matical tests.

The final results are given in Table I, which for comparison also contains the results of emulsion determinations by Birge et al., Alexander et al., and Taylor et al.

No clear example of a decay mode other than the six considered above was found, but it must be emphasized that no systematic search aimed specifically at the identification of rare modes has yet been completed.

We wish to express our appreciation to Dr. J. D. Van Putten and Dr. H. C. Bryant, and to the staff of the Bevatron for their invaluable help in the course of this experiment.

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INTERACTIONS OF LAMBDAS WITH PROTONS*

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In the course of an experiment to study the associated production processes,

$$\pi^- + p \to \Lambda + K^0 \quad (1)$$

and

$$\pi^- + p \to \Sigma^0 + K^0, \quad \Sigma^0 \to \Lambda + \gamma, \quad (2)$$

we have examined subsequent Λ interactions in hydrogen of the types

$$\Lambda + p \to \Lambda + p, \quad (3)$$

$$\Lambda + p \to \Sigma^0 + p, \quad (4)$$

$$\Lambda + p \to \Sigma^+ + n. \quad (5)$$

In this Letter we present results for reactions (3) and (4), based on a sample of 5000 Λ's produced in the Alvarez 72-in. hydrogen bubble chamber. [We postpone discussion of reaction (5) to a later publication.] In addition, we set an upper limit to the pion-producing reactions,

$$\Lambda + p \to \Lambda + p + \pi^0$$

and

$$\Lambda + p \to \Lambda + n + \pi^+. \quad (6)$$

The Λ "beam" momentum extends from 400 to 1000 Mev/c, and corresponds to the associated production processes (1) and (2) for incident π^-'s of 1035 Mev/c. The distribution of Λ momentum versus path length is shown in Fig. 1. It includes two cutoff corrections: (a) Single V^0 decays of K^0 or Λ (without subsequent scatter) are rejected if the neutral particle travels less than 0.5 cm before decaying; (b) only those Λ interactions that occur within 10 cm of the production point are accepted. Cutoff (a) serves to exclude spu-

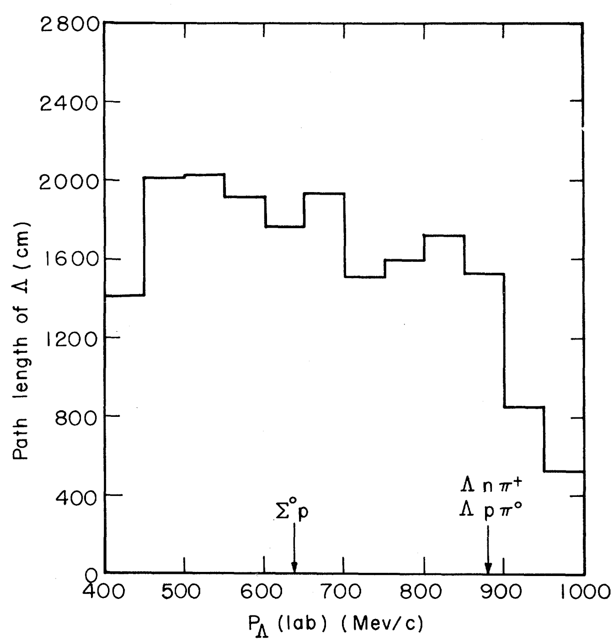

FIG. 1. Distribution of Λ path length versus momentum. The arrows indicate the thresholds for reactions (4) and (6).

rious V^0's due to two-prong events. Cutoff (b), while including most of the Λ path length before decay, serves to minimize the geometrical escape correction, and helps to exclude random background recoil protons from candidacy.

Lambda interactions that are followed by the charged decay $\Lambda \to p + \pi^-$ are detectable whether or not the associated K^0 undergoes charged decay. Interactions followed by the neutral decay $\Lambda \to n + \pi^0$ are also detectable and are used, provided that the K^0 decays via the charged mode. The kinematics and measuring errors are such that there is no difficulty in distinguishing between reactions (3) and (4).

