PHYSICAL REVIEW D VOLUME 16, NUMBER 1 1 JULY 1977

Inclusive V^0 and γ production in pd interactions at 18 GeV/c*

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(Received 3 August 1976)

Inclusive cross sections are presented for γ, K_S^0, and Λ particles produced by pd interactions at 18 GeV/c. Approximate cross sections are given for $\bar{\Lambda}$. The data are separated into neutronlike and protonlike samples.

INTRODUCTION

In this paper, we present inclusive cross sections and distributions for neutral-particle production in pd interactions at 18 GeV/c. No correction for initial- or final-state interaction is made.[1] The data were collected to study the following inclusive reactions:

$$p + d \to \gamma + \text{anything}, \tag{1}$$

$$p + d \to K_S^0 + \text{anything}, \tag{2}$$

$$p + d \to \Lambda + \text{anything}, \tag{3}$$

$$p + d \to \bar{\Lambda} + \text{anything}. \tag{4}$$

For reactions (1), (2), and (3), we present inclusive cross sections and inclusive single-particle spectra. Approximate inclusive cross sections only are given for reaction (4).

EXPERIMENTAL DETAILS

The data come from film taken in the 80-in. bubble chamber at Brookhaven National Laboratory; a discussion of the technical details has been published previously.[2] About 50 000 pictures taken at the incident proton momentum of 18.3 GeV/c were scanned for events with the V^0 topology for inclusive studies.

The scanning and measuring were normally done in the same pass on image-plane digitizing machines at Vanderbilt University. The scanner recorded the multiplicity of charged tracks at the production vertex. The beam track, at least one outgoing charged track, and the decay tracks of the vees associated with the event were digitized. Any stopping proton track was measured, and if it was very short, a second outgoing track was also measured. Each vee was associated with any production vertex from which it might have come, so that in some cases a vee would be measured with two or more production vertices in a frame. The resolution of such ambiguities was performed at the analysis stage. To measure scanning efficiency, every fifth frame was scanned twice. A beam-track count was recorded every tenth frame. The above procedure produced approximately 16 000 measured candidates. The single-scan efficiency was determined to be 85%. No differential scanning efficiency for multiple vee events was included.

The measurements were processed with TVGP/SQUAW. A logical selection procedure was used to choose acceptable hypotheses for the events. After eliminating off-beam-track candidates, each event was required to pass a fiducial-volume test before any hypotheses were considered. The scanning efficiency, beam-track count, and fiducial-volume cut combine to give a sensitivity of (1.00 ± 0.02) μb/event for this exposure. The fiducial volume for the primary interaction vertex is defined as

$$-66 \text{ cm} \leq x \leq +27 \text{ cm},$$

$$-18 \text{ cm} \leq y \leq +18 \text{ cm},$$

$$+21 \text{ cm} \leq z \leq +45 \text{ cm},$$

where the origin of the coordinate system is centered approximately in the back of the chamber, the x axis is parallel to the length of the chamber in the beam direction, the z axis is toward the cameras, and the y axis is such that a right-handed coordinate system is formed.

The fiducial volume for the vee vertex is defined as follows:

$$-66 \text{ cm} \leq x_V \leq +51 \text{ cm},$$

$$-27 \text{ cm} \leq y_V \leq +27 \text{ cm},$$

$$+3 \text{ cm} \leq z_V \leq +75 \text{ cm}.$$

For events satisfying the above criteria, the zero-constraint electron-pair hypothesis of $\gamma d \to d e^+ e^-$ was accepted if the invariant mass of the electron pair was consistent with 10 MeV/c^2 or less and the recoil momentum of the deuteron was consistent with 10 MeV/c or less. If more than one production vertex satisfied the above criteria for an electron pair, the pair was rejected. This situation occurred for about 100 vees which were mostly very-low-energy pairs. If the electron-pair hypothesis was unacceptable, the three-constraint neutral decay hypothesis for K_S^0, Λ, or $\bar{\Lambda}$ was accepted if the confidence level of the fit was above 0.4%. If more than one hadron hypothesis satisfied the criterion, the Λ hypothesis was selected if present; otherwise, the kaon hypothesis was selected. About 300 events were in this ambiguous category. Only unambiguous $\bar{\Lambda}$ hypotheses were accepted. The above selection procedure was developed from several alternatives by comparing its choices from a subsample of events with physicists' output scan at the scan table. The procedure produced about 8300 accepted events.

