ON THE POSSIBLE SCHEME OF PRODUCTION OF Λ HYPERONS VIA ISOBARS IN π^-p-*INTERACTION AT* 7–8 BeV

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The momentum-distribution grouping of Λ hyperons found in Dubna[1] is satisfactorily explained by assuming that the Λ hyperons are the decay products (via strong interaction) of hyperon and nucleon isobars, including $N_3^* \rightarrow \Lambda + K$[4]. A kinematic analysis of the Λ hyperons is made under the assumption that the transverse momentum of the isobars formed in π^-p-interactions is small. The results of the kinematic analysis agree well with the experimental data. The relative probabilities of the corresponding Λ-hyperon production channels are estimated. The experimental data provide some indication that the π^-p interactions with production of strange particles occur with appreciable probability as two-particle reactions, the products of which may be isobars.

1. INTRODUCTION

PROPANE bubble-chamber experiments performed in Dubna[6] have shown that the momentum distribution of the Λ hyperons produced by 7–8 BeV π^- mesons on protons has two maxima. It was also shown that all the indicated hyperons can be divided, in accordance with several kinematic characteristics, into two groups. This corresponds, in the opinion of the authors of these experiments, to two types of π^-p interactions, which they arbitrarily called central and peripheral. The aggregate of the kinematic characteristics of the Λ hyperons of both groups do not agree with the statistical theory, and the authors are inclined to seek an explanation within the framework of the one-meson approximations, with allowance for Kπ resonance. Later on the "double hump" character of the momentum distribution was observed also for Λ hyperons produced on protons by 16-BeV π^- mesons[2]. We describe here an analysis of the material obtained in [1], carried out on the basis of kinematics brought about by the so-called isobar model.

As is well known, from the point of view of the isobar model the interaction between a nucleon and other particles occurs in two stages: first the nucleon becomes "excited," forms an isobar, and then, emitting a π or K meson, the isobar goes over to a lower level. Our analysis is based upon the assumption that along with the π and K mesons there can be emitted also meson isobars, many of which have been observed in recent years. Using the presently known data on the resonant states of such systems as the π or K meson plus nucleon or π meson plus hyperon, and regarding them as excited states of nucleons[3] and hyperons, we can construct a system of excited baryon levels (baryon isobars) and determine, on the basis of the conservation laws, the possible transitions between them.

All these considerations have been described and discussed by us in detail in [4], where a specific scheme was presented along with a table of the possible levels and transitions.

2. KINEMATICS OF Λ HYPERONS PRODUCED VIA ISOBARS[1)]

Let us consider the reaction

$$\pi^- + p \rightarrow A + B, \qquad (1)$$

where A is the Λ hyperon or isobar which gives rise to Λ hyperons, and B is the aggregate of all the remaining particles. The process of isobar production is characterized completely by the Lorentz factor γ_c of the π^-p center of mass system (c.m.s.), by the mass m_A and the transverse momentum q of the isobar A, and by the so-called coefficient of elasticity η of the interaction. If $\frac{1}{2}(m_\pi/m_p\gamma_c)^2 \ll 1$, the coefficient η takes the form

1)The derivations of the kinematic relations employed here will be published separately.

$$\eta = \frac{E^c_A}{E^c_p} \sim \frac{1}{2}\left\{1 + \beta_c + \frac{m^2_A - m^2_B}{(m_p\gamma_c)^2(1+\beta_c)}\right\}. \quad (2)$$

Here E^c_A and E^c_p are the total energies of the isobar A and of the proton in the π^-p c.m.s., and β_c is the velocity of this system. The reduced mass of the aggregate of the particles is

$$m_B = \frac{1}{\gamma^c_B}\sum m_i\gamma^c_i,$$

where γ^c_B and γ^c_i are the Lorentz factors of the aggregate of the particles B and the particles contained therein, in the π^-p c.m.s.

If the particles contained in the aggregate B are not interconnected, then m_B and consequently η can assume a variety of values. For simplicity we assume in the calculations that B is either a meson or a meson isobar. In this case m_B and η assume perfectly defined values.

