Vol. A37 (1970) *ACTA PHYSICA POLONICA* Fasc. 1

THE PRODUCTION OF HYPERNUCLEI BY THE ABSORPTIONS OF Σ^- HYPERONS AT REST IN EMULSION NUCLEI

G. Bohm and F. Wysotzki

Institut für Physik hoher Energien der Deutschen Akademie der Wissenschaften zu Berlin, Berlin-Zeuthen

M. Csejthey-barth*, J. Sacton, G. Schorochoff* and G. Wilquet*

Service de Physique des Particules Elémentaires, Université Libre de Bruxelles

A. Thompson

Institute of Advanced Studies, Dublin

F. Esmael and D. Stanley**

Physics Department, University College, London

D. H. Davis, E. R. Fletcher, S. P. Lovell, N. C. Roy and J. H. Wickens***

Physics Department, University College, London

J. E. Allen and A. Fishwick

Physics Department, Westfield College, London

A. Filipkowski, K. Garbowska-Pniewska and E. Skrzypczak

Institute of Physics, University of Warsaw**** and Institute for Nuclear Research, Warsaw

(Received July 25, 1969)

The production of hypernuclei by the interactions at rest of Σ^- hyperons has been studied in emulsion. The rates of trapping of Λ° hyperons following absorptions in both heavy (Ag, Br) and light (C, N, O) nuclei have been estimated. These are compared with the corresponding rates found for K^- meson captures. An analysis of the production reactions proved to be of little help in the assignment of hypernuclear identities.

---

* Chercheur agréé de l'Institut Interuniversitaire des Sciences Nucléaires, Belgique.

** Now at the Institute of Mining and Technology, Soccoro, New Mexico, U. S. A.

*** Now at the Université Libre de Bruxelles.

**** Address: Instytut Fizyki, Uniwersytet Warszawski, Warszawa, Hoża 69, Polska.

1. *Introduction*

The capture of a Σ^- hyperon in a complex nucleus must give rise to the production of a Λ^0 hyperon via the reaction

$$\Sigma^- + p \to \Lambda^0 + n \tag{1}$$

with an energy release of about 80 MeV. As in the case of K^- meson capture, the Λ^0 hyperon may be emitted free or bound within a light hypernucleus, either directly or in the ensuing evaporation stage of the capture process. If on the other hand the Λ^0 hyperon is not emitted, it will form a so-called "spallation hypernucleus".

Whereas the production of hypernuclei following K^- meson absorptions at rest in emulsion nuclei has been extensively studied [1, 2, 3], the available data for the corresponding processes following Σ^- hyperon captures are meagre [4, 5, 6, 7]. In this work, the statistics, especially those for Σ^- hyperons originating from K^- meson captures on hydrogen, have been much increased. With these additional data an attempt has been made to compare the processes of hypernucleus production by K^- meson and Σ^- hyperon captures.

2. *Experimental procedure*

The material used in this study was obtained from three stacks of Ilford K 5 emulsions which had been exposed to a total of about 10^6 stopping K^- mesons at the CERN PS. The procedures used to locate the K^- meson capture stars are fully described in References [2, 8, 9, 10]. All black and grey tracks were followed from the K^- meson capture star to the point where they left the pellicle or ended. In order to reduce the contamination of non-mesonic decays of hypernuclei and π^- meson captures among the sample of Σ^- hyperon captures used to calculate the production rates for hypernuclei, it was required that the range of the Σ^- hyperon should exceed 200 μm. During the course of this work all Σ^- hyperon capture stars, defined as previously as having one prong of length greater than 200 μm or two prongs each longer than 5 μm, were recorded. The same procedure used in the K^- meson work was adopted in order to detect decays of hypernuclei originating from Σ^- hyperon captures. For those stars which gave rise to an hypernucleus the range of the hypernucleus was measured and the presence was noted at both the production and decay stars of short prongs (of length between 3 and 30 μm), recoil (<3 μm) and electron[1] tracks. When the hypernucleus decayed π^- mesonically the ranges and directions of all charged particles at the Σ^- capture star were measured.

