Production of Photons Associated with the ψ by 217-GeV/c π^- Mesons

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Dimuon production is studied in 217-GeV/c π^--hydrogen and π^--beryllium collisions with a lead-glass array to detect photons associated with the ψ. The ψ-γ mass spectrum shows a 2.6-standard-deviation excess of events above background at ~3.5 GeV. This excess, if attributed to the decay $\chi(\sim 3.5) \to \psi\gamma$, implies that 0.70 ± 0.28 of the ψ's are produced via radiative decay of one of the χ states.

We have observed production of $\chi(\sim 3.5\text{ GeV})$ states in an experiment performed at Fermilab using a 217-GeV/c π^- beam incident on beryllium and liquid-hydrogen targets. It has been suggested[1-3] that hadronic production of the ψ occurs primarily through the ψ occurs primarily through the production of an intermediate χ state, followed by the decay $\chi \to \psi + \gamma$ or $\chi \to \psi + \text{hadrons}$. Recent results[4,5] from the CERN intersecting storage rings have indicated that such intermediate χ states may be important in proton-proton collisions. We report here on results obtained in a search for $\chi \to \psi + \gamma$ in $\pi^- N$ interactions.

The Chicago Cyclotron Magnet Spectrometer Facility (shown in Fig. 1) was used to detect and identify particles associated with dimuon production. Negative pions of 217 GeV/c strike a 2.5-cm-long beryllium target followed by a 40-cm-long liquid-hydrogen target. The trigger required two penetrating particles in diagonally opposed quadrants of a scintillation counter hodoscope located downstream of a steel hadron absorber. This geometric constraint reduced the trigger rate due to prompt low-mass dimuons (ρ, φ) and due to low-mass dimuons originating from pions decaying in flight. The K^- and $\bar{p}$ contaminations of the beam were about 2.5% and 0.5%, respectively. This report is based on a total incident beam flux of 4×10^{10} pions.

A 76-element lead-glass Cherenkov array (each 6.35 cm × 6.35 cm × 61 cm, 20.5 radiation lengths) detected photons. The lead-glass array calibration was monitored during this experi-

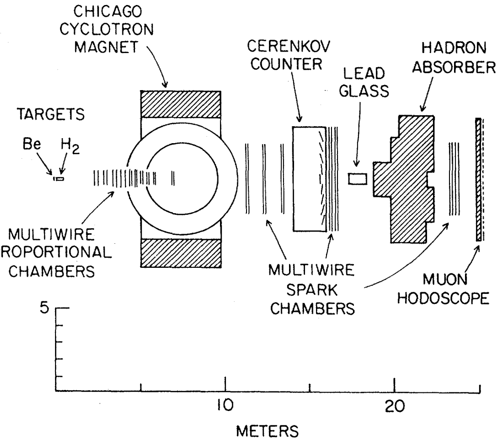

FIG. 1. The Chicago Cyclotron Magnet Spectrometer Facility as configured for this experiment.

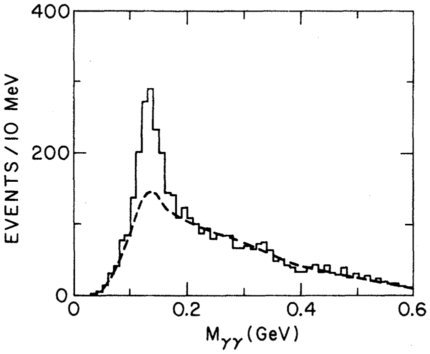

FIG. 2. The γ-γ mass spectrum for a sample of hadronic triggers. The curve is a background calculated with the use of uncorrelated γ's and is normalized to the number of events in the mass range 0.25–0.50 GeV.

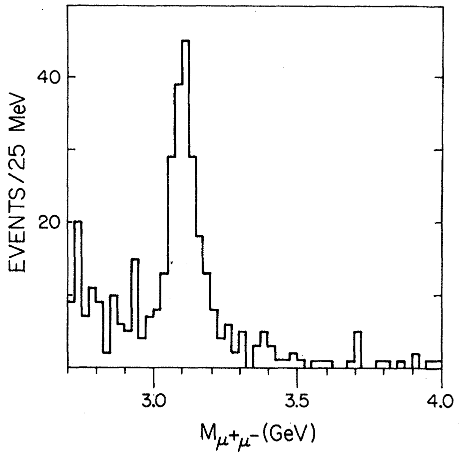

FIG. 3. The $\mu^+\mu^-$ invariant-mass spectrum.

ment with light-emitting-diode system. Following the data run, the array was moved into an electron beam in the Proton Area at Fermilab for calibration. To demonstrate the resolution of the lead-glass system, we show in Fig. 2 the γ-γ mass spectrum for a sample of hadronic triggers from the data run. There is a clear π^0 peak with a full width at half maximum of ~35 MeV. The η^0 is not seen because of the limited transverse acceptance of the array.

