ARTICLES

Neutral-strange-particle production in 200-GeV/c $p/\pi^+/K^+$ interactions on Au, Ag, and Mg

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We have used the Fermilab 30-in. bubble-chamber–hybrid spectrometer to study neutral-strange-particle production in the interactions of 200-GeV/c protons and π^+ and K^+ mesons with nuclei of gold, silver, and magnesium. Average multiplicities and inclusive cross sections for K^0 and Λ are measured, and a power law is found to give a good description of their A dependence. The exponent characterizing the A dependence is consistent with being the same for K^0 and Λ production, and also the same for proton and π^+ beams. Average K^0 and Λ multiplicities, as well as their ratio, have been measured as functions of the numbers of projectile collisions ν_p and secondary collisions ν_s in the nucleus, and indicate that rescattering contributes significantly to enhancement of Λ production but not to K^0 production. The properties of events with multiple K^0's or Λ's also corroborate this conclusion. K^0 rapidities are in the central region and decrease gently with increasing ν_p, while Λ rapidities are in the target-fragmentation region and are independent of ν_p. K^0 and Λ multiplicities increase with the rapidity loss of the projectile, but their rapidities do not.

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I. INTRODUCTION

We have studied neutral-strange-particle production by 200-GeV/c protons and π^+ and K^+ mesons on thin targets of gold, silver, and magnesium. There have been very few studies of strange particle production in hadron-nucleus collisions at high energy. The NA5 and NA35 streamer chamber experiments at CERN have reported interesting results [1–3] with p and $\bar{p}$ beams at 200 and 60 GeV/c, but these experiments have not employed meson beams. π-beam experiments [4–6] have focused on other topics, with exceedingly limited information on strange particle production. We are not aware of any K^+-nucleus results. ($\bar{p}$-nucleus data also have been reported [7,8] at very low energies of 4 and 0.6 GeV/c.) Theoretical work has examined the exciting possibility that strangeness enhancement (over the hadron-nucleon case) might be indicative of the formation of a quark-gluon plasma [9]. Another possibility, that nuclear reinteractions may enhance the production of strange particles (especially Λ's), has also been addressed [10].

From this experiment we have previously published [11,12] results on multiplicities, dispersions, and rapidities of charged pions produced in the hadron-nucleus interactions, with an emphasis on correlating these quantities with the numbers of projectile and secondary collisions in the nucleus. In the present paper on neutral-strange-particle production, we measure the beam type and A dependence, and also investigate the effect of multiple nuclear collisions on multiplicities, multiplicity ratios, and rapidities of K^0's and Λ's.

II. EVENT SELECTION

This experiment (E565/570) was performed at Fermilab, using the 30-in. bubble-chamber–hybrid-spectrometer system. Because we have previously provided [11,13] the experimental details, we will only summarize the salient features here. A tagged secondary beam of 200-GeV/c positively charged particles was incident on the detector. The upstream spectrometer achieved beam definition using scintillator counters and proportional wire chambers (PWC's), and identified each beam particle by using three Cherenkov counters. For the data reported in this paper, the beam composition was 49% π^+, 35% p, and 16% K^+. The targets consisted of six metal plates, two each of gold, silver, and magnesium, located inside the bubble chamber at its upstream end. The plates varied in thickness from 0.3 to 11.1 mm. The chamber itself was filled with liquid hydrogen and placed in a 2-T magnetic field. The downstream spectrometer used PWC's and drift chambers to track fast charged particles for accurate momentum determination.

Photographs of the chamber were scanned for events

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occurring in the plates, and for vees pointing to the primary interaction. Precision measurements of all tracks of events and vees were made with a semiautomatic precision-encoding and pattern-recognition (PEPR) device. Physicists examined all events on the scan table to identify each track by its ionization whenever that was possible. This technique allowed the identification of protons up to a momentum of 1.2 GeV/c, and electrons up to a momentum of 140 MeV/c. All other tracks were taken to be pions, and are commonly referred to as "produced particles" in the literature.

The final sample for this work consisted of 1402 events in the metal targets, fully reconstructed as described above. These events contained 1001 vees, of which 918 satisfied our acceptance criteria. For a vee to be accepted, its decay length had to exceed 0.5 cm in space from the primary vertex in the plate. In addition, a fiducial volume was imposed on the secondary vertex in such a way as to maximize the volume visible in all three views of the chamber. This volume was bounded by intersecting planes which were displaced 5 cm into the chamber in order to provide adequate length for decay track measurement. The scan efficiency for finding neutrals was determined to be $(95\pm3)\%$.

Kinematic fitting of the vees to the primary vertex was accomplished with the program SQUAW. For each vee, three-constraint (3C) and one-constraint (1C) fits were attempted corresponding to the following hypotheses: $K_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$, and $\gamma(p) \to (p)e^+e^-$. All vees making a 3C fit with a probability greater than 0.1% were accepted into the data sample. Vees that failed the 3C fit, but made a 1C fit with a probability over 0.1%, were also accepted if the angular difference between the measured and fitted neutral direction was less than 60 mrad. (These 1C fits comprised only about 1% of the total, and their inclusion did not appreciably affect any of the results presented in this paper.)

