# Experimental Study of the $A$ Dependence of $J/\psi$ Photoproduction

M. D. Sokoloff,[5] J. C. Anjos,[3] J. A. Appel,[5] S. B. Bracker,[8] T. E. Browder,[1] L. M. Cremaldi,[4] J. R. Elliott,[4],[a] C. O. Escobar,[7] P. Estabrooks,[2] M. C. Gibney,[4] G. F. Hartner,[8] P. E. Karchin,[1] B. R. Kumar,[8] M. J. Losty,[6] G. J. Luste,[8] P. M. Mantsch,[5] J. F. Martin,[8] S. McHugh,[1] S. R. Menary,[8] R. J. Morrison,[1] T. Nash,[5] P. Ong,[8] J. Pinfold,[2] M. V. Purohit,[5] J. R. Raab,[1] A. F. S. Santoro,[3] J. S. Sidhu,[2] K. Sliwa,[5] M. H. G. Souza,[3] W. J. Spalding,[5] M. E. Streetman,[5] A. B. Stundžia,[8] and M. S. Witherell[1]

(The Tagged-Photon Spectrometer Collaboration)

[1]*University of California, Santa Barbara, Santa Barbara, California 93106*

[2]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*

[3]*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

[4]*University of Colorado, Boulder, Colorado, 80309*

[5]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[6]*National Research Council, Ottawa, Ontario, Canada K1A 0R6*

[7]*Universidad de São Paulo, 01000 São Paulo, Brazil*

[8]*University of Toronto, Toronto, Ontario, Canada M5S 1A7*

(Received 20 August 1986)

We have studied the photoproduction of $J/\psi$ mesons on H, Be, Fe, and Pb targets using real photons at a mean energy of 120 GeV. The $p_t^2$ spectra were used to separate the coherent diffractive signals from the incoherent signals. Parametrizing the *per-nucleus* cross sections in terms of power-law dependences, $A^\alpha$, we find that $\alpha_{\rm coh}=1.40\pm0.06\pm0.04$ for the coherent diffractive signals and $\alpha_{\rm incoh}=0.94\pm0.02\pm0.03$ for the incoherent signals.

PACS numbers: 13.60.Le, 25.20.Lj

In the past ten years various groups have measured $J/\psi$ 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 $J/\psi$ production is greater for Fe targets than for lighter targets (H, D, and Li). We report here measurements of the relative cross sections for $J/\psi$ production by real photons in the energy range 80–190 GeV incident on H, Be, Fe, and Pb targets. The resolution in $p_t^2$ allows good separation of coherent and incoherent signals so that we have been able to extract the $A$ dependences of both coherent and incoherent production.

*Experimental details.*— Our experiment (E691) was run in the Tagged Photon Laboratory at Fermilab. A 210-GeV $e^-$ beam passed through 0.53 radiation lengths of material where bremsstrahlung photons were generated. A 1-m liquid-hydrogen ($LH_2$) target was followed by one of three long ($\approx 2.7$ radiation length) heavy targets (see Fig. 1) which were alternated regularly. The ratios of photon fluxes incident on the $LH_2$ 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 $\psi$ decays were detected in the Tagged Photon Spectrometer, an earlier version of which has been described elsewhere.[11]

*Data and analysis.*— The dimuon mass spectra for the four targets are shown in Fig. 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 $\psi$ mass region are shown in Fig. 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 describe the observed $\psi$ mass resolution well predict that a spike produced at $p_t^2=0$ will be observed as an exponential distribution, $dN/dp_t^2 \propto \exp(-bp_t^2)$, with $b=33$ (GeV/$c$)$^{-2}$.

As essentially all $\psi$'s with $p_t^2>0.15$ (GeV/$c$)$^2$ are produced *incoherently,* we use this sample for a first, simple measurement of the relative incoherent signals produced in each of the targets (elastic and inelastic sig-

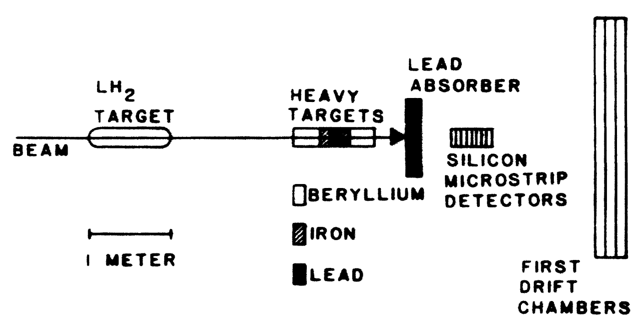


FIG. 1. Target region schematic drawing.

