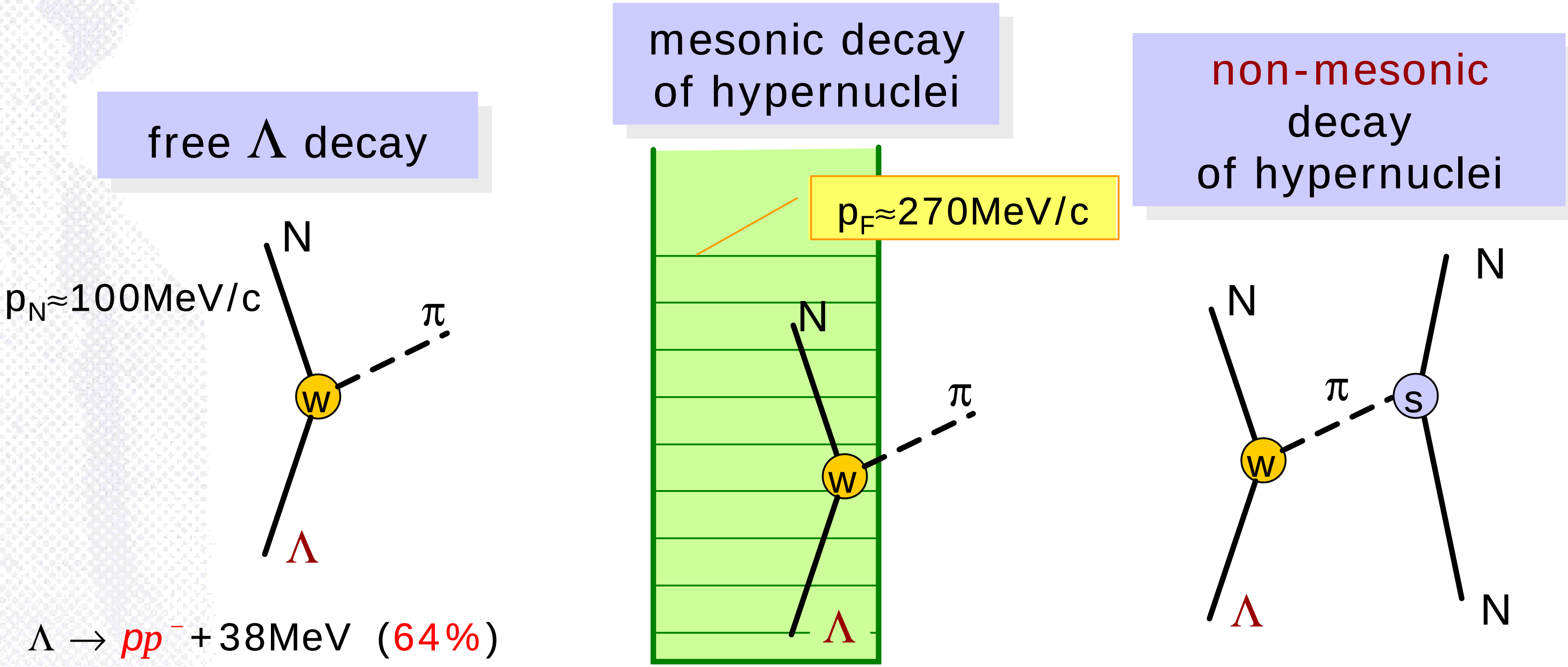
Future Experiments on Hypernuclei and Hyperatoms

1. The Physics Case
2. Present Status
3. Hypersystems in $p\bar{p}$ Interactions
4. The Experiment

1. The Physics Case

Two Sides of a Coin

- baryons tagged with a strange quark as a probe of the nuclear structure
- nuclei as a femto-laboratory for strange baryons



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

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

$t_\Lambda = 263 ps$

suppressed by Pauli blocking

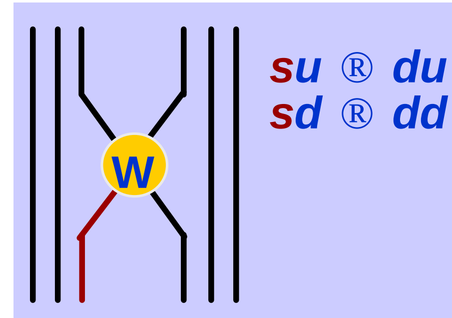
$\Lambda p \rightarrow np + 176\text{MeV}$

$\Lambda n \rightarrow nn + 176\text{MeV}$

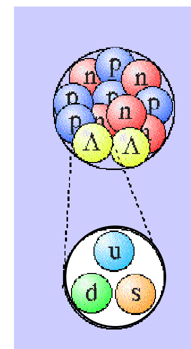
To use nuclei as a QCD-laboratory we have to understand the laboratory

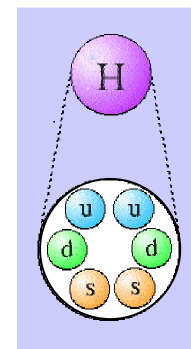
Strange Baryons in Nuclear Systems

- s=1: Λ-, Σ-hypernuclei
  - nuclear structure, new symmetries
    - the presence of a hyperon may modify the size, shape… of nuclei
    - new specific symmetries
  - Y-N interaction
  - strange baryons in nuclei
  - weak decay



- s=2: Ξ-atoms, Ξ-, ΛΛ-hypernuclei
  - nuclear structure
  - baryon-baryon interaction in $SU(3)_f$
  - H-dibaryon





- s=3: Ω-atom, (Ω-,ΛΞ-, ΛΛΛ-hypernuclei ?)
  - quadrupole moment of the Ω

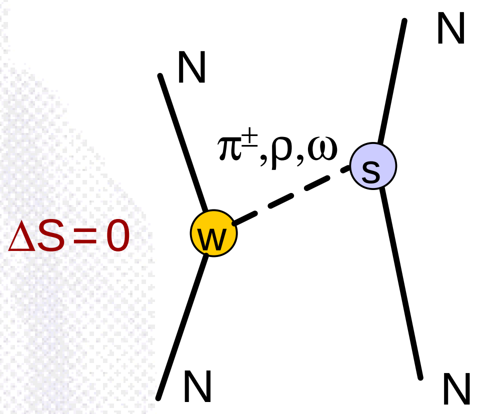
meson vs.
gluon/quark
exchange

Hypernuclei provide a link between nuclear physics and QCD

Weak baryon-baryon interaction

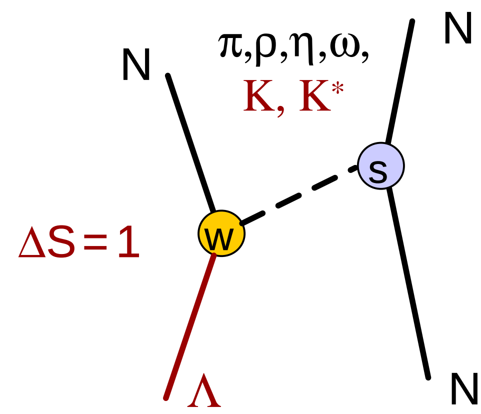
- non-mesonic weak decay of hypernuclei explore the baryon-baryon weak interaction

