INSTITUTE FOR NUCLEAR STUDY
UNIVERSITY OF TOKYO
Tanashi, Tokyo 188
Japan

INS-Rep.-658
Nov. 1987

HYPERON COMPOUND NUCLEUS

Toshimitsu Yamazaki

INS-Rep.-658
Nov. 1987

Lecture given at the Enrico Fermi Summer School (Varenna, June 29 - July 9, 1987)

HYPERON COMPOUND NUCLEUS

Toshimitsu Yamazaki

Institute for Nuclear Study, University of Tokyo
3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan

Abstract

The formation of various hypernuclei from K^- absorption at rest is discussed from the viewpoints of compound decay of highly excited hypernuclei in contrast to the direct reaction mechanism. Recent (stopped K^-, π) experiments at KEK as well as old data of emulsion and bubble chamber experiments are discussed. Some future direction of hypernuclear spectroscopy is suggested.

1. INTRODUCTION

Since Niels Bohr the concept of compound nucleus is well established and materialized for nuclear physics. When a nucleon hits a nucleus, it gets absorbed by the target nucleus and fused into a compound nucleus. Microscopically, this is the result of the strong nucleon-nucleon interaction. The first hit induces a particle-hole excitation and the excited nucleon induces another particle-hole excitation, and so on, and this multiple process tends to end up in a thermal equilibrium, if not completely. From such highly excited well-cooked compound states are evaporated nucleons, alpha particles, etc., to populate residual nuclei.

"Strange baryons" such as Λ and Σ particles, as listed in Table 1, are called hyperons. They have "strangeness" quantum number, or in modern expression, a strange quark as a constituent. They can be implanted into nuclei to form "strange nuclei" or hypernuclei. Their behaviors are very important to study, and by now many interesting results have been obtained /1/. The present lecture is concerned with "how to study" one of the many facets of hypernuclear physics.

Here, we raise a question, what happens when a nucleus is hit by a hyperon? The hyperon-nucleon interaction is weaker than the nucleon-nucleon interaction, and thus we expect that the hyperon absorption by a nucleus may be weaker. If we use the known Λ-proton elastic scattering cross section $\sigma_{\Lambda N}$, which increases from 30 mb at 400 MeV/c to 100 mb below 250 MeV/c /2/, then the quasi-elastic cross section in a nucleus is expressed by

(1) $\sigma_{\Lambda}(p_{\Lambda}) = \sigma_{\Lambda N}(p_{\Lambda}) \cdot P(p_{\Lambda}),$

where $P(p_{\Lambda})$ is a suppression factor due to the Pauli blocking effect on the scattered nucleon. This factor was estimated by Yazaki /3/ based on the Fermi gas model. It is around 0.3 at 250 MeV/c and increases with the Λ momentum. As a result, the $\sigma_{\Lambda}(p_{\Lambda})$ is around 30 mb irrespective of p_{Λ} in the momentum region of our interest (100-300 MeV/c). So, we estimate the mean free path of Λ to be around 2 fm. The Λ absorption following the strong $\Sigma \rightarrow \Lambda$ conversion has a similar mean absorption length. This means that a hyperon causes the first collision with substantial probability. Once the hyperon hits a nucleon, this nucleon causes compound nucleus formation independent of the initial hit. Thus, "hyperon compound nucleus" is formed. Here, the hyperon is merely one of the many constituents in the democratic nuclear society. Furthermore, the hyperon does not feel Pauli exclusion from surrounding nucleons so that it may easily go down to its deeper energy states. So, most likely, only nucleons are emitted and the hyperon remains in one of the residual nuclei, forming lower excited states of a hypernucleus.

There are old bubble chamber data /4/ which showed that a large fraction of the strangeness brought by K^- absorption dies in nuclei by the weak interaction of Λ in contrast to the usual belief that most hyperons escape the nucleus and decay in a free space. This is very suggestive and provides experimental evidence for the formation of hyperon compound nucleus. Actually, it was found in the former time that various hypernuclear fragments were produced abundantly from K^- absorption at rest. The ground state properties (energy and decay mode) as well as their production branching ratios were studied comprehensively, though the parent nuclei were not necessarily identified in emulsion experiments.

In this lecture the author will revisit this problem with renewed interest.

2. CONTINUUM PART IN STRANGENESS EXCHANGE REACTIONS

In usual hypernuclear spectroscopy one employs strangeness exchange reactions such as (K^-, π) and (π, K^+). The elementary branching ratios are listed in Table 2. The pion momentum is related to the hypernuclear energy level, as shown symbolically in Fig.1. The corresponding single-particle potential for hyperon is also shown. Discrete peaks below the hyperon emission threshold ($B_{HY} = 0$) correspond to bound states. Above the threshold the pion spectrum exhibits a large continuum part which is often called "quasi-free continuum". Literally, it means that the continuum part consists of pions which are emitted in quasi-free process

(2) $K^- + \text{"N"} \rightarrow HY + \pi,$

where "N" is a nucleon in a target nucleus that carries a Fermi momentum. The quasi-free process claims that not only the pion but also the hyperon (HY) are in free space. The "quasi-free" continuum is, however, quite a misleading name by which one is supposed to believe without experimental verification that the final state of the hyperon is in free space. Do hyperons in the unbound energy region always escape the nucleus?

