Inelastic and Elastic Photoproduction of J/ψ (3097)

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(Received 9 November 1983)

Inelastic and elastic J/ψ photoproduction on hydrogen are investigated at a mean energy of 105 GeV. The inelastic cross section with $E_\psi/E_\gamma < 0.9$ is significantly lower than the corresponding result for muoproduction on iron targets, but is consistent with a second-order perturbative QCD calculation.

PACS numbers: 13.60.Le, 12.35.Eq, 14.40.Gx

There has been considerable interest in the use of perturbative QCD to describe J/ψ production by real and virtual photons.[1-5] Success has been achieved in describing the energy dependence, and, to a lesser extent, the magnitude of the elastic cross section.[5,6] In the inelastic case, where $z = E_\psi/E_\gamma$ is < 0.9, the exchanged gluon is hard and the calculation is believed to be reliable.[2] This process is therefore a potential source of information on gluons in the nucleon. Recent measurements of inelastic muoproduction cross sections on iron targets[7,8] confirm the dependence upon z predicted[2] by QCD, but significantly exceed the predictions in magnitude. In what follows, and in a more detailed presentation,[9] we describe the production of J/ψ mesons on hydrogen by real photons. The elastic cross section is presented and the inelastic process is described in detail, including the first z dependence measured in photoproduction.

The experiment was performed with the Fermilab tagged-photon spectrometer.[9-11] A tagged photon beam containing 1.0×10^{12} photons with energies

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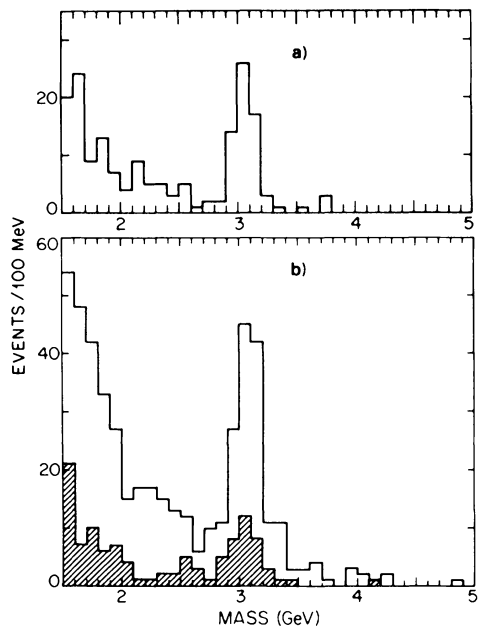

FIG. 1. (a) Dielectron mass spectrum. There are 63 events in the J/ψ mass region, 2.8–3.4 GeV/c^2. (b) Dimuon mass spectrum. There are 147 events in the J/ψ region. The hashed region represents the forward-inelastic events (category 3 of Table I).

from 60 to 160 GeV, and with an average energy of 105 GeV, interacted with a 1.5-m liquid-hydrogen target. The forward spectrometer had nearly full acceptance for charged particles, whose momenta were determined by a system of 29 drift-chamber planes and two magnets, and for photons, whose positions and energies were measured in two large electromagnetic calorimeters. Muons were identified by minimum-ionizing signals in an iron-scintillator hadron calorimeter and hits in a set of scintillator hodoscopes downstream of an iron muon filter. A recoil detector[12] was used to determine the momenta and particle types of tracks emerging from the target at large angles.

A dimuon trigger was created by hits in two or more of the muon hodoscopes. Off line, events with dimuon triggers were required to have at least one pair of oppositely charged identified muons which form a vertex within the target. The resulting dimuon mass plot is shown in Fig. 1(b). The J/ψ mass region is taken to be 2.8 to 3.4 GeV/c^2. The J/ψ is also seen in the e^+e^- decay mode [Fig. 1(a)]. The dielectron events were recorded by a trigger which used measurements of the recoiling proton to select events with a forward mass larger than 2.0 GeV. The elastic cross section is found to be the same, within statistical errors, for both the dielectron and dimuon final states, giving a consistency check on the efficiency of the dimuon trigger. The recoil trigger, used for the dielectron events, had an unknown efficiency for inelastic production since, in this trigger, events were rejected if a second particle was produced within approximately one unit of rapidity of the proton.[10] Consequently, only the dimuon events are used in the inelastic analysis.

Events are classified as inelastic if they satisfy one or both of the following criteria: (1) *Forward inelastic*—Additional forward tracks, photons, or hadronic neutrals accompany the J/ψ. (2) *Recoil inelastic*—The data from the recoil detector are inconsistent with the parameters of the single recoil proton calculated from the incident photon and the reconstructed J/ψ, under the assumption of elastic production. The systematic uncertainty in assigning the 147 dimuon events corresponds to errors of ±11% and ±18% for the forward-inelastic and

TABLE I. The J/ψ data are divided into seven categories as indicated. The first error is statistical; the systematic error follows. Cross sections (only) have an additional 25% normalization uncertainty. Category abbreviations are as follows: FE, forward elastic; FI, forward inelastic; RE, recoil elastic; RI, recoil inelastic.