N-N scattering



- only parity violating part of weak interaction
- parity-conserving part masked by strong interaction

ΛN→N N

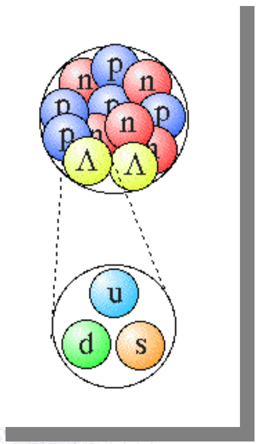


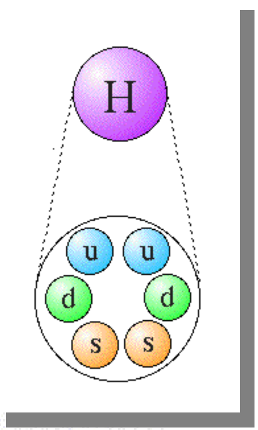
- parity violating *and* parity-conserving part of weak, strangeness changing, interaction
- q~400 MeV/c

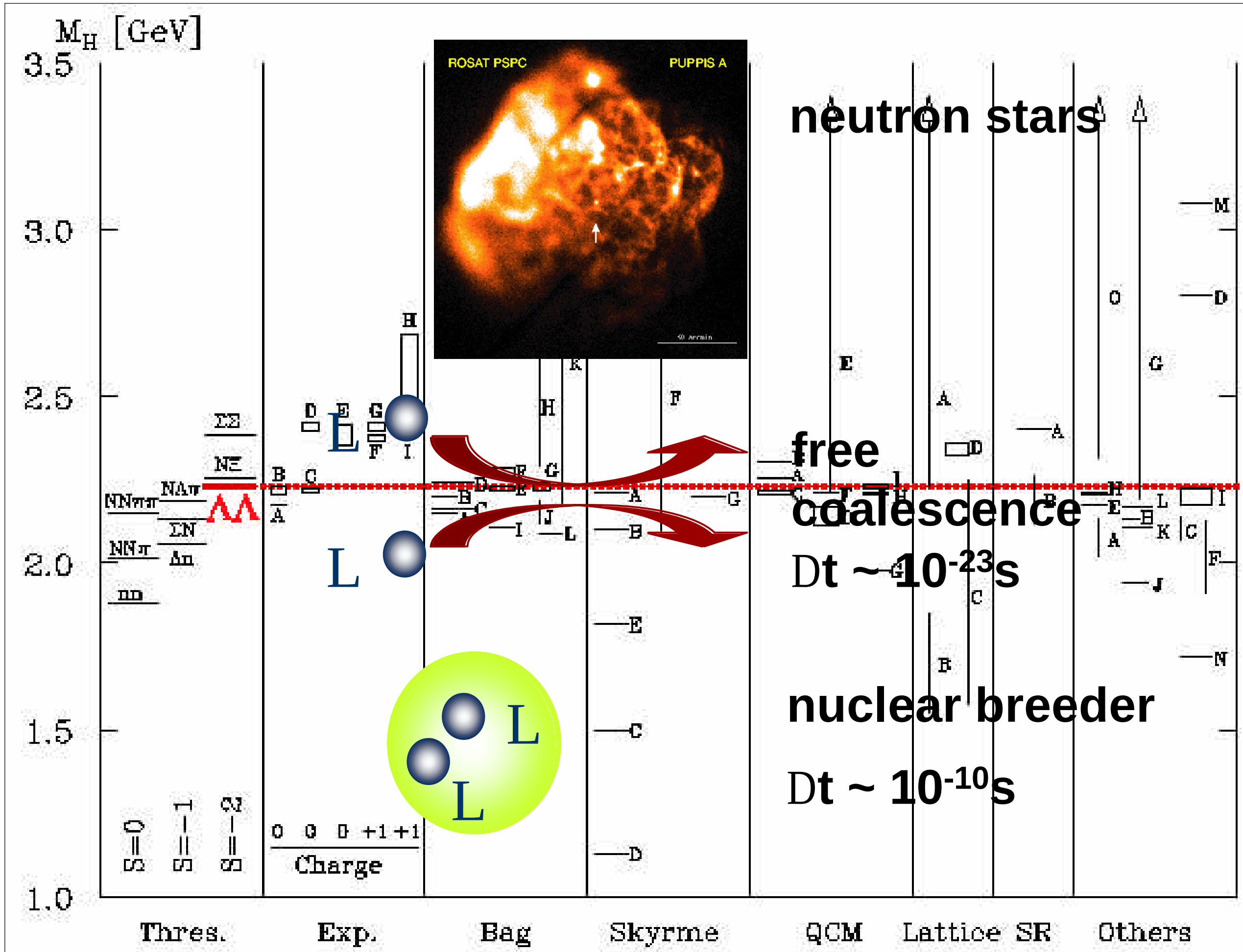
  ⇒ probes short distances

ΛΛ Nuclei as Femto-Laboratory

- *H*-Particle   R.L. Jaffe (1977)





