Search for a Λp Resonance

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The energy distribution of Λ's coming from K^- capture stars at rest has been obtained measuring Λ's found by area scanning in photographic emulsion. This distribution is compared to a theoretical one obtained with an optical-model calculation. The conversion process $(\Sigma N) \to \Lambda p$ plays an importqnt part in the final state of Λ production. Our results indicate that the conversion process is dominated by the (ΣN) triplet state and also that there is an enhancement in the Λp invariant-mass plot at about 2110 MeV with $\Gamma \simeq 20$ MeV.

I. INTRODUCTION

THE study of free hyperon-nucleon interactions is of the utmost importance in obtaining a complete picture of the baryon-baryon forces. But the short lifetime values of the hyperon prohibit the construction of conventional secondary beams as used in the study of pion, kaon, and nucleon interactions. Thus, because of the unavailability of rich hyperon beams, the study of Y-N final-state interactions may be useful in the search for strangeness -1, dibaryon resonant states.

In the analysis of K^- capture at rest with nuclear emulsions, we reported,[1] in 1963, with rather limited statistics, the possible existence of Λ-hyperon and proton (Λp) correlation at about 2100 MeV with a full width at half-maximum of about 20 MeV. Cohn *et al.*[2] also investigated the triton momentum spectrum in the capture reaction at rest for 93 events of $\Sigma^- + He^4 \to \Lambda + n + H^3$ with a sharp peak in the invariant mass of $(\Lambda n)^*$ at a value approximately the same as mentioned above. Oakes,[3] using the SU_3 symmetry scheme for the classification of dibaryon states, predicted the existence of a hyperon-nucleon $(Y=1)$ resonance state with the spin and parity of a deuteron, i.e., $J=1^+$ and with an isotopic doublet belonging to the multiplet $\overline{10}$. Using the mass formula,[4] Oakes estimated the mass of this resonance to be around 2130 MeV.

Further evidence for a ΣN strong interaction comes from Dahl *et al.*[5] from the study of K^- mesons stopping in deuterium. They find that the kinetic energy spectrum of the final-state pion in the reaction $K^- + d \to \Lambda + p + \pi^-$ shows two peaks, one at 147 and the other at 92 MeV. The higher peak has been interpreted as being caused by the K^- meson interacting directly with the neutron in the deuteron to produce a Λ and a π^-, while the proton remains as a spectator. The lower peak at 92 MeV corresponds to the expected energy if the K^- meson interacted directly with the nucleon to produce a Σ and a π^-, while the other nucleon was merely a spectator. Since the observed final state contains a Λ rather than a Σ, a two-step process is suggested in which the K^- is first absorbed by one of the nucleons to produce a Σ and a π^-, after which the rather low-energy Σ interacts with the other nucleon and converts into a Λ. Analyses[6] based on the above-suggested mechanism and the phenomenological models are in agreement with the data in this region of the pion energy spectrum. These calculations suggest that the conversion reaction $\Sigma N \to \Lambda N$ occurs primarily in the S state and is quite strong.

Recently, Cline *et al.*[7] have also observed the conversion process $\Sigma^+ n \to \Lambda p$ in the reaction $K^- d \to \pi^- \times (\Sigma^+ n) \to \pi^- (\Lambda p)$ at $p_K \simeq 400$ MeV/c. They filter out most of the events corresponding to the ^1S-state of the ΣN system by restricting their analysis to only those events which satisfy $\cos\theta_{K\pi} > 0.8$. Their data show the existence of an $I=\frac{1}{2}$, $J=1$, $l=0$, Λp resonance at 2125 MeV, with a width of less than 10 MeV.

