Strange quarks in nuclear matter

at zero temperature

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Outline

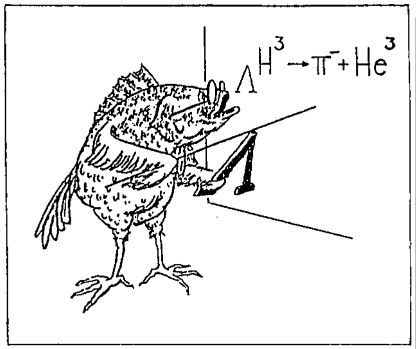
- Discovery potential of the strangeness nuclear physics
  - recent experimental results
  - unexpected effects
- Need of sub-MeV resolution apparatuses
  - γ-ray spectroscopy
- Ideas for PANDA apparatus

A. Feliciello / 2nd International Workshop on the Future Accelerator Facility for Beams of Ions and Antiprotons, October 14-17, 2003, GSI – Darmstadt (Germany)

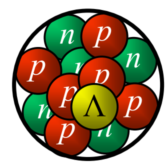
What is the strangeness nuclear physics?

Strangeness nuclear physics born exactly 50 years ago

60's

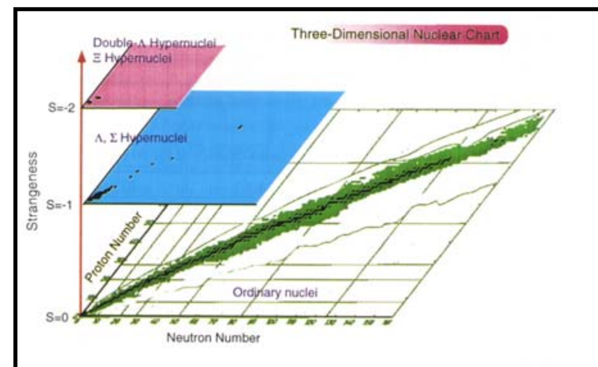


80's



nuclei with a tracer

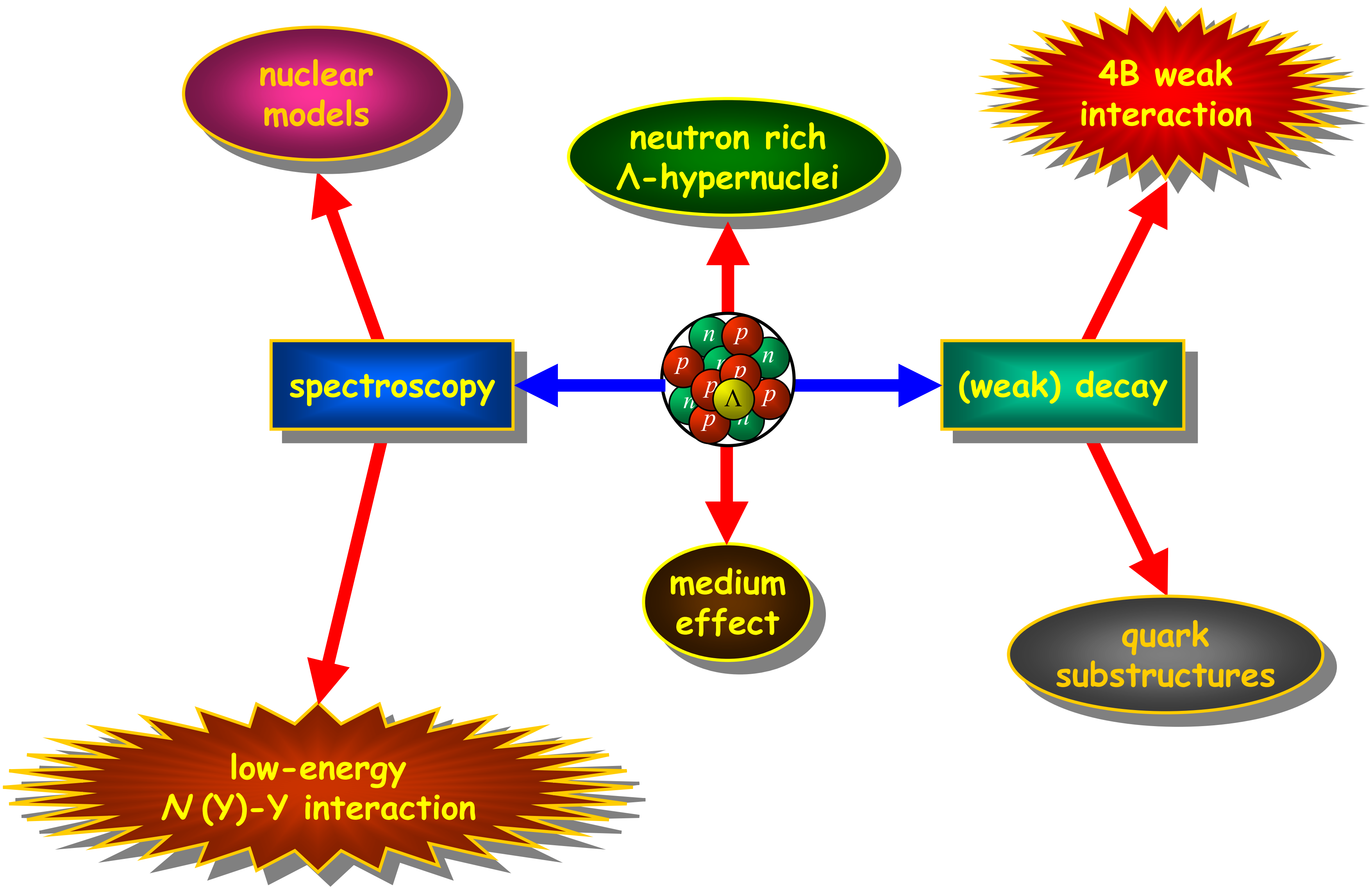
90's



Today hypernuclear physics is a mature research field with a well defined "personality"

- ☑ number of exp. physicists involved is growing
- ☑ significative theoretical effort well tuned on exp. data
- ☑ dedicated beams and apparatus
- ☑ main item in several future physics program

Physics output



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Λ-hypernucleus production

1) strangeness exchange (both in flight and at rest):

$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

2) associated production:

$$\pi^+ + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + K^+$$

3) electro-production:

$$e^- + {}^{A}Z \rightarrow e^{-\prime} + K^+ + {}^{A}_{\Lambda}(Z-1)$$

A hypernucleus is the outcome
of a genetic engineering manipulation
applied to the nuclear physics domain

Λ-hypernucleus spectroscopy

The simple structure of light hypernuclear systems can be described in the frame of the shell model

$$V_{\Lambda-N}(r) = V_0(r) + V_\sigma(r)\vec{s}_N \cdot \vec{s}_\Lambda + V_\Lambda(r)\vec{l}_{N\Lambda} \cdot \vec{s}_\Lambda + V_N(r)\vec{l}_{N\Lambda} \cdot \vec{s}_N + V_T(r)[3(\vec{\sigma}_N \cdot \vec{r})(\vec{\sigma}_\Lambda \cdot \vec{r} - \vec{\sigma}_N \cdot \vec{\sigma}_\Lambda)]$$

Each of the 5 terms (V, Δ, S_Λ, S_N, T) correspond to a radial integral that can be phenomelogically determined from the low-lying level structure of *p*-shell hypernuclei

The knowledge of the spin-dependent components of the ΛN interaction allows to improve baryon-baryon interaction models and to discriminate between the ones based on meson exchange picture and those including quark-gluon degrees of freedom

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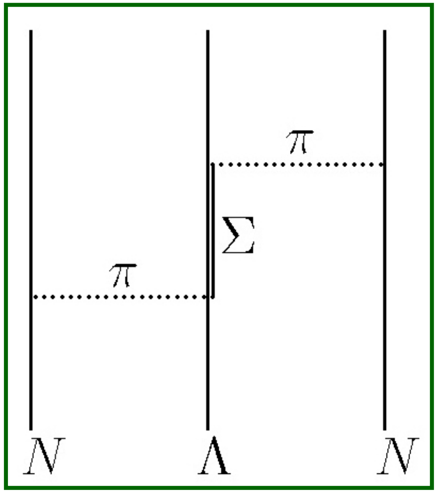
3-body force

The energy spectrum of hypernuclei cannot be completely reproduced by a simplified 2-body effective interaction scheme



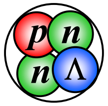
Study of ΛNN 3-body and of ΛN 2-body forces is of great importance to understand the structure of hypernuclei

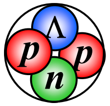
- $\Delta m_{\Sigma-\Lambda} \ll \Delta m_{\Delta-N} \rightarrow \Lambda NN \gg NNN$
- $\Lambda NN > \Lambda N$