Some of the interactions were found by scanners in the first scan. However, the main search for interactions consisted of (a) a systematic examination on the scanning table of all single and double V^0 events which failed to satisfy the kinematics for production via reactions (1) and (2), and (b) an examination on the scanning table of all single V^0 events where the decaying neutral is identified as a K^0. Here one looks for a recoil proton starting from the line of flight of the Λ.

Recoil protons of less than 0.5 cm are difficult to detect, and have been excluded. Our elastic-scattering cross section [Reaction (3)] therefore does not include small-angle scatters of the Λ. The excluded angular region depends on the momentum of the incident Λ, and is indicated by the shaded region in Fig. 2.

The correction to the integrated cross section depends on the shape of the angular distribution. The elastic-scattering cross sections include a cutoff correction for which uniformity in $\cos\theta_\Lambda$ (c.m.) and P_Λ (lab) is assumed. From Fig. 2 we see that, within the limited statistics, these assumptions are satisfied. The correction factor amounts to 1.074 for P_Λ(lab) from 400 to 638 Mev/c, and 1.028 for P_Λ(lab) above 638 Mev/c, the threshold for $\Sigma^0 - p$ production.

In the cases of the endothermic processes (4), (5), and (6), the proton range exceeds 0.5 cm for all production angles over the entire range of P_Λ(lab), so that there is no corresponding cutoff correction.

Details of the individual events are found in Table I. Figure 2 shows the laboratory momentum of the incident Λ and the c.m. angle of the final hyperon (relative to the incident Λ) for each event. Table II gives our cross-section results. The elastic-scattering cross section is given for the entire momentum interval, and separately for the intervals below and above 638 Mev/c, the threshold for reaction (4). The upper limit given for the pion-producing reaction (6) is the cross section that would correspond to finding a single event instead of the number (zero) actually found.

Our elastic-scattering cross section can be compared with the previous result of Crawford et al.,[1] obtained in substantially the same momentum interval. Based on four events, they found a cross section of 40 ± 20 mb, which is not in disagreement with our result of 22.3 ± 5.9 mb.

Information from study of hyperfragments has been used by Kovacs and Lichtenberg[2] to calculate the elastic-scattering cross section at 416 Mev/c (75 Mev) and at 598 Mev/c (150 Mev). They chose a phenomenological central potential with a hard core and considered only angular momenta of ≤ 2. Their calculated results are 26 and 21 mb at 416 and 598 Mev/c, respectively, when no spin-orbit term is included, and 34 and 32 mb

