The International Student School
SELECTED TOPICS IN NUCLEAR THEORY
Dubna, July 27, 2004

HYPERNUCLEI:
YESTERDAY, TODAY and TOMORROW

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PLAN

Hypernuclei INTRODUCTION

Yesterday (1953 – 1975)

	DISCOVERY :	Random Hyperfragments
	EKC	*Pauli Principle*

Today (1975 – 2000)

	PRODUCTION :	Systematic studies
	BNL	*BB STRONG Interaction*
	KEK	τ *(A)*

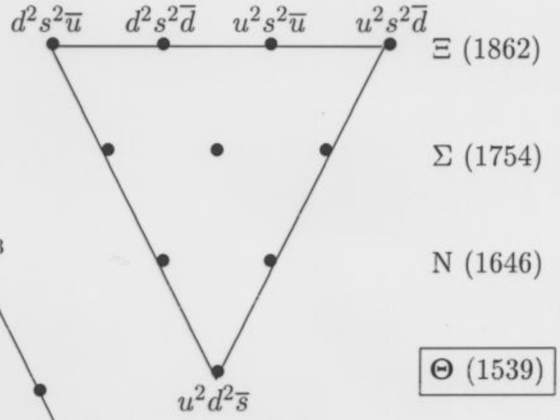
Tomorrow (2000 – 2010)

	DEDICATED experiments :	
	HYPERBALL	γ spectroscopy
	FINUDA	*HN with Neutron Halo*
	NUCLOTRON	*NM WEAK Decay*
	J-PARC, PANDA	$\Lambda\Lambda$ *Hypernuclei*

BARYONS SU(3)$_f$ MULTIPLETS

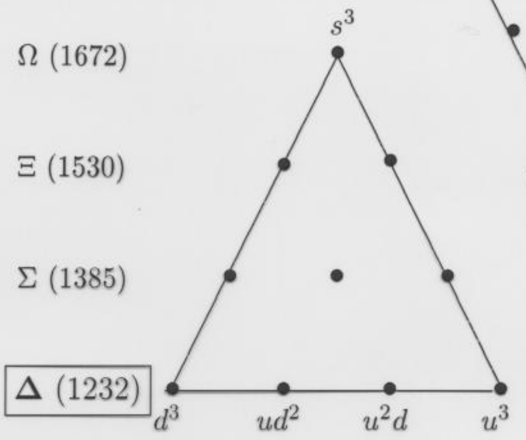
PENTAQUARKS

$q^4\,\overline{q}$: (02) $\otimes$ (01) = (03)



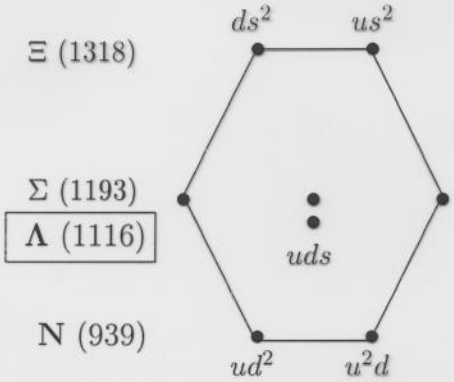
DECUPLET

q^3 : (30)



OCTUPLET

q^3 : (11)



NOMENCLATURE

Hypernucleus is specified by

N - the number of neutrons

Z - the number of protons

Y - the number of hyperons

$$N + Z + Y = B$$

X : element - total CHARGE
(not number of protons !)

$$^{B}_{Y}\mathbf{X}$$

number & type of hyperons = Y

EXAMPLES

$^{10}_{\Lambda}$Be
4 p
1 Λ
5 n

$^{4}_{\Sigma}$He
$1\ p + 1\ \Sigma^+ + 2\ n$
$2\ p + 1\ \Sigma^0 + 1\ n$
$3\ p + 1\ \Sigma^- + 0\ n$

$^{6}_{\Lambda\Lambda}$He
2 p
2 Λ
2 n

HYPERNUCLEI

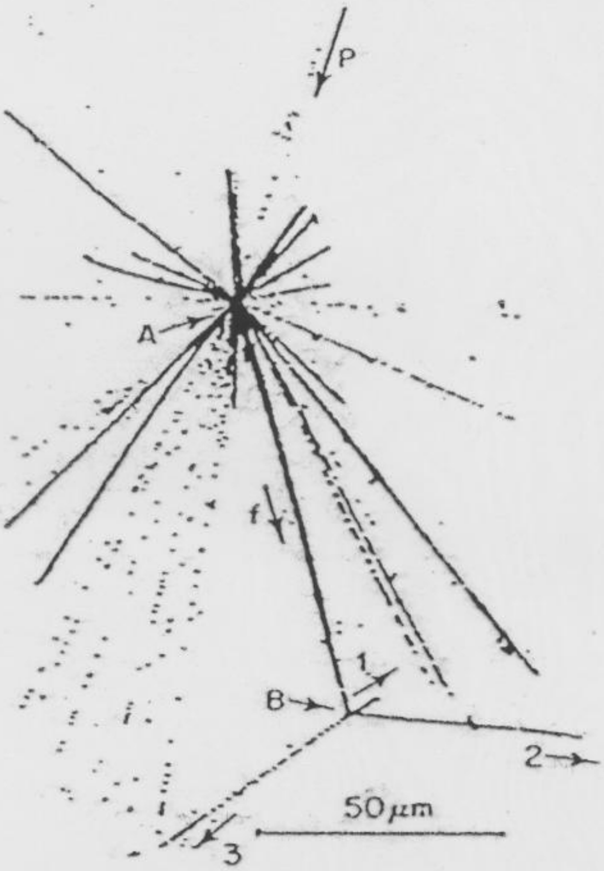
Hypernuclei were discovered by M. Danysz and J. Pniewski

Bull. Acad. Polon. Sci. 3, 42 (1952); Phil. Mag. 44, 348 (1953)

in a baloon-flown emulsion stack where salient picture

TWIN stars :

strong production of primary hypernucleus and



The first observation of the decay of a hypernucleus.

weak decay of hyperfragment connected with
a path corresponding to lifetime $\approx 10^{-10}$ sec
were easily recognized.

CONSEQUENCES of the DISCOVERY

The original discovery suggesting that Λ - hyperons can exist not only as free particles but also bound within nuclei was due to Danysz and Pniewski.

An excited hydrogen atom, to use the simplest example, consists of a proton and electron in a state of higher energy than in the normal atom. The analogy might then suggest that the excited nucleon consists of a proton and an associated π^- - that the Λ is a composite particle.
Such a view could not have been finally excluded while our knowledge was confined to the decay of free Λ-particle.
These considerations suggest that

the Λ-particle is an excited state nucleon

in a different sense from that suggested by familiar analogies.

We are entering a new field where basically new concepts remain to be established.

C. N. Powell: *Excited Nucleons*
Nature, 173 **(1954)** 469

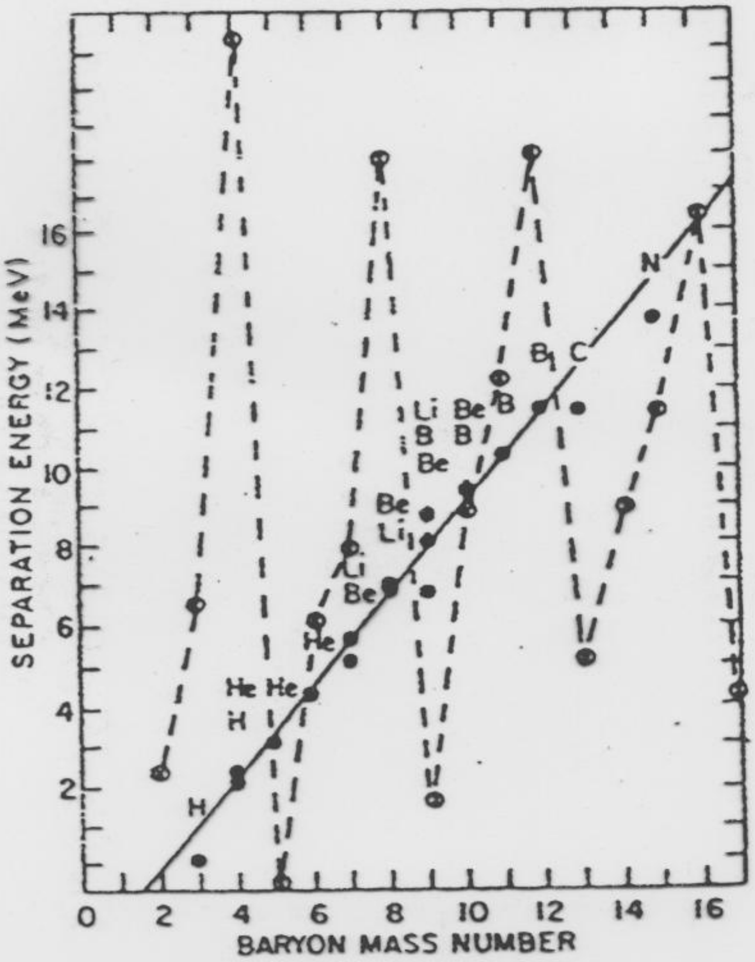
The hypothesis was made that the nuclear fragment contained a bound Λ in a nucleus like an ordinary nucleon.

It is an essential fact in the chain of reasoning which makes of hyperon just a new species of baryons, and hence leads to SU_3, quarks etc.