This problem was studied experimentally in old days by using emulsions and bubble chambers in which they identified secondary decays of free hyperons (as listed in Table 1) and asked whether or not the number of free decays agrees with the number of strangeness brought into nuclear targets /4/. The answer was as follows. About 50% of Σ produced inside a nucleus escape the nucleus but the rest remain and eventually die in the conversion process

(3) $\Sigma + N \rightarrow \Lambda + N + 77$ MeV.

The produced Λ here, though carrying a large kinetic energy, is absorbed by the nucleus again. Thus far, the strangeness remains inside the nucleus. Ultimately, the strangeness dies in the nuclear weak decay process.

The old-day experiments were restricted to only a few targets but their implication is strong enough. They indicate that the mean free path of a hyperon in a nucleus is around 1.5 fm. In the K^- absorption at rest most hyperons are born in the surface region of the target nucleus. Those hyperons moving inwards are absorbed, while those going outwards may escape. The simple estimate, 2 fm, of the hyperon mean free path in a nucleus, as given in section 1, can account for the observed absorption coefficient. Once the kinetic energy of the hyperon is transferred to a kicked-out nucleon, then the resultant process is the formation of a compound nucleus. From this viewpoint one can say that the hyperon sitting in the unbound energy region (see Fig.1) forms a hyperon compound nucleus with 50% probability (the rest is really "quasi-free"). The pion once produced together with a hyperon is also subject to secondary interactions within the nucleus. Usually, it is about 50% absorbed. From an intuitive geometrical consideration (see Fig.2) we expect that the pion observed outside corresponds to a well absorbed hyperon. It would be nice to examine experimentally the whole concept of hyperon compound nucleus by looking at the absorption process of external hyperons in nuclear targets. Such an experiment can be conceived in view of advanced experimental techniques such as an emulsion-counter hybrid system.

Usually, it is believed that the pions in the "quasi-free" continuum do not contribute to the formation of hypernuclei (namely, the strangeness produced in this continuum flies away!). *On the other hand, if the continuum corresponds to hyperon* compound state, it should subsequently proceed to hypernuclear residual states after the emission of one or a few nucleons. The excess energy of the hyperon compound state is most likely taken away by nucleons, not by the hyperon. This means that hypernuclei of a few nucleons less than in the original compound hypernucleus are produced abundantly compared to those populated directly. Actually, various hyperfragments were produced after K^- absorption in old emulsion experiments /5/. Some of the data are reproduced in Table 3. Unfortunately, in those emulsion experiments the parent nuclei cannot be identified. Recently a new data has been obtained in a modern counter experiment on stopped K^- absorption carried out at KEK /6,7/.

Another example of hypernuclear production not through direct reaction spectroscopy is to use anti-proton absorption by nuclei. A group at CERN studied delayed fission products after anti-proton stopping in a heavy target /8/. Here, nothing in the production stage was measured and a delayed fission component, though it is a very small fraction was clearly identified and was interpreted as the weak decay of heavy hypernuclei. In this case the hypernuclear ground states are most likely formed through hyperon compound decay. In this context hypernuclei are expected to be produced abundantly in anti-proton reactions not only in heavy targets but also in lighter ones. How to distinguish hypernuclear decays from others is, however, an open problem. Another delayed fission component produced in the bombardment by 1.3 GeV electrons has also been reported by a Russian group, who assigned this to the weak decay of heavy hypernuclei /9/. This assignment sounds less certain, but it is a very interesting phenomena.

3. NUCLEAR WEAK DECAY OF Λ: ANOTHER SOURCE OF PIONS

If the hyperon compound nucleus produces more hypernuclei than in the direct reaction process, one is tempted to make use of those hypernuclei. From the spectroscopical viewpoints the most interesting are gamma decays and pionic weak decays. Let us consider this problem. There are two kinds of sources of pions emitted in K^- absorption. One is the pion in the formation process of a hyperon, and the other is the pion in the weak decay process of hyperons. In particular, a free Λ decays in the following way with lifetime of 263 psec

(4) $$\Lambda \rightarrow p + \pi^- + 37.8 \text{ MeV} \quad (64\%)$$

$$\rightarrow n + \pi^o + 41.1 \text{ MeV} \quad (36\%)$$

The ground state of Λ hypernuclei decays as follows

(5) $$^{A}_{Z}A_N \rightarrow {}_{Z+1}A_N + \pi^- + Q_-$$

$$\text{with } Q_- = 37.8 \text{ MeV} - B_\Lambda$$

$$+ \text{MASS EXCESS}[{}_Z(A-1)_N - {}_{Z+1}A_N] + m_e c^2$$

(6) $$\rightarrow {}_Z A_{N+1} + \pi^o + Q_o$$

$$\text{with } Q_o = 41.1 \text{ MeV} - B_\Lambda$$

$$+ \text{MASS EXCESS}[{}_Z(A-1)_N - {}_Z A_{N+1}]$$

In addition, the Λ in nuclei undergoes a special weak decay

(7) $$\Lambda + N \rightarrow N + N + 177 \text{ MeV}$$

without emission of pions. While the pionic decay process in heavy hypernuclei is suppressed by its nearly vanishing overlap between the initial Λ state and final proton states due to the Pauli blocking /10/, the latter non-pionic process with a large Q value occurs rather freely. Thus in medium and heavy nuclei the latter process dominates over the pionic decay. In spite of, and probably because of, its expected small branching ratio the pionic decay process is quite interesting; it is extremely sensitive to many effects, such as short-range correlations, that are not considered in naiive picture.