Of the 918 vees in the fiducial volume, a total of 832 survived into the final data sample, and about 18% of these had ambiguous fits. Some of these ambiguities were easy to resolve, because the relative probabilities for the competing fits differed by a factor of 10 or more. In these cases the more probable fit was selected. About 12% of the vees remained ambiguous after this step, and the following procedure was used for them.

(a) If the ambiguity included a γ fit, we examined the transverse momentum of the negative decay track with respect to the line of flight of the neutral decaying track. This momentum is a useful quantity because for strange particles its spectrum is sharply peaked at the kinematic maximum, while for γ conversions it is peaked at zero. Thus this quantity provides a clean separation of strange-particle fits ambiguous with γ's. If the transverse momentum of the negative decay track was less than 40 MeV/c, the neutral was assigned to the γ sample; otherwise the competing strange-particle fit was chosen.

(b) Ambiguities involving only strange-particle fits were resolved as follows. An ambiguous vee was selected as a $\overline{\Lambda}$ only if its probability as a $\overline{\Lambda}$ was more than that for Λ, and more than twice that for K_S. A vee was selected as a K_S if its probability as a K_S was more than 2.5 times that for Λ. The reason for using this particular algorithm was that it rendered the K_S and Λ decay angular distributions roughly isotropic. These are distributions of the cosine of the angle between the neutral line of flight and the direction of the negative decay product in the rest frame of the neutral. This distribution must be isotropic for the spinless K, and also isotropic for the Λ and $\overline{\Lambda}$ if they are produced with no longitudinal polarization.

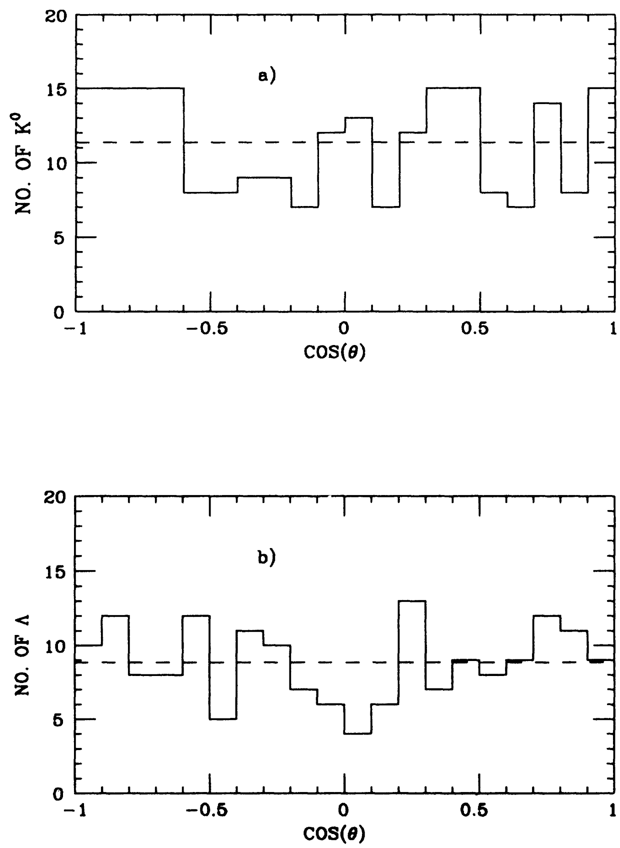

FIG. 1. Distribution of the cosine of the angle between the V^0 line of flight and the negative decay product in the V^0 rest frame, for (a) K_S and (b) Λ. The dashed line indicates the average number of events in each bin. The distributions are expected to be isotropic.

This procedure resulted in a final sample of 227 K_S's, 177 Λ's, 16 $\overline{\Lambda}$'s, and 412 γ's. Figure 1 shows the decay angular distributions for the K_S and Λ; it is apparent that these are approximately isotropic, so that the allocation of ambiguities is reasonable. Table I summarizes the number of vees of each type in the final sample for each of our nine reactions, representing three beam types and three targets.

III. PHYSICS RESULTS

To obtain V^0 production rates, we corrected the observed number of vees for various sources of loss. The geometric detection efficiency, which was momentum dependent, was calculated separately for each vee by us-

TABLE I. Number of observed, fitted K_S, Λ, $\bar{\Lambda}$, and γ for each reaction.