Ch. Peyrou: *The role of cosmic rays in the development of particle physics*
Colloque International sur l'Historie de la Physique des Particules, Paris, 1982

From

A. Wròblewski: Hypernuclei (and strange particles) - how it all began ?
XXVIII Mazurian Lakes School of Physics, Poland, September 2003
Acta Physica Polonica B **35** (2004) 901 – 927


SEPARATION ENERGY (MeV)
BARYON MASS NUMBER
0
2
4
6
8
10
12
14
16
H
He
H
He
He
Li
Be
Be
Li
Li
B
Be
Be
B
B
B
C
N

Production and Decay of Hypernucleus

FORMATION

primary

${}^{A_i}\mathrm{Z_i}$	(K^-,π^-)	${}^{A_i}_{\Sigma}\mathrm{Z}^*$	strangeness exchange	$K^- + N \rightarrow \Sigma + \pi$
${}^{A_i}\mathrm{Z_i}$	(K^-,π^-)	${}^{A_i}_{\Lambda}\mathrm{Z_i^*}$	strangeness exchange	$K^- + n \rightarrow \Lambda + \pi^-$
${}^{A_i}\mathrm{Z_i}$	(π^+,K^+)	${}^{A_i}_{\Lambda}\mathrm{Z_i^*}$	associative reaction	$\pi^+ + n \rightarrow \Lambda + K^+$
${}^{A_i}\mathrm{Z_i}$	$(p,p'K^+)$	${}^{A_i}_{\Lambda}\mathrm{Z_f^*}$	associative reaction	$p + p \rightarrow p' + \Lambda + K^+$

secondary

Σ conversion ${}^{A_i}_{\Sigma}\mathrm{Z}^* \rightarrow N + {}^{A_f}_{\Lambda}\mathrm{Z_f^*}$

B-emission ${}^{A_i}_{\Lambda}\mathrm{Z_i^*} \rightarrow B + {}^{A_f}_{\Lambda}\mathrm{Z_f^*}$

DECAY

gamma

$${}^{A_f}_{\Lambda}\mathrm{Z_f^*} \rightarrow \gamma_f + {}^{A_f}_{\Lambda}\mathrm{Z_f}$$

weak

$$\Lambda + N \rightarrow n + N$$

$${}^{A_f}_{\Lambda}\mathrm{Z_f} \rightarrow {}^{A_f-2}\mathrm{Z_i} + \mathrm{Nn}$$

$$\searrow \Sigma\, {}^{A_j}\mathrm{Z_j} + \pi_w^-$$

$$\Lambda \rightarrow p + \pi^-$$

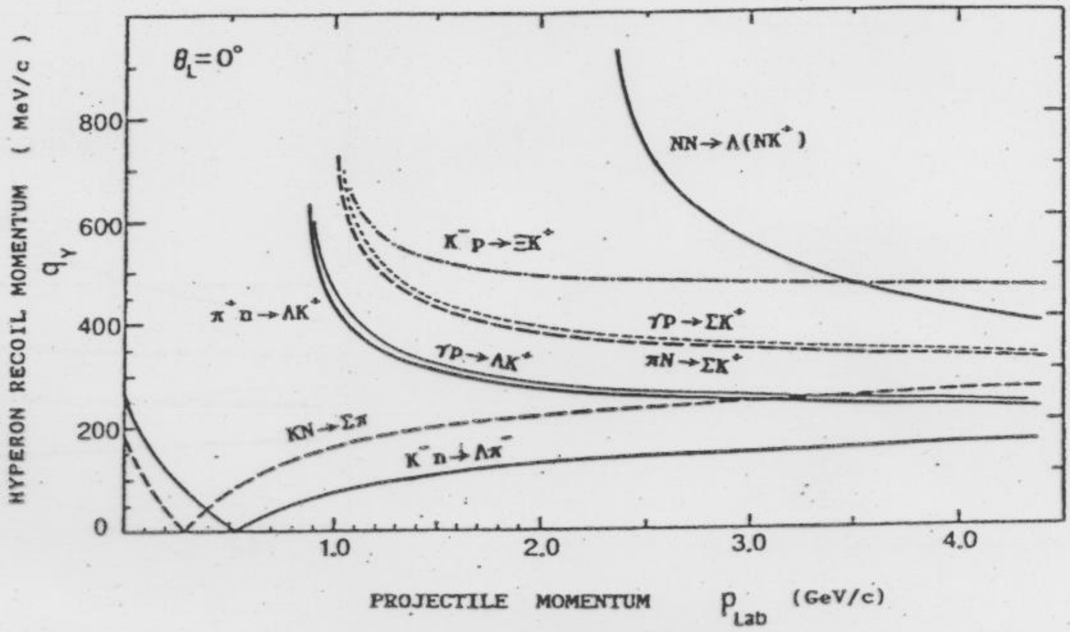
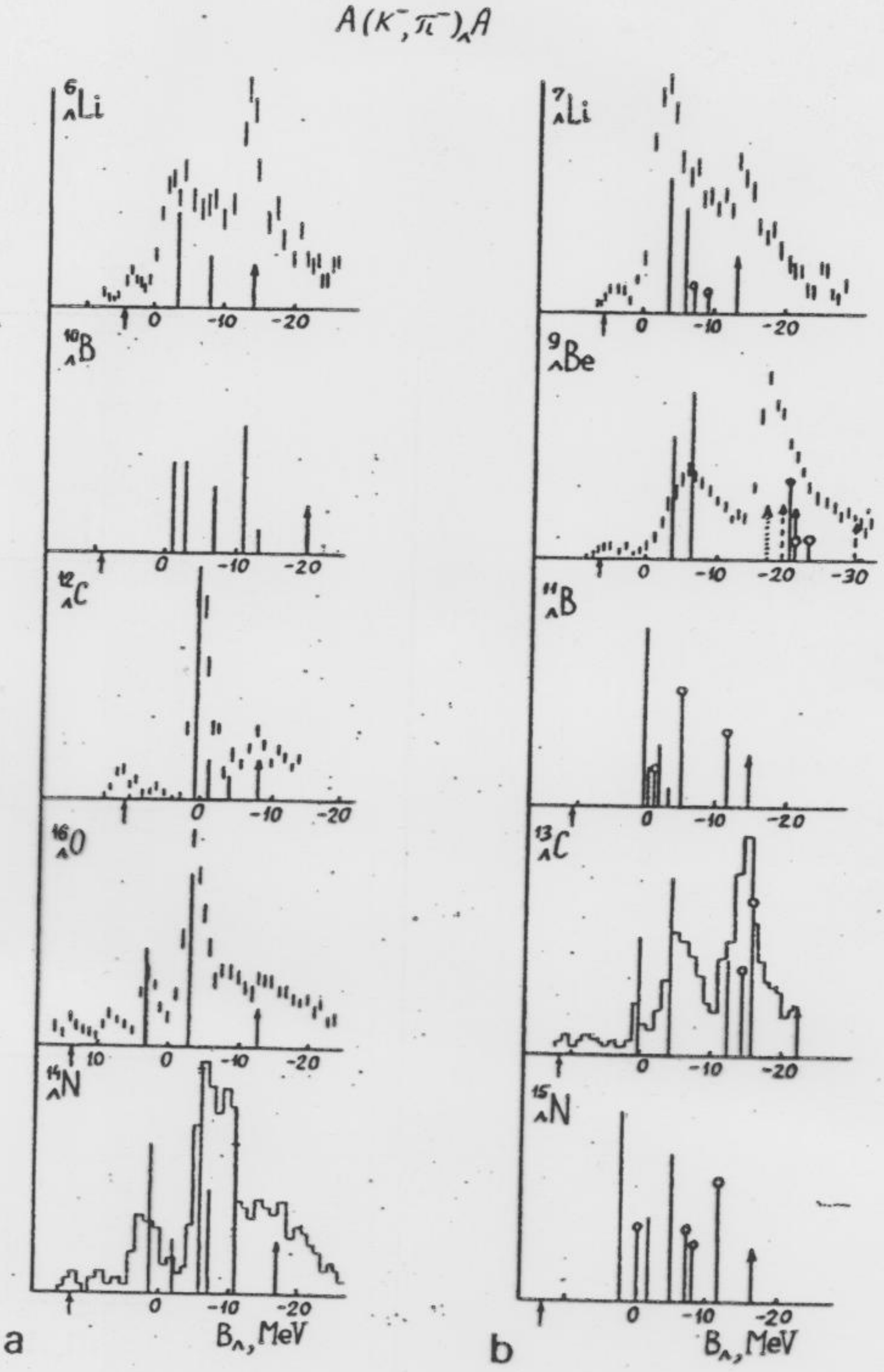
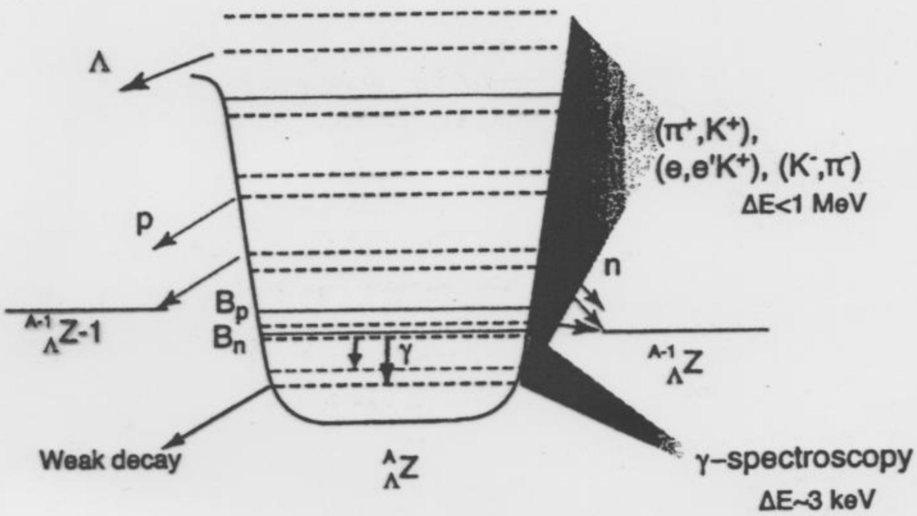


Fig. 2.3. The momentum q_Y transferred to the hyperon Y as a function of the projectile momentum $p_{proj} = p_a$ in the reaction $aN \rightarrow Yb$ at $\theta_{b,L} = 0°$.


A(K⁻,π⁻)ΛA
6ΛLi
10ΛB
12ΛC
16ΛO
14ΛN
7ΛLi
9ΛBe
11ΛB
13ΛC
15ΛN
0
-10
-20
-30
10
BΛ, MeV
a
b



Excitation energy levels of heavy Λ-hypernuclei and their decay modes. The low excitation region could be explored with gamma-ray spectroscopy in very high precision, while for the higher excitation region missing-mass spectroscopy such as the (π^+,K^+) spectroscopy would be a good tool.