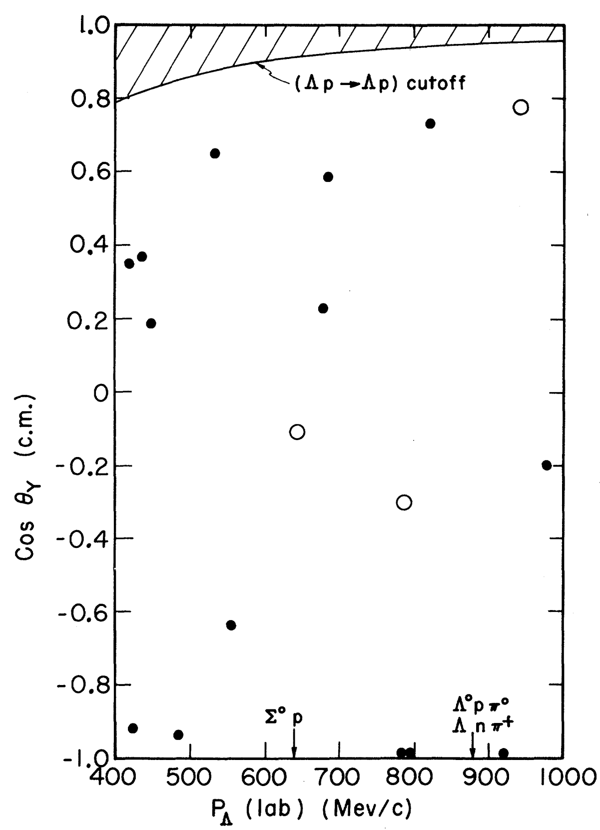

FIG. 2. Details of the interactions. Solid circles indicate elastic scattering events [reaction (3)]. Open circles represent Σ^0-p production [reaction (4)]. The shaded region corresponds to elastic scattering in which the recoil proton has a range of <5 mm.

Table I. Details of the interactions.

Frame	Initial lab momentum of Λ (Mev/c)	Center-of-mass momentum Initial	Center-of-mass momentum Final	$\cos\theta_Y$(c.m.)
		A. $\Lambda+p\to\Lambda+p$		
602 103	418	188	188	+0.35
722 504	421	189	189	-0.92
739 246	436	196	196	+0.37
865 515	447	200	200	+0.19
818 550	483	216	216	-0.94
586 135	532	236	236	+0.65
537 508	555	246	246	-0.64
834 420	678	297	297	+0.23
864 246	684	300	300	+0.58
814 534	787	341	341	-0.99
602 317	796	345	345	-0.99
857 282	822	355	355	+0.73
539 021	921	393	393	-0.99
724 478	977	413	413	-0.20
		B. $\Lambda+p\to\Sigma^0+p$		
861 205	646	284	42	-0.11
586 381	788	341	193	-0.30
692 127	943	401	285	+0.78

when spin-orbit interaction is included. Our measured value of 24.7 ± 9.3 mb for the interval 400 to 638 Mev/c is compatible with either calculated result. Thus we agree with the prediction from hyperfragment data, but cannot distinguish between the presence or absence of spin-orbit terms.

In the doublet approximation (DA),[3] the Σ-Λ mass difference is neglected and $\Sigma^{\pm,0}$ and Λ are combined into the two doublets,

$$N_2=[\Sigma^+,\ (\Lambda-\Sigma^0)/\sqrt{2}]\text{ and }N_3=[(\Lambda+\Sigma^0)/\sqrt{2},\ \Sigma^-].$$

Both N_2 and N_3 have the same coupling to the pion field. This pion coupling need not be the same as that of the nucleon doublet $N_1=[p,\ n]$. In addition, a new quantum number is introduced which prevents mixing of the doublets.[3] (For instance, $\Sigma^-+p\to\Sigma^++n+\pi^-$ is forbidden in DA.) The mass difference between N_2 or N_3 and the nucleon N_1 is not neglected.

One can then show that

$$2[\sigma(\Lambda p\to\Lambda p)+\sigma(\Lambda p\to\Sigma^0 p)]$$
$$=\sigma(\Sigma^+p\to\Sigma^+p)+\sigma(\Sigma^-p\to\Sigma^-p). \qquad (7)$$

Of course, Eq. (7) can only be valid at energies high enough that the actual Σ-Λ mass difference is negligible compared with the c.m. kinetic energy. For instance, Eq. (7) is certainly inapplicable below threshold for $\Lambda p\to\Sigma^0 p$. As a first approximation to a test of Eq. (7), we compare our results for the reactions on the left side of Eq. (7) to those of Stannard[4] for those on the right side. We consider the $\Lambda p\to\Lambda p$ cross section only

Table II. Summary of cross-section results.

