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PHOTOPRODUCTION OF THE PSI PARTICLES*

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ABSTRACT

The s and t dependence of incoherent $\psi(3100)$ photoproduction from deuterium has been measured at the Stanford Linear Accelerator Center. $\psi(3700)$ photoproduction and $\psi(3100)$ photoproduction from hydrogen have also been measured.

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Two narrow resonances have recently been discovered, the $\psi(3100)$ and the $\psi(3700)$.[1] Since the original discovery, the $\psi(3100)$ has been observed in photoproduction by 100-200 GeV photons from a Beryillium target at Fermilab.[2] This paper reports the results of photoproduction measurements of psi particles at the Stanford Linear Accelerator Center (SLAC). Both psi particles were detected by observing the decays into lepton pairs.

The experiment was carried out using the 8 GeV and 20 GeV spectrometers instrumented to detect both electron and muon pairs from psi decay. A bremsstrahlung beam from a 5% radiator was incident on 30.3 cm liquid hydrogen or liquid deuterium targets. Identical empty target cells were available for background studies. The beam intensity was monitored with the SLAC 1.6 GeV spectrometer, which was periodically calibrated against a secondary emission quantameter. The overall accuracy of beam intensity monitoring was better than 3%. Typical beam intensities were 2×10^{10} equivalent quanta (EQ) per 1.6 μsec SLAC beam pulse.

The detection system was essentially identical in each spectrometer. Electrons were identified by a threshold gas Cerenkov counter, a lead glass preradiator, and a lead-lucite shower counter. The measured single arm electron yields were principally due to electrons produced directly in the target, and from electrons produced by $\pi^0 \to \gamma\gamma$ decays with subsequent conversion of one of the photons in the target material. Muons were identified with an iron-scintillation counter range telescope. The single arm muon yields, primarily due to muons from pion decay, were typically 3-4% of the pion flux and a factor of 20-30 higher than the single arm electron yields.

The trigger pulses were used to strobe momentum and angle defining hodoscopes. These hodoscopes consisted of proportional wire chambers in the 20

GeV spectrometer, and scintillation counter hodoscopes in the 8 GeV spectrometer. The hodoscope information was used to determine the invariant mass of the electron or muon pair and this information, as well as relative coincidence times between the spectrometers and various pulse height information, was logged on magnetic tape and displayed online by an SDS 9300 computer. The resolution of the hodoscopes was approximately .15% in momentum and 0.3 mrad in production angle, giving an invariant mass resolution of ~20 MeV full width half maximum (FWHM) at an invariant mass of 3 GeV. The mass acceptance of the system, determined by a Monte Carlo calculation using the known acceptances of the individual spectrometers, was ~150 MeV (FWHM). The photon energy acceptance for elastic production was ±2%.

Data were taken for a variety of settings of the spectrometers. Most of the data were taken using the deuterium target in order to maximize the number of nucleons per radiation length. The conditions indicating the detected mass M, the photon energy k assuming elastic production, the bremsstrahlung end point energy E_0, and the invariant momentum transfer t are given in Table I. In each case the spectrometers were set for psi decays near 90° in the psi rest frame. Most data points were taken with a deuterium target and a bremsstrahlung end point energy set 0.50 GeV or 1.0 GeV above the psi energy. Measurements with a bremsstrahlung end point energy 0.50 GeV above the detected psi energy have about 50% acceptance for a recoil mass of 1340 MeV and zero acceptance for recoil masses greater than 1450 MeV. This condition therefore constrains the inelasticity of the production process. The large minimum momentum transfer for psi production at these energies ensures that psi production from the deuteron will be incoherent. Finally, the kinematic conditions are such that $\psi(3100)$ detection from the cascade decay of the $\psi(3700)$ is heavily suppressed.

Figures 1a and 1b show time-of-flight distributions between the two spectrometers for both electron and muon pair triggers for a large sample of the $\psi(3100)$ data. The random background was typically 1% for electron pairs and 20-30% for muon pairs. The hodoscopes were used to sample the invariant mass distribution of the electron and muon pairs. Figures 1c and 1d show the ee and $\mu\mu$ invariant mass distributions for a sample of events which satisfy the time-of-flight criteria. Figure 1e shows the combined muon and electron pair data for the $\psi(3700)$ events which gave a reconstructible mass. The mass plot contains 8 events and a negligible random background.