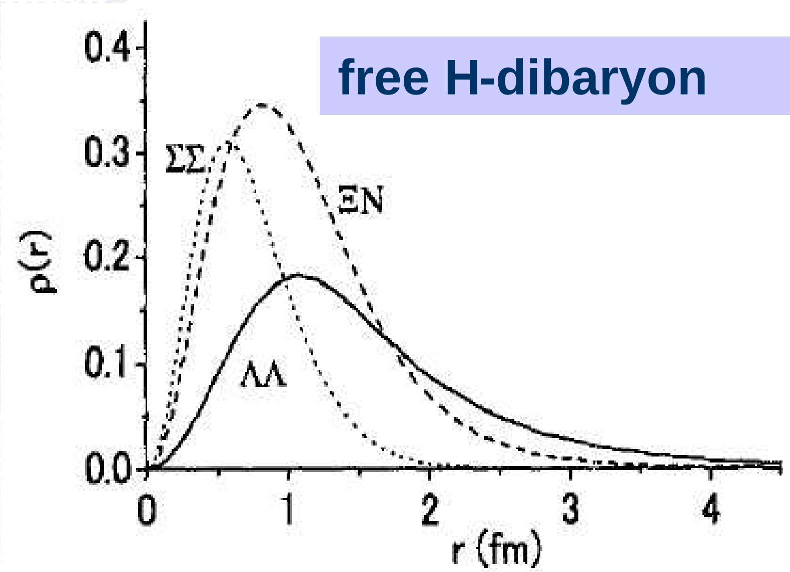


T. Sakai, K. Shimizu, K. Yazaki
Prog.Theor.Phys.Suppl. 137 (2000) 121-145

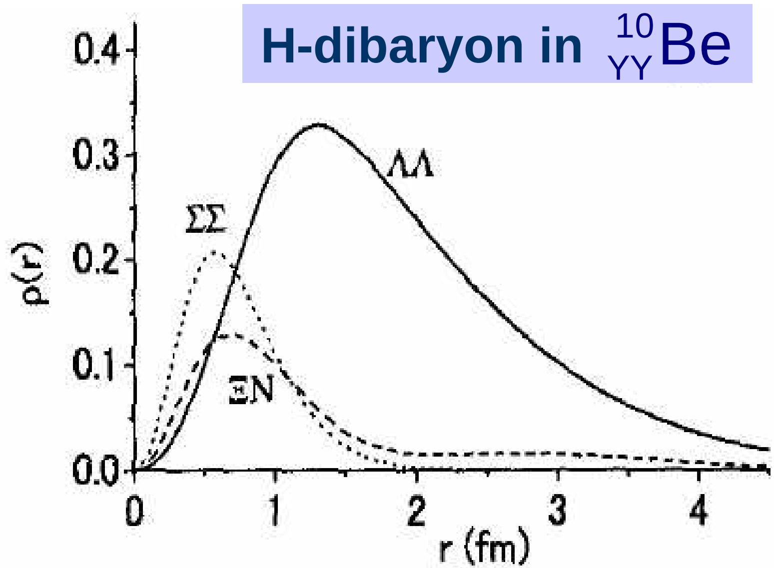
S=-2 Nuclei and H-dibaryon States

- *H*-particle in a nucleus ≠ free *H*

  (see e.g. T. Yamada, NP A691 (2001) 250c; (3q)+(3q) quark cluster model)



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



$B_{\Lambda\Lambda}$=24.0 MeV

Formation of an H-particle in nuclei may modify levels in ΛΛ-nuclei

Fundamental Properties of Baryons

- Contributions to *intrinsic* quadrupole moment of baryons
  - One-gluon exchange
  - Meson exchange

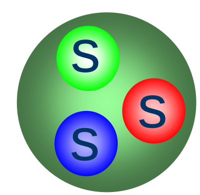
$$Q_i = \int d^3r\, r(r)(3z^2 - r^2)$$

- J=1/2 baryons have no *spectroscopic* quadrupole moment

$$Q_s \propto (3J_z^2 - J(J+1)) \xrightarrow[J_z=1/2]{J=1/2} 0$$

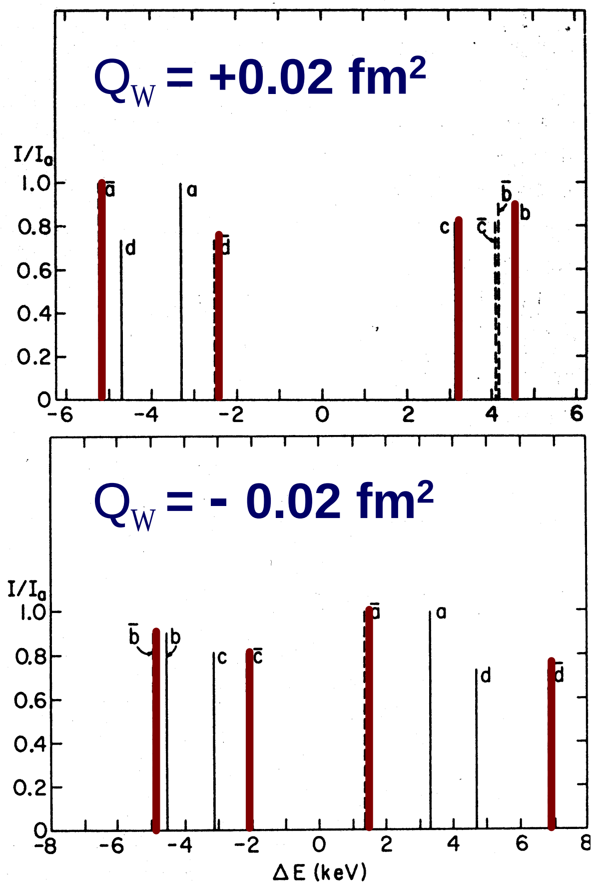
- Ω^- Baryon:
  - J=3/2
  - long mean lifetime $0.82 \cdot 10^{-10}$ s
  - only one-gluon contributions to quadrupole moment

  (A.J. Buchmann Z. Naturforsch. **52** (1997) 877-940)



The Ω quadrupole moment is an unique testcase for the quark-quark interaction

A very Strange Atom



- hyperfine splitting in Ω-atom
  ⇒ electric quadrupole moment of Ω

spin-orbit	$\Delta E_{ls} \sim (\alpha Z)^4\, l\cdot m_\Omega$
quadrupole	$\Delta E_Q \sim (\alpha Z)^4 Q_\Omega m^3_\Omega$

- prediction $Q_\Omega = (0 - 3.1)\ 10^{-2}\ \mathrm{fm}^2$
- E(n=11, l=10 → n=10, l=9) ~ 515 keV
- ΔE_Q ~ few keV for Pb

R.M. Sternheimer, M. Goldhaber
PRA 8, 2207 (1973)

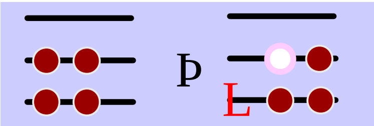
2. Present Status

Single Hypernuclei

- strangeness deposition (stopped K^-,π^-) — FINUDA@DAΦNE
  - tagged kaon „beam“
  - low momentum (T=16MeV)
  - low background
  - also (stopped K^-,π^+) ⇒ neutron rich nuclei

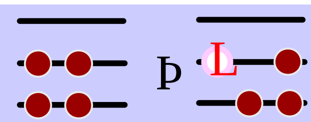
$$e^+ + e^- \rightarrow \Phi \rightarrow K^+ + K^-$$
$$K^-_{stopped} + {}^A Z \rightarrow {}^A_\Lambda Z + p^-$$

