Interactions of K^--Mesons at Rest in Nuclear Emulsions

V. The Multi-Nucleon Capture Mode

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Abstract. From a complete study of about 1100 K^--absorptions at rest in nuclear emulsions, it was determined that the multinucleon capture mode forms $37\% \pm 5\%$. The energy spectra of the Σ-hyperons were measured and calculated and a separation between Σ-hyperons resulting from single nucleon and multinucleon K^--captures was performed. Some evidence to the fact that multinucleon captures take place mostly in the heavy emulsion nuclei is presented. A method of determining all the multinucleon reaction rates is suggested and applied to our own data. This method makes use of the number and spectra of fast protons emitted from the K^--capture stars obtained in the present work. The results are compared with the predictions of a model recently proposed.

1. Introduction

In the present work we wish to report about K^--captures at rest leading to a multinucleon reaction. The work was based upon a complete study of about 1600 K^--interactions in nuclear emulsions. We have previously published results about the K^--interactions in flight[1]) and a partial analysis of the captures at rest[2]). In the next work[3]) we shall discuss in detail the single nucleon K^--captures at rest and in the present paper we shall concentrate on the multinucleon captures.

A single nucleon K^--capture ($1N$) is, by definition, any K^--absorption, yielding a π-meson and a hyperon (Y) in the final state, namely:

$$K^- + N \rightarrow Y + \pi.$$

A multinucleon (or 2-nucleon, $2N$) capture per definition does not yield a pion in its final state, namely:

$$K^- + 2\,N \rightarrow Y + N,$$

where N stands for a nucleon (n or p) and Y for a Λ^0 or any Σ-hyperon. On the basis of the present analysis we shall show that a K^--meson is absorbed via the $2N$-absorption channel in about 35% of all K^--absorp-

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tions at rest. This number is in good agreement with previously published results by the K^--Collaboration[4]), and with the results of IV. However, as we shall see later, the entire analysis of the $2N$-reactions depends, to a large extent, upon the number of identified charged $2N$-Σ-hyperons. In the present work we have analysed about 1100 K^--captures at rest, and we estimate that about 400 of these were due to $2N$-captures. But, as will be shown, the emitted number of charged Σ-hyperons due to multinucleon capture is only 36 and only a small fraction of these were completely identified. Therefore, some of our results should be regarded as qualitative only, and a much better statistics (probably a factor of ten) is necessary before any final quantitative conclusions about the $2N$-capture mode could be reached.

From the present data (see VI) we have some evidence that the $2N$-capture takes place mostly on the heavy emulsion nuclei. This evidence comes from a study of the electrons associated with certain $1N$- and certain $2N$-K^--absorptions. It yields that about 50% of captures in AgBr and 10–25% of absorptions in CNO lead to the $2N$-reaction.

The raw observed data are summarized in the next section. For more details concerning the π-data in particular and the $1N$-absorptions in general, one should consult VI. In section 3, the Σ-hyperon events are discussed in detail and a separation between $1N$-Σ-hyperons (that is, Σ-hyperons produced in $1N$-K^--capture) and $2N$-Σ-hyperons is performed. In section 4, a method of differentiating between the various $2N$-reaction rates is described and applied to our own data. This method could, in principle, yield reasonably good results; but, as we stated before, due to the small number of completely identified $2N$-Σ-hyperons, the final results should be regarded as merely qualitative. We have confidence in the value of the relative yield ($\sim 35\%$) of the $2N$-captures, but the $2N$-reaction rates given in section 4 should be trust to only within $\sim 50\%$, particularly since the $2N$-Σ-absorption probability (see sec. 4) may depend upon the relative heavy/light $2N$-capture yield. Finally, in section 5, a short discussion of the present work is presented.

2. Observed values

Our scan method was 'along the track' (see ref. 5 for details concerning exposure, stack and scan method), from a certain pick-up point, about 3·5 cm from the K^--entrance edge.

All tracks selected by ionization criteria and leading to $K\varrho$ events (namely endings of tracks without visible secondary prongs) were followed back until the point of entrance to the stack. Thus, contamination arising from secondary protons produced in the stack before the pick-up strip and having, by chance, similar direction and ionization as true K-particles, was eliminated. By studying the range distribution in the stack of all $K\varrho$ and $K\sigma$ events (namely, endings producing a visible capture star), protons entering the stack were eliminated.

The raw observed values obtained in the present experiment are summarized in Table 1. (The K^--free proton absorptions in the emulsion as well as 10 reemitted K^--mesons coming to rest are not included). Of all 1104 K^--captures the fraction of $K\varrho$'s is 11,2%. The classification of the events is phenomenological. Thus, a (π^+, HF) type of event, for example, means that from a K^--capture star an unidentified π-meson and a hyperfragment were emitted together, generally with other stable charged particles. Under the column "O stable prongs" we have listed the number of K^--captures, of each type, giving rise to unstable particles only ("clean events") and the $K\varrho$ events. In general, a prong is a track longer than 2 μ. In the last 3 columns we give the number of events of each class, associated with the emission of at least one fast proton having a kinetic energy over 20, 30 and 60 MeV, respectively. The numbers in brackets indicate the number of events associated with two fast protons.

By studying the distribution in depth of K^--captures producing π-mesons, a small deficiency was found in the top and bottom of the emulsion. The pion loss in the central parts of the emulsions is estimated to be very small. A total number of 37 pions (namely a 10% correction) should be added to the values given in Table 1 in order to account for the observation loss. These 37 events were distributed proportionally among the various classes of pions observed.