The mass of the $\psi(3100)$ based on the muon pair events was determined to be 3098 MeV with a systematic uncertainty of 6 MeV. The mass plot for the $\psi(3700)$ data points is centered at a mass of 3684 MeV with an estimated uncertainty of 9 MeV. In all cases the calculated background due to Bethe-Heitler pairs was negligible. The hodoscope information was used only to determine that the observed coincidence signal was in fact psi production and to measure the masses. Cross sections were determined by using the full aperture trigger counter event rate together with the time-of-flight distributions for random background subtraction. The following assumptions were made for cross section determinations:

a. The yields are due to elastic psi production, i.e., $\gamma N \rightarrow \psi N$.

b. The branching ratios for decay into e or μ pairs are 6.9% and 1% for the $\psi(3100)$ and $\psi(3700)$, respectively.[3]

c. The psi particles decay with a $(1 + \cos^2\theta^*)$ distribution in their own rest frame. (The data points correspond to $\theta^* \approx 90^\circ$.)

The cross section results are based on approximately 1200 $\psi(3100)$ events and 13 $\psi(3700)$ events. At high energies where kinematic factors are favorable, yields of 70-90 $\psi(3100)$ events per day were obtained. The measured muon pair yield was approximately a factor 1.7 greater than the electron pair yield. When the data are corrected for the trigger counter acceptances and for radiative corrections, the muon and electron yields are equal within the estimated systematic and statistical errors. Yields from the $\psi(3700)$ were much smaller, primarily due to the smaller branching ratio into lepton pairs.

The results are presented in Table I and Figures 2a and 2b. Table I lists the conditions for which data were taken and the corresponding values of $d\sigma/dt$. Radiative corrections have been made to both the electron and muon yields. The errors indicated in Table I are statistical only. The systematic errors for the electron yields is dominated by the correction for radiative losses, and for the muons is primarily from the uncertainty in solid angle. The overall systematic error for the cross sections is estimated to be 15%. In order to compare cross sections as a function of energy, the t_{min} data have been extrapolated to $t = 0$ by the correction factor $e^{-bt_{min}}$ with $b = 2.9\ (\mathrm{GeV}/c)^{-2}$. The resultant $\psi(3100)$ $t=0$ cross sections are shown as a function of photon energy in Fig. 2a. Fig. 2b shows the $k = 19$ GeV, $E_0 = 20$ GeV data points as a function of t. The main features of the results are as follows:

1. The $k = 19$ GeV, $E_0 = 19.5$ GeV point was run with both a deuterium and a hydrogen target. The deuterium-hydrogen cross section per nucleon ratio is

$$\frac{d\sigma/dt\big|_{D_2}}{d\sigma/dt\big|_{H_2}} = 1.12 \pm .16$$

indicating that $\psi(3100)$ production from the proton and neutron is very similar.

2. Several points taken with different bremsstrahlung end point energies indicate a possible 20-30% inelastic contribution. The measurements made at t_{min} with $k = 15$ GeV and end point energies E_0 of both 16 and 20 GeV indicate that inclusive psi production contributions to the cross section are small. Specifically, using the notation (k, E_0), the cross section ratios were determined to be

$$\frac{d\sigma/dt\ (19,\ 20)}{d\sigma/dt\ (19,\ 19.5)} = 1.25 \pm .14$$

and

$$\frac{d\sigma/dt\ (15,\ 20)}{d\sigma/dt\ (15,\ 16)} = 1.3 \pm .3.$$

3. The values of $d\sigma/dt$ extrapolated to $t = 0$ rise from $\sim$ 7.6 nb/(GeV/c)^2 at $k = 13$ GeV to $\sim$ 20 nb/(GeV/c)^2 at 21 GeV. The rise appears to take place primarily in the region from 13 - 17 GeV.

4. The t distribution at $k = 19$ GeV, $E_0 = 20$ GeV has a fitted slope parameter $b = 2.9 \pm .3$(GeV/c)$^{-2}$ where b is defined by $d\sigma/dt \sim e^{bt}$. This slope is significantly smaller than the slopes associated with the photoproduction of the other vector mesons.

5. A small sample of data was taken with an incident electron beam. Subtracting the contribution from real and virtual photons, the direct electron production cross section for the $\psi(3100)$ is determined to be $\leq$ 5% of the photon production cross section.