The isobar A can decay in accordance with either a simple or a cascade scheme:

$$A \to \Lambda + b, \quad (3)$$

$$A \to \alpha + \beta \to \Lambda + b. \quad (4)$$

In the π^-p c.m.s. we have the following relation between the momentum p^c_Λ of the Λ hyperon and its angle of emission θ^c_Λ:

$$\cos(\theta^c_\Lambda - \delta) = T_c E^c_\Lambda / p^c_\Lambda - W_c / p^c_\Lambda, \quad (5)$$

where T_c and W_c are coefficients that depend on η and q and are constant for each specific process; δ is the phase shift, proportional to the transverse momentum of the isobar A.

Formula (5), with different values of η and m_B, was used to calculate and plot kinematic curves for the following processes from the scheme and table of [4]:

$$\pi^- + p \to N^*_3(1688) + B^0_0,\quad N^*_3 \to \Lambda + K, \quad (1\Lambda)$$

$$\pi^- + p \to \Lambda + B^0_{+1}, \quad (2\Lambda)$$

$$\pi^- + p \to Y^*_1(1385) + B^0_{+1},\quad Y^*_1 \to \Lambda + \pi, \quad (3\Lambda)$$

$$\pi^- + p \to N^*_4(1922) + B^0_0,\quad N^*_4 \to N^*_3(1688) + \pi,\quad N^*_3 \to \Lambda + K, \quad (4\Lambda)$$

$$\pi^- + p \to N^*_4(1922) + B^0_0,\quad N^*_4 \to Y^*_1(1385) + K,\quad Y^*_1 \to \Lambda + \pi, \quad (5\Lambda)$$

$$\pi^- + p \to N^*_4(1922) + B^0_0,\quad N^*_4 \to \Sigma^0 + K,\quad \Sigma^0 \to \Lambda + \gamma, \quad (6\Lambda)$$

$$\pi^- + p \to Y^*_0(1815) + B^0_{+1},\quad Y^*_0 \to Y^*_1(1385) + \pi,\quad Y^*_1 \to \Lambda + \pi. \quad (7\Lambda)$$

The indices n and S correspond here to the baryon number and the strangeness of the meson or isobar B^n_S. Only known mesons or isobars for which n and S ensured the conservation laws in each given reaction were used. This governed the choice of the values of m_B and consequently η. In some cases we used, for comparison, the values of m_B which did not correspond to known isobars. The calculations were carried out for the values of m_B and η listed in Table I.

In all the listed processes, the specified values of the transverse momentum were 0, 0.3, 0.5 BeV/c. It was assumed here that the isobar A moves in the rear hemisphere, since, as is well known, the direction of motion of the baryon following the interaction remains essentially the same as prior to the interaction. For the Λ hyperons that result from the cascade decay of the isobars, an additional parameter was introduced, cos Ψ, where Ψ is the

Table I

Process	m_B, BeV	η	Process	m_B, BeV	η
(1 Λ)	~0.7	1.10	(3 Λ)	~0.5	1.04
	~1.5	1.00		~0.9	1.02
(2 Λ)	~0.5	1.00		~1.2	1.00
	~0.9	0.97	(4Λ) — (6Λ)	~1.0	1.10
	~1.5	0.88		~1.9	1.00
			(7Λ)	~0.9	1.10
				~1.5	1.00

angle between the Λ hyperon and the intermediate isobar α in the rest system of the isobar A. The curves so obtained are shown in Fig. 1.

Analogous curves for different values of η and m_B were calculated also for K mesons. Figure 2 shows three series of such curves for the processes

$$\pi^- + p \to K + B_{\pm 1}^{+1}, \qquad (1K)$$

$$\pi^- + p \to K^* + B_{\pm 1}^{+1}, \quad K^* \to K + \pi, \qquad (2K)$$

$$\pi^- + p \to N_3^* + B_0^0, \quad N_3^* \to K + \Lambda. \qquad (3K)$$

The values of m_B and η used for these processes are listed in Table II.