Due to the dimensions of the stack, most particles could be followed and identified. 15 secondary baryons escaped from the stack. From their times of flight and the relations between the emitted hyperons and protons from the K^--stars, the conclusion can be drawn that probably none of these tracks belonged to a hyperon. All interactions of secondary particles in flight were analyzed in order to identify the possible $\Sigma^\pm$-interaction in flight. Two such interactions were found. Since charge exchange scattering of pions and Σ-hyperons produced in $1N$-reactions seems to be very small (only one example of an associated π^- and Σ^--production was found), the charge of the pion (or hyperon) was infered from the charge of its partner in several associated (π, Σ) events. These events were included as completely identified events in Table 1. In all (π, Σ) events it was possible to identify at least one of the unstable particles.

In Table 1 only identified Σ^--mesons are included, i. e. Σ^- one prong absorption stars having a prong length greater than 200 μ as well as all Σ^- capture stars with two or more prongs.

The charge division of the ($\pi^\pm$, OY) events is discussed in VI, and the division of the ($O\pi$, $\Sigma^\pm$) events in next section of the present work.

In the present analysis we shall have to use the number of fast protons

Table 1

Raw Observed Data

Type of event	Total Number observed	Number of events with stable prongs, n =							Number of events with fast protons, Tp		
		0 "clean"	1	2	3	4	5	$\geqslant 6$	20 MeV	30 MeV	60 MeV
π^+, Σ^-	16	10	4	1	1	0	0	0	1	0	0
π^+, HF	3	0	2	0	0	1	0	0	1	1	0
π^+, OY	35	6	21	7	0	1	0	0	3	2	0
π^-, Σ^+	48	34	8	2	4	0	0	0	0	0	0
π^-, HF	6	2	0	1	1	1	1	0	3	3	0
π^-, OY	146	15	56	28	24	15	7	1	64 (4)	49 (2)	13
$\pi^\pm, HF$	6	1	0	3	1	1	0	0	2	2	0
$\pi^\pm, OY$	113	31	39	19	16	5	2	1	25 (1)	21	3
$0\,\pi, \Sigma^+$	13	7	0	1	5	1	0	0	3 (1)	2	0
$0\,\pi, \Sigma^-$	21	6	8	1	5	1	0	0	8 (1)	5	4
$0\,\pi, \Sigma^\pm$	31	4	10	5	3	5	2	0	15 (3)	14 (2)	8
$0\,\pi, HF$	27	2	9	5	3	4	1	3	14 (2)	11 (2)	9
$0\,\pi, OY$	638	124	127	139	99	83	46	20	294 (81)	235 (41)	128 (9)
π^-, Σ^-	1	0	0	1	0	0	0	0	0	0	0
All	1104										

(> 60 MeV) emitted in $2N$-capture processes. Therefore, we wish to estimate how many fast protons produced in $1N$-reactions are among the $(O\pi, OY)$ class of events.

From Table 1 it seems that (π^-, OY) events are accompanied by the emission of fast protons, in contrast to the (π^+, OY) events. The fast protons in (π^-, OY) class may come from Σ° or Σ^+ absorptions, or also from Λ° absorption (formation of a cryptofragment). The contribution of the latter process to the fast proton (> 60 MeV) yield can be neglected, as can be seen from our data*). The contribution of π^- inelastic scattering to the number of fast protons in the (π^-, OY) class of events is also small but was taken into account for the (π^-, Λ°) events. (The pions from the (π, Σ)-reaction have an average energy of 53 MeV, and thus would not give protons over 60 MeV, when inelastically scattered). Also Σ^--absorption does not give rise to fast protons, since no (π^+, OY) star had an associated fast proton. Thus, most of the fast protons come from Σ° and Σ^+-absorption. This is clear in view of the different Σ-absorption reactions:

$$\Sigma^+ + n \to \Lambda^\circ + p \qquad \Sigma^\circ + p \to \Lambda^\circ + p \qquad \Sigma^- + p \to \Lambda^\circ + n$$
$$\Sigma^\circ + n \to \Lambda^\circ + n$$

From our $1N$-reaction rates and Σ-hyperon absorption probabilities (see VI) we can get the numbers of Σ^+ and Σ°-absorptions associated with π^--emission. Assuming that the fast (> 60 MeV) proton yield in Σ°-captures is half of the fast proton yield of Σ^+-absorptions, and using the number of fast protons associated with π^--emission, we get that the fast (> 60 MeV) proton yield in Σ^+-captures is 17% and in Σ° capture

Table 2
Estimate of fast protons (over 60 MeV) in the $(0\,\pi, OY)$ type of events arising from $1N$-K^--captures

Hyperon and pion absorbed	3
Hyperon absorbed, pion escapes:	
(i) π° escapes	3
(ii) π^+ escapes but is not detected (loss correction – 10% of observed fast protons associated with emitted π's	2
Pion absorbed, hyperon escapes:	
(i) Neutral hyperon escapes	6
(ii) Σ^- escapes but is not detected because it produces a zero or a short one prong capture star	3
Total number of expected $1N$ fast protons	17

8·5%. This yield is about half the corresponding yield in π-absorptions (40% for π^+)[6][7]) as should be expected, since the energy release in Σ-captures is considerably smaller than the energy release in π-captures. Assuming also that the fast (> 60 MeV) proton yield in π^0-captures is

*) See also VI.

half the yield of π^+'s, we can now estimate the total number of fast protons ($>$ 60 MeV) arising from $1N$-reactions in the $(O\pi, OY)$ type of events. This estimate is summarized in Table 2.

