Inclusive Single-Particle Production at 90° in the Center-of-Mass System for Nuclear Targets and 28.5-GeV/c Incident Protons*

U. Becker, J. Burger, M. Chen, G. Everhart, F. H. Heimlich, T. Lagerlund,
J. Leong, D. Novikoff, W. Toki, M. Weimer, and S. L. Wu
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

D. Lowenstein
Brookhaven National Laboratory, Upton, New York 11973

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The invariant cross section for the inclusive production of π^+, π^-, K^+, K^-, p, and $\bar{p}$ is presented for proton-nucleon interactions at $p_{\rm lab} = 28.5$ GeV/c. Beryllium, titanium, and tungsten targets were used and the yields were extrapolated to $A = 1$ using the power law $\sigma \sim A^\alpha$. The exponent α increases with p_T, except for protons. The p_T dependence of the cross sections is compared with a simple fireball model.

It is necessary to study the production of particles with large transverse momenta in hadron-hadron collisions in order to understand the nucleon structure at small distances. In this Letter, we present an experiment on hadron ($h = \pi^\pm$, $K^\pm$, $p, \bar{p}$) production with 28.5-GeV protons from the Brookhaven alternating gradient synchroton (AGS) impinging on Be, Ti, or W targets according to the reaction

$$p + A \to h^\pm + X,$$

where X is the undetected rest and A = Be, Ti, or W. The reactions take place at $\sqrt{s} \sim 7.43$ GeV. The angle in the center-of-mass system (CMS) was ~90°; more precisely, we used only data in a small interval of the Feynman parameter $x = 2p_L^*/\sqrt{s}$ (where p_L^* is the longitudinal center-of-mass momentum) so that $-0.02 \leq x \leq 0.02$ for pions, $-0.04 \leq x \leq 0$ for kaons, $-0.08 \leq x \leq -0.04$ for p and $\bar{p}$ with $p_T \geq 1.25$ GeV/c, and $-0.14 \leq x \leq -0.10$ for p and $\bar{p}$ with $p_T < 1.25$ GeV/c.

The existing data exhibit a gap between the CMS energies $\sqrt{s} = 6.8$ GeV and $\sqrt{s} = 23.7$ GeV. For kaons and antiprotons especially, data are scarce.[1] We extrapolated the nuclear cross sections to the nucleon value at $A = 1$, assuming a form $\sigma \sim A^\alpha$. Cronin *et al.*[1] observed that the exponent α increases with the transverse momentum p_T to values even exceeding 1.0. It is interesting to see whether this phenomenon persists at our energies and in the p_T range between 0.75 and 2.25 GeV/c covered in this experiment.

A beam of 28.5-GeV/c protons was generated by the Brookhaven National Laboratory AGS and focused to a spot of 3×3 mm^2 in size at target position. The intensity of 10^9–10^{10} protons per pulse was measured by a secondary emission counter which in turn was calibrated daily through the reaction ^{27}Al$(p, 3pn)^{24}$Na. The targets were rectangular plates (25×80 mm^2 in size) of metallic Be (0.662 g/cm^2), Ti (0.538 g/cm^2), and W (0.418 g/cm^2) with natural isotopic abundances. The produced particles were detected in one arm of a magnetic double-arm spectrometer.[2] Each arm consists of three vertically bending dipole magnets, four proportional wire chambers of three planes each with 2-mm spacing for track reconstruction, two 8×8 scintillator hodoscopes, and three Cherenkov counters filled with 1-atm H$_2$, 0.9–1.2-atm isobutane, and 6.1–22.0-atm ethylene, depending on the momentum setting, in order to detect electrons, pions, and kaons, respectively. The horizontal angular acceptance is 14.6 ± 1° (90 ± 5°, CMS), the vertical acceptance ± 2°. The momentum acceptance is $0.6p_0 \leq p \leq 1.8p_0$, with p_0 being the central momentum. The spectrometer has been described in detail previously.[2]

The data cover the transverse-momentum range between 0.75 and 2.25 GeV/c in three overlapping momentum settings. In order to reduce systematic errors, both arms were used and the magnet polarities were changed in both arms for all targets and for corresponding measurements without target. No significant differences between the right- and left-arm counting rates for the different particles were found, proving the consistency of the reconstruction process. The final data are combined from both arms.