Charge symmetry breaking

$$\Lambda \begin{cases} I = 0 \\ q = 0 \end{cases} \Longrightarrow \Lambda p = \Lambda n$$

if the charge symmetry holds exactly

$^{4}_{\Lambda}H$ 

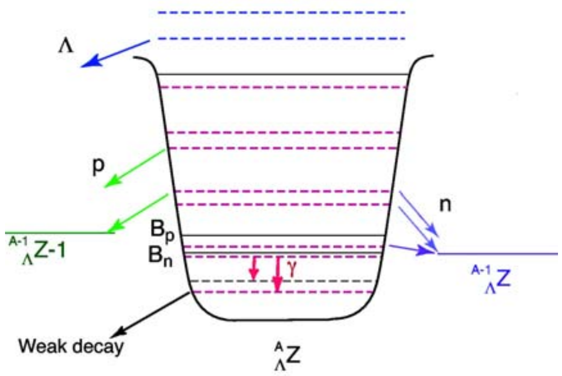
$^{4}_{\Lambda}He$ 

$$B_\Lambda(^{4}_{\Lambda}H) \neq B_\Lambda(^{4}_{\Lambda}He)$$

Λp more attractive than Λn

Possible explanations:
- $\Lambda\Sigma^0$ mixing
- $\Lambda N - \Sigma N$ coupling

Odd-state interaction



even-states ΛN (*s*-wave)
odd-states ΛN (*p*-wave) } interactions

$$\frac{s\text{-wave}}{p\text{-wave}} = ?$$

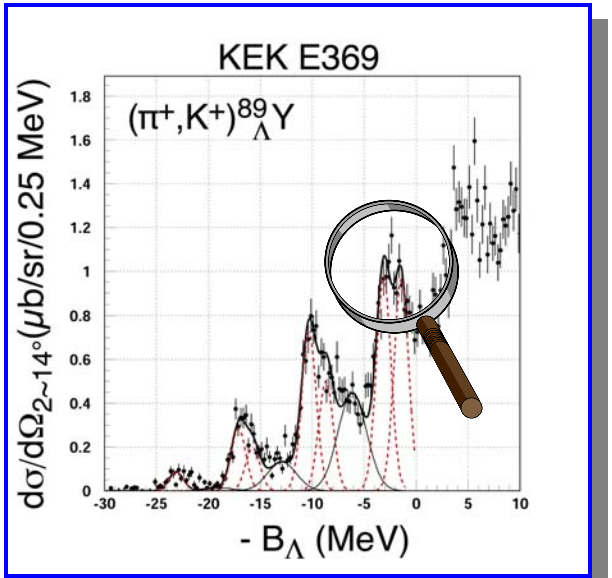
- ND model: attractive odd-state force
- NSC97 model: repulsive odd-state force

in contrast with data on $^{13}_{\Lambda}C$!

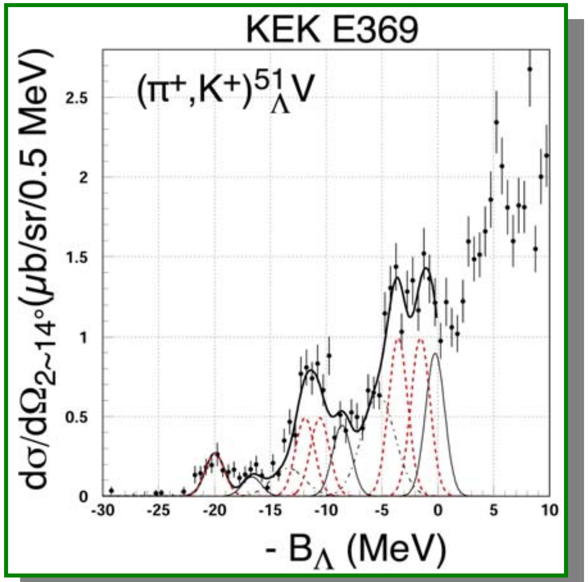
odd-states are usually particle unbound for light (A < 50) hypernuclei
→ best candidate hypernuclei $^{89}_{\Lambda}Y$ and $^{208}_{\Lambda}Pb$

The status of the art

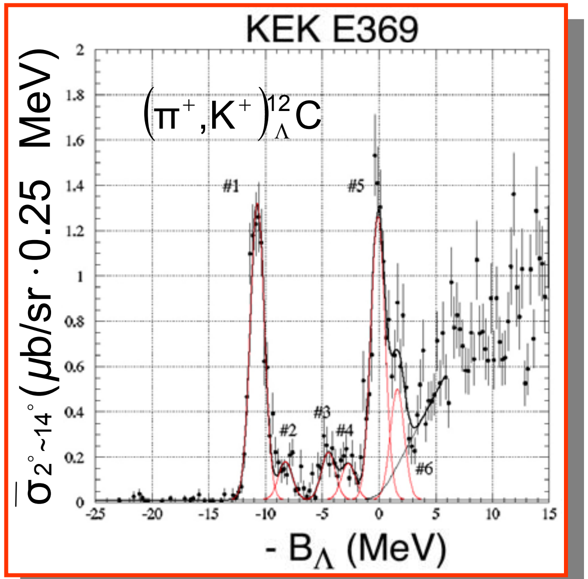
ΔE ~ 1.65 MeV FWHM



ΔE ~ 1.95 MeV FWHM



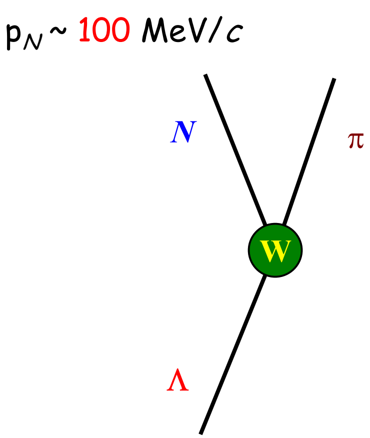
ΔE ~ 1.45 MeV FWHM



f-orbit splitting
into two peaks observed?

Λ-hypernucleus decay

free Λ decay



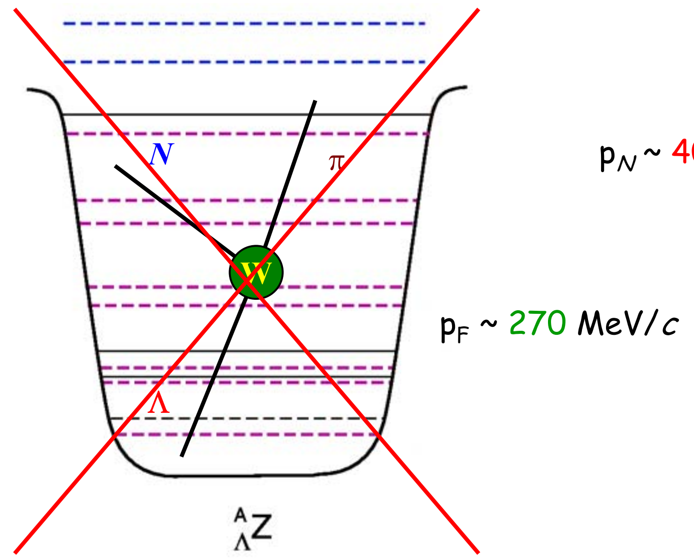
$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

$\tau_\Lambda = 263$ ps

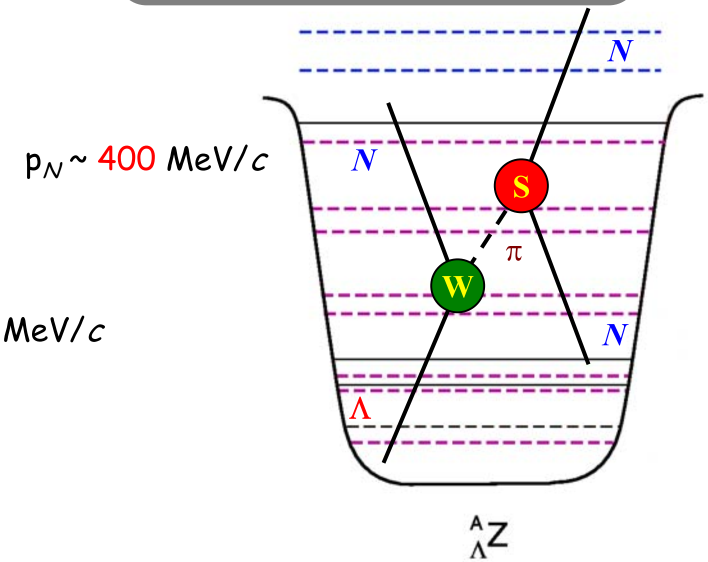
ΔI = ½ rule
(not understood)

hypernucleus mesonic decay



suppressed by Pauli blocking

hypernucleus non-mesonic decay



$\Lambda + n \rightarrow n + n + 176$ MeV

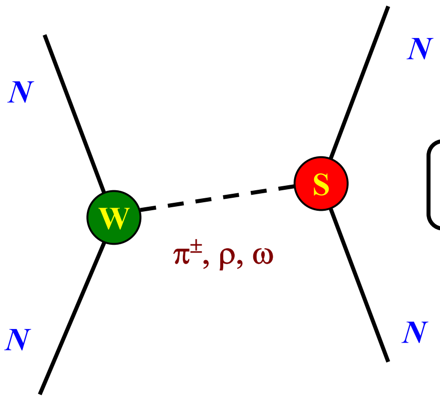
$\Lambda + p \rightarrow n + p + 176$ MeV

dominant in all but the lightest hypernuclei

4 baryon weak interaction

The hypernucleus non-mesonic decay provides primary means of studying the baryon-baryon weak interaction

