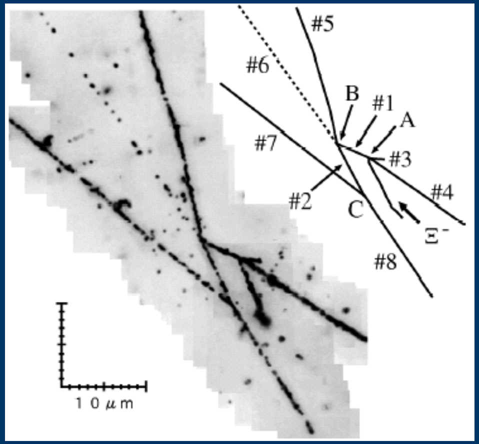
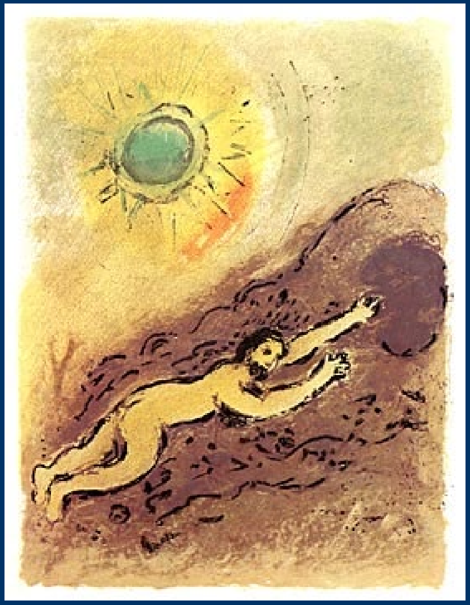


Duet of Strange Baryons: Double Hypernuclei



Pentaquarks Facts and Mysteries

Duet of Strange Baryons
Double Hypernuclei

- a short reminder
- why are double hypernuclei interesting?
- how to make them?
- what do we know today?
- future: double hypernuclei @PANDA
- even more crazy ideas

a short reminder

Nomenclature

- a hypernucleus is specified by
  - the number of neutrons N
  - the number of protons Z
  - the number of hyperons Y

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

- number of baryons N+Z+Y
- (number of) hyperons Y
- element = total charge (not number of protons)

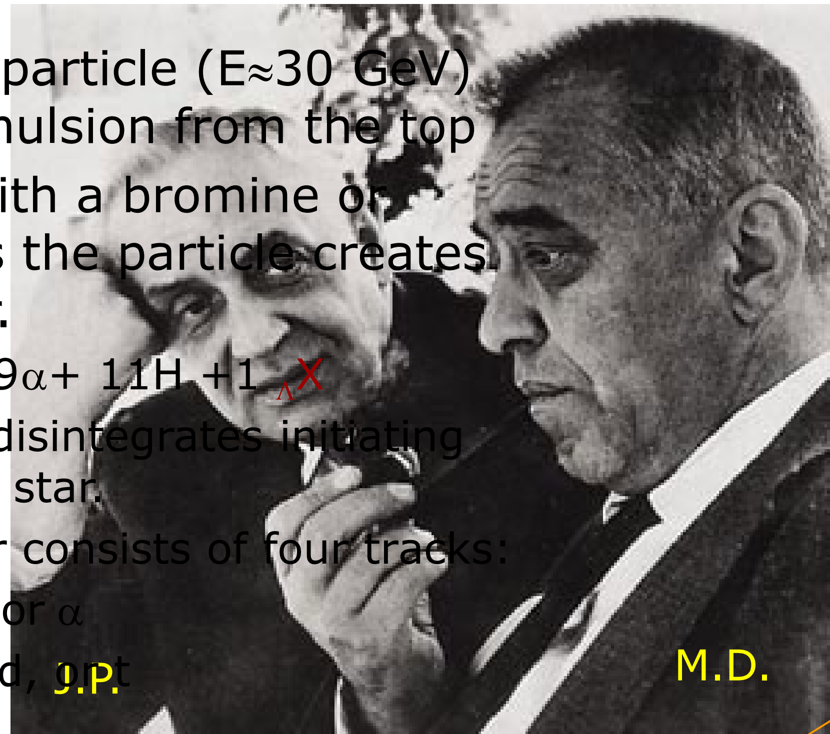
  - since we have more than one hyperon (Λ, Ξ^-, Σ^{-+0}) one usually writes explicitely the symbols of one (or more) hyperon
  - examples:

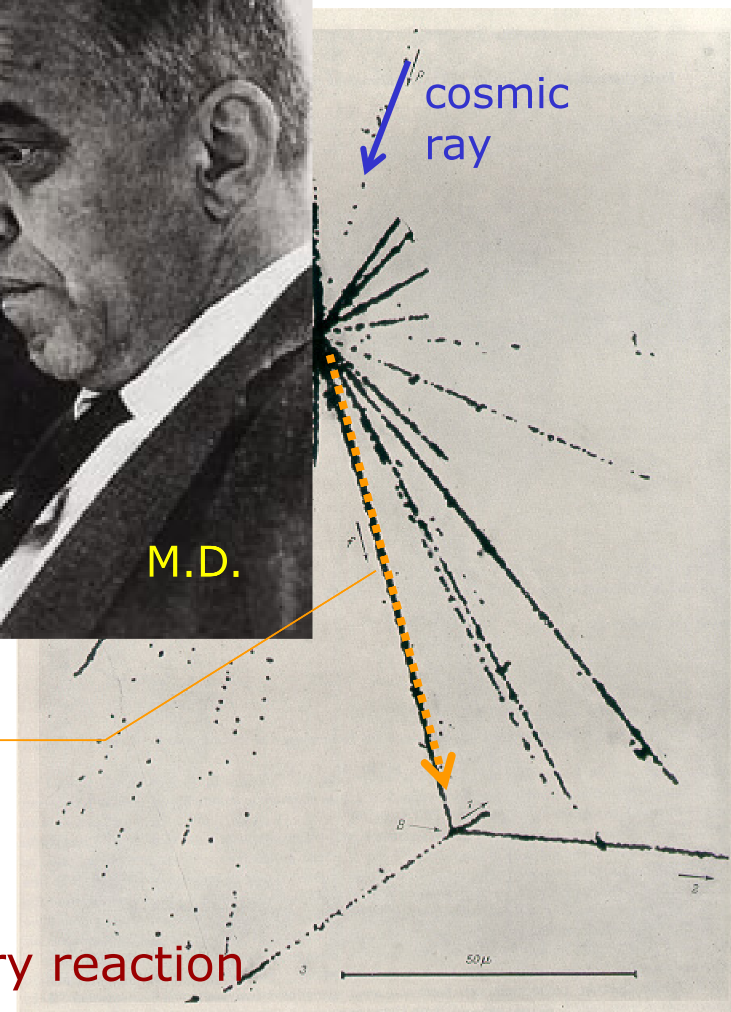
$${}^{10}_{\Lambda\Lambda}Be \rightarrow \begin{cases} Be & \rightarrow \text{4 protons} \\ \Lambda\Lambda & \rightarrow \text{2 lambdas} \\ 10 & \rightarrow 10\text{-}4\text{-}2=4 \text{ neutrons} \end{cases}$$

$${}^{4}_{\Sigma}He \rightarrow \begin{cases} 1p+2n+1\Sigma^+ \\ 2p+1n+1\Sigma^0 \\ 3p+0n+1\Sigma^- \end{cases} \quad \text{indistinguishable}$$

How it began

- Marian Danysz, Jerzy Pniewski, et al. Bull. Acad. Pol. Sci. III **1**, 42 (1953)
- Marian Danysz, Jerzy Pniewski, Phil. Mag. **44**, 348 (1953)





- A cosmic ray particle ($E \approx 30$ GeV) enters the emulsion from the top
- Interacting with a bromine or silver nucleus the particle creates an upper star.
  - 21 tracks: $9\alpha + 11H + 1\,{}_{\Lambda}X$
  - Finally, ${}_{\Lambda}X$ disintegrates initiating the bottom star.
  - second star consists of four tracks:
    - 2 p,d,t or α
    - 1 π, p, d, or t
    - 1 recoil
  - energy release >140MeV

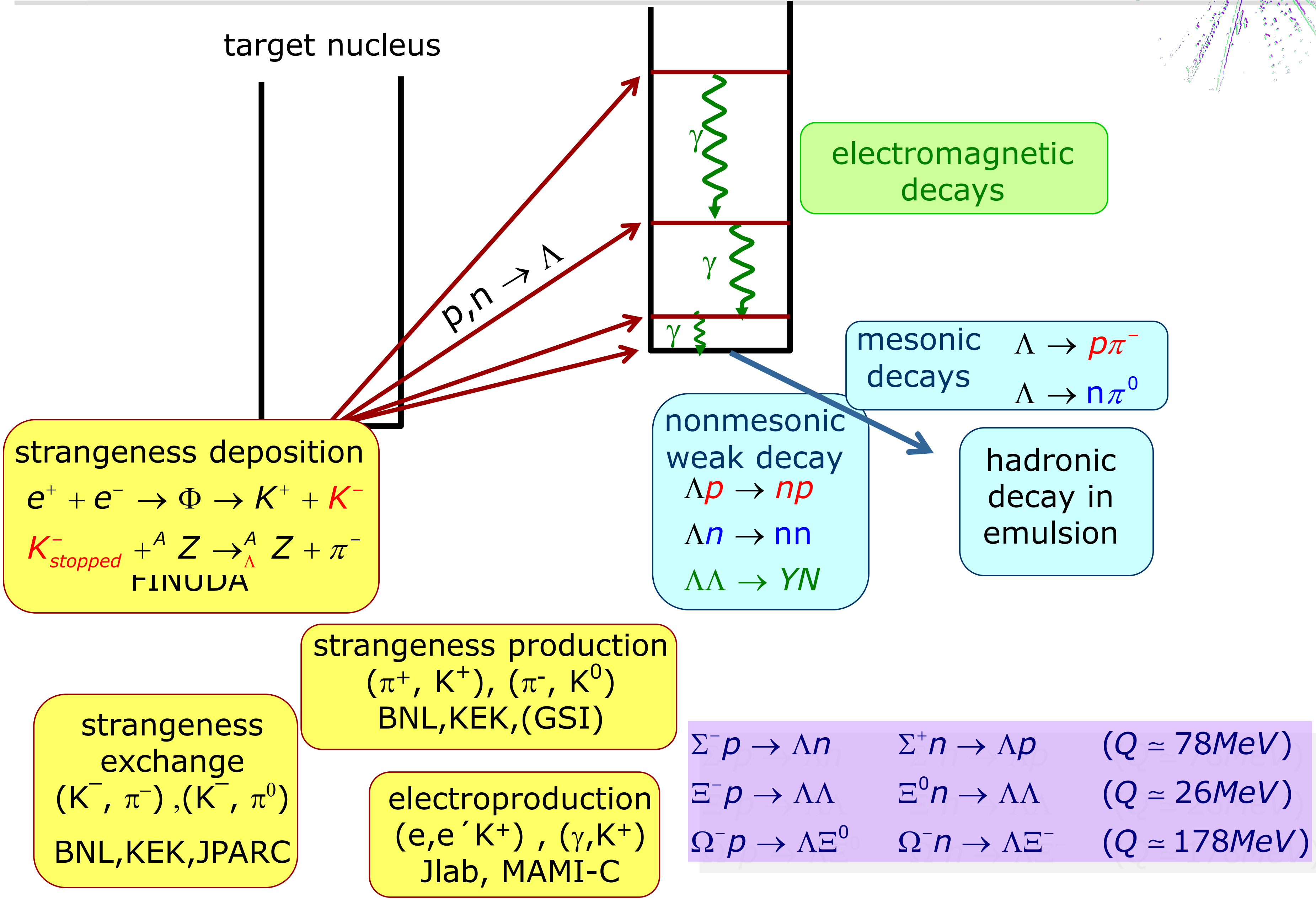
$$t > \frac{s}{c} \sim \frac{80\mu m}{300000 km/s} \approx 2.6 \cdot 10^{-13} s$$
$$\tau(\Lambda) = 2.6 \cdot 10^{-10} s$$
$$\Rightarrow \text{typical for weak decay}$$