3. The Σ-hyperon events

The best indication for a substantial multinucleon K^--capture at rest comes from the Σ-hyperon energy spectra. Since the Q value for the single nucleon captures ($K^- +$ nucleon $\to \Sigma + \pi + 100$ MeV) is much smaller than the Q value for the $2N$-captures ($K^- + 2N \to \Sigma + N +$ 240 MeV) and since in the $1N$ capture most of the energy is carried away by the light particle (π-meson), it is to be expected that the Σ-energy spectrum should be entirely different in these two cases. In Fig. 1a and 1b we give the energy spectrum of the hyperons from the $\Sigma - \pi$

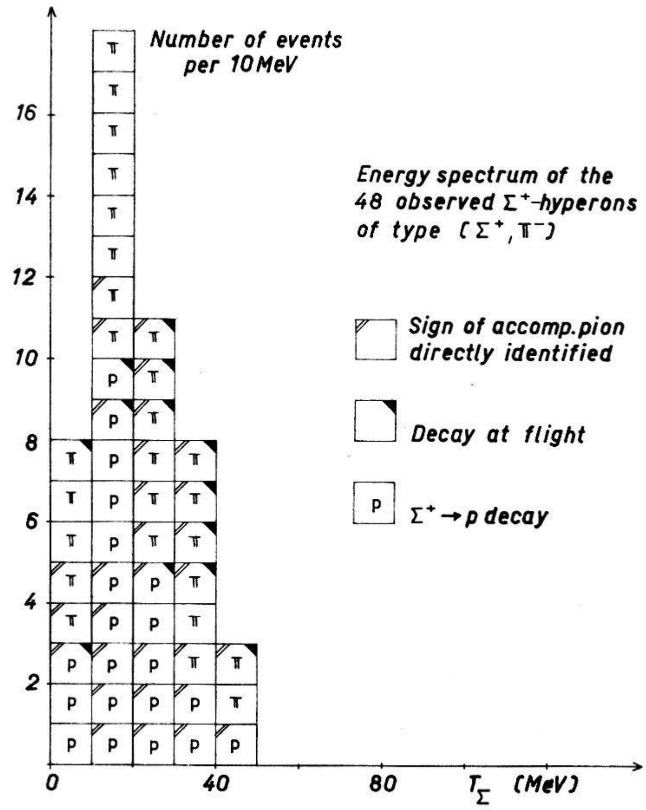

Fig. 1 a

events (that is, K^--stars from which both a Σ-hyperon and a π-meson were emitted), being clearly $1N$-absorptions, and in Fig. 2 the spectrum of the $(O\,\pi, \Sigma)$ events is plotted. The $(O\pi, \Sigma)$ class of events is composed of $2N$-K^--captures, and of $1N$-captures with the subsequent absorption of the pion, or with the emission of a π^0-meson. By inspecting Fig. 2 it becomes clear that the $(O\,\pi, \Sigma)$ events could be separated, in a natural way, into two groups: the first group having an energy distribution similar to the (π, Σ) events (Fig. 1a and 1b) and which must therefore, be due to $1N - \Sigma$ production, and a second group, containing Σ's

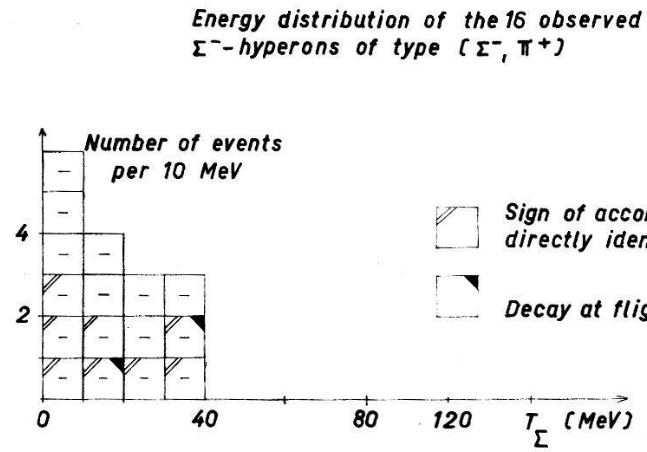

Fig. 1 b

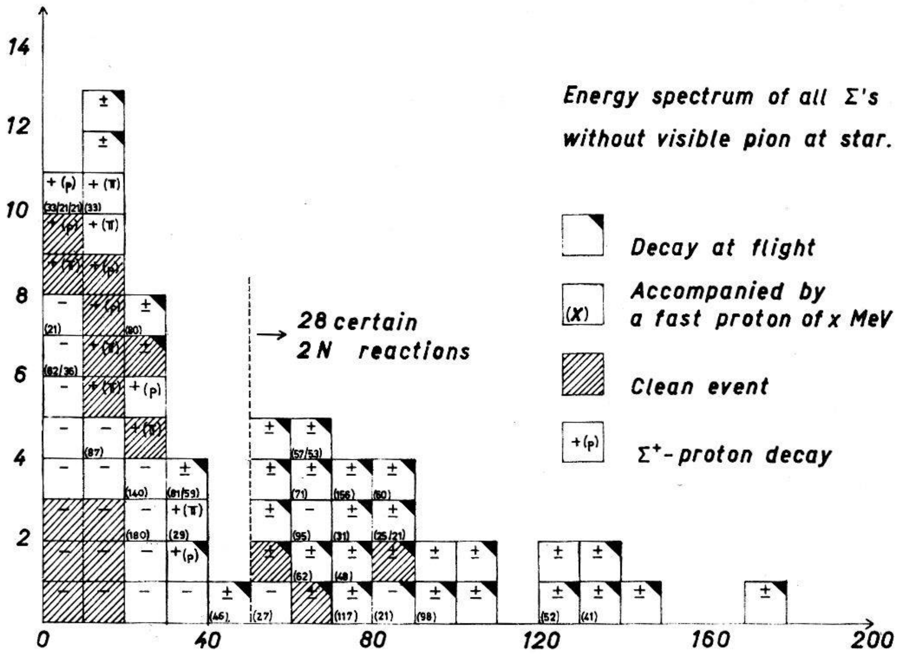

Fig. 2

of much higher energies, which must be due to K^--captures on two or more nucleons.