N-N scattering

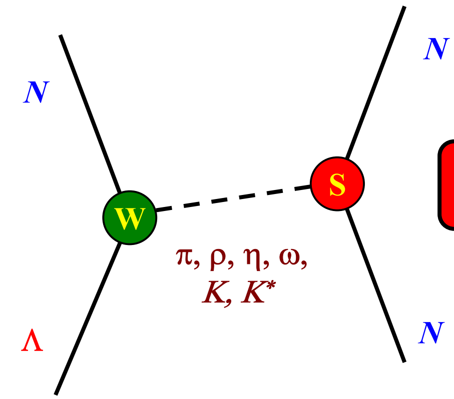


ΔS = 0

- only information on the parity violating part of weak interaction is accessible
- parity conserving part is masked by strong interaction

Λ + N → N + N

in nuclear medium only



ΔS = 1

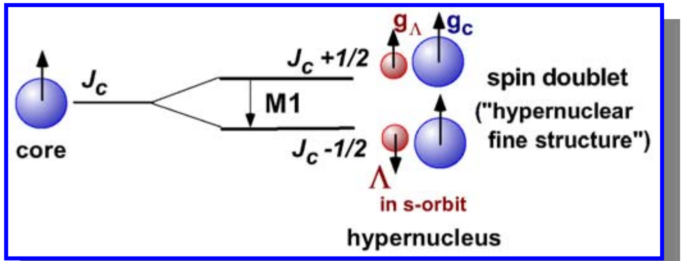
- both information on the parity violating and parity conserving parts of weak interaction can be extracted
- q ~ 400 MeV/c ⇒ probes short distance

☛ $\Delta = \frac{1}{2}$ rule applies also to non-mesonic weak decay?

☛ The role of explicit quark/gluon substructures can be put in evidence?

Medium effect

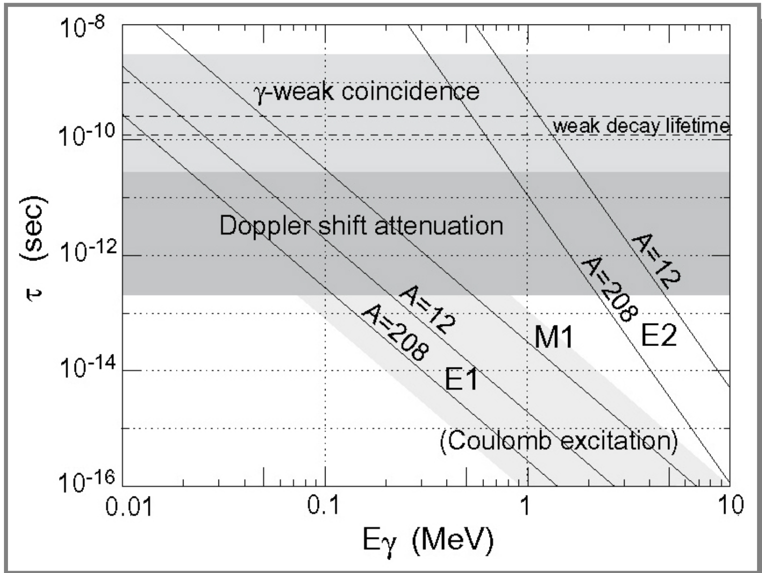
If the mass or the size of a hyperon is modified in a nucleus, its magnetic moment may be changed



$$B(M1) \propto \left| \left\langle \phi_{lo} \middle| \mu^z \middle| \phi_{up} \right\rangle \right|^2 = \left| \left\langle \phi_{lo} \middle| g_N J_N^z + g_\Lambda J_\Lambda^z \middle| \phi_{up} \right\rangle \right|^2$$
$$\propto (g_N - g_\Lambda)^2$$

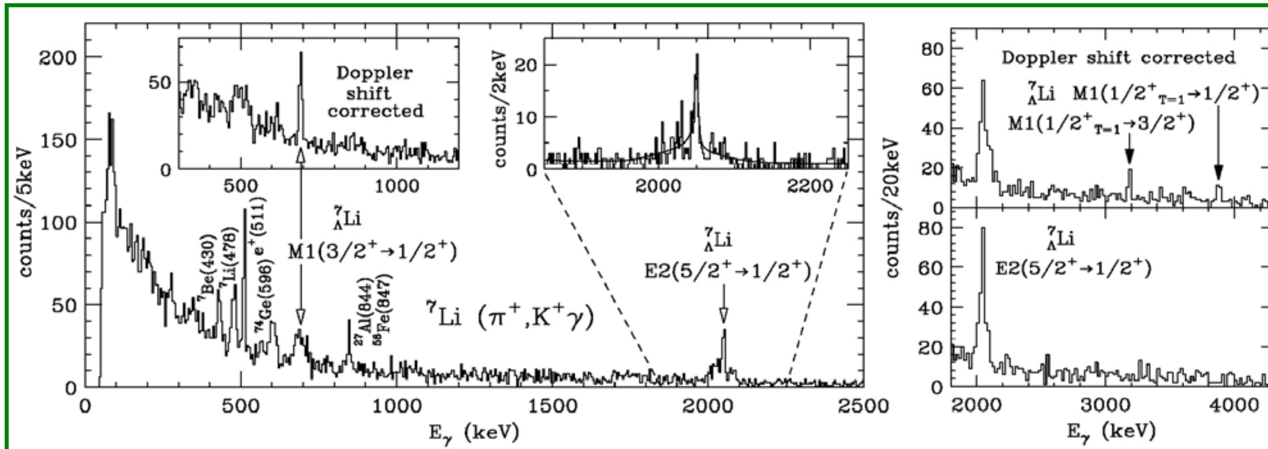
B(M1) can be derived from excited states lifetimes

- Doppler-shift attenuation method
- γ-weak coincidence method



One step beyond

KEK E419



Precise hypernuclear γ-spectroscopy has been established as new frontier in strangeness nuclear physics

Impurity nuclear physics

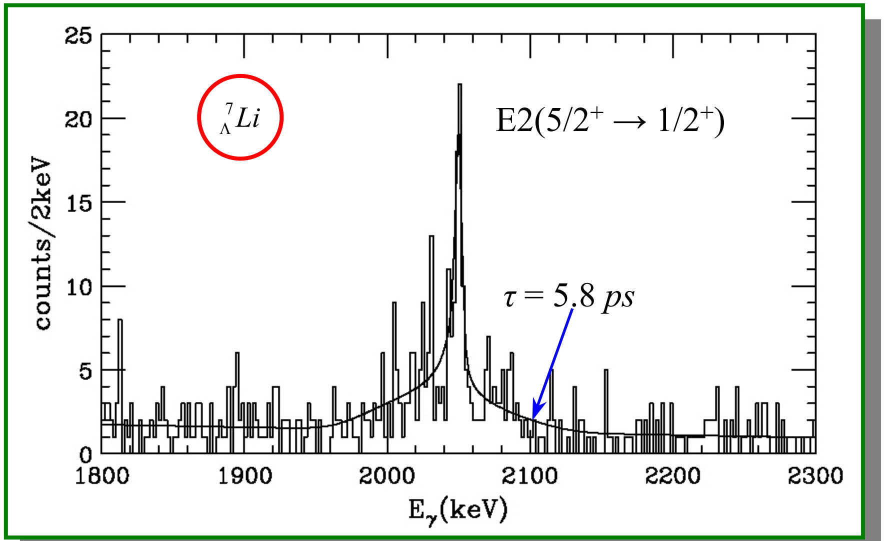
The introduction of 1 (or 2) hyperons in a nucleus may give rise to various changes of the nuclear structure

- changes of the size and of the shape
- changes of the cluster structure
- manifestation of new symmetries
- change of collective motions
- …

study of hypernucleus level schemes and B(E2) ← Doppler-shift attenuation method

The Λ glue role

KEK E419

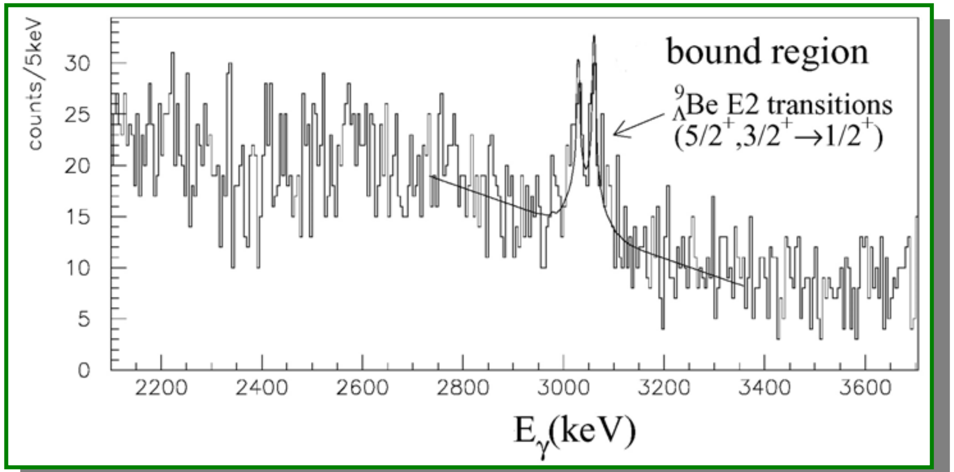


$$\frac{B(E2;{}^7_\Lambda Li : 5/2^+ \rightarrow 1/2^+)}{B(E2;{}^6Li : 3^+ \rightarrow 1^+)} = \frac{3.6 \pm 0.5^{+0.5}_{-0.4} \;\; e^2 fm^4}{10.9 \pm 0.9 \;\; e^2 fm^4} \approx \frac{1}{3}$$

B(E2) $\propto r^4 \Rightarrow$ shrinkage of ^6Li core by ~ 20%

Which model description?