	K_S	Λ	$\bar{\Lambda}$	γ
p-Au	40	35	2	66
p-Ag	63	40	5	87
p-Mg	9	11	0	36
π^+-Au	42	33	3	65
π^+-Ag	36	27	0	73
π^+-Mg	10	4	2	22
K^+-Au	15	15	2	27
K^+-Ag	9	11	2	27
K^+-Mg	3	1	0	9
Total	227	177	16	412

ing the minimum length cut of 0.5 cm and a maximum potential length which was the distance from the primary vertex to the edge of the fiducial volume along the particular vee's line of flight. There was also some loss of vees at low lifetimes, because such vees were close to the primary vertex and sometimes could not be distinguished from the typically large multiplicity of charged tracks emanating from the vertex. To correct for this loss, we examined the proper decay length distribution for the K^0 as measured beyond the initial 0.5-cm minimum length cut in the laboratory. In this distribution there was a depletion below $c\tau=0.5$ cm. An exponential fit to the distribution from $c\tau=0.5$ cm to 5.5 cm yielded a mean proper decay length of 2.2 ± 0.3 cm, with a χ^2 of 7.4 for 8 degrees of freedom, consistent with the known value [14] of 2.675 cm. Then the fit was extrapolated to $c\tau=0$, and the low-lifetime loss was calculated by comparing the expected number of K^0's with the observed number below $c\tau=0.5$ cm. The correction for K^0 was 1.13 ± 0.04, and the same procedure for Λ's gave a weight of 1.10 ± 0.04. (We also used this weight of 1.10 for $\bar{\Lambda}$'s, which had too small a sample for independent determination of low-lifetime loss). Finally, the numbers of vees were corrected for the $(95\pm3)\%$ random scan efficiency and for undetected decay modes using the known branching ratios [14]. In particular, the branching ratio for K^0 included the factor of 2 for K_L, so that our rates are for all $(K^0+\bar{K}^0)$. Fully corrected mean multiplicities of K^0, Λ, and $\bar{\Lambda}$ are given in Table II for each of our nine reactions.

Table III gives inclusive cross sections for the production of K^0, Λ, and $\bar{\Lambda}$, derived by using our mean multiplicities and fits by Carroll *et al.* [15] to their measurements of total cross sections. For comparison, we have also included cross sections for the three beams on hydrogen targets, using results [16] from our previous Fermilab experiment (E299). That experiment was at a slightly lower beam energy of 147 GeV/c, compared to 200 GeV/c for the current work, but is useful for comparison because it used the same bubble chamber, and the data analysis techniques were essentially identical. There does exist one measurement [17] of V^0 cross sections in hydrogen at 200 GeV/c, but is only for baryon beams, and the cross sections suffer from much larger errors than E299.

We have investigated the A dependence of neutral-strange-particle production cross sections by plotting our data in Fig. 2, along with other results [1–3] at 200 GeV/c, and the hydrogen-target values [16] at 147 GeV/c. We have fit the results to the form $\sigma_{hA}=\sigma_{hp}A^{\alpha}$, where the subscripts hA and hp refer to hadron-nucleus and hadron-proton reactions, respectively, and A is the mass number of the nucleus. The best fits are shown in

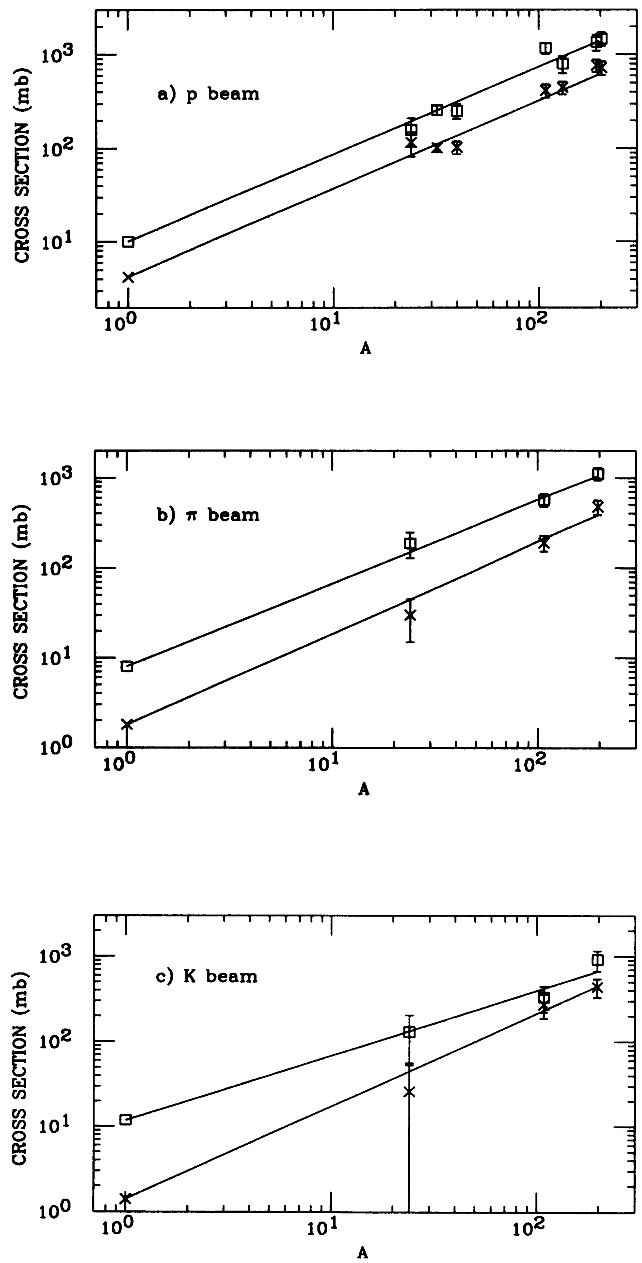

FIG. 2. A dependence of inclusive cross sections for the production of K^0 (squares) and Λ (crosses) by (a) proton beams, (b) π^+ beams, and (c) K^+ beams. The lines represent best power-law fits, constrained to pass through the values for hydrogen targets obtained from Ref. 16, which was at a lower beam momentum of 147 GeV/c.

