Brief Reports

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Hadronic production of charmonium in 225-GeV/c π^-Be interactions

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Events in which the charmonium states J/ψ and ψ' are produced in 225-GeV/c π^-Be collisions have been selected with a dimuon trigger. Coincidences with detected photons have identified radiative decays from the charmonium P states (χ) to the J/ψ. The fraction of J/ψ's resulting from such decays is determined to be 0.37 ± 0.09.

Recent experimental results in π^-/N (Refs. 1 and 2) and pp (Ref. 3) interactions have indicated that the fraction of hadronic J/ψ production by radiative χ decay is substantial. Other experiments[4–6] have shown that decays from ψ' also contribute to the observed J/ψ cross sections. Theoretical models[7–10] attempt to explain these charmonium results via gluon-gluon or quark-antiquark fusion with or without the radiation of soft gluons. We report here new data from a 225-GeV/c π^- experiment with improved photon detection specifically designed to study χ production.

The Chicago Cyclotron Magnet Particle Spectrometer (CYCLOPS) facility at Fermilab is shown in Fig. 1. The spectrometer consisted of 25 multiwire-proportional-chamber planes followed by three large drift chambers. Events were recorded for interactions defined by two scintillation counters downstream of the beryllium target. We also required the presence of a high-mass, opposite-sign muon pair tagged by counters behind a steel hadron filter. Photon detection was provided by the lead-glass detector shown in Fig. 2. A transverse array containing lead-glass blocks with dimensions 6.35 cm × 58.4 cm × 6.35 cm thick (2.2 radiation lengths) together with 0.9 radiation length of lead and steel sheet served to develop the shower for position measurement. A proportional-tube array, located between the transverse and longitudinal lead-glass blocks, consisted of three planes of 194 tubes each. The distance between tube centers orthogonal to the beam was 0.794 cm. Tube pulse heights were used to locate shower centroids. Finally, longi-

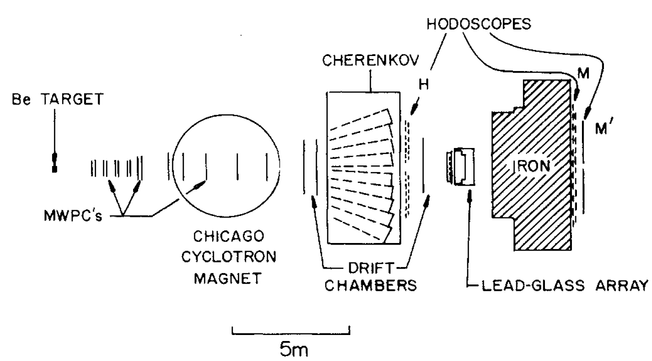

FIG. 1. The Chicago Cyclotron Particle Spectrometer (CYCLOPS) facility in the bend-plane view. The 4.9-m-diameter circle indicates the region with a 1.4-T field perpendicular to the page.

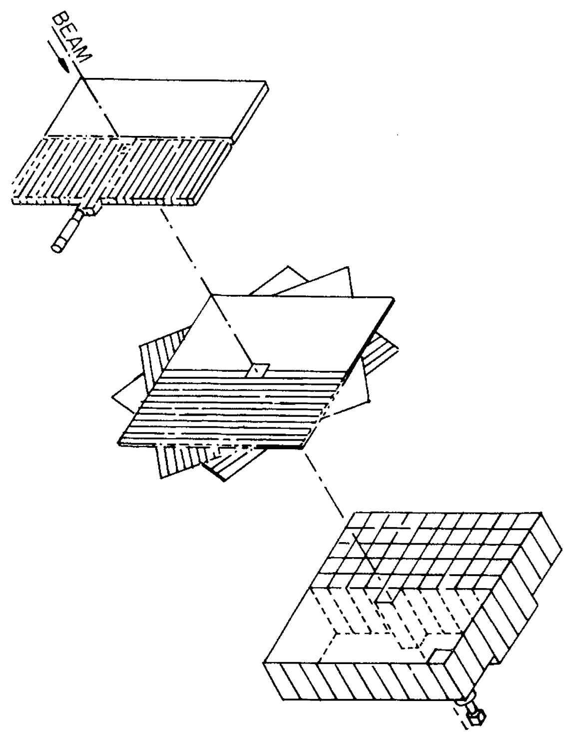

FIG. 2. An exploded view of the lead-glass detector. The detector consisted of a set of transverse lead-glass blocks to initiate the showers, three planes of proportional tubes with 60° stereo to measure shower position, and a 10×10 array of longitudinal lead-glass blocks.

tudinal blocks of lead glass were arranged in a 10-by-10 array with one block left out to allow passage of the beam. Each block was 15 cm square with a length parallel to the beam of 46 cm (18 radiation lengths). The total shower energy was then derived from pulse heights in the nearby transverse and longitudinal blocks.

