Search for Narrow Two-body Enhancements at Fermilab*

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A search has been made in neutron-beryllium interactions for neutral narrow enhancements produced at Feynman $x \geq 0.2$. Upper limits are presented for production cross-sections times branching ratio into the two-body channels $\pi^+\pi^-$, π^+K^-, and $p\bar{p}$ for masses in the interval 2 GeV $\lesssim m \lesssim$ 4 GeV. Comparisons are made with ψ production observed in the same experiment.

Mounting evidence from hadronic,[1] electromagnetic,[2] and weak[3] interaction experiments indicates that new quantum numbers are being excited in hadrons. Mesons and baryons explicitly possessing these new quantum numbers are predicted to have masses $\gtrsim$ 1.5 GeV.[4] The lowest-mass states will presumably decay weakly and have small decay widths.

Our experiment has searched for the inclusive production of such long-lived states in neutron-induced reactions at Fermilab. Two-body decay channels were analyzed for resonances produced with Feynman $x \geq 0.2$ and with $p_\perp \leq 1.0$ GeV/c, for example by associated production. This forward geometry has potentially smaller backgrounds from uncorrelated large-$p_\perp$ secondaries than experiments at $x \sim 0$.

The spectrometer is shown schematically in Fig. 1. The neutron beam is incident from the left onto a beryllium target just upstream of counter S_1. Charged-secondary tracks are reconstructed using eleven 1-mm- and 2-mm-spacing proportional-chamber planes upstream of and between two BM109 dipole magnets. These are followed by fourteen planes of magnetostrictive wire spark chambers. Both upstream and downstream arms contain x, y and rotated u, v planes. The magnet aperture is 8 in. vertically and 24 in. horizontally.

Produced particles were analyzed by a low-pressure N_2 threshold Cherenkov counter, divided optically into two cells and instrumented with RCA 31000M phototubes. Cherenkov pressure curves, using 300-GeV/c diffracted protons down the neutral beam line, confirmed that the two cells had equal efficiencies to within 10% and predicted a maximum of ~4.5 photoelectrons for π threshold set at 20 GeV/c. This choice of threshold allowed pions to be distinguished from kaons and protons since typical particle momenta were ~45–50 GeV/c. The detailed particle-selection criteria were as follows. Particles producing light in the Cherenkov counter and having momenta in the range 22 GeV/$c \leq p \leq$ 130 GeV/c were classified as pions. Particles yielding no light in the Cherenkov counter were classified as kaons for 25 GeV/$c \leq p \leq$ 80 GeV/c and/or as protons for 25 GeV/$c \leq p \leq$ 140 GeV/c. We estimate that these momentum cuts result in $\lesssim$ 40% π^- contamination in the K^- or $\bar{p}$ data. Finally, muons were identified by a 10-ft range requirement in steel.

The neutron beam, produced at ~1 mrad from 300-GeV/c p-Be interactions in the meson laboratory target, peaked at ~240 GeV/c and had $\lesssim$ 1% $K_L{}^0$ contamination above 100 GeV/c.[5] Photons in the neutral beam were removed with a

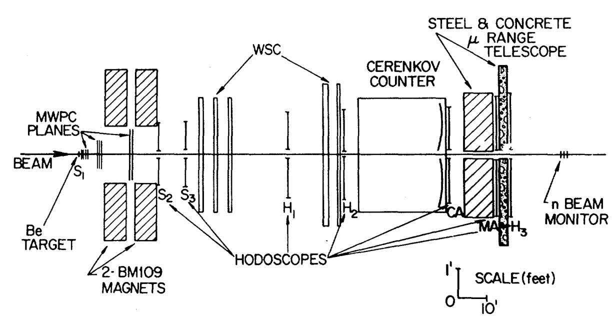

FIG. 1. Plan view of the spectrometer.

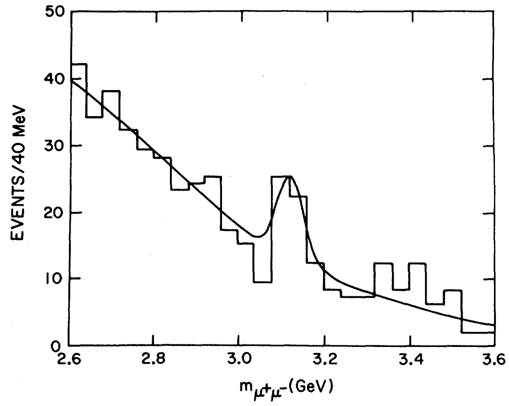

FIG. 2. $\mu^+\mu^-$ mass distribution near the ψ. The smooth curve is a polynomial fit to the data plus a Gaussian for the ψ.

lead absorber of ~9 radiation lengths. The neutron flux was continuously monitored using a 1.7% converter-counter telescope placed downstream of the spectrometer.