The pionic decay populates not only continuum states but also final discrete states of the daughter nucleus, as the decay energy available is limitd to 30-50 MeV. In such cases, the pion momenta are monoenergetic, and discrete peaks stand out in a pion momentum spectrum. From the pion momentum one can determine the binding energy of Λ in the parent hypernucleus. This is actually the way how the binding energies of Λ in light hypernuclei were determined in earlier days /5/.

The pionic decay of hypernuclei is one of the nuclear weak decay processes. In contrast to beta decays and muon-capture processes one can identify individual "discrete" decay pions to final states. It should be mentioned that these decay pions are delayed transitions through the hypernuclear ground state which is expected to have lifetime of subnanoseconds and thus can in principle be discriminated from prompt pions which are emitted in the formation process of hyperons. The pionic decay process is only one non-leptonic weak decay in which individual final states can be distinguished, while in the dominating non-pionic decay process only highly excited continuum states are involved. Since the momentum transfer involved in pionic decay is around 100 MeV/c, the pionic transition is limited to s wave and p wave. This severe selection rule together with spin selection governs what kinds of discrete pionic transitions take place.

It should be stressed that the pionic decay probability provides important information on the wavefunctions of ground-state hypernuclei just like beta decays. It is an extremely interesting question to ask whether the Λ in nuclei really distributes according to the $0s_{1/2}$ wavefunction or not. The best clue would be to examine the pionic branching. As an example, the density of Λ in the ground state of ${}^{5}_{\Lambda}$He is discussed from its decay branching ratios and lifetime, which infers that the Λ bound by an alpha particle resides not inside but rather outside /11,12/. If this is really true, it may indicates strong short-range repulsive interaction between Λ and a nucleon and/or Pauli blocking in the quark level. Such arguments can be extended to heavier nuclei but so far no experimental information available. This rather classical subject has been forgotten for many years but now attracts renewed interests. It can be revisited by introducing modern experimental methods. Indeed, high-precision pion momentum measurements in stopped K^- on nuclear targets as a byproduct of direct spectroscopy of hypernuclei have revealed very interesting aspects. In the following section we shall describe recent experiments at KEK.

4. RECENT KEK EXPERIMENT

The experiment was designed so that we can measure a wide pion momentum spectrum of the formation process for both Σ (around 170 MeV/c) and Λ (around

260 MeV/c). For this purpose, a magnetic spectrometer which covers momentum range 100-300 MeV/c was used. The acceptance of the spectrometer in the range of 100 MeV/c for Λ decay was nearly at the lower edge but nevertheless an interesting structure was observed.

Fig.4 shows an unconstrained inclusive spectrum of negative pions when negative kaons were stopped in a $(CH)_n$. In this spectrum as well as in others on Be and Li targets there is a distinct peak of momentum of 132 MeV/c. This peak is identified as the pion coming from the two-body decay process of ${}^4_\Lambda H$

(8) ${}^4_\Lambda H \rightarrow {}^4He + \pi^- + 55.5$ MeV.

This is the well known decay pion which has the highest momentum of all the decay pions because of the extraordinarily large Q value of the above process (namely, the residual nucleus is ${}^4He$). The branching ratio of this process is known to be 70% of the total decay of ${}^4_\Lambda H$. Thus, we obtain the yield of ${}^4_\Lambda H$ in the K^- absorption in these targets, as shown in Table 4.

We also measured a lower momentum portion of the π^- spectrum in the case of ${}^{12}C$ target, but it it too preliminary. Such a spectrum should exhibit additional peaks around 100 MeV/c which have been identified in the emulsion experiment /5/. To this end we have to tune the optimum momentum of the spectrometer system to be around 100 MeV/c. For instance, a pion peak as coming from

(9) ${}^9_\Lambda Be \rightarrow {}^9B + \pi^0 + 30.9$ MeV.

should be seen prominently. If we combine the emulsion data with the preBsent absolute branching rario for ${}^4_\Lambda H$, and further assume the branching ratio for this ground-state transition to be 10% as estimated by theory /10/, then, we obtain the yield of ${}^9_\Lambda Be$ to be 4×10^{-3} per stopped K^-.

On the other hand, in the same π^- spectra on the ${}^{12}C$ target two discrete peaks at 261 and 273 MeV are observed in the Λ formation region. They are identified as direct peaks for the population of the ground $[p_{3/2}]_n^{-1}$ $[s_{1/2}]_\Lambda$ and the excited $[p_{3/2}]_n^{-1}$ $[p]_\Lambda$ states. In Fig.5 the branching ratios obtained for this direct population are compared with those of the typical hyperfragments which are indirectly produced. It is to be noticed that the branching ratios for ${}^4_\Lambda H$ and ${}^9_\Lambda Be$ are by one order of magnitude larger than those for the direct population of the discrete hypernuclear states in ${}^{12}_\Lambda C$. There are many other hyperfragments produced. The total yield should be substantial.

