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Decaymode and Lifetime of Σ^+ in Emulsions and Some Remarks about the $\Sigma^\pm$-Lifetime

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Summary. In the present paper we report lifetimes of Σ^+ and $\Sigma^\pm$-hyperons obtained from 1600 K^--interactions in emulsions. In agreement with other emulsion data the lifetime of the fast Σ's which are mostly arising from multi-nucleon reactions seems to be different from the lifetime of Σ's produced in 1-nucleon reactions, in bubble chambers as well as in emulsions.

Two possible explanations of this discrepancy are considered below:

a) An attempt is made to explain the difference between the results as due to several experimental biases.

b) The results are taken at face value and the possibility of a real physical reason is taken into account.

Suggestions are made, how to decide between the both alternatives.

1. Experimental results

In the course of a detailed analysis of 1600 K^--interactions in emulsions[1–3]) 33 stars were separated from which a π^- and simultaneously a Σ-hyperon were emitted. In each of these cases the π^- came to rest in the stack and could directly be identified by sign. The charge of the accompanying hyperon was thus inferred as positive, and the sample can be considered as highly unbiased with respect to a fault in charge determination of the Σ's**).

The observed characteristics of the hyperons are shown in Table I.

Among the 12 decays in flight 4 are of the Σ^+-p type. In order to avoid confusion between elastic p-scatterings and Σ^+-p decays at flight, we included only those Σ-p decays which had a change of ionization at the decaypoint from Σ/p of more than $\pm$ 30%. The correction for loss was then performed by assuming isotropic decay of the Σ-p in the Σ-CM

*) On leave of absence from the Institute of Nuclear Sciences, Boris Kidrich, Belgrade.

**) The contamination by Σ^--hyperons can be considered as small, see f. i. (Y. Eisenberg *et al.*)[3]), p. 355. Charge exchange can thus be neglected.

Table I

Event No.	Charged decay-prod.	T^{Star} (MeV)	T^{Decay} (MeV)	Potential time of flight, star $\times 10^{13}$ sec	Potential time of flight decay $\times 10^{13}$ sec	Lifetime $\times 10^{13}$ sec
I 296	π	5	0	79	0	> 79
M 22	P	7	7	116	0	2
S 201	π	9	0	152	0	>152
B 367	P	10.5	0	182	0	>182
B 539	P	11	0	192	0	>192
H 114	P	12.5	0	225	0	>225
I 76	P	12.5	0	225	0	>225
S 139	π	14.5	0	260	0	>260
B 486	π	15.5	0	289	0	>289
M 28	P	15.5	0	289	0	>289
B 410	P	16	4	400	60	340
B 65	π	23	19	470	370	100
I 44	π	23	0	470	0	>470
Ch 56	π	23	0	470	0	>470
S 52	P	23	19	470	370	100
H 107	P	24	0	495	0	>495
B 375	π	24.5	0	508	0	>508
B 552	P	24.5	0	508	0	>508
B 331	π	25.5	21	533	422	110
H 27	P	26.5	0	560	0	>560
B 33	π	28	24	596	495	100
B 342	P	31	0	681	0	>680
K 68	π	32	0	707	0	>710
H 68	P	32.5	0	721	0	>720
Ch 106	π	35	34·5	790	790–21	21
K 24	π	37	20	847	394	450
I 207	π	37.5	34·6	860	780	80
K 187	π	38.5	10·5	892	182	710
K 242	P	40.5	0	964	0	>965
B 533	π	42.5	35	1004	790	215
H 36*	P	28	0	595	0	>595
I 171*	P	54	34	1355	760	595
I 82*	π	57	0	1450	0	>1450

* From K^--interaction at flight.

system*). For these 4 cases the correction turned out to be $\sim 10\%$ (0.5 events). Thus 1/2 Σ-p decay with the average lifetime of the 4 Σ-p decays was added.

The branching ratio of the two decaymodes is:

$$\frac{\Sigma^+ - p}{\Sigma^+ - \pi^+} = \frac{16.5}{17} = 1^{+0.8}_{-0.4}$$

in agreement with other and statistically more significant data[5]) and with the isotopic spin $\Delta I = 1/2$-rule[6])[7]).

The lifetime, using decays at flight and at rest simultaneously, obtained with the maximum likelihood method[8]), becomes

$$\tau_{\Sigma^+} = (1.05^{+0.88}_{-0.33}) \times 10^{-10} \text{ sec.}$$

in agreement with other emulsion data and with bubble chamber experiments[5])[9]).

Table II shows the decay characteristics of 26 fast Σ's ($T >$ 50 MeV). These Σ's are produced in a reaction in which no pion is created[3])[10]), they arise from the so called 'multinucleon' captures of K^--mesons. Thus their kinetic energy is much higher than the energy of the sample of Table I and practically all of them decay at flight.