To obtain a mass-selective trigger we utilize the technique of "point to parallel focusing" often used in K^0 experiments[6]; thus, the required transverse-momentum "kick" from the dipole was approximately one-half the two-body mass. This geometry provided the optimal invariant-mass resolution for a forward spectrometer, and the large magnetic field strongly defocused low-transverse-momentum secondaries. The parallelism trigger required $\geqslant 1$ track on each side of the beam line plus "parallel logic," using hodoscope elements on H_1 and H_2, to accept particles within ± 10 mrad of the beam direction. This trigger resulted in a mass bite of $\Delta m \sim 600$ MeV for the spectrometer and necessitated four mass (magnet) settings to survey the mass interval ~2 to ~4 GeV.

Tracks were reconstructed starting downstream of the dipoles using hodoscopes H_1 and H_2 to establish roads. Downstream line segments were then extrapolated through the magnet creating roads in the proportional chambers. Finally, a fit was made constraining the tracks to originate from a common vertex. Accepted high-mass pairs were required to satisfy the experimental trigger independent of additional background tracks in the events.

Running was divided into two basic modes: "hadronic," using the parallel two-body trigger (and for part of the data a semi-inclusive trigger requiring a multiplicity of two in H_1 and H_2), and "2μ," requiring two penetrating particles in addition to the parallel trigger. Hadronic data were obtained with $\sim 2\times 10^6$ n/pulse incident on a 3.75-cm Be target, the 2μ data with $\sim 4\times 10^6$ n/pulse on a 7.25-cm, two-piece Be target. These targets were clearly resolved in the reconstructed vertex distributions. Accidentals from multiple beam interactions at these low intensities were $\lesssim 1\%$.

The mass distribution of the 2μ data near 3 GeV is shown in Fig. 2. A two-bin enhancement is observed at the ψ mass; the 2μ continuum is primarily from hadronic decays before the iron absorber. To obtain the ψ cross section we assume an isotropic decay distribution in the ψ rest frame and take the production model

$$\frac{d^2\sigma}{dx\,dp_\perp^{\,2}} \approx f(x)\exp(-ap_\perp^{\,2}) \tag{1}$$

with $f(x)$ constant near $x=0$ [7]:

$$f(x) = \begin{cases} 1.0 \text{ for } x < 0.35, \\ e^{-5(x-0.35)} \text{ for } x \gtrsim 0.35. \end{cases}$$

The resulting ψ cross section times branching ratio into 2μ for $x \gtrsim 0.2$ is 3.6 ± 2.0 nb/nucleon for $a = 1$ GeV^{-2} [8] in agreement with the results of Refs. 7 and 9. The cross section is ~10% larger if $f(x) = e^{-5x}$ for all $x \geqslant 0$. To obtain the cross section per nucleon we have taken the cross section per nucleus to have a linear dependence on atomic number.[9]

The invariant-mass distributions for the two-body hadronic channels $\pi^+\pi^-$, π^+K^-, pK^-, and $p\bar{p}$ are shown in Fig. 3. Data from the lowest mass (magnet) setting and the three higher mass settings are plotted separately; the former indicates primarily the mass acceptance of the spectrometer. The relative normalization of these data is arbitrary. Additionally, some overlap does exist in these data since protons and kaons are indistinguishable below 70 GeV/c.

