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Spectra and correlations of Λ and $\bar{\Lambda}$ produced in 340-GeV/c $\Sigma^{-}+C$ and 260-GeV/c $n+C$ interactions

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We have measured the production of strange baryons and antibaryons in 340-GeV/c $\Sigma^{-}+C$ and 260-GeV/c $n+C$ interactions. The single x_F distributions show the expected leading particle effect, and the single p_t^2 distributions show a distinct nonthermal behavior. The x_F distributions of Λ-Λ pairs indicate two different phase space distributions for the two coincident baryons. On the other hand two $\bar{\Lambda}$'s show identical distributions. Momentum conservation during the formation process may represent a significant source for the observed behavior.

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The study of inclusive production of hadrons in hadron beams with a diversity of strangeness content in the projectiles and the produced particles can provide new insights into hadron interactions, since various degrees of valence quark overlap between incoming and outgoing hadrons can be isolated. Furthermore production of excited states with identical quark flavor content but different spin structure may help to explore the importance of possible diquark structures in excited hyperons [1]. Indeed the role of the valence quark overlap in the so-called "leading particle effect" has been known for a long time and has been clearly demonstrated in earlier hyperon beam experiments [2,3]. This effect suggests the presence of—at least—two distinct production stages (or even mechanisms) for hadrons [4]: At low x_F, a soft hadronization process may dominate which is described, e.g., by several breakups of a color string stretched between the partons, while recombination of projectile spectator quarks or diquarks with quarks produced in the interaction may be more relevant at high x_F.

Strange particle production in hadron-nucleus collisions also represents an important baseline for the interpretation of strange particle distributions in nucleus-nucleus (A-A) collisions [5]. Considering the fast expansion time as well as the long equilibration time in $A+A$ interactions it has been argued that the observed hadrochemical equilibrium [6,7] may serve as a fingerprint of an early hadronization process [7–9]. Clearly, the existence of two distinct production stages—if present within a single $N+A$ interaction—would

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not permit a straightforward extrapolation to $A+A$ collisions since the relative importance of the various stages might change with projectile or target mass. For example, the role of conservation laws may differ for hadron-induced and nucleus-induced reactions. Like strangeness conservation [10] momentum conservation may also cause a significant interrelation between various stages of a hadron-nucleus reaction, while nucleus-nucleus reactions may be less affected by momentum constraints.

In this paper we demonstrate that x_F correlations between two Λ's or two $\bar{\Lambda}$'s may help to clarify the question of whether two coincident strange baryons have independent and identical phase space distributions or whether additional constraints or even more than one production mechanism are simultaneously at work in a reaction.

The hyperon beam was derived from an external proton beam of the CERN-SPS hitting a production target placed 16 m upstream of the experimental target. Negative secondaries with a mean momentum of 345 GeV/c and a momentum spread of $\sigma(p)/p \approx 9\%$ were selected in a magnetic channel. At the experimental target, the beam consisted of π^-, K^-, Σ^-, and Ξ^- in the ratio 2.3:0.025:1:0.012. $\Sigma^- \rightarrow n+\pi^-$ decays upstream of the target were a source of neutrons used in our measurement as a neutron beam. For neutron interactions the π^- track from the Σ^- decay had to pass the reconstructed interaction point with a distance of at least 6σ ($\sigma \approx 25$ μm). The momenta of these neutrons were defined as the difference between the average Σ^- beam momentum and the momentum of the associated π^- measured in the spectrometer. The neutron spectrum had an average momentum of 260 GeV/c and a width of $\sigma(p)/p \approx 15\%$.

The experimental target consisted of one copper and three carbon blocks arranged in a row along the beam, with thicknesses corresponding to 0.026 λ_I and three times 0.0083 λ_I, respectively. Tracks of charged particles were measured inside the CERN OMEGA magnet and in the field-free regions upstream and downstream by multiwire proportional counters and drift chambers, with a total of 130 planes. More details of the hyperon beam setup and parameters can be found in Ref. [11]. For the purpose of this paper, only interactions in the carbon target were used.

V^0 candidates (Λ or $\bar{\Lambda}$) were selected from all pairs of positive and negative tracks which formed a vertex downstream of the target with the distance between the two tracks at the decay point being smaller than 0.3 cm. The reconstructed decay points had to be at least 0.5 m downstream of the target and at least 3 m upstream of the center of the OMEGA magnet, i.e., outside the core of the magnetic field. The reconstructed V^0 track had to pass the interaction vertex at a distance of less than 1.2 cm. The reconstructed V^0 mass had to be within ± 15 MeV/c^2 and $\pm 5\sigma_m$ of the true V^0 mass, where σ_m, the experimental mass resolution, was 2 MeV/c^2 typically. Finally the V^0 momentum had to be below 260 GeV/c. For Σ^-- (neutron) induced interactions the background integrated over the peak region amounts to 14% (13%) and 48% (35%) for Λ and $\bar{\Lambda}$, respectively.