The dimuon mass spectrum above 2.7 GeV is shown in Fig. 3. There is a peak of about 160 events above background. The full width at half maximum of the ψ peak is 100 MeV and is consistent with the expected resolution of the apparatus. Figure 4 shows the Feynman x (x_F) and transverse momentum (p_T) distributions for the ψ events. The raw x_F distribution peaks at 0.45, while the acceptance corrected distribution can be fitted with the form $(1/E_\psi)(1-x_F)^A$ with $A = 1.12 \pm 0.24$, where E_ψ is the center-of-mass energy of the ψ. The p_T dependence fits the form $p_T \exp(-Bp_T)$ with $B = 1.61 \pm 0.16$. We have also fitted the x_F and p_T distributions separately for $\pi^- p$ and π^-Be events. These results agree with each other and with previous data for $\pi^- N$ interactions[6,7] at nearby energies (see Table I).

We have examined the photons associated with the ψ events. Photon candidates with (1) energy less than 5 GeV, (2) lateral shower distribution consistent with a hadronic shower, or (3) γ-γ invariant mass consistent with the π^0 were removed. The cut (1) removes photons in an energy range where our shower-finding algorithm is uncertain, but does not remove any χ signal (photons from χ's must have $E_\gamma > 10$ GeV in our apparatus). The cut (2) on lateral shower distributions removes ~70% of hadronic showers and ~15% of real photon showers. Figure 5(a) shows the ψ-γ invariant-mass spectrum.

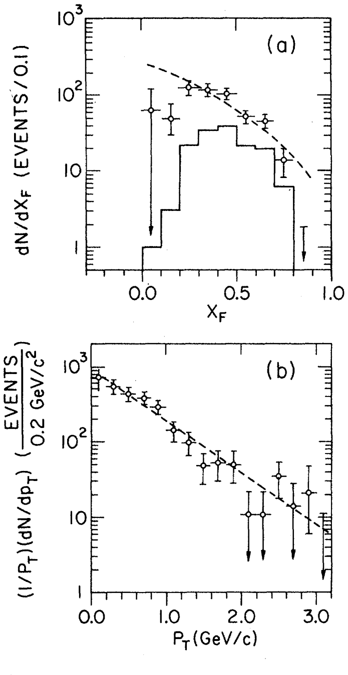

FIG. 4. (a) The x_F distribution for the ψ events. The solid histogram indicates the raw data distribution and the open circles are the acceptance-corrected points. The dashed curve is a fit of the form $dN/dx_F \sim (1/E_\psi) \times (1-x_F)^{1.12}$ (see text). (b) The acceptance-corrected distribution $(1/P_T)\, dN/dp_T$ for the ψ events. The curve is a fit of the form $\exp(-1.61 p_T)$ (see text).

TABLE I. Results of ψ invariant–cross-section fits for acceptance-corrected distributions in x_F and p_T. $E_\psi dN/dx_F$ was fitted with the form $(1-x_F)^A$ in the x_F range 0.1–0.9. $(1/p_T)dN/dp_T$ was fitted with the form $\exp(-Bp_T)$ in the p_T range 0.0–3.2 GeV/c.

Interaction (beam momentum)	A	Confidence level	B [(GeV/c)$^{-1}$]	Confidence level
217 GeV/c				
π^-p	1.13±0.31	0.15	1.69±0.23	0.90
π^-Be	1.12±0.29	0.20	1.50±0.23	0.59
200 GeV/c				
π^-Fe[a]	1.20±0.20	···	1.60±0.20	···
225 GeV/c				
π^-C[b]	1.93±0.20	···	1.98±0.13	···
π^+C[b]	1.33±0.21	···	2.06±0.10	···

[a] These results are from Ref. 6.

[b] These results are from Ref. 7.

The estimated background [dashed line in Fig. 5(a)] was obtained by taking photons from events with $\mu^+\mu^-$ invariant mass in the range 2.7–2.9 and 3.3–4.0 GeV (non-ψ events) and combining these photons with the complete sample of ψ's. This background was then normalized to the number of photons observed in the non-ψ events, scaled by the ratio of ψ events to non-ψ events. The error bar on the background curve reflects an estimated ±20% systematic uncertainty in the normalization. The result of subtracting this background is shown in Fig. 5(b). An alternate but independent method of determining the background is based on two assumptions: The background photons arise primarily from π^0 decay, and the π^0 kinematic distributions are obtainable by averaging the π^+ and π^- distributions. We used the distributions of charged pions associated with the ψ events as input to a Monte Carlo program and found the resulting ψ-γ background spectrum to be nearly identical to that shown by the dashed curve in Fig. 5(a).