TABLE II. Mean multiplicities of neutral strange particles, fully corrected for all detection efficiencies and unseen decay modes. The K^0 multiplicity includes $(K^0+\bar{K}^0)$.

	$\langle n_{K^0}\rangle$	$\langle n_\Lambda\rangle$	$\langle n_{\bar{\Lambda}}\rangle$
p-Au	0.86±0.14	0.42±0.07	0.07±0.05
p-Ag	1.05±0.14	0.37±0.06	0.05±0.02
p-Mg	0.41±0.14	0.30±0.09	
π^+-Au	0.76±0.12	0.32±0.06	0.03±0.02
π^+-Ag	0.60±0.10	0.20±0.04	
π^+-Mg	0.63±0.20	0.10±0.05	0.10±0.07
K^+-Au	0.67±0.18	0.32±0.08	0.04±0.03
K^+-Ag	0.39±0.13	0.32±0.10	0.08±0.06
K^+-Mg	0.49±0.28	0.10±0.10	

the figure separately for each beam type, and the fitted values of the exponent α are given in Table IV. (The uncertainties in α correspond to an increase of one in the χ^2 of the fit.) It may be noted that our values of α are significantly greater than the geometrical value of $\frac{2}{3}$, so there is only a limited amount of shadowing. It is also interesting that for the proton beam the values of α for K^0 and Λ production are consistent with being equal to each other, and the same is true for the π beam. Furthermore, the values for the two beams are also consistent with each other. However, these observations do not seem to extend so clearly to the K^+ beam, for which we have the least statistics.

In our previous work [11,12] we found that the most important quantity for describing the interaction between a hadron beam and a target nucleus is ν_p, the number of projectile collisions that occurred inside the nucleus. For a given reaction (hA) the average value of this quantity is [18] $\langle\nu_p\rangle = A(\sigma_{hp}/\sigma_{hA})$, where σ_{hp} and σ_{hA} are the inelastic cross sections for hadron-proton and hadron-nucleus collisions, respectively. To obtain an event-by-event estimate of this quantity, we define [19] $\nu_p(n_p)=C_{hA}\sqrt{n_p}$, where n_p is the number of "grey" protons (i.e., identified protons of momentum greater than 0.3 GeV/c) in the event. The proportionality constant C_{hA} is chosen so that the average value of $\nu_p(n_p)$ over all events of a given reaction (hA) will be equal to $\langle\nu_p\rangle$ for that reaction as given by the formula above from the cross sections. With this prescription, we previously found [11,12] that produced-particle multiplicities and rapidities depend only on $\nu_p(n_p)$ and not on beam or target type separately.

In Fig. 3 we show the average multiplicities of K^0 and Λ as a function of ν_p, combining data from all three beams and three targets. As expected, we find that the rates increase with ν_p. Although not shown in Fig. 3, the

TABLE III. Total inclusive cross sections for K^0, Λ, and $\bar{\Lambda}$ production. The values for proton targets are from experiment E299 which was at 147-GeV/c beam momentum, compared to 200 GeV/c for this experiment.

	σ_{K^0} (mb)	σ_Λ (mb)	$\sigma_{\bar{\Lambda}}$ (mb)
p-Au	1478±241	722±120	120±86
p-Ag	1171±156	413±67	56±22
p-Mg	157±53	115±34	
p-p (Ref. [16])	10.0±0.4	4.2±0.2	0.8±0.2
π^+-Au	1110±175	468±88	44±29
π^+-Ag	554±92	185±37	
π^+-Mg	187±59	30±15	30±21
π^+-p (Ref. [16])	8.0±0.6	1.8±0.2	0.7±0.1
K^+-Au	913±245	436±109	55±41
K^+-Ag	332±111	272±85	68±51
K^+-Mg	130±74	26±27	
K^+-p (Ref. [16])	11.8±2.0	1.4±0.4	0.5±0.2

TABLE IV. Exponent α characterizing the A dependence of K^0 and Λ production cross sections by proton, π^+, and K^+ beams.