Our dimuon mass spectrum in Fig. 3 shows clear J/ψ and ψ' peaks. The background results mostly from hadron decays in flight. Gaussian fits to the peaks with an exponential background give 1056 ± 36 J/ψ events above background and 26 ± 7 ψ' events above background, with a χ^2 per degree of freedom of 1.1. The J/ψ width [standard deviation (SD)] is 28 MeV and the ψ' width is 21 MeV, as expected in our apparatus. Geometric acceptances and apparatus detection efficiencies have been computed via Monte Carlo methods using the kinematic distributions from Ref. 4 as input. The resulting total detection efficiency is 0.105 ± 0.006 for both J/ψ and ψ'. Using the known $\mu^+\mu^-$ branching ratios,[11] we calculate the fraction of J/ψ's resulting from decays of the ψ' to be 0.11 ± 0.05, in agreement with other measured values.[5,6] In the following analysis we identify dimuon events in the mass range 3.05–3.15 GeV as J/ψ events. These dimuons were fixed at the J/ψ mass of 3.097 GeV using a one-constraint fit.

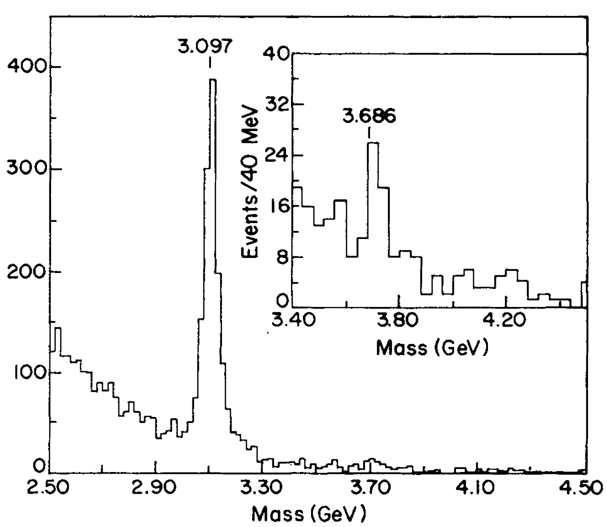

FIG. 3. The dimuon mass spectrum above 2.5 GeV. The inset shows the high-mass data in 40-MeV bins.

In order to search for χ states, we examined photons associated with the J/ψ event sample. The lead-glass detector was calibrated at the beginning and end of the data-taking with electrons of known momenta between 7.5 and 50 GeV/c to determine the photon energy scale. The results are consistent with an energy resolution $\Delta E(\mathrm{SD})/E$ of $2\% + 14\%/\sqrt{E}$ (E in GeV) and an average position resolution (SD) of 0.46 cm for the array. Substantial radiation damage in a few central blocks made it difficult to use our light-flasher monitors to follow the lead-glass gains with time. Instead, twelve statistically equal sections of data were combined, and individual block gains adjusted so as to give the correct π^0 mass in each section. For two-photon events only, Fig. 4 shows a clear π^0 peak at 135 ± 2 MeV with a width (SD) of 9 MeV, and the η peak at 546 ± 2 MeV with a width of 21 MeV. Photon-reconstruction efficiency was determined as a function of longitudinal block and photon multiplicity by inserting electron-calibration events into dimuon data and then attempting to recover the electronic-shower location and energy with the actual reconstruction algorithm. For electrons with energies between 5 and 30 GeV, the fraction of such showers found was 0.51 ± 0.06. When the J/ψ is detected in our apparatus, photons from radiative χ decays would lie in the energy range 10 to 25 GeV. The geometric acceptance for photons from χ decay was determined via Monte Carlo to be 0.41 ± 0.03. The overall detection efficiency for χ-like photons, obtained by combining the geometric efficiency with the photon-reconstruction efficiencies, is 0.21 ± 0.03.

The J/ψ + photon mass spectrum for photons in the 5–30-GeV range is shown in Fig. 5. The background curve superimposed is produced by combining J/ψ's from one

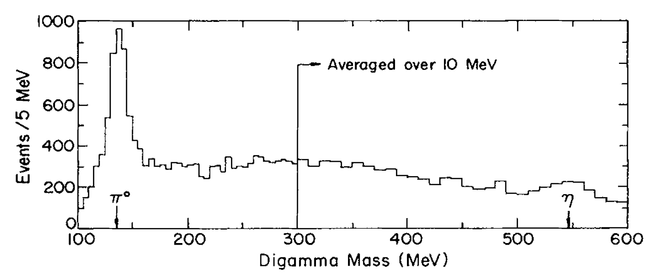

FIG. 4. The photon-photon mass spectrum for showers in the 5–30-GeV energy range. The bin size has been changed from 5 to 10 MeV at a mass of 300 MeV.