BNL E930



	experiment	OME	QM
${}^{9}_{\Lambda}Be(5/2^+ \rightarrow 3/2^+)$	31 ± 2 keV	80 - 200 keV	35 - 40 keV
${}^{13}_{\Lambda}C(3/2^- \rightarrow 1/2^-)$	152 ± 36 keV	390 - 960 keV	150 - 200 keV

BUT
quark based models have yet to provide
an extensive and satisfactory description of YN interaction

S = -2 systems

S = -2 systems study is not just a simple extension of what has been done for S = -1 system

- new physics items:
  - a detailed and consistent understanding of the quark aspect of the baryon-baryon forces in the SU(3) space will not be possible as long as experimental information on the *YY* channel is not available
  - search for *H* particle
  - neutron star composition

- challenges:
  - (abundant) production of ΛΛ-hypernuclei is very difficult
  - identification of produced hypersystems is problematic
  - γ-ray measurement in coincidence

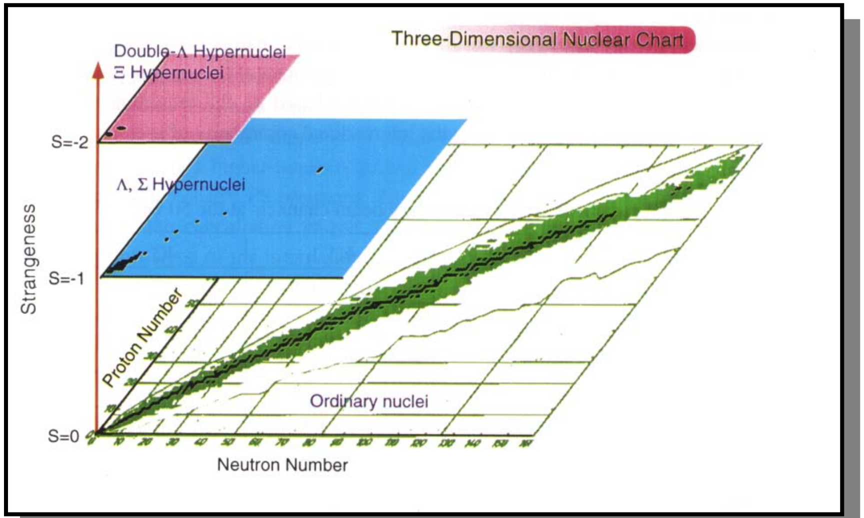
Observed ΛΛ-hypernuclei

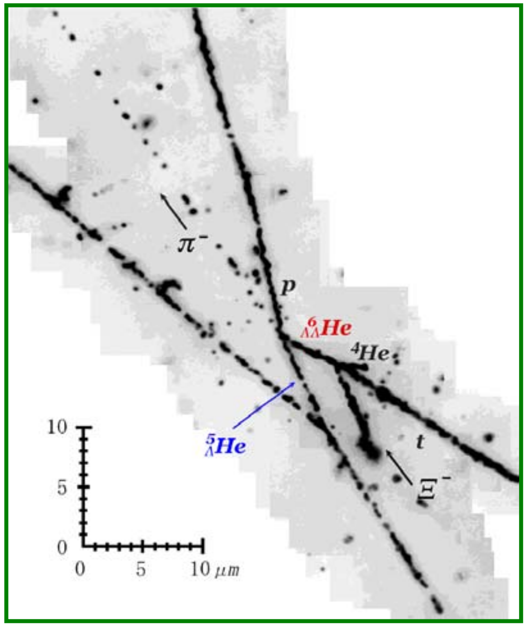
- 1963: Danysz et al. ${}^{10}_{\Lambda\Lambda}Be$ (emulsion)
- 1966: Prowse ${}^{6}_{\Lambda\Lambda}He$ (emulsion, Dalitz criticises the interpretation)
- 1991: KEK-E176 ${}^{13}_{\Lambda\Lambda}B$ (or ${}^{10}_{\Lambda\Lambda}Be$, emulsion counter hybrid experiment)
- 2001: BNL-E906 ${}^{4}_{\Lambda\Lambda}H$
- 2001: KEK-E373 ${}^{6}_{\Lambda\Lambda}He$
- 2001: KEK-E373 ${}^{10}_{\Lambda\Lambda}Be$

$$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$$

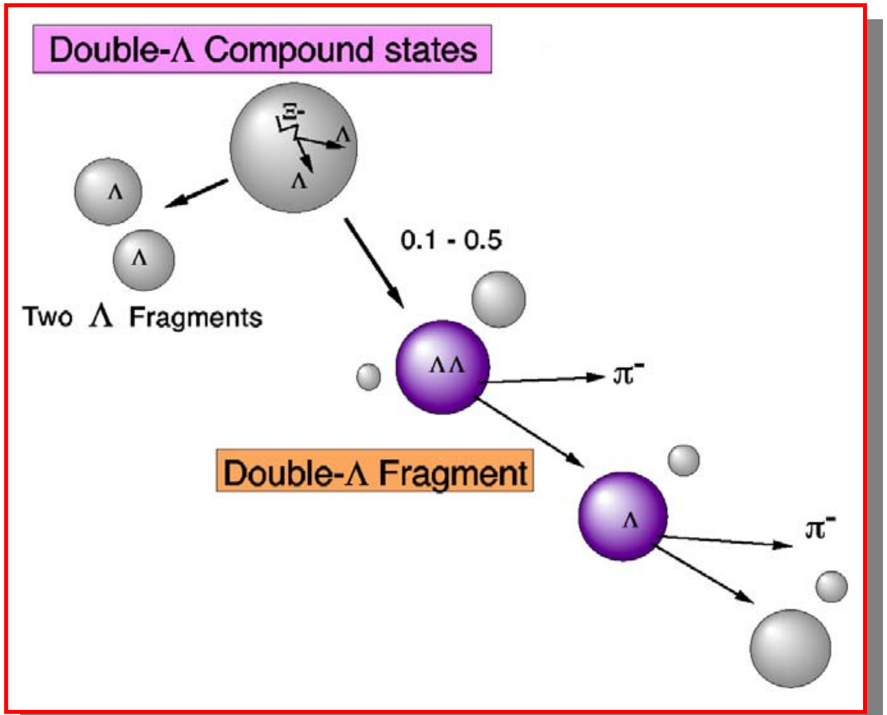
$$\hookrightarrow \; {}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

After 40 years!





How to identify a ΛΛ-hypernucleus

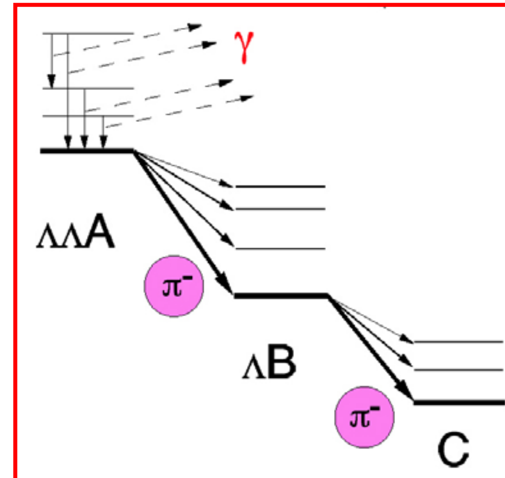


limited target choice
(at least for the pilot runs)