Each vee was weighted to correct for scanning and decay losses. The usual weighting procedures were followed, requiring a minimum flight path of 1 cm for photons and 0.5 cm for hadron vees. The mean-free path for photons was determined from the pair production cross section[3] and the mean decay path for hadrons was determined from the known lifetimes. The average weight per vee is

γ: 24.6,

K_S^0: 1.11,

Λ: 1.16.

RESULTS

In order to classify events into neutron-target or proton-target categories, the definition of a spectator proton is taken to be a stopping proton with momentum less than 300 MeV/c. An even-pronged event with no spectator is designated protonlike (p-like), while an odd-pronged event or an even-pronged event which has a spectator as one of the prongs is designated neutronlike (n-like). Table I shows the raw numbers for each type of event observed in the two categories. The anomalous excess of p-like events and the distorted angular distribution of the spectators has been discussed elsewhere.[1] The flux factor,[4] which corrects for the Fermi motion of the target, is inadequate by at least a factor of 3, to explain the distortion in the angular distribution.

The separation of our data into p-n and p-p interactions is obscured by the possible complex initial- and final-state interactions.[1] To perform the separation completely, at least a description of the spectator interaction must be included. At the present time, such a description exists only in model-dependent calculations. Alternatively one might hope to isolate a "pure" sample of events by examining, for example, only events which have a backward (in lab) spectator. Elementary rescattering models would predict such a sample to be undistorted by interactions with the spectator nucleon. We have examined this sample and find it to have the same characteristics as the entire sample, although the statistics are poorer. In view of these uncertainties, we choose to present the data in the simplest model-independent form so that further analyses with a variety of models may use the data without prejudice.

Table II gives the single-particle inclusive cross sections, defined as the sum of products of the number of particles produced and the production cross sections. The π^0 inclusive cross section is obtained by dividing the γ inclusive cross section by 2. Using a total inelastic cross section[5] of 30 mb, we obtain the average number of π^0's per inelastic collision as 1.08 for n-like events and 1.61 for p-like events. Because of the final-state-in-

TABLE I. Numbers of events observed.

Observed neutrals	n-like	p-like
γ	2255	3279
$\gamma\gamma$	163	267
$\gamma\gamma\gamma$	6	13
$\gamma\gamma\gamma\gamma$	0	1
K_S^0	314	524
$K_S^0\gamma$	41	60
$K_S^0\gamma\gamma$	3	2
$K_S^0K_S^0$	15	21
$K_S^0K_S^0\gamma$	1	1
Λ	416	662
$\Lambda\gamma$	52	69
$\Lambda\gamma\gamma$	2	7
ΛK_S^0	37	72
$\Lambda K_S^0\gamma$	2	4
$\Lambda\Lambda$	6	4
$\Lambda\Lambda\gamma$	0	3
$\bar{\Lambda}$	5	3
$\bar{\Lambda}\gamma$	0	5
Total	3318	4997

TABLE II. Inclusive cross sections in mb. The quoted errors are statistical only.

	n-like	p-like
$\sum n_\gamma\sigma_\gamma$	64.7 ± 1.5	96.6 ± 1.9
$\sum n_{\pi^0}\sigma_{\pi^0}$	32.4 ± 0.8	48.3 ± 1.0
$\sum n_K\sigma_K$	1.39 ± 0.07	2.30 ± 0.09
$\sum n_\Lambda\sigma_\Lambda$	0.94 ± 0.04	1.49 ± 0.05

TABLE III. Semi-inclusive cross sections for K^0 and Λ production in μb.