Our Σ-spectra are very similar to that published by the K^--Collaboration[4]), and both indicate that a large proportion of the K^--stars are due to $2N$-absorptions. However, it is not easy to derive directly the percentage of $2N$-captures from the relative numbers of fast Σ-hyperons, since the capture mechanism, the Σ-absorption probability and the ratio of charged to neutral hyperons might be different in $1N$ and in $2N$-captures.

The best estimate of the total number of $2N$-absorptions could be derived from a complete analysis of the $1N$-events (see VI). From the total numbers of pions observed, the π-absorption probability, and by assuming charge independence, we get that (see VI for details) in 400 $\pm$

50 events, out of a total of 1104 events, the K^--particle must have been captured by two or more nucleons.

We wish now to turn to the complete analysis of the Σ-events. The raw observed values are given in Table 3. These numbers have to be corrected for possible pion loss which is rather small (about 10%. See sec. 2 for details), and for unidentified Σ^--hyperons. The second correction is the most serious one and we wish to discuss it in more detail. Since Σ^--hyperons when coming to rest are captured by nuclei, they can be identified only if they make a 2 or more prongs capture star, or a one prong star, provided this prong is longer than 200 μ. Σ^--capture stars with zero prongs and short single prongs would easily be confused with proton endings in the emulsion. The best way of estimating the Σ^--correction factor is by studying the ends of Σ^-'s resulting from K^- free proton absorption: $K^- + p \rightarrow \pi^+ + \Sigma^-$. The world collection, based upon 107 events (63 collected by the K^--Collaboration[8]) and 44 communicated privately to us by kindness of Dr. Ceccarelli), yields the following correction factor: (all Σ^--captures)/(Σ^--yielding one prong $\leqslant$ 200 μ, or 2 and more prongs) = 2,6 so that each observed Σ^--capture star having 2 or more prongs, or at least 1 prong longer than 200 μ, is equivalent to 2,6 Σ^--hyperons emitted. This factor will be exclusively used in the present work.

We wish now to remark about the +/− division of the slow $\Sigma^\pm \rightarrow \pi^\pm$-decays at flight. In our 50 examples of observed (π, Σ) production, there is only one event of probable charge exchange, namely an associated (π^-, Σ^-)-emission. Therefore we may safely deduce the charge of an unidentified particle, if the charge of its partner was identified. In the ($\pi^\pm$, $\Sigma^\pm$) class of events we were always able to identify at least one particle. Thus, in all cases of this type the charge of the pion and the Σ-hyperon was known. The 6 slow ($T_\Sigma \leqslant$ 50 MeV) unidentified Σ's from ($O\pi$, $\Sigma^\pm$) events were divided according to the Σ-life time expected values, since every Σ coming to rest after a time of flight t_i should correspond to a total number of exp (ti/τ_Σ) Σ's decaying in flight and coming to rest.

Finally we had to estimate the number of slow (below 50 MeV) Σ-hyperons produced by the $2N$-capture mechanism. By comparing our calculated $2N$-hyperon spectrum (obtained from Capps[9]) model and the nucleon momenta distributions with a peak at 170 MeV/c; see Fig. 3), with the experimental spectrum we estimate that about 5 $2N$-hyperons could be among the slow ($O\,\pi$, Σ) events. This number is also compatible with the estimate obtained by using the mean $2N$ Σ-energy and arguments concerning the Σ life time.

The best estimates of the Σ-hyperon emission values are given in the following Table 4. The numbers in Table 4 were obtained by using the

Table 3
Σ-Hyperon Observed Values

Type of event	Total number		'clean' events	Stars emitting fast protons $Tp \geq$		
	$T_2 < 50$	$T_3 > 50$		20MeV	30MeV	60MeV
(π^-, Σ^+)						
$\Sigma^+ \to p$ decay at rest .	17	0	12	0	0	0
$\Sigma^+ \to \pi$ decay at rest .	18	0	13	0	0	0
$\Sigma^+ \to p$ decay in flight .	4	0	4	0	0	0
$\Sigma^+ \to \pi$ decay in flight .	9	0	5	0	0	0
$(0\,\pi, \Sigma^+)$						
$\Sigma^+ \to p$ decay at rest .	3	0	2	0	0	0
$\Sigma^+ \to \pi$ decay at rest .	7	0	4	2	1	0
$\Sigma^+ \to p$ decay in flight .	3	0	1	1 (1)	1	0
(π^+, Σ^-)						
$\Sigma^- \to \pi^-$ decay in flight.	2	0	2	0	0	0
Σ^--capture stars	14 (*)	0	8	1	0	0
$(0\,\pi, \Sigma^-)$						
$\Sigma^- \to \pi^-$ decay in flight.	0	1	0	1	0	0
Σ^--capture stars	18	2	6	7 (1)	5	4
$(0\,\pi, \Sigma^\pm)$						
$\Sigma^\pm \to \pm\,\pi$ decay in flight	6	23	4	15 (3)	14 (2)	8
(π^-, Σ^-)						
Σ^--capture stars	1	0	0	0	0	0
$(0\,\pi, \Sigma^\pm)$						
$\Sigma^\pm$ interactions in flight	0	2	0	0	0	0

*) One of these events, though a certain Σ^-, was not included in final analysis, since it did not satisfy exactly our definition of an observed Σ^--hyperon.