^{6}Li, ^{7}Li, ^{8}Be, ^{9}Be, ^{12}C

sequential pionic decay

$${}^{A}_{\Lambda\Lambda}Z \to {}^{A'}_{\Lambda}Z' \to {}^{A''}_{\Lambda}Z''$$



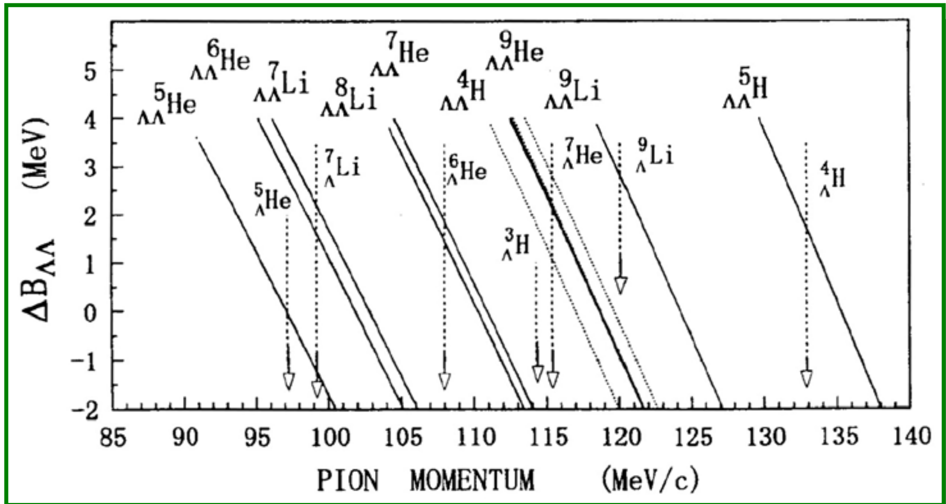
main background

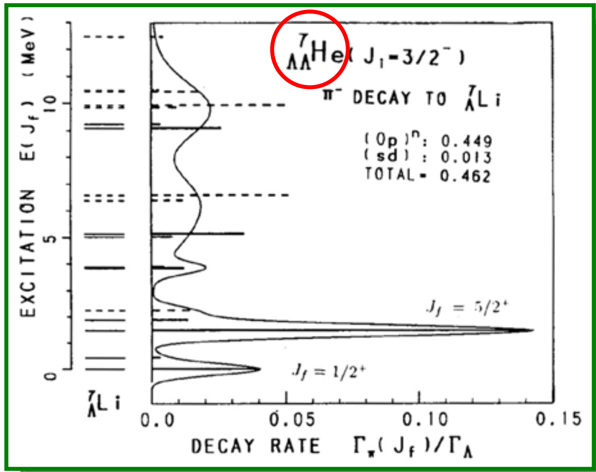
$\Xi^- \to \Lambda + \pi^-$

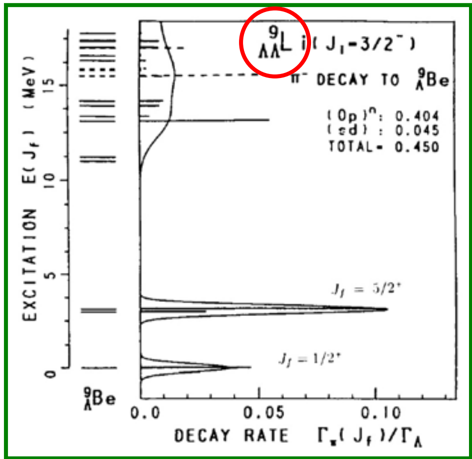
$\Lambda \to p + \pi^-$

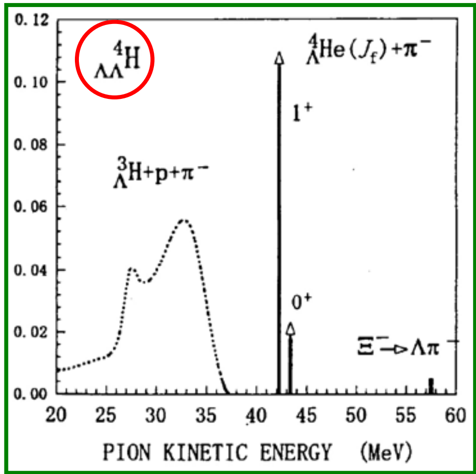
critical!

Expected π⁻ momentum spectrum







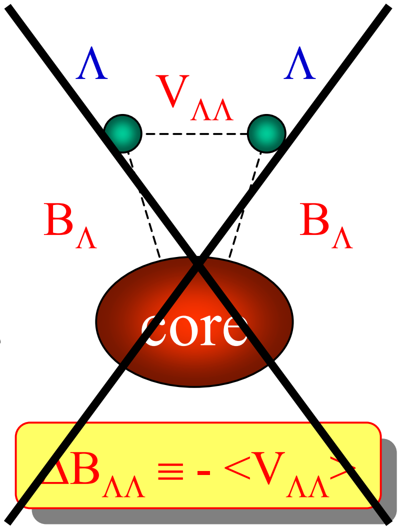


The status of the art

Hypernucleus	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
$^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4
$^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6
$^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$
same event! $^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7
same event! $^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7
$^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$	

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$



one can not to interpret $\Delta B_{\Lambda\Lambda}$ as ΛΛ binding energy because of:

- dynamical change of the core nucleus
- ΛΛ spin-spin interaction for non-zero spin of core
- possible excited states

if ΛΛ- or intermediate Λ-hypernuclei are produced in excited states:

- Q-value is difficult to extract (especially for heavy nuclei)
- nuclear fragments are difficult to identify with usual emulsion technique

new concept required! → γ-spectroscopy

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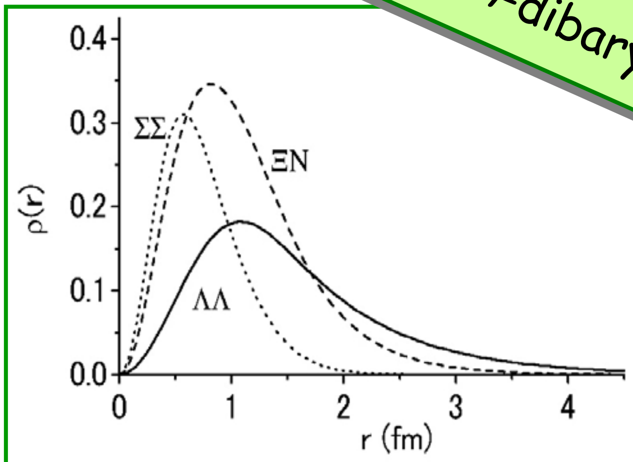
Open questions

decay properties:

- ? total decay rate
- ? lifetime measurements
- ? non-mesonic weak decay modes
- ? influence of the *H*-like structure