- many associated particles in primary reaction

Nuclear Emulsion

- Cecil Frank Powell (1903-1969)
  - Nobel Prize in Physics 1950
  - 1. Speaker of 1. course at Varenna 1953
- Multiple layers of emulsion were historically the first means of visualizing charged particle tracks
  - very high positional precision
  - ionisation density (dE/dx)
  - range
  - 3-dimensional view of the interaction
- An emulsion is made, as for photographic film, of a silver salt, (AgBr), embedded in gelatine and spread thinly on a substrate.
  - grain size 0.2-0.5μm
  - during developement excited grains are reduced to elemental silver
- Data acquisition by automated means (e.g. by scanning the film with a CCD camera) has been found possible in some circumstances.

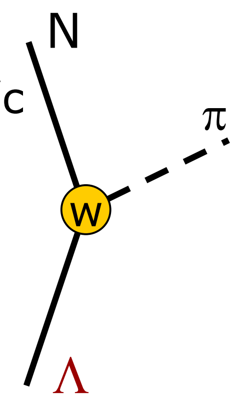
Birth, life and death of a hypernucleus



Weak decay of hypernuclei

free Λ decay

$p_N \approx 100\text{MeV/c}$



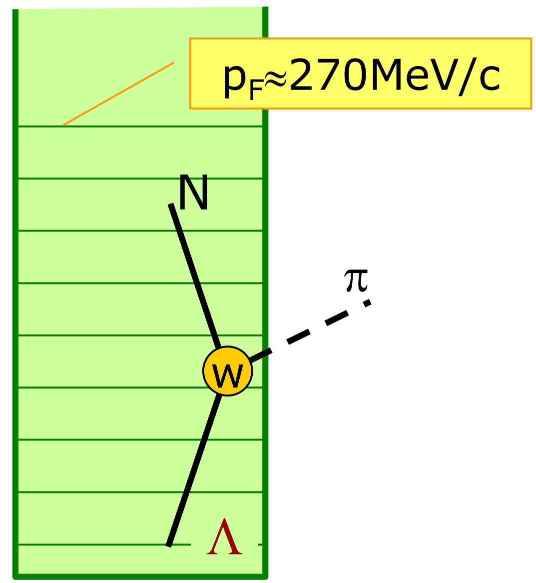
$\Lambda \to p\pi^- + 38\text{MeV}$ (64%)

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

$\tau_\Lambda = 263ps$

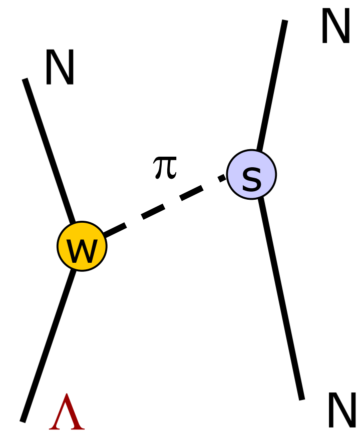
ΔI=1/2 rule

mesonic decay of hypernuclei



suppressed by Pauli blocking

non-mesonic decay of hypernuclei



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

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

dominant in all but the lightest hypernuclei

- q~400 MeV/c ⇒ probes short distances of baryon-baryon weak interaction

Why are double hypernuclei interesting?