Beam	$\alpha(K^0)$	$\alpha(\Lambda)$
p	0.93±0.02	0.94±0.02
π^+	0.92±0.02	1.01±0.03
K^+	0.76±0.05	1.09±0.05

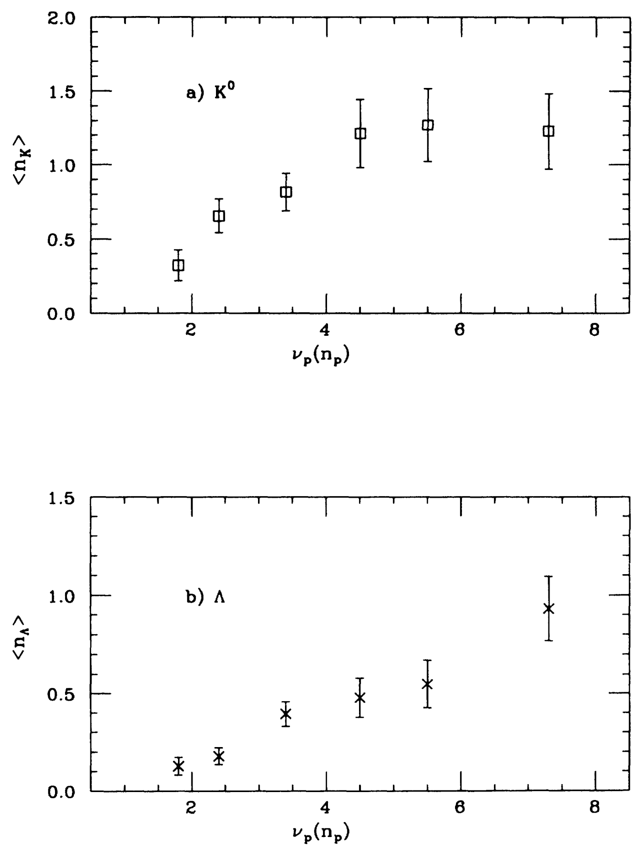

FIG. 3. Average multiplicity of (a) K^0 and (b) Λ as a function of number of projectile collisions estimated event by event from grey-proton multiplicity n_p. Data from all beams and targets have been combined.

TABLE V. Properties of events with single observed V^0's compared to events with multiple observed V^0's.

	$\langle \nu_p \rangle$	$\langle \nu_S \rangle$	$\langle n_p \rangle$	$\langle n_\pi \rangle$
Events with 1 observed Λ	3.9±0.2	12.5±0.9	4.7±0.3	20.5±0.9
Events with >1 observed Λ	5.6±0.7	21.8±3.8	7.8±1.5	24.5±2.1
Events with 1 observed K^0	3.4±0.2	10.7±0.8	3.9±0.3	19.0±0.8
Events with >1 observed K^0	3.7±0.4	10.1±1.7	4.3±0.8	18.5±1.4

trend is the same for each subsample of beam and target. There is also some evidence in Fig. 3 that the K^0 multiplicity might be leveling off at large ν_p while the Λ multiplicity keeps rising, in accord with the suggestion of Nikolaev [10] that reabsorption in the nucleus is appreciable for K^0's but not for Λ's.

We ask next whether the increase of multiplicities with ν_p is entirely due to projectile collisions, or whether there is also a contribution from secondary collisions inside the nucleus. For produced particles (charged pions), we had found [11] no evidence of rescattering, and the usual explanation is that in the rest frame of a relativistic hadron, the nucleus is a highly Lorentz-contracted disk which passes by in a time less than is required for producing the hadron ($\sim 10^{-23}$ sec), i.e., the pions are formed outside the nucleus and consequently cannot undergo rescattering. However, particles that are slow in the laboratory frame, notably protons, would have a much shorter formation length and may well participate in an intranuclear cascade. We can examine this possibility by noting that the net charge Q of an event reveals, on the average, the total number of collisions (projectile plus secondary) that took place, because every collision with a proton increases Q by one, while collisions with neutrons leave Q unchanged. Therefore, in a nucleus of charge Z and mass number A, if there are ν_t total collisions induced by a positively charged beam particle, the net charge would be, on average, $Q=\nu_t Z/A+1$. Since our events are fully reconstructed, we can determine Q for each event, and thereby obtain ν_t. The number of projectile collisions ν_p is calculated for each event from the number of grey protons, as described above. Then the number of secondary collisions is derived to be $\nu_S=\nu_t-\nu_p$. (Of course, ν_S tends to increase with ν_p [11].)

Figure 4 shows the dependence of K^0 and Λ mean multiplicities on the number of secondary collisions, again combining data from all beams and targets. The trend for K^0 is rather similar to that for charged pions, exhibiting an initial increase but then a leveling off as ν_S increases, suggesting that rescattering is not a significant source of K^0 production. By contrast, the Λ multiplicity increases over the whole range of ν_S, so there is evidence that secondary collisions are enhancing Λ production. A sensitive way to strengthen this conclusion is to inspect the ratio of Λ to K^0 production rates as functions of ν_p and ν_S, and this is displayed in Fig. 5. The ratio clearly increases with both variables, thereby indicating that Λ's are enhanced by some additional means that are not applicable to K^0's. It is consistent with the argument of Nikolaev [10] that intranuclear cascading causes Λ enhancement, and the so-called Λ-retention property prevents any significant absorption of Λ's inside the nucleus.