The total number of triggers for each momentum window, polarity and target varied between 3×10^4 and 12×10^4. The rates were corrected and transformed into invariant cross sections $E\cdot d^3\sigma/dp^3$ using Monte Carlo acceptances of the spectrometer calculated for each particle and momentum setting individually.[3] The main corrections applied are the following: (1) Subtraction of background obtained from measurements without target: (5–10)% after reconstruction. (b) Decay correction factors: 1.10 to 1.03 for pions, and 2.0 to 1.27 for kaons depending on the momentum. (c) Nuclear absorption: The averaged absorption was determined by varying the thickness of an aluminum absorber in front of the third Cherenkov counter. The ratios between different particles were calculated from the known inelastic cross sections. The resulting correction was (12–10)% for pions, (7–6)% for K^+, (11–9)% for K^-, (16–13)% for p, and (27–23)% for $\bar{p}$, respectively, for low to high p_T. (d) Multiple scattering in the spectrometer material: The overall effect is only about 1%; however, Monte Carlo calculations revealed up to 20% changes in individual p_T bins. (e) A geometrical inefficiency of the third Cherenkov counter caused a loss of (7.5–12)% for pions and kaons and misidentified kaons as protons. The correction was (7–1)% for protons, (25–5)% for antiprotons, determined in each bin from the kaon spectrum. (f) Knock-on electrons and fast particles produced in the ethylene or the 0.79-cm iron wall of the third Cherenkov counter were estimated from a measurement done with the first Cherenkov counter. (2.7–1.7)% of p and $\bar{p}$ are lost and misidentified as kaons. The correction of (25–15)% for K^+ and up to 5% for K^- was determined in each bin from the proton or antiproton spectra.

All other corrections amounted to $\leq 1\%$ and were neglected. The total correction factors range from 1.85 to 1.40 for pions (at $p_T = 0.75$ and 2.25 GeV/c), 3.30 to 1.40 for kaons, 1.70 to 1.25 for protons, and 1.90 to 1.35 for antiprotons. Multiple scattering dominates the momentum resolution ranging from ± 10 to ± 12 MeV/c.

The cross sections obtained from the Be, Ti, and W targets were fitted for each particle species with a form

$$\sigma(A, p_T) = \sigma(A=1, p_T)\cdot A^{\alpha(p_T)}.$$

As a result, we obtain for every 100-MeV/c p_T bin an exponent $\alpha(p_T)$ and an extrapolated "nucleon" cross section $\sigma(A=1, p_T) \equiv E\cdot d^3\sigma/dp^3$ averaged over protons and neutrons. Since $\alpha(p_T)$ depends on the relative A dependence of $\sigma(A, p_T)$, only the statistical errors from "target in," "target out," and an additional 5% error were used, the latter based on the average reproducibility of runs. However, in the determination of $\sigma(A=1, p_T)$ also enter the systematic errors of the acceptance and the corrections (b)–(f), estimated to be ± 20%. The value of $\alpha(p_T)$ is plotted versus p_T in Fig. 1 with standard errors from the fitting procedure. Pions show a surprising increase of $\alpha(p_T)$ with p_T in Figs. 1(a) and 1(b), which with lesser significance is observed for kaons in Figs. 1(c) and 1(d) and antiprotons in Fig. 1(f), too. For protons, however, $\alpha(p_T)$ tends to be constant and unity. With the exception of protons these measurements are compatible with results of Cronin *et al.*[1] measured at $p_{\rm lab} = 300$ GeV/c and shown as crosses in Fig. 1, confirming the increase of $\alpha(p_T)$.

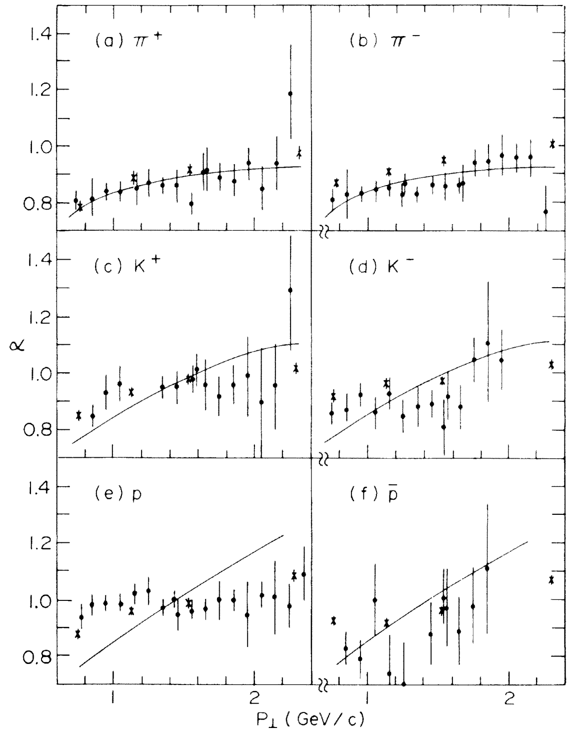

FIG. 1. Exponent α (obtained from the A dependence) vs p_T. Points, this experiment, 28.5 GeV/c; crosses, Cronin *et al.*, (Ref. 1) $p_{\rm lab} = 300$ GeV/c; solid lines, estimate from a rough multiple-interaction model (see text).