- strangeness production (π^+, K^+) γ ,(π^-, K^0) γ — BNL, KEK, (GSI?)
  - $p_{BEAM} \approx$ 1 GeV/c
  - high beam intensity
  - low cross section (1-10 mb/sr)
  - q > 300 MeV/c ⇒ large Δp, ΔL



non-substitutional state

- strangeness exchange (K^-, π^-) ,(K^-, π^0) — BNL, KEK, J-PARC
  - low beam intensity
  - larger cross section (100 mb/sr)
  - magic momentum ⇒ low Δp, ΔL



substitutional state

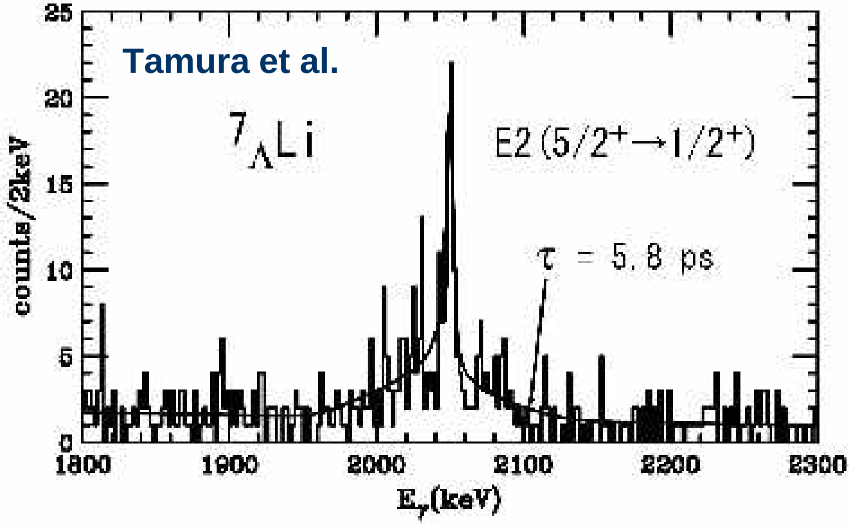
- (e,e´K^+) , (γ,K^+) — TJNAF, MAMI-C
  - spin-flip amplitude ⇒ unnatural parity states
  - new nuclei (p → Λ: ${}^{10}_{\Lambda}$Be)
  - polarised beam
  - sub-MeV resolution possible (→0.3 MeV) for *particle unstable* states

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

Status of Single Hypernuclei

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

KEK, BNL

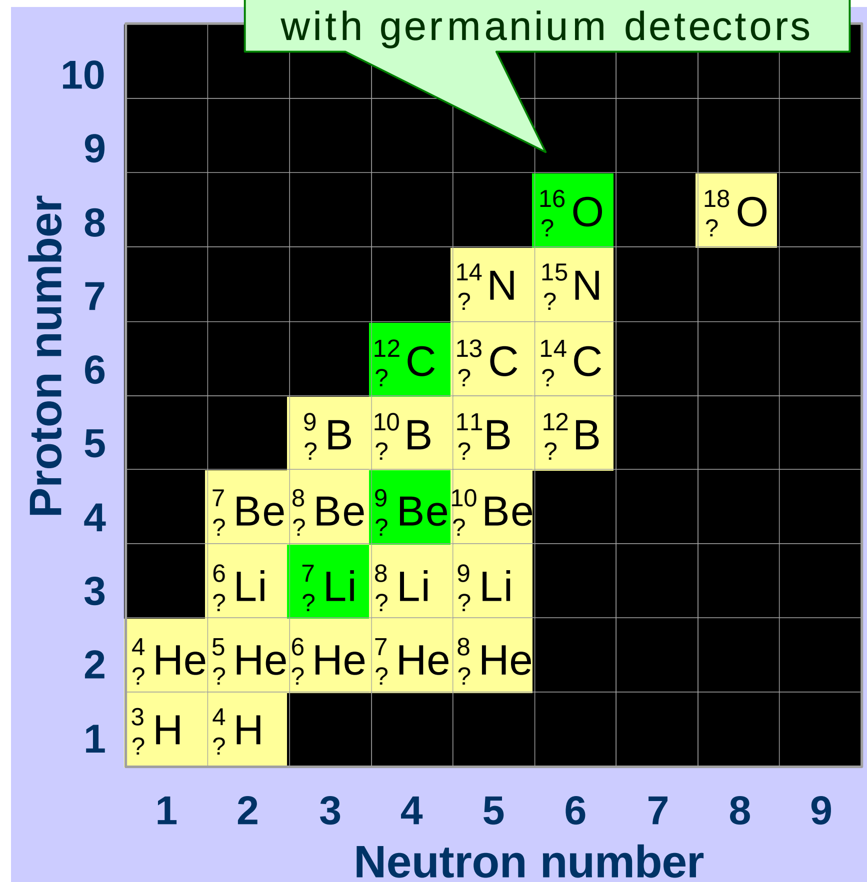


- B(E2) ~ R^4

⇒ shrinkage of ^{6}Li core by ~20%

high resolution γ-spectroscopy is crucial to understand the structure of hypernculei

high resolution γ-spectroscopy with germanium detectors



Double Hypernuclei

- Multi-Hypernuclei are *terra incognita*, but they exist !

1963: Danysz *et al*. $_{\Lambda\Lambda}{}^{10}$Be

1966: Prowse $_{\Lambda\Lambda}{}^{6}$He

1991: KEK-E176 $_{\Lambda\Lambda}{}^{13}$B (or $_{\Lambda\Lambda}{}^{10}$Be)

2001: AGS-E906 $_{\Lambda\Lambda}{}^{4}$H (~15);

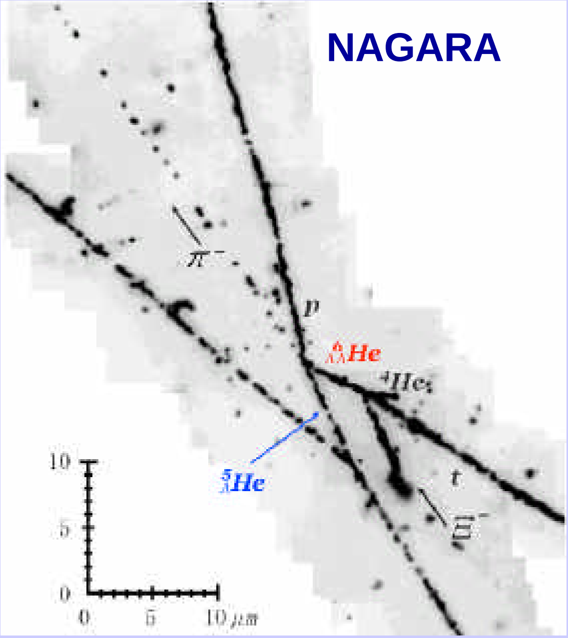
no binding energies

2001: KEK-E373 $_{\Lambda\Lambda}{}^{6}$He (Nagara)

“ $_{\Lambda\Lambda}{}^{10}$Be (Demachi-Yanagi)

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

$${}^{6}_{??}He \rightarrow {}^{5}_{?}He + p + p^-$$



H. Takahashi *et al*., PRL 87, 212502-1 (2001)

What is known?