Σ^- prong correction factor mentioned above, by Σ life time consideration and by extrapolating the fast Σ energy spectrum to lower energies. The single nucleon emission values will be used in VI, and the $2N$-values in the next section of the present work.

Details of the derivation of the final $1N$-emission values.

(Σ^-, π^+) *39 events:* $13 \times 2{\cdot}6 = 34$ Σ^-'s coming to rest, 2 $\Sigma^- \to \pi^-$ decays at flight and 3 taken from the $(\Sigma^-, O\,\pi)$ class to account for the π loss correction (sec. 2).

(Σ^+, π^-) *54 events:* 48 directly observed, 3 taken from the $(\Sigma^+, O\,\pi)$ events because of the π-dip correction (sec. 2) and 3 more from the $(O\,\Sigma, \pi^-)$ events to account for the π loss correction in $\Sigma \to \pi$ decay.

$(\Sigma^-, O\,\pi)$ *46 events:* $18 \times 2{\cdot}6 = 47$ slow Σ's coming to rest. To these we added 5 from slow $(\Sigma^\pm, O\,\pi)$ decay in flight. From the total number, 3 should be substracted as slow $2N$-contribution, and other 3 removed to the (Σ^-, π^+) class of events because of the π-loss correction (sec. 2).

Table 4
Corrected Σ-hyperon emission values

Type of event	Numbers emitted	
$1N$-K^--captures:		
(Σ^-, π^+)	39	
(Σ^-, $0\,\pi$)	46	
All Σ^-		85
(Σ^+, π^-)	54	
(Σ^+, $0\,\pi$)	10	
All Σ^+		64
All $1N$ Σ-hyperons . .		149
$2N$-K^--captures:		
Σ^+	2	
Σ^-	9	
Σ^+	25	
All $2N$ Σ-hyperons . .		36
Total number of emitted Σ-hyperons		185

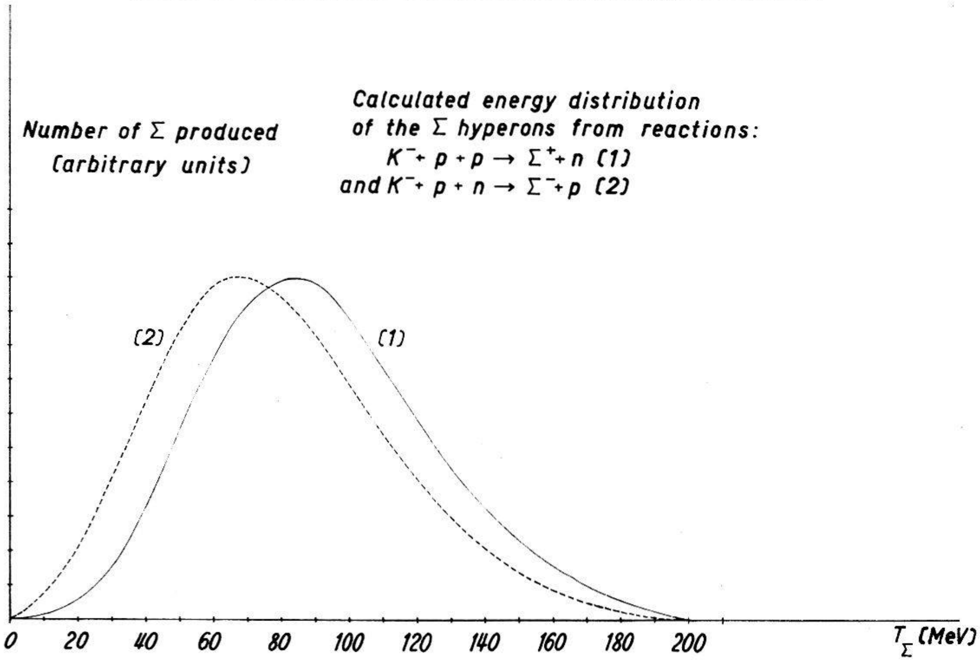

Fig. 3

(Σ^-, $O\,\pi$) *10 events:* 13 slow Σ^+'s directly observed. One out of the 6 slow ($\Sigma^{\pm}$, $O\,\pi$) was assumed positive and one more was added because of the $\Sigma \to \pi$ loss correction. From these we substract 2 for the slow $2N$-contribution, and other 3 to account for the π^- loss correction (removed to the Σ^+-π^--class).

4. The 2N-reaction Rates

In the present section we would like to estimate the reaction rates of the K^--$2N$-capture mode, using the data obtained in the present experiment, as well as other published data. The seven possible $2N$-reactions are listed in Table 5, together with the calculated reaction rates, for a self conjugate nucleus assuming charge independence (IV).