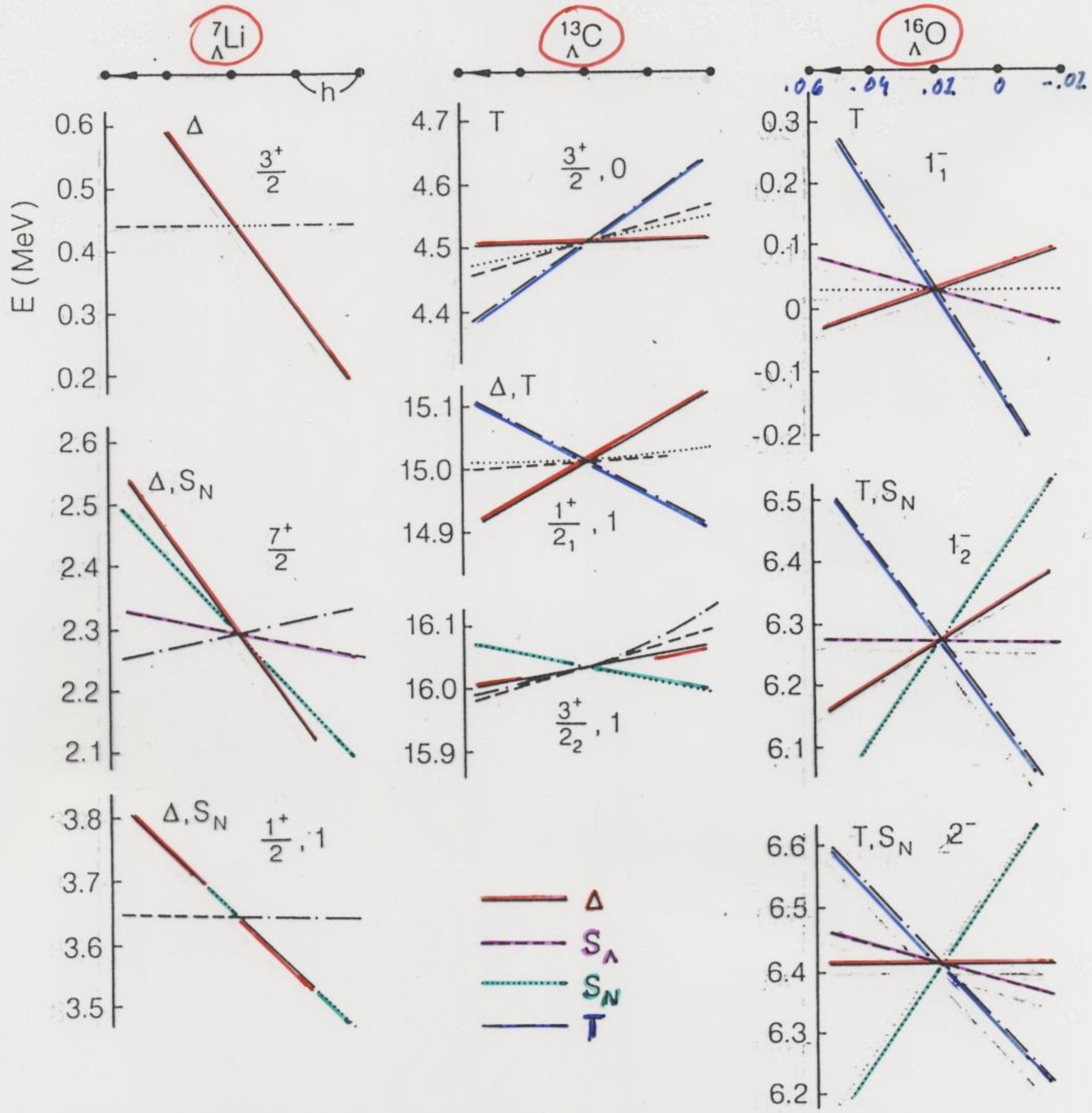
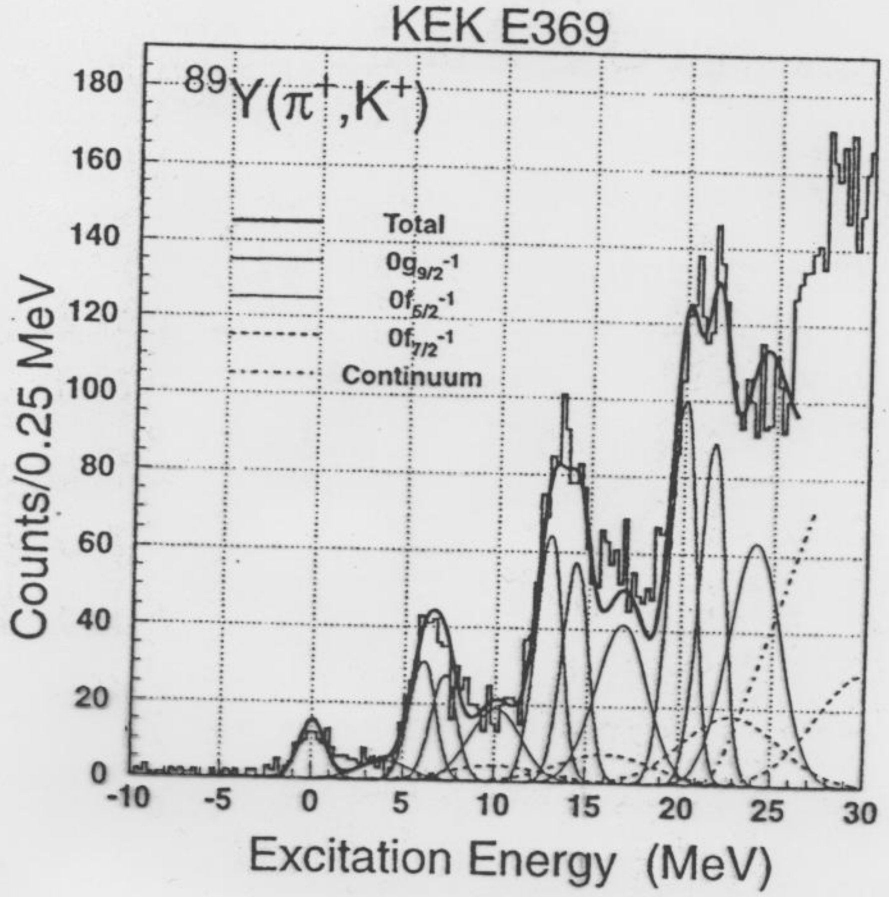


Fig. 4. The dependence of the $^{7}_{\Lambda}$Li, $^{13}_{\Lambda}$C, and $^{16}_{\Lambda}$O level energies on the parameters Δ, S_Λ, S_N, and T. The arrows in the upper part of each figure show the direction of increase of the one of the parameters (at fixed values of the remaining three parameters) and indicate the interval of the values of a varied parameter with step h within the following intervals:

$$0.5 \geqq \Delta \geqq 0.1\ (h=0.1),\ 0.02 \geqq S_\Lambda \geqq -0.06\ (h=0.02),$$

$$0.1 \geqq S_N \geqq -0.3\ (h=0.1),\ 0.06 \geqq T \geqq -0.02\ (h=0.02).$$

For $^{7}_{\Lambda}$Li, the parameters S_N and T were varied within intervals $-0.05 \geqq S_N \geqq -0.65\ (h=0.15)$, $0.08 \geqq T \geqq 0\ (h=0.02)$



An excitation energy spectrum of $^{89}_{\Lambda}Y$ obtained in E369.

There are several realistic models for the free YN interactions, based on boson exchanges.

Well-known are YN potentials of the **Jülich** group constructed along the same guidelines as in the Bonn NN potential
B. Holzenkamp, K. Holinde, J. Speth, Nucl. Phys. A 500 (1989) 483
A. G. Reuber, K. Holinde, J. Speth, Czech. J. Phys. 42 (1992) 1115

The **Nijmegen** group for many years has developed several one-boson exchange potential models: NSC89, NSC97a-f, ESC00
Th. A. Rijken, Nucl. Phys. **A 691** (2001) 322c
They use SU(3) constrains on the coupling constants to fit about **4300** pp+np data (cross sections and spin correlations) together with **35** scattering ΛN and ΣN data.

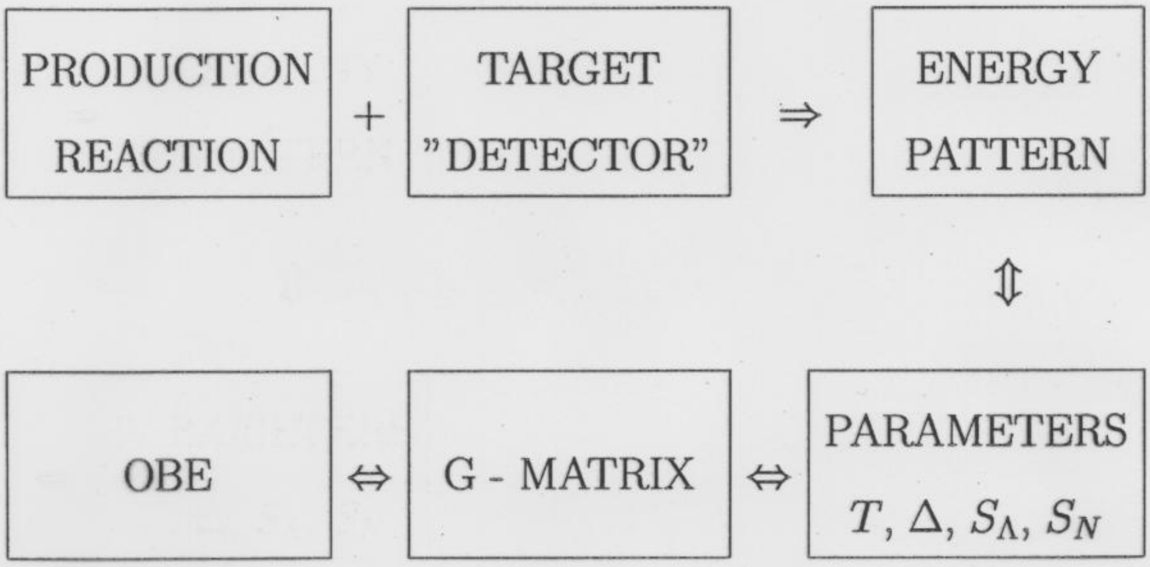
Very important result was obtained by Miyagawa and Glöckle
K. Miyagawa, H. Kamada, W. Glöckle, V. Stocks, Phys. Rev. C 51 (1995) 2905
Faddeev equations were solved for coupled ΛNN-ΣNN system. For the ***YN*** system, various interactions were used, and only NSC89 and NSC97f bind the $^3_\Lambda$H at correct binding energy.
The Jülich $\tilde{A}$ interaction cannot generate a bound state.
These results do not depend on the choice of NN potentials.

The Λ-Σ conversion was found to be crucial for binding energy.

	SC89	SC97d	SC97e	SC9f	Experiment
$B_\Lambda(^{3}_{\Lambda}H)$	0.37	0.01	0.10	0.18	0.13±0.05
P_Σ	0.65	0.06	0.15	0.23	
$B_\Lambda(^{4}_{\Lambda}H)$	2.55	1.67	2.06	2.16	2.04±0.04
P_Σ	3.73	1.27	1.49	1.88	
$B_\Lambda(^{4}_{\Lambda}H^*)$	un-	1.20	0.92	0.63	1.00±0.04
P_Σ	bound	1.37	0.98	1.09	
$B_\Lambda(^{4}_{\Lambda}He)$	2.47	1.62	2.02	2.11	2.39±0.03
P_Σ	3.59	1.24	1.45	1.83	
$B_\Lambda(^{4}_{\Lambda}He^*)$	un-	1.17	0.90	0.62	1.24±0.04
P_Σ	bound	1.35	0.96	1.08	
$B_\Lambda(^{5}_{\Lambda}He)$	0.35	3.17	2.75	2.10	3.12±0.02
P_Σ	1.33	2.09	1.55	1.87	

H. Nemura, Y. Akaishi and Y. Suzuki, PRL **89** (2002) 142504

HYPERON - NUCLEON INTERACTION



HYPERNUCLEAR WEAK DECAY

The properties of the **free** Λ hyperon are well known:
it decays nearly 100 % via a nonleptonic mode $\Lambda \to N + \pi$:

$$\tau_{free} = 1/\Gamma_\Lambda = 2.63 \cdot 10^{-10} s$$
$$\Gamma^{\pi^-}/\Gamma_\Lambda = 0.639, \quad \Gamma^{\pi^0}/\Gamma_\Lambda = 0.358,$$

in agreement with other hyperon decays   Particle Data Properties.