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

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

Hyperkern	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)		
${}^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6	Prowse	(1966)
${}^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373	(2001)
${}^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4	Danysz	(1963)
${}^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7	KEK-E176	(1991)
${}^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7	KEK-E176	(1991)
${}^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$		KEK-E373	(2001, unpublished)

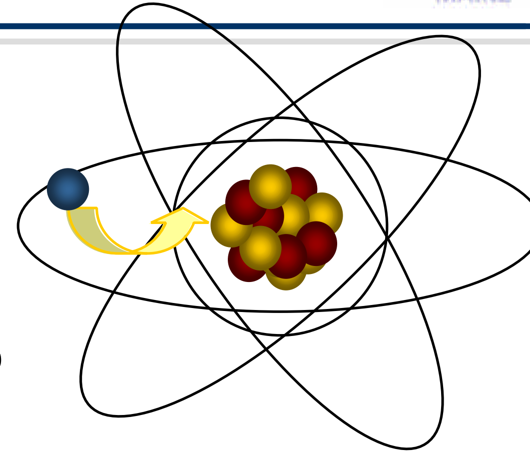
same event

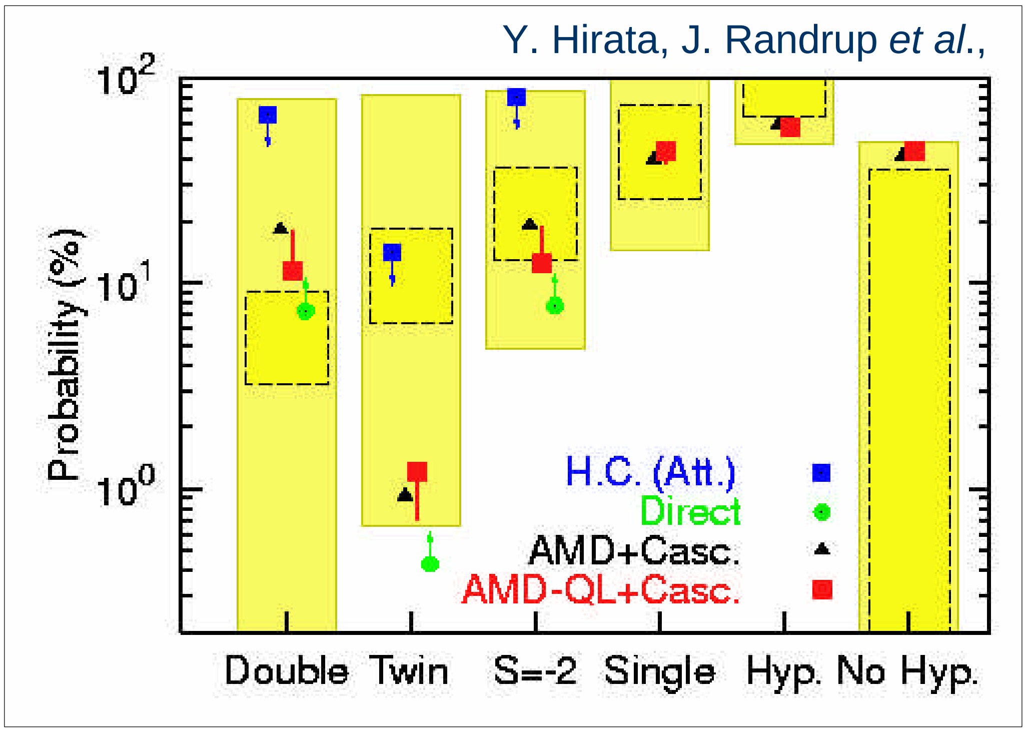
- Interpreting $\Delta B_{\Lambda\Lambda}$ as $\Lambda\Lambda$ bond energy one has to consider e.g.
  - dynamical change of the core nucleus
  - ΛN spin-spin interaction for non-zero spin of core
  - excited states possible
- if $\Lambda\Lambda$- or intermediate Λ-nuclei are produced in excited states
  - Q-value difficult to determine (particularly for heavy nuclei)
  - nuclear fragments difficult to identify with usual emulsion technique
- new concept required $\Rightarrow$ γ-spectroscopy!

3. Hypersystems in $p\bar{p}$ Interactions

Ξ⁻ capture

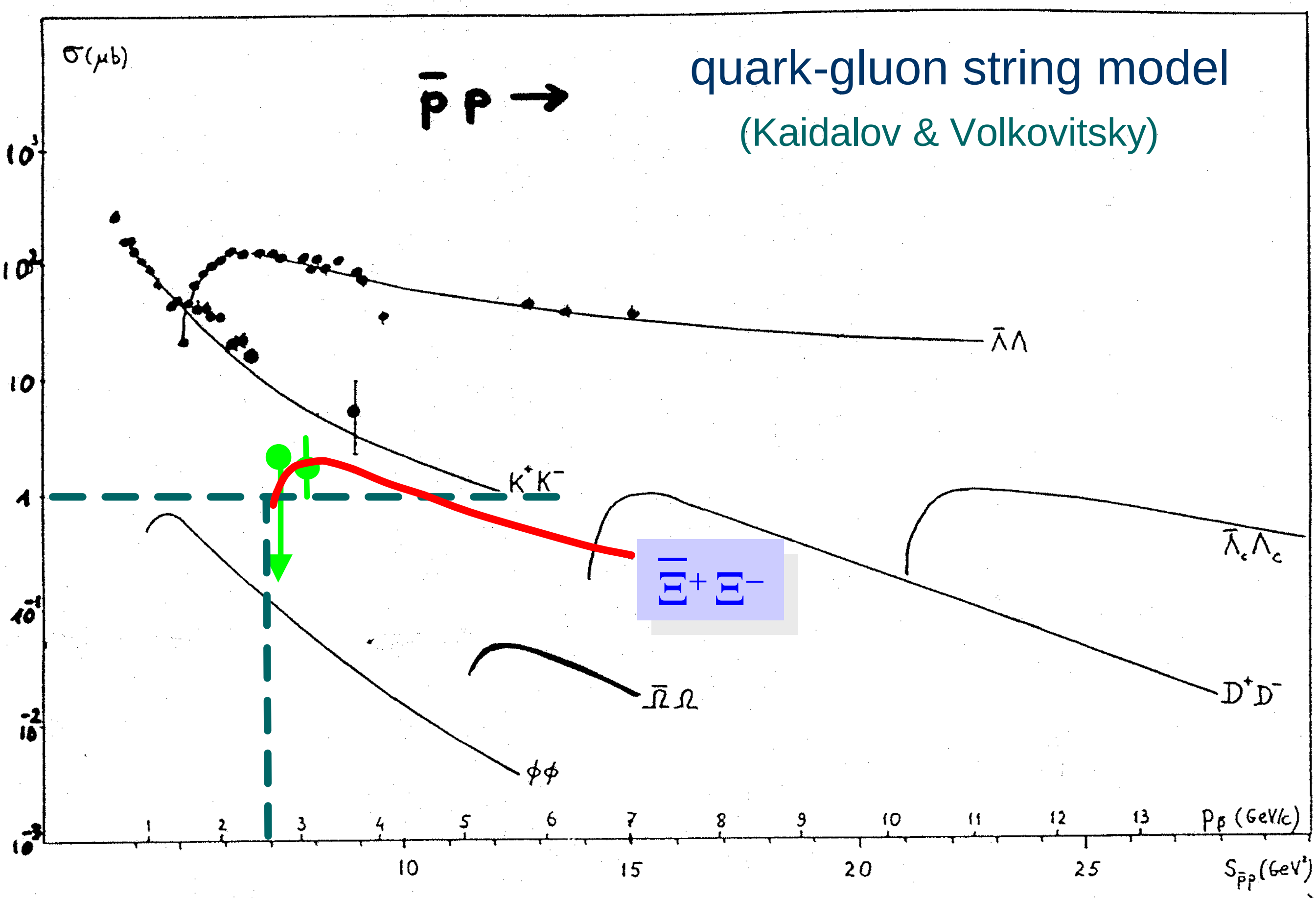
- Ξ⁻-atoms: x-rays
- conversion
  - **Ξ⁻(dss) p(uud) ® Λ(uds) Λ(uds)**
  - ΔQ = 28 MeV
- Conversion probability approximatly 5-10%

