Projectile Dependence of Multiparticle Production in Hadron-Nucleus Interactions at 100 GeV/c

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Average multiplicities and pseudorapidity distributions for 100-GeV/c p-, K^+-, and π^+-nucleus collisions are presented. The average multiplicities increase with nuclear thickness. The fractional increase is independent of incident particle species, provided that nuclear thicknesses are calculated in units of mean free path of the incident hadron. This scaling behavior suggests that the immediate product of a hadron-nucleon collision is a state similar to the incident hadron.

We have measured the average multiplicities, $\langle n\rangle_A$, and the pseudorapidity distributions of charged, relativistic ($\beta \gtrsim 0.85$) secondaries produced in collisions between an incident hadron (p, $\bar{p}$, K^+, π^+, and π^-) and a target nucleus (atomic number A) at 50, 100, and 200 GeV/c. This experiment was carried out in the M6 secondary beam at Fermilab, and a brief description of the experiment and the proton-nucleus results were presented in a previous publication.[1] In this Letter, we compare the p, K^+, and π^+ data at 100 GeV/c.

The average-multiplicity results, $\langle n\rangle_A$, are given in Table I. A measure of the amount of intranuclear multiplication is given by the ratio $R_A = \langle n\rangle_A/\langle n\rangle_H$, where $\langle n\rangle_H$ is the average hydrogen multiplicity. Existing high-energy data[2] indicate that R_A is independent of the incident-particle type when the nuclear thickness is measured in terms of $\bar{\nu}$. The parameter $\bar{\nu}$ is the average number of inelastic collisions that the incident hadron h would undergo in traversing the nucleus, assuming that all collisions are governed by the cross section of the incident hadron. It should be noted that for all collisions other than the first, the incident hadron h need not be involved, provided that it is replaced by a state with the same cross section. The values of $\bar{\nu}$ shown in Table I are given by the formula $A\sigma_{hp}/\sigma_{hA}$, where σ_{hp} (σ_{hA}) is the absorption cross section of h on hydrogen (nucleus).[3] Thus $\bar{\nu}$ depends not only on the target nucleus A but also on the incident hadron h.

In contrast to earlier comparisons,[4] the data reported here permit a test of this apparent scaling of R_A with $\bar{\nu}$ free from the systematic difficulties involved in combining the data from several experiments. Furthermore, previous to this experiment, no K^+-nucleus multiplicity data were available.

Since our hydrogen multiplicities are obtained by a $CH_2 - C$ subtraction, the uncertainties are relatively large. We have, therefore, chosen to use the multiplicities measured in a bubble-chamber experiment[5] in our determination of R_A. These multiplicities, $\langle n\rangle_{ch}$, are also given in Table I. Unlike the nuclear multiplicities measured in this experiment, $\langle n\rangle_{ch}$ includes nonrelativistic

TABLE I. The average multiplicities of relativistic charged particles produced in 100-GeV/c hadron-nucleus collisions for several values of $\bar{\nu}$. The errors include all statistical and systematic uncertainties. The bubble-chamber multiplicities $\langle n\rangle_{ch}$ of Ref. 5 are also shown.

Target	Projectile	$\bar{\nu}$	Average multiplicity
C	π^+	1.27 ± 0.02	7.86 ± 0.15
	K^+	1.24 ± 0.02	6.92 ± 0.33
	p	1.43 ± 0.01	7.72 ± 0.16
Cu	π^+	2.01 ± 0.04	10.29 ± 0.26
	K^+	1.85 ± 0.04	8.89 ± 1.10
	p	2.41 ± 0.02	11.00 ± 0.32
Pb	π^+	2.77 ± 0.09	13.21 ± 0.30
	K^+	2.47 ± 0.09	12.92 ± 0.79
	p	3.49 ± 0.05	14.75 ± 0.38
U	π^+	2.87 ± 0.09	14.57 ± 0.39
	K^+	2.55 ± 0.10	12.93 ± 1.33
	p	3.64 ± 0.05	15.94 ± 0.50
Hydrogen bubble chamber	π^+	1.0	6.62 ± 0.07
	K^+	1.0	6.65 ± 0.31
	p	1.0	6.37 ± 0.06

prongs. We calculate $\langle n\rangle_H$ using the formula $\langle n\rangle_H = \langle n\rangle_{ch} - 0.5$.[6]

Figure 1(a) is a plot of R_A vs $\bar{\nu}$. There is little or no incident-particle dependence. The results can be fitted by $R_A = 0.47 + 0.61\bar{\nu}$ with a χ^2 of 13 for 10 degrees of freedom. For comparison, Fig. 1(b) shows that R_A does not scale with the physical thickness of the target as measured by $A^{1/3}$.