3. COMPARISON OF THE CALCULATED DATA WITH EXPERIMENT; DISCUSSION

Comparing the kinematic curves by the character of the angular and momentum distributions of

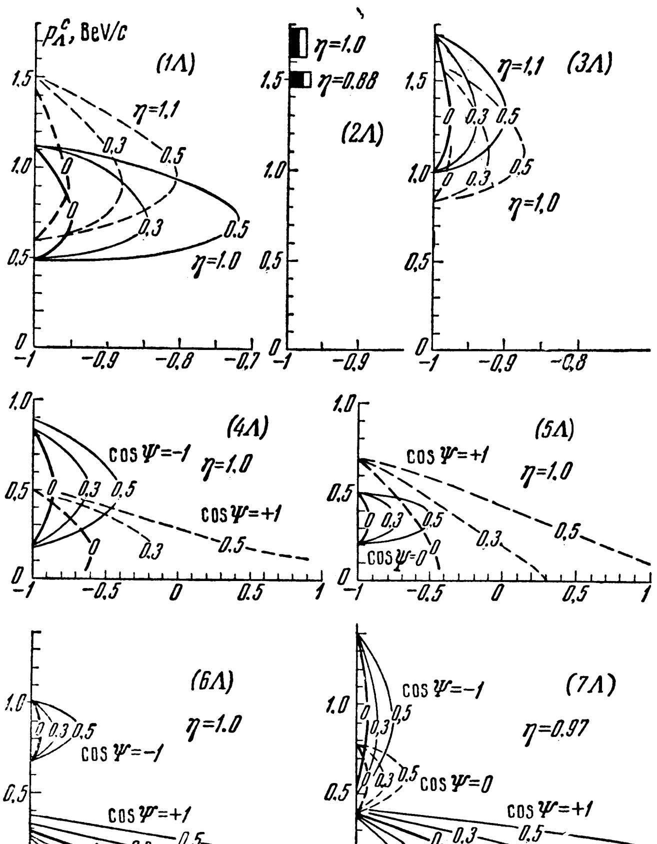

FIG. 1. Kinematic connection between p_Λ^c and cos θ_Λ^c for the Λ hyperons produced via isobars. The numbers on the curves—values of q.

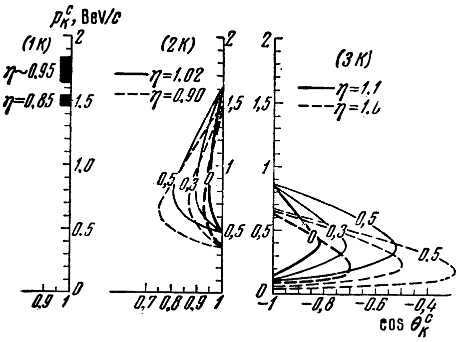

Fig. 2. Kinematic connection between p_K^c and cos θ_K^c and for K mesons produced in processes (1K) – (3K). The curves are calculated for transverse momenta 0, 0.3, and 0.5 BeV/c (numbers on the curves).

the Λ hyperons, we can separate all the processes considered above (which correspond to real isobars) in three groups as shown in Table III.

We note first that this distribution by groups agrees with the distribution of the experimental points on the (p_Λ^c, cos θ_Λ^c) plane, as can be readily verified by comparing the calculated kinematic curves with Fig. 3. The distribution shown here was obtained by suitable recalculation of the data of Fig. 5 from [1a].

Further, Fig. 4 shows the experimental angular (a) and momentum (b) distributions obtained in [1] for the Λ hyperons. The shaded parts pertain to those called arbitrarily peripheral in [1], while the unshaded particle responds to the Λ hyperons called central. Figure 4c shows the kinematic curves of the Λ hyperons produced in processes of the first and second groups (for simplicity, the figure shows only one curve from each group and none from the third group of reactions). As follows from the comparison, the character of the angle scatter and the momentum distribution of the Λ hyperons of the first group coincides fully with the corresponding experimentally established characteristics of the "peripheral" Λ hyperons. An analogous conclusion follows from a comparison of the kinematic characteristics of the "central" Λ hyperons and hyperons which arise in the second and third group of processes, taken together.