How can we account for these branching ratios? This is an open question. Fig.6 shows "hypernuclear mass excess" of various hypernuclei for A = 12 system. It is clear that most of hyperfragments should be produced from highly-excited continuum region of ${}^{12}_\Lambda C$ and/or ${}^{12}_\Lambda B$. Based on the idea of hyperon compound nucleus one would be able to estimate the branching just as in heavy ion compound reactions. For instance the production of ${}^4_\Lambda H$ may be understood in terms of the evaporation of two alphas from the compound ${}^{12}_\Lambda B$ which is formed in the "door-way" reaction of

(10) ${}^{12}C + K^- \rightarrow {}^{12}_\Lambda B + \pi^0 + 187$ MeV.

There is another interesting possibility, that is, the absorption of K^- by an alpha cluster which is supposed to be present in the surface region of the target nucleus. Since the K^- absorption takes place in the nuclear surface region as K^- cascades down in its atomic orbits, it is extremely sensitive to the surface region of the nucleus. Such a cluster absorption was investigated in pion reactions as well as in kaon reactions, but the situation is not yet clear. In the present case, the signature for this "alpha-cluster absorption" is the production of ${}^4_\Lambda H$ by

(11) $K^- + \text{"alpha"} \rightarrow {}^4_\Lambda H + \pi^0$

Unfortunately, the rate for the direct production of ${}^4_\Lambda H$ from ${}^4He(K^-, \pi^-)$ reaction is not known experimentally. If we use a theoretical estimate by Matsuyama and Yazaki /13/, 3 % per total Λ, the maximum possible rate assuming that the K^- absorption would take place entirely on an alpha cluster would be 1.2×10^{-3} per total stopped K^-, this being below the experimental observation. Thus, we conclude that the ${}^4_\Lambda H$ fragments are produced mainly through the hyperon compound process.

If one can measure discrete pion lines, those can be used as an efficient tagging for gamma decays preceding the ground state hypernuclei. A famous example is the identification of the 0^+ to 1^+ gamma transition in ${}^4_\Lambda H$ which is observed in a singles gamma-ray spectrum in the K^- absorption by Li /13/. In the present KEK experiment this gamma transition was observed, without any dedicated effort, in coincidence with the 132 MeV/c pion line, as shown in Fig.7.

5. PREVIEW: POSSIBLE HYPERNUCLEAR SPECTROSCOPY FOLLOWING HYPERON COMPOUND PROCESS

We have seen that the hyperon formation in the continuum energy region in nuclei by strangeness exchange reactions associates hyperon compound nucleus which decays to residual hypernuclei without losing the strangeness. This suggests a new type of hypernuclear spectroscopy without depending on the formation process. This reminds us of the in-beam gamma-ray spectroscopy from continuum compound reactions initiated by Morinaga and Gugelot in 1963 /15/. Before this revolution the old gamma-ray spectroscopy in nuclear reactions had assumed some kind of formation tagging such as inelestic scattering or particle-transfer reaction. What they showed both experimentally and theoretically was that one can simply obtain level structure (for instance, rotational bands) from a singles gamma-ray spectrum because of the continuum compound state decays dominantly to high-spin states of one residual nucleus. Is a similar situation expected in K^- stopping process? This is not obvious yet. The main stream of strangeness may be divided into several residual hypernuclei. It is certainly an important subject to investigate this problem both experimentally and theoretically . If one can tag gamma rays by using discrete pions from the pionic decay, it will yield a gamma-decay sequence based on an individual hypernucleus, as shown in Fig.3. It is demonstrated in the present preliminary experiment for the easiest case of ${}^4_\Lambda H$. It is worthwhile to investigate this problem in heavier nuclei. It should be mentioned that all the decay pions are delayed transitions. Thus, in principle, they can be distinguished from pions in the formation stage.

The University of Tokyo group at KEK is now constructing a large-acceptance pion spectrometer with a superconducting toroidal magnet, which covers a wide momentum range up to 300 MeV/c and a large solid angle (12 % of 4π). This spectrometer system was designed for pion spectroscopy in the formation process of Σ and Λ hypernuclei in K^- absorption at rest, but it is as well suited to pion spectroscopy in the hypernuclear decay process. This device will enlarge the data rate by an order of magnitude compared to the present spectrometer system. This multi-gap spectrometer will also permit to investigate the correlation of the produced residual hypernuclei with the energy of continuum states formed. This can also be connected to in-flight formation of hypernuclei. In such cases, most of pions in the formation stage go in the forward direction and thus pions of 100 MeV/c range detected at 90-degree geometry come only from the decay process; the spectrum will be cleaner. Furthermore, when combined with possible polarization it will be even more interesting.