	n-like	p-like
$\sigma(pd \to K^0X$(excluding Λ or other K^0))	860 ± 88	1482 ± 106
$\sigma(pd \to K^0K^0X$(excluding Λ))	176 ± 46	228 ± 49
$\sigma(pd \to K^0\Lambda X$(excluding other Λ or K^0))	224 ± 36	442 ± 52
$\sigma(pd \to \Lambda X$(excluding K^0 or other Λ))	695 ± 47	1035 ± 61
$\sigma(pd \to \Lambda\Lambda X$(excluding K^0))	18 ± 8	21 ± 8
$\sigma(pd \to \bar{\Lambda}X)$	9 ± 4	13 ± 5

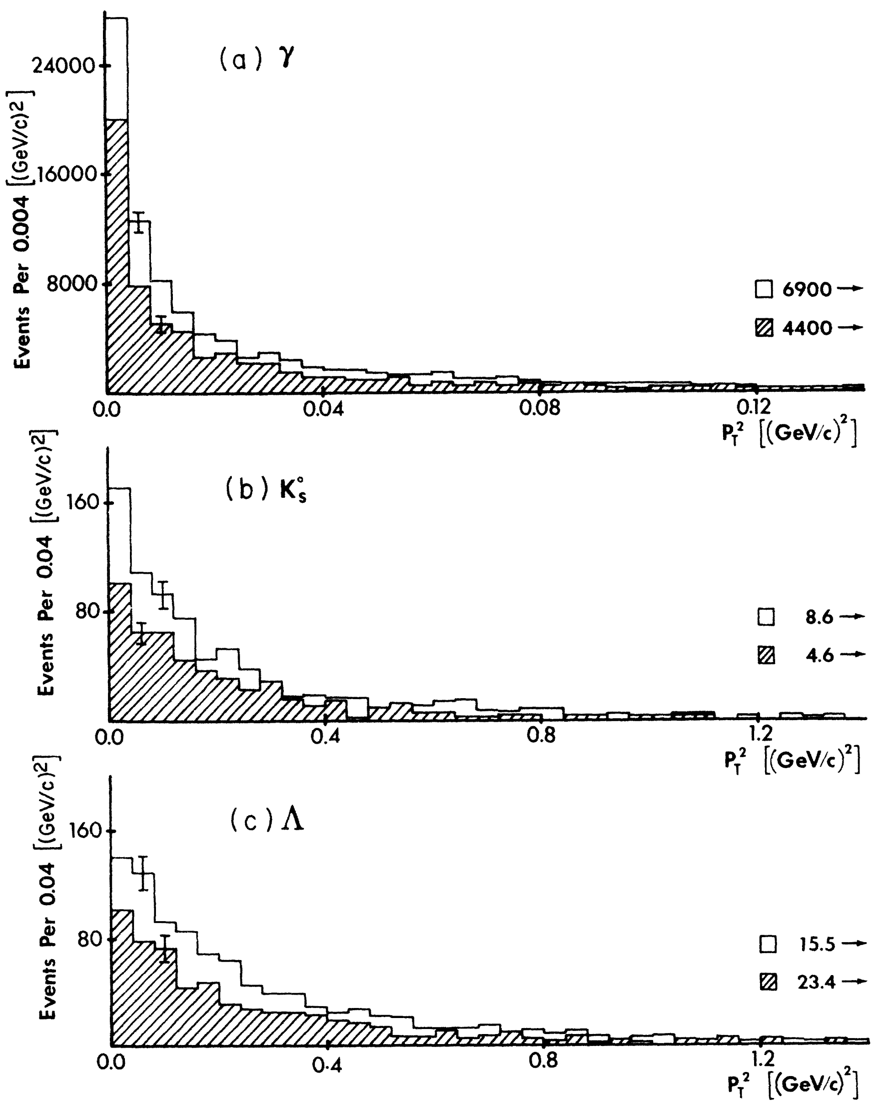

FIG. 1. Center-of-mass transverse-momentum-squared distributions for events associated with a visible (a) γ, (b) K_S^0; (c) Λ. The shaded distribution is for neutronlike events; the open distribution is for protonlike events. All distributions are corrected for geometrical losses. (The large numbers quoted for the γ events are due to the weighting procedure.)

