

Inclusive Pion Production in Collisions of Relativistic Protons, Deuterons, Alphas, and Carbon Ions with Nuclei*

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We have measured single-particle inclusive spectra of π^+ and π^- mesons produced at 2.5° (lab) in the collision of 1.05–4.2-GeV protons, 1.05- and 2.10-GeV/nucleon deuterons and α particles, and 2.10-GeV/nucleon ^{12}C nuclei with various targets at an angle of 2.5° (lab). The negative-pion spectra show scaling behavior. The results are compared to a simple model in which individual nucleons in the projectile interact with the target to produce pions.

We report here results on pion production by relativistic protons, deuterons, and α particles on various nuclear targets. In addition, some data were obtained with use of a ^{12}C beam. Our initial motivation was to determine to what extent very energetic pions, that is, pions with energies considerably larger than those which result from simple nucleon-nucleus collisions, would be produced by deuteron and α projectiles of the same kinetic energy per nucleon. How often does a complex nucleus like ^4He transfer a significant fraction of its energy to the production of a single pion? When such a process occurs, is it because several nucleons inside the projectile acted collectively, or is it mainly a process involving nucleon-nucleon collisions in which the nucleons have high-Fermi-momentum components? We were also interested in seeing how the pion production depended on the type of target and the beam energy, and how well charge symmetry is satisfied in pion production by deuterons and α 's on an isospin-zero target. Finally we wanted to see whether high-energy ideas such as scaling¹ could be applied to pion production from nuclear collisions at kinetic energies as low as 1 GeV/nucleon.

The external beam of the Lawrence Berkeley Laboratory Bevatron was focused onto our targets (Be, C, Cu, and Pb). Typical fluxes were $(1-3) \times 10^{11}$ protons, $(1-10) \times 10^{10}$ deuterons, $(1-10) \times 10^9$ α 's, and $(1-3) \times 10^6$ carbon nuclei per pulse. Secondary particles produced at 2.5° were momentum analyzed and transmitted to our detection system by a double-focusing spectrometer which could be set to transport either positive or negative particles. The basic detection system consisted of two scintillation counters to measure time of flight over a 15-m flight path. Additional scintillation counters were used to further define the beam and to measure dE/dx . A

gas Cherenkov counter was used to measure lepton contamination and to help distinguish π^+ 's from protons at momenta above 1.75 GeV/c. Data were typically taken at momentum intervals of 0.25 GeV/c over the range $0.5 \leq k_\pi \leq 5.0$ GeV/c, where the upper limit was set by limitations on the current in the spectrometer magnets and the lower limit was chosen so as to keep manageable the correction factors associated with pion decay and lepton contamination. A scintillation-counter telescope at 90° to the production target was used to monitor the primary-beam intensity. Absolute normalization of the data was obtained by periodically calibrating this monitor against an ionization chamber located in the primary beam just upstream of the production targets. The uncertainties in the absolute calibration of the ion chamber, the acceptance of the spectrometer, and the steering and focusing of the primary beam onto the production targets, which were our major sources of systematic error, resulted in an estimated overall uncertainty of $\pm 20\%$ in normalization, and a relative uncertainty between points of $\sim 10\%$. The data presented here have been corrected for absorption in the target, decay in flight, and lepton contamination.

Our results on the yields of negative pions from collisions of 1.05–4.2-GeV (kinetic energy) protons with a carbon target are shown in Fig. 1(a). The Lorentz-invariant cross section $(E/k^2)d^2\sigma/d\Omega dk$, where E is the energy of the outgoing π^- and k is its momentum, is plotted against the scaling variable $x' = k_{\parallel}^*/(k_{\parallel}^*)_{\max}$, where k_{\parallel}^* is the longitudinal momentum of the pion in the overall center-of-mass system. The most striking feature of the data is that the spectra tend to lie on top of each other. Similar results are obtained for other targets. Higher-energy data^{2,3} (12-, 19-, and 24-GeV protons on Be) also fall on the same curve. Scaling behavior, where the pion