The energy release in the pionic decay produces a nucleon having a momentum of only some 100 MeV/c   ($T_N \approx 5$ MeV).
Thus, the pionic decay modes are severely inhibited by Pauli blocking.

The dominant mechanism of a **hypernuclear** decay is
a far more complex $\Lambda + N \to n + N$ process.
The 176 MeV energy release corresponds $p_N \approx 400$ MeV/c.

The total decay width of a hypernucleus, Γ_{tot}, is defined in terms of its mesonic and nonmesonic decay modes

$$\begin{aligned} \Gamma_{tot} &= \Gamma_{mesonic} + \Gamma_{nonmesonic} \\ \Gamma_{tot} &= \Gamma^{\pi^-} + \Gamma^{\pi^0} + (\Gamma^{\pi^+}) + \Gamma^{p} + \Gamma^{n} + (\Gamma^{mb}), \end{aligned}$$

where Γ^{mb} as well as Γ^{π^+} are the possible many-body decay modes.

The main observables, which can be measured experimentally and should be confronted with theoretical calculations, include

- the hypernuclear lifetime τ;
- the partial widths Γ^{π^-}, Γ^{π^0}, Γ^{p} and Γ^{n};
- the ratio of parity-violating to parity-conserving decay, (proton asymmetry in a polarized hypernuclear decay).

Λ DECAY MODES

$p\ \pi^-$	0.639	$\pm$ 0.005	101 MeV
$n\ \pi^0$	0.358	$\pm$ 0.005	104 MeV
$n\ \gamma$	0.00175	$\pm$ 0.00015	162 MeV
$p\ \pi^-\gamma$	0.00084	$\pm$ 0.00014	101 MeV
$p\ e^-\ \bar{\nu}_e$	0.000832	$\pm$ 0.000034	163 MeV
$p\ \mu^-\bar{\nu}_\mu$	0.000157	$\pm$ 0.000035	131 MeV

Particle Data Group (K. Hagivara *et al.,*) Phys. Rev. D **66** 010001-61.

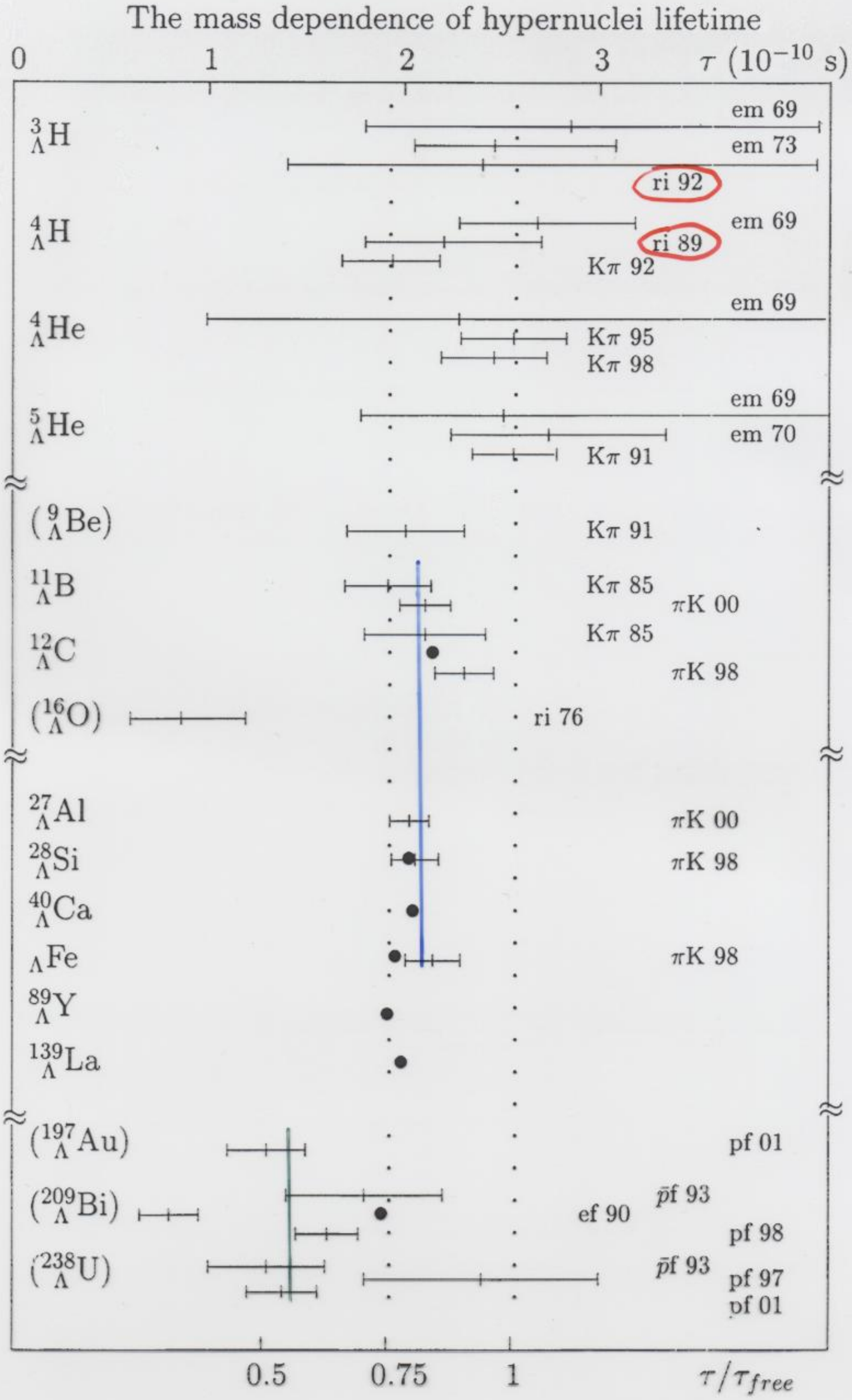
Charged electroweak currents

	lepton currents			hadron currents								
	$e\nu_e$	$\mu\nu_\mu$	$\tau\nu_\tau$	ud	**us**	ub	cd	cs	cb	td	ts	tb
$(e\nu_e)$	√	√	√	√	√	√		√	√			
$(\mu\nu_\mu)$		√	√	√	√	√		√	√			
$(\tau\nu_\tau)$				√	√							
(ud)				√	√	√			√			
(us)												
⋮												

leptonic processes		semi leptonic processes	
$(e\nu_e)\,(e\nu_e)$	$\nu_e\, e \to \nu_e\, e$	$(e\nu_e)$ (du)	$n \to p\, e\, \nu_e$
$(e\nu_e)\,(\mu\nu_\mu)$	$\mu \to e\, \nu_e\, \nu_\mu$	$(e\nu_e)$ (us)	$\mathrm{K} \to \pi\, e\, \nu_e$

non leptonic processes

(ud) (ud)	P viol NN	**(ud) (cs)**	$\mathrm{D} \to \mathrm{K}\, \pi\pi$
(ud) (us)	$\Lambda \to \mathrm{N}\ \pi$	**(ud) (cb)**	$\mathrm{B} \to \mathrm{D}\, \pi\pi$


The mass dependence of hypernuclei lifetime
0
1
2
3
τ (10^−10 s)
em 69
em 73
ri 92
em 69
ri 89
Kπ 92
em 69
Kπ 95
Kπ 98
em 69
em 70
Kπ 91
Kπ 91
Kπ 85
πK 00
Kπ 85
πK 98
ri 76
πK 00
πK 98
πK 98
pf 01
p̄f 93
ef 90
pf 98
p̄f 93
pf 97
pf 01
0.5
0.75
1
τ/τ_free

At present, there are four hypernuclei for which the complete set of partial rates has been measured. The survey of the results for the Γ^n/Γ^p ratio is displayed in Figure.
We see that

$$0.5 \leq (\Gamma^n/\Gamma^p)^{exp} \leq 2$$

and

$$(\Gamma^n/\Gamma^p)^{th} \ll (\Gamma^n/\Gamma^p)^{exp}.$$

The main problem concerning the weak decay of Λ-hypernuclei is the disagreement between the theoretical and experimental values for the ratio Γ^n/Γ^p.

In order to solve the Γ^n/Γ^p puzzle, many attempts have been made up to now, but without success. Among these we recall

- the introduction of mesons heavier than the pion in the $\Lambda N \to NN$ transition potential

  J. F. Dubach, Nucl. Phys. **A 450** ('86) 71c;
  J. F. Dubach *et al.*, Ann. Phys. **249** ('96) 146.
  A. Parreño, A. Ramos and C. Bennhold, Phys. Rev. **C 56** ('97) 339.

- the role of the two-nucleon stimulated decay

  W. Alberico *et al.*, Phys. Lett. **B 256** ('91) 134.
  A. Ramos *et al.*, Phys. Rev. **C 50** ('94) 2314.
  W. Alberico *et al.*, Phys. Rev. **C 61** ('00).

- the description of the short-range baryon-baryon interaction in terms of quark degrees of freedom

  D. P. Heddle and L. S. Kisslinger, Phys. Rev. **C 33** ('86) 608.
  K. Sasaki, T. Inoue and M. Oka, Nucl. Phys. **A669** ('00) 331; **A678** ('00) 455.

One has to point out that present experiments cannot identify the final state of the residual (A-2) nucleus in the case of nonmesonic decays

$$^{A}_{\Lambda}\mathrm{Z} \to {}^{A-2}\mathrm{Z} + \mathrm{n} + \mathrm{n} \qquad \text{and} \qquad ^{A}_{\Lambda}\mathrm{Z} \to {}^{A-2}(\mathrm{Z\text{-}1}) + \mathrm{n} + \mathrm{p},$$

and an **average** over many nuclear final states has to be performed.

Now, we focus your attention on one peculiar case which makes it possible to detect some of such final states.