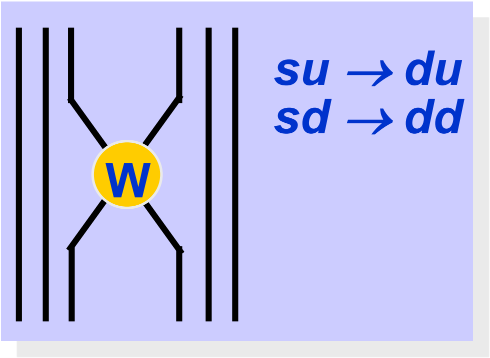
Double Hypernuclei as a Laboratory

- hyperon-hyperon interaction in SU(3)
  - N-N,N-Y,Y-Y

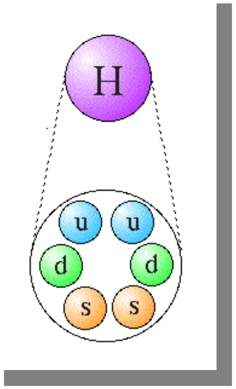
- non-mesonic weak decays

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

$\Rightarrow$ weak baryon-baryon interaction



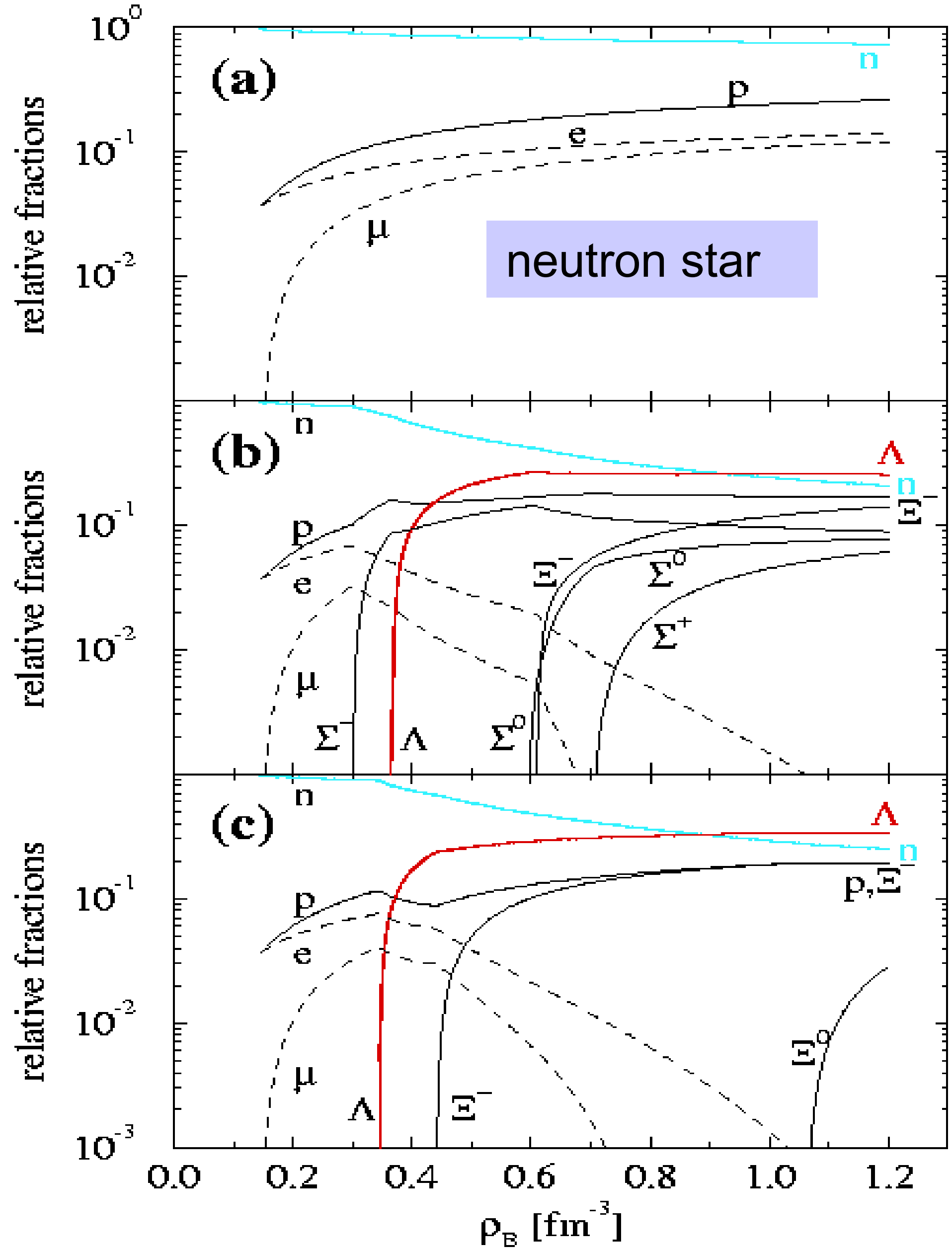
- exotic quark structures



From Double Hypernuclei to Baryonstars

- Hyperonstars
  - expectation: lower mass and smaller radii

    S. Balberg *et al.*

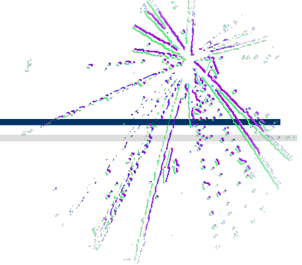


$p + e^- \rightarrow \Lambda + \nu_e$

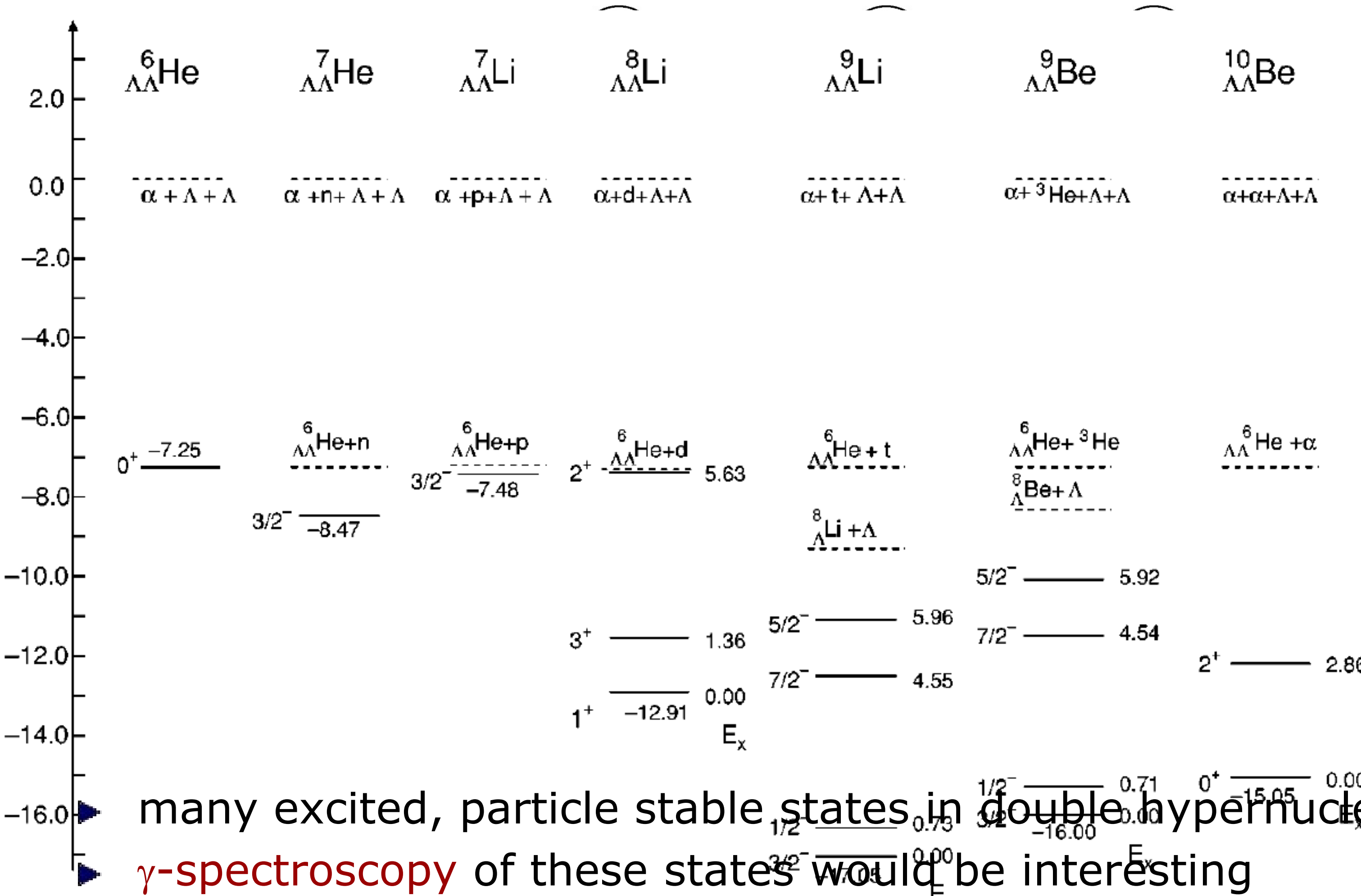
$n + n \rightarrow \Lambda + n$

...

Excited states in double hypernuclei



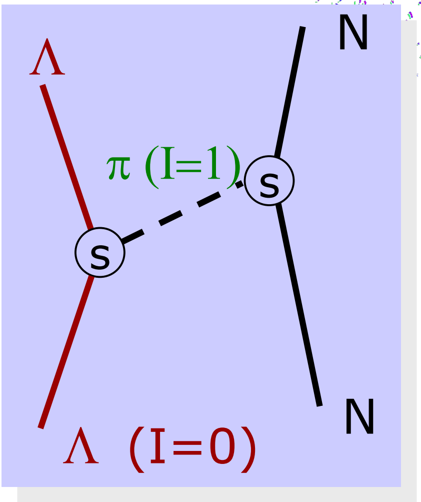
- E. Hiyama *et al.*, Phys. Rev. C **66**, 024007 (2002)
- 4-body cluster model for light nuclei
- parameters adjusted to single hypernuclei and one double hypernucleus event (NAGARA)



- many excited, particle stable states in double hypernuclei predicted
- γ-spectroscopy of these states would be interesting

Weak baryon-baryon interaction

- mesonic decay suppressed in heavier nuclei (Pauli principle)
- one pion exchange forbidden (isospin symmetry)

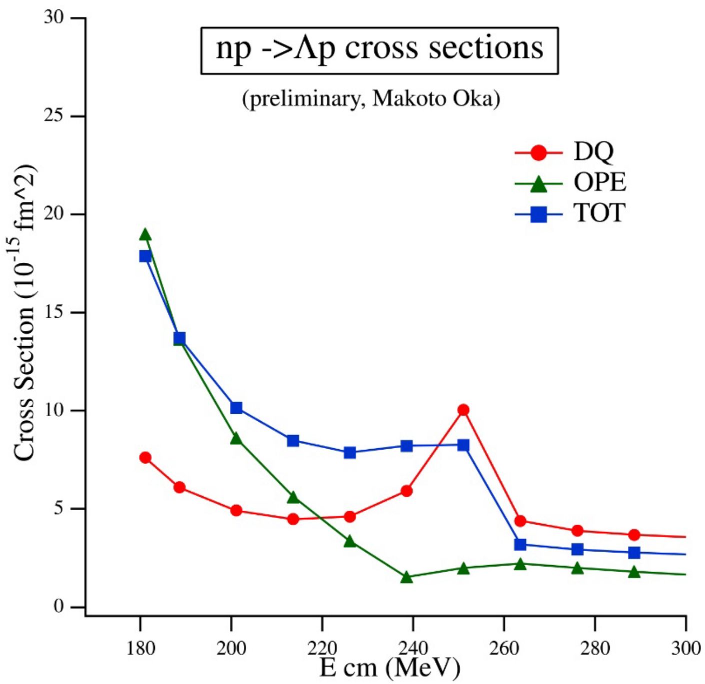


- Investigation of the weak, strangeness changing baryon-baryon interaction

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

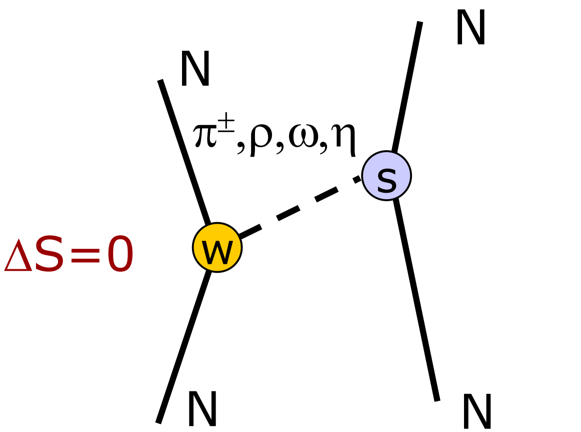
is only possible in hypernuclei

- cross section of inverse reaction p+n→p+Λ $\sigma \sim 10^{-12}$mb with huge strong background

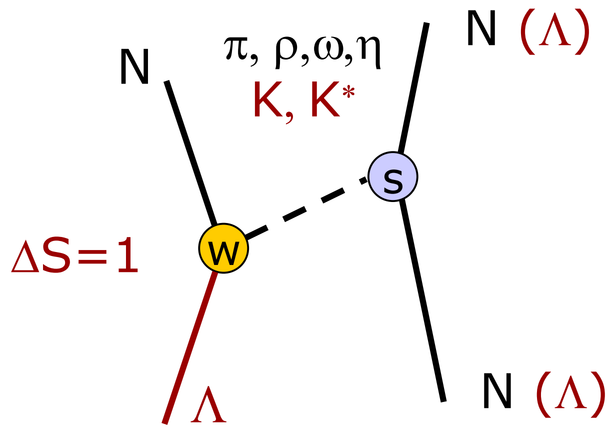


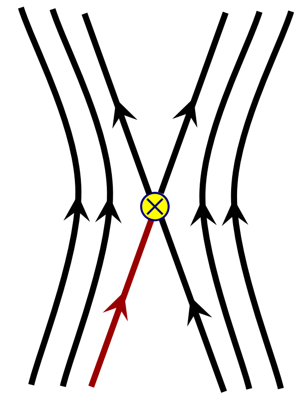
Weak baryon-baryon interaction

N-N scattering



ΛN→N N and ΛΛ→Y N





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

- parity violating *and* parity-conserving part of weak, strangeness changing interaction
- meson vs. direct quark process

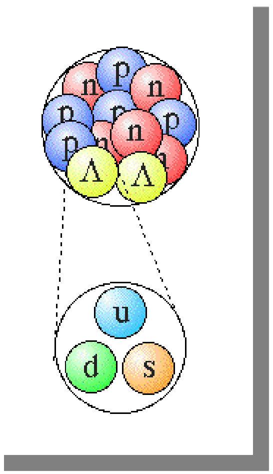
- Interesting theoretical developments:
  - Effective Field Theories in S=-1 sector
    A. Parreno, C. Bennhold and B.R. Holstein, nucl-th/0308074 & 0308056

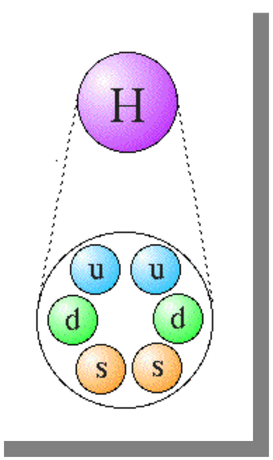
weak decay studies need the detection of the decay pion or nucleon