We have attempted some consistency checks on our hypothesis that rescattering of secondaries contributes significantly to Λ production, but not to K^0 production. In Table V we compare some of the properties of those events in which we have exactly one V^0 of a particular type (K^0 or Λ) with those events containing more than one. (There were 10 events with multiple Λ's, and 22 with multiple K^0's.) The table shows that events with multiple Λ's have significantly more secondary collisions

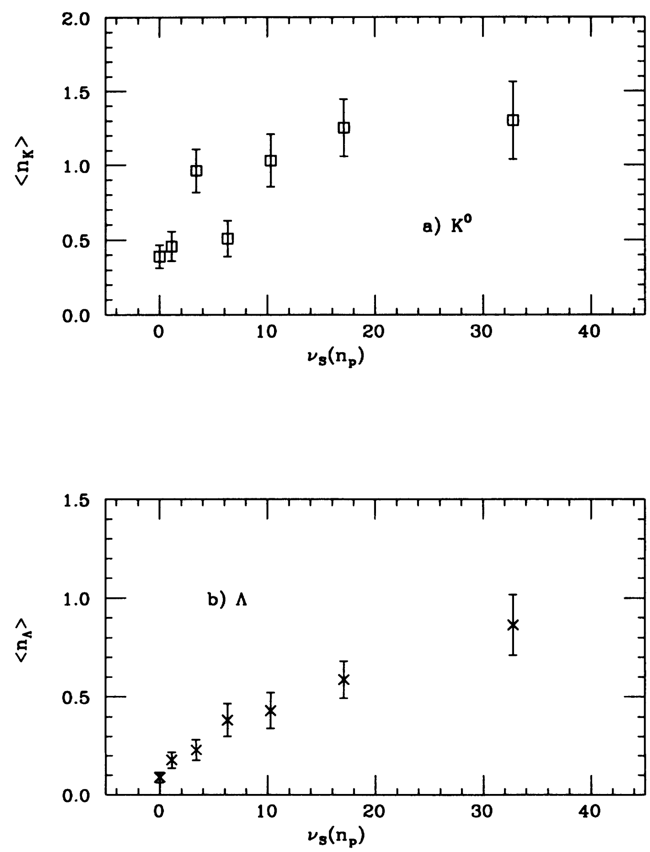

FIG. 4. Average multiplicity of (a) K^0 and (b) Λ as a function of number of secondary collisions. Data from all beams and targets have been combined.

than do events with one Λ, but there is no difference either in ν_p or in ν_S for events with single versus multiple K^0's. This clear difference between K^0's and Λ's corroborates the hypothesis. Indeed, the table shows that single-K^0 and multiple-K^0 events are very similar in other properties as well, such as the multiplicities of grey protons and pions, while single-Λ and multiple-Λ events are quite dissimilar.

Another consistency check is provided by examining the so-called particle multiplication ratio R, which is the ratio of V^0 multiplicity in hadron-nucleus collisions to that in hadron-nucleon collisions: $R_K = \langle n_K \rangle_{hA} / \langle n_K \rangle_{hp}$ and an analogous definition for R_Λ. Such a ratio for charged pions has often been fit to the form $R = 1 + \beta(\nu_p - 1)$. In the absence of rescattering, it is expected [20] that β should equal 0.5, and if rescattering does contribute significantly, than β should be greater. In our own previous work [11], we found that for charged pions, β was consistent with 0.5 for each of our three beams. To evaluate the denominator in the definitions of R_K and R_Λ, we have used the hydrogen-target results [16] at 147 GeV/c. Then a fit for K^0's yields $\beta = 0.46 \pm 0.07$, consistent with 0.5, the value expected for no rescattering. A similar fit for Λ's yields $\beta = 0.69 \pm 0.10$. This is a two-standard deviation excess over 0.5, so it plainly cannot be considered a decisive effect, but it is certainly consistent with our other evidence that secondary collisions contribute significantly to Λ enhancement.

Information on production mechanisms is obtained by measuring the rapidities and transverse momenta of K^0 and Λ. We define the rapidity in the laboratory frame as $y = \frac{1}{2} \ln[(E + P_L)/(E - P_L)]$, where E and P_L are the total laboratory energy and longitudinal momentum of the particle under consideration. (The rapidity in the hadron-nucleon center-of-mass frame is shifted by 3.0 units.) The average rapidities of K^0 and Λ are shown in Fig. 6 as a function of ν_p, and the average transverse momenta squared in Fig. 7. The K^0 show a gentle decrease of rapidity with ν_p, which is exactly what we had previously observed [12] for charged pions. (The magnitude of the K^0 rapidity is also consistent with that of pions, and is in the central production region.) As the number of projectile collisions increases, so does the total multiplicity, and therefore the energy of the projectile has to be shared by more particles, thereby reducing the average rapidity of each one. This argument should not affect transverse momenta, and indeed we see in Fig. 7 that the K^0 transverse momentum is unchanged as ν_p increases. The Λ rapidity, shown in Fig. 6(b), is significantly lower