On account of the importance of the ΛN interaction near the ΣN threshold, we extended our previous work[1] on the Λp resonance. The capture reaction of K^- mesons in heavier nuclei such as emulsion nuclei (C, N, O, Ag, and Br) are somewhat more favorable for the search for a Y-N resonance since the reaction may take place with two nucleons simultaneously. A two-nucleon capture may form a Σ-N bound state that in turn decays into Λ-N, yielding a peak in the Λ-N invariant mass distributions. When K^- mesons are captured at rest by emulsion nuclei, the different types of reactions which produce Λ hyperons are

(a) capture by a single nucleon (most of the energy is carried by the π^- meson),

$$K^- + N \to \Lambda + \pi \text{ (direct } \Lambda \text{ production)} \quad (1)$$

$$\to \Sigma + \pi \text{ } (\Sigma \text{ conversion, } \Sigma + N \to \Lambda + N); \quad (2)$$

(b) capture by two nucleons,

$$K^- + 2N \to \Lambda + N + (\pi) \text{ (direct production)} \quad (3)$$

$$\to \Sigma + N + (\pi) \text{ } (\Sigma \text{ conversion, } \Sigma + N \to \Lambda + N). \quad (4)$$

[1] P. L. Jain, post-deadline paper at the Spring Meeting of the American Physical Society in Washington, D. C., 1963 (unpublished).

[2] H. O. Cohn, K. H. Bhatt, and W. M. Bugg, Phys. Rev. Letters **13**, 668 (1964).

[3] R. J. Oakes, Phys. Rev. **131**, 2239 (1963).

[4] M. Gell-Mann, Phys. Rev. **125**, 1067 (1962); S. Okubo, University of Rochester Report (unpublished).

[5] O. I. Dahl, N. Horwitz, D. H. Miller, J. J. Mruray, and P. G. White, Phys. Rev. Letters **6**, 142 (1961); W. Gibbs, B. P. Roe, D. Sinclair, and J. C. Vander Velde, Bull. Am. Phys. Soc. **11**, 358 (1966). They found the resonance at 2100 MeV.

[6] R. Karplus and L. Radberg, Phys. Rev. **115**, 1058 (1959); T. Kotani and M. Ross, Nuovo Cimento **14**, 1282 (1959); A. Fujii and R. E. Marshak, *ibid.* **8**, 643 (1958); T. Kotani and M. Ross, *ibid.* **14**, 1282 (1959); Y. Y. Chen, *ibid.* **19**, 36 (1961); R. Chand, *ibid.* **31**, 1013 (1964); **57**, 413 (1968).

[7] D. Cline, R. Laumann, and J. Mapp, Phys. Rev. Letters **20**, 1452 (1968).

It has been pointed out[8] earlier that Σ conversion ($\Sigma N \rightarrow \Lambda N$) plays a very substantial role in the final state of Λ production and the conversion cross section in nuclear matter[9] seems to point to a value large compared to the geometric cross section. For the analysis here, we have applied a direct method consisting in first collecting a sample of Λ hyperons and then searching along their line of flight for their origins in K^- absorption in emulsion nuclei.

II. EXPERIMENTAL PROCEDURE

For our analysis, we used two large stacks of nuclear emulsion exposed to 450- and 435-MeV/c K^- mesons stopping in nuclear pellicles at the Bevatron. In order to measure the space distribution of K^- interactions at rest in nuclear emulsions, five different plates were area-scanned for K^- capture stars. Thus the scanning was done in the same area as the rest of the pellicles where there was a concentration of kaon tracks.

A. Scanning Procedure

In both the stacks, the events corresponding to Λ-hyperon decays were located by area-scanning the region with maximum K^- stopping density. The following criteria were used in the identification of Λ-like events:

(i) The vertex of the two-pronged event must be clean, i.e., characterized by the absence of any Auger electron grain or blob, indicative of an interaction.

(ii) An increase in grain density of both tracks must be observed as each is followed outward from the origin, except for a short dark track, in which it is not generally possible to detect such a change.

(iii) Both the tracks must have the proper terminal behavior for the supposed identities (i.e., pion and proton). We found about 175 Λ-like events in both the stacks in a scanned volume of about 225 cm^3. The two prongs of the event were then followed until they came to rest, and their ranges were carefully measured; when they interacted or left the stack, their velocities were derived from ionization measurements.

