Fermi National Accelerator Laboratory

FERMILAB-Pub-86/120-E
7000.691
(CBPF-N.F.- 031/86)

An Experimental Study of the A-Dependence of J/ψ Photoproduction*

The Fermilab Tagged Photon Spectrometer Collaboration
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August 1986

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*Submitted to Phys. Rev. Lett.

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Abstract

In an experiment using the Tagged Photon Spectrometer at Fermilab we have studied the photoproduction of J/ψ mesons on hydrogen, beryllium, iron, and lead targets at a mean photon energy of 120 GeV. The p_T^2 spectra were used to separate the coherent diffractive signals from the incoherent signals. We have parameterized the *per nucleus* cross-sections in terms of power law dependences, A^α. For a sample of approximately 2100 $\psi \to \mu^+\mu^-$ events with $E_\psi > 80$ GeV we find that $\alpha = 1.40 \pm 0.06 \pm 0.04$ for the *coherent* diffractive signals and that $\alpha = 0.94 \pm 0.02 \pm 0.03$ for the *incoherent* signals.

Introduction

In the past ten years various groups have measured J/ψ production by real and virtual photons incident on hydrogen and nuclear targets[1–9]. Comparing the results of these experiments, a simple and consistent picture has failed to emerge[10]. In particular, there is some indication that the per-nucleon cross-section for incoherent J/ψ production is greater for Fe targets than for lighter targets (H, D, and Li). We report here measurements of the relative cross-sections for J/ψ production by real photons in the energy range 80 GeV to 190 GeV incident on H, Be, Fe, and Pb targets. The heavier targets were alternated regularly while the hydrogen target was continuously in the beam. Systematic errors due to uncertainties in determining relative fluxes, acceptances, and reconstruction efficiencies are therefore small. The resolution in p_T^2 allows good separation of coherent and incoherent signals. We present the first measurement of the A-dependence of the cross-section for *incoherent* J/ψ production from a single experiment. We also present the first measurement of the A-dependence of the cross-section for *coherent* J/ψ production.

Experimental Details

Our experiment (E691) was run in the Tagged Photon Laboratory at Fermilab in 1985. A 210 GeV e^- beam passed through 0.53 radiation lengths of material where bremsstrahlung photons were generated. The photons were incident on a one meter liquid hydrogen target followed by one of three long ($\approx$2.7 radiation lengths) heavy targets (Figure 1). These were cycled six times through the sequence Be, Fe, Be, Pb over the course of two and a half weeks. The ratios of photon fluxes incident on the hydrogen target for running with Be, Fe, and Pb targets downstream were 1.00:2.57:2.46 with 1% statistical and 2% systematic errors. A 30 radiation length lead absorber shielded the detector from electromagnetic showers initiated in the targets. Dimuons from leptonic ψ decays were detected in the Tagged Photon Spectrometer, an earlier version of which has been described extensively[11].

Data and Analysis

The dimuon mass spectra for the four targets are shown in Figure 2. For this analysis each muon must have momentum greater than 9 GeV/c and the pair must have momentum greater than 80 GeV/c.. The p_T^2 distributions for dimuon pairs in the ψ mass region are shown in Figure 3. For heavy targets the peaks at small p_T^2 arising from coherent scattering off nuclei[12,13] are smeared substantially by multiple scattering in the lead absorber. Monte Carlo studies which correctly describe the observed ψ mass resolution predict that a spike produced at $p_T^2 = 0$ will be observed as an exponential distribution, $dN/dp_T^2 \propto e^{-bp_T^2}$, with $b = 33$ (GeV/c)$^{-2}$.

Essentially all ψs with $p_T^2 > 0.15$ (GeV/c)^2 were produced *incoherently*, so we can use this sample for a first, simple measurement of the relative incoherent signals produced in each of the targets (elastic and inelastic signals combined). The results of fits of the dimuon mass distributions to the sums of Gaussian signal and exponentially falling background shapes are summarized in Table I.

We separate the contributions of the coherent and incoherent signals at low p_T^2 with a simultaneous fit of the $(mass, p_T^2)$ spectra for $p_T^2 < 1$ (GeV/c)^2 to the sums of coherent plus incoherent signal and coherent plus incoherent background shapes. The background shapes are products of exponentials in mass and p_T^2. The signal shapes are Gaussian in mass and exponential in p_T^2. The incoherent p_T^2 exponentials are constrained to be the same for all four target samples except at the lowest p_T^2 (< 0.15 (GeV/c)^2) where the Pauli exclusion principle suppresses incoherent production[12]. The coherent shapes were determined from Monte Carlo studies which convoluted the nuclear elastic scattering form factors and the multiple scattering in the lead absorber. For $p_T^2 > 1$ (GeV/c)^2 all the signal is incoherent and a simple maximum likelihood fit to the mass spectra is used. The total coherent and incoherent signals determined by this procedure are collected in Table I. The projections of these fits are shown as solid curves in Figures 2 and 3.

