pp Interactions at 303 GeV/c: Inclusive Studies of γ, $K_S{}^0$, and Λ^0 Production

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From analysis of V^0 events observed in an exposure of the National Accelerator Laboratory 30-in. bubble chamber to 303-GeV/c protons, we obtain these results: (1) $\langle n_{\pi^0}\rangle$ rises approximately linearly with n_-, implying strong coupling of neutral and charged pions, while $\langle n_{K_S{}^0}\rangle$ is less coupled to n; (2) γ, $K_S{}^0$, and Λ^0 production cross sections are approaching a scaling limit by 303 GeV/c; (3) within the limited statistics, $d\sigma/dy$ is flat in the central region for $K_S{}^0$ and low-multiplicity γ events.

In this Letter we report on our study of V^0 events from an exposure of 303-GeV/c protons in the 30-in. hydrogen bubble chamber at the National Accelerator Laboratory (NAL). In spite of the limited size of this chamber, it has been particularly valuable in the survey of neutral-particle production in high-energy collisions. Results on multiplicity, total cross section, and inclusive Δ^{++} production have already been reported.[1] A total of 311 V^0 events were recorded in a fixed fiducial volume.[2] These events were processed by the programs TVGP and SQUAW and fitted with the following hypotheses: $K_S{}^0 \to \pi^+\pi^-$, $\Lambda^0 \to p\pi^-$, $\bar{\Lambda}^0 \to \pi^+\bar{p}$, and $\gamma(p) \to e^+e^-(p)$. After two measurements, 71% of the 311 events had satisfactory fits, 19% did not point to the primary vertex, and 10% were unmeasurable. The events were examined on a scan table by physicists. Of the 311 fitted events, 18% had more than one satisfactory fit. A selection on the transverse momentum of the negative outgoing track with respect to the neutral particle[3] was effective in resolving all the γ ambiguities. The small number of $K_S{}^0/\Lambda^0$ ambiguities was resolved by ionization and χ^2.

After all selections there were 119 γ's, 50 $K_S{}^0$'s, 20 Λ^0's, and 2 unique $\bar{\Lambda}^0$'s.[4] The data for $K_S{}^0$, Λ^0, and $\bar{\Lambda}^0$ were restricted to the backward hemisphere in the pp c.m. system as the detection efficiency in the forward direction was extremely low. The average weighting factors[5] are 71.9 for γ, 3.44 for $K_S{}^0$, 4.25 for Λ^0, and 4.69 for $\bar{\Lambda}^0$. The final sample was further corrected by a scanning efficiency of 0.93. The inclusive cross sections measured (that is, the product of the average number of particles produced per inelastic collision and the total inelastic cross section) are as follows: $\sigma(\gamma) = 253 \pm 24$ mb, $\sigma(K_S{}^0) = 9.8 \pm 1.3$ mb, $\sigma(\Lambda^0) = 4.2 \pm 1.0$ mb, and $\sigma(\bar{\Lambda}^0) = 0.4^{+1.0}_{-0.3}$ mb. Assuming that all γ's come from $\pi^0 \to 2\gamma$, we we get $\sigma(\pi^0) = 127 \pm 12$ mb.

The dependencies of these cross sections on the incident lab momentum[6-9] are shown in Figs. 1(a)–1(c). Note that $\sigma(\Lambda^0)$ has increased threefold from 28 to 303 GeV/c and remains much larger than $\sigma(\bar{\Lambda}^0)$ at 303 GeV/c. The $K_S{}^0$ cross section has increased more than 8 times from 28 to 303 GeV/c. However, the rapid rise in $\sigma(K_S{}^0)$ may level off at energies beyond 303 GeV/c, as indicated by the intersecting-storage-ring data.[10] The π^0 cross section in Fig. 1(c) is consistent with a logarithmic growth with incident momentum and is equal to $\sigma(n_-)$ or $\sigma(\pi^-)$ if we assume all