"ALPHA DECAYS" of ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B HYPERNUCLEI

We propose to use the unique feature of the ^{9}Be nucleus, namely that after removing a neutron from its ground state several groups of α-particles appear from different excited states of a residual nucleus ^{8}Be

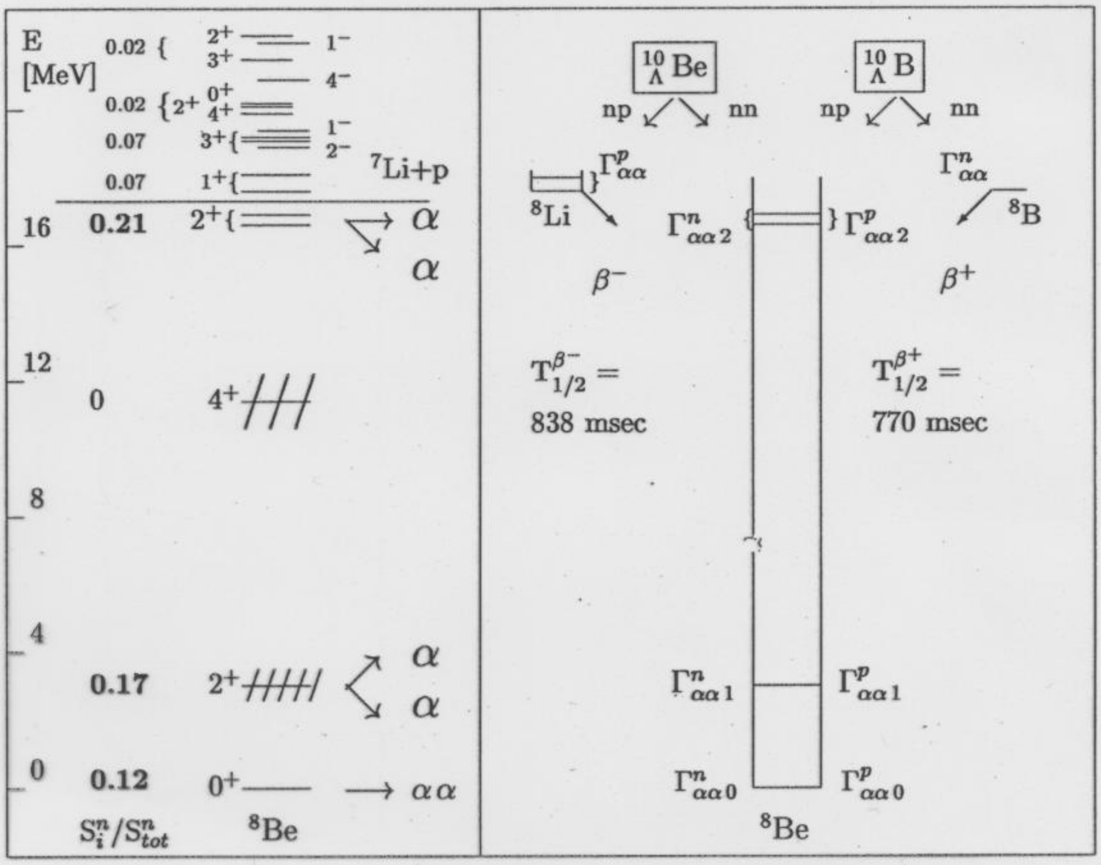


Figure 1: Left panel: pattern of the ^{8}Be spectra produced in the ^{9}Be (p,d) Be* reaction. Right panel: "$\alpha\alpha$"-decay of ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B hypernuclei and notation of $\Gamma^{\tau}_{\alpha\alpha i}$.

Due to their specific cluster structure – alpha alpha NΛ – it may be possible to measure in the ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B hypernuclei the partial decay widths $\Gamma^{\tau}_{\alpha\alpha i}$ corresponding to states of the residual nucleus ^{8}Be decaying through the $\alpha\alpha$-channel.

In such a way we can determine
not only a **partial rate** (including **neutron** ones),
but also an **exactly ONE-nucleon** stimulated process $\Lambda N \to nN$.

The study of $\Gamma^{\tau}_{\alpha\alpha i}$ offers a unique possibility to determine ALL NEEDED matrix elements of the weak interaction $\Lambda N \to nN$.

Experiment is approved for NUCLOTRON accelerator at Dubna.

PARTIAL DECAY WIDTHS of the ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B

A one meson exchange model to describe the $\Lambda N \to NN$ transition including pseudoscalar (π, η, K) and vector (ρ, ω, K^*) meson exchanges was developed in J. F. Dubach, NP **A 450** ('86) and AP **249** ('96).
Following these lines, a **full One Meson Exchange** potential was constructed to study the nonmesonic decay of **finite mass hypernuclei**

A. Parreño, A. Ramos, C. Bennhold, Phys. Rev. C56 ('97).

Hadronic weak matrix elements $\langle B'M|H_{weak}|B\rangle$ were implanted into the nucleus with usual many-body shell model wave functions.
A convenient compact expression for the potential is given by

$$V_{weak}(r) = \sum_i \sum_\alpha V_\alpha^{(i)}(r)\, O_\alpha\, I_\alpha^{(i)},$$

where the index i runs over mesons exchanged $(\pi, \rho, K, K^*, \eta, \omega)$, and index α runs over spin operators O_α (central, tensor, PV); the isospin operator $I_\alpha^{(i)}$ depends on meson type.

The nonmesonic decay rate Γ_{nm} can be written as

$$\Gamma_{nm} = \sum_\tau \Gamma^{(\tau)} = \sum_{\tau=\mathrm{n,p}} \sum_i \Gamma_i^{(\tau)}$$

where the **partial width** Γ_i^τ is

$$\Gamma_i^{(\tau)} = |\langle\, \Psi^{A-2}(\{i\}) \otimes \psi^{NN}(JT) \mid V_{weak} \mid [\Psi^{A-1}(\{c\}) \otimes \psi^{\Lambda}(\tfrac{1}{2})\,]^{\mathcal{J}} \rangle|^2$$

Shorthand notation $\{i\} \equiv E_i, J_i, T_i, \tau_i$ (see Fig. 3) and $\{c\} \equiv E_c, J_c, T_c, \tau_c$ is used.

OVERSIMPLIFIED $\tilde{\Gamma}_i^{\tau}$

Recently the values of $\Gamma^{\tau}({}^4_{\Lambda}\text{H})$ and $\Gamma^{\tau}({}^4_{\Lambda}\text{He})$ were calculated with several models of weak interactions between hyperons and nucleons

Two Pion Exchange	Itonaga, Ueda, Motoba: PR **C65** (2002),
Hybrid Quark	Sasaki, Inoue, Oka: NP **A707** (2002),
One Meson Exchange	Krmotić, Tadić, nucl-th/0212040.

Now it is possible now to extract ratios of $R_{\tau S}$
from theoretical $\Gamma^{\tau}({}^4_{\Lambda}\text{H})$ and $\Gamma^{\tau}({}^4_{\Lambda}\text{He})$ **values.**

We use results A. Parreño, A. Ramos, C. Bennhold, Phys. Rev. **C56** ('97).:

The interaction matrix elements for L=1 are very small, so we neglect them for a moment and write extremely simple expression for $\tilde{\Gamma}_i^{\tau}$

$$\tilde{\Gamma}_i^{\tau} = \nu_i \varepsilon_1^2 \beta_0 \left[G_i^0 R_{\tau 0} + G_i^1 R_{\tau 1} \right], \tag{1}$$

where $R_{\tau S}$ are phenomenological rates introduced by Dalitz and Block;
ν_i - normalization of the spectroscopic factor; and
G_i^0 (G_i^0) - weight of the singlet (triplet) state in the wave function of the NΛ pair.
The coefficients ν_i and ε_i actually are related to strong interaction. They disappear in the ratio:

$$\gamma_i^{np} \equiv \frac{\tilde{\Gamma}^{\text{n}}_{\alpha\alpha i}({}^{10}_{\Lambda}\text{Be})}{\tilde{\Gamma}^{\text{p}}_{\alpha\alpha i}({}^{10}_{\Lambda}\text{B})} = \frac{R_{n0}}{R_{p0}} \cdot \frac{G_i^{(0)} + (1 - G_i^{(0)})(R_{n1}/R_{n0})}{G_i^{(0)} + (1 - G_i^{(0)})(R_{p1}/R_{p0})}, \tag{2}$$

which depends on single structure characteristic, G_i^0, only.
But it differs strongly for two 2^+ states in ^{8}Be:

$G_1^{(0)} = 0.5$ for state at E = 3 MeV : [4] $^{11}\text{D}_2$,
and
$G_2^{(0)} = 0.1$ for state E = 16.7 MeV : [31] ($^{13}\text{P}_2 + {}^{33}\text{P}_2$),

Ratios $\gamma_i^{n/p}$ for different models of weak interaction.

model		$A=4$			$A=10$	
		R_{n0}/R_{p0}	R_{n1}/R_{n0}	R_{p1}/R_{p0}	$\gamma_1^{n/p}$	$\gamma_2^{n/p}$
IUM	V_π	2.0	1.0	27.0	0.14	0.08
	$+ V_{2\pi/\rho}$	2.5	2.6	35.0	0.25	0.19
	$+ V_\omega$	2.0	0.57	10.0	0.28	0.14
	$+ V_{2\pi/\sigma}$	2.0	0.39	3.40	0.63	0.28
SIO	π	2.0	0.54	15.0	0.19	0.09
	$\pi + K$	1.8	4.6	19.0	0.50	0.44
	HQ	0.85	1.3	0.74	1.12	1.41
	all	0.13	26	4.40	0.65	0.75
OME	π	2.0	0.7	12.1	0.25	0.13
	PS	2.0	7.6	30.0	0.56	0.51
	PS+PV	2.0	35	21.3	3.22	3.26
phenomenological						
	AG1	0.6	2.2	1.2	0.87	1.06
	AG2	2.0	2.2	5.0	1.07	0.90

PHENOMENOLOGICAL ANALYSIS

STRONG INTERACTION

PRODUCTION REACTION	+	TARGET "DETECTOR"	$\Rightarrow$	ENERGY PATTERN
(K^-, π^-) (π^+, K^+)		*p-shell nuclei*		*doublet splittings:* $^3S_1 \times s_\Lambda$, $^1D_2 \times s_\Lambda$ ...