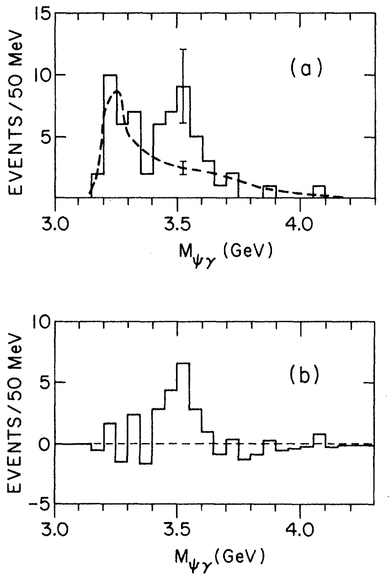

FIG. 5. (a) The ψ-γ invariant-mass spectrum. The dashed curve is the estimated background (see text). (b) The ψ-γ invariant-mass spectrum after subtraction of the background shown in (a).

Figure 5 then shows an excess of events in the ψ-γ mass spectrum at ~3.5 GeV. We fit the distribution in Fig. 5(a) with a Gaussian plus the background shape and find an excess of 17.2 ±6.6 events centered at 3.51 ±0.02 GeV with a standard deviation σ of 75 ±28 MeV and a background normalization factor of 1.0 ±0.2. The confidence level of this fit[8] is 99%. We expect a ψ-γ mass resolution with σ~60 MeV based on the observed width of our π^0 peak (see Fig. 2) since the error is primarily in the photon energy determination.

If we attribute the excess events at 3.5 GeV to the process $\chi\rightarrow\psi\gamma$, we obtain, with a Monte Carlo–determined[9] acceptance of 0.15,

$$[B_{\chi\rightarrow\psi\gamma}\,\sigma_\chi/\sigma_\psi]_{x_F\sim0.5}=0.70\pm0.28.$$

This result compares favorably with the value of 0.43 ±0.21 obtained by Cobb *et al.*[4] but tends to contradict the value of $0.15^{+0.10}_{-0.15}$ found by Clark *et al.*[5] Both these earlier values were measured at $x_F\sim0$ in pp collisions at $\sqrt{s}\sim55$ GeV while our data are near $x_F\sim0.5$ in π^-N collisions at $\sqrt{s}=20$ GeV.

Our σ~60 MeV ψ-γ mass resolution does not allow us to clearly separate the $\chi(3415)$:$\chi(3510)$:$\chi(3555)$ states, although our fit indicates the higher mass is preferred. We note that a recent gluon fusion model[2] predicts production cross sections for these states in the ratio 3:4 for $\chi(3415)$:$\chi(3555)$. Production of the $\chi(3510)$ by fusion of two gluons is forbidden. Folding in the measured[10] branching ratios for $\chi \rightarrow \psi\gamma$, we would expect to see ψ-γ's in the ratio 1:6.5 for $\chi(3415)$:$\chi(3555)$. Our data are consistent with this ratio.

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[8] The confidence level of a fit to the data in Fig. 5(a) by the background curve alone (no signal) is 12%.

[9] The Monte Carlo calculation assumed $\chi(\sim 3.5)$ production according to $d^2N/dx_F\,dp_T \sim (1-x)^2 p_T \exp(-2p_T)$ and an isotropic decay of $\chi \rightarrow \psi\gamma$.

[10] Particle Data Group, Phys. Lett. 75B (1978).

Backbending in ^{22}Ne

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The yrast line in ^{22}Ne has been investigated by the reaction ^{11}B + ^{13}C up to the 10^+ state which is found at 15.46-MeV excitation energy. A backbending in ^{22}Ne shows up around spin 8. The Strutinsky method is applied to interpret the ^{22}Ne rotational motion.

The investigation of yrast lines of light nuclei ($A < 30$) at high excitation energy is of great importance because here, in contrast to heavier nuclei, very reliable nuclear-structure calculations are available.[1-3] Therefore, phenomena like backbending, etc., can possibly be related to particular microscopic mechanisms in a more unique way than in heavy nuclei. Moreover, in this mass region purely microscopic (shell model) and macroscopic (Strutinsky) methods both can be applied to the same phenomena and thus can be compared with each other.

The ^{22}Ne nucleus lying between the two best known light nuclei ^{20}Ne (Refs. 4 and 5) and ^{24}Mg (Ref. 6) is one of the most highly deformed light nuclei. The yrast line in ^{22}Ne is at present clearly identified only up to the 6^+ state at 6.305 MeV,[7] a member of the $K^\pi = 0^+$ band built on the ^{22}Ne ground state. Broude *et al.*[8] suggested a candidate for the 8^+ yrast state at 11.00-MeV excitation energy. Almost no information exists for levels above this energy. This is mainly due to the low threshold for particle emission that limits the applicability of particle-γ correlation studies to excitation energies of ~ 10 MeV in ^{22}Ne. For higher excitation energies, however, a powerful method is particle spectroscopy by heavy-ion compound reactions.[6, 9-11]