	Category	Events Raw	Events Background	σ (nb)	Fraction	$\sigma-\psi'$ (nb)	Fraction $-\psi'$
(1)	All	147	23	21.5 ± 2.1 ± 1.4	1.0	19.6 ± 2.1 ± 1.4	1.0
(2)	FE	110	18	14.2 ± 1.6 ± 1.3	0.66 ± 0.03 ± 0.07	14.2 ± 1.6 ± 1.3	0.72 ± 0.03 ± 0.08
(3)	FI	37	4	7.3 ± 1.3 ± 1.0	0.34 ± 0.05 ± 0.06	5.4 ± 1.3 ± 1.1	0.28 ± 0.04 ± 0.05
(4)	FE and RI	33	5	4.4 ± 0.9 ± 1.1	0.20 ± 0.03 ± 0.05	4.4 ± 0.9 ± 1.1	0.22 ± 0.03 ± 0.06
(5)	FE and RE	77	13	9.8 ± 1.4 ± 1.5	0.46 ± 0.04 ± 0.08	9.8 ± 1.4 ± 1.5	0.50 ± 0.04 ± 0.08
(6)	FI or RI	70	9	11.7 ± 1.6 ± 1.3	0.54 ± 0.05 ± 0.07	9.8 ± 1.6 ± 1.3	0.50 ± 0.04 ± 0.07
(7)	Inelastic $z < 0.9$	30	3	6.6 ± 1.3 ± 0.7	0.31 ± 0.05 ± 0.04	5.1 ± 1.3 ± 0.8	0.26 ± 0.04 ± 0.04

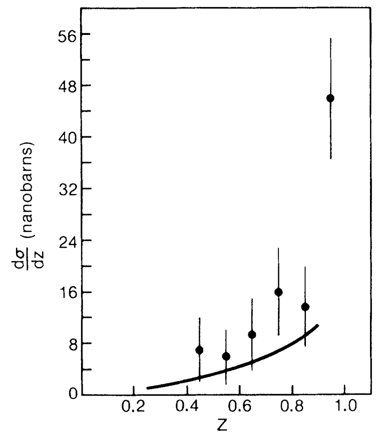

FIG. 2. z distribution for inelastic J/ψ photoproduction. The data have been corrected for ψ' decays. The errors do not include an overall normalization uncertainty of 25%. The data point at $z=0.95$ includes all of the forward-elastic, recoil-inelastic events. The curve shown is the prediction of Berger and Jones (Ref. 2).

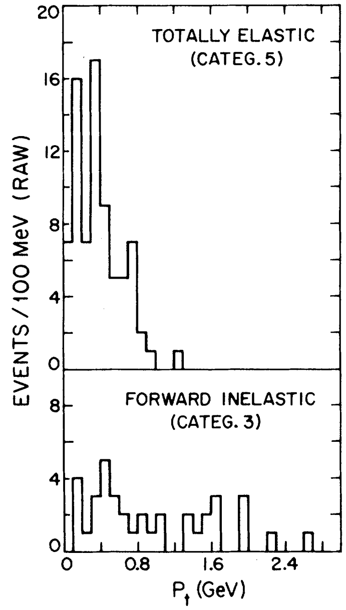

FIG. 3. p_t distributions for totally elastic and forward-inelastic J/ψ events. The mean p_t for the totally elastic events is 0.39 ± 0.11 GeV/c; for the forward-inelastic events, 0.96 ± 0.11 GeV/c.

recoil-inelastic cases, respectively.

The data were divided into seven categories based upon the above classifications (and upon a z cut, as discussed below). In Table I, column 2, the raw numbers of events in each category are displayed. Background was estimated by joining the mass regions above and below the J/ψ with a smooth curve. The hashed area in Fig. 1(b) is the mass spectrum for the forward-inelastic events.

The efficiencies for detection of elastic and inelastic events were calculated by separate Monte Carlo programs. In both cases the efficiency depended mainly on the energy of the J/ψ and was sensitive only at about the 5% level to the exact kinematical distributions. For the inelastic case, large variations in the assumed distribution of the accompanying particles resulted in a 10% variation in the detection efficiencies. The efficiency was essentially zero for $z < 0.4$.

The z value for each event was determined by $z = E_\psi/E_\gamma$, for the case of low-z events; for the higher-z events, where tagging energy resolution can allow $z > 1$, the formula $z = E_\psi/(E_\psi + FE_x)$ was used, where E_x is the detected energy accompanying the J/ψ and F is a factor, 1.84 ± 0.51, which corrects for the average loss of low-energy particles. A cut of $z < \sim 0.9$ (category 7 of Table I) is often used both experimentally[7,8] and in the theory[2] to isolate the truly inelastic process from elastic and quasielastic processes. The cross sections in each

TABLE II. Comparison of inelastic and elastic J/ψ data with other experiments. The first error is statistical if followed by a second (systematic) error; otherwise it is the overall error. The systematic errors for this experiment also contain the normalization uncertainty. Cross sections are in nanobarns.