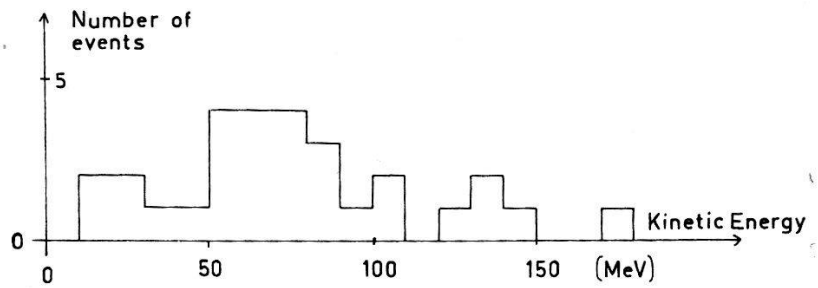

Fig. 1

Before continuing here with a lifetime calculation we want to make some remarks. Fig. 1 is showing the energy-distribution of those Σ's at their emission, which later undergo $\Sigma - \pi$ decay at flight and the sign of which could not be deduced. For these Σ's the lifetimes reported in the literature yield too low a value, even compared with the already short Σ^+-lifetime. Most of the Σ's in Fig. 1 have kinetic energies > 50 MeV. For simplicity we considered only the latter ones.

Generally a lifetime determination of Σ's in emulsions, if it uses *all* informations, has to make use also of the number of particles which come to rest. According to Table II there were 2 Σ^- of this kind. In order to keep the consideration as stringent as possible, one should leave out these Σ^-, but one must do this in the right way. We used thus another

*) There is certainly no *strong* F/B asymmetry (see f. i. M. Nikolič *et al.*)[4]), in the Σ's CM system, and assumption of isotropic decay is sufficient.

maximum likelihood formula than that for the Σ^+ of Table I (see ref.)[8] 3b–9·3), which accounts for Σ-decays at flight, but which takes care of the fact, that several Σ's were not included in the calculations, since they came to rest.

Once assuming one lifetime for these multinucleon Σ's and applying the maximum likelihood method, one gets*)

$$\tau = (0.7^{+0.19}_{-0.16}) \times 10^{-10} \text{ sec.}$$

Table II

Event No.	Charged decay-prod.	T_{Star} (MeV)	T_{Decay} (MeV)	Potential time of flight, star $\times 10^{13}$ sec	Potential time of flight decay $\times 10^{12}$ sec	Lifetime W 10^{13} sec
B 327	π	80	78	2220	2145	75
Ch 142	π	67	63	1780	1645	135
I 22*		56	0	1420	0	>1420
K 107*		62.5	0	1630	0	>1630
B 468	π	86	80	2420	2220	200
Ch 154	π	81	75	2250	2045	205
B 28	π	131	125	4090	3860	230
B 31	π	50	42	1230	1000	240
Ch 214	π	141	134	4485	4210	275
T 59	π	98	89	2850	2530	320
Ch 268	π	56	45.5	1420	1095	325
B 109	π	105	94	3105	2705	400
M 46	π	85	72	2400	1945	455
I 323	π	57	41.5	1450	975	475
H 125	π	74	55	2010	1385	625
B 399	π	121	104	3700	3065	635
B 507	π	71	49	1905	1200	705
B 5	π	54.5	29	1370	625	745
S 195	π	79	52.8	2180	1320	860
S 88	π	67.5	36.5	1790	835	955
B 226	π	62	29	1610	625	985
M 56	π	65	32	1710	710	1000
B 490	π	131	103	4090	3030	1060
I 59	π	70	29	1875	625	1250
H 57	π	100	60.5	2925	1565	1360
Lo 100	π	177	130	5940	4050	1890

* Σ^- at rest.

This is a rather low value and would indicate that practically all the Σ's are positively charged, since the Σ^--lifetime has more than twice

*) The errors quoted here and in the discussion are the Poisson fiducial limits with $p = 0.84$.

that value. On the other hand we know that some Σ^- *must* be among these Σ's (the Σ^- in Table II which come to rest produce stars with more than 1 visible prong, a correction of 2.6*) for observability has still to be applyed), and furthermore we observed no Σ^+-p decay. Together with other corresponding data[5]) this indicates a heavy deviation from the 'ordinary' Σ-lifetime**).

2. Attempts to explain the results as due to possible errors connected with the method of investigation

We introduce and discuss the following items in order to account for the difference in lifetimes, obtained from fast or slow Σ's.

a) The influence of the limited dimensions of the stack.

b) Loss of Σ-decays at flight, i.e., loss of thin tracks emerging from the Σ-decays.

c) Possible loss of those Σ-interactions at flight, which could not clearly be claimed as Σ-interactions.

d) The influence of the statistical error in energy-determination of the Σ-hyperons.

e) Fault in following through of tracks.