Finally, Fig. 5 compares the experimentally obtained[1] dependences of the three-dimensional momentum transfer $|\boldsymbol{\Delta}| = |\mathbf{p}_p^c - \mathbf{p}_\Lambda^c|$, energy transfer $\Delta_0 = E_p^c - E_\Lambda^c$, and the 4-momentum transfer[2] $\Delta = \sqrt{\boldsymbol{\Delta}^2 - \Delta_0^2}$ on the value of p_Λ^c (histograms a, b, and c) with the corresponding curves (e, f, and g)

[2] Under the assumptions made in the calculations, the values of $\boldsymbol{\Delta}$, Δ_0, and Δ will no longer correspond to the transferred 3-momentum, energy, and 4-momentum, since the idea is to refer them to the isobar, but in our case they pertain to the product of the isobar decay.

Table II

Process	m_B, BeV	η	Process	m_B, BeV	η
(1K)	~1.1	0.98	(2K)	~1.4	0.97
	~1.2	0.95		~1.8	0.90
	~1.8	0.85	(3K)	~0.7	1.1
(2K)	~1.1	1.02		~1.5	1.00

Table III. Separation of reactions (1Λ)—(7Λ) into groups according to the kinematic characteristics of the Λ hyperons

No. of group	Method of production	Momentum range (approximate)	Angle intervals $\cos\theta^c_\Lambda$	Relative no. of Λ hyperons produced in the given group
1	Reactions (2Λ) and (3Λ) [direct and via Y^*_1 (1385)]	900—1800	(—1.00)—(—0.90)	4
2	Reactions (1Λ) [via the isobar N^*_3 (1688)]	500—1500	(—1.00)—(—0.80)	3
3	Reactions (4Λ)—(7Λ) cascade decay of isobars N^*_4(1922) and Y^*_0(1815)	0—1000	(—1.00)—(+1.00)	3

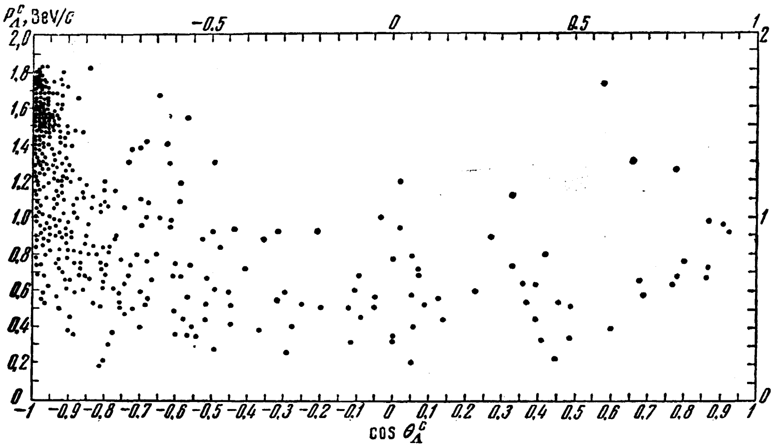

Fig. 3. Experimental distribution of the points on the (p^c_Λ, $\cos\theta^c_\Lambda$) plane for Λ hyperons produced in π^-p interactions. The distribution is obtained by recalculation of the data from [1a] (see Fig. 5 of [1a]).