3. *Σ^- hyperons from K^- meson captures on hydrogen*

In the initial scanning for K^- meson capture stars, those on hydrogen giving rise to charged ($\Sigma\pi$) pairs were recorded. The Σ^- hyperon track was followed to its endpoint in the emulsion. In this way, 1284 Σ^- hyperon captures were found for which there is no bias

---

[1] An Auger electron track was defined as having at least three grains, the first of which was required to be less than 3 μm from the Σ^- hyperon capture point.

against small or even zero — prong stars. The ranges of charged secondary particles were measured and the presence of Auger electron tracks was sought for all the events.

The prong number distribution of these Σ^- hyperon capture stars, separated on the basis of the presence or absence of Auger electron tracks and short prongs is given in Table I. The presence of an Auger electron track is a strong indication that the absorption took place on a heavy emulsion nucleus (Ag, Br), whereas the Coulomb barrier makes improbable the emission of particles of short range from heavy nuclei. Indeed, it may be seen from Table I that very few, about 3%, of the events show presence of both Auger electron tracks and short prongs.

TABLE I

Prong number distribution for Σ^- hyperon captures at rest in which the Σ^- hyperon originates from a rest $K^- - p$ event

Presence of Auger electron or blob	Presence of short prong	Number of prongs							Total
		0	1	2	3	4	5	6	
No	No	319	55	14	16	12	4	1	421
No	Yes	0	80	97	41	7	0	0	225
Yes	No	439	104	25	23	9	2	1	603
Yes	Yes	0	18	14	3	0	0	0	35
TOTAL		758	257	150	83	28	6	2	1284

These events were also used to find the correction factor needed to allow for these Σ^- hyperon capture stars which did not fulfil the adopted criteria (so called ϱ — endings). This number, $(\Sigma^-\sigma + \Sigma^-\varrho)/\Sigma^-\sigma$, was 3.25 ± 0.18 and has been combined with that previously obtained by Davis and Skjeggestad [11], namely 3.63 ± 0.53, to give a correction factor equal to 3.29 ± 0.17.

The correction factor applicable to Σ^- hyperon absorptions in heavy nuclei has been calculated on the basis of an Auger electron track criterion and has been found to be 4.22 ± 0.38. This value is in agreement with that found by Davis and Skjeggestad [11], namely 4.16 ± 0.75, the combination of the two results giving 4.21 ± 0.32. Assuming that 40% of all Σ^- hyperon captures occur on light nuclei, as in the case of muons, π^- and K^- mesons [14, 15, 16], the correction factor for light nuclear captures is 1.91 ± 0.40.

From Table I it is seen that about 50% of the Σ^- hyperon captures gives rise to an Auger electron. Assuming again that 60% of all absorptions occur in heavynuclei and that the Auger electron rate is 3% in light nuclei, this rate in heavy nuclei is found to be of the order of 80%.

4. *Results*

The observed number of Σ^- hyperon absorptions leading to recognizable stars was 4271 and this corresponds thus to a total of 14050 ± 730 Σ^- hyperon absorptions. The emission of a hypernucleus was seen in 442 cases, giving rise to a lower limit of the production rate of hypernuclei by the capture at rest of Σ^- hyperons in emulsion nuclei of

TABLE II

Hypernucleus production rates by the capture at rest of Σ^- hyperon in emulsion nuclei

Reference	Andersen *et al.* [5]	Mora [7]	Present work	Weighted mean
Rates (in %)	$2.7^{+0.5}_{-0.4}$	3.0±0.5	3.15±0.23	3.05±0.19

3.15±0.23%. This result is compared with those previously published in Table II. These values are seen to be consistent[2], the weighted average being 3.05±0.19%.

A further 279 hypernuclei were observed for which the range of the primary Σ^- hyperon was less than 200 μm. Although these events are not used to determine the production rates they have been added to the sample for other aspects of the analysis.

The characteristics of production and decay of all the hypernuclei are set out in Table III.