The ratios of luminosities (*nucleons* per unit area) for the four target samples are 1.00:1.62:0.92:0.42 (H:Be:Fe:Pb). Similarly, the ratios of the geometric acceptances are 0.91:0.99:1.00:1.00. From these numbers and the measured signals we calculate the relative cross-sections which are listed in Table II. The errors there are statistical only. Systematic errors in the relative cross-sections come from instrumental uncertainties, from uncertainties in the assumptions of the fit, and from uncertainties in the corrections, described below, to recover the asymptotic A-dependences[15]. Instrumental uncertainties generate systematic errors in determining the total cross-section for one target relative to the others. Uncertainties in the assumptions of the fits generate systematic errors in separating the coherent and incoherent signals for any one target. These systematic errors for one target tend to be highly correlated with those for the other targets. For example, if the p_T^2 resolution is worse than assumed, all the coherent signals have been underestimated and the incoherent signals overestimated. In calculating the systematic errors for the variation of the cross-sections with A these correlations are included.

Coherent A-Dependence

A simple vector meson dominance model for coherent production of vector mesons by photons[13] predicts that the *per nucleus* cross-section grows as $A^{4/3}$ at asymptotically high energies. Averaging over the energies of this experiment, the requirement that $|t| > |t_{min}|$ reduces the cross-sections for coherent ψ production on Be, Fe, and Pb targets to 0.92, 0.76, and 0.57 times their asymptotic high energy values[16]. Dividing the coherent cross-sections of Table II by these factors, we fit the asymptotic A-dependence of the coherent cross-section (*per nucleus*) to a power law:

$$\sigma_{coh} = \sigma_{coh}^0 A^{\alpha_{coh}}.$$

This yields

$$\alpha_{coh} = 1.40 \pm 0.06 \pm 0.04.$$

The variations in relative cross-sections due to systematic uncertainties which produce the most extreme changes in α define a range of anticipated variation in α. The systematic error has been estimated as the root-mean-square deviation of this range about its central value.

Incoherent A-Dependence

We fit the A-dependence of the incoherent cross-section (*per nucleus*) to the power law form

$$\sigma_{incoh} = \sigma^0_{incoh} A^{\alpha_{incoh}}.$$

For the cross-sections of the simple fit to the $p_T^2 > 0.15$ (GeV/c)^2 data

$$\alpha_{incoh} = 0.94 \pm 0.02 \pm 0.02.$$

For the cross-sections of the multi-dimensional fit to the whole data sample, corrected for suppression due to the Pauli exclusion principle,

$$\alpha_{incoh} = 0.94 \pm 0.02 \pm 0.03.$$

The systematic error is larger here due to the uncertainties of extending the fit to lower p_T^2 where incoherent and coherent signals are mixed.

In hadronic interactions the values of α which describe the A-dependence of inclusive distributions vary with Feynman x and p_T^2[17]. We don't measure Feynman x directly, but a previous experiment has established that low p_T^2 ψ events are predominantly elastic ($\gamma N \to \psi N$) while $p_T^2 > 1$ (GeV/c)^2 event are predominantly inelastic ($\gamma N \to \psi N X$). If incoherent elastic and incoherent inelastic cross-sections have different variations with A, α_{incoh} will vary with p_T^2. Fitting the mass distributions for the indicated p_T^2 ranges we find

$$\begin{array}{ll} \alpha_{incoh} = 0.91 \pm 0.03 & 0.15\ (\text{GeV/c})^2 < p_T^2 < 0.55\ (\text{GeV/c})^2 \\ \alpha_{incoh} = 0.92 \pm 0.04 & 0.55\ (\text{GeV/c})^2 < p_T^2 < 1\ (\text{GeV/c})^2 \\ \alpha_{incoh} = 0.99 \pm 0.04 & p_T^2 > 1\ (\text{GeV/c})^2 \end{array}$$

where only the statistical errors are given. Most systematic errors drop out in comparing these values. The confidence level for the hypothesis that these three values of α_{incoh} are equal is approximately 25%.

