Structure of Nucleons at Small Distances*

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We report here the observation of surprisingly simple behaviors in the massive-hadron-pair ($m > 2$ GeV) production from proton-nucleon collisions. With a 28.6-GeV incident proton beam and a pair spectrometer to detect the hadrons, the measured cross section decreases like $d^2\sigma/dx\,dm \propto e^{-5m}$ and can be grouped into three groups: $\pi^- + p$; $\pi^+ + \pi^-$, $\bar{p} + p$, $K^- + p$; and $K^- + \pi^+$, $\pi^+ + \bar{p}$. Within a given group the yield is the same to ±20%; different groups are separated by a factor of ~10 from each other.

We report in this Letter the measurement of yields of hadron pairs from the reactions

$$p + \text{Be} \to \pi^- + p + X; \quad \text{(1a)}$$

$$p + \text{Be} \to \begin{cases} \pi^+ + \pi^- + X, \\ \bar{p} + p + X, \\ K^- + p + X; \end{cases} \quad \text{(1b)}$$

$$p + \text{Be} \to \begin{cases} K^- + \pi^+ + X, \\ \pi^+ + \bar{p} + X. \end{cases} \quad \text{(1c)}$$

The experiment was done at the 30-GeV alternating-gradient synchrotron at the Brookhaven National Laboratory. To detect hadron pairs we used a pair spectrometer described previously[1] for the discovery of the J particle. The incident beam intensity was monitored by a secondary-emission monitor. In order to reduce random accidentals to a minimum we put in a new target system of five $4\times4\times4\text{-mm}^3$ pieces of Be separated from each other by 6 in. The targets are supported by thin piano wires and mounted inside a He bag. This arrangement enables us to know the location of the interaction and to reduce the random accidentals by requiring that particles from each arm trace back to the same point of interaction. Because of the smallness of the target and the instability of the incident proton beam, the absolute normalization of the cross section is estimated to be uncertain by a factor of ~3. Since all the reactions were recorded simultaneously, the relative yields between various final states are accurate to ~±20%, the error being dominated by accidentals in the rare state of $\pi^+ + \bar{p}$.

To study the yields of hadron final states we assume that they all come from the decay of a particle A with mass m which decays isotropically into a pair of hadrons in the A rest system. The

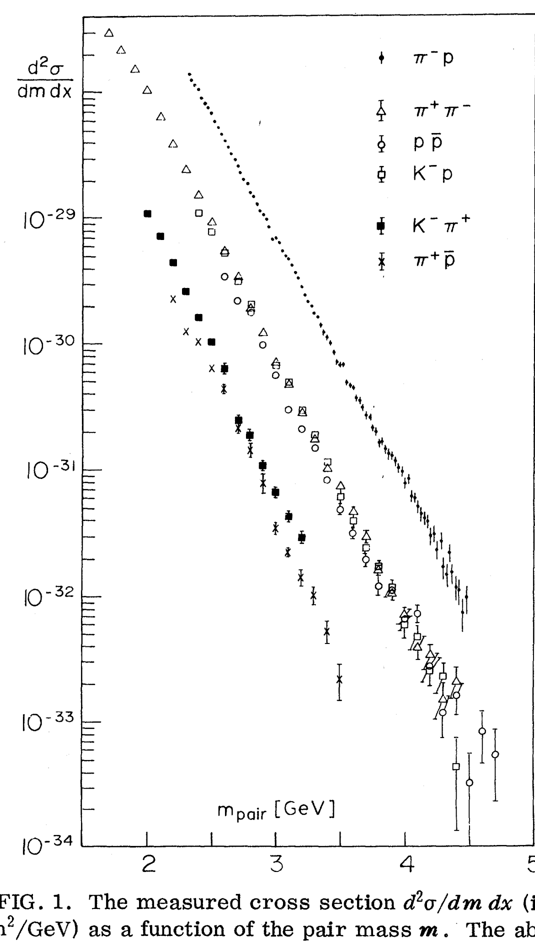

FIG. 1. The measured cross section $d^2\sigma/dm\,dx$ (in cm^2/GeV) as a function of the pair mass m. The absolute cross section is accurate to a factor of ~3. The relative yields between different reactions is accurate to ~20%.

$P_\perp$ dependence of A production was constructed to agree with the data. The acceptance was calculated with a Monte Carlo program taking into account π and K decays along their flight path. We define $x = 2P_\parallel/\sqrt{s}$, where $P_\parallel$ is the longitudinal momentum of A and $\sqrt{s}$ is the total energy in the p-N center-of-mass system. The acceptance is peaked near $x = 0$.

The cross sections are shown in Fig. 1. We make two important observations: (1) The relative mass dependence is the same for all final states and decreases with m like $d^2\sigma/dm\,dx \approx e^{-5m}$ (m in GeV). (2) There is a strong degeneracy in the production cross section for hadron pairs. The $\pi^- + p$ state (group a) is a factor of ~10 higher than the $\pi^+ + \pi^-$, $\bar{p} + p$, and $K^- + p$ states (group b) which in turn are a factor of ~10 higher than the $K^- + \pi^+$ and $\pi^+ + \bar{p}$ states (group c). *The cross section within a group is the same to ± 20%.*

It should be noted that the $K^+ + \pi^-$ state is very close to group b and the $K^+ + \bar{p}$, $K^+ + K^-$ states are very close to group c. But since the nuclear-absorption correction on K^+ and p in the thick wall of the last Cherenkov counter can not be accurately made the K^+ yields may have large p contaminations. We have not included these reactions in the figures. Measurements on $\pi^- + \pi^-$, $K^- + K^-$, $\bar{p} + \bar{p}$, and $p + p$ will be published later.