TABLE III

Characteristics of Σ^- hypernuclei*

Range intervals (μm)	0—3	3—5	5—10	10—30	30	Total
Total number of events	259 (171)	101 (62)	157 (9)	87 (56)	117 (63)	721 (442)
Number of mesonic HF	29 (16)	28 (17)	64 (34)	38 (29)	67 (31)	226 (127)
Number of non mesonic HF	72 (49)	71 (43)	93 (56)	49 (27)	50 (32)	335 (207)
Number of mesonic DC	8 (7)	0 (0)	0 (0)	0 (0)	0 (0)	8 (7)
Number of non mesonic DC	150 (99)	2 (2)	0 (0)	0 (0)	0 (0)	152 (101)
Q^- ratio	6.0±0.9 (6.4±1.3)	2.6±0.4 (2.6±0.6)	1.5±0.2 (1.6±0.3)	1.3±0.2 (0.9±0.2)	0.7±0.1 (1.0±0.2)	2.1±0.1 (2.3±0.2)
% of HF primary star with short prong	23.8±4.2 (21.5±5.1)	39.4±4.9 (50.0±6.5)	40.1±3.9 (37.8±5.1)	49.4±5.4 (51.8±6.7)	58.1±4.6 (63.5±6.1)	42.2±2.1 (44.0±2.7)
% of primary star with Auger electron or blob	41.7±3.1 (39.2±3.7)	5.9±2.4 (3.2±2.2)	6.4±1.9 (7.8±2.8)	9.2±3.1 (7.1±3.4)	14.5±3.3 (15.9±3.6)	20.7±1.5 (20.4±1.9)
% of non mesonic events with short prong at primary or secondary star	25.7±2.9 (25.0±3.6)	67.1±5.5 (73.3±6.6)	65.6±4.9 (60.7±6.5)	69.4±6.6 (70.4±8.8)	72.0±6.3 (71.9±7.9)	48.7±2.3 (47.4±2.8)

* The numbers in brackets refer to those Σ^- hyperons with range larger than 200 μm.

The true rate of production of hypernuclei should include the contribution from those which are not directly observable. Such events may be conveniently grouped into three categories:

(*i*) those which decay at a point so close to the production vertex as to be indistinguishable from it (so-called cryptofragments, a category embracing the majority of the heavy spallation hypernuclei).

---

[2] The results presented by Frodesen *et al.* [6] form part of the statistics previously published by Andersen *et al.* [5].

(*ii*) those which decay π° mesonically. In this work, an estimate of their number has been made by assuming that the overall π^-/π° decay ratio is the same[3] as for the free decay of the Λ° hyperon, *i.e.* 2.

(*iii*) those non-mesonic decays where the hypernucleus is of short range and is the only charged product issuing from the Σ^- hyperon capture. The number of such events has been estimated from the number of similar events where the decay of the hypernucleus is π^- mesonic, and by adopting a somewhat arbitrary value of 5 for Q^-, the non-mesonic to π^- mesonic ratio for these hypernuclei [12].

These corrections were applied, where appropriate, in what follows.

5. The Λ° hyperon trapping probability following the absorptions at rest of Σ^- hyperons in heavy emulsion nuclei

The Σ^- hyperon captures on heavy nuclei have been defined as those which exhibit an Auger electron track but no short prong at the capture star. From the data obtained from Σ^- hyperons produced by K^- meson captures on hydrogen it is seen that 47±3% of all captures are in this category, *i.e.* 6603±823 events. The number of observed decays of hypernuclei in this sample is 77, leading to a production rate of 1.17±0.20%. Sixty seven hypernuclei have ranges less than 3 μm and must, from consideration of the effect of the Coulomb barrier, be attributed to heavy spallation products which received sufficient momentum to be observed. The 10 hypernuclei of long range ($\geqslant$ 30 μm) are light evaporation products (mainly hydrogen).

An estimate of the rate of production of unseen heavy spallation hypernuclei has been made by comparing the frequencies of emission of protons of energy greater than 50 MeV from Σ^- hyperon absorption son heavy nuclei and from observed heavy spallation hypernuclei produced by 800 MeV/c K^- meson interactions. On the assumption that the probability of emission of a fast proton is the same from heavy spallation hypernuclei formed by stopping Σ^- hyperons and 800 MeV/c K^- mesons, the rate of production of unseen heavy spallation hypernuclei by Σ^- hyperon captures is found to be 15±3%. This figure may be somewhat underestimated if, as pointed out by Lagnaux *et al.* [13], a considerable fraction of non-mesonic decays of heavy hypernuclei do not involve the emission of charged particles and therefore remain undetected.