Our data are also inconsistent with the hypothesis that all collisions other than the first are governed by the cross section of a pion rather than that of the incident hadron. We plot R_A against $\bar{\nu}'$ in Fig. 1(c). The parameter $\bar{\nu}'$ is the average number of inelastic collisions that the incident hadron h would undergo in traversing the nucleus, assuming that while the initial collision is governed by the cross section of the incident hadron, all subsequent collisions are governed by the pion cross section. The values of $\bar{\nu}$ are given by the formula $\bar{\nu}' = 1 + (\bar{\nu} - 1)\sigma_{\pi p}/\sigma_{hp}$.

The scaling of R_A with $\bar{\nu}$ is compatible with a picture in which a beamlike state interacts successively with different nucleons within the nucleus.[7] To investigate further this phenomenon, we examine the multiplicity ratio $r(\eta)$ for different regions of laboratory pseudorapidity $\eta = -\ln(\tan\frac{1}{2}\theta)$ where θ is the polar angle of the secondary. As in the determination of R_A, the hydrogen values are derived from bubble-chamber measurements.[8] Figure 2 shows $r(\eta)$ as a function of η interpolated to $\bar{\nu} = 3$. The scaling effect is seen to hold for individual regions of pseudorapidity.

In summary, our data are consistent with models in which the multiplicity increase is governed by the parameter $\bar{\nu}$, independent of the incident-particle species. The parameter $\bar{\nu}$ was derived using the assumption that after each collision in the nucleus, the produced state has a cross section equal to that of the incident particle. Thus the data strongly suggest that the immediate product of a hadron-nucleon collision is a state similar to the incident hadron.

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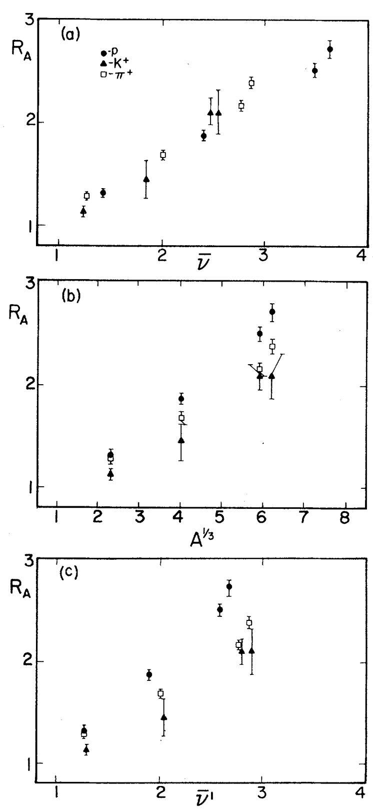

FIG. 1. (a) R_A vs $\bar{\nu}$. (b) R_A vs $A^{1/3}$. (c) R_A vs $\bar{\nu}'$. The errors on the data points include all statistical and systematic uncertainties.

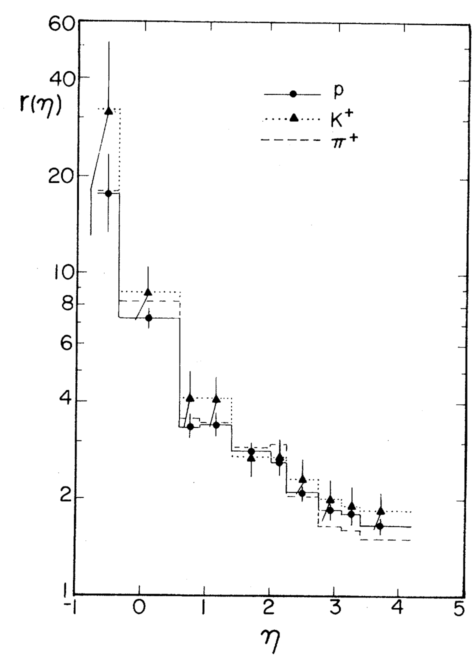

FIG. 2. The multiplicity ratio $r(\eta)$. The errors shown include all statistical and systematic uncertainties. In the interest of clarity, errors on the π^+-induced data are not shown. They are comparable to the proton data. The region $\eta > 4.2$ is not shown because our data in this region have significant uncertainties introduced by acceptance corrections as discussed in Ref. 1.