The left part of Fig. 1 shows the inclusive differential cross sections $d\sigma/dx_F$ of Λ production (top) and $\bar{\Lambda}$ production (bottom) in Σ^- (dots) and neutron (squares) interactions in carbon. The Feynman variable x_F is defined as $x_F = 0.5 \cdot p_\parallel / \sqrt{s}$ where $p_\parallel$ denotes the longitudinal V^0 momentum and $\sqrt{s}$ the invariant mass of the beam particle and the target nucleon.

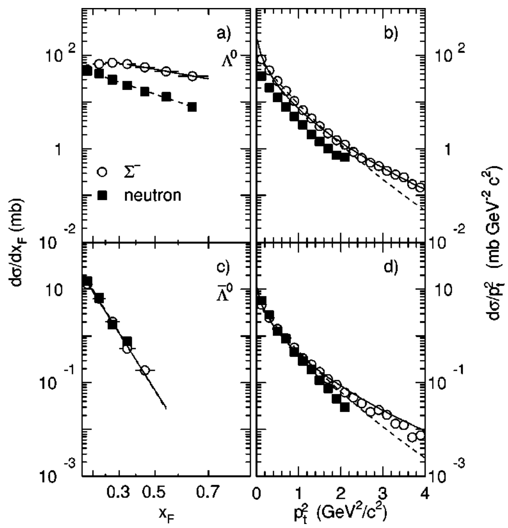

FIG. 1. Inclusive x_F (left parts) and transverse momentum distributions (right parts) of Λ's (top parts) and $\bar{\Lambda}$'s (bottom parts) in Σ^-- (dots) and neutron- (squares) induced reactions on a carbon target. The lines are described in the text.

The striking difference between the x_F distributions observed in Λ and $\bar{\Lambda}$ production and also the difference between Λ production by Σ^- and by neutrons demonstrate the leading particle effect, i.e., the increase of the hardness of the x_F distribution with increasing valence quark overlap between beam particle and produced particle. This effect is well known from hyperon production in hyperon beams [2,3] and also from $D^\pm$ production in a pion beam [3]. We also note that the present Λ spectrum for neutron interactions is compatible with hyperon spectra from p-p interactions at 360 GeV/c [4] (note that in Ref. [4] the invariant cross section is used). Fits according to a distribution function$\propto(1-x_F)^n$ are given by the lines in Figs. 1(a) and 1(c). The values obtained for n are listed in Table I together with the production cross sections in the range $x_F>0$. The errors of n include systematic uncertainties due to the fit interval and possible efficiency variations as a function of x_F. The cross

TABLE I. Number of detected events, inclusive production cross section, and shape parameter n of the x_F distribution for Λ and $\bar{\Lambda}$ production.

Beam; particle	Number of events	Cross section (mb)	n	b (c/GeV)
Σ^-; Λ	1 132 019 ± 1140	41.3 ± 1.5	0.95 ± 0.06[a]	4.0 ± 0.1
Σ^-; $\bar{\Lambda}$	70 913 ± 324	2.2 ± 0.2	8.20 ± 0.13	3.9 ± 0.1
n; Λ	30 585 ± 186	18.1 ± 0.8	1.80 ± 0.07	3.6 ± 0.1
n; $\bar{\Lambda}$	3 841 ± 71	2.4 ± 0.2	8.46 ± 0.36	4.0 ± 0.1

[a]In the case of Λ's produced in Σ^--induced reactions, the fit range was limited to $x_F \geqslant 0.3$.

TABLE II. Number of pairs, cross sections per nucleus, and their statistical uncertainties for the different baryon pairs.

Beam	Particle pair	Events	Cross section (mb)
Σ^-	ΛΛ	8830±96	1.57±0.02
Σ^-	$\overline{\Lambda\Lambda}$	142±13	0.029±0.002
n	ΛΛ	187±14	0.44±0.03

sections have, in addition to the quoted statistical error, a systematic normalization uncertainty of 20%.