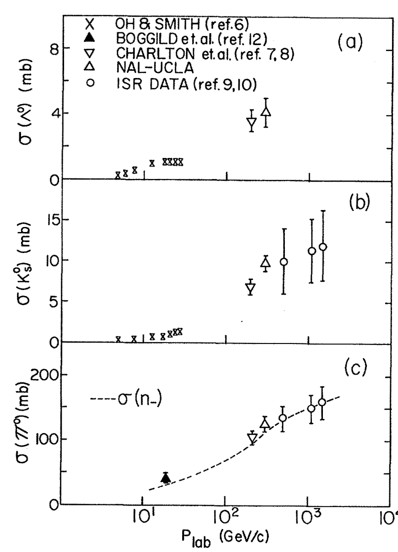

FIG. 1. (a) $\sigma(pp \to \Lambda^0 X)$, (b) $\sigma(pp \to K_S{}^0 X)$, and (c) $\sigma(pp \to \pi^0 X)$ versus incident lab momentum $P_{\rm lab}$. See Ref. 10 for derivation of data points beyond 303 GeV/c.

TABLE I. Cross sections for $pp \to \pi^0 X$ and $K_S{}^0 X$.

n = Number of Charged Particles	$\sigma_n(pp \to \pi^0 X)^a$ in mb	$\langle n_{\pi^0} \rangle$	$\sigma_n(pp \to K_S{}^0 X)$ in mb	$\langle n_{K_S{}^0} \rangle$
2	1.7 ± 1.2	1.0 ± 0.7	0.2 ± 0.2	0.1 ± 0.1
4	11.8 ± 3.1	2.4 ± 0.7	0.8 ± 0.4	0.2 ± 0.1
6	19.4 ± 4.1	3.4 ± 0.8	2.9 ± 0.7	0.5 ± 0.1
8	16.0 ± 3.7	3.0 ± 0.7	1.4 ± 0.5	0.3 ± 0.1
10	22.8 ± 4.4	4.8 ± 1.0	1.6 ± 0.5	0.4 ± 0.1
12	20.3 ± 4.1	4.8 ± 1.4	1.3 ± 0.4	0.3 ± 0.1
14	15.7 ± 2.5	7.2 ± 1.5	0.6 ± 0.2	0.3 ± 0.1
16	9.3 ± 2.8	6.7 ± 2.2	0.8 ± 0.4	0.6 ± 0.3
18	7.2 ± 2.5	8.3 ± 3.2	---	---
20	1.6 ± 1.1	3.3 ± 2.4	0.2 ± 0.2	0.3 ± 0.3
22	---	---	---	---
24	---	---	---	---
26	0.9 ± 0.9	17.0 ± 17.0	---	---
TOTAL	126.7 ± 12.0	3.95 ± 0.38	9.8 ± 1.3	0.31 ± 0.04

[a]Calculated from $\sigma_n(pp \to \pi^0 X) = \sigma_n(pp \to \gamma X)/2$.

negatively charged particles to be π^-'s. This is in accord with multiperipheral models that predict $\langle n_{\pi^0} \rangle = \langle n_{\pi^-} \rangle = \langle n_{\pi^+} \rangle$,[11] where $\langle n_x \rangle$ is the average number of particles of type x produced per inelastic pp collision. The topological cross sections and $\langle n_{\pi^0} \rangle$ and $\langle n_{K_S{}^0} \rangle$ versus topology for inclusive π^0 and $K_S{}^0$ production are listed in Table I.

In Figs. 2(a) and 2(b) $\langle n_{\pi^0} \rangle$ and $\langle n_{K_S{}^0} \rangle$ are plotted as a function of charged-particle multiplicity n_c. Two possible dependencies are shown: $\langle n_{K_S{}^0} \rangle = 0.31$ assumes $K_S{}^0$ production independent of topology; $\langle n_{K_S{}^0} \rangle = 0.09 n_-$ is based on $\sigma_{K_S{}^0}/\sigma_{\pi^-}$ being independent of topology. In contrast, $\langle n_{\pi^0} \rangle$ tends to rise linearly with n_c for $n_c \leq 18$. The latter linear dependence which has been observed here and earlier at 205 GeV/c is very different from the low-energy pp data.[12] The dashed line in Fig. 2(b) is given by $\langle n_{\pi^0} \rangle = n_-$. If we assume all the negative particles to be pions, the data imply that the isospin states of the pion are strongly correlated. Berger, Horn, and Thom-