Table 5

(1)	$K^- + n + n \to \Sigma^- + n$	p^2
(2)	$K^- + n + p \to \Sigma^- + p$	$2/9\ p^2 + 2/9\ q^2 + 2/3\ s^2 - 4/9\ pq \cos \delta$
(3)	$\to \Sigma^\circ + n$	$4/9\ p^2 + 1/9\ q^2 + 1/3\ s^2 + 4/9\ pq \cos \delta$
(4)	$\to \Lambda^\circ + n$	$1/3\ q_\Lambda^2 + s_\Lambda^2$
(5)	$K^- + p + p \to \Sigma^+ + n$	$1/9\ p^2 + 4/9\ q^2 \qquad + 4/9\ pq \cos \delta$
(6)	$\to \Sigma^\circ + p$	$2/9\ p^2 + 2/9\ q^2 \qquad - 4/9\ pq \cos \delta$
(7)	$\to \Lambda^\circ + p$	$2/3\ q_\Lambda^2$

For comparison with actual emulsion experiments (n/p ratio $\sim 1{\cdot}3$), the first reaction should be multiplied by $(1{\cdot}3)^2 = 1{\cdot}69$, and reactions (2), (3) and (4) by $1{\cdot}3$. All notations are the same as in IV. We shall summarize then briefly here:

$$\left\langle T = \frac{3}{2} \middle| H^{2N} \middle| T = \frac{3}{2} \right\rangle = p\ e^{i\alpha}$$

$$\left\langle T = \frac{1}{2} \middle| H^{2N} \middle| T = \frac{1}{2} \right\rangle_s = q\ e^{i\beta}$$

$$\left\langle T = \frac{1}{2} \middle| H^{2N} \middle| T = \frac{1}{2} \right\rangle_a = s\ e^{i}$$

and $\delta = \alpha - \beta$. The definition of q_Λ and s_Λ is similar to that of q and s, only H_Λ^{2N} should be substituted for H_Σ^{2N}.

By inspecting Table 5 it becomes clear that charged hyperons could be produced only in reaction (1), (2) and (5); namely (Σ^-, n), (Σ^-, p) and $(\Sigma^+$, n) pairs. In the primary process, the hyperons from the (Σ^-, n) and (Σ^+, n)-reactions are produced without charged partners, whereas hyperons from the reaction (Σ^-, p) are produced with a charged particle. Now subsequent interactions of the hyperon and the nucleon will distort the production picture to a large extent, but nevertheless one can hope to identify the above reactions, when direct identification of the hyperon is not possible, by a study of the accompanying stable prongs. In particular (Σ^+, n) and (Σ^-, n) production processes should be expected to appear, to some extent, as $\Sigma^\pm$ clean events, and (Σ^-, p) production should seldom appear as Σ^- clean events, and quite often appear as a Σ^--hyperon accompanied by a fast proton. Indeed, from systematic studies of proton and neutron initiated stars[10] [11]), one can estimate that about 25% of the neutron interactions (in our energy range) produce zero prong stars and that only 3% of the proton interactions yield zero prong stars. Thus, one expects that about 25% of the (Σ^+, n) and (Σ^-, n) productions would appear as $\Sigma^\pm$ clean events, and that practically none of the (Σ^-, p) productions appears as a "Σ^- clean event".

If we turn now to the world collection of identified fast hyperons ($T_\Sigma \geqslant 50$ MeV) produced by K^--captures at rest in nuclear emulsions [4]), [8]), [12]), which represents certain examples of $2N$-K^--captures, we find the following very interesting results:

(i) Out of 13 identified Σ^+-hyperons, 5 were "clean events" (4 were accompanied by a proton with kinetic energy over 30 MeV).

(ii) Out of 15 identified Σ^--hyperons not a single one was a "clean event" (6 of 11 of these were accompanied by a proton with kinetic energy over 30 MeV).

The only reasonable interpretation of the above phenomena, as was pointed out already by the K^--Collaboration [8]), is that the production rate of the (Σ^-, n)-reaction is very small. In analogy with the (Σ^+, n) events, a production of merely 3 (Σ^-, n) events should have manifested itself by giving rise to a single "clean event". No such event was observed, therefore we may conclude that the (Σ^-, n) to (Σ^-, p) production ratio is probably smaller than 3/13. In the following analysis we shall assume that the production rate of the (Σ^-, n)-reaction is zero. This point will be eventually checked by identifying more fast Σ^--hyperons, but probably we could not be very wrong by assuming that the (Σ^-, n)-production rate is zero – namely that the $T = 3/2$ $2N$ – matrix element (p) is zero.

We wish to comment about the multinucleon hyperon absorption probability. Since the energy of $2N$-hyperons is quite large, the transmission probability and therefore also the absorption probability A_Σ^{2N} of positive and negative $2N$-hyperons is assumed to be equal. One cannot use here the $1N$ A_Σ's obtained in VI, because the $2N$-reaction is expected to take place in a region of high nuclear density and also we have some evidence that the $2N$-captures take place mostly in the heavy emulsion nuclei (see VI). In the analysis of our stars in flight (III) we have obtained $A_\Sigma = 0{\cdot}77 \pm 0{\cdot}14$. A recent analysis of interactions of fast K^--mesons in flight, performed by the Livermore [13]) group, yielded similar results. Since it is reasonable to assume that the fast K^--mesons are absorbed uniformly throughout the nucleus, one may use the Σ mean free path in nuclear matter given by the Livermore group for calculating A_Σ [13]). Using our data (III) as well as the Livermore data, we estimate A_Σ^{2N} to be $\approx 0{\cdot}7$. Since the Σ-energy distribution in the stars in flight (III) is similar to the $2N$-Σ-energy spectrum in the present experiment (see Fig. 2), we shall use here this value. It should be pointed out that, unfortunately, the $2N$-reaction rates are rather sensitive to the value of A_Σ^{2N}. A change of A_Σ^{2N} from $0{\cdot}7$ to $0{\cdot}8$ would increase the estimated number of produced $2N$-Σ-hyperons by about 50%. Thus, a better estimate of the $2N$-reaction rates would require more exact knowledge of the fast Σ-hyperon absorption probability.