These mass spectra are compared to smoothed distributions, for example generated with randomized tracks from different events, to search for $\geqslant$ 4-standard-deviation enhancements. One such enhancement is observed[10] in the π^+K^- mass distribution at $m_{\pi K} = 2.29 \pm 0.03$ GeV with a width consistent with the experimental mass resolution,[11] $\delta m_{\rm FWHM} \approx 0.01m$; no significant peaks are observed in our $\pi^+\pi^-$ data when interpreted as π^+K^-. Assuming the production model of Eq. (1) with $a = 3$ GeV^{-2}, we obtain a cross section times branching ratio of 65 ± 26 nb/nucleon for $x \geqslant 0.2$. This corresponds to a production cross section of $\sim 36\sigma(\psi \to \mu\mu)$.[8] We note that this "$4\sigma$" enhance-

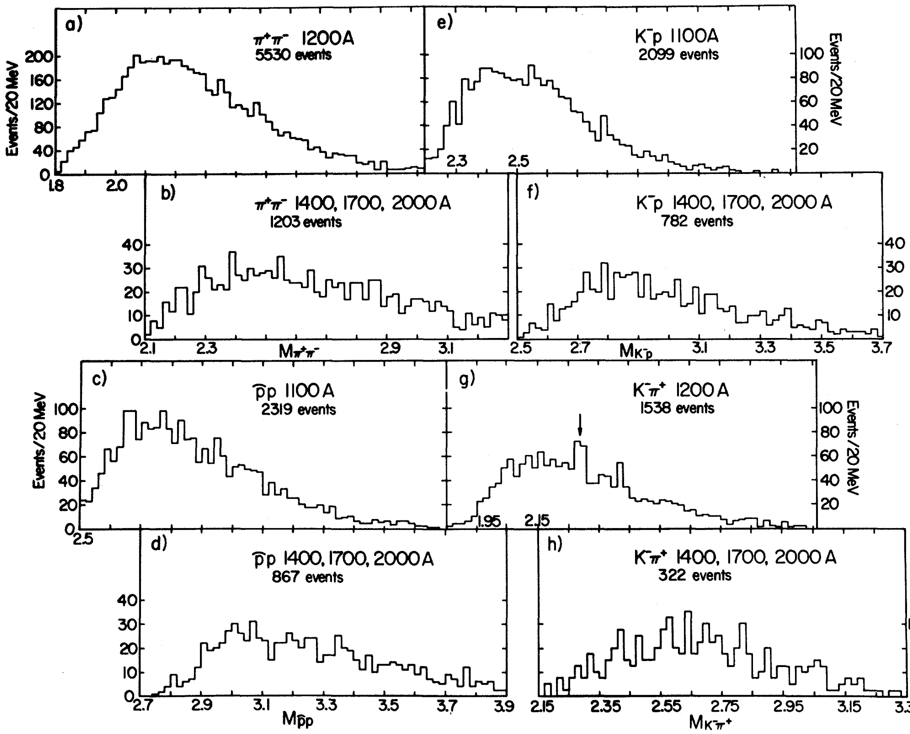

FIG. 3. $\pi^-\pi^+$, $\bar{p}p$, K^-p, and $K^-\pi^+$ mass distributions from (a), (c), (e), (g) the lowest mass settings and (b), (d), (f), (h) the three higher mass settings of the spectrometer.

ment has a purely statistical probability of ~3%.[12] Additional data are now being taken to increase our sensitivity in the 2.3-GeV mass region.

In the absence of enhancements, upper limits on cross section times branching ratio for $x \geq 0.2$ are calculated corresponding to a "4σ" effect. These results, shown in Fig. 4, incorporate the experimental mass resolution, and include corrections for two-track reconstruction inefficiencies (~13%), losses from secondary interactions and decays of particles, Cherenkov counter efficiencies, losses from vertex cuts and χ^2 cuts on track reconstruction (~5%), trigger bias losses for data obtained with the H_1, H_2 multiplicity cut (50 ± 10%), and neutron beam attenuation before the monitor. The neutron beam normalization is known to ± 10%. The resulting upper limits are at the level of $\geq 20\sigma(\psi \rightarrow \mu\mu)$.

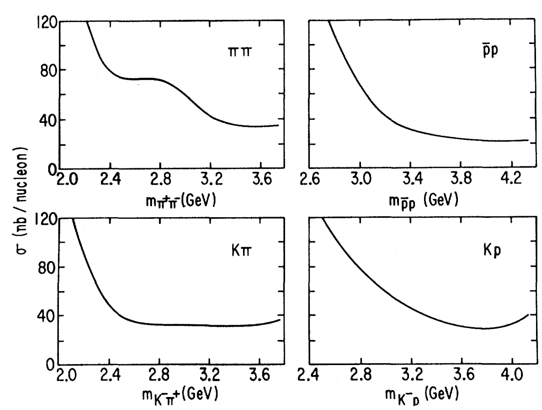

FIG. 4. "4σ" upper limits for the inclusive production of narrow resonances in the channels $\pi^-\pi^+$, $K^-\pi^+$, $\bar{p}p$, and K^-p.