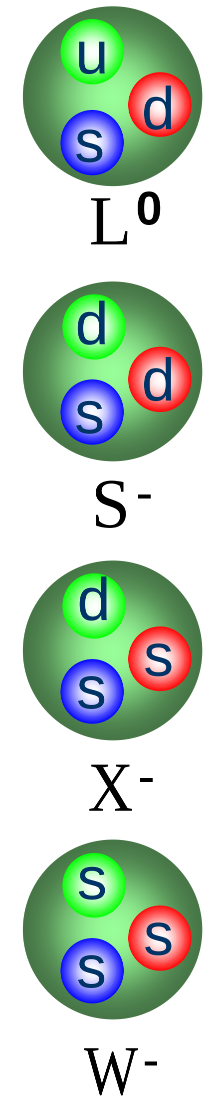




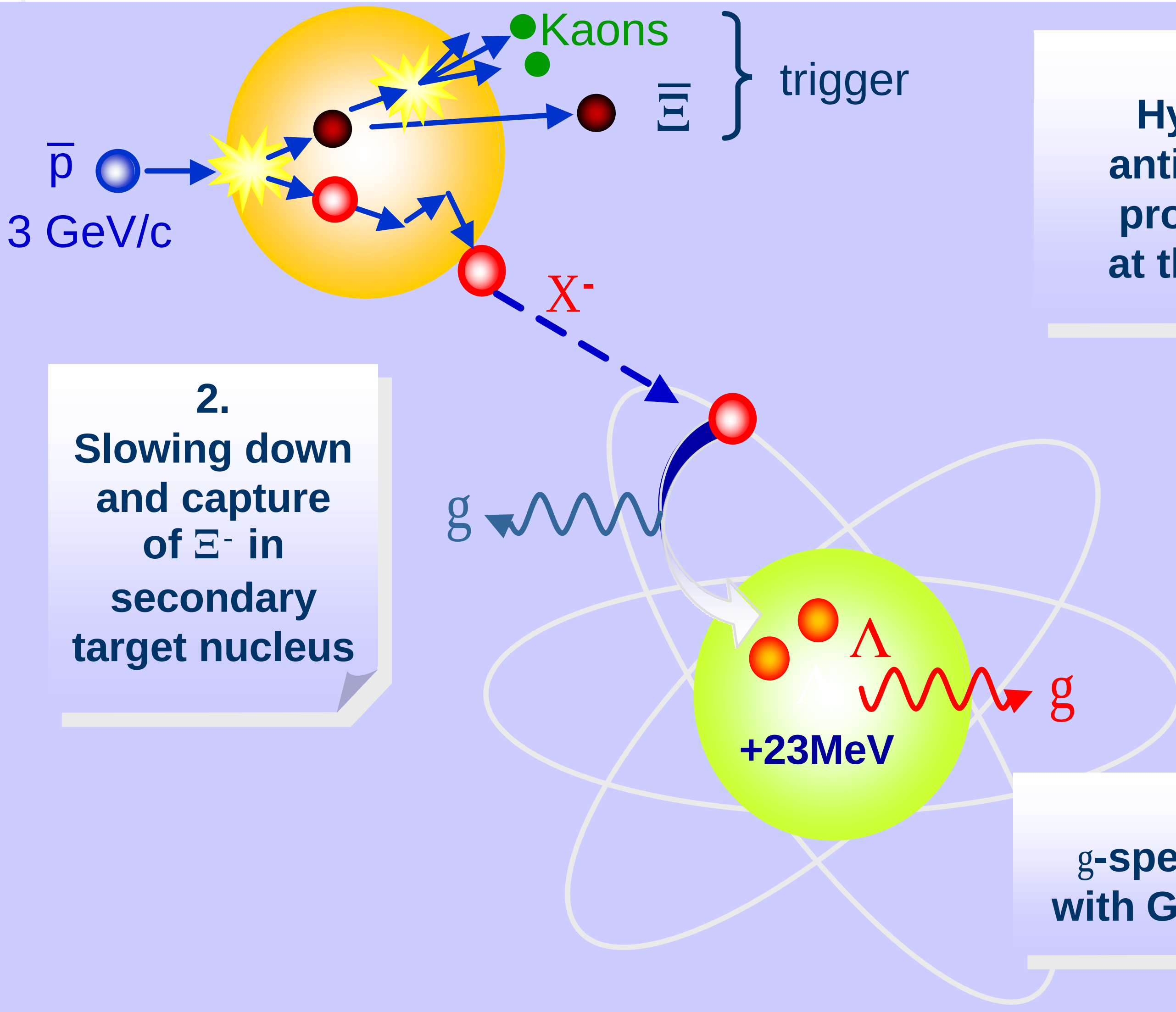
General Idea

- Use $p\bar{p}$ Interaction to produce a hyperon "beam" ($t \sim 10^{-10}$ s) which is tagged by the antihyperon or its decay products