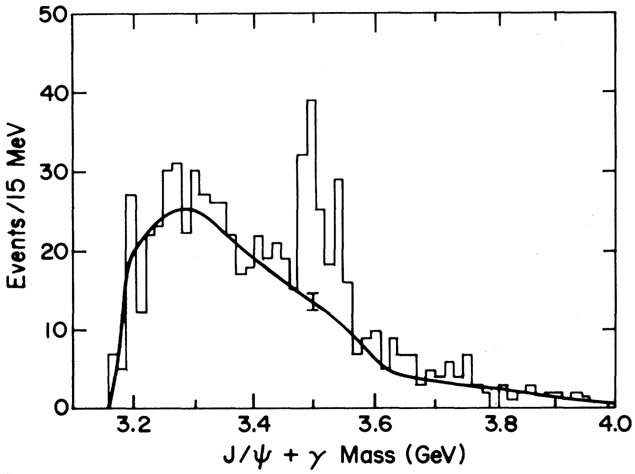

FIG. 5. The J/ψ + photon mass spectrum for showers in the 5–30-GeV energy range. The solid curve is the estimated background described in the text. The error bar indicates the estimated uncertainty in the background at 3.5 GeV.

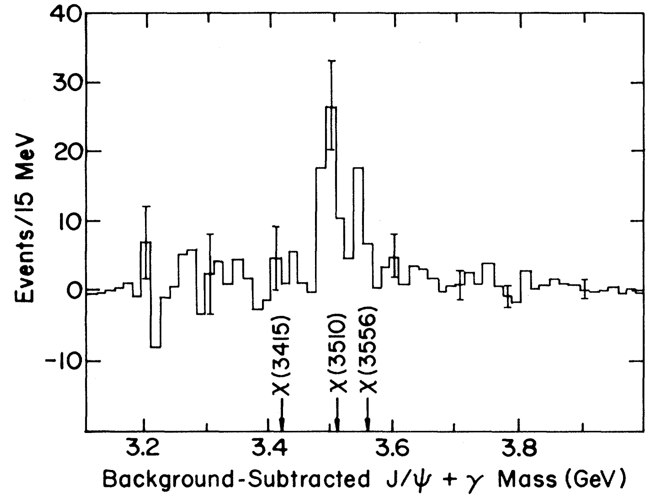

FIG. 6. The background-subtracted J/ψ + photon mass spectrum. The error bars reflect the statistical uncertainty in the unsubtracted spectrum of Fig. 5.

event with showers from other J/ψ events. This background is determined in shape and in absolute normalization to the level indicated in Fig. 5. The background has been iteratively corrected to account for a kinematic enhancement due to photons from real-χ events mixed with uncorrelated J/ψ's, resulting in a correction of less than 10% in the χ region. The number of events seen above background near 3.5 GeV in Fig. 5 is 84 ± 15. The three known χ states are at 3415, 3510, and 3555 MeV. Our χ signal is dominated by the two higher-lying states, as expected from the branching ratios[11] into J/ψ + photon [0.8% for the $\chi(3415)$, 28% for the $\chi(3510)$, and 16% for the $\chi(3555)$]. Using our photon efficiency and the number of J/ψ's seen in the experiment, we obtain the value 0.37 ± 0.09 for the fraction of J/ψ's produced via χ states. This result is in agreement with the value 0.305 ± 0.05 found at 185 GeV/c.[2] If the ψ' and χ states are the only higher-lying states with appreciable decay modes to the J/ψ, the fraction of J/ψ's produced indirectly is 0.48 ± 0.10.

Figure 6 shows the background-subtracted χ signal. The correct position of the η peak in Fig. 4 implies that the J/ψ + photon mass scale is correct to ± 4 MeV. We estimate our χ mass resolution (SD) to be 20 ± 3 MeV based on the observed η width. Our resolution and statistics are not sufficient to separate the two higher-lying χ states cleanly, but the observed signal is clearly wider than the expected resolution. We have fitted the enhancement near 3.5 GeV with two 20-MeV-wide Gaussians centered at the $\chi(3510)$ and $\chi(3555)$ masses. We find the ratio of observed events for the two χ states to be

$$\frac{\text{Number of } \chi(3555) \text{ events seen}}{\text{Number of } \chi(3510) \text{ events seen}} = 0.51 \pm 0.19 \ .$$

Since the acceptance for each χ state is identical, the number of events seen is just proportional to the branching ratio for $\chi \rightarrow J/\psi + \gamma$ times the χ production cross section. We therefore find the ratio of the χ production cross sections (σ) to be

$$\frac{\sigma(\chi(3555))}{\sigma(\chi(3510))} = 0.9 \pm 0.4 \ .$$

These results are consistent with the value 1.3 ± 0.4 found in π^-Be interactions at 185 GeV/c.[12] These measurements do not allow a clear discrimination among the theoretical models for χ production. The gluon-gluon-fusion model[7] suppresses $\chi(3510)$ production while the quark-antiquark-fusion model[9] predicts that this state completely dominates. Either a mixture of these mechanisms or the inclusion of soft-gluon evaporation[9] would suffice to explain the observed ratio.

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