To study the $P_\perp$ dependence of the massive pair we note that for a particle A produced near $x = 0$ the production can only depend on the energy E like e^{-5E}. Assuming the production to be isotropic so that

$$\langle P_\perp^2 \rangle = \tfrac{2}{3}\langle p^2 \rangle ,$$

and defining the kinetic energy

$$T = E - m = (m^2 + \tfrac{3}{2}P_\perp^2)^{1/2} - m ,$$

we have

$$E\, d^3\sigma/d^3p = Ce^{-5E} = Ce^{-5m}e^{-5T}, \qquad (2)$$

where C is a constant. The e^{-5T} term describes the $P_\perp$ dependence as a function of mass as shown in Fig. 2(a). To check the T behavior of Eq. (2) we show in Fig. 2(b) the $\pi^+ + \pi^-$ spectra at three narrow mass bands of $1.9 < m < 2.1$ GeV, $2.4 < m < 2.6$ GeV, and $2.9 < m < 3.1$ GeV. As seen the data are quite consistent with the e^{-5T} dependence of Eq. (2). We note that it follows from Eq. (2) that as $m \to 0$, $E\, d^3\sigma/d^3p \to c\, \exp(-6P_\perp)$ and we have the well-known behavior for single-particle production.

The simple behaviors of hadron-pair production shown in Fig. 1 may imply that additional degrees of freedom or simple structures exist inside nucleons at very small distances.

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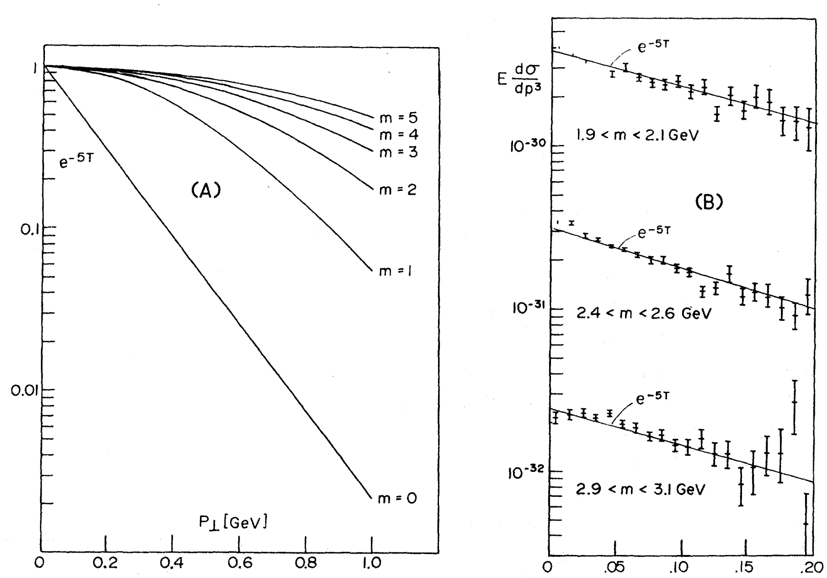

FIG. 2. (a) The $P_\perp$ behavior of e^{-5T} as a function of m [see Eq. (2)]. (b) The T dependence of the invariant cross section (in units of cm^2/GeV^2) for $\pi^+ + \pi^-$ at three narrow mass bands. The e^{-5T} line is a visual fit to the data.

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[1]J. J. Aubert *et al.*, Nucl. Phys. B89, 1 (1975); J. J. Aubert *et al.*, Phys. Rev. Lett. 35, 416 (1975).

Systematics of Pion and Proton Interactions with Ni Nuclides*

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γ-ray spectra have been observed following the interaction of 220-MeV π^+ and π^- and 200-MeV protons with ^{58}Ni and ^{60}Ni and 100-MeV π^+ with ^{58}Ni. Product nuclides have been identified from characteristic γ-ray lines corresponding to total cross sections of ~ 500 mb. The systematic trends with projectile and energy are explored; rather substantial differences are found between pions and protons.

Our knowledge of the interaction of pions with complex nuclei is rather limited. A number of experiments carried out with stopped negative pions, primarily on light targets, have provided some information on the pion-absorption process; in addition we have some knowledge of elastic scattering and total cross sections at higher energies.[1] For nuclei heavier than ^{12}C almost nothing is known of how much of the total cross section corresponds to the pion suffering an inelastic collision and maintaining its identity, and how much to the pion disappearing altogether. Nor is there much information on whether pion absorption occurs mainly on pairs of nucleons or whether larger clusters play a role. We have investigated the distribution of residual nuclides produced by the bombardment of ^{58,60}Ni with $\pi^\pm$ and also with protons; such results can provide substantial constraints on the gross features of possible models of the pion-nucleus interaction.

The residual nuclides were identified by measuring prompt γ-ray spectra. In contrast to activation measurements, this technique is sensitive to stable residual nuclei, where most of the total cross section is concentrated. γ rays are seen when a given residual nuclide is left with insufficient excitation energy for particle emission; this technique cannot distinguish whether