Production of Double Hypernuclei



1.
Hyperon-antihyperon production at threshold

2.
Slowing down and capture of Ξ- in secondary target nucleus

3.
g-spectroskopy with Ge-detectors

Competition

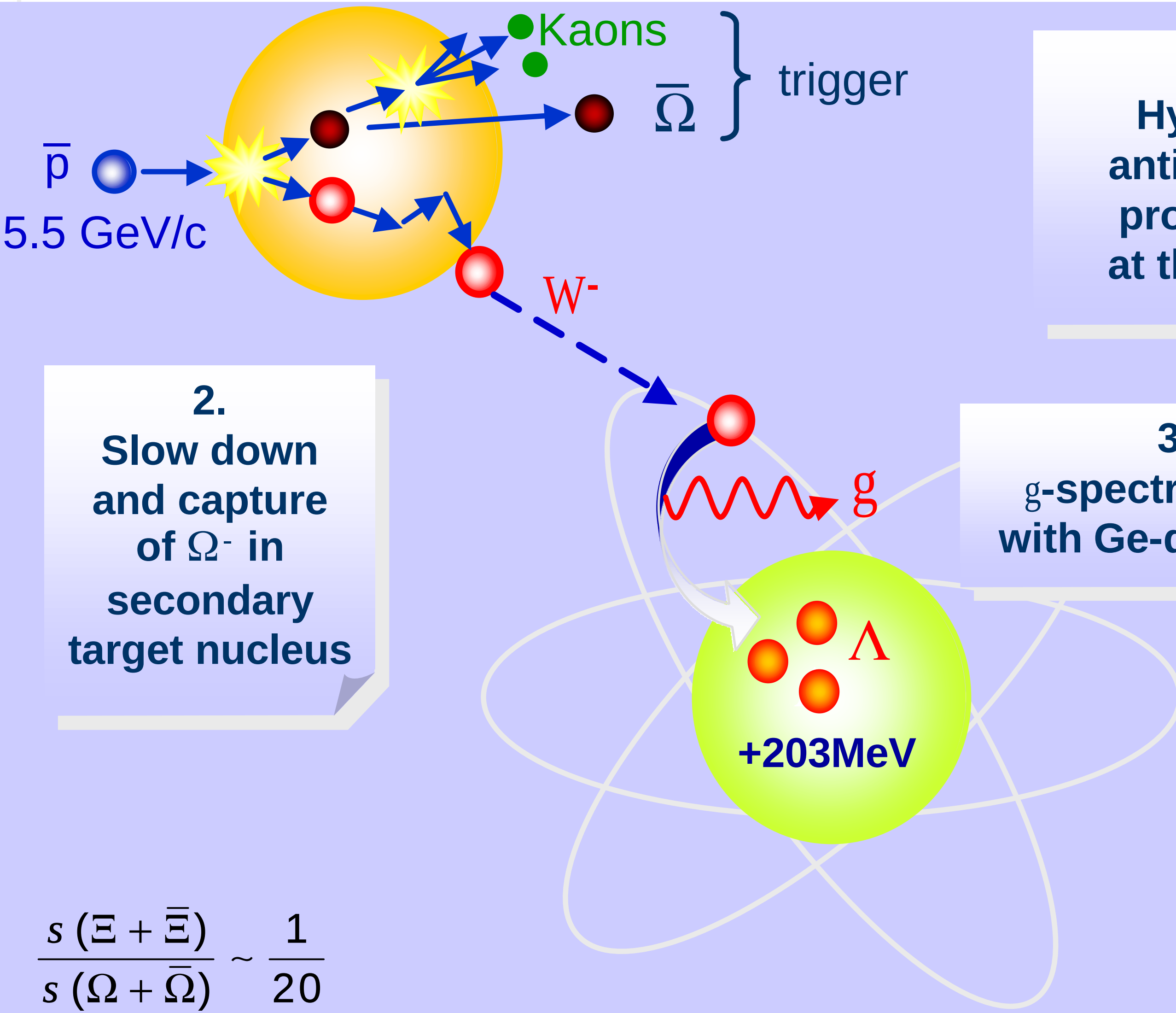
experiment	*reaction*	*device*	*beam/ target*	*status*
BNL-AGS E885	$(\Xi^{--},{}^{12}C) \rightarrow {}^{12}_{LL}B + n$	neutron detector arrays	K^- beam, diamond target	20000 stopped Ξ^-
BNL-AGS E906	2π decays	Cylindrical Detector System	K^- beam line	few tens 2π decays of ${}^{4}_{\Lambda\Lambda}H$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

Expected Count Rate

- Ingredients (golden events)
  - luminosity $2 \cdot 10^{32}$ $cm^{-2}s^{-1}$
  - $\Xi^+\Xi^-$ cross section 2mb for pp → 700 Hz
  - p(100-500 MeV/c) $p_{500} \approx 0.0005$
  - Ξ^+ reconstruction probability 0.5
  - stopping and capture probability $p_{CAP} \approx 0.20$
  - total captured Ξ^- → 3000 / day
  - Ξ^- to $\Lambda\Lambda$–nucleus conversion probability $p_{\Lambda\Lambda} \approx 0.05$
  - total $\Lambda\Lambda$ hyper nucleus production → 4500 / month
  - gamma emission/event, $p_\gamma \approx 0.5$
  - γ-ray peak efficiency $p_{GE} \approx 0.1$
- ~7/day „golden“ γ-ray events (Ξ^+ trigger)
- ~ 700/day with *KK* trigger

high resolution γ-spectroscopy of double hypernuclei will be feasible

Production of Ω-Atoms



1.
Hyperon-antihyperon production at threshold

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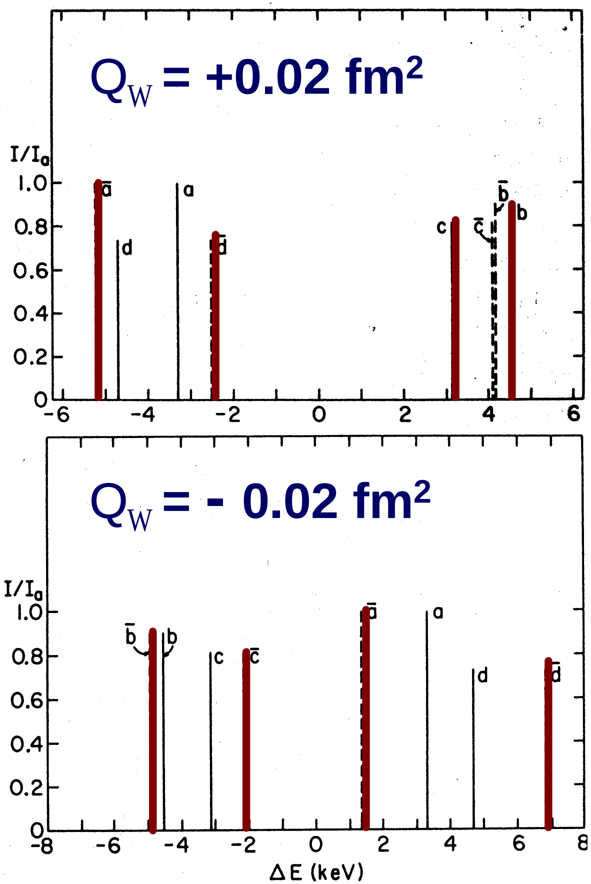
Slow down and capture of Ω⁻ in secondary target nucleus