$\Updownarrow$

OBEP Jülich, NSC	$\Leftrightarrow$	G - MATRIX	$\Leftrightarrow$	**PHENOMENOLOGICAL PARAMETERS** T, Δ, S_Λ, S_N

WEAK INTERACTION

PRODUCTION REACTION	+	"DETECTOR"	$\Rightarrow$	$\Gamma^{n}_{\alpha\alpha\, i}$ ($^{10}_{\Lambda}$Be) $\Gamma^{p}_{\alpha\alpha\, i}$ ($^{10}_{\Lambda}$B)
relativistic hypernuclei		^{8}Be		

$\Updownarrow$

model WI OME, TPE, HQ	$\Leftrightarrow$	$\Gamma^n(^4H)$, $\Gamma^n(^4He)$ $\Gamma^p(^4H)$, $\Gamma^p(^4He)$	$\Leftrightarrow$	R_{nS}, R_{pS}

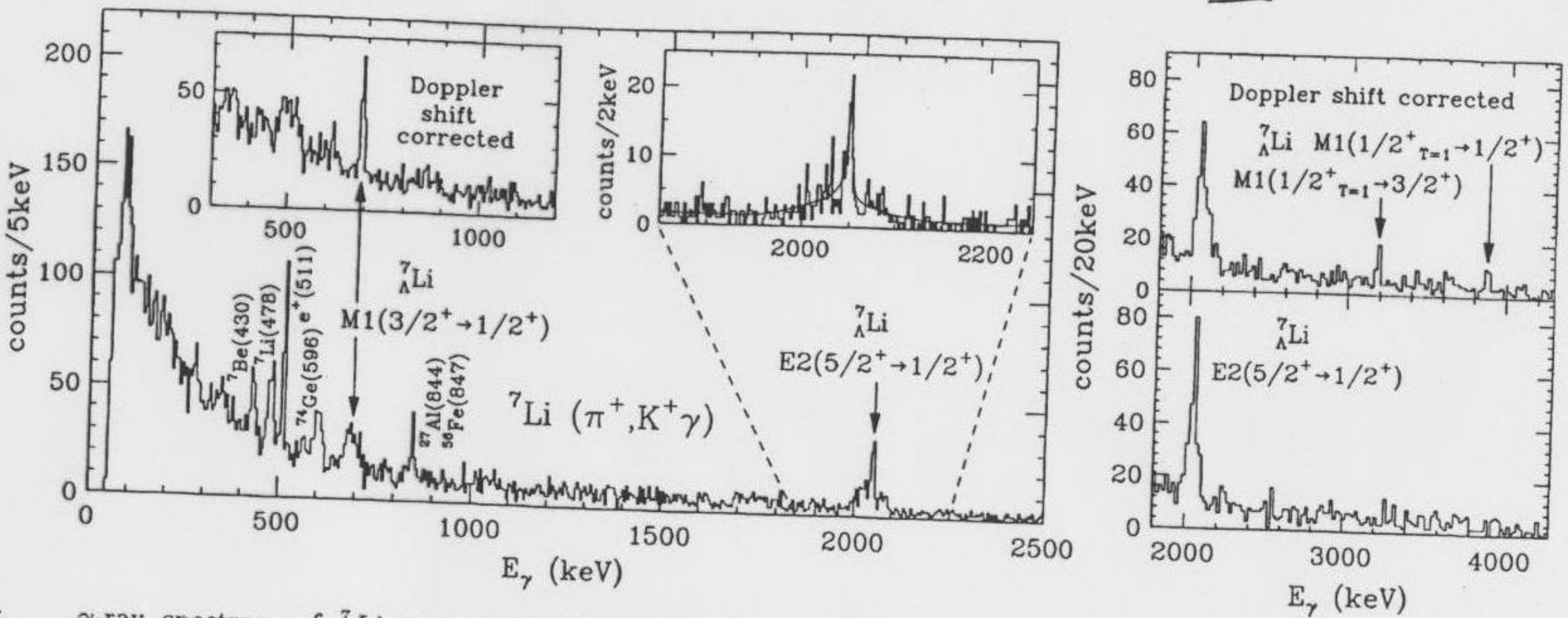


Fig. γ-ray spectrum of $^7_\Lambda$Li measured with Hyperball. Four hypernuclear transitions, $M1(\frac{3}{2}^+ \to \frac{1}{2}^+)$, $E2(\frac{5}{2}^+ \to \frac{1}{2}^+)$, $M1(\frac{1}{2}^+(T=1) \to \frac{3}{2}^+)$, and $M1(\frac{1}{2}^+(T=1) \to \frac{1}{2}^+)$, were observed.

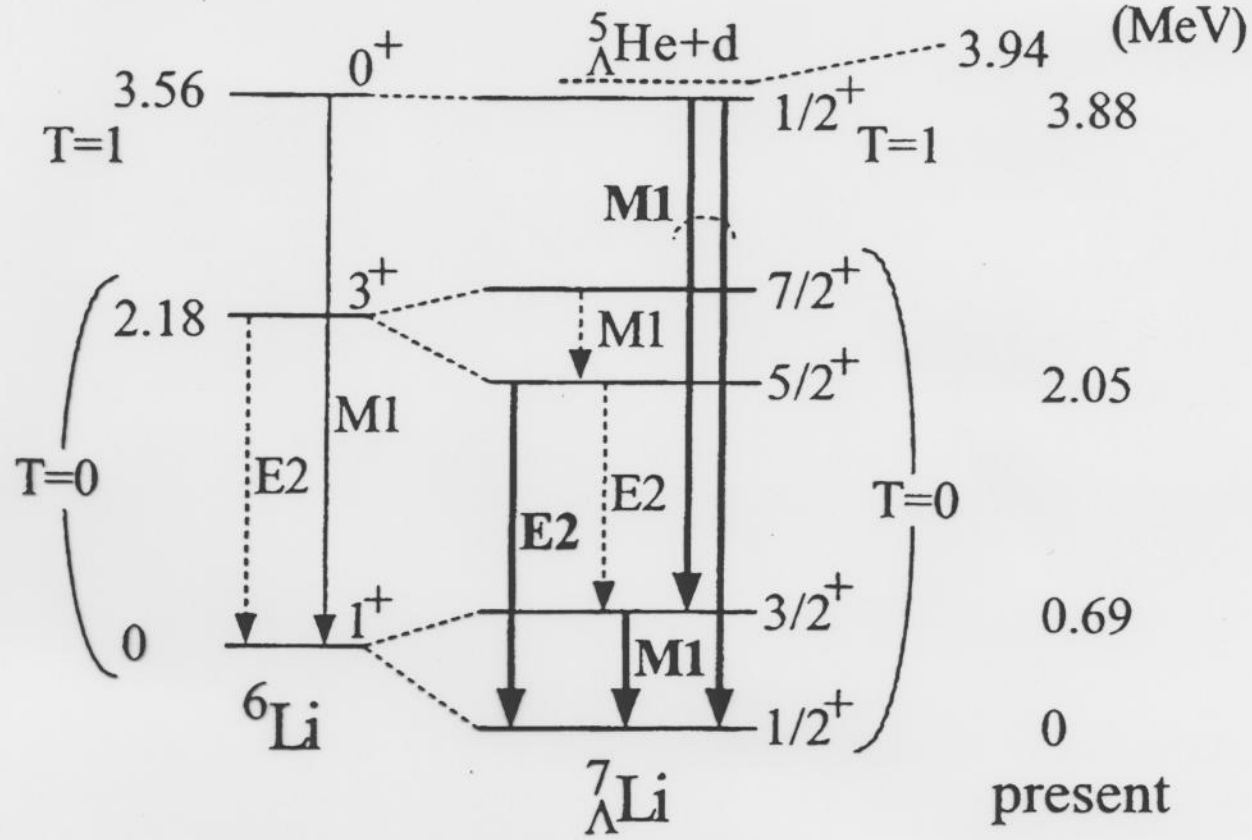


Fig. Level scheme of $^7_\Lambda$Li established by the E419 experiment, shown together with the level scheme of the core nucleus ^{6}Li. Observed transitions are shown in thick arrows.

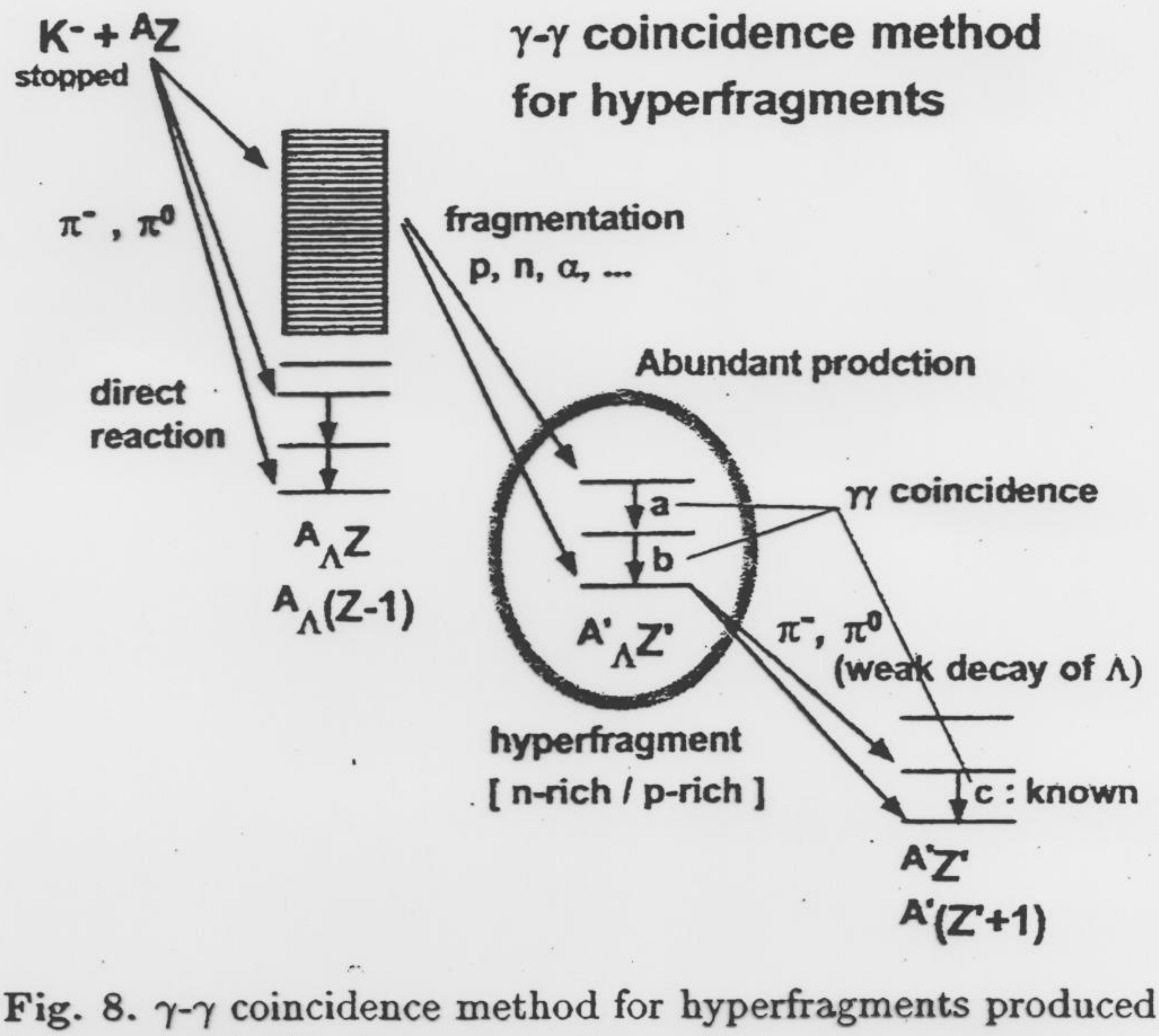


Fig. 8. γ-γ coincidence method for hyperfragments produced from stopped K^- absorption.