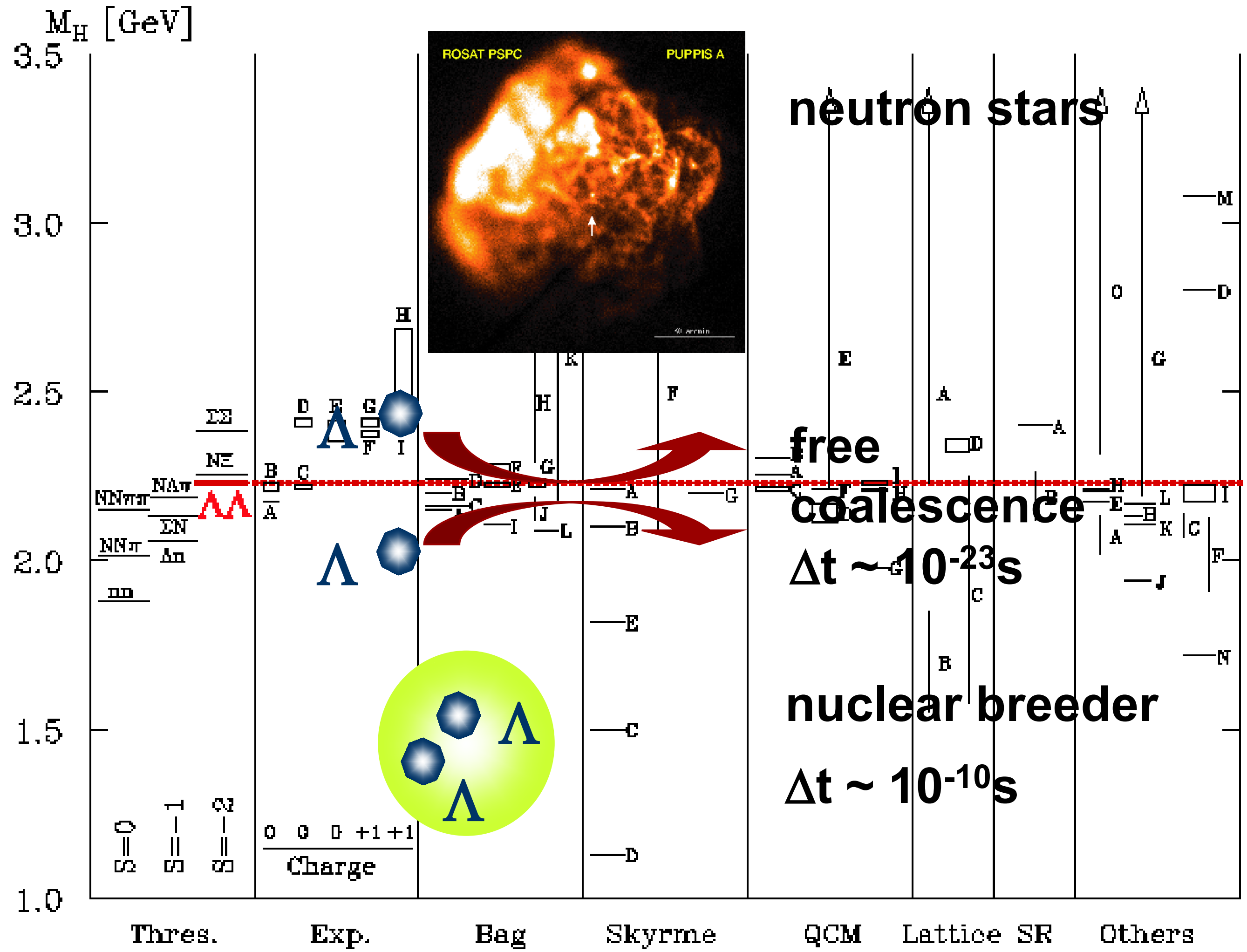
S.R. Beane et al., nucl-th/0311027

ΛΛ Nuclei as Laboratory for H

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







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

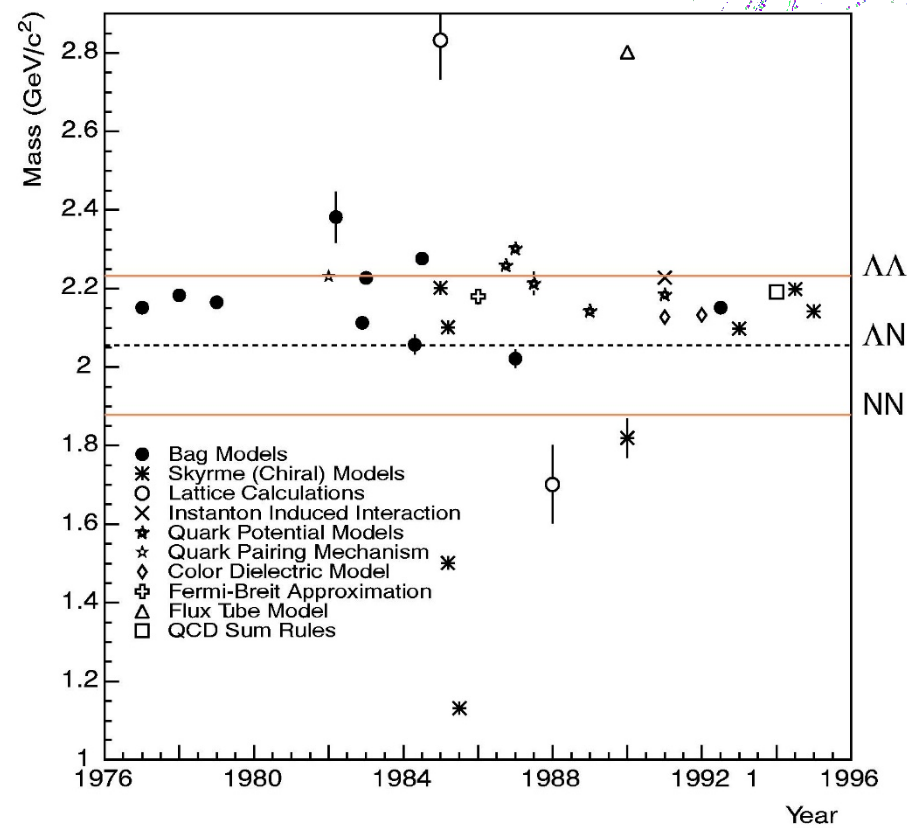
Bound or not bound?

- No experimental evidence yet in production experiments
- Observation of weak decay seems to contradict the existence of an H-particle below $2m_\Lambda$
- but…
  - H-particle may be rather compact: R~0.5fm

    F.G. Scholtz *et al.* (1993)
  - and formation probability may be therefore reduced

    D.E. Kahana & S.H. Kahana (1999)

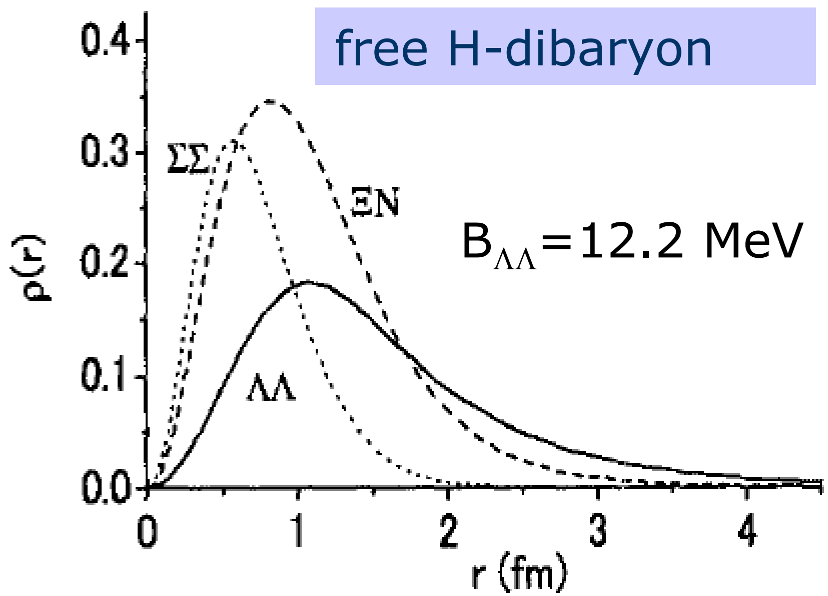
    G.R. Farrar et al. (2003)

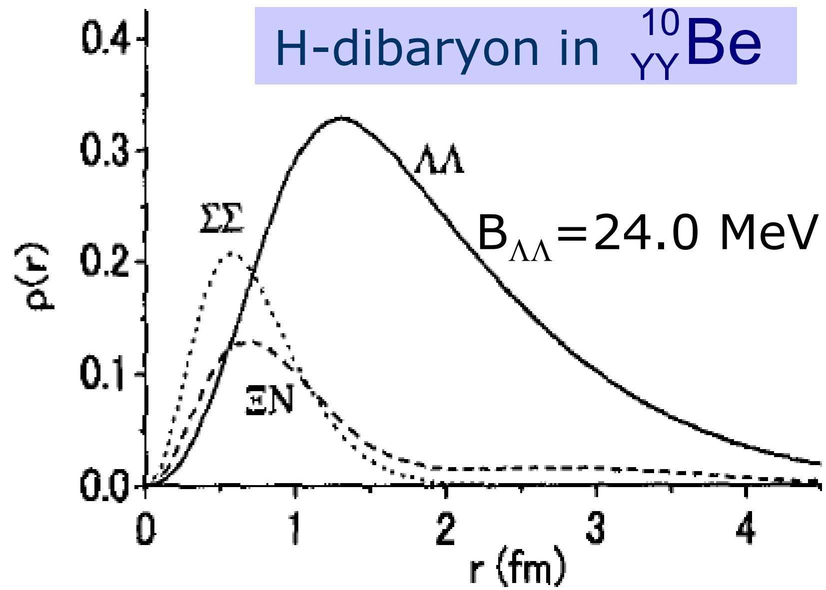


- need consistent predictions for other exotics: tetra-, penta-, hexa-…quarks

H-dibaryon in nuclei

- ΛΛ-ΞN-(ΣΣ) coupling important (ΔE=22-28MeV)
- Consequences
  - *H*-particle and „ΛΛ" state will mix
  - *H*-particle in a nucleus ≠ free *H*