B. Range Measurements

All range measurements were performed on microscopes equipped with 10$\times$ oculars and 53$\times$ oil-immersion objectives. Because of multiple scattering, the true range of a particle cannot be measured; it is rather approximated by a series of straight-line segments whose end points are chosen according to the convention used in establishing the range-energy relation; i.e., a new segment was started whenever the track had changed direction by an amount $\geqslant 5°$. Such a rectification of the path of the particle results in a measured range in error less than 0.1% of the true range, and introduces no error in the determination of the particle energy, this energy being found from the range-energy relation. Since the range-energy relation is established for emulsion with the standard density 3.815 g/cm^3, a correction must be applied to ranges measured in emulsion of a different density. The range corrections in the first and the second stack are of the order of 0.20 and 0.40% for proton and 0.24 and 0.5% for pion, respectively. The energies corresponding to the corrected ranges are obtained from the range-energy relation for protons in emulsion of standard density.[10] The statistical errors present in the range measurements are (i) measurement errors, which were calculated from repeated measurements of pions and protons, and (ii) range straggling, which has been evaluated by Barkas *et al.*[11] as a function of velocity. Various systematic errors are inherent in the range calculations, primary among these being the errors in measured emulsion density and in shrinkage factors. The fractional errors in the range arising from the uncertainty in emulsion density can be found by using the relation $\Delta R/R = K(\rho_m/\rho_s)(\Delta\rho_m/\rho_m)$, where K is the percent range decrease per percent density increase, ρ_s is the standard density, ρ_m is the measured density, and $\Delta\rho_m$ is the error in ρ_m. K is of the order of 0.8 for typical secondary ranges encountered in moderate-energy Λ decays. We may point out that the uncertainty in density, though small, is reflected almost directly into a range uncertainty of the same order of magnitude. In general, an uncertainty in the shrinkage factor (S) produces a range error more difficult to evaluate since the magnitude of the error is dependent upon the geometry of the track, i.e., the larger the Z component of the range, the greater this error. The error in S is reflected into the range according to the formula $\Delta R/R = (\Delta S/S) \times \sin^2\delta$, where δ is the angle of inclination in unprocessed emulsion measured with respect to the emulsion surface. The shrinkage-factor uncertainty in shrinkage was estimated to be about 1% in both the stacks.

As far as the space angle is concerned, its only systematic error has its origin in the shrinkage-factor error of $\pm 1\%$, which introduces a systematic error in dip-angle measurements. We may point out that the effects of emulsion distortion were negligible in both the stacks. The $\langle Q \rangle$ value from the distribution of our Λ-like events was found to be 37.6 MeV.

C. Correlation between Λ and K^-

For each of the Λ events, the direction of its flight was computed in space with respect to the coordinate system of the grid marked at the bottom of each pellicle. The path length ($l_p = \gamma\beta c\tau$ with $\tau = 2.5\times 10^{-10}$ sec) was also calculated. In order to correlate a Λ to its K^--

[8] J. W. Patrick and P. L. Jain, Nucl. Phys. **73**, 681 (1965). The contribution of $\Sigma^0 \rightarrow \Lambda + \gamma$ has been neglected since near the c.m. energy of 1500 MeV, the cross section for $K^- n \rightarrow \Sigma^0 \pi^-$ is small as compared with $K^- p \rightarrow \Sigma^\mp \pi^\pm$ [see M. B. Watson, M. Ferro-Luzzi, and R. D. Tripp, Phys. Rev. **131**, 2248 (1963)].

[9] T. Bowen, J. Hardy, Jr., G. T. Reynolds, C. R. Sun, G. Tagliaggerri, and A. E. Werbrouck, Phys. Rev. **119**, 2030 (1960).

[10] W. H. Barkas, Nuovo Cimento **8**, 201 (1958).

[11] W. H. Barkas, F. M. Smith, and W. Birnbaum, Phys. Rev. **98**, 605 (1955).