ACKNOWLEDGEMENT

This lecture is based on the thought the author has reached during the collaborative work in the KEK experiment on hypernuclear spectroscopy using stopped K^-. The author would like to express his thanks to the members of the SKY group, in particular, Prof. R.S. Hayano, Dr. T. Ishikawa and Mr. H. Tamura. He is grateful to the helpful discussions of Professors K. Yazaki, H. Bando, A. Arima, M. Muraoka, M. Ishihara and T. Fukuda. This work is supported by the Grant-in-Aid for Special Project Research on Meson Science of the Ministry of Education, Science and Culture of Japan.

REFERENCES

/1/ See, for instance, B. Povh, Ann. Rev. Nucl. Sci. 28 (1978) 1.
/2/ Particle Data Table, Phys. Lett. 170B (1986) 1.
/3/ K. Yazaki, private communication (1987).
/4/ C. Van der Velde-Wilquet et al., Nuovo Cimento 39A (1977) 537.
/5/ G. Bohm et al., Nucl. Phys. B4 (1968) 511.
/6/ T. Yamazaki, T. Ishikawa, A. Matsuyama and K. Yazaki, Phys. Lett. 144B (1984) 177.
/7/ H. Tamura et al., Proc. Int. Symposium on Strangeness in Hadronic Matter (June 1987, Bad Honnef) to be published in Nucl. Phys.
/8/ J.P. Bocquet et al., Phys. Lett. B182 (1986) 146.
/9/ V.I. Noga et al., Sov. J. Nucl. Phys. 43 (1986) 856.
/10/ R.H. Dalitz and L. Liu, Phys. Rev. 116 (1959) 1312; D.M. Harmsen et al., Nucl. Phys. B4 (1968) 277; H. Bando and H. Takaki, Prog. Theor. Phys. 72 (1984) 106; T. Motoba, K. Itonaga and H. Bando, private comm. (1987).
/11/ Y. Kurihara, Y. Akaishi and H. Tanaka, Phys. Rev. C31 (1985) 971.
/12/ T. Yamazaki, Nucl. Phys. A463 (1987) 39c.
/13/ A. Matsuyama and K. Yazaki, to be published.
/14/ A. Bamberger et al., Nucl. Phys. B60 (1973) 1.
/15/ H. Morinaga and P.C. Gugelot, Nucl. Phys. 46 (1963) 210; see also, H. Morinaga and T. Yamazaki, "In-Beam Gamma-Ray Spectroscopy" (North-Holland Pub. Co., 1976)

Table 1

Properties of stable hyperons of strangeness -1.

Hyperon	Mass (MeV)	Isospin (I, I3)	Quark structure	Decay mode
Λ	1115.6	(0, 0)	$s(ud)_o$	$\rightarrow p\pi^-$ (64%)
				$\rightarrow n\pi^0$ (36%)
Σ^+	1189.4	(1, 1)	s(uu)	$\rightarrow n\pi^+$ (48%)
				$\rightarrow p\pi^0$ (52%)
Σ^o	*1192.5*	*(1,,0)*	$s(ud)_1$	$\rightarrow 2\gamma$
Σ^-	1197.3	(1,-1)	s(dd)	$\rightarrow n\pi^-$

Table 2

Elementary processes for hyperon productions from K^- absorption at rest.

Initial	Final	Momentum (MeV/c)	Branching ratio (%) elementary	Branching ratio (%) in ^{12}C
$K^- + p$	$\Sigma^+ + \pi^-$	181.4	14.9(2)	37.7(13)
	$\Sigma^0 + \pi^0$	181.1	21.4(7)	25.7(9)
	$\Sigma^- + \pi^+$	172.9	34.9(5)	16.8(5)
	$\Lambda + \pi^0$	254.2	4.9(5)	4.4(3)
$K^- + n$	$\Sigma^0 + \pi^-$	179.5	7.1(21)	3.3(8)
	$\Sigma^- + \pi^0$	177.3	7.1(21)	3.3(8)
	$\Lambda + \pi^-$	253.3	9.7(9)	8.7(4)
$K^- + NN$	$\Sigma^+ + N$			7.3
	$\Sigma^0 + N$			10
	$\Sigma^- + N$			4.3

Table 3

π^- decays of light Λ hypernuclei.
From the old emulsion experiment /5/.

Hypernuclei	Number of π^- decay events		Q value	π^- momentum
	2-body	others	(MeV)	(MeV/c)
${}^{3}_{\Lambda}H$	112	22	43.1	114.2
${}^{4}_{\Lambda}H$	760	93	55.5	132.9
${}^{4}_{\Lambda}He$	-	179	-	-
${}^{5}_{\Lambda}He$	-	1025	-	-
${}^{6}_{\Lambda}He$	0	11	38.1	108.2
${}^{7}_{\Lambda}Li$	3	64	37.8	108.0
${}^{7}_{\Lambda}Be$	-	10	-	-
${}^{8}_{\Lambda}Li$	0	229	48.2	124.1
${}^{8}_{\Lambda}Be$	17	12	31.0	97.0
${}^{9}_{\Lambda}Li$	5	9	46.1	121.1
${}^{9}_{\Lambda}Be$	159	16	30.9	96.8
${}^{11}_{\Lambda}B$	4	7	36.2	105.9
${}^{12}_{\Lambda}B$	0	24	42.3	115.7
${}^{13}_{\Lambda}C$	1	0	28.5	92.9

Table 4

Observed formation probabilities of ${}^{4}_{\Lambda}H$ from K^- absorption at rest by $(CH)_n$, Be and Li targets. From a KEK experiment /7/.