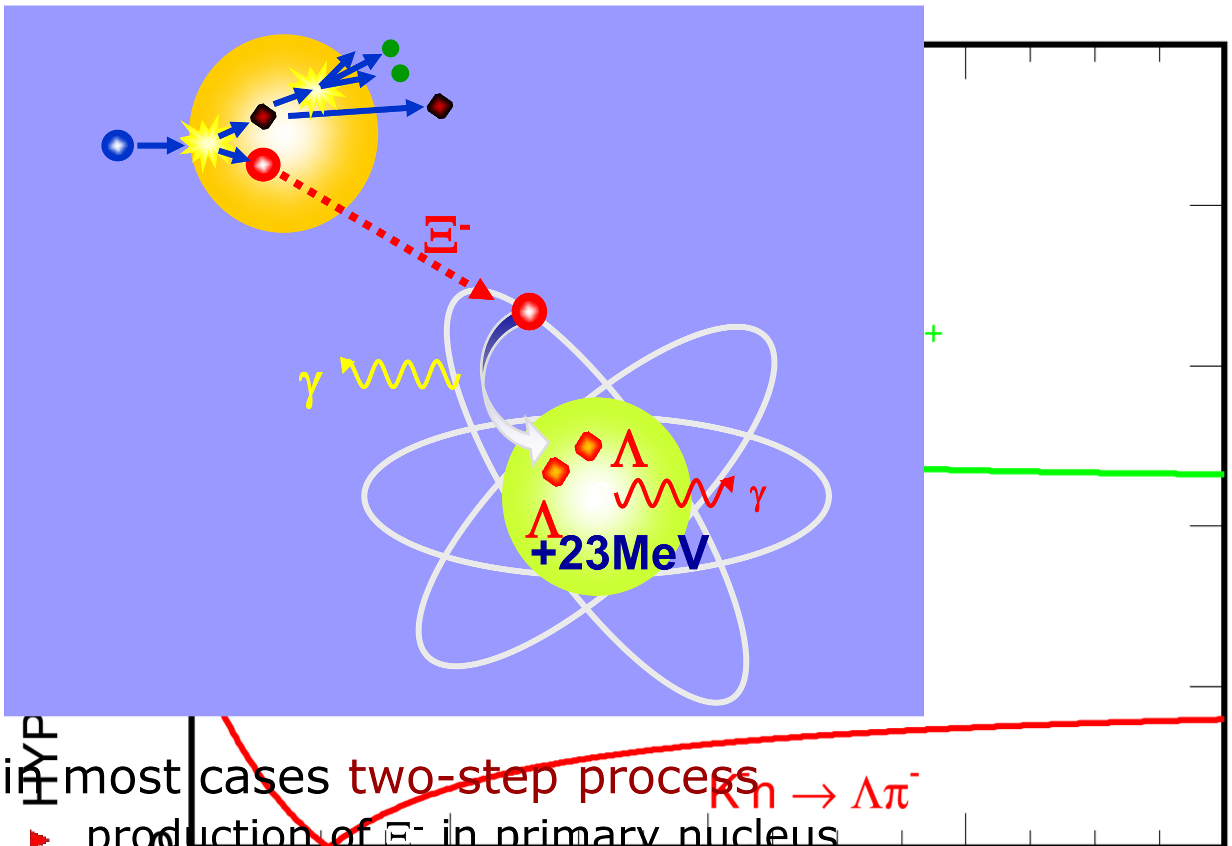
- level structure may be modified ⇒ γ-spectroscopy mandatory

T. Yamada, Phys. Rev. C62, 034319-1 (2000)

Double Hypernuclei
How to make them?

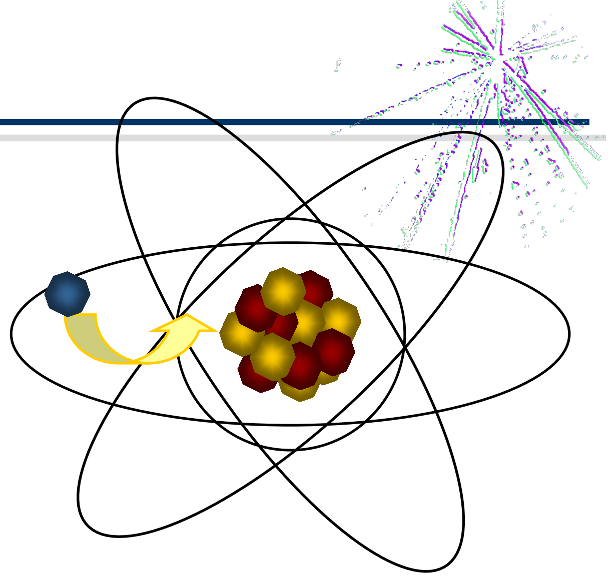
Production of ΛΛ–Hypernuclei

- simultaneous implantation of two Λ is not feasible
- reaction with lowest Q-value: $\Xi^- p \rightarrow \Lambda\Lambda$: 26MeV
- direct implantation of a Ξ^- via a two-body reaction difficult because of large momentum transfer

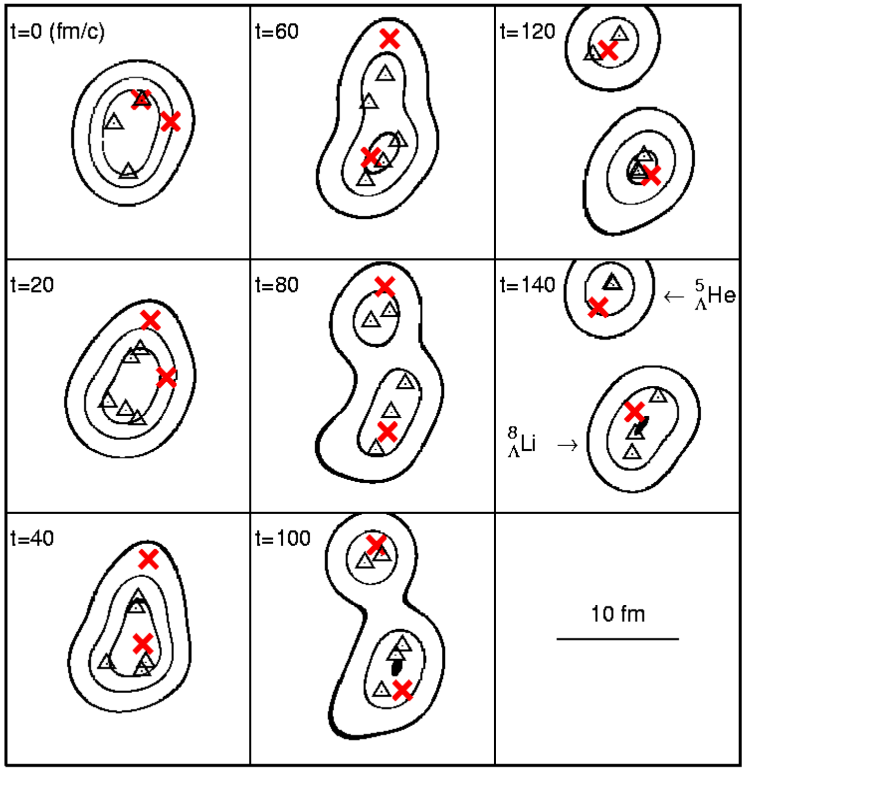


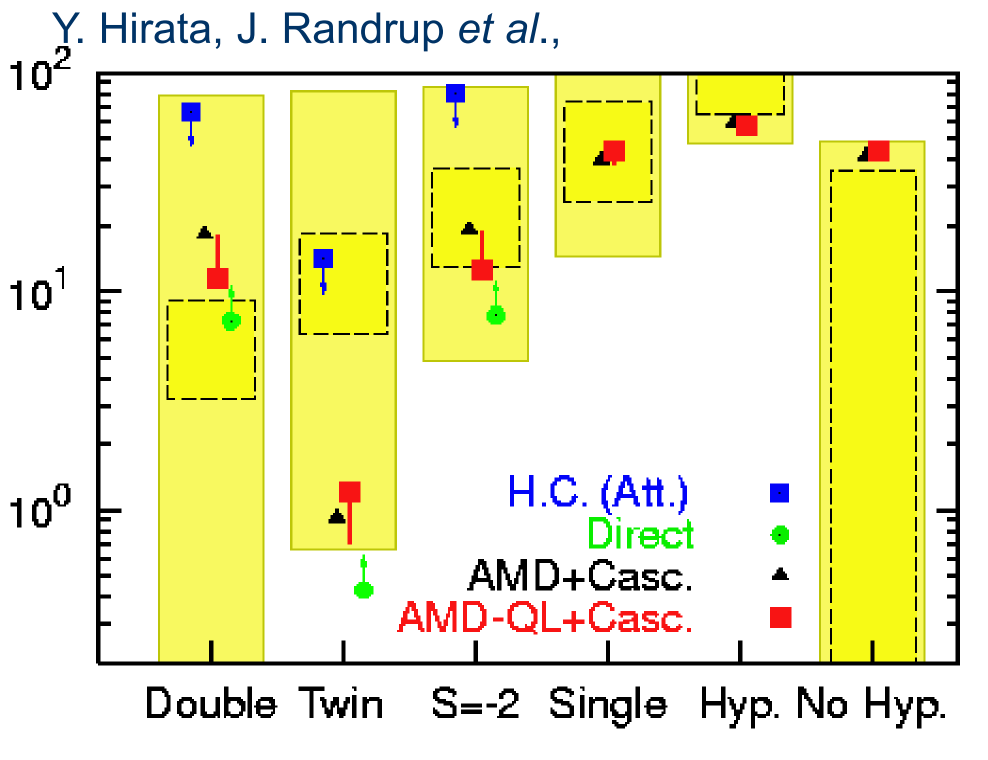
- in most cases two-step process
  - production of Ξ^- in primary nucleus
  - slowing down and capture in a secondary target nucleus
- spectroscopic studies only possible via the decay products

Ξ⁻ capture



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





Ξ^-(dss)p(uud) Þ Λ(uds)Λ(uds)

- Ξ^- capture on ^{12}C
  - T. Yamada and K. Ikeda, PRC 56, 3216 (1997)

TABLE VIII. Calculated production rates per Ξ (R/Ξ) averaged over the absorption rates in the case of $V_{0\Xi}=16$ MeV.