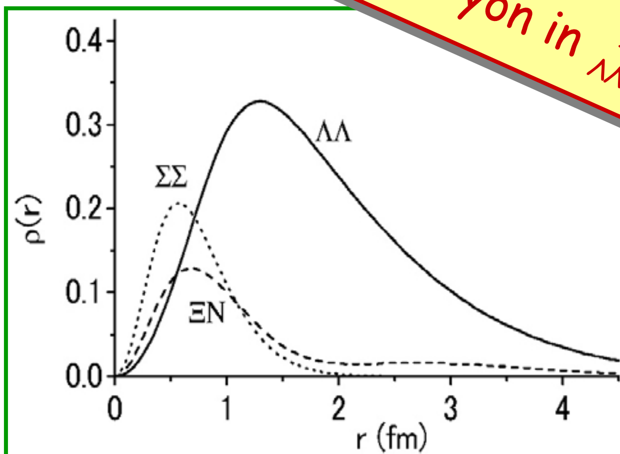
S = - 2 systems and H-dibaryon states

free H-dibaryon



$B_{\Lambda\Lambda}$ = 12.2 MeV

H-dibaryon in $^{10}_{\Lambda\Lambda}Be$

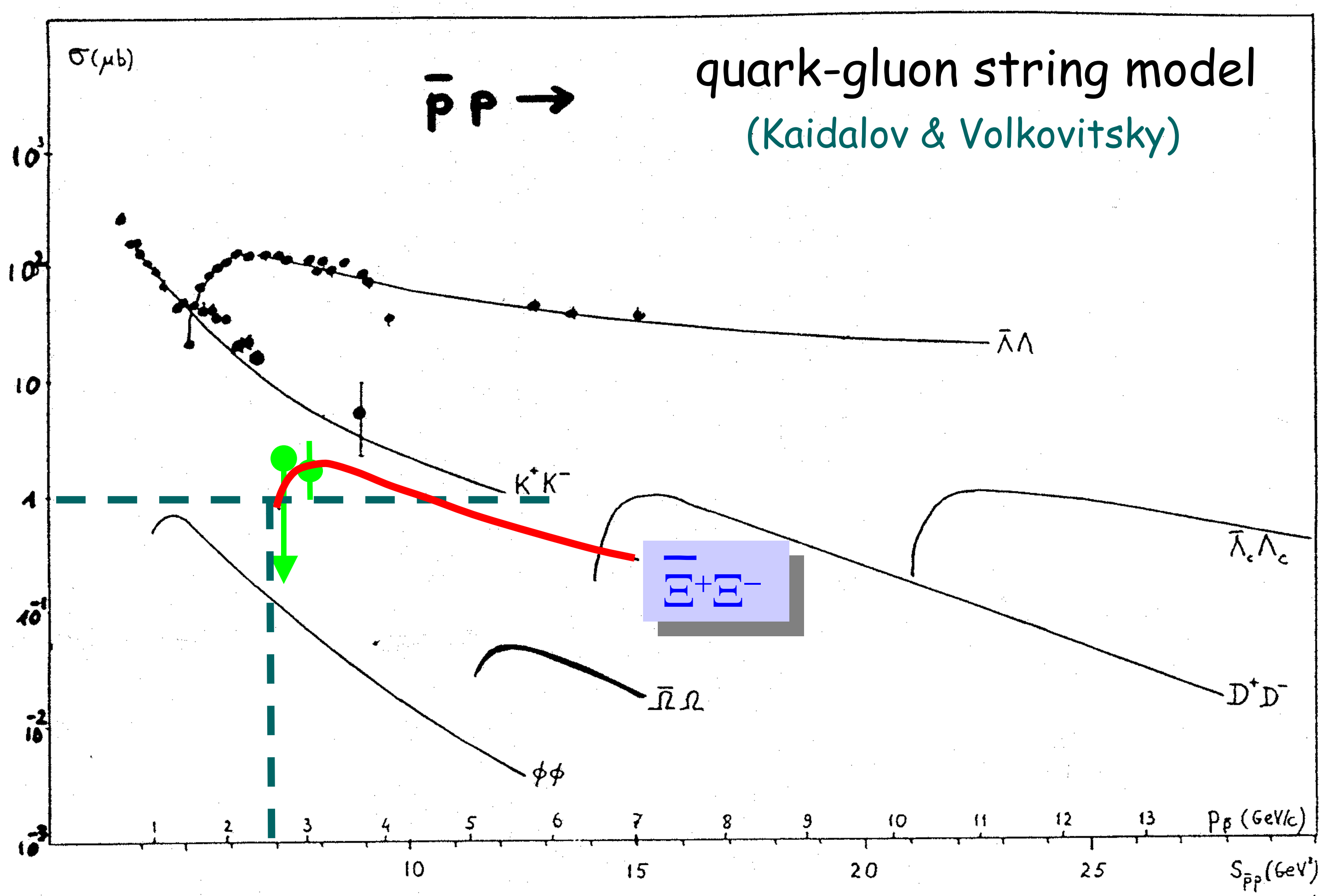


$B_{\Lambda\Lambda}$ = 24 MeV

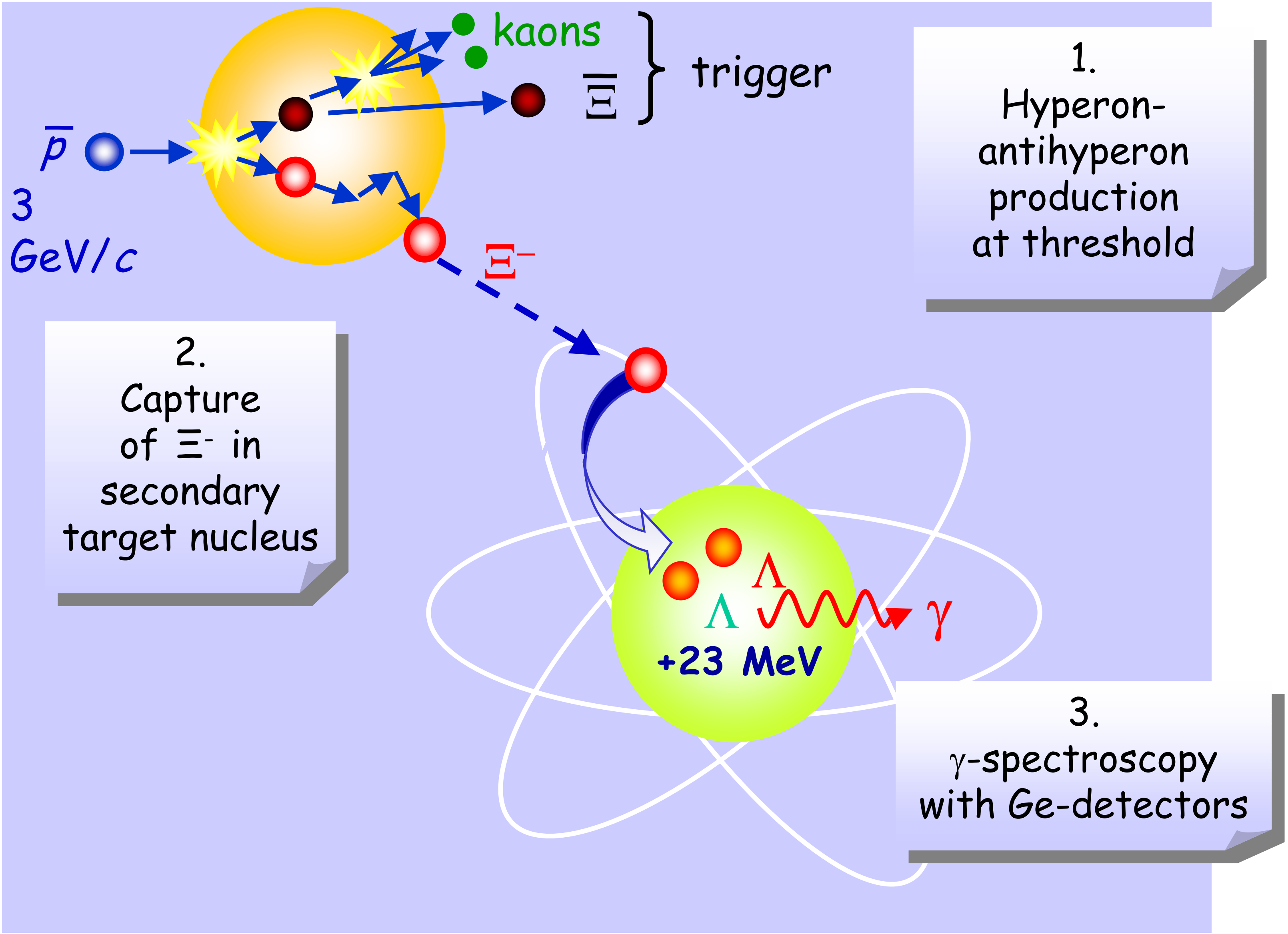
H particle formation can be revealed by a modification of the energy levels of ΛΛ-hypernuclei

General idea

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28\ \mathrm{MeV}$$



ΛΛ-hypernucleus production @ GSI



Expected rates

$$\sigma_{\bar{p}p}(\Xi\bar{\Xi}) = 2 \;\; \mu b \;\; @ \;\; 3 \;\; \text{GeV}/c$$

$$\sigma_{\bar{p}A}(\Xi\bar{\Xi}) = A^{2/3} \cdot \sigma_{\bar{p}p}(\Xi\bar{\Xi})$$

by using, e.g., a ^{12}C wire target:

@ $\mathcal{L} = 10^{32}$ cm^{-2} s^{-1} HESR will produce $\Xi^-\bar{\Xi}$ pairs @ ~ 7 × 10^2 Hz

- joint $\Xi^-\bar{\Xi}$ escape probability: 5 × 10^{-4}
  (trigger on $\bar{\Xi}$ + p_{Ξ^-} = 100 – 500 MeV/c)
- $\bar{\Xi}$ reconstruction efficiency: ~ 50%
- Ξ^- stopping and capture probability: ~ 20%