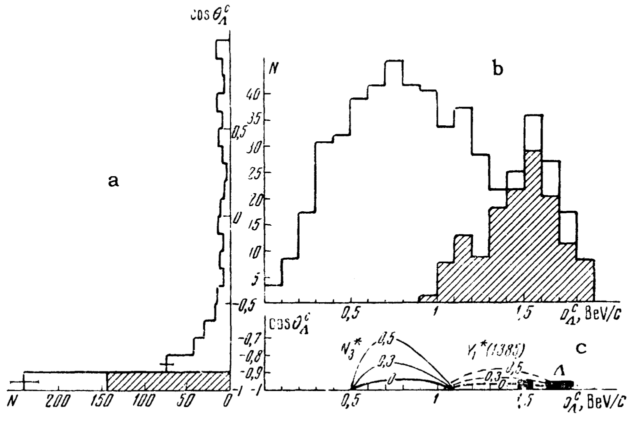

FIG. 4. Experimental angular (a) and momentum (b) distributions of the Λ hyperons obtained in [1]. The shaded areas pertain to Λ hyperons with $\Delta < 700$ meV/c. c—calculated kinematic curves for Λ hyperons produced directly in the interaction act via the reaction (2Λ) with $\eta = 0.88$ and $\eta = 1.00$, and via isobars N^*_3 via the reaction (2Λ) with $\eta = 1.00$, and Y^*_1 (1385) via the reaction (3Λ) with $\eta = 1.04$.

calculated for the Λ hyperons belonging to the first two groups. Again (if we bear in mind the curves for the third-group processes, which are not shown in the figure), the agreement is not bad.

We thus arrive at the conclusion that the experimentally observed separation of the Λ hyperons into two groups in π^-p interactions[1] can be the natural consequence of the kinematics of processes (1Λ)—(7Λ). We can apparently explain analogously the formation of two peaks in the momentum distribution of the Λ hyperons produced by 16 BeV π^- mesons[2], and possibly the two peaks in the momentum distribution of the protons produced in π^-p interactions at 7—8 BeV[5-7].

The experimental distributions shown in Fig. 4 can be used for a rough estimate of the relative number of Λ hyperons produced in the first, second, and third groups of the reactions. Thus, taking into account the character of the distribution of the Λ hyperons, we obtain a ratio of 4:3:3.