In contrast to the different inclusive x_F distributions, the shapes of the transverse momentum spectra are very similar. Only the $\bar{\Lambda}$'s from neutron reactions show a slightly steeper distribution [squares in Fig. 1(d)]. Particularly striking is a marked flattening of the Λ and $\bar{\Lambda}$ spectra beyond $p_t^2 \approx 1\ \mathrm{GeV}^2/c^2$ for Σ^- interactions. These spectra are quite well parametrized by an exponential function $d\sigma/dp_t^2 \propto \exp(-b\cdot p_t)$ [solid lines in Figs. 1(b) and 1(d)], while a thermal distribution of the form $d\sigma/dp_t^2 \propto m_t^{3/2}\cdot \exp(-m_t/T)$ cannot describe the Σ^- data over the whole p_t^2 range (dashed lines).

Kinematic correlations between two strange baryons have been studied before in Z^0 decays [12–14], in *pp* interactions at 360 GeV/*c* [15], and more recently also in relativistic Pb+Pb collisions [16]. While the latter experiment analyzed correlations at small relative momenta between two identical baryons, the former ones focused on rapidity correlations of $\Lambda\bar{\Lambda}$ pairs. The high statistics of strange particles recorded in the present experiment allowed us to study for the first time kinematic correlations between two identical strange baryons or anti-baryons in hadron-nucleus interactions.

For the extraction of the ΛΛ and $\overline{\Lambda\Lambda}$ pairs the same criteria as those for the single strange hadrons were applied. In addition it was required that the two hadrons have no track of the decay products in common. On average the background due to misidentifications did not exceed 20% of the coincident yield and was subtracted as described in Ref. [17]. The number of events and the corresponding cross sections for $x_F > 0$ are listed in Table II.

Figure 2(a) shows the x_F distribution of the two Λ's after sorting with respect to their x_F value. Due to the sorting procedure, the faster Λ shows a harder x_F distribution than the slow one. If both Λ's were produced independently with the same distribution $P(x_F) \propto (1-x_F)^n$, the x_F distribution of the fast particle is given by

$$P_f(x_F) = 2N[(1-x_F)^n - (1-x_F)^{2n+1}] \qquad (1a)$$

while the slow particle *s* will be distributed as

$$P_s(x_F) = 2N(1-x_F)^{2n+1}. \qquad (1b)$$

Calculations for the fast baryon according to Eq. (1a) are shown by the solid lines in Fig. 2(a). In these calculations the parameter *n* and the normalization constant *N* have been adjusted to enclose the x_F distribution of the faster Λ. The corresponding x_F distributions of the slower Λ [Eq. (1b)] are indicated by the two dashed curves. Clearly, if the two Λ's have independent and identical x_F distributions, the rearrangement with respect to x_F is not sufficient to explain the observed correlation.

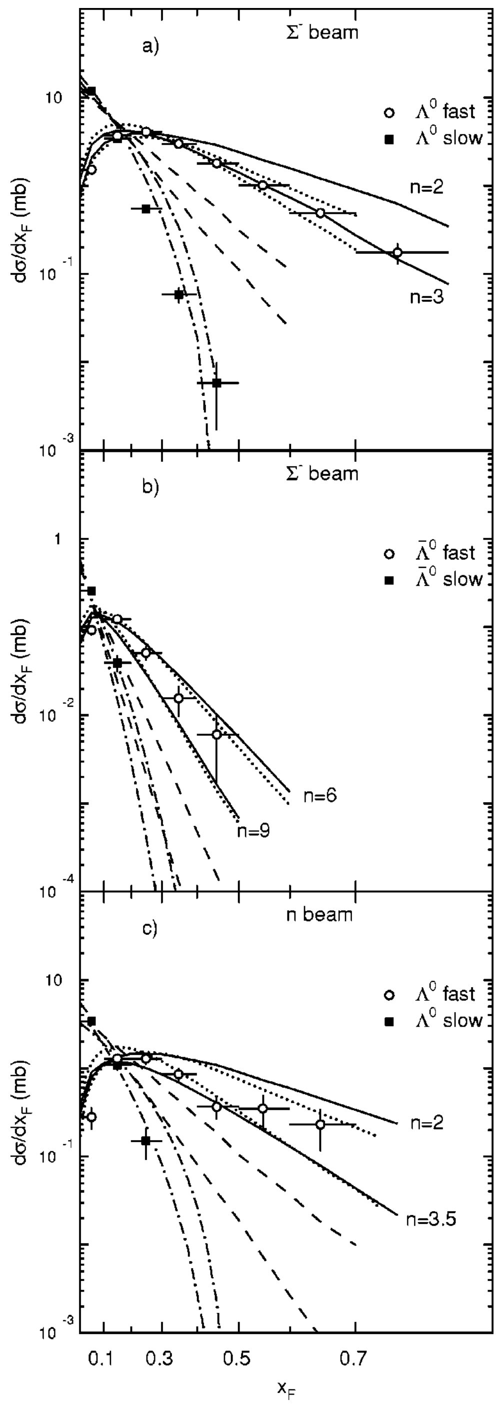

FIG. 2. x_F distribution of the fast (open points) and slow (closed squares) Λ [(a) and (c)], respectively. $\bar{\Lambda}$ (b) produced in Σ^-+C (a) and (b) or n+C (c) reactions. The solid and dashed lines illustrate the effect of sorting, the dotted and dot-dashed curves include in addition the effect of momentum conservation.