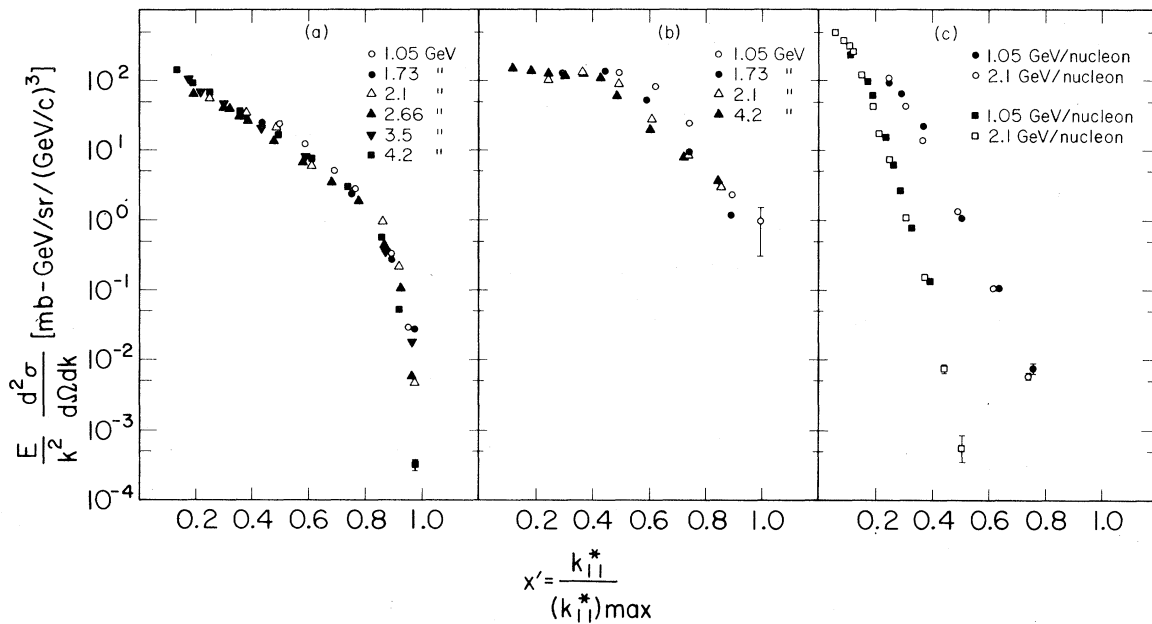


FIG. 1. Invariant cross section for pion production at 2.5° (lab) from a carbon target versus the scaling variable $x' = k_{\parallel}^*/(k_{\parallel}^*)_{\max}$: (a) Negative-pion production by 1.05–4.2-GeV protons, (b) positive-pion production by 1.05–4.2-GeV protons, (c) negative-pion production by 1.05- and 2.1-GeV/nucleon deuterons (circles) and α 's (squares).

yield does not depend on the energy but only on a scaling variable x' (at fixed k_{\perp}), is familiar in high-energy nucleon-nucleon interactions. The remarkable feature of the present data is that scaling behavior persists, at least approximately, down to 1 GeV. It must be kept in mind that since this experiment was performed at a fixed lab angle of 2.5°, k_{\perp} is not quite constant. This effect is most important near $x=1$ where it could change our results by as much as a factor of 2. However, since the scaling fit encompasses more than 6 decades, a variation of even a factor of 2 near the end points would not produce observable deviations from the trend of the data to scale. The π^+ production spectra are shown in Fig. 1(b). They do not scale nearly as well as those of negative pions, especially at low proton energies.

Invariant negative-pion production cross sections for 1.05- and 2.1-GeV/nucleon deuterons and α 's incident on carbon are shown as a function of x' in Fig. 1(c). Again scaling is reasonably well satisfied. We see that the heavier the projectile the more rapid is the falloff as x' increases. This result indicates that nuclei, which are relatively loosely bound objects, tend not to transfer a large fraction of their kinetic energy to individual pions. In the case of deuterons, our x' distributions in the interval $0.5 \leq x' \leq 1$ fall much more steeply than those of Baldin *et al.*,⁴

who measured π^- production at 0° by deuterons of about 8 GeV on Cu.

