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[9] To calibrate a detector, a plate of area A is mounted parallel to the end of the cylinder, forming capacitance C with the cylinder. A short sinusoidal voltage pulse of N cycles at half the cylinder resonance frequency and peak-to-peak amplitude V is applied. Under the assumption that edge effects contribute negligibly to the capacitance, the rms strain s produced in the cylinder is given by $s = C^2V^2N/4\sqrt{2}\epsilon_0 A^2 Y$, where ϵ_0 is the permittivity of free space and Y is Young's modulus.

[10] A. D. Whalen, *Detection of Signals in Noise* (Academic, New York, 1971).

[11] The first event occurred on 5 August 1973, $15^{\mathrm{h}}\ 23^{\mathrm{m}}\ 20.0^{\mathrm{s}}$ UT, with $E_{\mathrm{BTL}} = 1032$°K and $E_{\mathrm{Roch}} = 457$°K. We dismiss this event on the basis of its signature in the unfiltered data. On the Holmdel (BTL) detector the event appears to be the restoration of a sudden dc offset in the quadrature channel which had occurred about 10 sec earlier. No such abnormality is evident in the Rochester data. The second event occurred on 11 October 1973, $3^{\mathrm{h}}\ 48^{\mathrm{m}}\ 3.8^{\mathrm{s}}$ UT, $E_{\mathrm{BTL}} = 517$°K and $E_{\mathrm{Roch}} = 715$°K. We dismiss this event on the grounds that the Holmdel detector was experiencing a very high level of excitation for a period of time exceeding 200 sec while the ambient behavior of the Rochester detector was unchanged.

[12] If the filtering is linear, the distribution of noise pulses from the Brownian motion of the detector and the wide-band noise from the transducers and amplifiers remains exponential and can be characterized by an effective temperature T^*. The object of filtering is to make T^* as small as possible without diminishing the magnitude of any gravitational-wave-burst signals. In simple cases T^* can be expressed in closed form (Ref. 2) but in practice for the filters used it must be determined experimentally.

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Photoproduction of the ψ Particles*

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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.

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 beryllium target at Fermilab.[2] This paper reports the results of photoproduction measurements of ψ particles at the Stanford Linear Accelerator Center (SLAC). Both ψ particles were detected by observing their decays into lepton pairs.

The experiment was carried out by use of the 8- and 20-GeV spectrometers instrumented to detect both electron and muon pairs from ψ 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 per 1.6-μsec SLAC beam pulse.

The detection system was essentially identical in each spectrometer. Electrons were identified by a threshold gas Cherenkov 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 on-line by an SDS 9300 computer. The resolution of the hodoscopes was approximately 0.15% in momentum and 0.3 mrad in production angle, giving an invariant-mass resolution of ~20 MeV full width at half-maximum 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 full width at half-maximum. 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 with use of 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 ψ decays near 90° in the ψ rest frame. Most data points were taken with a deuterium target and a bremsstrahlung end-point energy set 0.50 or 1.0 GeV above the ψ energy. Measurements with a bremsstrahlung end-point energy 0.50 GeV above the detected ψ energy have about 50% acceptance for a recoil mass of 1340 MeV and 0 acceptance for recoil masses greater than 1450 MeV. This condition therefore constrains the inelasticity of the production process. The large minimum momentum transfer for ψ production at these energies ensures that ψ 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 1(a) and 1(b) 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 1(c) and 1(d) show the ee and $\mu\mu$ invariant-mass distributions for a sample of events which satisfy the time-of-flight criteria. Figure 1(e) shows the combined muon- and electron-pair data for the $\psi(3700)$ events which gave a reconstructible mass. The mass plot contains eight 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 hodo-

TABLE I. Differential cross sections and kinematic conditions for the data points of this experiment. $t'\equiv t-t_{\min}$.

k (GeV)	E_0 (GeV)	$t_{\min}$ $(\mathrm{GeV}/c)^2$	t' $(\mathrm{GeV}/c)^2$	$d\sigma(t)/dt$ $[\mathrm{nb}/(\mathrm{GeV}/c)^2]$
$\psi(3100)$ 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
$\psi(3100)$ from hydrogen target				
19.0	19.5	0.088	0.0	10.8 ± 1.1
$\psi(3700)$ from deuterium target				
21.0	21.5	0.164	0.0	2.1 ± 0.8

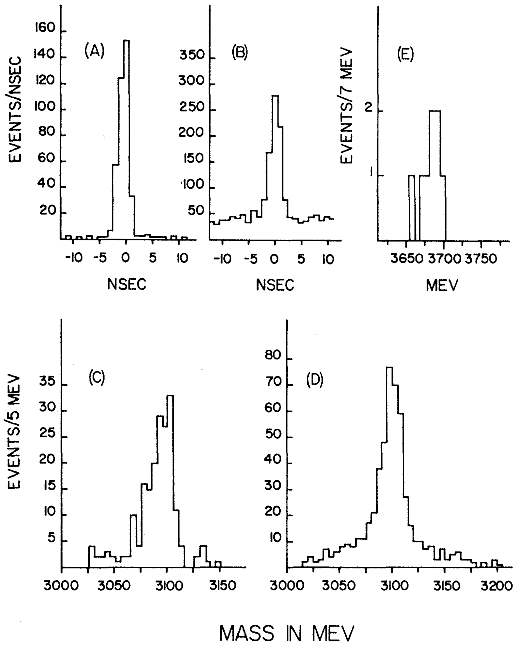

FIG. 1. Time of flight (a) for electrons and (b) for muons. Invariant mass for $\psi(3100)$ events for (c) electrons and (d) muons. (e) Invariant mass for $\psi(3700)$ for both electron and muon events.

scope information was used only to determine that the observed coincidence signal was in fact ψ 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 ψ 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 ψ particles decay with a $(1+\cos^2\theta^*)$ distribution in their own rest frame. (The data points correspond to $\theta^* \simeq 90°$.)