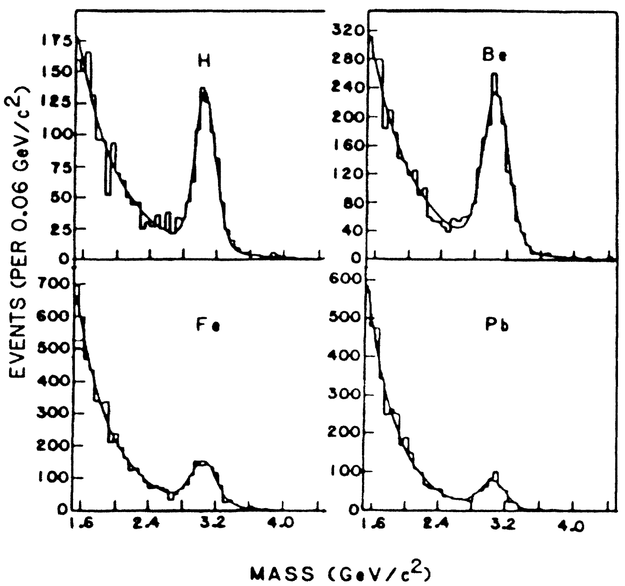


FIG. 2. The histograms are the dimuon mass spectra for the four target samples. The curves are the projections of the multidimensional maximum-likelihood fit described in the text.

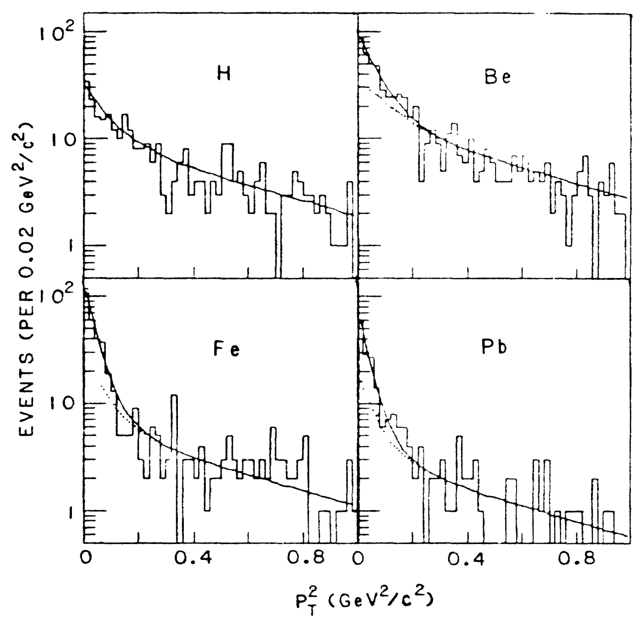


FIG. 3. The histograms are the $p_T^2$ spectra for the dimuons in the $J/\psi$ mass region, 2.9–3.3 GeV/$c^2$, for the four target samples. The solid curves are the projections of the complete multidimensional maximum-likelihood fit described in the text. The dotted curves are the sums of the background and incoherent signal contributions. The differences between the solid and dotted curves are the coherent signals' contributions.

nals combined). The results of fits to the dimuon mass distributions with the sum of Gaussian signals and exponentially falling backgrounds 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 signals and coherent plus incoherent backgrounds. The backgrounds are products of exponentials in mass and $p_T^2$. The signals 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.[12,13] 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/$c$)$^2$ 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 Figs. 2 and 3.

Using the ratios of luminosities (*nucleons* per unit area) for the four target samples (1.00:1.62:0.92:0.42 for H:Be:Fe:Pb) and the ratios of the geometric acceptances (0.91:0.99:1.00:1.00), we calculate the relative cross sections and statistical errors which are listed in Table II. Systematic errors in the extraction of the $A$ dependences come from instrumental uncertainties, from uncertainties in the assumptions used in the fits, and from uncertainties in the procedure described below to recover the asymptotic coherent $A$ dependence. These errors,[14] with their correlations, have been used in the estimation of the systematic errors of the $A$ dependences.