→ ~ 3 × 10^3 captured Ξ^- /d

- $\Xi^- p \rightarrow \Lambda\Lambda$ conversion probability: 5%

→ ~ 150 ΛΛ-hypernuclei /d

- γ-ray emission/event: 50%
- γ-ray Ge photopeak efficiency: 10%

→ ~ 7 "golden events" /d

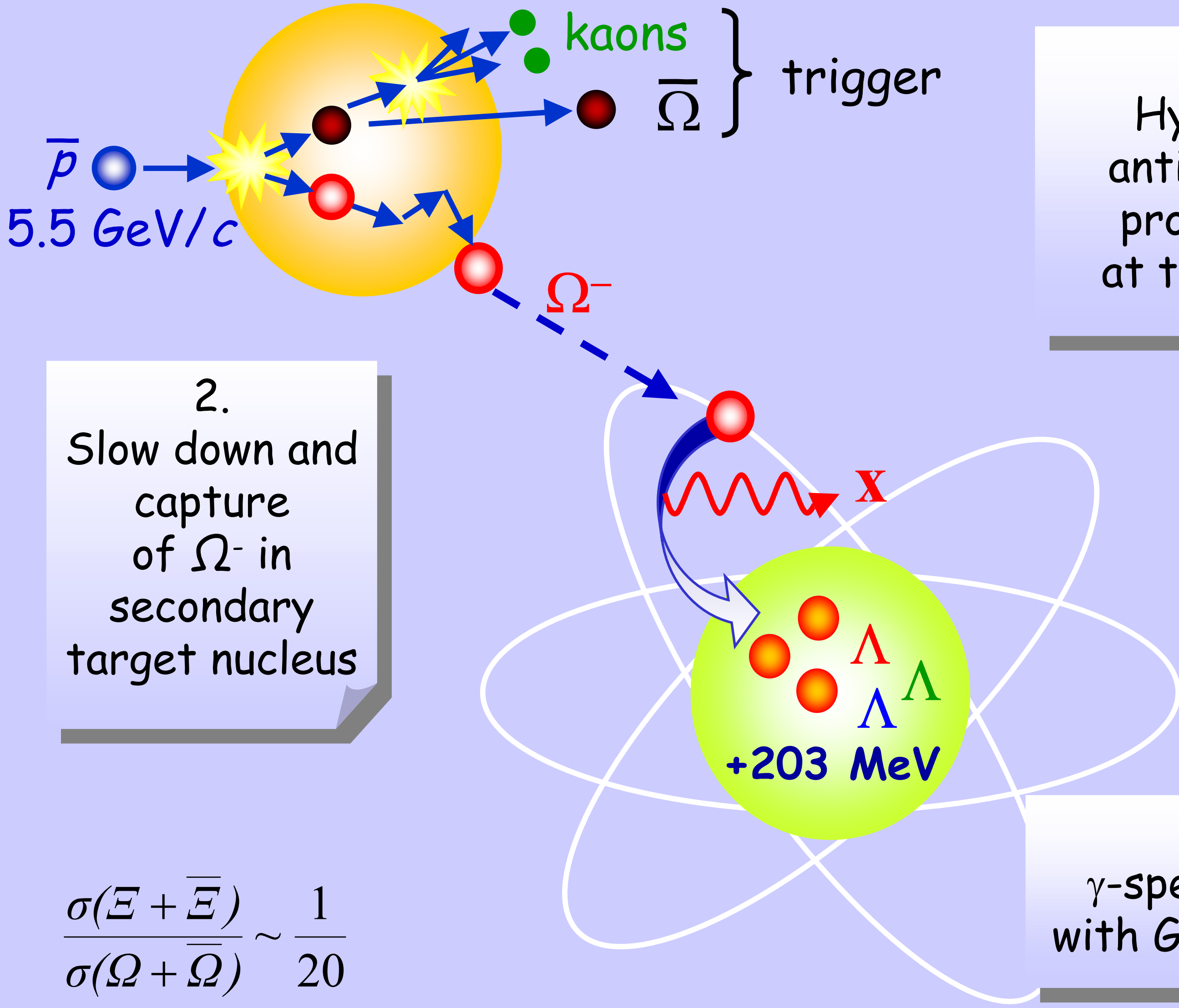
- K^+K^+ trigger

→ ~ 700 events /d

Competition

experiment	*reaction*	*device*	*beam/ target*	*status*
BNL-AGS E885	$(\Xi^-,{}^{12}C) \rightarrow {}_{\Lambda\Lambda}{}^{12}B + n$	neutron detector arrays	K^- beam, diamond target	20000 stopped Ξ^-
BNL-AGS E906	2π decays	Cylindrical Detector System	K^- beam line	few tens 2π decays of ${}_{\Lambda\Lambda}{}^{4}H$
KEK-PS E373	$(K^-,K^+)\ \Xi$	emulsion	(K^-,K^+)	several hundreds stopped Ξ^-
facility	*reaction*	*device*	*beam / target*	*Captured Ξ^- / day*
JPARC	$(K^-,K^+)\ \Xi$	spectrometer, $\Delta\Omega$ = 30 msr	$8\cdot10^6$/s 5 cm ${}^{12}C$	< 7000
cold anti-protons	$p\,\bar{p} \rightarrow K^+ \bar{K}^+$ $K^+ N \rightarrow \Xi\ K$	vertex detector	10^6 stopped $\bar{p}$/s	2000
GSI-HESR	$p\,\bar{p} \rightarrow \Xi\bar{\Xi}$	vertex detector + γ-spectrometer	$\mathcal{L} = 2\cdot10^{32}$, thin target, production vertex $\neq$ decay vertex	~ 3000 ~ 300000 KK trigger (incl. trigger)

Ω-atoms production @ GSI



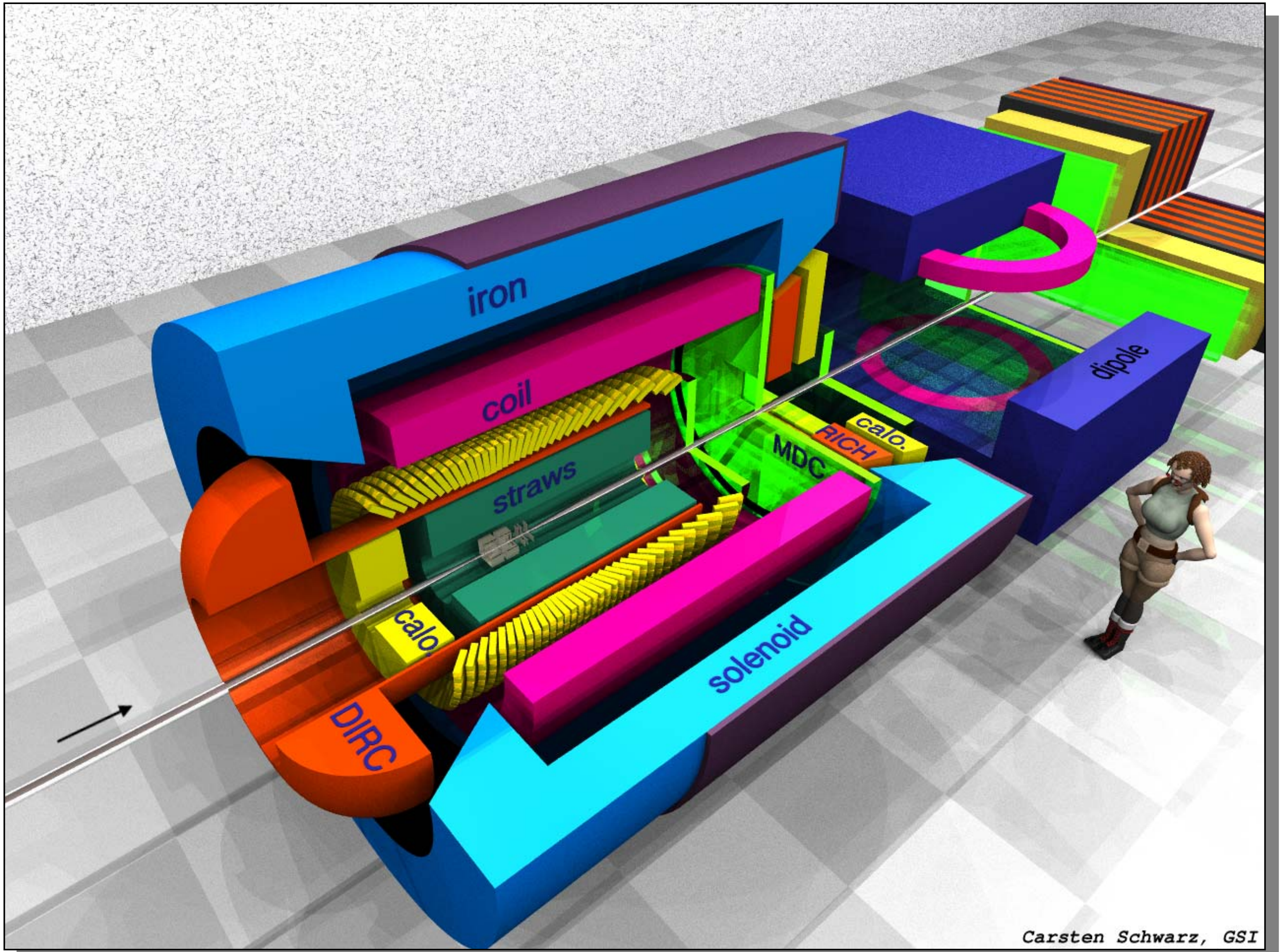
1.
Hyperon-antihyperon production at threshold