teraction effects reported previously,[1] the neutron-target sample contaminates the proton-target sample; thus it is more meaningful to compute the mean of these two measurements of the average number of π^0's. This result is then in good agreement with 1.4 ± 0.1, the result for pp experiments near this energy.[6,7] In this table and for all other data presented, no distinction is made between K^0 and $\bar{K}^0$. Thus the symbol K^0 means either K^0 or $\bar{K}^0$. The data in Table II have been corrected both for neutral decay modes and for geometrical loss.

In evaluating the data for hadron vees (K^0, Λ), additional information can be obtained by extracting the cross sections for producing exactly one K^0, exactly one Λ, exactly two K^0's, exactly one K^0 and one Λ, and exactly two Λ's. We term these cross sections "semi-inclusive" since the K^0 and Λ content is specified exclusively while the remainder of the final state is unspecified and may contain $K^{\pm}$ and $\Sigma^{\pm}$ as well as all nonstrange hadrons. This extraction can be performed because all of the aforementioned combinations occur in

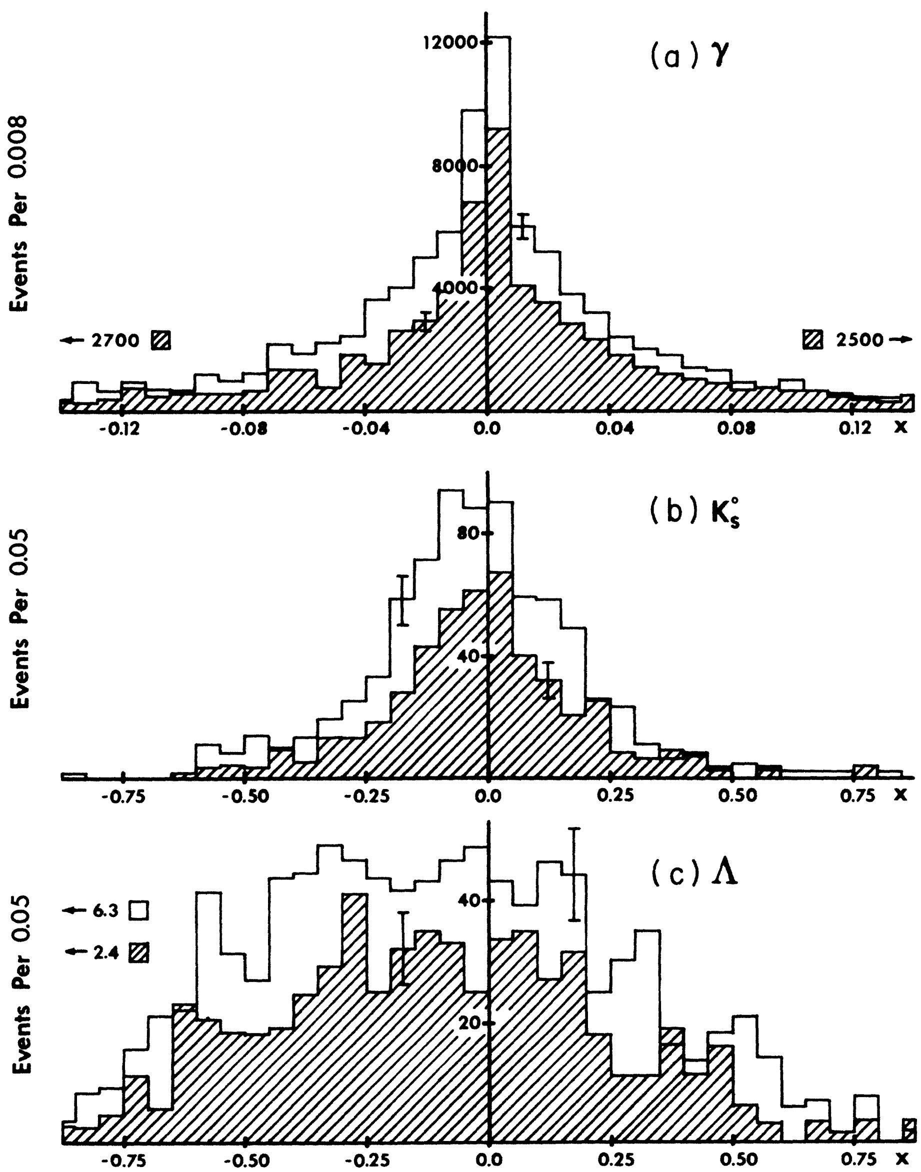

FIG. 2. Distribution of the Feynman variable $x = 2P_L^*/\sqrt{s}$, where P_L^* is the center-of-mass longitudinal momentum and s is the square of the total c.m. energy for (a) γ, (b) K_S^0; (c) Λ events. The shaded distribution is for neutronlike events; the open distribution is for protonlike events. All distributions are corrected for geometrical losses. (The large numbers quoted for the γ events are due to the weighting procedure.)

the data. Since no events are observed with a combination of three neutral strange hadrons, the production for such a final state is assumed to be negligible. Using the data, corrected for geometrical losses, and the known branching ratio for decay into charged particles, the semi-inclusive cross sections are calculated and are displayed in Table III. The $\bar{\Lambda}$ production cross section is included for completeness. As discussed above, the state X for each entry does not include either K^0 or Λ, although it may include $K^{\pm}$, etc. The presence of K^0 and/or Λ in the final state is exactly as stated.

The single-particle distributions of the square of the transverse momentum for γ, K^0, and Λ are displayed in Fig. 1. The transverse momentum is