The $2N$-Σ-absorption probability used in the present analysis is 0·7. We estimate that it could be between 0·6 and 0·8 and thus the total number of $2N$-Σ-hyperons produced turns out to be 180^{+90}_{-45}. Our best estimate of the total number of $2N$-K^--absorptions in our experiment (derived from the analysis of the $1N$ events; see VI) is 400 ± 50. Thus: $N\{(\Lambda^\circ, n) + (\Lambda^\circ, p)\} = 220 \pm {}^{+70}_{-100}$.

We wish now to estimate the individual $2N$-reactions. Since $(\Sigma^-, n) \approx 0$, the $T = 3/2$ matrix element (p) is assumed to be $\approx$ zero, and the reaction rates take a much simpler form – in particular we get that: $(\Sigma^0, n) = 1/2(\Sigma^-, p)$ and $(\Sigma^0, p) = 1/2(\Sigma^+, n)$. By using these simplified relations one can calculate the individual production rates of all the $2N$-Σ-reactions.

The analysis of our own data will be presented now. The details of the 25 unidentified fast $\Sigma^\pm$-hyperons (see Table 4) events are summarized below:

$\Sigma^\pm$, total	Number of stable prongs					
	0	1	2	3	4	5
25	3(0)	5(6)	3(2)	4(2)	3(2)	1(0)

The number of protons over 30 MeV is given in brackets.

By the arguments presented earlier in this section, we may assume that $(\Sigma^-, n) \approx 0$, and that the number of the "clean" events represent about 5/13 of all (Σ^+, n) productions. Also, in the world collection of identified $2N$-Σ-hyperons, 6 out of 11 Σ^-'s and 4 out of 13 Σ^+'s had an associated fast (> 30 MeV) proton. Therefore, the best division of the 25 observed Σ^+-hyperons would be 11 Σ^+ and 14 Σ^-, and thus, our estimate of the $2N$-charged hyperon emission value becomes:

Reaction	Numbers emitted	Clean events		With fast protons (> 30 MeV)	
		observed	expected*	observed	expected*
(Σ^+, n)	13	4	5	17 (all	4
(Σ^-, p)	23	0	0	together)	13

*) The expected number of "clean events" is 5/13 of the (Σ^+, n) emission value, and that of fast protons is 6/11 and 4/13 of the (Σ^-, p) and (Σ^+, n) emission values respectively.

Comparing these emission values with Table 4, we get that 17% of all Σ^+-hyperons and 21% of all Σ^--hyperons are produced in K^--multinucleon captures. This agrees with the recent number published by the K^--Collaboration[8]) (15% Σ^+ and 25% Σ^-). Using the Σ-emission values, the $2N$-absorption probability, and the above simplified relations among

Table 6

Reaction	(1) $\Sigma^- n$	(2) $\Sigma^- p$	(3) $\Sigma^\circ n$	(4) $\Lambda^\circ n$	(5) $\Sigma^+ n$	(6) $\Sigma^\circ p$	(7) $\Lambda^\circ p$
numbers of events (all 400)	~0	77	38	140	43	22	80
Rates in %	~0%	19%	9·5%	35%	11%	5·5%	20%

the Σ-reaction rates, we obtain the $2N$-Σ-production values. They are summarized in Table 6.

As we stated before, the estimate of the total $2N$-Λ-production was 220^{+70}_{-100}. The separation between the (Λ°, n) and (Λ°, p) reactions will be done by using the fast (> 60 MeV) proton data. We have observed 137 fast protons emitted from the ($0\,\pi$, $0\,\Sigma$) and ($0\,\pi$, HF) stars (see Table 1) and estimate that ~ 17 of these must be due to subsequent interactions of particles (π's and Σ's) produced by $1N$-K^--absorptions (see Table 2). One additional fast proton was subtracted to account for unidentified fast Σ^--coming to rest. The remaining 119 fast protons are, therefore, very probably emitted directly in one of the $2N$-reactions. The energy spectrum of the fast protons is plotted in Figure 4. An estimate of the total number of protons produced in the $2N$-reactions may be obtained