2.
Slow down and capture of Ω^- in secondary target nucleus

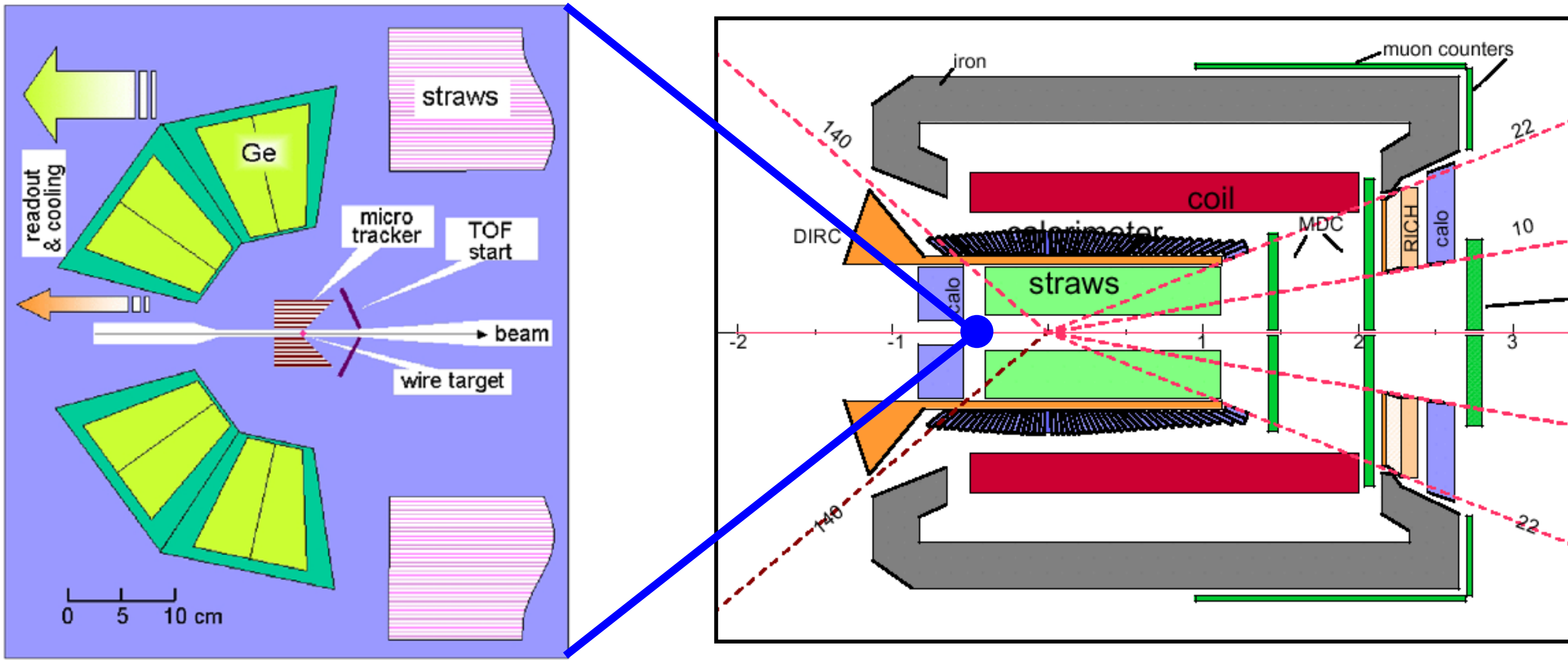
3.
γ-spectroscopy with Ge-detectors

$$\frac{\sigma(\Xi+\overline{\Xi})}{\sigma(\Omega+\overline{\Omega})} \sim \frac{1}{20}$$

The PANDA detector



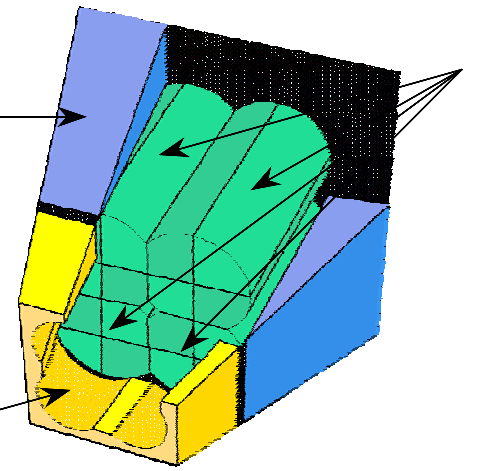
Ge array for hypernuclei detection



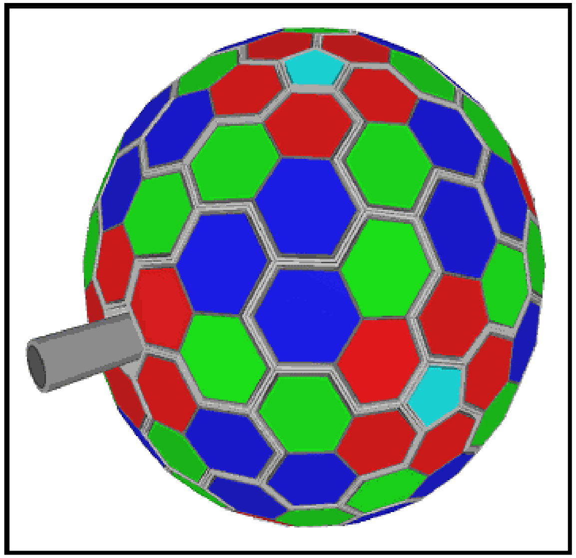
- solid state micro-tracker (diamond or silicon)
  - compact: thickness ~ 3 cm
  - high rate capability
  - high resolution
- capillar (2D) or pixel (3D) detector
- position sensitive Ge detector (VEGA or AGATA like)
  - high rate capability

VEGA (Versatile and Efficient GAmma detector)

The Segmented Clover Detector



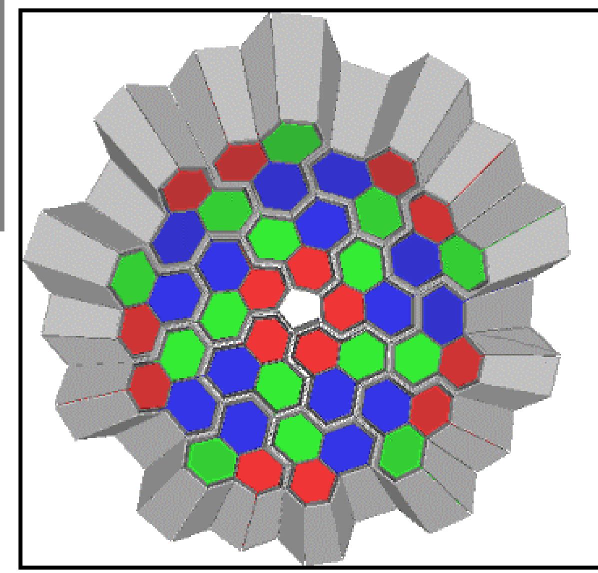
AGATA (Advanced Gamma-ray Tracking Array)

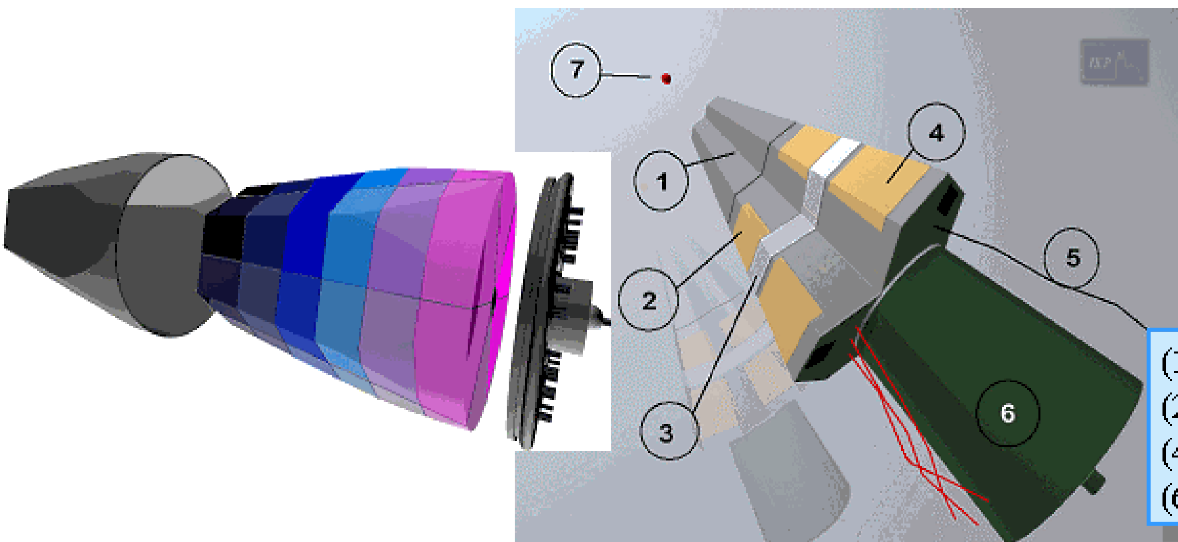


- ✓ 180 hexagonal crystals
  in 3 different, asymmetric shapes
  grouped in 60 triple-cluster cryostats
- ✓ 10 pentagonal crystals
  individually canned
- ✓ 230 kg of germanium
  crystals of ∅ 8 cm; L : 9 cm
- ✓ full sphere with
  solid angle coverage ~78 %
  inner-outer radius of 17-26 cm
  total of 6780 segments

☛ immersed in magnetic field

☛ exposed to huge hadronic background





(1) three 36-fold segmented Ge detectors
(2) 111 preamplifiers (3) frame support
(4) digital electronics (5) fiber-optics read-out
(6) LN_2 dewar (7) target position

Summary

hypernucleus **spectroscopy** and **decay**

- textbook evidence for the validity of the shell model
- spin-orbit terms in the optical potential
- glue-role of the Λ (nuclear medium effect)

→ very clean nuclear physics!

- 4 baryon weak interaction $\Lambda\mathcal{N} \rightarrow \mathcal{N}\mathcal{N}$ (validity of $\Delta I = \frac{1}{2}$ rule)
- low energy $\Lambda\mathcal{N}$ scattering (short range aspects of the nuclear force)
- $\Lambda\Lambda$ interaction
- search for *H* particle

→ unique particle physics!

Conclusions

- ✓ The fifty-year-old field of strangeness nuclear physics is still alive and has a great discovery potential
  - number of exp. physicist involved is growing
  - significative theoretical effort well tuned on exp. data
  - dedicated beams and apparatus
  - main item in several future physics program at new facilities

- By exploiting the potentialities of the new HESR machine a large number of ΛΛ-hypernuclei will be produced, allowing a significative step forward in multi-strange system knowledge

- 2013 will be the 50th anniversary of ΛΛ-hypernucleus discovery: GSI could successfully celebrate it with a long series of fundamental questions solved