6. $\psi(3700)$ photoproduction has been observed at t_{min} for $k = 21$ GeV. Assuming a branching ratio of 1% into either e or μ pairs for the $\psi(3700)$, the cross section ratio at t_{min} is:

$$\frac{d\sigma/dt(\psi(3100))}{d\sigma/dt\ (\psi(3700))} = 6.8 \pm 2.4$$

7. The value of $\left.\frac{d\sigma}{dt}\right|_{t=0} = 17.8 \pm 1.5$, nb/(GeV/c)^2 at 21 GeV can be compared with the recent photoproduction experiment performed at FNAL which gives a value of $\left.\frac{d\sigma}{dt}\right|_{t=0} = 40 \pm 13$ nb/(GeV/c)^2 at a mean energy of ~ 100 GeV.[4] $\left.\frac{d\sigma}{dt}\right|_{t=0}$ has therefore increased by a factor of ~ 2 in going from 21 GeV to 100 GeV incident photon energy.

8. If the photoproduction of the psi is psi dominated (in analogy to the usual vector dominance arguments), then

$$d\sigma/dt\Big|_{t=0}(\gamma N \rightarrow \psi N) = \alpha/4\left(\frac{\gamma\psi^2}{4\pi}\right)^{-1} d\sigma/dt\Big|_{t=0}(\psi N \rightarrow \psi N)$$

giving a value of

$$d\sigma/dt\Big|_{t=0}(\psi N \rightarrow \psi N) \simeq 25\ \mu b/(GeV/c)^2$$

for the $\psi(3100)$, and a similar value for the $\psi(3700)$. These values can be compared to

$$d\sigma/dt\Big|_{t=0} \simeq 30\ mb/(GeV/c)^2 \text{ for } \pi N \text{ elastic scattering or}$$

$$d\sigma/dt\Big|_{t=0} \simeq 4\ mb/(GeV/c)^2 \text{ for } \phi N \text{ elastic scattering.}^{5}$$

If, in addition, the phase of the forward ψN scattering amplitude is assumed to be pure imaginary, the optical theorem can be used to determine the ψN total cross section. More generally, this procedure sets an upper limit for $\sigma_{TOT}(\psi N)$ of $\sigma_{TOT}(\psi N) \leq 0.8$ mb, to be compared with typical hadronic total cross sections of ~ 25 mb.

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REFERENCES

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2. B. Knapp et al., Phys. Rev. Letters 34, 1040 (1975).

3. A. M. Boyarski et al., Stanford Linear Accelerator Center Report No. SLAC-PUB-1599 (1975).

4. B. Knapp et al., loc. cit. This reference does not give an explicit value for $d\sigma/dt|_{t=0}$. The value quoted in the text was obtained from the data in the reference by assuming that the forward cross section on Beryllium is A^2 times that for a single nucleon and also correcting for $\psi(3700)$ cascade production of $\psi(3100)$ using the $\psi(3700)$ photoproduction cross section from the present experiment.

5. SLAC Workshop Notes on Narrow States, SLAC-PUB-1531 (1975).

TABLE CAPTION

I. Differential cross sections and kinematic conditions for the data points of this experiment.

TABLE I

k (GeV)	E_0 (GeV)	t_{min} $(GeV/c)^2$	t' $(GeV/c)^2$	$d\sigma/dt(t)$ $[nb/(GeV/c)^2]$
a. $\psi(3100)$ from Deuterium Target				
21.0	21.5	0.069	0.0	14.6 ± 1.2
19.0	20.0	0.088	0.0	15.0 ± 1.0
19.0	19.5	0.088	0.0	12.0 ± 1.1
17.0	17.5	0.116	0.0	10.8 ± 1.0
16.0	16.5	0.135	0.0	8.2 ± 1.1
15.0	20.0	0.160	0.0	7.7 ± 1.5
15.0	16.0	0.160	0.0	5.9 ± 1.0
13.0	13.5	0.236	0.0	3.8 ± 0.8
19.0	20.0	0.088	0.20	8.2 ± 1.1
19.0	20.0	0.088	0.40	4.9 ± 0.7
b. $\psi(3100)$ from Hydrogen Target				
19.0	19.5	0.088	0.0	10.8 ± 1.1
c. $\psi(3700)$ from Deuterium Target				
21.0	21.5	0.164	0.0	2.1 ± 0.8

$$t' \equiv (t - t_{min})$$

74%

FIGURE CAPTIONS

1. Time of flight for electrons (a) and for muons (b). Invariant mass for $\psi(3100)$ events (c) and muons (d). Invariant mass for $\psi(3700)$ for both electron and muon events (e).