The cross-section results are based on approximately 1200 $\psi(3100)$ events and thirteen $\psi(3700)$ 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 because of the smaller branching ratio into lepton pairs.

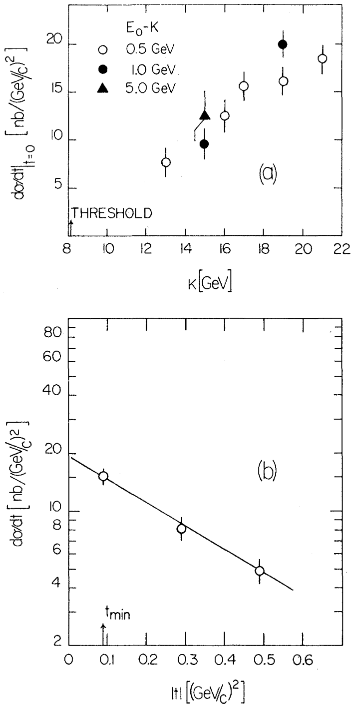

FIG. 2. (a) Cross section extrapolated to $t=0$ for $\psi(3100)$ as function of energy. Thresholds for $\psi(3100)$ and $\psi(3700)$ are indicated. (b) Differential cross section for $\psi(3100)$ for $k=19$ GeV and $E_0=20$ GeV as a function of t. $b=2.9$ (GeV/c)$^{-2}$.

The results are presented in Table I and Figs. 2(a) and 2(b). 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 the muon yields. The errors indicated in Table I are statistical only. The systematic error for the electron yields is dominated by the correction for radiative losses, and for the muons it 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 $\exp(-b \times t_{\mathrm{min}})$, with $b=2.9$ (GeV/c)$^{-2}$. The resultant $\psi(3100)$ $t=0$ cross sections are shown as a function of photon energy in Fig. 2(a). Figure 2(b) 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 ratio of the cross sections (per nucleon) for deu-

terium and hydrogen is

$$\frac{d\sigma/dt|_{\mathrm{D}_2}}{d\sigma/dt|_{\mathrm{H}_2}} = 1.2 \pm 0.16,$$

indicating that $\psi(3100)$ production from the proton and that from the neutron are 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-ψ-production contributions to the cross section are small. Specifically, with use of the notation (k, E_0), the cross-section ratios were determined to be

$$\frac{d\sigma(19, 20)/dt}{d\sigma(19, 19.5)/dt} = 1.25 \pm 0.14$$

and

$$\frac{d\sigma(15, 20)/dt}{d\sigma(15, 16)/dt} = 1.3 \pm 0.3.$$

(3) The values of $d\sigma/dt$ extrapolated to $t = 0$ rise from ~ 7.6 nb/(GeV/c)^2 at $k = 13$ GeV to ~ 20 nb/(GeV/c)^2 at 21 GeV. The rise appears to take place primarily in the region from 13 to 17 GeV. (4) The t distribution at $k = 19$ GeV, $E_0 = 20$ GeV, has a fitted slope parameter $b = 2.9 \pm 0.3$ (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 $\leqslant 5\%$ of the photonproduction cross section. (6) $\psi(3700)$ photoproduction has been observed at $t_{\min}$ for $k = 21$ GeV. Under the assumption of a branching ratio of 1% into either e or μ pairs for the $\psi(3700)$, the cross-section ratio at $t_{\min}$ is

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

(7) The value of $d\sigma/dt|_{t=0} = 17.8 \pm 1.5$ nb/(GeV/c)^2 at 21 GeV can be compared with the recent photoproduction experiment performed at Fermi National Accelerator Laboratory which gives a value of $d\sigma/dt|_{t=0} = 40 \pm 13$ nb/(GeV/c)^2 at a mean energy of ~ 100 GeV.[4] $d\sigma/dt|_{t=0}$ has therefore increased by a factor of ~ 2 in going from 21- to 100-GeV incident photon energy. (8) If the photoproduction of the ψ is ψ dominated (in analogy to the usual vector-dominance arguments), then

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

giving a value of

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

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

$$d\sigma/dt|_{t=0} \simeq 30\ \mathrm{mb}/(\mathrm{GeV}/c)^2$$

for πN elastic scattering or

$$d\sigma/dt|_{t=0} \simeq 4\ \mathrm{mb}/(\mathrm{GeV}/c)^2$$

for φN 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 $\sigma_{\mathrm{tot}}(\psi N)$ of $\sigma_{\mathrm{tot}}(\psi N) \leqslant 0.8$ mb, to be compared with typical hadronic total cross sections of ~ 25 mb.

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