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Neutral-Strange-Particle Production in 205-GeV pp Interactions*

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A bubble-chamber study of proton-proton interactions at 205 GeV yielded 66 K^0's, 28 Λ's, and 2 $\bar{\Lambda}$'s produced in the backward c.m. hemisphere. The cross sections for $p+p \rightarrow (\Lambda/\Sigma^0)+$anything and $p+p \rightarrow (K^0/\bar{K}^0)+$anything are 3.2 ± 0.6 and 12.9 ± 1.7 mb, respectively. Comparison of the invariant cross section with lower-energy data shows that (Λ/Σ^0) production is consistent with approximate scaling behavior above 28 GeV, whereas the $(K^0/\bar{K}^0)$ invariant cross section has increased considerably between 28 and 205 GeV.

We present results on Λ/Σ^0 and $K^0/\bar{K}^0$ inclusive reactions obtained from an exploratory exposure of the 30-in. hydrogen bubble chamber to 205-GeV protons at the National Accelerator Laboratory. A total of 15 000 pictures were scanned and analyzed as described previously.[1] A second independent examination of all primary interactions yielded first and second scan efficiencies for associated V's of 0.89 ± 0.02 and 0.94 ± 0.02, respectively.

A total of 401 V's pointing to beam-track interactions were found, of which 332 remained after fiducial region[2] cuts were made. These events were measured, up to 3 times if necessary, and the 309 events with successful geometrical reconstruction were kinematically fitted. After visual inspection of ionization densities, 36 of the events remained kinematically ambiguous, and these were mostly high-momentum V's giving a γ fit as well as a K^0, Λ^0, or $\bar{\Lambda}^0$ fit. These events were classified on a statistical basis using the expected transverse momentum ($P_\perp{}^\pm$) distributions of the decay products with respect to the neutral-particle direction.[3] Because of the loss of V's close to the production vertex, a minimum-length ($L_{\min}$) cut of 2 cm for V^0 (K^0, Λ, $\bar{\Lambda}$) decays and 4 cm for γ's was applied and, additionally, a minimum kinematic χ^2 probability

of 1% was required.[4] These procedures yielded 138 γ, 83 K^0, 32 Λ, and 4 $\bar{\Lambda}$ fits. Of the 23 unmeasurable V's (usually unmeasurable because of masking by the forward cone of tracks from the primary vertex), 11 could be uniquely identified by means of opening angle, ionization, and sagitta of tracks, or $\pi\mu e$ decay (giving 8 γ's, 2 K^0's, and 1 Λ), and 3 were excluded by the minimum length cuts. The remaining 9 were assigned for cross-section purposes in the ratios of the identified events.

The γ events are discussed elsewhere.[5] In this paper, we report results on the V^0 decays. Most V^0's produced in the forward c.m. hemisphere decay outside the chamber because of their large lab momentum. Therefore, we make use of the symmetry of the $p\bar{p}$ c.m. system and base our analysis only on fits corresponding to V^0's produced in the backward c.m. hemisphere. This leaves 66 K^0's, 28 Λ's, and 2 $\bar{\Lambda}$'s in our final sample.[6]

We believe that backward V^0's are not missed or misidentified even for c.m. longitudinal momenta ($P_\parallel$) near zero. This is based on the following observations: The weighted $P_\parallel$ distribution for the γ's is symmetric for all $P_\parallel$ and that for the K^0's is symmetric for $P_\parallel < +1$ GeV/c.[7] The latter corresponds to $p_{\mathrm{lab}} < 20$ GeV/c, so that the observed symmetry of the distributions shows that both K^0's and γ's are correctly detected up to at least 20 GeV/c. We infer from this that we have also correctly detected all backward Λ's which, on the average, are intermediate in appearance between K^0's and γ's. A backward Λ with $p_{\mathrm{lab}} > 20$ GeV/c must have a transverse momentum $P_\perp > 1.6$ GeV/c, and because of the steep falloff of the $P_\perp$ distribution, we do not expect any such events at our level of statistics.

To obtain cross sections, the events were weighted with the inverse of the probability of decay between $L_{\min}$ and the potential V^0 path length. The average weights for the K^0 and Λ^0 events were 1.5 and 1.6, respectively. After corrections for neutral decay modes (also for K_L^0 in the case of K^0), for V^0's produced in the forward c.m. hemisphere, and for scanning efficiency, the cross sections obtained are $\sigma(\Lambda/\Sigma^0) = 3.2 \pm 0.6$ mb, $\sigma(K^0/\bar{K}^0) = 12.9 \pm 1.7$ mb, and $\sigma(\bar{\Lambda}) = 0.3^{+0.3}_{-0.2}$ mb. (The notation $K^0/\bar{K}^0$ means that the observed K_s decays may have originated from K^0 or $\bar{K}^0$.)

