could not be completely ruled out in the GMR experiment, are negligible here because we use low-energy positrons and because the o-Ps is essentially free of the surface. All of the results, including the powder data, are consistent with a vacuum decay rate of 7.09 ± 0.02 μsec^{-1}, $(2.1 \pm 0.3)\%$ below the theoretical value.

The advances discussed in GMR and this work lead to many possibilities for future research. In particular, the high signal-to-noise ratio and good statistics of the present work should make possible a 200-ppm measurement of λ when the systematic effects are fully understood. Moreover, our method of detecting the time of the o-Ps formation may allow consideration of a pulsed excitation to the excited states. The Ps-atom and Ps-surface scattering can also be investigated. To help define the limits on the future use of powders in precision measurements, an attempt to observe the Ps ground-state fine-structure splitting in our uncompressed powders is now underway in collaboration with W. Frieze V. W. Hughes, and M. H. Yam.

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Limits on Charmed-Particle Production in Proton-Nucleus Collisions at 400 GeV/c*

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We have searched for the charmed and other new particles by measuring the hadron pair mass spectra in proton-nucleus collisions at 400 GeV/c. Results are presented for $\pi^- K^+$, $\pi^+ K^-$, and $\pi^+\pi^-$ pairs in the mass region from 1.5 to 4.0 GeV/c^2. No evidence for narrow resonances was found. The sensitivity of the search varied from 2×10^{-30} cm^2 at 2 GeV/c^2 to 5×10^{-32} cm^2 at 4 GeV/c^2. Experimental checks were provided by the observation of a clean $J/\psi(3.1)\to\mu^+\mu^-$ signal.

We report here the first results from a general search for massive narrow resonances produced near 90° in the center-of-mass system of proton-nucleon collisions and decaying to two hadrons. The search was inspired by the hypothesis of a fourth, "charmed," degree of freedom in the hadron spectrum.[1] The introduction of a charmed fermion yields a simple and natural explanation for the suppression of weak transitions involving changes in strangeness but not charge. This hypothesis and the recent discovery of the J/ψ particles[2] have led to several experimental efforts to find charmed particles.[3] Certain charmed mesons are expected to decay via the weak interaction partly into $\pi^{\pm}K^{\mp}$ final states; and our search has focused on finding a narrow signal in the πK mass spectra. Cabbibo-suppressed decays of such mesons would also yield $\pi^+\pi^-$ decays; our search has also included this combination.

The experiment was performed at the Fermi National Accelerator Laboratory using a 400-GeV/c diffractive proton beam incident on a segmented, 6.7-cm-thick, polyethylene target. Hadrons and muons produced by beam-target interactions were detected with an apparatus consisting of two spectrometers placed at 100 mrad with respect to the beam as shown in Fig. 1. Each spectrometer included sixteen planes of drift chambers arranged in modules DC1–DC5, three Cherenkov counters C1–C3, and sets of scintillation counters labeled F, A, E, and B. A and B were segmented to impose a minimum momentum requirement for particles traversing the spectrometer. Analyzing magnets with apertures of 20 cm×61 cm and field integrals of 32 kG m bent particle trajectories in the vertical plane. Hadrons were absorbed at the end of each spectrometer arm with steel and concrete, and muons were identified by a coincidence signal from the counters MU1 and MU2.

The basic trigger consisted of a coincidence of signals from F, A, E, and B in both arms. To eliminate low mass triggers, the counter geometry and logic strongly suppressed the acceptance of particles with momentum less than 7 GeV/c. At the normal beam intensity of 5×10^7, the trigger rate was 400 per spill. Approximately 50% of triggers contained real two-particle events. The data-handling system was capable of recording up to 110 events per beam spill.

The drift chambers were arranged in pairs with one plane shifted with respect to the other to resolve left-right ambiguities. Drift spaces of 1.0, 1.5, and 3.0 cm were chosen to keep the number of cells per plane roughly constant. The gas in the chambers was a mixture of 10% CO_2 and 90% argon which yielded drift speeds of 5 cm/μsec and an intrinsic coordinate resolution of $\sigma = 0.25$ mm. At normal beam intensities the rates in some wires were as high as 0.5 Mhz. The system efficiency for reconstructing pair events was 70%.

Particles were identified with three threshold Cherenkov counters: C1 (1 atm air), C2 (1.8 atm propane), and C3 (1.4 atm CO_2). A complete separation of the π, K, and p ($\bar{p}$) was possible in the momentum range from 7 to 20 GeV/c. Furthermore p ($\bar{p}$) could be identified up to 40 GeV/c. The quality of particle identification was affected primarily by the large flux of background particles (including electrons from showers) which often produced extra Cherenkov signals. By accepting only logically consistent Cherenkov combinations, particle misidentification was minimized but approximately 40% of real kaons and protons (accompanied by spurious Cherenkov signals) were rejected. The highest level of misidentification occurred for particles identified as "kaons" of which approximately 10–20% were actually protons or antiprotons.