An evaluation of our sensitivity to the production of narrow resonances can be obtained by scaling these cross sections for all Feynman x, a multiplicative factor of ~3 in the model of Eq. (1). With the exception of one possible π^+K^- enhancement, we observe no narrow resonances with a cross section times branching ratio of ≥ 0.1 μb.

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[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[2]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974); J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975); C. Chang *et al.*, Phys. Rev. Lett. 35, 901 (1975).

[3]J. von Krogh *et al.*, Phys. Rev. Lett 36, 710 (1976); E. G. Cazzoli *et al.*, Phys. Rev. Lett. 34, 1125 (1975).

[4]For example: M. K. Gaillard *et al.*, Rev. Mod. Phys. 47, 277 (1975); H. Harari, Phys. Lett. 57B, 265 (1975); Y. Achiman *et al.*, Deutsches Elektronen-Synchrotron Report No. DESY 75/27, 1975 (to be published); S. Okubo *et al.*, Phys. Rev. Lett. 34, 236 (1975).

[5]P. V. R. Murthy *et al.*, Nucl. Phys. B92, 269 (1975).

[6]A. R. Clark *et al.*, Phys. Rev. Lett. 26, 1667 (1971).

[7]K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1975); Yu M. Antipov *et al.*, Phys. Lett. 60B, 309 (1976).

[8]For comparison with our hadronic data the $\psi \to \mu\mu$ cross section is 1.8 ± 1.0 nb/nucleon with $a = 3$ GeV^{-2} in Eq. (1). Alternatively, with $a = 1$ GeV^{-2} our hadronic cross section upper limits increase by a factor of $\sim 2.1 \pm 0.2$.

[9]B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975); I. Gaines, in Proceedings of the Second International Conference at Vanderbilt on New Results on High Energy Physics; New Particles: Searches and Discoveries, Nashville, Tennessee, 1976 (to be published).

[10]For comparison two ~ 3 standard deviation peaks are observed: $\bar{p}p$ at 2.66 GeV and $K^-\pi^+$ at 2.42 GeV.

[11]Cherenkov momentum and geometrical cuts, as well as the thinner target used in the hadronic data, result in improved mass resolution with respect to the 2 μm data.

[12]This corresponds to a probability of occurrence of $6.34 \times 10^{-3}\%$ times ~ 500 data bins.

Coulomb Excitation into the Backbend Region of ^{164}Er†

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It has been demonstrated that multiple Coulomb excitation is an effective method for studying levels in the backbending region. Members of the ground band above the backbend in ^{164}Er have been excited. The ground-band $B(E2)$ values obey the rigid-rotor relation within ± 25%. A two-band mixing analysis shows that the intersecting bands have remarkably small interaction matrix elements at the backbend, i.e., < 40 keV. This weak band interaction is expected in the rotation-alignment model.

The discovery[1] of backbending (an anomalous behavior of the moment of inertia at high spin in nuclear rotational bands) has stimulated an intensive theoretical investigation of this phenomenon.[2-5] Present experimental evidence[3,4] suggests that backbending is caused by the intersection of the ground-state rotational band with a second rotational band possessing an appreciably larger moment of inertia. Two possibilities have emerged for the most likely nature of this second band. The Coriolis antipairing[6] model considers it to be a band for which the pairing has collapsed while the rotation-alignment[5] model attributes the band to two quasiparticles which are aligned with the rotating core by the Coriolis force. Observation of additional levels and a determination of the interaction matrix elements between the intersecting bands can shed considerable light on the structure of the bands.

Previously, backbending has been studied exclusively using (HI,xn) reactions to populate highly excited high-spin states which subsequently deexite by γ-ray cascades into the yrast sequence of states. In contrast, multiple Coulomb excitation specifically excites those collective bands which are strongly coupled to the ground state and thus is a complementary probe of the backbending phenomenon. In addition, Coulomb excitation can be used to study neutron-rich nuclei which cannot be reached by (HI,xn) reactions. The present paper describes the first case where states through a reasonably sharp backbend region have been Coulomb excited. The nucleus ^{164}Er has been studied because the high-spin