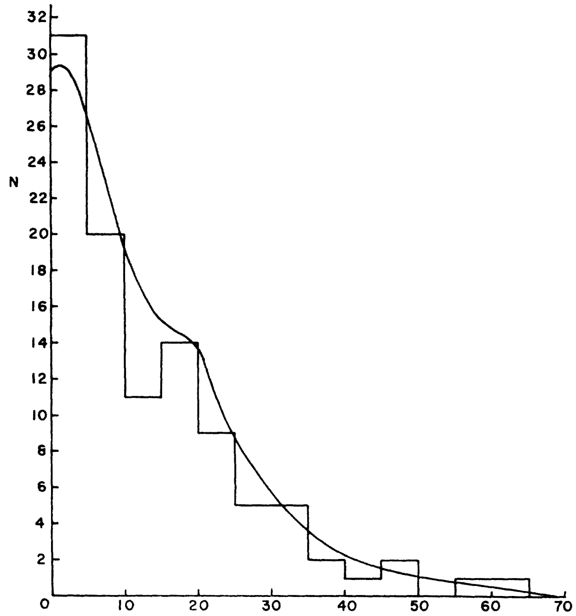

FIG. 1. Energy distribution of Λ events from both the stacks. The curve gives the calculated distribution by taking into account the scanned volume and the scanning efficiency effects for $2N$ reactions ~15%.

capture origin, a scan for stopping-K^- tracks was done along its line of flight. The tracing was done from pellicle to pellicle for the possible decay length. The uncertainty in the determination of the Λ direction, due to measurement errors, was taken to be $d_1 = 1°$ in the emulsion plane and $d_2 = 2°$ in dip. In very few cases, more than one K^--capture star corresponding to a particular Λ was found, and the star closest to the line of flight was selected so that there was no ambiguity in the choice of the K^- star with only one K^- capture in the cone of flight. Whenever possible, the coplanarity of the Λ hyperon with the K^--meson interaction was tested. The momentum components of the proton and the π^- meson perpendicular to the line joining the K^--meson interaction with the point of decay of the Λ hyperon were calculated and, if they were found to be equal within the experimental error, the Λ hyperon was taken to be associated. The selected K^--capture star in the allowed cone was then carefully analyzed. The energy of evaporation tracks was deduced from range measurements. Fast prongs were followed till they came to an end or left the stack. Under the above-mentioned criteria, we present, in Sec. III, the analysis of 105 Λ selected events out of a total of 175 Λ-like events.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In order to get an energy spectrum of the Λ particle produced when K's are captured at rest by emulsion nuclei, one must take into consideration the detection biases. The scanning efficiency for two-prong stars in emulsion is in most cases rather low. The energy distribution of these observed Λ events is shown in Fig. 1. In order to calculate the theoretical curve for the energy distribution of Λ hyperons emitted from emulsion nuclei when K^- mesons are captured at rest, one can consider it as a superposition of distributions corresponding to different Λ-producing channels from Eqs. (1)–(4). We made use of an optical model[12] and computed the energy distribution of Λ and Σ directly produced in K^- capture. From the Σ distribution we obtained the spectrum for Λ's which originated from the processes shown in Eqs. (2) and (4). In the calculations of the energy spectrum, the following assumptions were made: (i) The angular distribution of the Σ-emission direction relative to the proton direction is isotropic in the K^--p c.m. system. (ii) The sum of the internal momenta of Σ and pion is equal to the internal-momentum distribution of the protons in the nucleus and is taken to be Gaussian, i.e.,

$$f(b)dp = (4\pi^{-1/2}P_0^{-3})p^2 e^{-p^2/p_0^2},$$

where $f(b)dp$ represents the probability that the magnitude of the proton's momentum p is in the range dp. The constant p_0 is chosen so that $p_0^2/2M_p = 15$ MeV. It