Channel	R/Ξ (%)
$^{12}_{\Lambda\Lambda}$B$+n$	1.48
$^{12}_{\Lambda\Lambda}$Be$+p$	0.99
$^{11}_{\Lambda\Lambda}$Be$+d$	1.81
$^{10}_{\Lambda\Lambda}$Be$+t$	0.02
$^{9}_{\Lambda\Lambda}$Li$+\alpha$	0.02
$^{6}_{\Lambda\Lambda}$He$+^7$Li	0.23
$^{5}_{\Lambda\Lambda}$H$+^8$Be	0.20
$^{9}_{\Lambda}$Be$+^4_{\Lambda}$H	0.07
$^{8}_{\Lambda}$Li$+^5_{\Lambda}$He	0.04
$^{12}_{\Lambda}$B$+\Lambda$	1.08

- individual states may be populated with a probability of a fraction of 1%
- high production rate needed

What can we do

- we can only study the decay of double hypernuclei
- groundstate decay of the hypernucleus initiated by the decay of the hyperon(s)
- goal: mass of decaying system

  $\Rightarrow$ need detection of nearly all decay products (p,n,d,t,a,γ,…)

  but: usually we can only detect charged decay products

  $\Rightarrow$ only light nuclei which decay exclusively in charged particles

  still: low kinetic energies (few MeV per nucleon, few μm range)

  $\Rightarrow$ need sub-μm resolution

  $\Rightarrow$ emulsion

- γ-rays from particle stable, excited states

  $\Rightarrow$ need of high statistics

  $\Rightarrow$ electronic detectors

What do we know today?

The first event (1)

- 1.3-1.5 GeV/c K^-+Emulsion; 31000 K^-

VOLUME 11, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1963

OBSERVATION OF A DOUBLE HYPERFRAGMENT

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and

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and

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and

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and

D. O'Sullivan, T. P. Shah, and A. Thompson
Institute for Advanced Studies, Dublin, Ireland

and

P. Allen, Sr.,‡ M. Heeran, and A. Montwill
University College, Dublin, Ireland

and

J. E. Allen, M. J. Beniston, D. H. Davis, and D. A. Garbutt
University College, London, England

and

V. A. Bull, R. C. Kumar, and P. V. March
Westfield College, London, England
(Received 3 April 1963)

During a systematic scan for interactions of 1.3- and 1.5-GeV/c K^- mesons[1] in emulsions irradiated in the separated K^--meson beam at CERN,[2] an event has been found which is interpreted as the production and subsequent mesonic

of all the charged particles involved in these processes are summarized in Table I. All reasonable interpretations of this event other than that of a Ξ^- hyperon capture at B leading to the

- carefully reanalyzed
  - ~1963 by P.H. Fowler, V.M. Mayes and E.R.Fletcher
  - Dalitz *et al.*, Proc. R. Soc. Lond. A426, 1 (1989)

The first event (2)

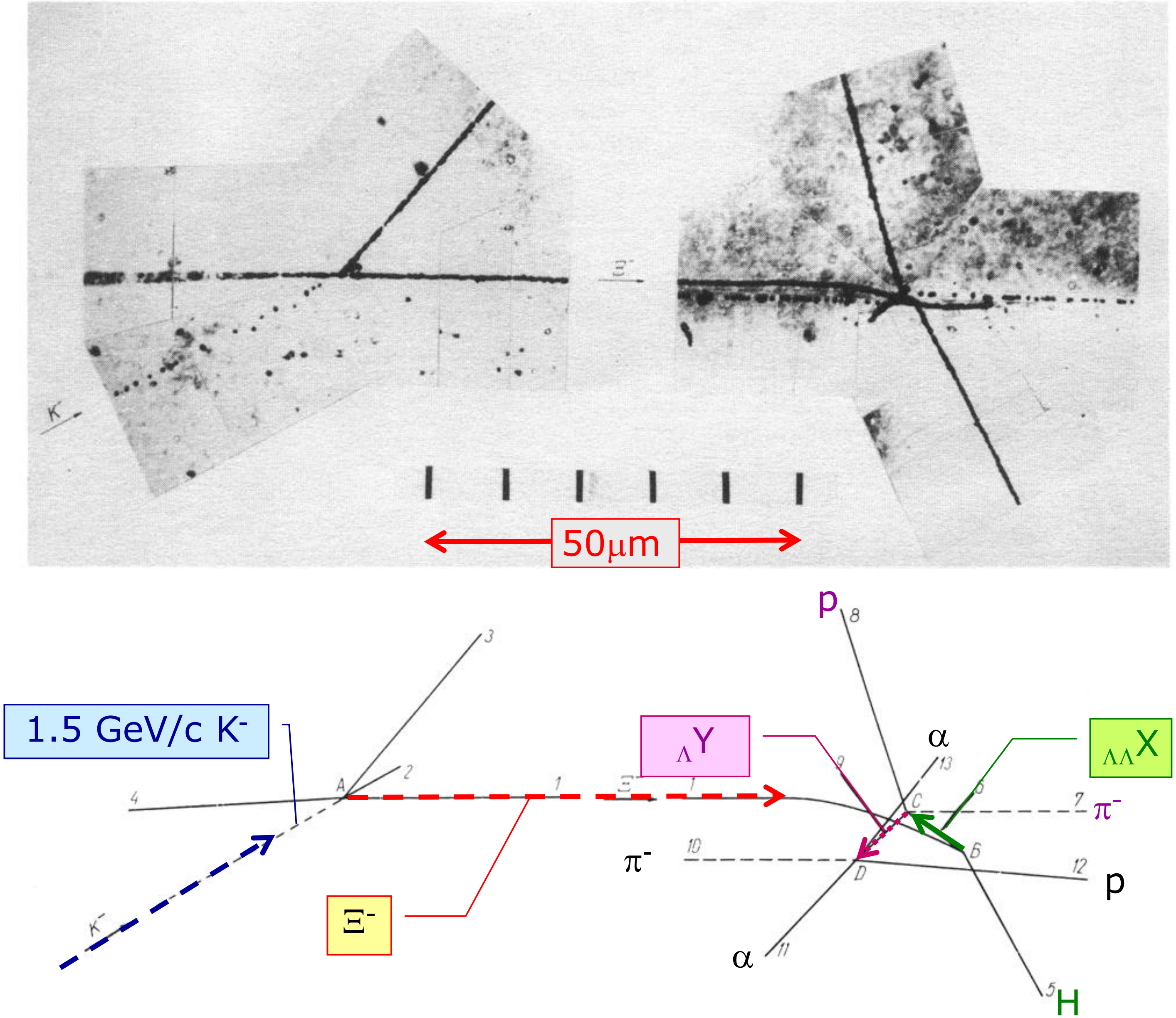
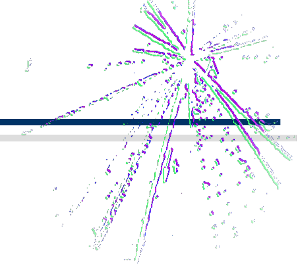


FIG. 1. A photomicrograph and a schematic drawing of the production of a Ξ^- hyperon in a 1.5-GeV/c K^--meson interaction at A followed by capture at rest of the Ξ^- hyperon at B with the emission of a double hyperfragment decaying in cascade at C and D.

Analysis of the Danysz-Event



- Ionisation density ⇒ dE/dx ⇒ charge, momentum
- Range ⇒ mass, charge, momentum
- angles ⇒ momentum balance
- there remains some ambiguity!

Table I. Results of the measurements.[a]

Star *C*		Star *D*		
Decay mode of the double *HF*	Binding energy of a Λ^0 hyperon in the double *HF* $B_{\Lambda\Lambda}({}_{\Lambda\Lambda}Z)$ (MeV)	Decay mode of the resulting ordinary *HF*	Binding energy of the Λ^0 hyperon in the ordinary *HF* $B_{\Lambda}({}_{\Lambda}Z)$ (MeV)	Momentum unbalance Δp(MeV/c)
${}_{\Lambda\Lambda}Be^{10} \to {}_{\Lambda}Be^{9} + H^1 + \pi^-$	11.0 ± 0.4	${}_{\Lambda}Be^{9} \to 2He^4 + H^1 + \pi^-$	7.2 ± 0.6	20 ± 12
${}_{\Lambda\Lambda}Be^{11} \to {}_{\Lambda}Be^{9} + H$ [illegible]	[illegible]	[illegible]	[illegible].6	20 ± 12
${}_{\Lambda\Lambda}Be^{11} \to {}_{\Lambda}Be^{10} +$ [illegible]	[illegible]	[illegible]	[illegible].6	17 ± 20
${}_{\Lambda\Lambda}Li^{8} \to {}_{\Lambda}Li^{7} + H^1$ [illegible]	[illegible]	[illegible]	[illegible].6	40 ± 14
${}_{\Lambda\Lambda}Li^{9} \to {}_{\Lambda}Li^{8} + H^1$ [illegible]	[illegible]	[illegible]	[illegible].6	27 ± 15
${}_{\Lambda\Lambda}Li^{10} \to {}_{\Lambda}Li^{8} + H^1 + n + \pi^-$	$< 7.5 \pm 0.5$	${}_{\Lambda}Li^{8} \to He^4 + H^3 + H^1 + \pi^-$	5.4 ± 0.6	27 ± 15

$$\Xi^- + {}^{12}C \to {}^{10}_{\Lambda\Lambda}Be + p + 2n$$

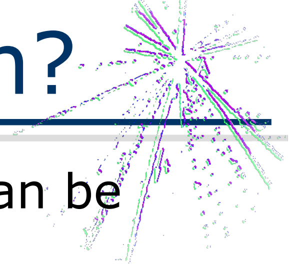
$$\hookrightarrow {}^{10}_{\Lambda\Lambda}Be \to {}^{9}_{\Lambda}Be + p + \pi^-$$

$$\hookrightarrow {}^{9}_{\Lambda}Be \to \alpha + \alpha + p + \pi^-$$

[c] Large errors in the determination of the range and direction of this track results from the observational difficulties and are to be treated as maximum errors.

[d] A capture star is observed at the end of this track.

Can we determine the ΛΛ interaction?