Reaction	p_Λ(lab) (Mev/c)	No. of events	Λ path length (cm)	Cross section (mb)
$\Lambda+p\to\Lambda+p$	400-1000	14	18 770	22.3 ± 5.9
$\Lambda+p\to\Lambda+p$	400- 638	7	8700	24.7 ± 9.3
$\Lambda+p\to\Lambda+p$	638-1000	7	10 070	20.4 ± 7.7
$\Lambda+p\to\Sigma^0+p$	638-1000	3	10 070	8.5 ± 4.9
$\Lambda+p\to\begin{Bmatrix}\Lambda+p+\pi^0\\ \Lambda+n+\pi^+\end{Bmatrix}$	880-1000	0	1986	<14 ± 14

for P_Λ(lab) above 638 Mev/c, the threshold for reaction (4). Our range of total c.m. energy corresponds to a Σ-p c.m. momentum range of 0 (at threshold) to 314 Mev/c [for P_Λ(lab) of 1000]. Stannard's results correspond to a Σ-p c.m. momentum range of 0 to about 600 Mev/c.

We find

$$2[\sigma(\Lambda p \to \Lambda p) + \sigma(\Lambda p \to \Sigma^0 p)] = 57 \pm 18 \text{ mb.}$$

Stannard finds

$$\sigma(\Sigma^+ p \to \Sigma^+ p) + \sigma(\Sigma^- p \to \Sigma^- p) = 48 \pm 17 \text{ mb.}$$

Within the statistical errors, the prediction [Eq. (7)] of the doublet approximation is well satisfied.

In the theory of global symmetry (GS),[5] the assumption (in addition to those of DA) is made that the pion coupling of N_2 and N_3 is the same as that of the nucleon N_1, and the mass difference between N_2 or N_3 and N_1 is neglected. One can then predict N_1-N_2 or N_1-N_3 interactions from N_1-N_1 (nucleon-nucleon) interactions. de Swart and Dullemond have used potentials that fit available nucleon-nucleon scattering data, in linear combinations prescribed by GS, to predict cross sections for hyperon-nucleon interactions.[6] They take exactly into account the Σ-Λ mass difference in the kinematics (but neglect the Σ-nucleon mass difference). Their predictions for Λ-p elastic scattering and for Σ^0-p production [reaction (4)] are shown in Fig. 3, together with our experimental results. Within statistics, our cross sections agree with the predictions of GS.

de Swart and Dullemond also predict angular distributions for Λ-p elastic scattering at 475, 640, and 815 Mev/c. These momenta cover our range of P_Λ fairly well (see Fig. 1). With our limited statistics we can check at most a single parameter of the angular distribution. We examine our ratios for forward-to-backward scattering (F/B) and for polar-to-equatorial scattering (P/E). Since we see no strong momentum dependence in the elastic-scattering cross section, and since the predicted angular distributions do not vary drastically over our momentum range, we average with equal weight the theoretical predictions for F/B and P/E and compare them with our entire sample of 14 events.

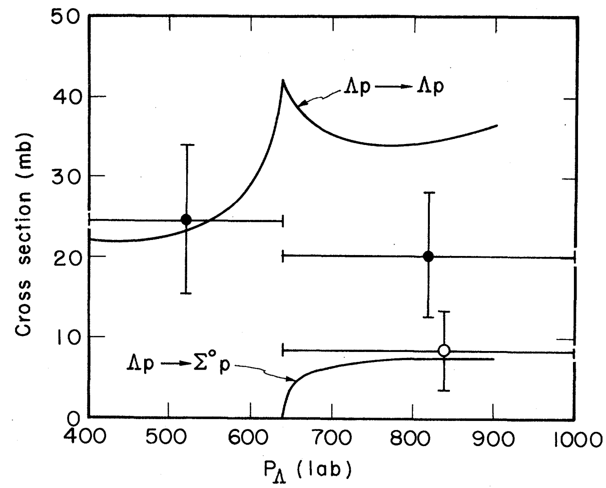

FIG. 3. Comparison of our experimental results with the predictions (based on global symmetry) of de Swart and Dullemond.[6] The upper curve and the solid circles represent elastic scattering. The lower curve and open circle correspond to Σ^0-p production.

For F/B we find 7/7 = 1.0 ± 0.5. The prediction of GS is 1.5.

For P/E we find 9/5 = 1.8 ± 1.0. The GS prediction is 2.0.

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