

nonresonant background is assumed to fall with increasing energy, as is to be expected on simple theoretical grounds.<sup>9</sup>

This theory makes a number of other simple predictions: (i)  $\psi$  particles are produced in pairs in white-hadron collisions. (ii) The main hadronic decay modes of  $\psi_1$  contain a real photon.<sup>10</sup> (iii) There are charged counterparts (positive and negative) to  $\psi_1$  and  $\psi_2$  (colored  $\rho$  mesons) with the same masses (apart from electromagnetic effects). The heavier decays into the lighter like  $\psi_2 \rightarrow \psi_1$ . The lighter has only weak decay modes. (iv) There are two colored  $1^- K^*$  mesons of masses 3.9 and 4.5 GeV/ $c^2$  [from (11), (12), and (13)]. (v) There are 56 other colored vector mesons of the (8, 8) multiplet with masses in the 4–5 GeV/ $c^2$  range all fixed by one further parameter. The lightest of these has a main decay mode into  $\psi_1 + K$ .

A more detailed discussion of the above points, together with an exposition of their weak interactions consistent with Salam-Weinberg theory and the observed selection rules of neutral currents for white hadrons will be published elsewhere.

\*On leave of absence from the Johns Hopkins University. Work supported in part by the National Science Foundation and the Science Research Council.

<sup>1</sup>J.-E. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974); J. J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974); G. S. Abrams *et al.*, Phys. Rev. Lett. **33**, 1453 (1974).

<sup>2</sup>M. Y. Han and Y. Nambu, Phys. Rev. **139**, B1006 (1965).

<sup>3</sup>We signify the neutral states by their  $I'$  spin,  $I''$  spin, and multiplets; e.g.,  $(I', I'')_{n'n''}$ . The combinations  $\pm$  indicate mixing but are not intended to imply that it is 50:50.

<sup>4</sup>S. Okubo, Progr. Theor. Phys. **27**, 949 (1962).

<sup>5</sup>We have adopted the convention that the state corresponding to  $M_j^-$  is  $|- , j\rangle = \cos\theta_j |8, 8\rangle - \sin\theta_j |1, 8\rangle$ .

<sup>6</sup>J.-E. Augustin *et al.*, Phys. Rev. Lett. **34**, 764 (1975).

<sup>7</sup>The dependence on the mass is that which gives the best fit of "magic" mixing to the observed  $e^+e^-$  partial widths of  $\rho$ ,  $\omega$ , and  $\phi$ . D. R. Yennie, Phys. Rev. Lett. **34**, 239 (1975).

<sup>8</sup>The errors on the observed partial widths are at present so large that  $M_0^+$  cannot be accurately predicted. However, universal magic mixing is so appealing that one is tempted to take it seriously. If we had worked with squared masses, magic mixing would give a somewhat lower value for  $M_0^+$  in which case interference effects with  $M_0^-$  would be important.

<sup>9</sup>See particularly Fig. 1 which may be interpreted as two wide bumps sitting on a falling background which passes smoothly through the data points for  $E_c < 3$  GeV.

<sup>10</sup>These modes are damped by the Feynman rule. R. P. Feynman, M. Kislinger, and F. Ravndal, Phys. Rev. D **3**, 2706 (1971).

## Measurement of $\psi(3.1)$ Meson Production by Pions and Protons\*†

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(Received 14 July 1975)

The production of  $\psi(3.1)$  mesons is reported for the reactions  $\pi^- + \text{Fe} \rightarrow \mu^+ + \mu^- + \text{anything}$ , at 200 GeV, and  $p + \text{Fe} \rightarrow \mu^+ + \mu^- + \text{anything}$ , at 240 GeV. For  $\psi$  production, distributions in  $x \equiv P_L/P_{\text{beam}}$  and  $P_\perp$  are given. For  $x \geq 0.5$ , the ratio of the  $\psi$  production cross sections in iron for pions to that for protons is found to be  $7.4 \pm 2.0$ .