RELATIVISTIC HYPERNUCLEI

KINEMATICS

beam		target		SLOW secondaries		FAST secondaries
K^-	$+$	^{A}Z	$\rightarrow$	$^{A}_{\Lambda}$Z	$+$	π^-
^{A}Z	$+$	p	$\rightarrow$	K^+	$+$	$^{A}_{\Lambda}$Z + n

FIRST EXPERIMENTS

1976	Berkeley	T. Bowen	PR C13	$^{16}_{\Lambda}$O
1989	Dubna	S. Khorozov, J. Lukstins	NC A 102	$^{4}_{\Lambda}$H
1992	Dubna	S. Khorozov, J. Lukstins	NP A 547	$^{3}_{\Lambda}$H

NEW PROPOSALS:
Dubna, Nuclotron, Juris Lukstins: Nucl. Phys A 691 (2001)

KEK, 50 GeV PS, A. Sakaguchi:
Int. Workshop on Nuclear and Particle Physics , KEK, Dec. 2001

RELATIVISTIC HYPERNUCLEI

The production of hypernuclei in **relativistic heavy ion collision** has several advantages:

- The points of the production and decay of relativistic hypernuclei are separated by many centimeters (instead of some microns in the emulsion);
- decay products are emitted into small laboratory solid angle.

M. I. Podgoretskii, E. O. Okonov,
in Proc. Sem. Nuclotron and Relativistic Nuclear Physics, June 1974, Dubna

J. Bartke *et al.*, *in* Proc. Int. Workshop on RELATIVISTIC NUCLEAR PHYSICS: from HUNDREDS of MeV to TeV, Varna, Bulgaria, September 2001.

At the end of the 80-ies hypernuclear experiments were performed on the Dubna synchrophasotron ion beams (^{3}He, ^{4}He, ^{6}Li) using the streamer chamber. The production cross sections as well as the lifetimes of ${}^4_\Lambda$H and ${}^3_\Lambda$**H** were measured S. Avramenko *et al.*, NP **A 547** ('92).
The advantage of these experiments were low background and unambiguous identification of observed hypernuclei.
The same group has prepared program for the Nuclotron accelerator: to measure the lifetimes for ${}^3_\Lambda$H, ${}^4_\Lambda$H and ${}^6_\Lambda$He hypernuclei during the initial runs of the Nuclotron J. Lukstins, NP **A 691** ('01).

The next step of the suggested hypernuclear experiments program will be investigation of nonmesonic decays by searching two α's from ^{8}Be. If ^{8}Be decays from the ground state, then the back to back momentum of two α's is very low and both α's hit the detectors at the same point. However, prevailing part of α's proceeds from **excited** states of ^{8}Be. These events **can be registered** by high resolution devices.

So, the **new trigger** tuned to search for two tagged α particles, opens an unprecedent possibility to **determine**
$\Gamma^{n}_{\alpha\alpha 2}({}^{10}_{\Lambda}\mathrm{Be})$, $\Gamma^{n}_{\alpha\alpha 1}({}^{10}_{\Lambda}\mathrm{Be})$, $\Gamma^{p}_{\alpha\alpha 2}({}^{10}_{\Lambda}\mathrm{B})$ and $\Gamma^{p}_{\alpha\alpha 1}({}^{10}_{\Lambda}\mathrm{B})$
at the **Dubna Nuclotron**.

Investigation of Hypernuclei and Δ, N – isobar Behavior in Nuclear Matter.

ABSTRACT

GIBS Collaboration, 2002 – 2006

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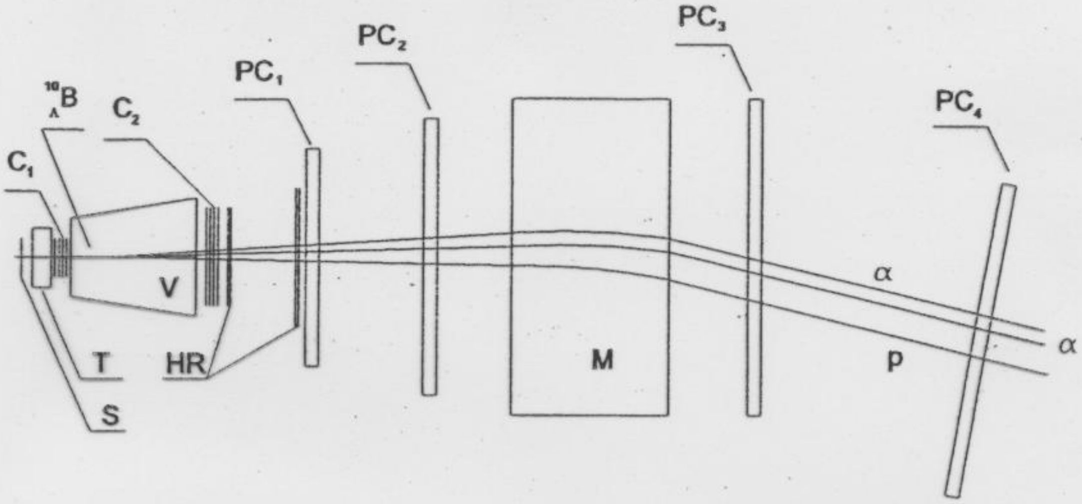
RELATIVISTIC HYPERNUCLEI

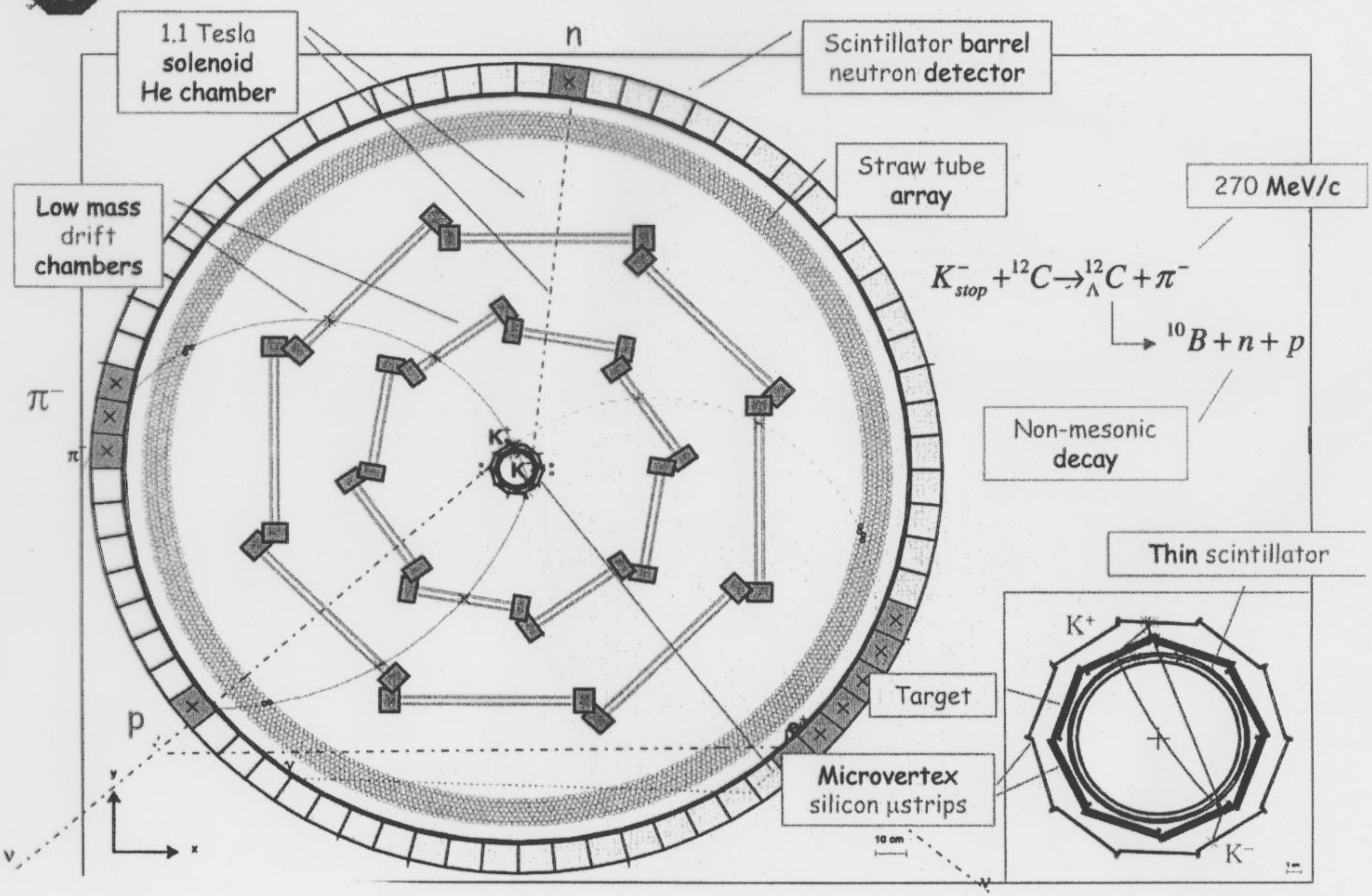
JINR DUBNA :



. SPHERE spectrometer for the investigation of nonmesonic decay of $^{10}_{\Lambda}B$ produced in the Nuclotron carbon beam. S – the beam control counters; T – target; $C_{1,2}$ – the trigger Čerenkov counters; V – vacuum decay volume; HR – high resolution detectors; M – magnet; PC_{1-4} – proportional chambers.