3.
g-spectroskopy with Ge-detectors

$$\frac{s\,(\Xi + \bar{\Xi})}{s\,(\Omega + \bar{\Omega})} \sim \frac{1}{20}$$

A very strange Atom



R.M. Sternheimer, M. Goldhaber
PRA 8, 2207 (1973)

- Ω atoms by $\Omega\bar{\Omega}$ produktion (~35/sec)
- hyperfine splitting in Ω-atom
  $\Rightarrow$ electric quadrupole moment of Ω

spin-orbit	$\Delta E_{ls} \sim (\alpha Z)^4\, l \cdot m_\Omega$
quadrupole	$\Delta E_Q \sim (\alpha Z)^4 Q_\Omega m^3_\Omega$

- prediction $Q_\Omega = (0 - 3.1)\ 10^{-2}\ fm^2$
- $E(n=11, l=10 \rightarrow n=10, l=9) \sim 515$ keV
- $\Delta E_Q \sim$ few keV for Pb

- taking production rate, stopping probability, capture probability and detection probability into account we expect

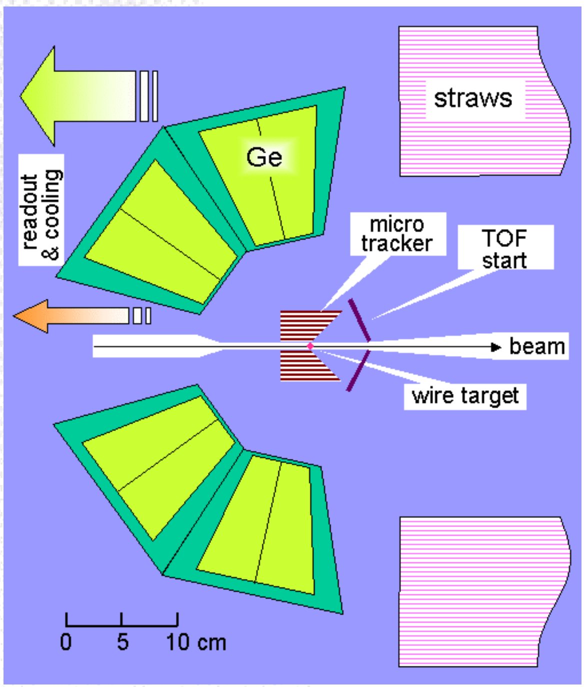
~10 detected γ-transitions per day
⇒with high resolution γ-spectroscopy feasible

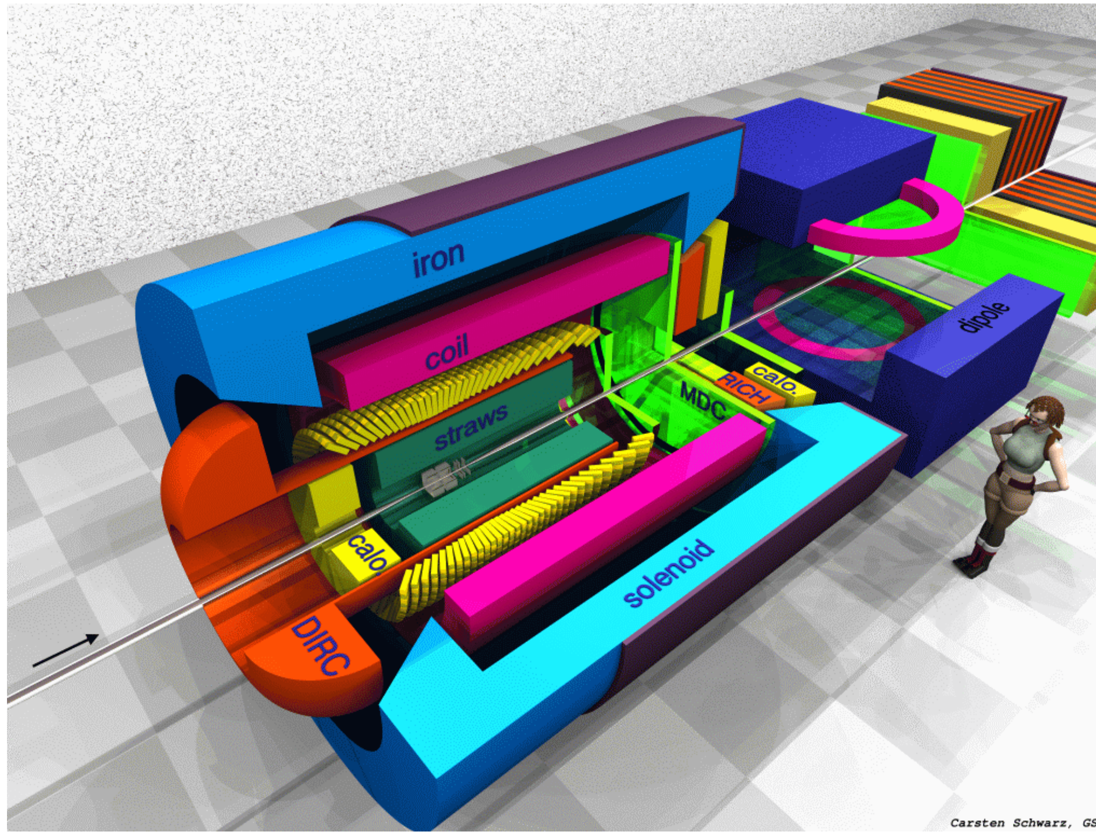
Count rate estimate needs more detailed studies!

4. The Experiment

The PANDA Detector

- hermetic (4π)
- high rate
- PID (γ, e, μ, π, K, p)
- trigger (e, μ, K, D, Λ)
- compact (€)
- modular





- Solid state-micro-tracker
  - thickness ~ 3 cm
- High rate germanium detector

Summary

- Hypersystems provide a link between nuclear physics and QCD
- They allow to study basic properties of strongly interacting systems
- These unique experiments will be feasible at the GSI-HESR