Target	Probability per stopped K^-
Li	$(6\pm2) \times 10^{-3}$
Be	$(3.6\pm1.4) \times 10^{-3}$
$(CH)_n$	$(3.4\pm1.0) \times 10^{-3}$

FIGURE CAPTIONS

Fig.1 A typical (K^-, π^-) spectrum and hypernuclear energy levels in the strangeness exchange reaction.

Fig.2 A cascade inside nucleus. The Λ produced together with π loses its energy at a collision with a nucleon, which then causes further collisions. This takes place when a Λ is produced toward the center of the nucleus.

Fig.3 Hypernuclear levels populated through highly excited continuum and subsequent weak decays of the Λ ground state emitting pions.

Fig.4 Observed π^- spectra in K^- absorption at rest by $(CH)_n$. From a recent KEK experiment /7/.

Fig.5 Production yields of ${}^{9}_{\Lambda}$Be and ${}^{4}_{\Lambda}$H hypernuclei from continuum decay as well as direct yields of the two low-lying states of Λ in the K^- absorption at rest by ^{12}C. The result of the KEK experiment /7/ is combined with a previous emulsion experiment /5/.

Fig.6 Hypernuclear mass excesses of various hypernuclei produced in the K^- absorption at rest by ^{12}C. Most of the hyperfragments observed lie above the Λ emission threshold at 10.4 MeV and can thus be produced only from the continuum region.

Fig.7 A gamma-ray spectrum tagged by the monoenergetic pion decay of ${}^{4}_{\Lambda}$H. The off-peak contribution has been subtracted. The well known 1.1 MeV gamma line is recognized.

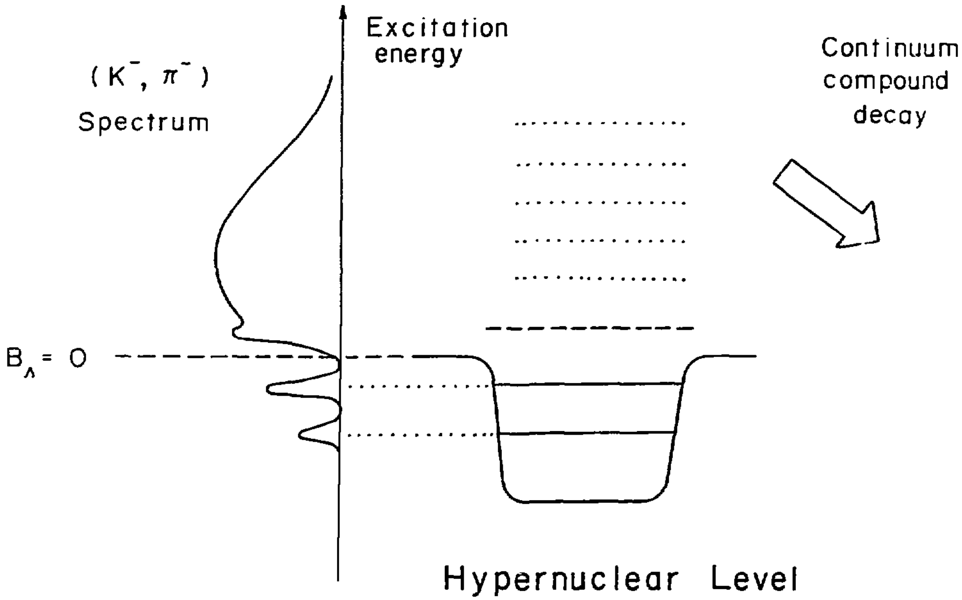

Excitation energy
(K^-, π^-) Spectrum
Continuum compound decay
$B_\Lambda = 0$
Hypernuclear Level