Comparison with Previous Experiments

Recently, the European Muon Collaboration (EMC) has reported the cross-section *per nucleon* for incoherent J/ψ production in interactions of 280 GeV μ^+ on H and D and also in interactions of 250 GeV μ^+ on Fe[18]. They find $[\sigma(Fe)/\sigma(H,D)]_\psi = 1.45 \pm 0.12 \pm 0.22$ after extrapolating to $Q^2 = 0$ and correcting for the slightly different beam energies. An early SLAC experiment measured J/ψ production from Be and Ta targets by observing the yield of single muons at a transverse momentum of 1.65 GeV/c with a bremsstrahlung beam produced by 20 GeV electrons[19]. The beam energy was low enough that $|t_{min}|^{1/2}$ was hundreds of MeV and the coherent cross-section very small. After various corrections, they find $[\sigma(Ta)/\sigma(Be)]_\psi = 0.83 \pm 0.06$ for the ratio of *per nucleon* incoherent cross-sections.

To compare our results with those of the EMC and SLAC experiments it is convenient to present their results in terms of a power law variation with A. This translation yields

$\alpha_{EMC} = 1.10 \pm 0.03 \pm 0.04$ (using $A_{H,D} = 1.6$ from the relative flux incident on the H and D targets) and $\alpha_{SLAC} = 0.94 \pm 0.03$. These compare to our result $\alpha_{incoh} = 0.94 \pm 0.02 \pm 0.03$. Although the energy scales of the two experiments are different, the A-dependence measured in the SLAC experiment is the same as the A-dependence measured in this experiment while the A-dependence reported by the EMC is qualitatively different. The observed A-dependence is consistent with the shadowing and absorption due to ψ–N scattering in the target nucleus. Assuming the traditional simple vector meson dominance model [12], $\sigma_{tot}(\psi \mathrm{N})$ is in the range 1-2 mb.

Summary

We have measured the A-dependence of ψ production by real photons in the energy range 80 GeV to 190 GeV. The cross-section for coherent production from nuclei increases with A asymptotically as $A^{\alpha_{coh}}$ with $\alpha_{coh} = 1.40 \pm 0.06 \pm 0.04$. The cross-section for incoherent production from nucleons increases with A as $A^{\alpha_{incoh}}$ with $\alpha_{incoh} = 0.94 \pm 0.02 \pm 0.03$.

Acknowledgements

We gratefully acknowledge the assistance we received from the Fermilab staff and the support staffs at the various universities. We especially thank Jim Peifer and the hydrogen target crew for their tremendous effort. This research was supported by the U. S. Department of Energy, by the Natural Science and Engineering Research Council of Canada through the Institute for Particle Physics, by the National Research Council of Canada, and by the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico.

Footnotes

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[15] We have estimated instrumental uncertainties which may lead to errors in the relative luminosities and the relative acceptances for each target sample. Summed linearly, these come to a few percent for each of the heavy target samples and about ten percent for the hydrogen target sample. We have estimated the uncertainties in the multi-dimensional fit due to the assumed p_T^2 resolution and due to the assumption that all of the incoherent shapes are the same. These uncertainties run from $\pm 1\frac{1}{2}\%$ (σ_{incoh} for Be, due to p_T^2 resolution) to -$7\frac{1}{2}\%$ (σ_{incoh} for Pb, due to incoherent shapes assumption).

[16] We have calculated the energy and t-dependences of the coherent cross-sections using the model of reference [12] with $\sigma_{\psi N} = 0$. The nuclear density function for Be was taken from R. Hofstadter, Ann. Rev. Nucl. Sci., **7**, 231 (1957) and the nuclear density functions for Fe and Pb from H. Alvensleben *et al.*, Phys Rev. Lett. **24**, 792 (1970). The asymptotic cross-sections calculated in this way predict $\alpha_{coh} = 1.40$ for our targets

rather than $\alpha_{coh} = 4/3$ as predicted by the more simple model found in reference [13]. Repeating these calculations assuming that the ψN forward scattering amplitude is purely imaginary and that $\sigma_{\psi N} = 1$ mb changes the energy dependences by less than 1%, reduces the absolute coherent cross-sections by 4% (Be) to 7% (Pb), and changes α_{coh} by less than 0.01.

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Table I: Fitted Signals

Target	H	Be	Fe	Pb
$p_T^2 > 0.15$ (GeV/c)^2	312 ± 19	514 ± 25	240 ± 17	94 ± 11
incoherent, all p_T^2	437 ± 23	673 ± 36	313 ± 22	141 ± 15
coherent	–	221 ± 29	236 ± 22	120 ± 15

These are the signals found by the fits described in the text. The errors reported here are statistical only.