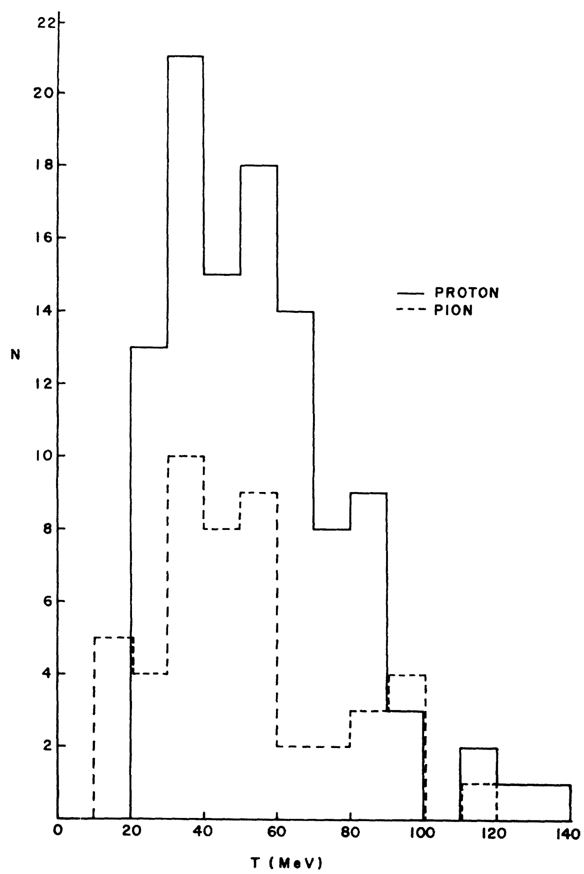

FIG. 2. Energy distribution of fast protons, $T_p \geq 28$ MeV, (solid line) and of charged pions (dashed line) emitted from a common Λ origin.

[12] R. Chapps, Phys. Rev. 107, 239 (1957).

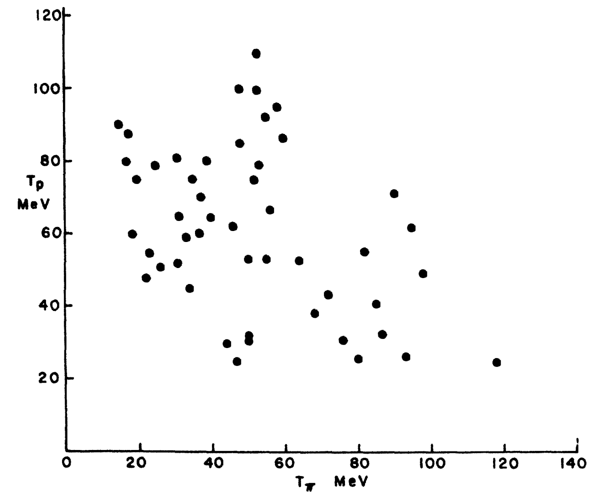

FIG. 3. Distribution of proton and pion kinetic energies.

is assumed that the probability for K^- capture is independent of proton momentum in this range. (iii) The values of the nuclear parameters used in the optical calculation corresponding to Λ-nuclear, Σ-nuclear, and π-nuclear potentials were 15, 15, and 35 MeV, respectively. The binding energy of the last proton together with the excitation energy value used was 20 MeV for a single-nucleon system and 40 MeV for a two-nucleon system. The conversion ratio ($\Sigma \rightarrow N$/all Σ's) was taken as 0.5 and the contribution of $2N$ reactions was assumed to be $\sim 15\%$.

The efficiency curve for both of the stacks were drawn as a function of Λ energy, for which one would need to compare, for each energy interval, an expected number of events having certain characteristics (angle, ionization, etc.) with the number actually observed. The scanning efficiency was also corrected for the finite volume used in the stacks. The calculated Λ energy distribution curve was then multiplied by the efficiency curve for two-pronged stars in emulsion and is shown in Fig. 1.

In 48 out of 105 such (Λp) stars, a charged-pion track was also present along with the track of a high-energy[13] proton, i.e., $E_p \gtrsim 28$ MeV. The efficiency for π detection was estimated to be nearly one. All of the pions were followed until they interacted, came to rest, or left the stack. Their spectrum is shown in Fig. 2; mostly, they are all produced in a single nucleon capture. In 18 cases, the pion came to rest in emulsion, so that its charge could be determined. The ratio of π^- to π^+ was $\simeq 6:1$. Only five events have momentum greater than 85 MeV, which is the largest value expected for the energy of a π emitted together with a Σ in a one-nucleon reaction. It has been already pointed out[8] that the probability for the emission of a Λ does not depend strongly on the weight of the nucleus in which the K^- was abosrbed, and also in about 75% of the cases of one-nucleon capture in nuclear emulsion, the Λ hyperon is presumably produced through the Σ-conversion reaction [Eq. (2)]. In such cases, an energetic nucleon ($E_p \gtrsim 28$ MeV) is also produced along with π^- meson. From a one-nucleon reaction followed by Σ conversion, one expects, in general, that the total energy of the fast proton will be less than 60 MeV. The Fermi motion of the nucleon, however, complicates the picture. In Fig. 2 is also shown the proton spectrum for these events produced at the kaon capture vertex. About 16 events with protons have energies >80 MeV, and these were produced mostly in two-nucleon reactions. The frequency of the two-nucleon reaction producing an energetic π meson is relatively very small. In most cases where a K^- is absorbed by a free nucleon, i.e., when there is no evidence

[13] This was done to separate out the proton tracks which were produced through the evaporation process.