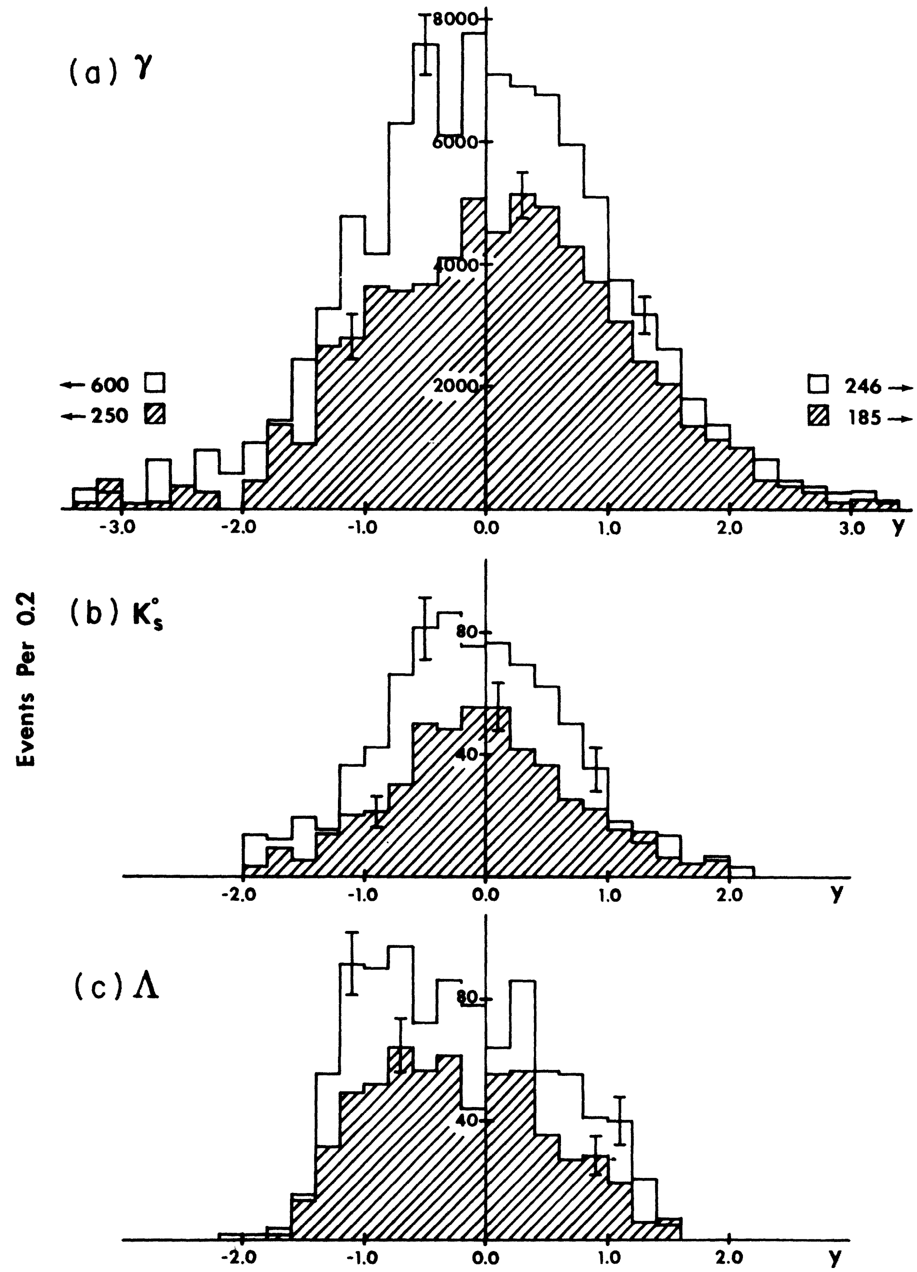

FIG. 3. Distribution of the rapidity $y = \frac{1}{2}\ln[(E^* + P_L^*)/(E^* - P_L^*)]$, where E^* and P_L^* are the center-of-mass energy and longitudinal momentum of the vee for (a) γ, (b) K_S^0, (c) Λ events. The shaded distribution is for neutronlike events; the open distribution is for protonlike events. All distributions are corrected for geometrical losses. (The large numbers quoted for the γ events are due to the weighting procedure.)

the component of the vee momentum perpendicular to the beam momentum. No branching-ratio correction is included for K^0 and Λ in this or any of the other figures. The excess of protonlike over neutronlike events is readily visible.

Figure 2 shows the distribution of the Feynman scaling variable $x = 2P_L^*/\sqrt{s}$, where P_L^* is the component of the vee momentum parallel to the beam in the center-of-mass system and s is the square of the total energy in the center of mass.

Figure 3 shows the distributions of the rapidity

$$y = \tfrac{1}{2}\ln[(E^* + P_L^*)/(E^* - P_L^*)],$$

where E^* is the energy of the vee and P_L^* is as before. These distributions are not symmetric about x or $y = 0$. This is particularly true of the Λ distributions. This effect can be explained as resulting from the final-state interaction discussed elsewhere.[1]

Figure 4 shows the distributions in the mass recoiling from the vee for γ, K^0, and Λ events. All mass distributions are featureless.

Figure 5 shows the multiplicity distributions. In these distributions n_{ch} is the number of prongs *not* including the spectator, if present. Thus the points with n_{ch} even are for protonlike events, and those with n_{ch} odd are for neutronlike events. Table IV presents the average charged-particle