2. (a) Cross section extrapolated to $t = 0$ for $\psi(3100)$ as function of energy. Thresholds for $\psi(3100)$ and $\psi(3700)$ are indicated. (b) Differential cross section for $\psi(3100)$ for $k = 19$ GeV and $E_0 = 20$ GeV as a function of t.

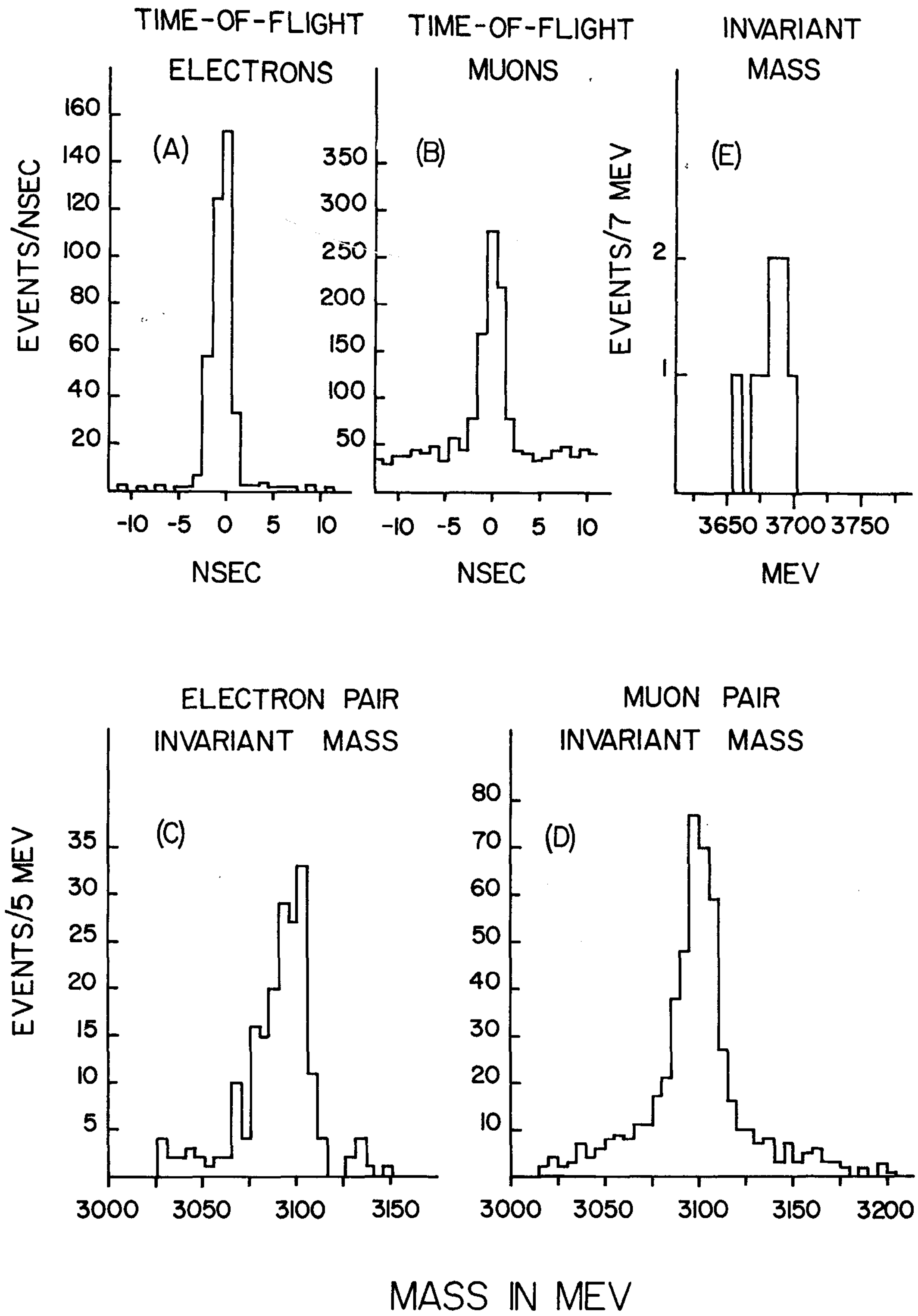
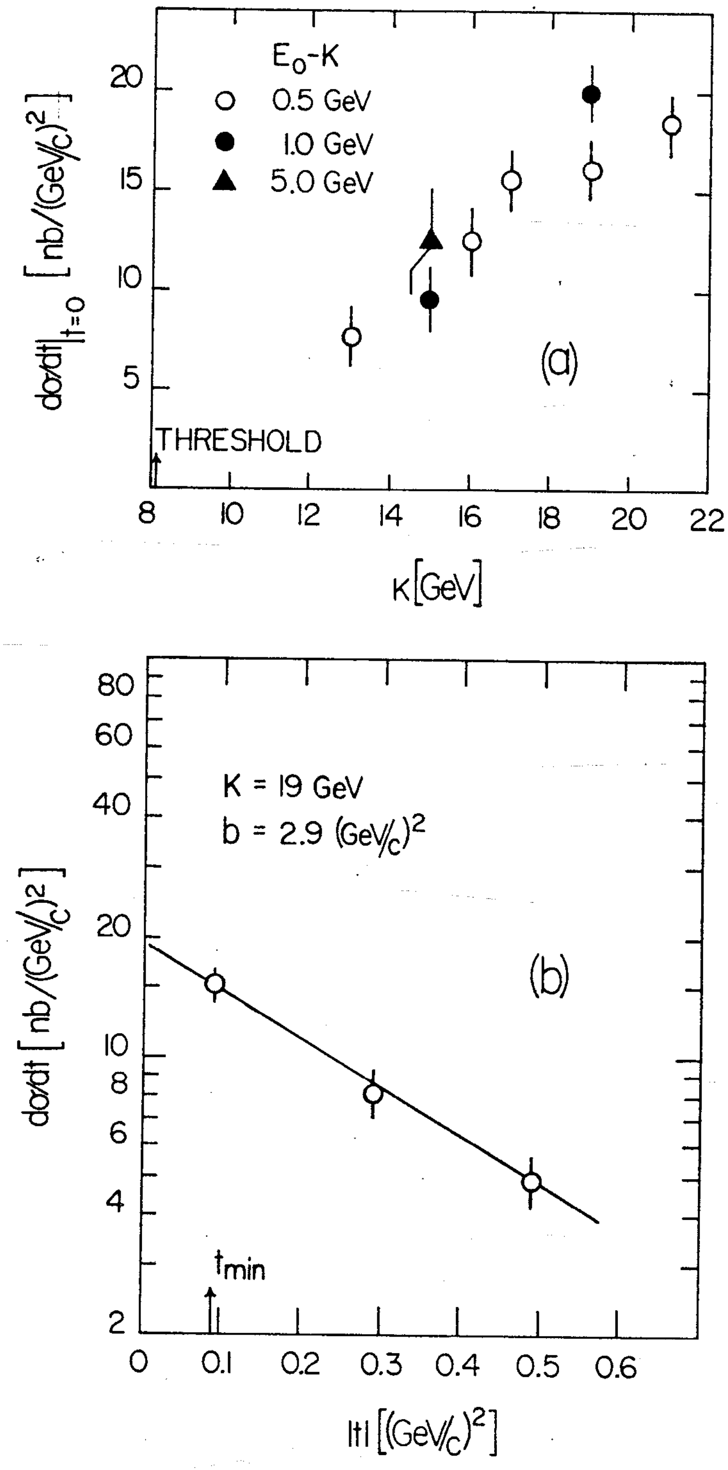

TIME-OF-FLIGHT
ELECTRONS
(A)
EVENTS/NSEC
160
140
120
100
80
60
40
20
-10 -5 0 5 10
NSEC
TIME-OF-FLIGHT
MUONS
(B)
350
300
250
200
150
100
50
-10 -5 0 5 10
NSEC
INVARIANT
MASS
(E)
EVENTS/7 MEV
2
1
3650 3700 3750
MEV
ELECTRON PAIR
INVARIANT MASS
(C)
EVENTS/5 MEV
35
30
25
20
15
10
5
3000 3050 3100 3150
MUON PAIR
INVARIANT MASS
(D)
80
70
60
50
40
30
20
10
3000 3050 3100 3150 3200
MASS IN MEV

Fig. 1



$E_0 - K$
0.5 GeV
1.0 GeV
5.0 GeV
(a)
THRESHOLD
$d\sigma/dt|_{t=0}$ [nb/(GeV/c)^2]
K[GeV]
K = 19 GeV
b = 2.9 (GeV/c)^2
(b)
t_{min}
$d\sigma/dt$ [nb/(GeV/c)^2]
|t| [(GeV/c)^2]

Fig. 2