Thus the overall Λ° hyperon trapping probability following Σ^- hyperon absorption in heavy emulsion nuclei is 16±3%.

There were 5 π^- mesonic decays of spallation hypernuclei and 4 cases in which a Σ^- hyperon capture in a heavy nucleus gave rise to the emission of a slow π^- meson. These results lead to an estimate of ~120 for Q^- for heavy spallation hypernuclei. This value confirms that found by Lagnaux *et al.* [13] and is in contradiction of the requirement that these hypernuclei should have a Q^- value of the order of 3500 if their lifetime is 10^{-12} sec as quoted by Bhalla *et al.* [21].

---

[3] It should be noted that the π^-/π° decay ratio for particular species of hypernuclei may depart considerably from this value of 2.

6. *The Λ° hyperon trapping probability following the absorption at rest of Σ^- hyperons in light emulsion nuclei*

It is not possible to select a pure and yet at the same time unbiased sample of Σ^- hyperon captures on light nuclei. It has therefore been assumed that the proportion of Σ^- hyperon captures on light nuclei in emulsion is 40% as it is for muons, π^- and K^- meson captures [14, 15, 16]. This leads to a total of 5620 ± 290 captures on light nuclei in the sample.

Those hypernuclei whose ranges lie between the limits 3 μm and 30 μm have been assumed to originate from captures on light nuclei. In addition it is found that the production star characteristics for hypernuclei of ranges greater than 30 μm are very similar and thus it is concluded that the majority of these hypernuclei come from light nuclei also. Only those which are associated with an Auger electron at the production vertex have been ascribed to heavy nuclear captures (10 events; see Section 5).

As shown in the previous section, there is an important contribution of heavy spallation hypernuclei in the 0–3 μm range interval. The fraction of non-mesonic hypernuclei with a short prong at either the production or decay star is nearly constant throughout the range interval 3–30 μm, and the mean value of this fraction is $(607. \pm 3.2)\%$. Assuming that for the light hypernuclei this fraction will remain at this constant value in the 0–3 μm interval and that the production and decays of heavy spallation hypernuclei do not give rise to short range particles, it is estimated that (56 ± 8) of the non-mesonic hypernuclei in this range interval are light.

The π^- mesonic hypernuclei in the 0–3 μm range interval were classified as heavy spallation hypernuclei if the range of the π^- meson was less than 8 mm and there was no short prong at either the production or decay vertex. All other π^- mesonic hypernuclei in this range interval were considered to be light, originating from light nuclei.

Finally it is necessary to estimate the number of non-mesonic hypernuclei which are not directly observable. There were 12 light π^- mesonic hypernuclei in the range interval 0–10 μm which were unaccompanied at the Σ^- hyperon capture star by any other prong. Adopting a value of 5 for Q^- for these events, which are expected to be of charge greater than 4, there should be about 60 unobserved non-mesonic decays in the sample. In addition, there were 4 Σ^- hyperon captures yielding π^- mesons which could be ascribed to the π^- mesonic decays of heavy spallation hypernuclei. These events must be examples of unseen light π^- mesonic hypernuclei. Assuming that the Q^- ratio for these is the same as that for observed light mesonic hypernuclei in the 0–3 μm interval it is estimated that there are 12 unseen non-mesonic hypernuclei (cryptofragments) originating from light nuclear captures.

The overall Λ° hyperon trapping probability in light nuclei is thus found to be $(8.5 \pm 0.5)\%$.

7. *The light π^- mesonic hypernuclei*

The production and decay reactions of all the π^- mesonically decaying hypernuclei have been analysed using the computer programme written by Gajewski [17]. In contrast to the results published by Frodesen *et al.* [6] it was found that the analysis of the production reaction was of little help in removing ambiguities existing in the identification of the events.

8. Comparison of the results from K^- meson and Σ^- hyperon captures at rest

These results have confirmed those obtained previously [4, 5] in that it is found that the trapping probability of Λ° hyperons following Σ^- hyperon captures is much less than it is for K^- meson absorptions.