We report here results of an experiment carried out at the Fermi National Accelerator Laboratory (FNAL) in which enhancements are observed in the dimuon invariant-mass spectra at about 3.1 GeV. The reactions studied were

$$\pi^- + \text{Fe} \rightarrow \mu^+ + \mu^- + \text{anything}, \quad P_B = 200 \text{ GeV}, \quad (1)$$

and

$$p + \text{Fe} \rightarrow \mu^+ + \mu^- + \text{anything}, \quad P_B = 240 \text{ GeV}, \quad (2)$$

where  $P_B$  is the monoenergetic beam momentum. We interpret the enhancements, whose widths are consistent with the resolution of our apparatus, as the  $\psi(3.1)$  meson.<sup>1</sup>

The  $\mu$ -pair detector is shown in Fig. 1(a). The  $\mu$  pairs were created at the front end of the first iron (Fe) absorber. Muons were identified by their traversal of 5.6 m of Fe. Muon momenta and angles were measured using a 56-kG-m gapless magnet and associated wire-chamber system.

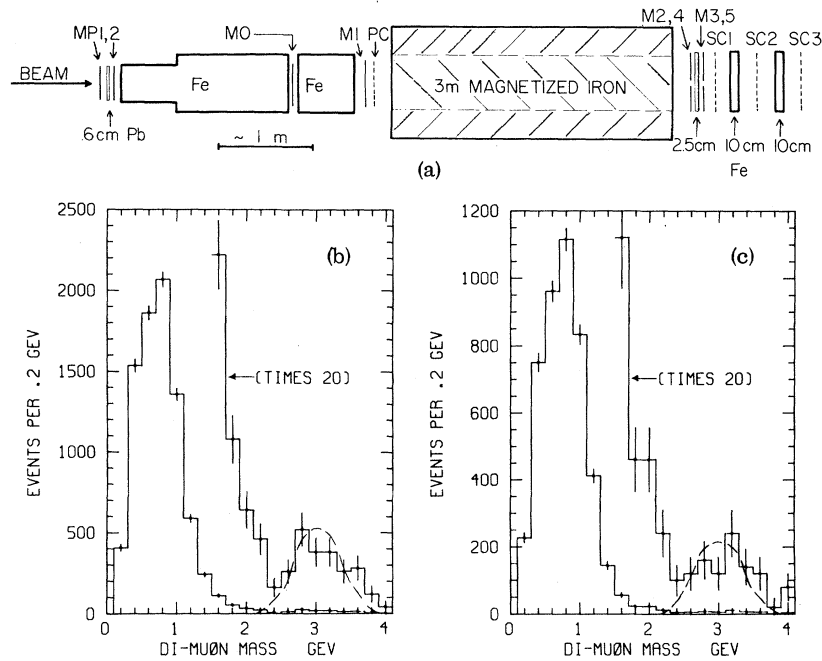


FIG. 1. (a) Muon-pair detector (top view). SC  $\equiv$  spark chamber; M  $\equiv$  scintillation counter; PC  $\equiv$  proportional chamber; SC2 limits the vertical aperture to  $\pm 24$  cm. (b), (c) Dimuon invariant-mass spectra for Reactions (1) (pion beam) and (2) (proton beam), respectively.

Events were recorded whenever there was a six-fold counter coincidence,  $M0 \cdot M1 \cdot (M2 \cdot M3) \cdot (M4 \cdot M5)$ , in time with a beam particle defined by scintillation counters and hodoscopes (not shown). The split-counter coincidence,  $(M2 \cdot M3) \cdot (M4 \cdot M5)$ , required that there be at least two particles at the rear of the magnet. For each event, coordinates from the chambers, counter tags, and pulse heights from counters MP1, MP2, M0, M1, two beam Cherenkov counters, and the final beam-defining counter were recorded.