- The binding energy B_Λ of a Λ particle in a hypernucleus can be determined from energy balance
  - for example

$${}^{9}_{\Lambda}Be \rightarrow \alpha + \alpha + p + \pi^-$$

$$m\left({}^{9}_{\Lambda}Be\right) = m(\alpha) + m(\alpha) + m(p) + m(\pi^-) + \sum T''_{kin}$$

$$B_\Lambda\left({}^{9}_{\Lambda}Be\right) = m({}^{8}Be) + m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right)$$

$$= m({}^{8}Be) + m(\Lambda) - m(\alpha) - m(\alpha) - m(p) - m(\pi^-) - \sum T''_{kin}$$

$${}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}Be + p + \pi^-$$

$$m\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{9}_{\Lambda}Be\right) + m(p) + m(\pi^-) + \sum T'_{kin}$$

$$B_\Lambda\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{9}_{\Lambda}Be\right) + m(\Lambda) - m\left({}^{10}_{\Lambda\Lambda}Be\right)$$

$$= m\left({}^{9}_{\Lambda}Be\right) + m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right) - m(p) - m(\pi^-) - \sum T_{kin}$$

$$= m(\Lambda) - m(p) - m(\pi^-) - \sum T_{kin}$$

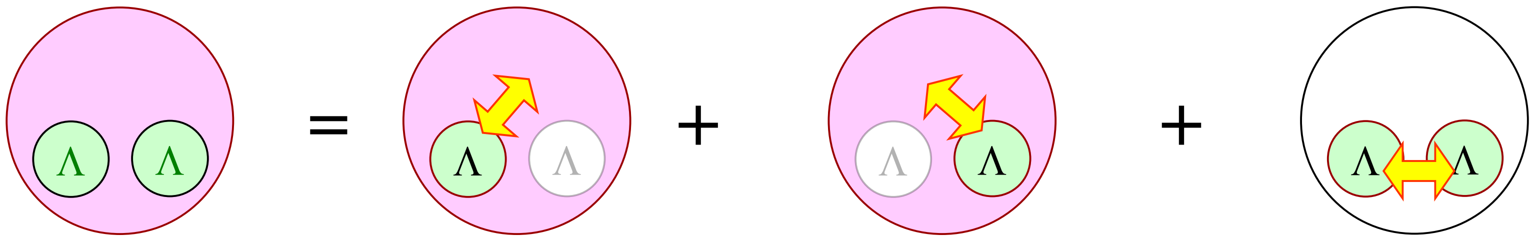
$$B_{\Lambda\Lambda}\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^{8}Be\right) + 2m(\Lambda) - m\left({}^{10}_{\Lambda\Lambda}Be\right)$$

$$= m\left({}^{8}Be\right) + 2m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right) - m(p) - m(\pi^-) - \sum T'_{kin}$$

$$= m\left({}^{8}Be\right) + 2m(\Lambda) - 2m(\alpha) - 2m(p) - 2m(\pi^-) - \sum T_{kin}$$

First approach to the $\Lambda\Lambda$ interaction

- We are mainly interested in the additinal binding energy *between* the two Λs



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

- in the case of the Danysz-event one obtains

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (17.7 \pm 0.4)\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (4.3 \pm 0.4)\,\mathrm{MeV}$$

- positive $\Rightarrow$ attractive interaction
- this is the net $\Lambda\Lambda$ binding provided that
  - the core is not distorted by adding one Λ after the other
  - the core spin is zero
  - no γ-unstable excited states are produced

note:

$\Delta B_{\Lambda\Lambda}$ is proportional to the kinetic energy of the produced pions

The Prowse Event (1)

VOLUME 17, NUMBER 14 PHYSICAL REVIEW LETTERS 3 OCTOBER 1966

$_{\Lambda\Lambda}He^6$ DOUBLE HYPERFRAGMENT*

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(Received 14 July 1966)

An event has been found in an emulsion stack exposed to about 10^6 K^- mesons at 4 to 5 BeV which appears to be consistent with the production and decay of a $_{\Lambda\Lambda}He^6$ double hyperfragment. It confirms that double hyperfragments exist and confirms the value of the low-energy Λ-Λ interaction, first measured by Danysz et al.,[1] at some 4.6 ± 0.5 MeV.

Description of the event.—(1) Production: The event shown in Fig. 1 is initiated by a Ξ^- hyperon which is apparently captured at rest by a light emulsion nucleus producing only two products, which are collinear. Their ranges are 13.4 and 30.0 μ; the shorter track appears by inspection to be caused by a fragment of a higher charge than the other track. Assuming that the fragment initiating the two-star chain is a double hyperfragment, there are three interpretations involving double hyperfragments and a relatively stable recoil fragment which balance momentum, and which are consistent with the capture of a Ξ^- hyperon by a light emulsion nucleus.

These interpretations, shown in Table I, are $_{\Lambda\Lambda}He^6$ together with Li^7, $_{\Lambda\Lambda}He^8$ with Be^7, or $_{\Lambda\Lambda}Li^7$ with Be^{10}. The visible energies for each of these possibilities are 14.5, 18.3, and 23.9 MeV, respectively. The Q values for the nuclear capture of a Ξ^- hyperon giving two free Λ hyperons are negative except for the $_{\Lambda\Lambda}He^6$ possibility. The total binding energies of the Λ hyperons necessary to explain the measured visible energies are 10.9, 27.8, and 32.0 MeV, respectively.

The Prowse event (2)

- interpreted as ${}^{6}_{\Lambda\Lambda}He$
- very likely no excited state
- core spin is zero

$$B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) = (10.9 \pm 0.5)\,\mathrm{MeV}$$
$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}He) = (4.7 \pm 0.6)\,\mathrm{MeV}$$

- no independent study of the event
- reconsidered by Dalitz *et al.*, Proc. R. Soc. Lond. A426, 1 (1989)
- event is now regarded as questionable

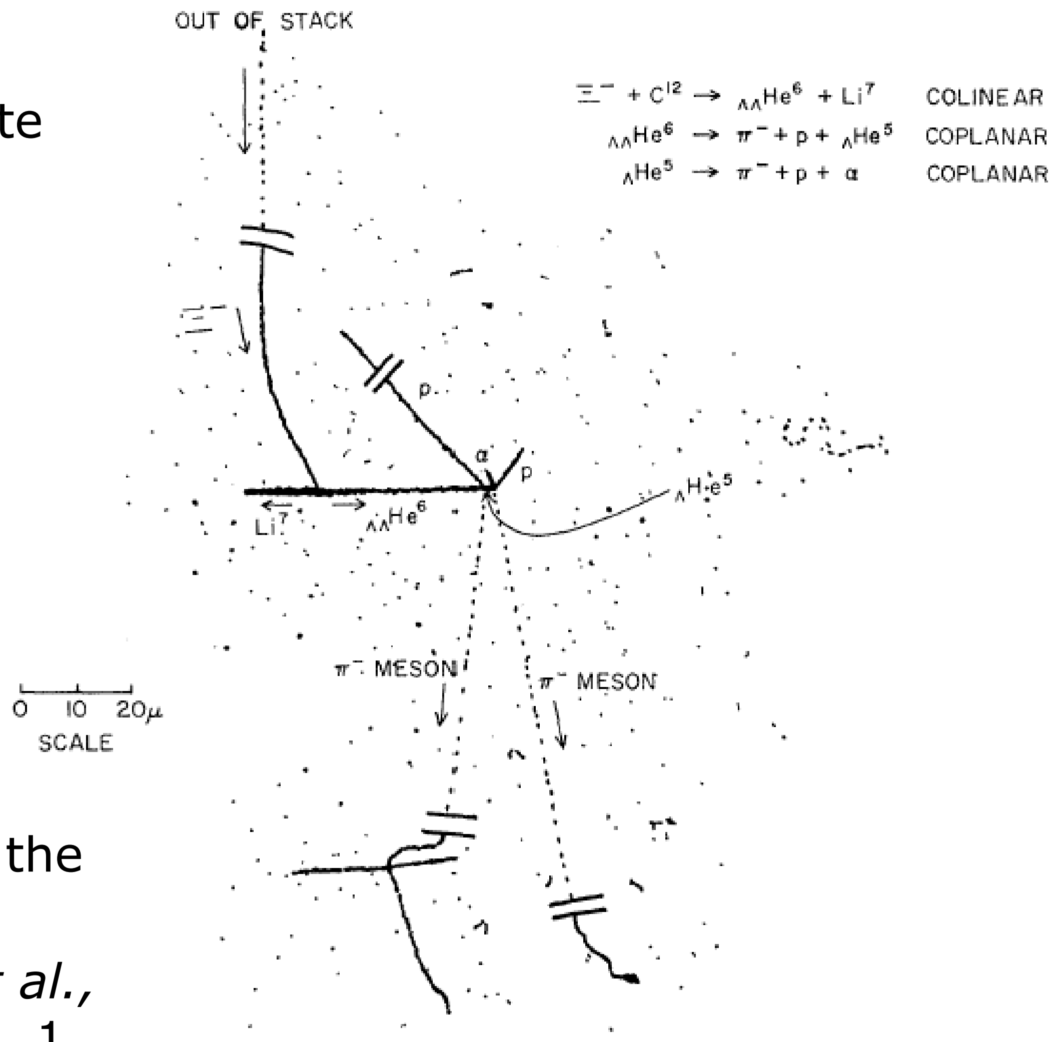


FIG. 1. Drawing of the event.

Pros and Cons of Emulsion Technique

R excellent track resolution

N time consuming analysis: it just takes a long time to find the very few interesting events

- higher K-rates needed
- combine emulsion technique with electronic counters
  - use (K^-,K^+) to produce Ξ^-
  - track K^- and K^+ to determine interaction point in the emulsion/target
  - e.g. suggested 1989 by Dalitz *et al*.