Table II: Relative Cross-Sections

Target	H	Be	Fe	Pb
Relative Cross-Sections				
σ_{incoh}/A, $p_T^2 > 0.15$ (GeV/c)^2	$0.72 \pm .04$	$0.68 \pm .03$	$0.57 \pm .04$	$0.50 \pm .06$
σ_{incoh}/A, all p_T^2	$1.02 \pm .05$	$0.89 \pm .05$	$0.74 \pm .05$	$0.74 \pm .08$
σ_{incoh}/A, all p_T^2, corrected for Pauli exclusion	$1.02 \pm .05$	$1.00 \pm .05$	$0.76 \pm .05$	$0.76 \pm .08$
σ_{coh}/A	–	$0.29 \pm .04$	$0.56 \pm .05$	$0.64 \pm .07$
σ_{coh}/A, corrected for $\|t_{min}\|$	–	$0.32 \pm .04$	$0.73 \pm .07$	$1.11 \pm .12$

These are the relative cross-section *per nucleon* for the signals of Table I. The errors are statistical only. All the cross-sections have been normalized to the cross-section for incoherent ψ production from beryllium, corrected for the suppression at low p_T^2 due to Pauli exclusion.

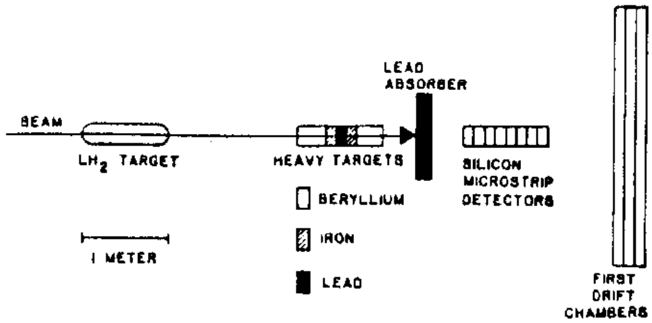

FIGURE 1

Target Region Schematic

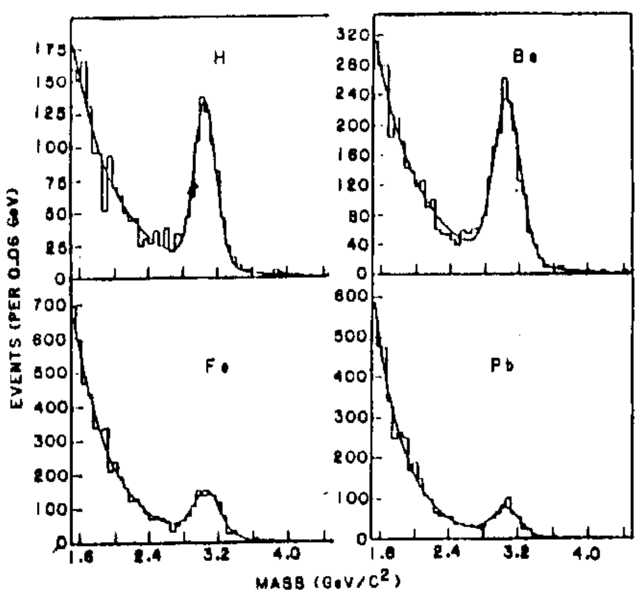

FIGURE 2

The histograms are the dimuon mass spectra for the four target samples. The curves are the projections of the multi-dimensional maximum likelihood fit described in the text.

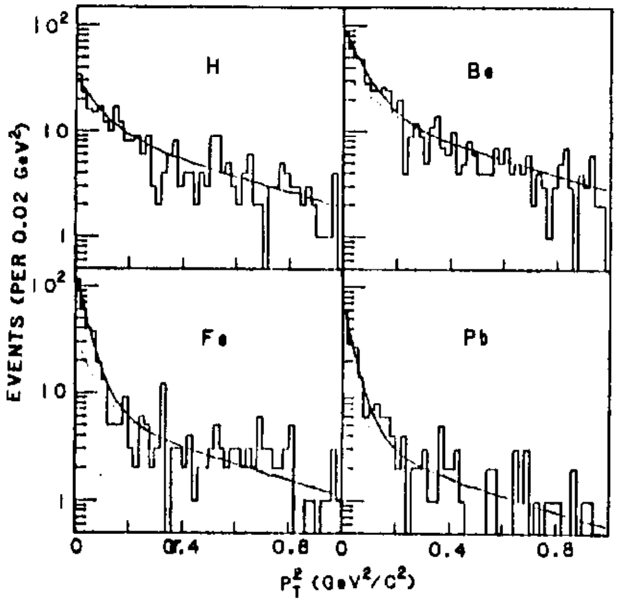

FIGURE 3

The histograms are the p_T^2 spectra for the dimuons in the J/ψ mass region, 2.9 GeV < 3.3 GeV, for the four target samples. The solid curves are the projections of the complete multi-dimensional maximum likelihood fit described in the text. The dotted curves are the sums of the background and incoherent signal contributions. The differences between the solid and dotted curves are the coherent signals' contributions.