The mass scale, mass resolution, and sensitivity of the experiment were checked by detecting the $J/\psi(3.1)$ particle. Triggers with $\mu^+\mu^-$ pairs were recorded continuously throughout the data run; and the resulting mass spectrum is shown in Fig. 2. Our measured J/ψ mass is 3.095 GeV with an estimated systematic error of ± 10 MeV. The observed width is consistent with a calculated mass resolution of 15 MeV [full width at half-maximum (FWHM)] at 3.1 GeV. Assuming that J/ψ particles decay isotropically and that the production cross section depends linearly on the atomic number of the target, we obtain $d\sigma/dy = 4.9$ nb/nucleon at a rapidity of $y = -0.39$ in the center-of-mass system. The statistical error of this measurement is ± 1.1 nb. Other experiments[4]

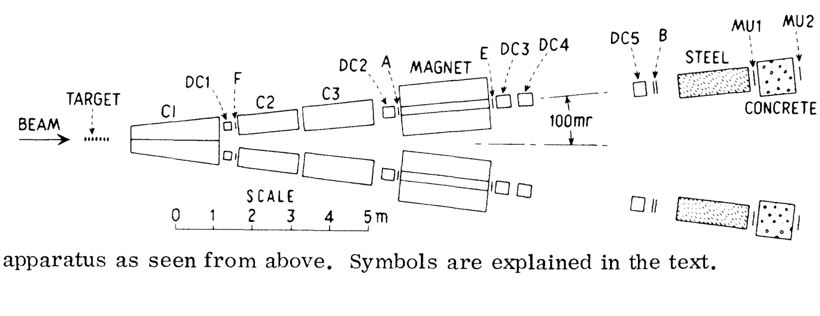

FIG. 1. The apparatus as seen from above. Symbols are explained in the text.

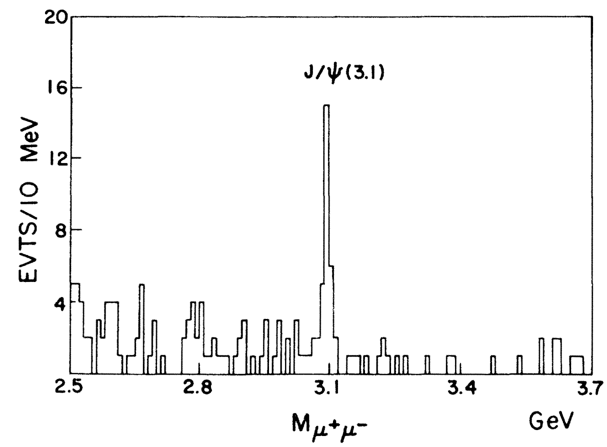

FIG. 2. $J/\psi(3.1)$ signal observed in the $\mu^+\mu^-$ effective mass spectrum.

have yielded similar values of $d\sigma/dy$.

We have collected data, based on 7 million triggers, for all $\pi^\pm$, $K^\pm$, p, and $\bar{p}$ pair combinations. As stated above, the π^+K^- and π^-K^+ mass spectra are of particular interest in the charm hypothesis and these are shown, along with the $\pi^+\pi^-$ spectrum, in Fig. 3. The rapidity distribution of these hadron pairs in the center-of-mass system is confined to the region around $y = -0.4$. The data have not been corrected for the mass-dependent acceptance of the apparatus. A charmed-meson signal would appear in the spectra as a sharp peak with a width given by the mass resolution which varies from 11 MeV (FWHM) at 2 GeV to 18 MeV (FWHM) at 4 GeV. This is equivalent to one to two mass bins in Fig. 3. The hadron mass spectra show no significant narrow peaks.[5] Our criterion for a significant signal is a peak of at least 4 standard deviations above a smooth background curve. For the πK data this curve was obtained by generating a random πK spectrum with very high statistics from pions and kaons belonging to different events. This random spectrum gave a good fit to our data. The other dihadron combinations were analyzed in a similar manner. Results on hadron pair combinations not shown here (K^+K^-, $\bar{p}p$, K^-p, etc.) will be presented elsewhere. We only mention that no significant narrow structures were observed in any of the pairs at high masses.