For K^- meson absorptions in the heavy emulsion nuclei, Lemonne *et al.* [2] estimated the Λ° hyperon trapping probability to be $(58\pm15)\%$ whilst from bubble chamber studies using a freon (CF_3Br) — propane mixture this probability for bromine was found to be $(51\pm14)\%$ [18] and $(54\pm13)\%$ [19]. It should be noted, however, that these results can only be considered as lower limits since in some 20 to 30% of the K^- meson absorptions a charged Σ hyperon is emitted.

The Λ° hyperon trapping probability following Σ^- hyperon capture on a light emulsion nucleus was estimated in this work to be 8.5%. This is to be compared with the values obtained for K^- meson captures in light emulsion nuclei [2]: $(8\pm2)\%$, in carbon or fluorine: $(18.5\pm3.5)\%$ [18] and $(9\pm5)\%$ [19] and in neon [20]: $9.5\pm3.0\%$.

9. Conclusions

a. From a study of Σ^- hyperons produced by K^- meson captures on hydrogen the correction factor $\frac{\Sigma_\varrho^- + \Sigma_\sigma^-}{\Sigma_\sigma^-}$ was found to be 3.25 ± 0.18. For captures on heavy nuclei, this number is 4.22 ± 0.18.

b. The total Λ° hyperon trapping probability following Σ^- hyperon capture on a heavy emulsion nucleus was found to be 16%, much lower than the value obtained for K^- meson captures.

c. An estimate of Q^- for heavy spallation hypernuclei was 120.

d. The total Λ° hyperon trapping probability following Σ^- hyperon capture on a light emulsion nucleus was estimated to be 8.5%.

e. Contrary to the experience of Frodesen *et al.* [16], the analysis of the production reaction proved to be of little aid in the identification of hypernuclear species.

Our thanks are due to our scanning team for its painstaking work.

REFERENCES

[1] D. Abeledo *et al.*, *Nuovo Cimento*, **22,** 1171 (1961).
[2] J. Lemonne *et al.*, *Nuovo Cimento*, **34,** 529 (1964).
[3] D. H. Davis *et al.*, *Nuovo Cimento*, **22,** 275 (1961).
[4] J. Sacton *et al.*, *Nuovo Cimento*, **23,** 702 (1962).
[5] B. Andersen *et al.*, *Phys. Rev.*, **132**, 2281 (1963).
[6] A. G. Frodesen *et al.*, *Nuclear Phys.*, **68,** 575 (1965).
[7] S. Mora, *Nuovo Cimento*, **52***A*, 800 (1967).
[8] M. Csejthey-Barth *et al.*, *Phys. Letters*, **16,** 180 (1965).
[9] C. Mayeur *et al.*, *Nuovo Cimento*, **43,** 180 (1966).
[10] G. Bohm *et al.*, *Nuclear Phys.*, *B*4, 511 (1968).
[11] D. H. Davis, O. Skjeggestad, *EFINS report* 63–7 (1963).
[12] M. W. Holland, *Nouvo Cimento*, **32,** 48 (1964).

[13] J. P. Lagnaux *et al.*, *Nuclear Phys.*, **60,** 97 (1964).
[14] A. Pevsner *et al.*, *Nuovo Cimento*, **19,** 409 (1961).
[15] M. Csejthey-Barth, J. Sacton, *Bulletin de L'Institut de Physique de l'Université Libre de Bruxelles*, **4,** (1962).
[16] R. D. Hill, *Suppl. Nuovo Cimento*, **19,** 83 (1961).
[17] W. Gajewski, *Bulletin de l'Institut de Physique de l'Université Libre de Bruxelles*, **29** (1966)
[18] W. L. Knight *et al.*, *Nuovo Cimento*, **32,** 598 (1963).
[19] G. Schorochoff, *Thesis*, Université Libre de Bruxelles, unpublished.
[20] H. O. Cohn *et al.*, *Phys. Letters*, **27***B*, 527 (1968).
[21] K. B. Bhalla *et al.*, *Nuovo Cimento*, **58***A*, 249 (1968).