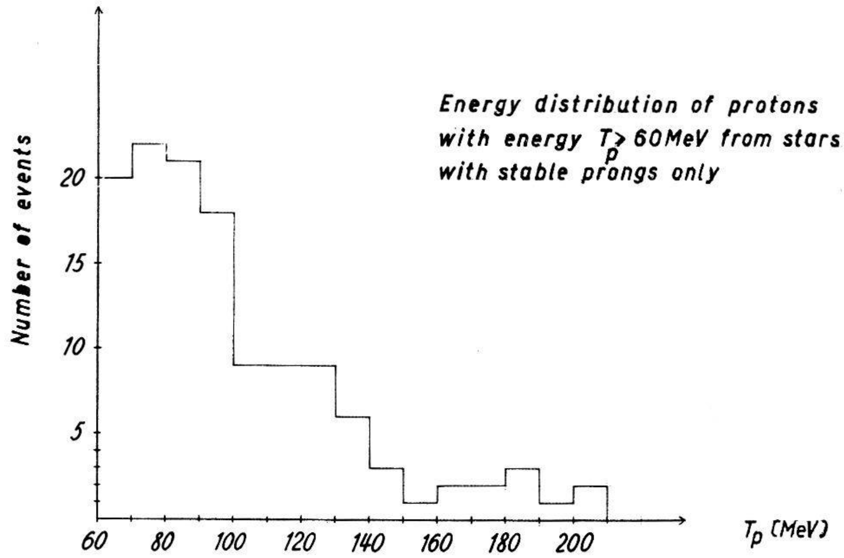

Fig. 4

by extrapolating the observed spectrum to zero energy (linearly). We thus get about 50 additional events. This means that the protons over 60 MeV represent about 70% of all protons directly emitted in a $2N$-reaction. Now the number of protons not associated with a Σ^--hyperon from reaction (2) (Σ^-, p) is 77–23 = 54, and similarly from reaction (6) we expect 22 protons, all together 76 events. About 70% of these should have kinetic energies above 60 MeV, namely 53 events. To these numbers we must add the expected number of fast protons from Σ^+ and Σ°-absorptions. The fast proton yield in $1N$-Σ^+-absorption (mean energy release $\sim$ 110 MeV) is about 17%, as was shown in section 2. On the other hand, the fast proton yield in high energy π^+-stars (energy release of $\sim$ 230 MeV) is about 40%[6][7]. Since the $2N$-Σ^+-hyperon absorption is associated with an energy release of $\sim$ 180 MeV ($M_\Sigma - M_\Lambda \approx 80$ MeV, and in addition to that about 100 MeV Σ-kinetic energy), we have estimated the fast proton (> 60 MeV) yield in $2N$-Σ^+ and Σ°-absorptions to be 30% and 15% respectively. A Σ^--absorption, similar to π^--absorption, would very rarely yield an emission of a fast proton. Thus, the 31 Σ^+-absorbed would give us 9 fast protons, and the 27 (since $(\Sigma^\circ, n) = 38$ and $A_\Sigma^{2N} = 0{\cdot}7$) Σ°-absorbed would yield 4 fast protons. The total number of fast protons produced directly and indirectly becomes now 66, and $122 - 66 = 56$ fast protons must be due to the (Λ°, p)-reaction. The production value of this reaction should be about $56/0{\cdot}7 \approx 80$, and therefore, that of the (Λ°, n) reaction $220 - 80 = 140$.

Our best estimate of all the $2N$-reaction rates are summ rized below. The errors are about 50%.

5. Discussion

In the present experiment we have analysed about 1100 K^--captures at rest on complex nuclei, and we estimate that about 400 out of the 1100 – namely about 35% – were multinucleon captures. Our best estimate of the frequencies of the various $2N$-capture modes is given in Table 6 above. However, we wish to emphasize that only the total number of multinucleon captures should be considered reliable, and that the individual reaction rates are known to an accuracy of 50% only. Apparently improved statistics and a better estimate of A_Σ^{2N} are required for a more exact determination of the various $2N$-reactions rates. Considering the world statistics, we may make more definitive statements about the $2N$-reaction rates of charged hyperons: the frequency of the (Σ^-, n)-reaction is quite small – its upper limit being about 30% of the (Σ^-, p)-reaction. Also the ratio of the reactions $(\Sigma^-, p)/(\Sigma^+, n)$ may be regarded as being $\approx 1{\cdot}5$. A less reliable statement could be made about the $2N$-Λ-production: if A_Σ^{2N} is indeed $\approx 0{\cdot}7$, then about 50% ($\pm$ 20%) of all $2N$-K^--absorptions give rise to a Λ°-hyperon (close to the yield from the $1N$-K^--absorptions; see VI) and the ratio of $(\Lambda^0, n)/(\Lambda^0, p)$ production is about 2 ± 1.

We wish to state that we have an indication (see VI for details) that the $2N$-absorptions take place more on the heavier emulsion nuclei (AgBr), since the percentage of electrons associated with certain $2N$-stars was $28{\cdot}7 \pm 4{\cdot}4$%, whereas the corresponding frequency in certain $1N$-captures was $18{\cdot}2 \pm 2{\cdot}1$%. It should be noted also that the $2N$-yield in K^--captures in deuterium is very small[14]). This is expected in the Σ^*-model (see below) but perhaps also from general considerations of the correlation among nucleons.

Now, wo wish to comment about a recently proposed model[15]) (the "Σ^*-model") accounting for the source of $2N$-K^--absorptions. According to this model, the fundamental K^--absorption occurs at the periphery of the nucleus; but this absorption may sometimes produce a relatively long lived K^--proton $T = 0$ resonant state (the Σ^*-state) which may penetrate the nucleus, collide with other nucleons and give rise to the reaction: $\Sigma^* + N \to Y + N$, namely a $2N$-reaction. In this model, the $2N$-reaction rates have a very simple form: $(\Sigma^-, n) = 0$, $(\Sigma^0, n) = (\Sigma^0, p) = 1/2\,(\Sigma^-, p) = 1/2\,(\Sigma^+, n)$ and $(\Lambda^0, n) = (\Lambda^0, p)$. In complex nuclei, having n/p ratio of $\approx 1{\cdot}3$, one should expect, according to the Σ^*-model, that $(\Sigma^-, p)/(\Sigma^+, n) \approx 1{\cdot}3$ and also that $(\Lambda^0, n)/(\Lambda^0, p) \approx 1{\cdot}3$. Our reaction rates (Table 6) do not contradict the predictions of the Σ^*-model, but this should not yet be taken seriously, because, as we mentioned before, the frequencies given in table 6 are uncertain to within $\sim 50\%$. We wish only to remark that the $(\Lambda^0, n)/(\Lambda^0, p)$ ratio could also serve as an independent check for the model, in addition to the $(\Sigma^-, p)/(\Sigma^+, n)$ ratio and the determination of the absolute yield of the (Σ^-, n)-reaction.

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