Fig.1

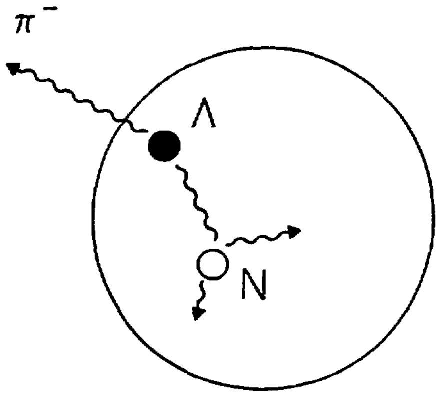


Fig.2

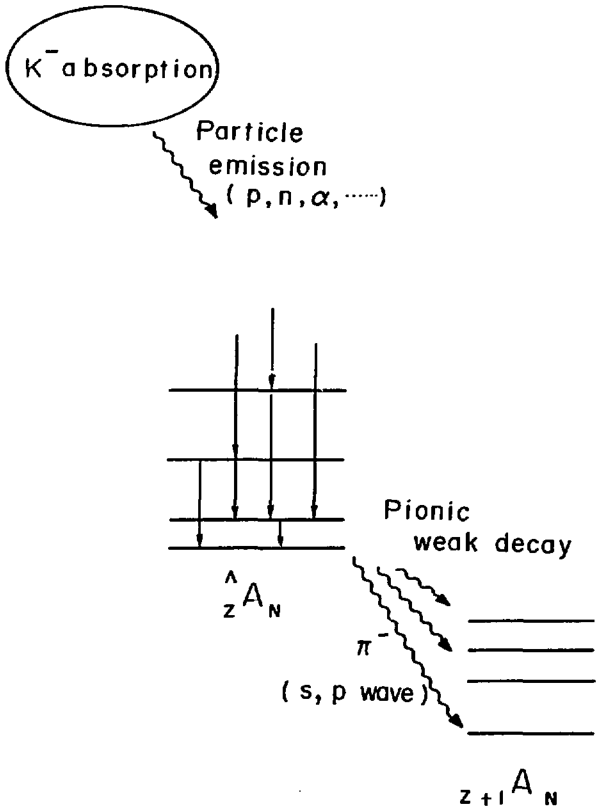

K⁻ absorption
Particle
emission
(p, n, α, ...)
Pionic
weak decay
$_{Z}^{\Lambda}A_{N}$
π^-
(s, p wave)
$_{Z+1}A_{N}$

Fig.3

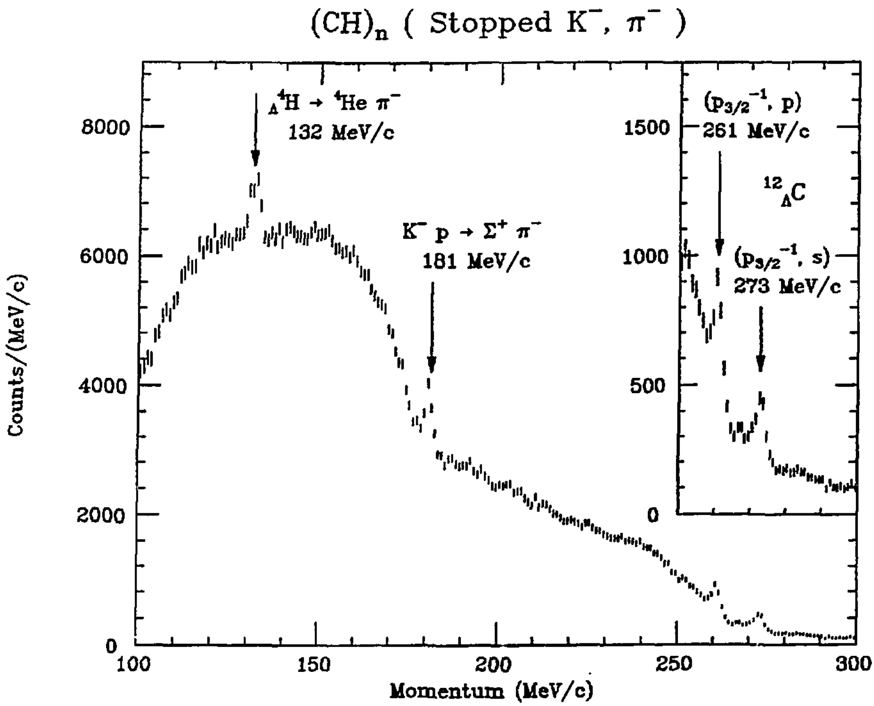

(CH)n (Stopped K⁻, π⁻)
ΛH → He π⁻
132 MeV/c
K⁻ p → Σ⁺ π⁻
181 MeV/c
(p3/2⁻¹, p)
261 MeV/c
12ΛC
(p3/2⁻¹, s)
273 MeV/c
8000
6000
4000
2000
0
1500
1000
500
0
100
150
200
250
300
Counts/(MeV/c)
Momentum (MeV/c)