The dimuon invariant mass was calculated from the tracks measured by the spark chambers, under the assumption that the dimuon was created inside the first Fe absorber 12.7 cm from its front edge along the beam line. The muon momenta and angles were reconstructed by taking into account the bending and energy loss of the muons in the magnetized Fe spectrometer. The proportional chamber was used only in checking the reconstruction technique and the spark-chamber efficiencies for a subsample of the data.

The reconstruction process selected  $\mu$  pairs for which the total charge was zero. This eliminated  $\approx 2\%$  of the  $2\mu$  events. Also, in the horizontal-plane projection, where there is no bending, each muon track was extrapolated back to the region

of the production point. In this region, the tracks were required to deviate horizontally from the production point by less than 2.2 times the expected standard deviation. The standard deviation,  $\Delta$ , was calculated from the bending of the muon in the vertical plane (muon momentum) and the expected multiple scattering of the muon in the spectrometer. (At 100 GeV,  $\Delta = 1$  cm.) This requirement removed  $\approx 10\%$  of the events. For the accepted events, the distribution of the track positions at the production point agreed well with the distribution calculated from the properties of the spectrometer. Monoenergetic muon beams with energies of approximately 100 and 200 GeV were used to calibrate and check the spectrometer and measure its resolution. Also, counters MP1 and MP2 were used to show that the contamination of the  $\psi$  data from  $\mu$  pairs produced upstream of the Fe is small and does not affect the results significantly. (A 60-cm hydrogen target was centered 60 cm upstream of the iron.)

The dimuon effective-mass ( $M_{\mu\mu}$ ) spectra observed in 45 h of beam time are shown in Figs. 1(b) and 1(c). Only events which satisfied the reconstruction criteria discussed above and which had a total laboratory dimuon momentum,  $P_L$ , above 90 GeV are plotted. These data are

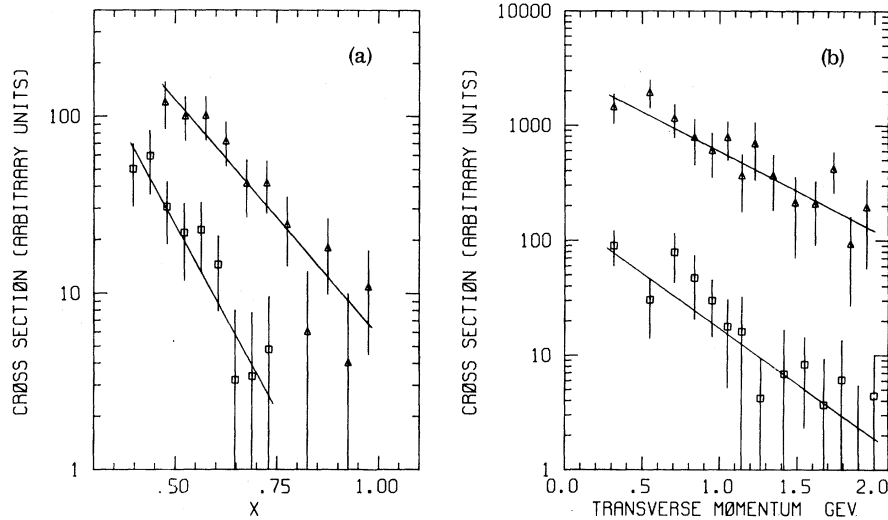


FIG. 2. (a)  $x$  distributions for pion ( $\Delta$ ) and proton ( $\square$ ) beams. For additional details, see text. (b)  $P_{\perp}$  distributions for pion [ $\Delta$ ], times 10] and proton ( $\square$ ) beams. For additional details see text.