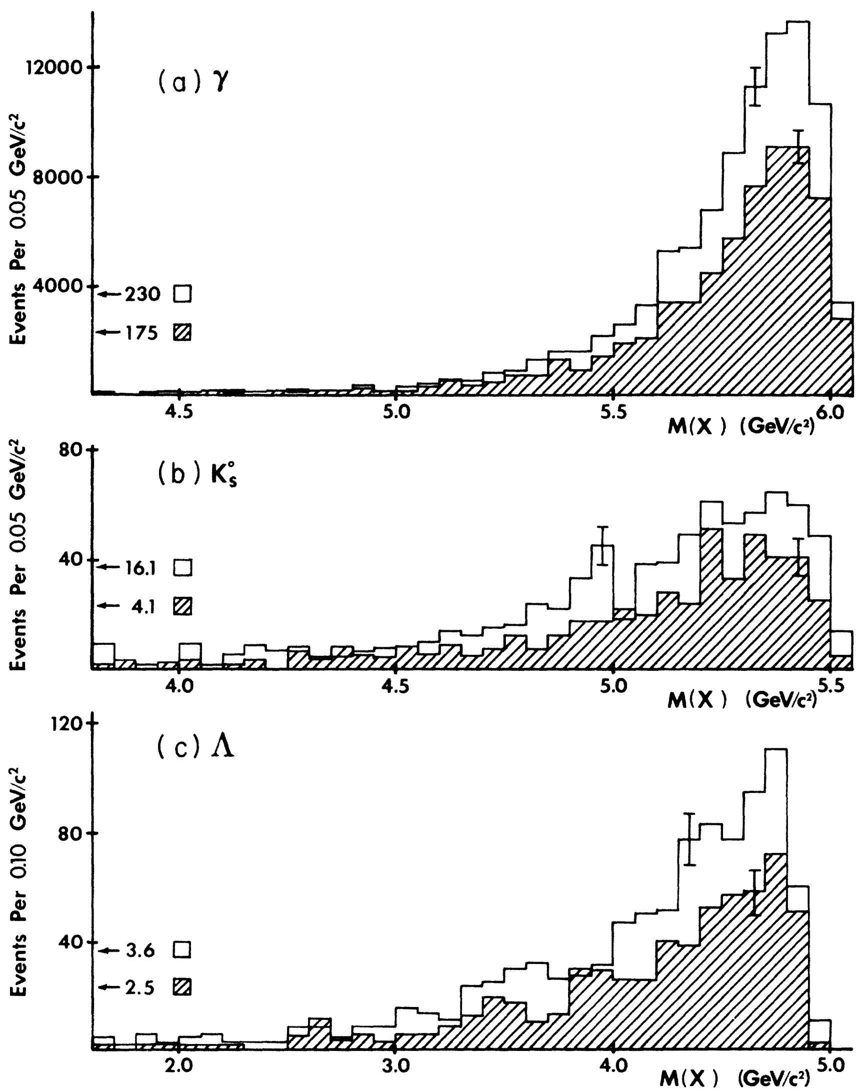

FIG. 4. Distribution of the mass recoiling from the vee for (a) γ, (b) K_S^0, (c) Λ events. The shaded distribution is for neutronlike events; the open distribution is for protonlike events. All distributions are corrected for geometrical losses. (The large numbers quoted for the γ events are due to the weighting procedure.)

TABLE IV. Multiplicity parameters.

	Observed neutral	Mean charged multiplicity $\langle n_{ch}\rangle$	Dispersion D	$\langle n_{ch}\rangle/D$
Neutron like	γ	3.98 ± 0.05	2.13 ± 0.04	1.87 ± 0.03
	K_S^0	3.73 ± 0.10	2.03 ± 0.11	1.84 ± 0.08
	Λ	3.69 ± 0.09	1.96 ± 0.08	1.88 ± 0.07
Proton like	γ	4.83 ± 0.04	2.20 ± 0.03	2.20 ± 0.03
	K_S^0	4.34 ± 0.08	1.99 ± 0.06	2.19 ± 0.06
	Λ	4.39 ± 0.07	1.98 ± 0.05	2.21 ± 0.05

multiplicity $\langle n_{ch}\rangle$ along with the dispersion D and the usual $\langle n_{ch}\rangle/D$ ratio[8] for all protonlike and neutronlike samples. It is interesting to note that the protonlike data fit very well onto the universal curve $D = 0.585\,(\langle n_{ch}\rangle - 1)$ discussed elsewhere,[8,9] whereas the neutronlike data do not behave according to this formula.