The sensitivity of this search is clearly limited by the physical hadronic background. (Uncorrelated random pairs constitute only about 10% of the accepted events.) Since we measure J/ψ production directly via the $\mu^+\mu^-$ decay mode, which is topologically equivalent to the two-particle decay of charmed mesons, we prefer to express the

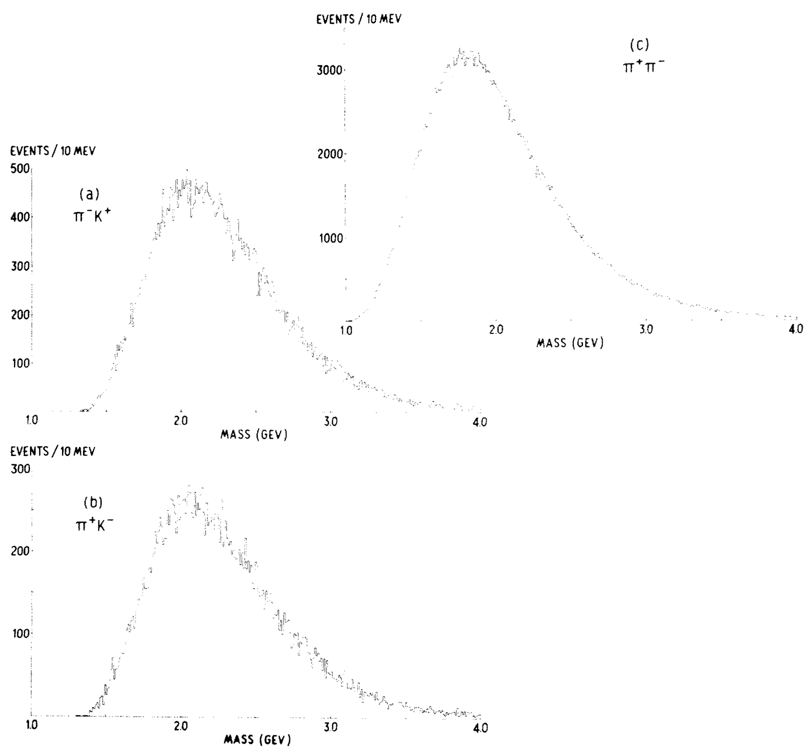

FIG. 3. Effective mass spectra for (a) π^-K^+ (46 963 events), (b) π^+K^- (26 503 events), and (c) $\pi^+\pi^-$ (328 803 events).

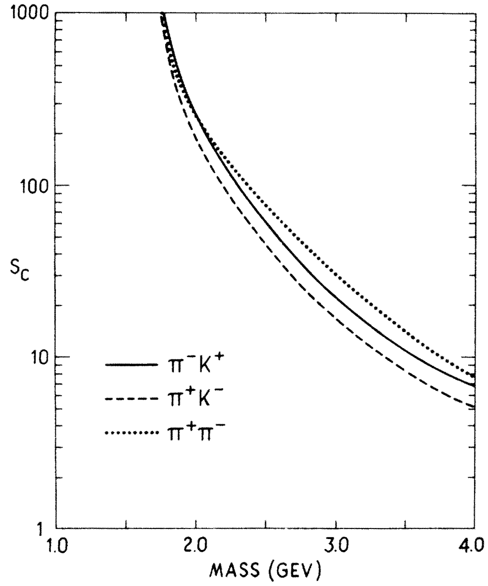

FIG. 4. Cross sections required for observing a 4-standard-deviation peak in $\pi^- K^+$, $\pi^+ K^-$, and $\pi^+\pi^-$ mass spectra as a function of the hadron pair effective mass. Cross sections are expressed in units of $\sigma_{J/\psi} B_{\mu\mu}$ ($\simeq 10$ nb) so that $S_C \equiv \sigma_C B_{hh}/\sigma_{J/\psi} B_{\mu\mu}$.

sensitivity to narrow resonance production in terms of the product of the $J/\psi(3.1)$ cross section ($\sigma_{J/\psi}$) and the $J/\psi \to \mu^+\mu^-$ branching ratio ($B_{\mu\mu}$).[6] Our sensitivity to peaks with a width equal to the mass resolution and, with a statistical significance of 4 standard deviations, is given in Fig. 4 as a function of mass for $\pi^+\pi^-$, $\pi^- K^+$, and $\pi^+ K^-$ and is expressed in units of $\sigma_{J/\psi} B_{\mu\mu}$. In Fig. 4, σ_C is the production cross section for new particles and B_{hh} is the branching ratio into the appropriate haron pair. The calculation of sensitivities includes the corrections for the mass acceptance of the apparatus, particle identification requirements, and differences in mass resolution and experimental "live" times between the J/ψ and the hadron data. From our estimate that $\sigma_{J/\psi} B_{\mu\mu} = 10$ nb $= 10^{-32}$ cm^2, we obtain the result that this experiment was sensitive to $\sigma_C B_{hh}$ at the 2×10^{-30} cm^2 level at 2 GeV. For hadron pair masses of 4 GeV/c^2 this limit decreases to around 5×10^{-32} cm^2. If charmed particles with masses near 2 GeV/c^2 are produced with cross sections similar to that of J/ψ, they will not be observable in a hadron experiment of this kind unless a more sophisticated trigger can be devised to reduce the large physical hadron background.

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[6]Except for possible differences in the momentum distribution of the J/ψ and charmed particles, this provides a measure of sensitivity which is relatively free of systematic errors.