Our result for $\sigma(\Lambda^0/\Sigma^0)$ at 205 GeV is about 2.5 times its value as measured[8] in the range 13–28 GeV. Only a small part of this increase may be attributed to production of $\bar{\Lambda}\Lambda$ pairs. Our result for $\sigma(K^0/\bar{K}^0)$ shows a large increase, about a factor of 5, over its value of 2.6 mb at 28 GeV. Thus, $\sigma(K^0/\bar{K}^0)$ is increasing much more rapidly with energy than $\sigma(\Lambda^0/\Sigma^0)$.

Using our previous measurement[1] of $\langle n^- \rangle$, we estimate that $(K^0/\bar{K}^0)/\pi^- = 0.17 \pm 0.02$ at 205 GeV. Similarly, using intersecting-storage-ring (ISR) measurements of K^-/π^-, K^+/π^+, and π^+/π^- ratios,[9] we estimate that $(K^+/K^-)/\pi^- \approx 0.21$ between 500 and 1500 GeV. Assuming that $K^0/\bar{K}^0 = K^+/K^-$, our results and the ISR results show that kaon production is proportional to pion production above 205 GeV.

To discuss further the energy dependence of the Λ and K^0 inclusive spectra, we use the invariant cross section

$$F(x, P_\perp, s) = \frac{2E}{\pi\sqrt{s}} \frac{d^2\sigma}{dx\, dP_\perp^2},$$

where E is the energy of the particle and $x = 2P_\parallel/\sqrt{s}$, all computed in the $p\bar{p}$ c.m. system. The integrals of F over $P_\perp^2$ and x are denoted by $F_1(x)$ and $F_2(P_\perp^2)$, respectively. Note that all distributions shown contain only events from the backward c.m. hemisphere, but are normalized to represent events from both hemispheres.

Figure 1(a) shows $F_1(x)$ for $K^0/\bar{K}^0$ production together with $d\sigma/dx$. $F_1(x)$ falls off like a typical meson distribution [$\sim \exp(-Ax)$] with a fitted slope of $A = 3.2 \pm 1.4$. This is compatible with the slope $A = 5.1 \pm 0.5$ that we find by fitting data

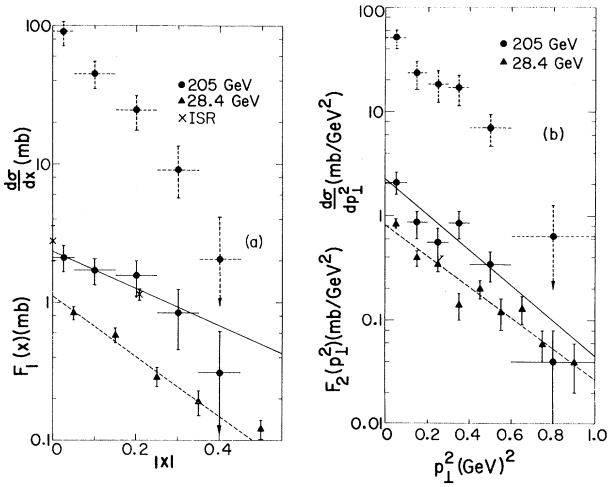

FIG. 1. K^0/K^0 events. (a) $F_1(x)$ and $d\sigma/dx$ (dashed error bars). The two ISR results (K^+/K^-) for $F_1(x)$ are from Ref. 11 ($x = 0$) and Ref. 12 ($x = 0.21$). (b) $F_2(P_\perp^2)$ and $d\sigma/dP_\perp^2$ (dashed error bars). Solid lines, exponential fits to our data; dashed lines, to the low-energy data (Ref. 10).

TABLE I. $K^0/\bar{K}^0$ and Λ/Σ^0 inclusive cross sections.

Prong No.	$\sigma_n(p+p \to K^0/\bar{K}^0 + \text{anything})$ (mb)	$\sigma_n(p+p \to \Lambda/\Sigma^0 + \text{anything})$ (mb)
2	0.30 ± 0.22	0.29 ± 0.17
4	2.05 ± 0.57	0.31 ± 0.16
6	3.02 ± 0.86	0.68 ± 0.24
8	2.62 ± 0.73	0.64 ± 0.25
10	3.10 ± 0.75	$0.40^{+0.34}_{-0.23}$
12	$1.40^{+0.68}_{-0.61}$	$0.48^{+0.38}_{-0.21}$
14	•••	0.11 ± 0.11
16	$0.38^{+0.33}_{-0.26}$	$0.03^{+0.08}_{-0.01}$
18	•••	0.25 ± 0.18

at 28.4 GeV,[10] which are also shown in Fig. 1(a). The F_1 distribution at 205 GeV is about a factor of 3 greater than that at 28.4 GeV. Two results for K^+/K^- production from the ISR[11,12] are plotted in Fig. 1(a). The compatibility of the ISR results and our results suggests that scaling at low x has set in by 200 GeV.[13] Figure 1(b) shows $F_2(P_\perp^2)$ together with $d\sigma/dP_\perp^2$ for the $K^0/\bar{K}^0$ events. F_2 falls off like $\exp(-BP_\perp^2)$ with $B = 3.9 \pm 0.9$. The 28.4-GeV results shown in Fig. 1(b) give $B = 3.4 \pm 0.2$.