not corrected for variation of spectrometer acceptance with mass. In the interval  $2 \leq M_{\mu\mu} \leq 4$  GeV, the mass acceptance is a smooth structureless function of mass and varies by about  $\pm 35\%$ . The low-mass regions of these spectra are presented as an indication of the overall  $\mu$ -pair spectrum and will be discussed elsewhere. The dashed curves drawn in the region  $M_{\mu\mu} \approx 3$  GeV represent the spectra calculated by a Monte Carlo method which takes into account the resolution and detection efficiency of the apparatus and assumes that all of the events in the interval  $2.5 \leq M_{\mu\mu} \leq 3.7$  GeV, the  $\psi$  region, result from the decay  $\psi \rightarrow \mu^+ + \mu^-$ . In the  $\psi$  regions, we observe 104 and 45 events in the pion and proton data, respectively. An extrapolation of the data with  $M_{\mu\mu} < 2.5$  GeV into the  $\psi$  regions indicates that the non- $\psi$  contributions to the  $\psi$  regions are less than 20%. Since the agreement between the dashed lines and the data is good,<sup>2</sup> we interpret the observed enhancements as  $\psi(3.1) \rightarrow \mu^+ + \mu^-$ .

The acceptance-corrected distributions in  $x \equiv P_L/P_B$  and dimuon transverse momentum,  $P_{\perp}$ , are shown in Figs. 2(a) and 2(b) for the  $\psi$  region. (In calculating the geometric acceptance, isotropy for the decay  $\psi \rightarrow \mu^+ + \mu^-$  was assumed.) The solid lines are fits to the measured cross sections of the form

$$d^2\sigma/dx dP_{\perp}^2 \propto \exp(-ax - bP_{\perp}).$$

The results of the fits<sup>3</sup> are  $a_{\pi} = 6.2 \pm 0.8$  and  $b_{\pi} = 1.6 \pm 0.2$  GeV<sup>-1</sup> for incident pions, and  $a_p = 9.7$

$\pm 1.6$  and  $b_p = 2.2 \pm 0.5$  GeV<sup>-1</sup> for incident protons. We calculate that for both  $\pi$ 's and  $p$ 's, the effect of  $\psi$  production from secondaries produced in the Fe is negligible.

We have compared the yields of  $\psi$  mesons per incident  $\pi^-$ ,  $Y_{\pi}$ , to the yield per incident  $p$ ,  $Y_p$ . The ratio of the yields,  $R = Y_{\pi}/Y_p$ , is  $x$  dependent. For  $x \geq 0.5$ ,  $R = 7.4 \pm 2.0$ , where the quoted error in  $R$  is dominated by the statistical uncertainty in  $Y_p$ . Systematic uncertainties in  $R$  are estimated to be significantly less than the statistical uncertainties and have been neglected. The fact that  $R$  is significantly greater than unity suggests that the mechanisms for  $\psi$  production at large  $x$  are basically different for  $\pi$ 's and  $p$ 's. This difference may indicate that the antiquark in the  $\pi^-$  plays a critical role in  $\psi$  production.

For a total Fe inelastic cross section of  $\sim 0.7$  b, our data give, for  $x \geq 0.5$ , a total inclusive cross section for  $\pi^- + \text{Fe} \rightarrow \psi \rightarrow \mu + \mu$  of  $\approx 85$  nb,  $\pm 50\%$ , where the error is dominated by systematic errors. Previous results for  $\psi$  production by neutrons<sup>4</sup> of average energy 250 GeV from beryllium gave the probability per interacting neutron for  $n + \text{Be} \rightarrow \psi \rightarrow \mu + \mu$ ,  $|x| > 0.32$ , as  $P(n) = 0.43 \times 10^{-7}$  (quoted error of a factor of 2). Our result for protons from Fe for  $|x| \geq 0.38$  is  $P(p) = (0.59 \pm 0.30) \times 10^{-7}$  in reasonable agreement with the neutron result. The distributions in  $x$  and  $P_{\perp}$  for the neutron data also appear consistent with our proton results.

We thank the Northeastern University Computa-

tion Center, the FNAL crew, and the FNAL fabrication procurement group for their support, and Brookhaven National Laboratory and Harvard University for the loan of equipment. We also thank B. Cairns, E. King, and D. Ronan for their help with this work.

\*Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Lett. **13**, 79 (1964)].