*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 [for $\sigma(\psi N)$ small]. The forward amplitude squared provides a factor of $A^2$ and the integral of the elastic-scattering form factor, $\approx \int \exp(-\beta R_0^2 t)dt$, contributes a factor $A^{-2/3}$ (on the assumption that $R_0 \approx A^{1/3}$ and $\beta$, which depends on nuclear density, is the same for all targets). Using more realistic nuclear wave functions one predicts $A^{1.40}$.[15] Averaging over the energies of this experiment ($\langle E_\gamma \rangle \approx 120$ GeV), the fact that $|t_{\min}| > 0$ reduces the cross sections for coherent $\psi$ production on Be, Fe, and

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

| Target | $p_T^2 > 0.15$ [(GeV/$c$)$^2$] | Incoherent, all $p_T^2$ | Coherent |
|---|---|---|---|
| H | 312 ± 19 | 437 ± 23 | · · · |
| Be | 514 ± 25 | 673 ± 36 | 221 ± 29 |
| Fe | 240 ± 17 | 313 ± 22 | 236 ± 22 |
| Pb | 94 ± 11 | 141 ± 15 | 120 ± 15 |

TABLE II. 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 $\psi$ production from beryllium, corrected for the suppression at low $p_T^2$ due to Pauli exclusion.

| Target | $\sigma_{\rm incoh}/A$, $p_T^2 > 0.15$ [(GeV/$c$)$^2$] | $\sigma_{\rm incoh}/A$, all $p_T^2$ | Relative cross sections $\sigma_{\rm incoh}/A$, all $p_T^2$, corrected for Pauli exclusion | $\sigma_{\rm coh}/A$ | $\sigma_{\rm coh}/A$, corrected for $\lvert t_{\rm min}\rvert$ |
|---|---|---|---|---|---|
| H | $0.72\pm0.04$ | $1.02\pm0.05$ | $1.02\pm0.05$ | ... | ... |
| Be | $0.68\pm0.03$ | $0.89\pm0.05$ | $1.00\pm0.05$ | $0.29\pm0.04$ | $0.32\pm0.04$ |
| Fe | $0.57\pm0.04$ | $0.74\pm0.05$ | $0.76\pm0.05$ | $0.56\pm0.05$ | $0.73\pm0.07$ |
| Pb | $0.50\pm0.06$ | $0.74\pm0.08$ | $0.76\pm0.08$ | $0.64\pm0.07$ | $1.11\pm0.12$ |

Pb targets to 0.92, 0.76, and 0.57 times their asymptotic high-energy values.[15] 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:

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

This yields

$$\alpha_{\rm coh}=1.40\pm0.06\pm0.04.$$

The variations in relative cross sections due to systematic uncertainties which produce the most extreme changes in $\alpha$ define a range of anticipated variation in $\alpha$. The systematic error has been estimated as the rms 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

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

From the cross sections of the simple fit to the $p_T^2>0.15$ (GeV/$c$)$^2$ data we find

$$\alpha_{\rm incoh}=0.94\pm0.02\pm0.02.$$

From the cross sections of the multidimensional fit to the whole data sample, corrected for suppression due to the Pauli exclusion principle, we find

$$\alpha_{\rm incoh}=0.94\pm0.02\pm0.03.$$

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

In hadronic interactions the values of $\alpha$ which describe the $A$ dependence of inclusive distributions vary with Feynman $x$ and $p_T^2$.[16] We do not measure Feynman $x$ directly, but a previous experiment[8] has established that low-$p_T^2$ $\psi$ production is predominantly elastic ($\gamma N\to\psi N$), while for $p_T^2>1$ (GeV/$c$)$^2$ it is predominantly inelastic ($\gamma N\to\psi NX$). If incoherent elastic and incoherent inelastic cross sections have different variations with $A$, $\alpha_{\rm incoh}$ will vary with $p_T^2$. Fitting the mass distributions for the indicated $p_T^2$ ranges we find

$$\alpha_{\rm incoh}=0.91\pm0.03,$$
$$0.15\ ({\rm GeV}/c)^2<p_T^2<0.55\ ({\rm GeV}/c)^2;$$
$$\alpha_{\rm incoh}=0.92\pm0.04,$$
$$0.55\ ({\rm GeV}/c)^2<p_T^2<1\ ({\rm GeV}/c)^2;$$
$$\alpha_{\rm incoh}=0.99\pm0.04,\quad p_T^2>1\ ({\rm GeV}/c)^2,$$

where the errors are statistical. Most systematic errors drop out in comparison with these values. The confidence level for the hypothesis that these three values of $\alpha_{\rm incoh}$ are equal is approximately 25%.

*Comparison with previous experiments.*— Recently, the European Muon Collaboration (EMC) has reported the cross section *per nucleon* for incoherent $J/\psi$ production in interactions of 280-GeV $\mu^+$ on H and D and also in interactions of 250-GeV $\mu^+$ on Fe.[17] They find

$$[\sigma({\rm Fe})/\sigma({\rm H,D})]_\psi=1.45\pm0.12\pm0.22$$

after extrapolating to $Q^2=0$ and correcting for the slightly different beam energies. An early SLAC experiment measured $J/\psi$ production from Be and Ta targets by observation of the yield of single muons at a transverse momentum of 1.65 GeV/$c$ with use of a bremsstrahlung beam produced by 20-GeV electrons.[18] The beam energy is low enough that $\lvert t_{\rm min}\rvert^{1/2}$ is hundreds of MeV/$c$ and the coherent cross section very small. After corrections, they find $[\sigma({\rm Ta})/\sigma({\rm Be})]_\psi=0.83\pm0.06$ for the ratio of *per-nucleon* incoherent cross sections.