7

Typical (p-n) non-mesonic decay event



$$K^-_{stop} + {}^{12}C \rightarrow {}^{12}_{\Lambda}C + \pi^-$$
$$\quad \hookrightarrow {}^{10}B + n + p$$

CHART of light hypernuclei

					$^{14}_{\Lambda}\mathrm{N}$ ●	$^{15}_{\Lambda}\mathrm{N}$ ●	$^{16}_{\Lambda}\mathrm{N}$ ○	
				$^{12}_{\Lambda}\mathrm{C}$ ●	$^{13}_{\Lambda}\mathrm{C}$ ●	$^{14}_{\Lambda}\mathrm{C}$ ○	$^{15}_{\Lambda}\mathrm{C}$ ○	$^{16}_{\Lambda}\mathrm{C}$ ★
		$^{9}_{\Lambda}\mathrm{B}$	$^{10}_{\Lambda}\mathrm{B}$ ●	$^{11}_{\Lambda}\mathrm{B}$ ●	$^{12}_{\Lambda}\mathrm{B}$ ○	$^{13}_{\Lambda}\mathrm{B}$ ○	$^{14}_{\Lambda}\mathrm{B}$ ★	$^{15}_{\Lambda}\mathrm{B}$ ★
	$^{7}_{\Lambda}\mathrm{Be}$	$^{8}_{\Lambda}\mathrm{Be}$	$^{9}_{\Lambda}\mathrm{Be}$ ●	$^{10}_{\Lambda}\mathrm{Be}$ ○	$^{11}_{\Lambda}\mathrm{Be}$ ○	$^{12}_{\Lambda}\mathrm{Be}$ ★	$^{12}_{\Lambda}\mathrm{Be}$ ★	
	$^{6}_{\Lambda}Li$ ●	$^{7}_{\Lambda}\mathrm{Li}$ ●	$^{8}_{\Lambda}\mathrm{Li}$	$^{9}_{\Lambda}\mathrm{Li}$ ○	$^{10}_{\Lambda}\mathrm{Li}$ ★	$^{11}_{\Lambda}\mathrm{Li}$ ★		
$^{4}_{\Lambda}\mathrm{He}$ ●	$^{5}_{\Lambda}\mathrm{He}$ ●	$^{6}_{\Lambda}\mathrm{He}$ ○	$^{7}_{\Lambda}\mathrm{He}$ ○	$^{8}_{\Lambda}\mathrm{He}$	$^{9}_{\Lambda}\mathrm{He}$ ★			
$^{3}_{\Lambda}\mathrm{H}$	$^{4}_{\Lambda}\mathrm{H}$ ●		$^{6}_{\Lambda}\mathrm{H}$ ★	$^{7}_{\Lambda}\mathrm{H}$ ★				

Notation

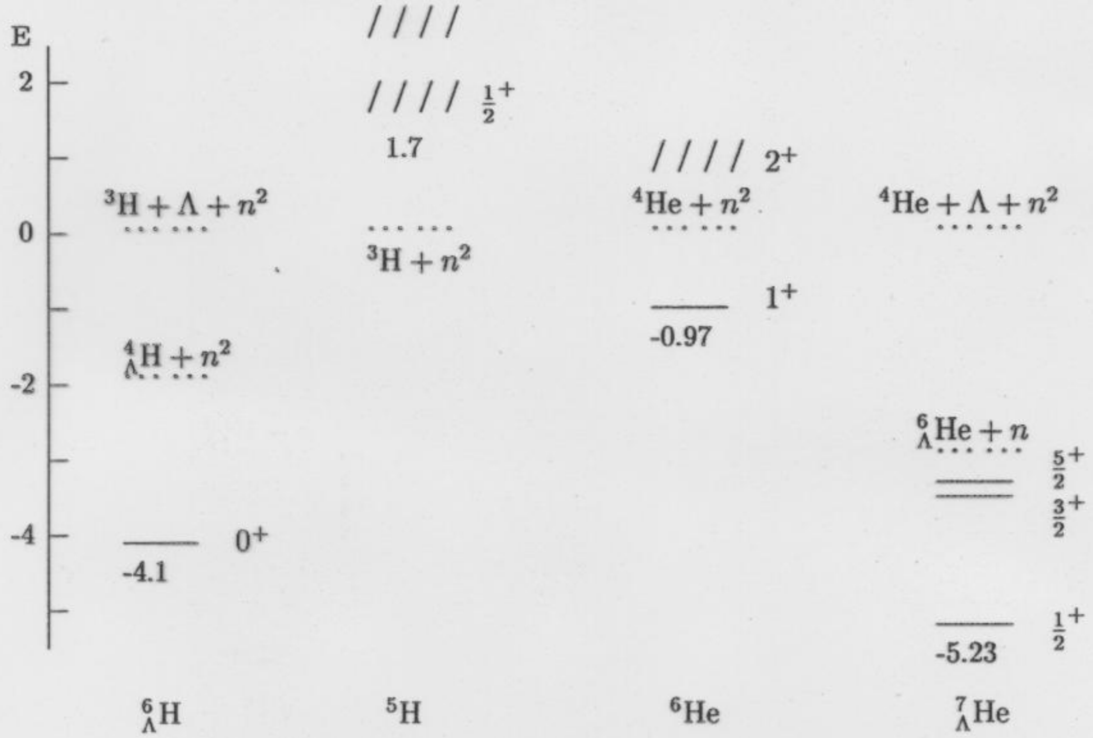
● $n \to \Lambda$ (K^-, π^-) and/or (π^+, K^+)

○ $p \to \Lambda$ (K^-, π^0) and/or (γ, K^+)

★ $pp \to n\Lambda$ (K^-, π^+) and/or (π^+, K^-)

ENERGY SPECTRA OF SOME (HYPER) NUCLEI WITH TWO BODY NEUTRON HALO

$$
\begin{array}{ccc}
{}^{6}\mathbf{He} & \xrightarrow{\otimes\Lambda} & {}^{7}_{\Lambda}\mathrm{He} \\
\downarrow p^{-1} & & \\
{}^{5}\mathrm{H} & \xrightarrow{\otimes\Lambda} & {}^{6}_{\Lambda}\mathrm{He}
\end{array}
$$



Myint & Akaishi	Korsheninnikov	Tilley	Hiyama et al
PTP Sup 146 ('02)	PRL 87 ('01)	NP A708 ('02)	PRC 53 ('96)

S & DCX $\quad {}^{A}Z(K^-, \pi^+)^{A}_{\Lambda}(Z-2)$

elementary processes:

(a) $K^- + p \rightarrow \pi^+ + \Sigma^-$

$\Sigma^- + p \rightarrow \Lambda + n$

(b): $K^- + p \rightarrow \Lambda + \pi^0$

$\pi^0 + p \rightarrow n + \pi^+$

$$K^- + {}^{6}\mathrm{Li} \rightarrow {}^{6}_{\Lambda}\mathrm{H} + \pi^+$$

p^{-1}:	$p +$	${}^{5}\mathrm{He}$	$\Sigma^- \otimes {}^{5}\mathrm{He}$	$[f] = [41]$
s^{-1}:	$p +$	${}^{3}\mathrm{H} \otimes {}^{2}\mathrm{H}$	${}^{4}_{\Lambda}\mathrm{H} \otimes nn$	$[f] = [32]$

Few-Body Systems Suppl. 9, 165–168 (1995)

Few-Body Systems

The Hypernuclei with Neutron Halo

2 Hypernucleus ${}^{7}_{\Lambda}$He and the Structure of the Neutron Halo in ^{6}He

Although the most spectacular nucleus of that class is ^{11}Li, some characteristics of the neutron halo, e.g., three particle (core$+n+n$) bound state, are studied in the simplest ^{6}He nucleus [10].

The wave functions of 0^+ and 2^+ $(T=1)$ states are extremely simple in the $\alpha+n+n$ model:

$$|2^+1> = \cos\theta_2\,|^{31}D_2> + \sin\theta_2\,|^{33}P_2>,$$
$$|0^+1> = \cos\theta_0\,|^{31}S_0> + \sin\theta_0\,|^{33}P_0>,$$

therefore, the structure of the ${}^{7}_{\Lambda}$He states is also transparent:

$$|\tfrac{5}{2}^+> = |2^+> \times |s_\Lambda>,$$
$$|\tfrac{3}{2}^+> = \cos\beta\,|2^+> \times |s_\Lambda> + \sin\beta\,|1^+> \times |s_\Lambda>,$$
$$|\tfrac{1}{2}^+> = \cos\alpha\,|0^+> \times |s_\Lambda> + \sin\alpha\,|1^+> \times |s_\Lambda>.$$

The location of the thresholds and energy levels in ^{6}He nucleus [11] and ${}^{7}_{\Lambda}$He hypernucleus is displayed in Fig.1.

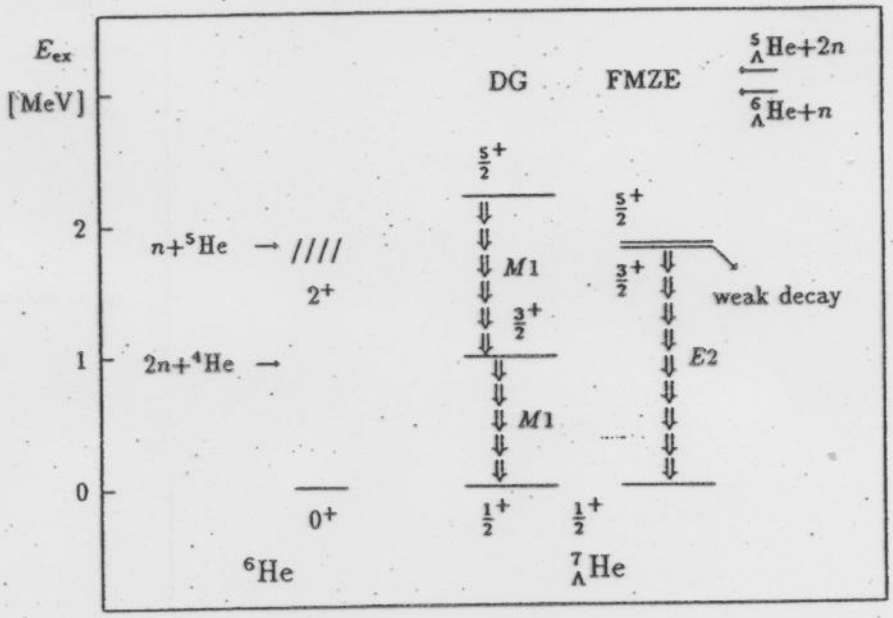


Figure 1. Spectrum of the ^{6}He (experiment) and ${}^{7}_{\Lambda}$He (calculations [12], [13])

The current calculations (see also [14]) locate the doublet of excited states *well below* the neutron threshold (2.92 MeV). Obviously, the electromagnetic decay rates for the excited states

$$\tfrac{5}{2}^+ \xrightarrow{M1} \tfrac{3}{2}^+ \xrightarrow{M1} \tfrac{1}{2}^+ \quad \text{and/or} \quad \tfrac{5}{2}^+ \xrightarrow{E2} \tfrac{1}{2}^+$$

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66 ('03) 1651

TRETYAKOVA

VA, LANSKOY

Table 2. Differential cross sections (in nb/sr) of the (π^-, K^+) reaction at zero angle at $p_\pi = 1.05$ GeV/c

Final hypernucleus	State	One-step mechanism	Two-step mechanism
$^{10}_{\Lambda}$Li	2^-		66.8
	1^-		3.2
$^{12}_{\Lambda}$Be	1^-	1.4	6.5
	0^+	0.1	2.1
$^{16}_{\Lambda}$C	2^+	0.3	0.4
	0^+	0.01	0.1

$^{10}B(\pi^-,K^+)$ spectrum with Year02+Year03

In total, about 40 counts in the bound region