The curves in Figs. 1(a)–1(f) represent a rough estimate for the p_T dependence of the exponent α, assuming that some of the produced particles make secondary interactions within the same nucleus. The simple form $\exp[-5T(p_T)]$, $T = (m_i^2 + \frac{3}{2}p_T^2)^{1/2} - m_i$, with m_i being the particle mass[4] was used for both the first and the second interaction. If the transverse momenta are assumed

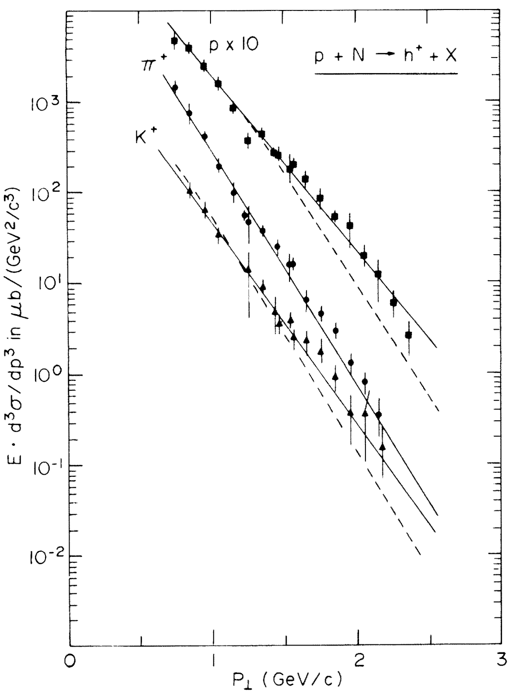

FIG. 2. Invariant cross sections for protons (multiplied by 10, squares), π^+ (points), and K^+ (triangles) vs p_T, extrapolated from Be, Ti, and W to $A = 1$. Error bars shown are standard fit errors. Solid lines: exponential fits, $\sigma \sim \exp(-b \cdot p_T)$; for parameters, see text. Broken lines: $\sigma \sim \exp(-5T)$. For pions, these lines coincide.

to add linearly, the p_T dependence is given by $f(p_T) = \int_{-\infty}^{\infty} g(p_T')h(p_T - p_T')dp_T'$, with both g and h being $\exp[-5T(p_T)]$. This is justified for nearly parallel and antiparallel transverse momenta, whereas a perpendicular configuration would not change the original amount of p_T. According to the simple character of our model, the two-dimensional problem has thus been reduced to one dimension with a reduced number of particles changing the amount of p_T in the second interaction. The ratio of the latter particles to all unchanged ones was arbitrarily assumed to be 5% per absorption mean free path. This order of magnitude may be justified by counting the particles from the decaying "hard" and "soft" hadrons[5] and the observed multiplicity increase[6] with A. Other more extensive treatments have been quoted.[7] All curves are normalized to an average experimental value of 0.85 at 1 GeV/c. We notice the following qualitative features: (a) the estimates for α increase with p_T, even above a value of 1.0; (b) the curves increase faster and to a higher level for heavier particles. This agrees with the observation of Cronin *et al.*[1]

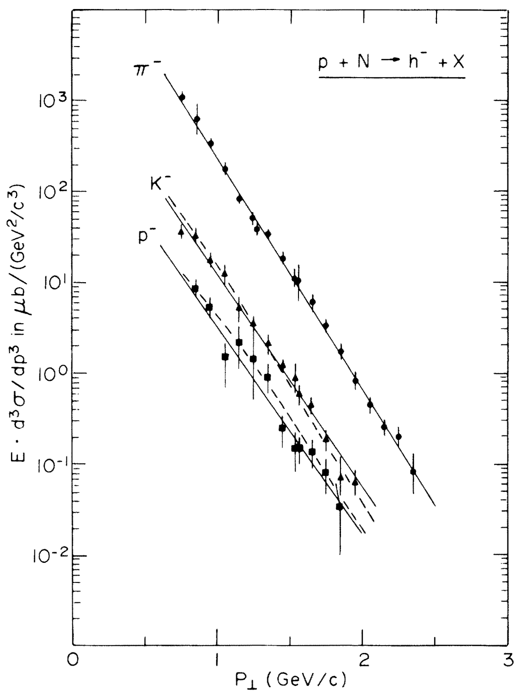

FIG. 3. Invariant cross section of π^- (points), K^- (triangles), and antiprotons (squares). Solid and broken lines as in Fig. 2.

