 3 : $W(\theta) = A (1 + D \cos^2 \theta_D)$

Fit 4 : $W(\phi) = A (1 + E \cos 2\phi_{D-P})$

Sample	D	E
$Q^2, P_t^2 < 0.5, Z > 0.95$	1.3 ± 0.8	-0.1 ± 0.1
$Q^2, P_t^2 > 0.5, Z > 0.95$	0.9 ± 0.97	0.07 ± 0.2
$Q^2, P_t^2 < 0.5, Z < 0.95$	0.46 ± 0.39	-0.18 ± 0.10
$Q^2, P_t^2 > 0.5, Z < 0.95$	1.6 ± 0.9	-0.06 ± 0.14
$Z < 0.7$	1.4 ± 0.8	

a) Gottfried-Jackson Frame.

Sample	D	E
$Q^2, P_t^2 < 0.5, Z > 0.95$	0.26 ± 0.45	-0.10 ± 0.09
$Q^2, P_t^2 > 0.5, Z > 0.95$	-0.07 ± 0.53	-0.09 ± 0.18
$Q^2, P_t^2 < 0.5, Z < 0.95$	-0.78 ± 0.30	0.09 ± 0.10
$Q^2, P_t^2 > 0.5, Z < 0.95$	-0.14 ± 0.42	-0.07 ± 0.14
$Z < 0.7$	-0.12 ± 0.63	

b) Helicity frame

FIGURE CAPTIONS

Fig. 1 - The photon gluon fusion process for J/ψ photoproduction.

Fig. 2 - The Vector Meson Dominance model for J/ψ production.

Fig. 3 - The $c\bar{c}$ fusion process for J/ψ photoproduction.

Fig. 4 - Plan view of apparatus showing a schematic three muon event.

Fig. 5 - Mass distribution of the produced muon pair from events of the type $\mu^+ N \rightarrow \mu^+ \mu^+ \mu^- X$. The hatched histogram is the distribution of events after all experimental cuts. The curves are a fit to a gaussian plus a Weibull distribution background.

Fig. 6 - Mass distribution of the produced muon pair obtained with the same apparatus, the STAC target being replaced by a H_2 or D_2 target.

Fig. 7 - $\sigma(\gamma^* N) \nu Q^2$ for different samples a) $\langle \nu \rangle = 90$ GeV, $Z > 0.95$; $\langle \nu \rangle = 160$ GeV, $Z > 0.95$; b) $\langle \nu \rangle = 90$ GeV, $Z < 0.95$; $\langle \nu \rangle = 160$ GeV, $Z < 0.95$. Open circles show data after coherence correction. The curves are fits to the form $1/(1+Q^2/M^2)^2$.

Fig. 8 - Fitted values of the propagator mass, M , as a function of ν ; a) $Z > 0.95$; b) $Z < 0.95$. Open circles show data after coherence corrections.

Fig. 9 - J/ψ photoproduction cross-sections ($Q^2 = 0$) versus ν . a) $Z > 0.95$ after coherence subtraction (open circles); b) $Z > 0.95$ (all data); c) $Z < 0.95$. The high Z curve is calculated by Weiler [43]. The low Z full curve is taken from Duke and Owens [20] for $Z < 0.95$ with $F = 1/6.5$. The dashed curve is the prediction of Baier and Rückl [24] using the model of Berger and Jones [18] but with a charmed quark mass $M_c = 1.25$ GeV.

Fig. 10 - $F_2(J/\psi)$ vs Q^2 ; a) $\langle v \rangle = 90$, $Z > 0.95$; b) $\langle v \rangle = 160$ GeV, $Z > 0.95$;
c) $\langle v \rangle = 90$ GeV, $Z < 0.95$; d) $\langle v \rangle = 160$ GeV, $Z < 0.95$.

Fig. 11 - Gluon momentum distribution derived using first order PGF model. The curve shows the distribution $G(\eta) = 3(1-\eta)^5/\eta$ where the normalisation is arbitrary.

Fig. 12 - $d\sigma/dP_t^2$ for $\langle v \rangle = 140$ GeV, $Q^2 = 0$, versus P_t^2 ; a) $Z > 0.95$,
b) $Z < 0.95$. The full curves are a fit to a sum of two exponentials. The dashed curve shows the predictions of ref. [23].

Fig. 13 - $\frac{d^2\sigma}{dZdP_t^2}$ versus P_t^2 for different bins of Z . The curves are fits to the form $1/P_t^n$, for data with $P_t^2 > 0.18$ GeV².

Fig. 14 - Fitted power of $1/P_t$ versus Z

Fig. 15 - $d\sigma/dZ$ integrated over P_t^2 . The curves are predictions of the $c\bar{c}$ fusion model [31] using different forms for the nucleon charm sea. (See ref. [39] and references therein) B+G = Buras and Gaemers [36], D+L = Donnachie and Landshoff [35]. S/3 = strange sea/3. IC = Intrinsic Charm [37].

Fig. 16 - $\frac{d^2\sigma}{dZdP_t^2}$ at different P_t . The curves are from ref. [23]. Full curves are second-order QCD [19,20], dashed curves are the colour singlet model [18] times a factor 5 (see text).

Fig. 17 - $d\sigma/d\phi_P$ a) $Z > 0.95$, $Q^2 > 0.5$ and $P_t^2 > 0.5$ GeV²;
b) $Z < 0.95$, $Q^2 > 0.5$ and $P_t^2 > 0.5$ GeV².
The curves are the result of the fit described in the text.

Fig. 18 - The one dimensional angular decay distributions $W(\theta_D)$, $W(\phi_{D-P})$.
a) $Z > 0.95$, $Q^2 < 0.5$, $P_t^2 < 0.5$ GeV²;
b) $Z > 0.95$, $Q^2 > 0.5$, $P_t^2 > 0.5$ GeV²;
c) $Z < 0.95$, $Q^2 < 0.5$, $P_t^2 < 0.5$ GeV²;
d) $Z < 0.95$, $Q^2 > 0.5$, $P_t^2 > 0.5$ GeV²;
e) $Z < 0.7$ all Q^2/P_t^2 . The curves are the results of the fits described in the text.

Fig. 19 - Virtual photon cross-sections versus ν for different Q^2 ranges showing the results of a fit to first order PGF. The fitted parameters were $M_c = 1.3$ GeV, $G(\eta) = 3.9 \frac{(1-\eta)^{6.8}}{\eta}$, $\Lambda = 700$ MeV, $F = 0.064$.

FIG. 1

FIG. 2

FIG. 3

Plan view

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

FIG. 14

FIG. 17

FIG. 18

FIG. 19