(a) One can ask, whether a larger fraction of longliving Σ's could have escaped observation by leaving the stack. The dimensions of the stack were $15.0 \times 17.5 \times 9.8$ cm^3 and the K^- beam was relatively well collimated in the central region. We observed altogether 16 baryons***) (among the 1100 K^--capture stars at rest) which left the stack. Their kinetic energy was measured. 13 of them had an energy of more than 50 MeV. Assuming all the leaving baryons to be Σ's with an average lifetime of 1.4×10^{-10} sec, we got that 2.5 of them would not have undergone decay inside the stack. But this is not the true number. It has still to be corrected with the ratio:

$$\frac{\text{Fast } \Sigma\text{'s}}{\text{Fast } \Sigma\text{'s} + \text{Fast } p\text{'s}}$$

which was obtained to be about 1:6. Thus approximately 1/2 Σ-hyperon has been lost. On account of particles leaving the stack this can be considered as negligible.

*) See f. i. reference [13]).

**) We did not perform mass measurements on the Σ-tracks. It is still possible that Σ-nucleon compounds – if they exist – are among these 'Σ's' and that their lifetime differs from the Σ-lifetime.

***) Excluding here and in the following considerations pion emitting stars. This was already discussed in section 1.

(b) A loss of decays at flight very probably exists*) and might somehow influence the resulting lifetime, if this loss is large. We had 5 fast baryon disappearences at flight, giving no rise to a visible prong. As was shown in[11]) the probability to overlook a thin track in our stack was 10%, and we had 24 decays at flight of multinucleon Σ's. Therefore about 1–2 events between the five disappearences might in fact belong to Σ-pion decays. This is a small number and it seems unreasonable to us that just these Σ's have been living extremely long. The probability for detection of a decay seems at first sight not to depend on the time of flight which the decaying particle had. This is right as long as the probability for detection of a Σ-pion decay is independent of the Σ-velocity. If it is not the case, such an effect would have prolongated the experimentally obtained lifetime. Decays of slower Σ's are easier to detect and in this manner, those Σ's which have been longer living would have been preferentially observed.

(c) It can easily be estimated how many Σ-interactions at flight one could expect. The total path of all fast Σ's of Fig. 1 is about 18 cm. This is only 1/2 geometrical m.f.p. and cannot account for a large bias in the 'shortliving' direction unless there exists an extremely large resonance for capture of slow Σ's. But then the same effect should be detected also for the 1-N hyperons**) and this is not the case. In addition the number of secondary interactions made by fast baryons is small. We had observed only 11 stars among about 160 fast baryons.

(d) Let us consider Fig. 1. The energy of the Σ's was determined with the method of mean-gap-length with an average of 150 to 300 gaps per hyperon. A statistical fluctuation, even if the distribution is symmetrical, could cause a bias. Taking all Σ-energies at emission 10% lower than measured, one sees easily that this would cause an average difference in the lifetime of about 10%. This is certainly a large overestimation.

(e) We observed about 160 fast baryons (Σ's with more than 50 MeV, p's with more than 60 MeV) and shall finally rise the question, how many of these have been followed through wrong. A large fault in this point would undoubtfully cause a loss in longliving Σ's. If one had originally a Σ-track and jumped, one would most probably come to a proton. This effect possibly could be serious.

Therefore we performed a second following through of 50 fast baryons, with the result, that only in one case an error was discovered. But the

*) There is the known effect that most emulsion experiments give a slightly too long K^--lifetime.

**) We distinguish 1-nucleon and multinucleon hyperons corresponding to the production reaction $K^- + N \rightarrow Y + \pi$ and $K^- + 2\,N \rightarrow Y + N$.

corresponding particle remained a proton. In addition we looked here most carefully for Σ-p decays at flight. No example was discovered.

We want to conclude this section with the remark that we feel rather sure, that – at least in our case – it would be difficult to construct a large bias in a Σ-lifetime determination. However one must emphasize that our data alone do in fact not yield statistically significant deviations. But it has to be kept in mind that the question of bias has to be considered for each stack separately, since it is highly dependent on the property of the emulsions, the kind of development and the dimensions of the stack. Later on we shall discuss possibilities to check this question.

3. The possibility of a real physical reason

The matter under investigation is of such a high actuality and an experimental bias of the necessary magnitude is so difficult to invent for the case of the stack in question, that it seems worthwhile at least to think about wheter such a discrepancy might have a real physical reason. The bubble chamber experiments today show clearly only one type of Σ-hyperon from the reaction $K^- + p \rightarrow \Sigma + \pi$ and from $\pi^- + p \rightarrow \Sigma + K$[5][9][12]. Could there be a possible explanation, which, in spite of this clear result could account for the emulsion observations?