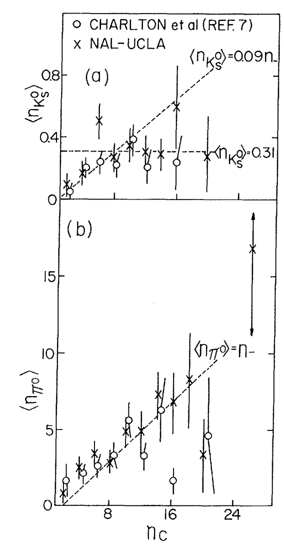

FIG. 2. (a) Average number of $K_S{}^0$ and (b) average number of π^0's produced per inelastic pp collision versus charged-particle multiplicity. The curves are described in the text.

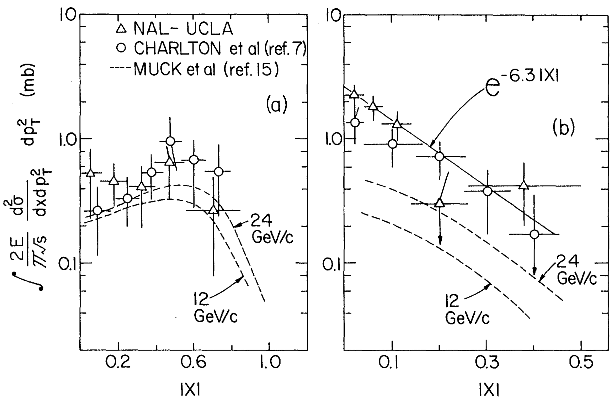

FIG. 3. Invariant single-particle distribution versus x for (a) $pp \to \Lambda^0 X$ and (b) $pp \to K_S^0 X$. E, p_T, and p_L are the energy, transverse, and longitudinal momentum of the particle in the c.m. system, respectively, and $x = 2p_L/\sqrt{s}$.

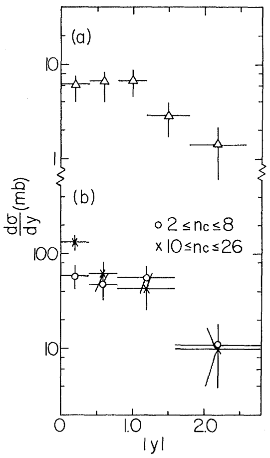

FIG. 4. $d\sigma/dy$ versus y for (a) $pp \to K_S^0 X$ and (b) $pp \to \gamma X$.

as[13] conclude that a linear rise of $\langle n_{\pi^0}\rangle$ versus n_c at high energies rules out models in which pions are independently emitted but is in accord with fragmentation models and multiperipheral models in which ρ- or ω-type meson clusters are emitted. The weaker dependence of $\langle n_{K_S^0}\rangle$ on n_c may reflect the lack of strong correlation between kaons and pions.

In Figs. 3(a) and 3(b), we show the invariant single-particle distribution in Feynman variable x for the inclusive K_S^0 and Λ^0 reactions. Our results combined with the 205-GeV/c data[7] give evidence that the inclusive K_S^0 and Λ^0 reactions have, within the accuracy of the data, reached their scaling limits from below, with Λ^0 approaching the limit at a much faster rate than K_S^0.

Figures 4(a) and 4(b) show $d\sigma/dy$ versus the rapidity variable y for the K_S^0 and γ reactions. There is evidence for a plateau with widths of two units in y for the K_S^0 and low-multiplicity γ events; $d\sigma/dy$ seems to peak at $y=0$ for high-multiplicity γ events. The average longitudinal momenta in the center of mass are $\langle |p_L| \rangle = 2.90 \pm 0.56$, 1.11 ± 0.17, and 0.88 ± 0.12 GeV/c for Λ^0, K_S^0, and π^0, respectively.[14] Thus, neutral pions and kaons are produced more frequently in the central region than Λ^0's.