Expt.	Elastic	Inelastic	Ratio
Present	$\sigma_{FE} = 14.2 \pm 1.6 \pm 3.8$	$\sigma_{z<0.9} = 6.6 \pm 1.3 \pm 1.8$	$\frac{\sigma_{z<0.9}}{\sigma_{FE}} = 0.46 \pm 0.07 \pm 0.08$
BFP	$\sigma_{elastic} = 19.5 \pm 0.7 \pm 2.9$	$\sigma_{z<0.9} = 15.5 \pm 0.7 \pm 3.1$	$\frac{\sigma_{z<0.9}}{\sigma_{elastic}} = 0.79 \pm 0.08$
EMC	$\sigma_{z\geq 0.95} = 12.9 \pm 1.0$	$\sigma_{z<0.95} = 20.6 \pm 1.8$	$\frac{\sigma_{z<0.95}}{\sigma_{z\geq 0.95}} = 1.6 \pm 0.2$
IF	$\sigma_{FE} = 21 \pm 3$	. . .	. . .

category and fractions of the total are shown in Table I, columns 4 and 5. The cross sections have an additional 25% normalization uncertainty.

Four of the forward-inelastic events were fully reconstructed as $\psi' \rightarrow \psi\pi^+\pi^-$. This implies a ψ' photoproduction cross section consistent with previously measured results.[8,13] For comparison with theory it is desirable to measure direct inelastic ψ production as opposed to cascade production from higher-mass charmonium states. To this end, we present in Table I, columns 6 and 7, the cross sections and fractions in each category after subtracting out the contributions estimated from the known ψ' cross section and branching ratios to ψX. The z spectrum for inelastic J/ψ production, after the ψ' correction, is shown in Fig. 2.

In Table II the elastic cross sections from this experiment are compared with extrapolations to $Q^2=0$ of muon measurements made by the Berkeley-Fermilab-Princeton (BFP) collaboration[7] and by the European Muon Collaboration (EMC).[8] These results have been corrected for nuclear effects and we have averaged them over the photon energy range of this experiment. Our elastic cross sections are consistent with both of these measurements within the rather large errors, and also with the Illinois-Fermilab (IF)[14] results, although these experiments are not all consistent with each other.

Also in Table II our $z < \sim 0.9$ inelastic cross section and its ratio to the forward-elastic value is compared with the approximately comparable quantities from the muon experiments. Here we see that our $z < 0.9$ inelastic cross section and the ratio are both significantly less than those values observed in the muon experiments, which again are not in good agreement with each other.

After ψ' subtraction our $z < 0.9$ inelastic cross section is 5.1 ± 1.3(stat.) ± 0.8(syst.) nb. This is slightly more than one standard deviation above the 2.9 nb given by the $z < 0.9$ part of the second-order QCD calculation of Berger and Jones.[2] The $z < 0.9$ inelastic to elastic ratio for this experiment becomes 0.36 ± 0.06(stat.) ± 0.06(syst.) after ψ' subtraction.

From this Table I we see that (31 ± 6)% of the forward-elastic events are recoil inelastic, in excellent agreement with the 30% reported by the IF group[14] for this number. Figure 3 shows that the forward-inelastic J/ψ p_t distribution is much flatter than that of the forward-elastic, recoil-elastic events. This phenomenon is reported also by the BFP[7] and EMC[8] groups.

We wish to acknowledge the assistance of the staff of Fermilab and the technical support staffs of all of the groups involved. This research was supported in part by the U. S. Department of Energy and in part by the Natural Sciences and Engineering Research Council, the Institute of Particle Physics, and the National Research Council (Canada).

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[1]H. Fritzsch and K. Streng, Phys. Lett. 72B, 385 (1978).

[2]E. Berger and D. Jones, Phys. Rev. D 23, 1521 (1981).

[3]D. Duke and J. Owens, Phys. Lett. 96B, 184 (1980).

[4]T. Tajima and T. Watanabe, Phys. Rev. D 23, 1517 (1981).

[5]L. Jones and H. Wyld, Phys. Rev. D 17, 2332 (1978).

[6]T. Weiler, Phys. Rev. Lett. 44, 304 (1980).

[7]T. 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), p. 594.

[8]J. J. Aubert *et al.*, Nucl. Phys. B213, 1 (1983).

[9]B. Denby, Ph.D. thesis, University of California, Santa Barbara, 1983 (unpublished).

[10]A. Duncan, Ph.D. thesis, University of Colorado, 1982 (unpublished).

[11]G. Gidal, B. Armstrong, and A. Rittenberg, Lawrence Berkeley Laboratory Report No. LBL-91, Supplement UC-37, March 1983 (unpublished).

[12]G. Hartner *et al.*, Nucl. Instrum. Methods. 216, 113 (1983).

[13]M. Binkley *et al.*, Phys. Rev. Lett. 50, 302 (1983).

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