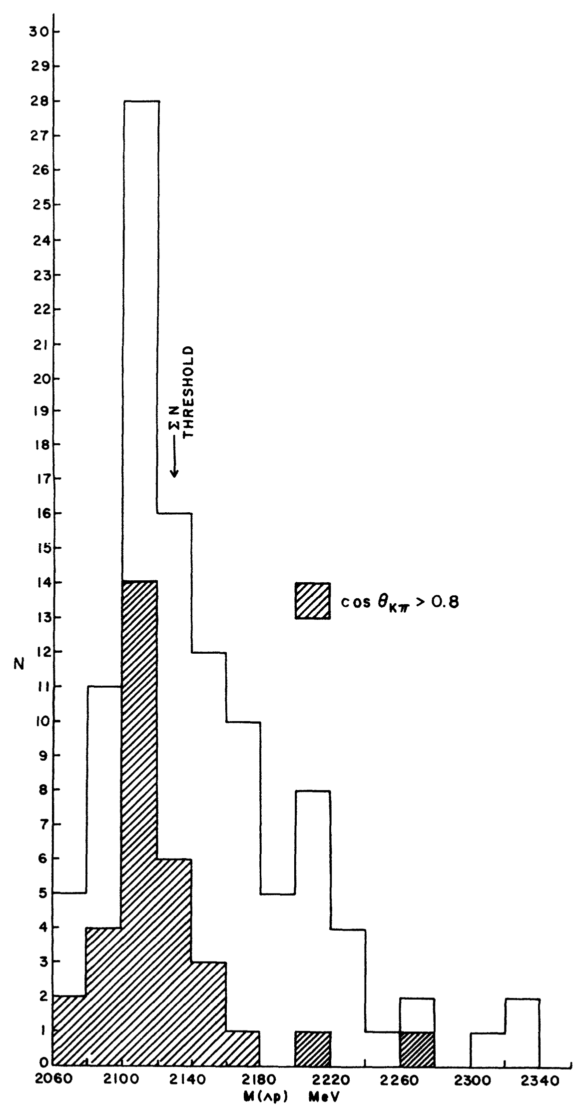

FIG. 4. Λp invariant-mass spectrum for reaction Eqs. (2) and (4). The dashed spectrum is for events with $\cos\theta_{K\pi} > 0.8$, where $\theta_{K\pi}$ is the angle between the incident K and the outgoing π in the K^-N c.m. system.

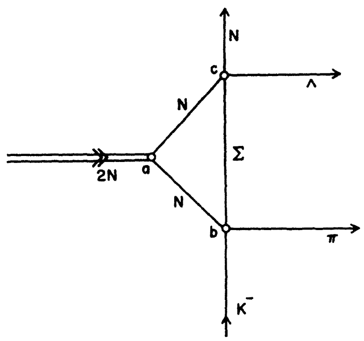

FIG. 5. Triangle diagram for the reactions shown by Eqs. (2) and (4) for a Λp final state above 2100 MeV.

of a recoil, a "blob", or an Augur electron, the angle between a hyperon and pion is peaked at large angles; also, it is conceivable that a reaction with a complex nucleus could satisfy these criteria, particularly if the K^- meson is captured by a peripheral nucleon. The production directions of the pion in most of the cases is peaked at large angles, just like the pion angle in the $\Sigma\pi$ rest system for the $K^-N\to\Sigma\pi$ intermediate state. The angular distribution of the Λp relative momentum is isotropic (within our statistics) with respect to the direction of the recoil pion (for 48 $\Lambda p\pi$ events) and for such a distribution, the frequency of events along lines of constT_π (when plotted against the related proton energy spectra) is almost independent of T_p, as shown in Fig. 3. This further supports our previous statement that the conversion ($\Sigma N\to\Lambda N$) occurs predominantly in the ΣN S-wave system.