In deriving Eq. (1) momentum conservation was neglected. In order to demonstrate the importance of momentum conservation we adopted a two-step scenario. First one hyperon was generated according to a distribution $P(x_F) \propto (1-x_F)^n$ where x_F was defined in the initial hadron-nucleon system. The second hyperon then was produced from the remaining system, assuming again a distribution $P(\tilde{x}_F) \propto (1-\tilde{x}_F)^n$ where $\tilde{x}_F$ now was defined in the remaining system, but the value of n was the same for both hyperons. Next the momenta of both hyperons were transformed to the laboratory system and the x_F values were calculated and sorted as in the analysis of the experimental data. Finally a cut at 260 GeV/c was imposed on the individual momenta and in addition the sum of the two laboratory momenta was not allowed to exceed the beam momentum.

The results obtained imposing momentum conservation are shown by the dotted curves for the faster Λ and the dot-dashed curves for the slower Λ. Obviously momentum conservation has little influence on the x_F distribution of the faster Λ. For the slower Λ, however, momentum conservation results in a significant depletion of events with $x_F > 0.4$. Momentum conservation—as implemented in our scenario—seems to account for the observed distribution of the slow Λ. The same analysis for two $\bar{\Lambda}$'s produced in Σ^--induced interactions is displayed in Fig. 2(b). Here the x_F distributions of the slow as well as the fast $\bar{\Lambda}$ are well described by an exponent $n \approx 6-9$. For such high values of n, momentum conservation can have very little effect. Finally, Fig. 2(c) shows the x_F distributions for two Λ's produced in neutron-induced interactions. Again the data indicates that a deviation from the simple model of independent production and momentum conservation seems to be important to understand the joint probability distributions of two Λ's.

In Fig. 3, we compare the measured x_F distributions to calculations from the PYTHIA 5.7 [18] and FRITIOF 7.02 [19] models using default parameters. Since FRITIOF calculations are not yet available for the Σ^- projectile we present only results for $n+{}^{12}$C interactions. The PYTHIA model (dashed lines) describes the data only qualitatively. The leading effect for Λ production is too pronounced and the cross section for double Λ production is severely underpredicted. Multiple interactions as, e.g., implemented in FRITIOF seem to account for the missing $\Lambda\Lambda$ yield (solid lines). In addition we obtain a good description of the x_F correlation. However FRITIOF still underpredicts the $\Lambda\Lambda$ to Λ ratio by $\approx 30\%$ and the $\bar{\Lambda}$ yield is overpredicted by a factor of 2.

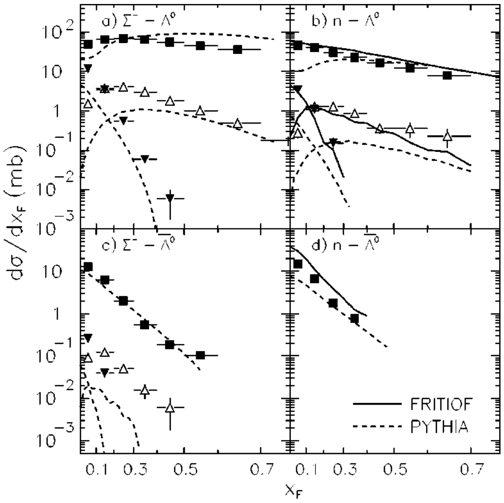

FIG. 3. Comparison of the measured inclusive (squares) and coincident (triangles) x_F distributions to predictions of PHYTIA and FRITIOF.

To conclude, the inclusive x_F spectra of Λ's and $\bar{\Lambda}$'s and the shape of the p_t distributions suggest various competing processes for strange baryon production in hadron-induced interactions. The x_F correlations between identical strange baryons signal different phase space distributions for coincident Λ's within a single event. A schematic model demonstrates that this behavior may be related to momentum conservation during the formation process. FRITIOF calculations indicate the importance of multiple interactions in the target nucleus for understanding the hyperon multiplicity distribution and the hyperon pair production.

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