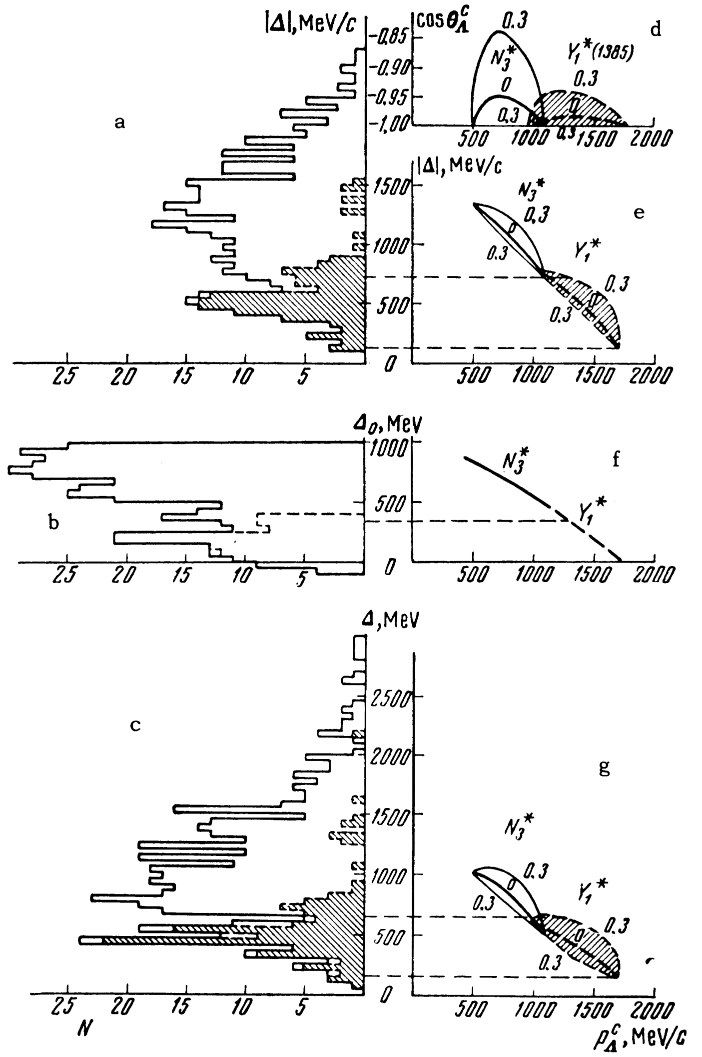

FIG. 5. Experimental and calculated distributions of Λ hyperons in the π^-p c.m.s.: a, e – over the 3-momentum transfer, b, f – over the energy transfers, c, g – over the 4-momentum transfer. The shaded area pertains to the cases $p^c_\Lambda > 1300$ MeV/c (in case b the shading has been left out in error – Ed.). The calculations are for the process involving the production of Λ hyperons via the isobar N^*_3 [reaction (1Λ)] and via the isobar Y^*_1 (1385) [reaction (3Λ)] with respective values $\eta = 1.00$ and 1.04 (the value of q is marked on the curves).

What is striking is the relatively large second group (about $^3/_{10}$ of all the Λ hyperons). If our assumptions are valid, this will mean a very high probability for the production of N^*_3. Evidence in favor of this is also the agreement of the peaks in the cross section of the reaction $\pi^- + p \rightarrow \Lambda + K^0$ and the total cross section of the π^-p interaction[8]. We cannot exclude, incidentally, the possibility that we are dealing here not with N^*_3 of spin $^5/_2{}^+$, but a different nucleon isobar of nearly equal mass but of spin $^1/_2$ [9].

4. SOME CONSEQUENCES OF THE MODEL UNDER CONSIDERATION

In order to obtain additional data on the correctness of the foregoing mechanism of Λ-hyperon production it is necessary, of course, to make a more detailed comparison between the consequences that follow from this mechanism and experiment. We describe below some of these consequences, which can be readily verified on the basis of materials usually obtained in experiments on Λ-hyperon production.

1. If the process (7Λ) really takes place, then the distribution in the (p^c_Λ, cos θ^c_Λ) plane for the Λ hyperons from the combinations $\Lambda\pi^+\pi^-$, the effective mass of which lies in the 1700–1900 MeV interval (the resonance $Y^*_0(1815) \rightarrow \Lambda\pi\pi$ was observed in this interval) should be situated within the envelope of the kinematic curves of Fig. 1, case (7Λ).

2. If we assume that $B^0_{\pm 1}$ in the reaction (3Λ) is a K meson or a K^* isobar, and assume further that the probability of exchange of two mesons is small compared with the probability of one-meson exchange, then the hyperon isobar $Y^*_1(1385)$ should be neutral. Then the Λ hyperons with $p^c_\Lambda \geq 1300$ MeV/c should not be in resonance with a K meson or a charged pion. The observed[10] peaks in the distributions with bound masses $M_{\Lambda\pi^+}$ and $M_{\Lambda K^0}$ must be assigned to those cases, for which $p^c_\Lambda \lesssim 1300$ MeV/c. Some of the hyperons with $p^c_\Lambda \geq 1300$ MeV/c should be in resonance with the π^0 mesons, but it is difficult to verify this (owing to the low efficiency for the registration of the γ quanta).

3. From the assumption that an appreciable part of the hyperons and K mesons is produced in reactions (1Λ) and (3K) via the nucleon isobar N^*_3, we can draw the following conclusions:

a) For ΛK pairs with momentum $p^c_\Lambda < 1300$ MeV/c there should exist a peak in the distribution over the effective masses $M_{\Lambda K}$ near the mass of the isobar N^*_3, that is, $M^{res}_{\Lambda K} = M_{N^*} \sim 1668$ MeV ($Q_{\Lambda K} \sim 75$ MeV).

b) The Λ hyperons and K mesons of the ΛK pairs with $Q \sim 75$ MeV from the region of the peak in the effective-mass distribution should have a momentum p^c_Λ in the range 500–1300 MeV/c and $p^c_{\Lambda K} < 700$ MeV/c (see Fig. 5), and should move backwards in the π^-p c.m.s.

c) Some angular correlation should exist between the Λ hyperons and the K mesons from the same pairs with values $Q_{\Lambda K} \sim 75$ MeV.