As may be seen from investigations of K^--capture stars at rest in emulsions[3][13][15] a very apreciable amount, according to our data about 80% of the $(\Sigma^\pm \rightarrow \pi^\pm)$ -decays (see Fig. 1) at flight of unknown sign belong to multinucleon captures and just for these the derived lifetimes yield too short a value. In bubble chambers however multinucleon reactions are extremely improbable because of the light media used there. From these facts, excluding an experimental bias, one can thus be lead to the speculation that the Σ-lifetime might depend on the production process. Perhaps there is some fundamental difference between the reactions:

reaction 1: $K^- + p \rightarrow \pi + \Sigma$; $\pi^- + p \rightarrow K + \Sigma$.

reaction 2: $K^- + 2\,p \rightarrow n + \Sigma$; $p + N \rightarrow N + \Sigma + K$

Investigations in emulsion exposed to cosmic radiation point in the same direction[14]. The basic reaction in that case is

$$p + N \rightarrow \Sigma + N + n\pi$$

Another effect could be taken in favour of this scheme. In spite of the extreme short lifetime obtained from multinucleon Σ's which, if anything*) would indicate a high percentage of Σ^+, no single Σ-p decay at

*) A loss of Σ-p decays at flight is possible, but a large loss is at least improbable, as was pointed out in section 2e.

flight has been observed by us and only few in other emulsion experiments[13][15][16]. As stated above, the Σ^+-p/Σ^+-π^+ ratio as obtained from samples like that in Table I is about 1. With the assumption of 2 different Σ's this ratio needs not to be the same for both[6]. The isotopic spin $\Delta I = 1/2$-rule does not require a certain distinct value of the Σ^+-branching ratio, (this is the case only for the Λ-hyperon with isotopic spin 0), the branching ratio could vary within wide limits.

Following YANG and LEE[17] the Σ-hyperon generally could be a mixture of two components with odd relative parity. The relative abundance of these components at production would be a function of the kind of the primary reaction and perhaps also a function of the momentum of the interacting particles. In addition the 2 components could flip between each other by weak interactions[18].

We want to conclude with a remark what could be the nature of the proposed difference between reactions 1 and 2. Today one knows that from the theoretical point of view parity needs not necessarily be conserved in strong interactions of strange particles [19–21]. So f. i. reaction 1 could be parity conserving, while reaction 2 would not conserve parity*).

Discussion

It is not the aim of this paper to claim evidence for one or the other of the two suggested possibilities, but we wanted to point at the presence of different production reactions for the observed Σ's.

We suggest two methods which could decide in favour of one or the other of the schemes discussed.

In order to get an idea about the magnitude of an eventual experimental bias influencing the lifetime determination of fast Σ's, one could use the K^--capture stars at flight. As was shown in ref. [2]) the contribution of the multinucleon reactions in these stars is small, but the average energy of the Σ's is comparable with the energy of the multinucleon Σ's from K^--capture stars at rest. Table III contains the data of 11 hyperons with more than 50 MeV kinetic energy. The application of the interpolation formula used in section 1. for the Σ^+-lifetime yields a lifetime value $> 2.6 \times 10^{-10}$ sec. This is unreasonably large and can only be due to a statistical fluctuation. We calculated therefore a lower limit taking the arithmetic mean of the lifetimes for all decays at flight. The value obtained in this way is

$$\tau = (1{\cdot}17^{+0{\cdot}47}_{-0{\cdot}35}) \times 10^{-10} \text{ sec.}$$

*) There are experimental results which indicate f. i. parity conservation in the process $\pi^- + p \rightarrow \Lambda + K$ [22]. But on the other hand we know cloud-chamber experiments [23] which could be consistent with parity nonconservation in the reaction $\Sigma + N \rightarrow \Lambda + N$.

Unfortunately the statistics is too poor, but it could easily be completed by a compilation of already existing data from K^--capture stars at flight in emulsions.

Finally we mention another possible check, namely a bubble chamber exposure of type $p + p \rightarrow \Sigma + N + K$ and a lifetime study of the resulting Σ's.

Table III

Event No.	Charged decay-product	T^{Star} (MeV)	T^{Decay} (MeV)	Potential time of flight star $\times 10^{13}$ sec	Potential time of flight decay $\times 10^{13}$ sec	Lifetime $\times 10^{13}$ sec
B 471	π	117	115	3650	3480	150
B 325	π	50	36	1235	820	415
B 72	π	98	84	2850	2350	500
K 235	π	52	28	1300	600	700
B 370	π	115	78	3480	2145	1335
B 252	π	63	16	1650	310	1340
Ch 269	Capture	54	0	1355	0	>1355
Lo 103	π	71	26	1925	545	1380
S 76	P	68	19	1820	370	1450
B 48	π^-	117	47	3650	1140	2510
Lo 19	π^-	107	27	3100	570	2530
I 171	P	54	34	1355	760	595
I 82	π^+	57	0	1450	0	>1450

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