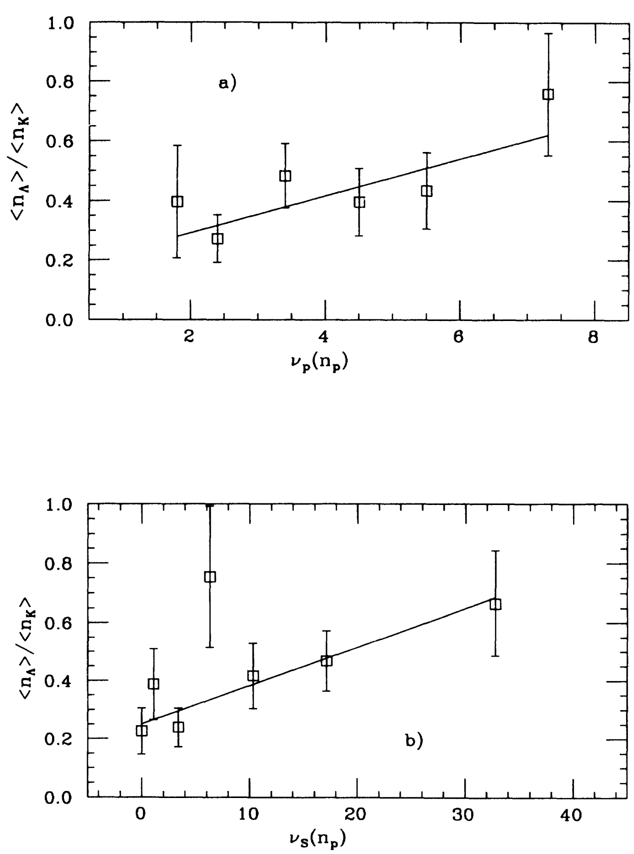

FIG. 5. Ratio of mean Λ to K^0 multiplicities as a function of (a) number of projectile collisions, and (b) number of secondary collisions. The lines represent linear fits to the data.

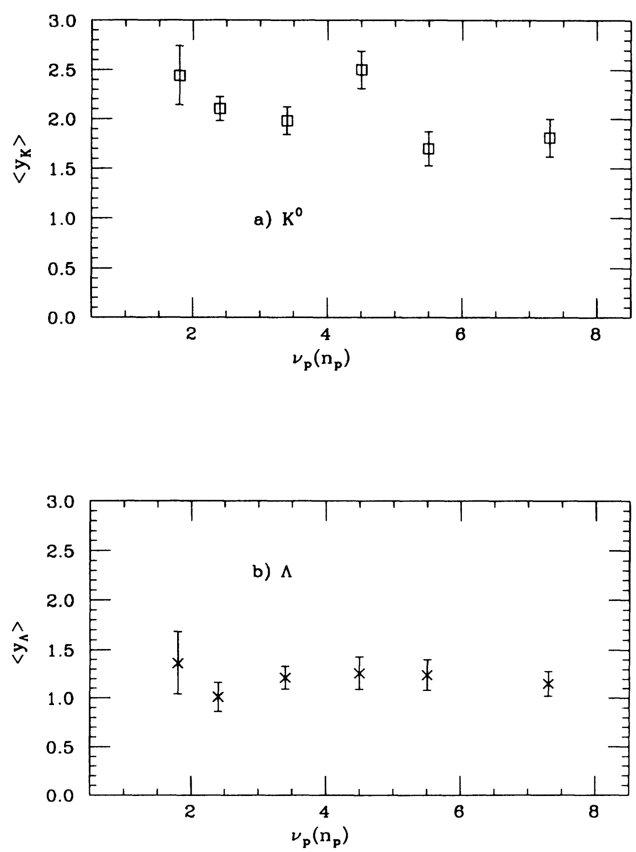

FIG. 6. Average rapidity of (a) K^0 and (b) Λ as a function of the number of projectile collisions. The rapidity was defined in the laboratory frame, which is shifted by 3.0 units from the hadron-nucleon center-of-mass frame.

than that of K^0's and pions, and is in the target-fragmentation region. No significant dependence on ν_p is seen, despite the fact that the event energy has to be shared by more particles as ν_p increases. This is just what would be expected if the Λ's originated from target fragmentation.

There has been considerable discussion [21] that in those cases where the projectile suffers a large rapidity loss, there may be unusually large energy deposition and energy density in the nucleus, which could materially affect the properties of strange particles produced. We have measured the rapidity loss Δy of the projectile by defining the leading particle in an event as the highest-momentum positive particle, assuming its mass to be the same as that of the projectile, and then subtracting its rapidity from that of the beam particle. As shown in Fig. 8, the K^0 and Λ rates do exhibit some increase with projectile rapidity loss, although the evidence is somewhat marginal, especially for the Λ. The average rapidities themselves, shown in Fig. 9, are consistent with being entirely independent of Δy, so that the higher energy density appears only to increase strange particle multiplicities, not their rapidities.