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[1] F. T. Dao *et al.*, Phys. Rev. Lett. 29, 1627 (1972); F. T. Dao *et al.*, Phys. Rev. Lett. 30, 34 (1973).

[2] The fiducial volume for the primary-interaction vertex was chosen to be smaller than the ones mentioned in Ref. 1 to allow enough track length for decay or conversion. The fiducial volume for the V^0 vertex was defined as $(x_v - 3)^2 + y_v^2 \le (28\text{ cm})^2$ and $0 \le z_v \le 37.72$ cm, where (x_v, y_v, z_v) are spatial coordinates for the V^0 vertex.

[3] The following cuts on the transverse momentum p_T in MeV/c were made: $0 \le p_T \le 15$ for γ, $15 \le p_T \le 210$ for K_S^0, and $15 \le p_T \le 105$ for Λ^0 and $\bar{\Lambda}^0$. Note that these cuts are equivalent to making a very small cut (0.3%) in the $\cos\theta$ distribution in the center of mass of K_S^0, Λ_0, and $\bar{\Lambda}_0$ decays.

[4] Ten $\bar{\Lambda}^0 \to \bar{p}\pi^+$ candidates were found and edited on the scan table using ionization information. The result was 2 unique $\bar{\Lambda}^0$, 3 unique K_S^0, and 5 events that fit $\bar{\Lambda}$ and at least one other hypothesis (usually K_S^0).

[5] Each event was weighted by a factor calculated from the potential decay length and neutral-decay branching ratio. The minimum length for efficient detection was 4 cm for γ and 2 cm for K_S^0, Λ^0, and $\bar{\Lambda}^0$. The pair-conversion cross section for γ was calculated by T. M. Knasel, DESY Reports No. 70/2 and No. 70/3.

[6] B. Y. Oh and G. A. Smith, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

[7] G. Charlton *et al.*, Phys. Rev. Lett. 30, 574 (1973).

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

[9] G. Neuhofer *et al.*, Phys. Lett. 28B, 51 (1972), and 27B, 438 (1971).

[10] The intersecting-storage-ring data points in Fig. 1(b) were computed on the assumption that neutral-kaon emission is as frequent as charged-kaon emission.

Thus,

$$\sigma(K_S{}^0)=\frac{R(K^+/\pi^+)+R(K^-/\pi^-)R(\pi^-/\pi^+)}{1+R(\pi^-/\pi^+)}\sigma(\pi^0),$$

where the ratios were obtained from A. Bertin *et al.*, Phys. Lett. 41B, 201 (1972), and the π^0 cross section from Ref. 9.

[11]J. Honerkamp and K. H. Mütter, Nucl. Phys. B38, 565 (1972).

[12]H. Boggild *et al.*, Nucl. Phys. B27, 285 (1971).

[13]E. L. Berger, D. Horn, and G. H. Thomas, ANL Report No. ANL/HEP 7240, 1972 (unpublished).

[14]G. I. Kopylov, Nucl. Phys. B52, 126 (1973), derives $\langle p_L(\pi^0)\rangle=2\langle p_L(\gamma)\rangle$.

[15]H. J. Mück *et al.*, Phys. Lett. 29B, 303 (1972).

ERRATA

SIGN OF THE HEXADECAPOLE MOMENTS OF ^{232}Th AND ^{238}U NUCLEI. E. Eichler, N. R. Johnson, R. O. Sayer, D. C. Hensley, and L. L. Riedinger [Phys. Rev. Lett. 30, 568 (1973)].

The following should be added to Ref. 5: K. A. Erb, J. E. Holden, I. Y. Lee, J. X. Saladin, and T. K. Saylor, Phys. Rev. Lett. 29, 1010 (1972). Also, T. K. Saylor, J. X. Saladin, I. Y. Lee, and K. A. Erb, Phys. Lett. 42B, 51 (1972).

NEUTRON-SCATTERING OBSERVATIONS OF CRITICAL SLOWING DOWN OF AN ISING SYSTEM. M. F. Collins and H. C. Teh [Phys. Rev. Lett. 30, 781 (1973)].

In the byline the first author's name should read M. F. Collins rather than M. R. Collins.