†Work supported in part by the National Science Founda-

tion under Grant No. MPS70-02059A5.

‡Alfred P. Sloan Foundation Fellow.

<sup>1</sup>J. J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1975); J.-E. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974).

<sup>2</sup>If all  $\psi$  production were via  $\psi'(3.7)$  production only ( $7 \pm 4\%$ ) of the yield in the  $\psi$  region of our data would be from  $\psi'(3.7) \rightarrow \mu^+ + \mu^-$ . This is based on the branching ratios from A. M. Boyarski *et al.*, Phys. Rev. Lett. **34**, 1357 (1975), and J. A. Kadyk *et al.*, Lawrence Berkeley Laboratory Report No. 3687 (unpublished).

<sup>3</sup>Fits to  $d^2\sigma/dx dP_{\perp}^2 \propto \exp(-b' P_{\perp}^2)$  give  $b_{\pi'} = 0.81 \pm 0.14$  GeV<sup>-2</sup> and  $b_{\psi'} = 1.1 \pm 0.3$  GeV<sup>-2</sup>.

<sup>4</sup>B. Knapp *et al.*, Phys. Rev. Lett. **34**, 1044 (1975).

## Measurement of the Radiative Decay Width $\Gamma(\bar{K}^{*0}(890) \rightarrow \bar{K}^0\gamma)$

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(Received 9 April 1975)

The differential cross sections for coherent production of  $\bar{K}^{*0}(890)$  were measured with nuclear targets. These measurements are interpreted using a two-component model which accounts for Coulomb production and  $\omega$  exchange. The radiative decay width is determined to be  $\Gamma(\bar{K}^{*0}(890) \rightarrow \bar{K}^0\gamma) = 75 \pm 35$  keV, which is 3 times lower than expected from a simple quark model.

Exact SU(3) symmetry leads to definite relations among the radiative widths for the various examples of the generic reaction: vector meson - pseudoscalar meson +  $\gamma$ .<sup>1</sup> In a less restrictive quark model, the rate for this reaction is proportional to the transition magnetic moment between quark levels.<sup>2</sup> In either case, the octet radiative transition is an important (electromagnetic) probe of SU(3) symmetry breaking. Following the original suggestion of Primakoff,<sup>3</sup> several experiments have measured radiative widths using virtual photons in the Coulomb field of heavy nuclei as a target. We report a measurement of the radiative width  $\Gamma(\bar{K}^{*0} \rightarrow \bar{K}^0\gamma)$  using the Primakoff effect.

The experiment was carried out in the 4.7° neutral beam at the Brookhaven National Laboratory alternating gradient synchrotron (AGS). The  $\bar{K}^0$  component of the incident  $K_L^0$  beam produces  $\bar{K}^{*0}$  coherently from the target nuclei according to

$$\bar{K}^0 + A \rightarrow \bar{K}^{*0}(890) + A \rightarrow K^- \pi^+ \quad (1)$$

The outgoing  $K^- \pi^+$  system was detected in a modified version of a proportional-wire-chamber spectrometer originally developed for  $K_L^0$  decay studies and described in detail by Carithers *et al.*<sup>4</sup> Pions were identified with a threshold Cherenkov counter.

Thin targets of Pb, U, Cd, Cu, Al, and C ranging in thickness from 0.1 to 0.25 radiation lengths were used. The targets were enclosed in an evacuated volume and surrounded by a lead-scintillator-sandwich anticoincidence system to suppress nuclear breakup reactions.

The  $K_L^0$  beam decays provide a convenient calibration reference for measuring both the  $t'$  resolution and the flux normalization. A 50-cm decay region upstream of the target was maintained under vacuum and events with a vertex in this region were identified as  $K_L^0$  decays. Thus the relative cross-section normalization for the six targets was provided by  $K_L^0 \rightarrow$  (all charged) decays. Since these data were recorded simultaneously with Reaction (1), beam-rate effects and ineffi-