4. Inasmuch as the Λ hyperons and K mesons of the ΛK pairs with momentum $p^c_\Lambda > 1300$ MeV/c

should be formed in channels (2Λ) and (3Λ), and not via an isobar, we should expect the following:

a) The Λ hyperons from these pairs are sharply peaked forward in the π^-p center of mass system ($-1.00 \leq \cos\theta_\Lambda^c \leq -0.90$), and the K mesons (see Fig. 5) move predominantly forward; the angle between the Λ hyperon and the K meson in each pair is large. If we assume that B_{+1}^0 in channels (2Λ) and (3Λ) is K or K*, then according to the kinematics for the processes (1K) and (2K) the K mesons should be directed forward in a narrow cone $+0.80 \leq \cos\theta_K^c \leq +1.0$. Then $\cos\theta_K^c$ is close to -1.

b) The Λ hyperons and the K mesons from these pairs are not in resonance.

5. Under the considered assumptions, the K mesons with $p_K^c > 1300$ MeV/c are formed by the reaction (1K) (see Fig. 2), and consequently:

a) They should likewise not be in resonance with the Λ hyperons.

b) The K mesons from the ΛK pairs with $p_K^c > 1300$ MeV/c should be sharply peaked forward in the π^-p c.m.s. ($+0.90 \leq \cos\theta_K^c \leq +1.00$), and the Λ hyperons should be peaked predominantly backwards. The angles between the Λ hyperons and the K mesons in each such ΛK pair are large.

6. In reactions (1Λ) and (4Λ) — (6Λ) the Λ hyperons and the K mesons are products of isobar decays, moving predominantly in the rear hemisphere in the π^-p c.m.s. On the other hand, in reactions (2Λ), (3Λ), and (7Λ) the Λ hyperons move predominantly in the rear hemisphere, and the K mesons in the forward hemisphere. Such a difference should appear in the experiment and apparently does actually manifest itself (see Fig. 5 of [11]). It follows from Sec. 2 that the ΛK^0 pairs for which $p_\Lambda^c > 1300$ MeV/c or $p_K^c > 1300$ MeV/c should have $\cos\theta_{\Lambda K}^c \leq -0.4$ and the pairs ΛK^0 with values $Q_{\Lambda K} \sim 75$ MeV should correspond to $\cos\theta_{\Lambda K}^c \geq -0.2$.

CONCLUSIONS

The separation of the Λ hyperons produced on protons by mesons with energy 7—8 BeV into two groups with different kinematic characteristics, which was observed in the cited experiments [1] and cannot be explained by statistical theory, can be interpreted by assuming that the Λ hyperons are produced in two-particle reactions of the type $\pi^- + p \rightarrow A + B$, where A can be a Λ hyperon or any one of the known baryon isobars, while B can be a meson or one of the known meson isobars. Such A and B are centers of emission of secondary particles following the interaction. The choice of A and B, and also their decay, are determined by the conservation laws. From among all the possible reactions of the indicated type, as follows from a comparison with the experimental data [1], the most probable are those in which the Λ hyperons are produced directly in π^-p interactions or via the isobars $Y_1^*(1385)$, $N_3^*(1688)$, $N_4^*(1922)$, and $Y_0^*(1815)$.

All the foregoing processes can be subdivided in accordance with the kinematic characteristics of the Λ hyperons produced in them into three groups (see Table III). This separation actually corresponds to reality.

It is pleasant to note that Barashenkov et al.[12] have arrived by other means at the conclusion that the second peak in the momentum distributions of the Λ hyperons in the interval 1.3 BeV/c $\leq p_\Lambda^c \leq$ 1.8 BeV/c is due to resonant interaction between the primary negative pion and the intermediate K meson, which transfers the bulk of the interaction in peripheral π^-p collisions. This agrees with our explanation of the formation of these Λ hyperons via processes (2Λ) and (3Λ).

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