The extrapolated invariant nucleon cross sections $\alpha(A = 1, p_T) \equiv E \cdot d^3\sigma/dp^3$ ($A = 1$) are shown for π^+, K^+, and protons in Fig. 2, and for π^-, K^-, and antiprotons in Fig. 3. For the sake of simplicity, the cross sections have been fitted with an exponential form in p_T:$E \cdot d^3\sigma/dp^3 = C \cdot \exp(-bp_T)$. The resulting best-fit parameters are given in the following table:

Incident particle	C mb/(GeV^2/c^3)	b (GeV/c)$^{-1}$
π^+	117 ± 23	5.97 ± 0.15
π^-	83 ± 17	5.86 ± 0.15
K^+	8.1 ± 2.8	5.13 ± 0.26
K^-	2.5 ± 0.7	5.32 ± 0.23
p	15.1 ± 2.3	4.40 ± 0.11
$\bar{p}$	0.7 ± 0.5	5.32 ± 0.51

The slopes for π^+ and π^- are equal within the errors; the K^+, K^-, and $\bar{p}$ slopes are somewhat lower. Protons show a distinctively flatter slope in our momentum region. Also shown in Figs. 2 and 3 are the curves derived from the simple fireball version, $E \cdot d^3\sigma/dp^3 \sim e^{-5T}$, normalized to the experimental point at 0.95 GeV/c. The data are very well described except for protons in the region $p_T > 1.5$ GeV/c. A comparison shows agreement with the bubble-chamber data of Blobel *et al.*[8] at 12 and 24 GeV/c for π^+, π^-, and p. Furthermore, our data fit well into the global plots of Cronin *et al.*[1]

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Search for Superheavy-Element Decay in Samples of Madagascar Monazite*

B. H. Ketelle, G. D. O'Kelley, R. W. Stoughton, and J. Halperin
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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Two samples of Madagascar monazite from the same geological formation as the biotite studied by Gentry *et al.* were examined by using a neutron multiplicity counter capable of detecting binary or ternary spontaneous fission decay in any element. No events characteristic of spontaneous fission decay of superheavy elements were found. Derived limits indicate that if superheavy elements were present, then their spontaneous fission half-lives must be extremely long or their concentrations extremely small.

A recent communication reported[1] x-ray energy spectra of monazite inclusions in biotite mica subjected to low-energy proton bombardment. Spectral analyses were interpreted as evidence for at least three superheavy elements with most probable atomic numbers of 116, 124, and 126. These results indicate unusual stability, because the existence of primordial superheavy elements in nature implies half-lives $\gtrsim 10^8$ years. Such long-lived superheavy elements might be expected to decay by α-particle emission or by spontaneous fission.[2] Since all heavy nuclei are energetically unstable with respect to binary fission, it is expected that long-lived α-decay chains beginning with a superheavy element would eventually terminate with a spontaneous-fission step.

The mass of primordial superheavy elements present in the giant halo inclusions was estimated to be as high as several hundred picograms.[1] If we assume, conservatively, an average value of only 100 pg in a 2-μg inclusion, the mass ratio of superheavy element is 5×10^{-5}, or 50 ppm. This concentration is so large that, even if bulk monazite deposits near the sites of the giant halo monazite inclusions were to contain somewhat lower concentrations of superheavy elements, it should be possible to observe spontaneous fission events from decay of the superheavy elements, or from daughter nuclei in radioactive equilibrium. Neutron-multiplicity counting is capable of detecting spontaneous-fission decay of any element, either in the binary- or ternary-fission mode, with high sensitivity and low background.

The average total number of neutrons per fission $\bar{\nu}$ is determined primarily by the average total excitation energy and by the neutron separation energies of the fission fragments. Most calculations predict an increase in $\bar{\nu}$ with increasing Z for binary fission.[2,3] For spontaneous binary-fission decay of superheavy elements, the num-