The pion production cross sections for 2.1-GeV/nucleon protons, deuterons, and α particles on carbon are compared in Fig. 2. Two features

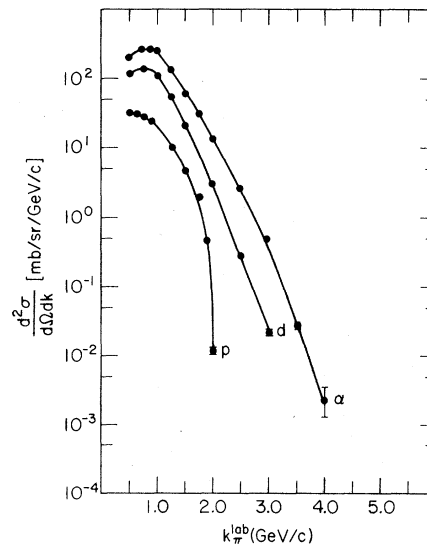


FIG. 2. Laboratory cross section $d^2\sigma/d\Omega dk$ for negative-pion production at 2.5° (lab) by 2.1-GeV/nucleon proton, deuteron, and α beams on carbon target versus the laboratory momentum of the pion. The solid lines are hand-drawn and are to serve as a guide to the eye only. Only statistical errors are shown.

are evident: (1) The ratio of the cross sections for producing low-momentum negative pions (~ 1 GeV/c) by α 's, deuterons, and protons is approximately 10:5:1. (2) The spectrum of observed pions extends to higher energies as the mass of the projectile is increased. The larger production cross sections in the case of deuterons and α 's can be attributed to the presence of neutrons, which produce π^- 's more copiously than do protons, and to the increased energy of the system. Our measurements of π^- production by beams of 1.05-GeV/nucleon ^{12}C show that the ratio of π^- production by ^{12}C to π^- production by α particles is 3.0 ± 0.3 at a momentum of 750 MeV/c for all targets.

In an attempt to determine the importance of mechanisms in which several nucleons in an energetic nuclear projectile act cooperatively to produce pions, we have compared our experimental results to calculations based on a model in which all pions are produced in individual nucleon-nucleus collisions. We assume that

$$\sigma_{aA} \pi(\vec{P}_a, \vec{k}_\pi) = \sum_N^a \int W_{aN}(\vec{P}_a, \vec{P}_N) \times \sigma_{NA} \pi(\vec{P}_N, \vec{k}_\pi) d^3P_N,$$

where a refers to the projectile and A to the target nucleus. $W_{aN}(\vec{P}_a, \vec{P}_N)$ is the momentum distribution of the nucleon N inside the projectile as transformed to the lab system. By charge symmetry $\sigma_{pC} \pi^+(\vec{P}_N, \vec{k}_\pi) = \sigma_{nC} \pi^-(\vec{P}_N, \vec{k}_\pi)$. For $\sigma_{pC} \pi^-(\vec{P}_N, \vec{k}_\pi)$ we have used our experimentally determined cross sections at 2.5° (lab) and corrected them for the transverse-momentum variation by assuming that at all momenta considered in these measurements such a variation can be fitted with an exponential of the form $\exp[-5|k_\pi \sin(\theta_{\vec{k}_\pi} - \theta_{\vec{P}_N})|]$.

In the case of the deuteron $W_{dA}(\vec{P}_d, \vec{P}_N)$ was obtained from the Lorentz transformation of a normalized Hulthén wave function of the form $|\varphi(q)|^2 \sim |(q^2 + \alpha^2)^{-1} - (q^2 + \beta^2)^{-1}|^2$ with $\alpha = 45.7$ MeV and $\beta = 5.2$ MeV (q is the nucleon momentum in the rest frame of the deuteron). The predictions are shown together with the data points in Fig. 3(a). The fits reproduce quite well the general behavior of the measured cross sections for fast pions as a function of pion momentum. There are no free parameters. These results disagree with the conclusions of Baldin *et al.*⁴ who claim to be unable to fit their data with such a model.

The case of α 's is complicated by the fact that the single-nucleon momentum distribution is not well known. From electromagnetic-form-factor

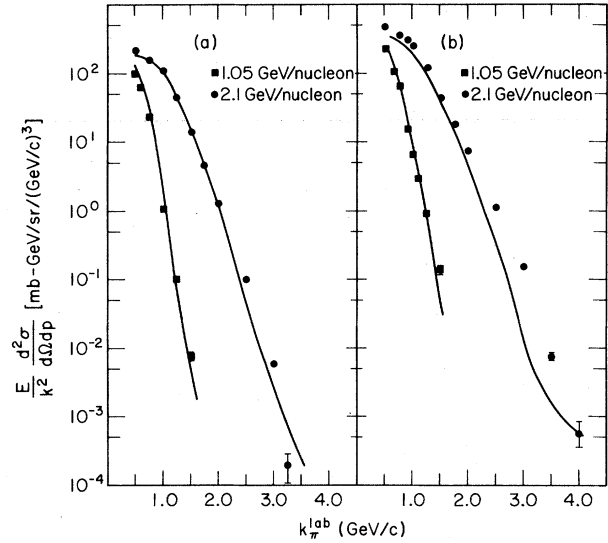


FIG. 3. Invariant cross section for negative-pion production at 2.5° (lab) by 1.05- and 2.1-GeV/nucleon (a) deuteron and (b) α beams versus the laboratory momentum of the pion. The solid lines in each case represent the predictions of the model as described in the text.