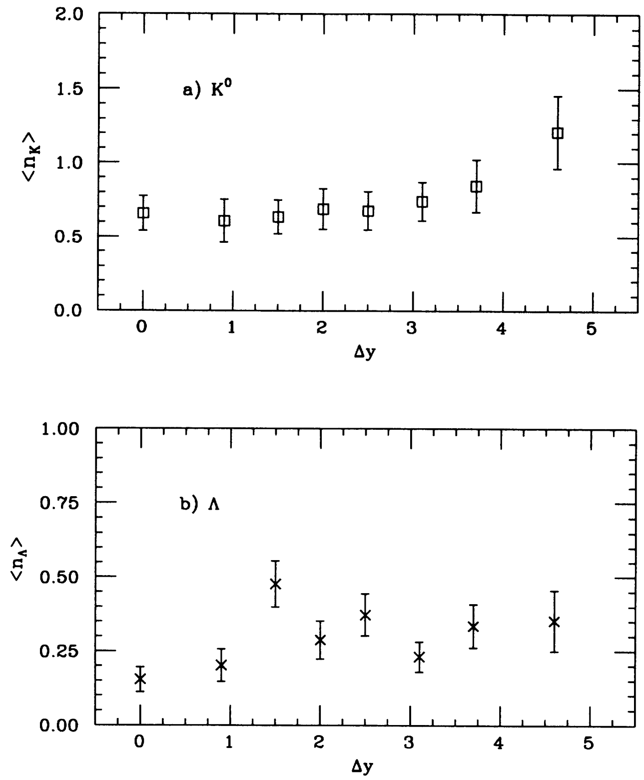

FIG. 8. Average multiplicity of (a) K^0 and (b) Λ as a function of rapidity loss of the projectile, determined by subtracting the rapidity of the leading positive particle from that of the beam particle.

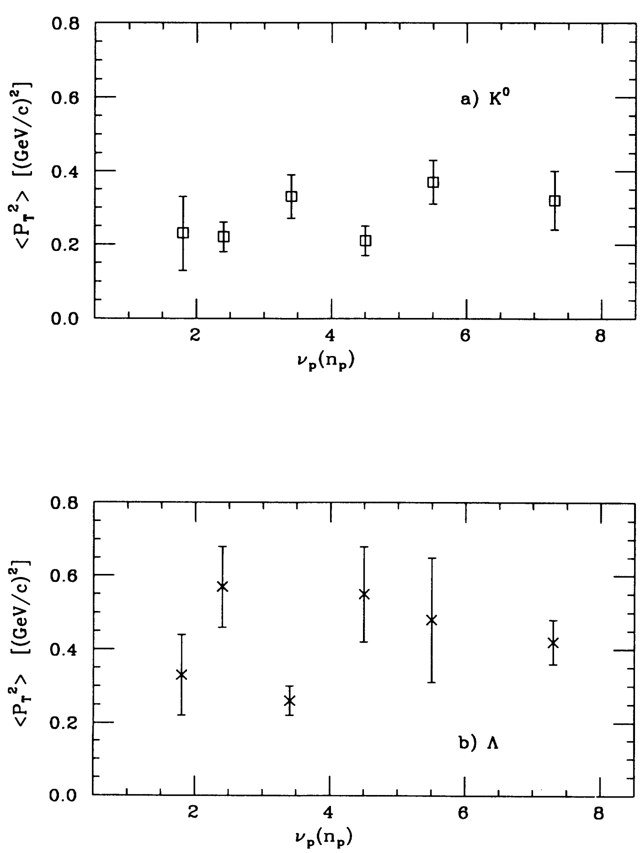

FIG. 7. Average transverse momentum squared of (a) K^0 and (b) Λ as a function of number of projectile collisions.

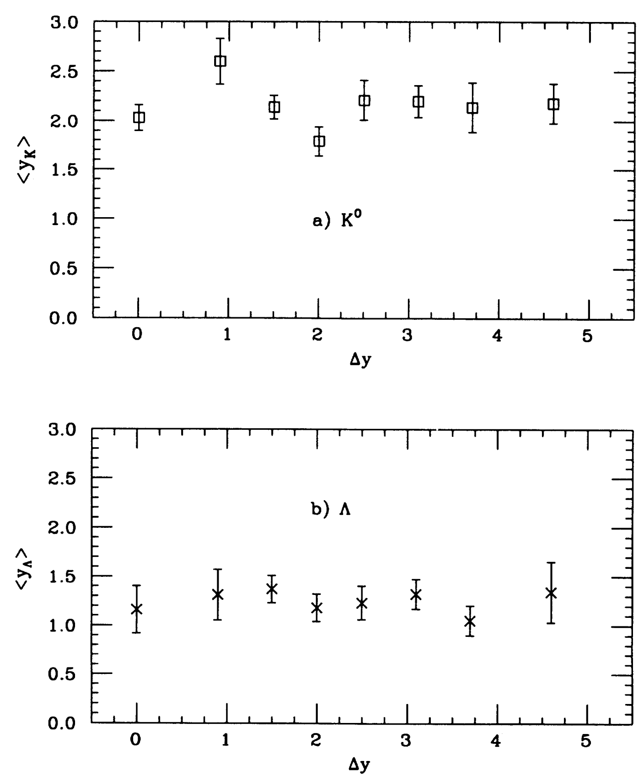

FIG. 9. Average rapidity of (a) K^0 and (b) Λ as a function of rapidity loss of the projectile.

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