In Fig. 4, the Λp invariant-mass spectrum for all events, with and without pion, is shown. A strong enhancement near ΣN threshold is evident and has also been observed by other authors.[2,5,7] Following the arguments given by Cline *et al.*,[7] we see that for $\cos\theta_{K\pi}=0.4-0.7$, the intermediate ΣN state will be in a mixed $^3S_1$ and $^1S_0$ state. In order to separate out most of the events corresponding to the ^1S state of the ΣN system, we restrict the analysis to production in angles with $\cos\theta_{K\pi}>0.8$. There are only 48 events which have charged pions along with ΛP at their vertices. The shaded area of Fig. 4 shows the Λp mass spectrum for which the ΣN system is expected to be predominantly in the $^3S_1$ state ($\cos\theta_{K\pi}>0.8$, the same as the deuteron state). There are a number of events with π^0 production which have their (Λp) invariant mass value under the main peak of 2110 MeV. The requirement of a forward-going π^- in the KN c.m. system considerably enhances the strong Λp peak near 2110 MeV. The majority of events in the peak region are produced by the internal conversion process, and below the Λp mass of 2100 MeV this process probably does not play an important role.

In Fig. 5 is shown a diagrametric representation of processes characterized by Eqs. (2) and (4). The amplitude for the triangle diagram can be written under the general assumption that all virtual particles are nonrelativistic, while the initial and final particles may have arbitrary energies. Thus the amplitude for Fig. 5 is given by[14]

$$A_\Delta=A_0A_aA_bA_c,$$

where A_a, A_b, and A_c represent the amplitudes for the transitions a ($2N\to NN$), b ($KN\to\Sigma\pi$), and c ($\Sigma N\to\Lambda N$). A_0 represents the effects of various kinematic factors, and is expected to have a variety of kinematic singularities. The basic assumptions in this analysis are (i) that there is a conservation of four-momentum of all particles at each vertex of the graph, (ii) that the vertex-b process is identical to the scattering process of reaction Eq. (2), and (iii) that the polarization and the spin-flip probability for the intermediate state Σ is described by the known amplitudes for reaction Eq. (2). The nature of the process at vertex a suggests that the nucleon will be predominantly of low momentum and also not far from the mass shell; this leads to the expectation that the reaction at vertex b will be dominantly at the same c.m. energy as that for collisions with free nucleons. The production direction of the pion in most of the cases has been observed to follow the pion angle in the $\Sigma\pi$ system for the intermediate state. Furthermore we may also look at the forward-backward ratio, i.e., $(F-B)/(F+B)\simeq0.08\pm0.02$, and the polar-equatiorial ratio, i.e., $(P-E)/(P+E)\simeq0.18\pm0.06$, where F and B refer to the number of forward and backward Λ's in the rest system and P and E refer to the number of events having $|\cos(\theta_\Lambda)|>0.5$ and $|\cos\theta_\Lambda)|<0.5$, respectively, θ_Λ being the angle in the ΛP c.m. system between Λ and the line of flight of the Λp system. For the Λ angular distribution in the Λp c.m. system, it appears that, for our limited statistics, the angular distribution is nearly isotropic near 2110 MeV, while above and below the enhancement value, the angular distribution deviates from an isotropy. This is further evidence that the process $\Sigma N\to\Lambda p$ is being observed in this experiment and that near ΣN threshold the orbital angular momentum state is primarily $l=0$.

In conclusion, the results presented here are strong evidence[15] that the ΣN conversion process is dominated by the triplet state, and they also show the existence of an $I=\frac{1}{2}$, $J=1$, $l=0$, Λp possible resonance[1-3,7] at 2110 MeV with $\Gamma\simeq20$ MeV.

We thank the late Professor W. H. Barkas for the loan of an emulsion stack. We also thank Dr. R. Chand for an interesting discussion.

[14] L. D. Landau, Nucl. Phys. **15**, 261 (1960); I. S. Shapiro, *Interaction of High Energy Particles with Nuclei* (Academic Press Inc., New York, 1967), p. 245.

[15] That the ΣN system may have a bound state for $I=\frac{1}{2}$ is consistent with observations of low-energy Σ^-p scattering [see R. A. Burnstein, University of Maryland Technical Report No. 469, 1965 (unpublished)].