experiments one can deduce a charge distribution but it is difficult to translate this to the momentum distribution of the individual nucleons $|\varphi_\alpha(q)|^2$. As a first approximation to $\varphi_\alpha(q)$ we Fourier transformed the square root of the nuclear charge distribution.⁵ As before $W_{\alpha N}(\vec{P}_\alpha, \vec{P}_N)$ was then obtained by transforming $|\varphi_\alpha(q)|^2$ to the lab system. The results are shown in Fig. 3(b). Although the general trends of the data are reproduced by the model, quantitatively the agreement is not good. At this point we are unable to say whether this is due to a poor choice for $W_{\alpha N}(\vec{P}_\alpha, \vec{P}_N)$ or to a breakdown of the model. Further work is in progress for both deuterons and α 's.

Pion production from Be, Cu, and Pb is quite similar to that from carbon. The shape of the spectra is independent of the target material for $k_\pi > 1$ GeV/c. The magnitude of these cross sections is proportional to $A^{1/3}$, suggesting that fast pions are produced in peripheral collisions. For lower-momentum pions, the A dependence becomes more pronounced (e.g., $\sigma \propto A^{1/2}$ for $k_\pi = 500$ MeV/c), suggesting that slow pions are produced in more central collisions.

For isospin-zero nuclei like deuterons, α particles, and ^{12}C charge symmetry predicts that in the reactions $d + C \rightarrow \pi^+ + X$ and $\alpha + C \rightarrow \pi^+ + X$ the ratio of π^+ to π^- production should be unity. In

every case our results are consistent with this prediction to within the experimental errors of about 10%.

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Measurements of $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$, and $e^+e^- \rightarrow \gamma\gamma$ at Center-of-Mass Energies Close to 3105 MeV*

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Independent evidence is presented for the decay of the recently discovered particle $\psi(3105)$ into electron-positron pairs and new evidence is presented for the decay of this particle into muon pairs. Measurements of the rate of the reaction $e^+e^- \rightarrow \gamma\gamma$ at center-of-mass energies in the vicinity of 3105 MeV are also reported.

We report here independent evidence for the decay of the recently discovered particle¹⁻³ $\psi(3105)$ into electron-positron pairs and new evidence for the decay of this particle into muon pairs. We also report the results of a measurement of the reaction $e^+e^- \rightarrow \gamma\gamma$ at center-of-mass energies in the vicinity of 3105 MeV. These measurements were begun immediately following the discovery of the $\psi(3105)$ at SPEAR.¹ At that time an apparatus primarily designed for the study of quantum electrodynamics (QED) was operating in the second interaction region at SPEAR and was applied immediately thereafter to the study of the $\psi(3105)$. This apparatus is very similar to that described recently by Beron *et al.*,⁴ and is capable of identifying the reactions $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$, and $e^+e^- \rightarrow \gamma\gamma$. The detection apertures and procedures used to recognize each of these reactions are identical to those described by Beron *et al.*,⁴ except that the detection aperture for the reac-

tion $e^+e^- \rightarrow \mu^+\mu^-$ is larger by a factor of 2.6. All of the measurements reported in this Letter were made with the detection apparatus set to accept particles produced at angles θ close to 90° with respect to the colliding beams.

Figure 1 shows the observed event rate for the reaction $e^+e^- \rightarrow e^+e^-$ at center-of-mass energies in the vicinity of 3105 MeV.⁵ A clear enhancement associated with the $\psi(3105)$ is observed with a width consistent with the upper limit of 1.9 MeV reported by Augustin *et al.*¹ and Abrams *et al.*⁶ The event rates shown in Fig. 1, and those in the subsequent figures of this Letter, are normalized with respect to the observed rate of $e^+e^- \rightarrow e^+e^-$ events in an independent apparatus viewing the interaction region at angles close to 3.5° . This latter apparatus, or luminosity monitor, is a substitute at the present time for a precision monitor that is in preparation for later work. The statistical accuracy of the present monitor