Fig.4

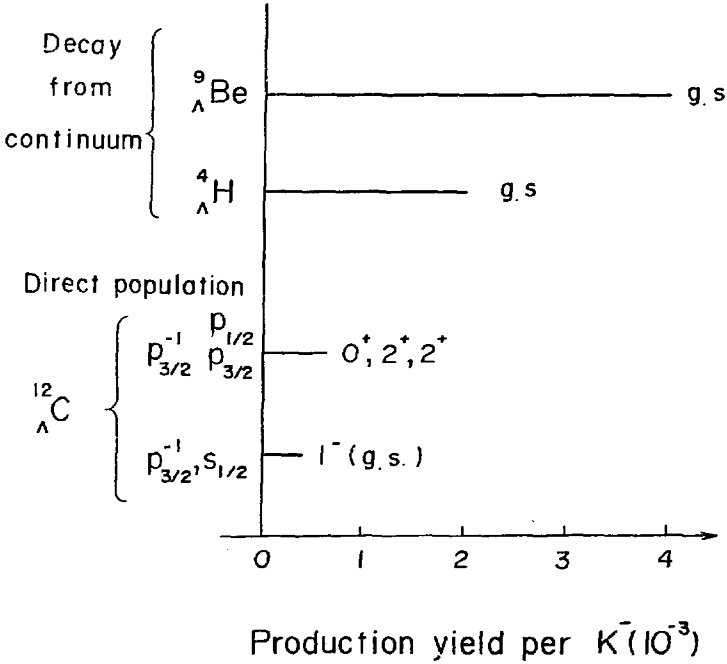
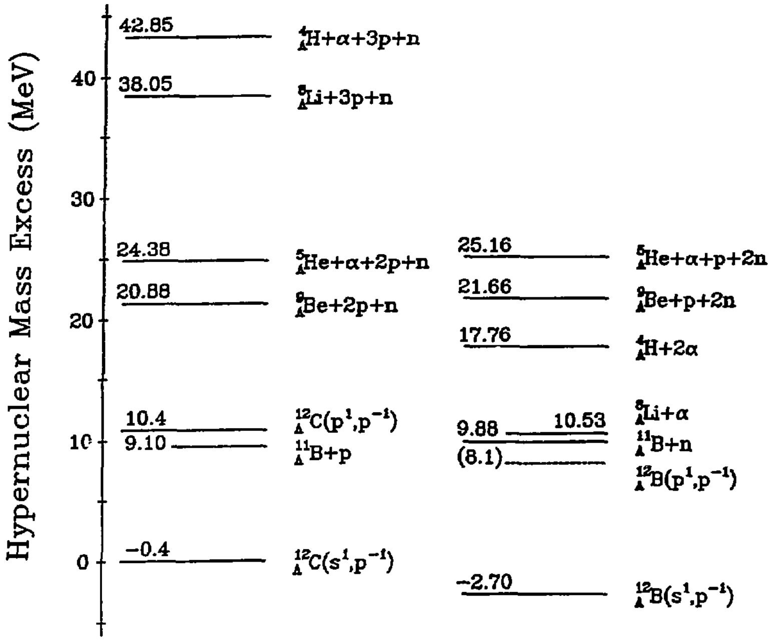
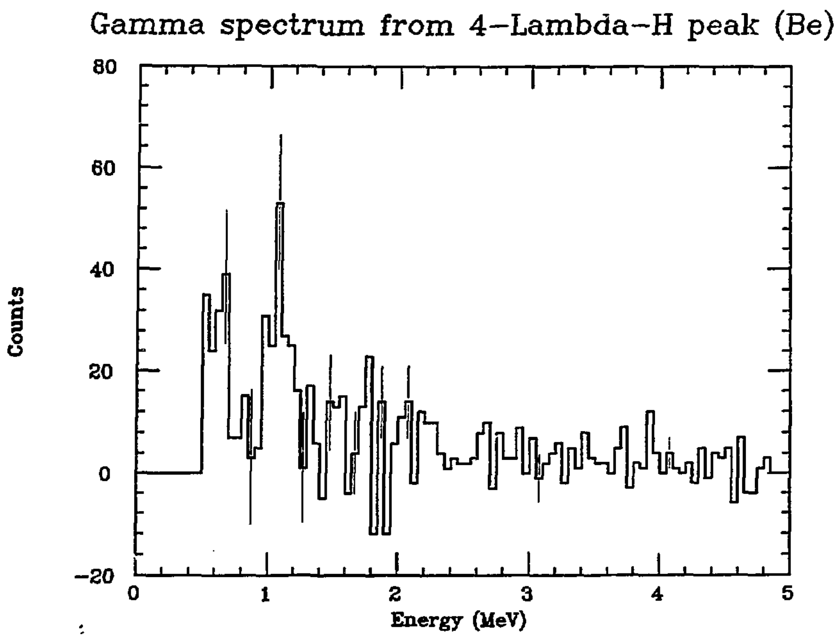

Decay
from
continuum
$^{9}_{\Lambda}Be$
g.s
$^{4}_{\Lambda}H$
g.s
Direct population
$^{12}_{\Lambda}C$
$p_{3/2}^{-1}\ p_{1/2}$, $p_{3/2}$
$0^+, 2^+, 2^+$
$p_{3/2}^{-1}, s_{1/2}$
1^- (g.s.)
0
1
2
3
4
Production yield per K^- (10^{-3})

Fig.5



Hypernuclear Mass Excess (MeV)
40
30
20
10
0
42.85
$^{4}_{\Lambda}$H+α+3p+n
38.05
$^{8}_{\Lambda}$Li+3p+n
24.38
$^{5}_{\Lambda}$He+α+2p+n
20.88
$^{9}_{\Lambda}$Be+2p+n
10.4
$^{12}_{\Lambda}$C(p^{1},p^{-1})
9.10
$^{11}_{\Lambda}$B+p
−0.4
$^{12}_{\Lambda}$C(s^{1},p^{-1})
25.16
$^{5}_{\Lambda}$He+α+p+2n
21.66
$^{9}_{\Lambda}$Be+p+2n
17.76
$^{4}_{\Lambda}$H+2α
9.88
10.53
$^{8}_{\Lambda}$Li+α
$^{11}_{\Lambda}$B+n
(8.1)
$^{12}_{\Lambda}$B(p^{1},p^{-1})
−2.70
$^{12}_{\Lambda}$B(s^{1},p^{-1})

Fig.6



Gamma spectrum from 4-Lambda-H peak (Be)
80
60
40
20
0
-20
Counts
0
1
2
3
4
5
Energy (MeV)

Fig.7