[1]C. Halliwell *et al.*, Phys. Rev. Lett. 39, 1499 (1977).
[2]For example, π^--nucleus data from W. Busza *et al.*, Phys. Rev. Lett. 34, 836 (1975); p-W and p-Cr data from J. R. Florian *et al.*, Phys. Rev. D 13, 558 (1976); and p-emulsion data from a compilation by I. Otterlund, Acta Phys. Polon. B8, 119 (1977).
[3]The hadron-nucleus cross sections used to calculate $\bar{\nu}$ are from S. P. Denisov *et al.*, Nucl. Phys. B61, 62 (1973). These cross sections were extrapolated to 100 GeV/c using the energy dependence of the hadron-nucleon inelastic cross sections quoted by D. S. Ayres *et al.*, Phys. Rev. D 15, 3105 (1977). A Woods-Saxon distribution of nuclear matter was assumed.
[4]Busza *et al.*, Ref. 2.
[5]W. M. Morse *et al.*, Phys. Rev. D 15, 66 (1977).
[6]G. Calucci, R. Jengo, and A. Pignotti, Phys. Rev. D 10, 1468 (1974).
[7]Similar conclusions have been arrived at for 300-GeV/c proton-induced data for production of Λ^0's in the forward projectile-fragmentation region [see K. Heller *et al.*, Phys. Rev. D 16, 2737, (1977)].
[8]The rapidity distributions measured in Ref. 5 were normalized to $\langle n\rangle_H = \langle n\rangle_{ch} - 0.5$, and were then used to calculate $r(\eta)$. The difference between rapidity and pseudorapidity is ignored. This procedure may distort the shape of $r(\eta)$, but should not affect the comparison of p, K^+, and π^+ results.

How Many Neutrinos?

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Measurement of $e^+e^- \to \gamma\nu\bar{\nu}$ at the new colliding-beam facilities can determine directly the total number of neutrino types (ν_e, ν_μ, ν_τ, etc.).

It has long been established that there are at least two pairs of leptons (ν_e, e) and (ν_μ, μ). Now there is mounting evidence for a third, (ν_τ, τ).[1] How many times will this pattern be repeated? Cosmological arguments place an upper limit of about 7 on the number of different neutrinos[2] and another upper limit of about 27 eV on the sum of their masses.[3] But there is no direct laboratory evidence at all in this regard. Therefore, we propose that the process $e^+e^- \to \gamma\nu\bar{\nu}$ be measured at the new colliding-beam facilities as a means of determining N_ν, the total number of neutrino types. (Other processes such as $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \gamma\nu\bar{\nu}$ also depend on N_ν, but they all have very small branching ratios.[4] Another process which might be considered is the sequential decay $\psi' \to \psi\pi\pi$, then $\psi \to \nu\bar{\nu}$.[5])

Consider the process $e^+e^- \to \gamma\nu\bar{\nu}$ (Fig. 1). Let the effective neutrino-electron interaction be given by

$$H_{\rm int} = (G_F/\sqrt{2})\sum_i[\bar{\nu}_i\gamma^\alpha(1-\gamma_5)\nu_i][\bar{e}\gamma_\alpha(g_V{}^i - g_A{}^i\gamma_5)e], \tag{1}$$

where the sum is over all neutrino types. If $\nu_i \neq \nu_e$, only neutral-current effect are present, so that if universality is assumed, $g_V{}^i = g_V$ and $g_A{}^i = g_A$. If $\nu_i = \nu_e$, then there is an additional charged-current contribution, so that $g_V{}^e = g_V + 1$ and $g_A{}^e = g_A + 1$. In the standard weak-electromagnetic gauge model,[6]

$$g_V = -\tfrac{1}{2} + 2\sin^2\theta_W, \quad g_A = -\tfrac{1}{2}, \tag{2}$$

The parameter $\sin^2\theta_W$ has an experimentally determined value of about 0.25.

Since only the photon can be detected in this process, the appropriate differential cross section is $d\sigma/dE_\gamma d\theta_\gamma$, where θ_γ is measured relative to the beam axis. In the high-energy limit where m_e can be neglected, we find

$$\frac{d\sigma}{dx\,dy} = \frac{G_F{}^2\alpha}{6\pi^2}[N_\nu(g_V{}^2 + g_A{}^2) + 2(g_V + g_A + 1)]\frac{s}{x(1-y^2)}\left\{(1-x)(1-\tfrac{1}{2}x)^2 + \tfrac{1}{4}x^2(1-x)y^2 + \tfrac{1}{4}\left(\frac{x^2y^2}{1-y^2}\right)\right\}, \tag{3}$$

where $x = 2E_\gamma/\sqrt{s}$, $y = \cos\theta_\gamma$, and s is the square of the total center-of-mass energy. This expression shows the usual infrared divergence at $x = 0$ associated with a radiative process,[7] as well as the forward-backward peaking at $y^2 = 1$. For comparison, consider the kinematically similar process $e^+e^- \to \gamma\gamma\gamma$, for which the exact differential cross section is known.[8] Assuming the ratio $\sigma(e^+e^- \to \gamma\nu\bar{\nu})/$