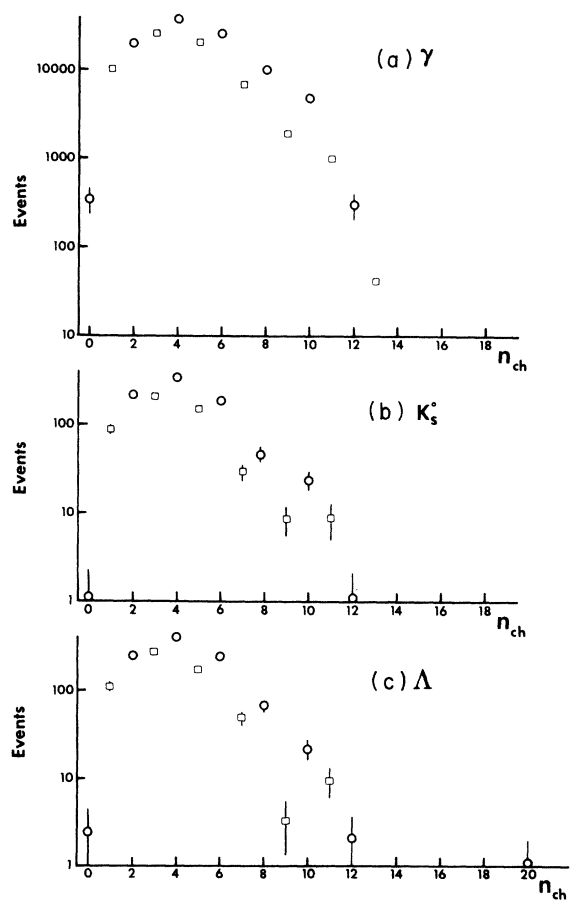

FIG. 5. Multiplicity distributions for (a) γ, (b) K_S^0; (c) Λ events. The circles are for protonlike events (n_{ch} even); the squares are for neutronlike events (n_{ch} odd). The spectator prong is not included in n_{ch}. All distributions are corrected for geometrical losses. (The large numbers quoted for the γ events are due to the weighting procedure.)

POLARIZATION

Table V shows the product of the Λ polarization and the Λ asymmetry parameter α computed separately for the neutronlike and protonlike samples as a function of the Λ transverse momentum P_T. The values were obtained from the up-down ratio of the decay proton relative to the Λ production plane. That is, $\alpha P = 2(U - D)/(U + D)$, where U and D represent the numbers of events with $\cos\xi > 0$ and < 0, respectively. The angle ξ is the angle between the decay proton and the normal to the production plane $\hat{n}$, where $\hat{n} = \hat{p} \times \hat{\Lambda}$ and $\hat{p}$ and $\hat{\Lambda}$ are unit vectors in the beam proton and Λ directions, respectively. Apart from two 2-standard-deviation effects in the low P_T region for the neutronlike events, the values of αP are all zero. This is interesting in the light of the recent evidence for high Λ polarization (> 0.15) at large values of P_T in the work of Bunce *et al.*[10] using 300-GeV/c protons on a beryllium target. It is interesting to note that if, for the neutron-target events, all events with P_T below 0.8 GeV/c are combined, one obtains $\alpha P = 0.25 \pm 0.09$. Taking into account the published value[11] for α of 0.647 ± 0.013, this gives a Λ polarization of 0.39 ± 0.14.

TABLE V. Λ polarization.

P_T (GeV/c)	$\alpha P(\Lambda)$ n-like	$\alpha P(\Lambda)$ p-like
0.0–0.4	0.26 ± 0.12	0.04 ± 0.10
0.4–0.8	0.24 ± 0.14	0.07 ± 0.10
0.8–1.2	0.12 ± 0.29	-0.02 ± 0.22
>1.2	0.12 ± 0.49	0.06 ± 0.58

ACKNOWLEDGMENTS

We are grateful for the efforts of the scanning and measuring staff at Vanderbilt University. In particular, we would like to thank the scanning supervisor, Anastasia Koshakji. It is a pleasure to acknowledge the contributions made by Dr. R. S. Panvini and Dr. A. Weinberg in the early phases of the experiment.

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*Work supported by the U. S. National Science Foundation under Grant Nos. GP-24451 and PHY73-08392.

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