If we express these results in terms of power-law variations with $A$, $\alpha_{\rm EMC}=1.10\pm0.03\pm0.04$ (by use of $A_{\rm H,D}=1.6$ from the relative flux incident on the H and D targets) and $\alpha_{\rm SLAC}=0.94\pm0.03$. These compare to our result $\alpha_{\rm incoh}=0.94\pm0.02\pm0.03$. 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. With the assumption of a traditional vector-meson-dominance model,[12,13] the incoherent $A$ dependence observed in this experiment is consistent with shadowing and absorption in the target nucleus with $\sigma_{tot}(\psi N)$ in the range 1–2 mb.

We have measured the $A$ dependence of $\psi$ production by real photons in the energy range 80–190 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 increases as $A^{\alpha_{incoh}}$ with $\alpha_{incoh}=0.94\pm 0.02 \pm 0.03$.

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, the National Science and Engineering Research Council of Canada through the Institute for Particle Physics, the National Research Council of Canada, and the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico.

[(a)]Present address: Electro Magnetic Applications, Inc., Denver, CO, 80226.

[1]B. Knapp, *et al.*, Phys. Rev. Lett. **34**, 1040 (1975).

[2]U. Camerini *et al.*, Phys. Rev. Lett. **35**, 483 (1975).

[3]B. Gittelman *et al.*, Phys. Rev. Lett. **35**, 1616 (1975).

[4]T. Nash *et al.*, Phys. Rev. Lett. **36**, 1233 (1976).

[5]J. J. Aubert *et al.*, Phys. Lett. **89B**, 267 (1980); J. J. Aubert *et al.*, Nucl. Phys. **B213**, 1 (1983).

[6]T. W. Markiewicz, Ph.D. thesis, University of California, Berkeley, 1981 (unpublished); M. Strovink, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Bonn, 1981*, edited by W. Pfeil (Physikalisches Institut, Universität Bonn, Bonn, 1981), pp. 703–729.

[7]M. Binkley *et al.*, Phys. Rev. Lett. **48**, 73 (1982).

[8]B. H. Denby *et al.*, Phys. Rev. Lett. **52**, 795 (1984).

[9]D. Treille *et al.* (NA-14 Collaboration), presented at the International Europhysics Conference on High Energy Physics, Bari, Italy, 1985 (unpublished).

[10]T. Nash, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Ithaca, New York, 1983*, edited by D. Cassel and D. Kreinick (Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY, 1983).

[11]K. Sliwa *et al.*, Phys. Rev. D **32**, 1053 (1985), and references therein.

[12]R. J. Glauber, in *High Energy Physics and Nuclear Structure*, edited by S. Devons (Plenum, New York, 1970), p. 207.

[13]T. H. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978).

[14]Instrumental uncertainties in the relative luminosities and the relative acceptances for each target sample sum linearly to a few percent for each of the heavy target samples and about 10% for the $LH_2$ target sample. The uncertainties in the multidimensional fit due to the assumed $p_T^2$ resolution and due to the assumption that all of the incoherent shapes are the same run from $\pm 1.5\%$ ($\sigma_{incoh}$ for Be, due to $p_T^2$ resolution) to $-7.5\%$ ($\sigma_{incoh}$ for Pb, due to incoherent shapes assumption).

[15]We calculated the energy and $t$ dependences of the coherent cross sections by use of the model of Ref. 13 assuming the $\psi N$ forward cross section is purely imaginary and $\sigma_{\psi N} \rightarrow 0$. 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 coherent $t$ distributions observed experimentally for $\gamma A \rightarrow \psi A$ from Be (Ref. 1) and Li (Ref. 9) targets are consistent with those predicted by this model. Setting $\sigma_{\psi N}=1$ mb changes the energy dependences by less than 1%, reduces the absolute coherent cross sections by 4% (Be) to 7% (Pb), and changes $\alpha_{coh}$ by less than 0.01.

[16]D. S. Barton *et al.*, Phys. Rev. D **27**, 2580 (1983).

[17]J. J. Aubert *et al.*, Phys. Lett. **152B**, 433 (1985).

[18]R. L. Anderson *et al.*, Phys. Rev. Lett. **38**, 263 (1977).