Figure 2(a) shows $F_1(x)$ for Λ/Σ^0 production together with $d\sigma/dx$ and data from Ref. 9 between 21 and 28 GeV. The F_1 distribution is typical for a baryon and indicates approximate scaling behavior above 28 GeV. However, near $x = 0.6$, F_1 at 205 GeV is somewhat higher than the 21–28-GeV data suggesting that proton fragmentation is an important source of Λ production.[14]

The $P_\perp^2$ distributions for Λ/Σ^0, shown in Fig. 2(b), fall off as $\exp[-(2.7 \pm 0.7)P_\perp^2]$ at 205 GeV and $\exp[-(3.6 \pm 0.4)P_\perp^2]$ between 21 and 28 GeV.

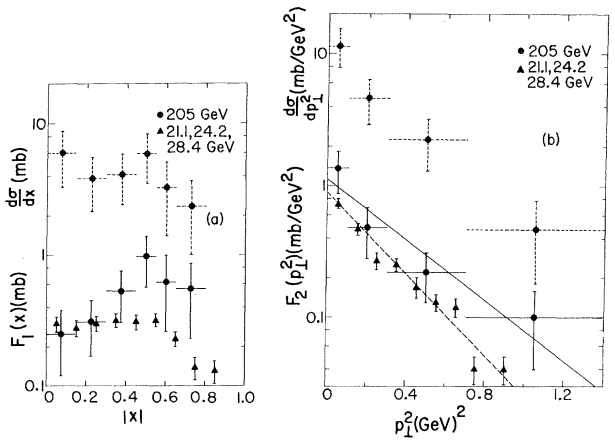

FIG. 2. Λ/Σ^0 events. (a) $F_1(x)$ and $d\sigma/dx$ (dashed error bars). (b) $F_2(P_\perp^2)$ and $d\sigma/dP_\perp^2$ (dashed error bars).

The Λ/Σ^0 and $K^0/\bar{K}^0$ topological cross sections are given in Table I. Comparison of the latter with the cross section for $p+p \to \pi^0 + n$ charged particles + anything[5] shows that the K^0/π^0 ratio is roughly independent of prong number.

We find the average numbers of Λ/Σ^0 and $K^0/\bar{K}^0$ per inelastic pp collision to be 0.10 ± 0.02 and 0.39 ± 0.05, respectively, whereas 19-GeV values[15] are 0.06 and 0.08. The average transverse momenta for our data are 0.49 ± 0.09 and 0.42 ± 0.05 GeV/c for Λ/Σ^0 and $K^0/\bar{K}^0$, respectively, to be compared with 0.475 ± 0.005 and 0.406 ± 0.005 GeV/c at 19 GeV.

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[1]G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972).

[2]The fiducial volume for the primary interactions is ~85% of that used in Ref. 1. It leaves at least 15 cm decay path and a minimum of 12 cm track length for the V^0.

[3]The maximum transverse momenta $P_\perp^\pm$ for the e^- from the γ conversion, π^- from K^0, and π^- (π^+) from Λ ($\bar{\Lambda}$) are 0.0, 9.206, and 0.101 GeV/c, respectively. The expected $P_\perp^\pm$ distributions as well as the data peak sharply at these values.

[4]Events with χ^2 probability less than 1% were used

for cross-section calculations, but were excluded from distributions.

[5]G. Charlton *et al.*, Phys. Rev. Lett. 29, 1759 (1972).

[6]The 66 K^0's (which have lab momenta less than 8 GeV/c) are unique fits. Of the 28 Λ's, 22 are unique, and 4 (2) also give a K^0 (γ) fit discarded by the $P_\perp^\pm$ selection. One of the two $\bar{\Lambda}$'s is unique and one also has a K^0 fit rejected by the $P_\perp^\pm$ criterion. In addition, among the backward V's three had fits ambiguous between Λ and γ, one between $\bar{\Lambda}$ and γ, and one between K^0 and γ. These were classified as γ's by the transverse-momentum selection and are not included in our V^0 sample.

[7]In fact, the weighted forward-backward ratios for both K^0's and Λ's are consistent with 1, although the statistics are poor in the forward hemisphere because of escape losses.

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[13]We caution that the error bars on the ISR results do not realistically reflect the uncertainty of the ISR results. A compilation of K^+/K^- production at various ISR energies by E. Lillethun [see Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published)] shows that the data fluctuate by up to 50%.

[14]We observe two $\bar{\Lambda}$'s and ten Λ's in the interval $0 < x < 0.3$. The $\bar{p}/p$ ratio at $x = 0$ increases to about $\frac{1}{2}$ at the highest ISR energies (see Lillethun, Ref. 13).

[15]Scandinavian Bubble Chamber Collaboration, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).