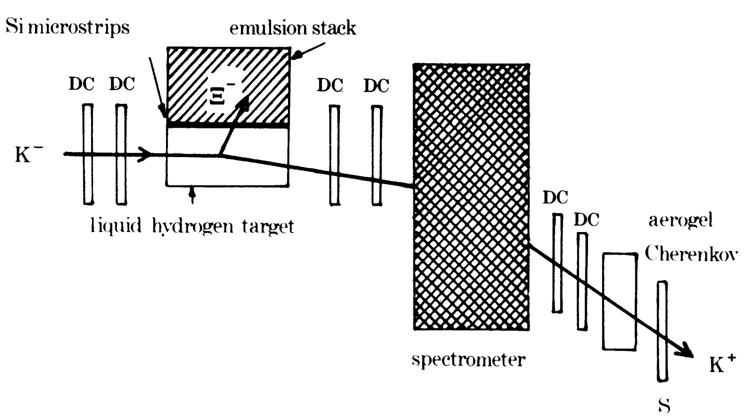
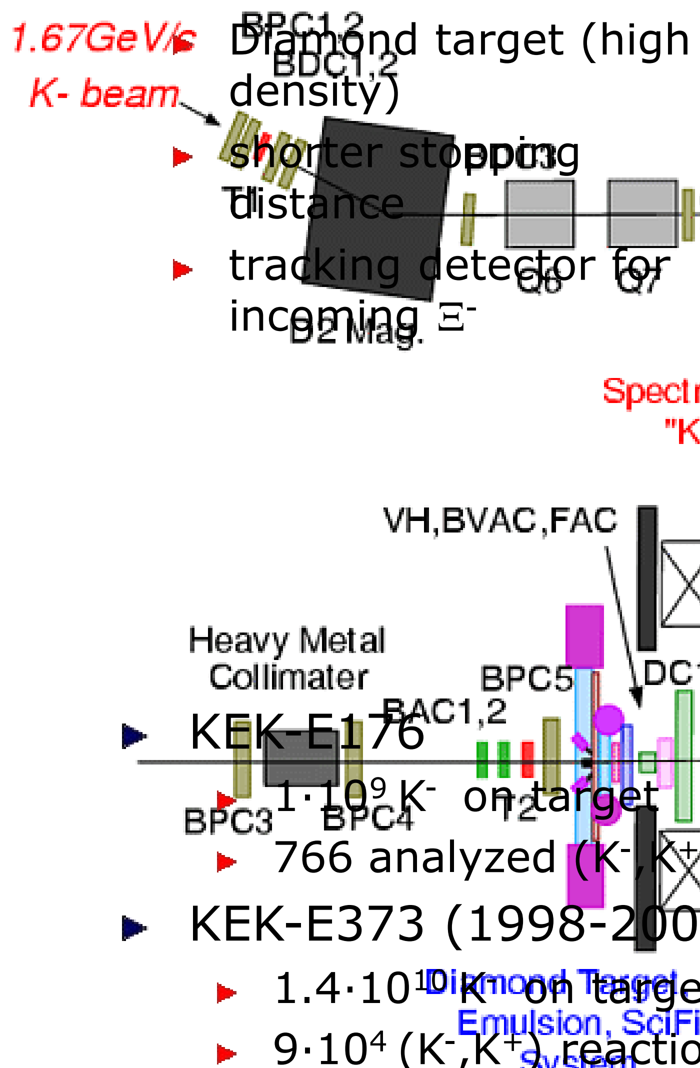


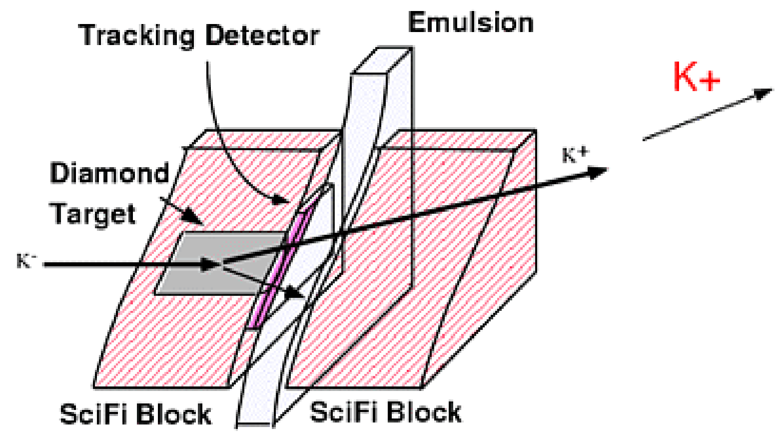
FIGURE 3. Schematic diagram of proposed hybrid emulsion experiment to study double hypernuclei. (DC is drift chamber and S is scintillator.)

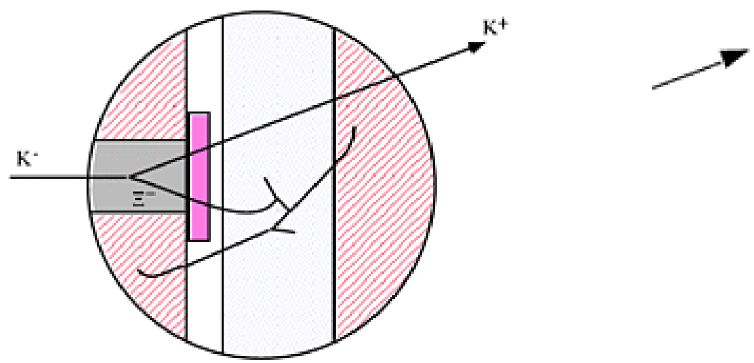
- applied by KEK-E176 and KEK-E373 collaboration

The KEK-E373 Experiment

- KEK proton synchrotron
- 1.66 GeV/c K^- beam







  - Diamond target (high density)
  - shorter stopping distance
  - tracking detector for incoming Ξ^-

- KEK-E176
  - $1 \cdot 10^9$ K^- on target
  - 766 analyzed (K^-,K^+) reactions, 497 Ξ^- candidates
- KEK-E373 (1998-2000)
  - $1.4 \cdot 10^{10}$ K^- on target, $1.3 \cdot 10^7$ trigger
  - $9 \cdot 10^4$ (K^-,K^+) reactions, 5096 Ξ^- tracks in SciFi

The Aoki-Event (KEK-E176)

- S. Aoki *et al*., Prog. Theor. Phys. **85**, 1287 (1991)

at point A: $\Xi^- + {}^{12}C \rightarrow {}^{3}H + {}^{10}_{\Lambda\Lambda}Be$

at point B: ${}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{10}_{\Lambda}B + \pi^-$

at point C: ${}^{10}_{\Lambda}B \rightarrow {}^{3}He + {}^{4}He + p + 2n$

$\Rightarrow \Delta B_{\Lambda\Lambda} = -4.9 \pm 0.7\text{MeV}$

- repulsive $\Lambda\Lambda$ interaction!?

- re-interpretation: C.B. Dover, D.J. Millener, A. Gal and D.H. Davis, Phys. Rev. C 44, 1905 (1991)

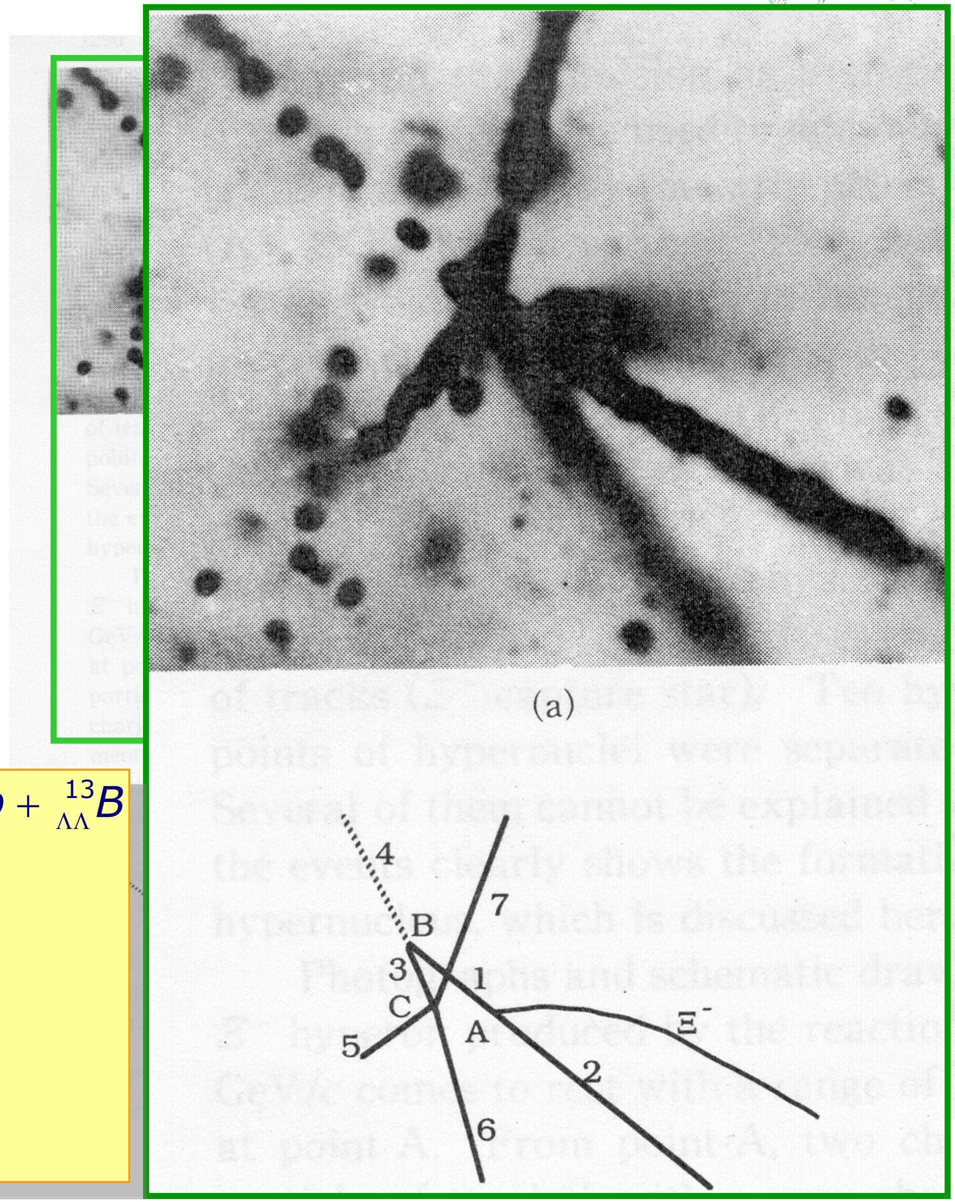
at point A: $\Xi^- + {}^{14}N \rightarrow n + {}^{14}_{\Lambda\Lambda}C^* \rightarrow n + p + {}^{13}_{\Lambda\Lambda}B$

at point B: ${}^{13}_{\Lambda\Lambda}B \rightarrow {}^{13}_{\Lambda}C + \pi^-$

at point C: ${}^{13}_{\Lambda}C \rightarrow {}^{3}He + {}^{4}He + {}^{4}He + 2n$

or $\rightarrow {}^{6}Li + {}^{4}He + p + 2n$

$\Rightarrow \Delta B_{\Lambda\Lambda} = +4.8 \pm 0.7\text{MeV}$



DIE WELT 4. September 2001

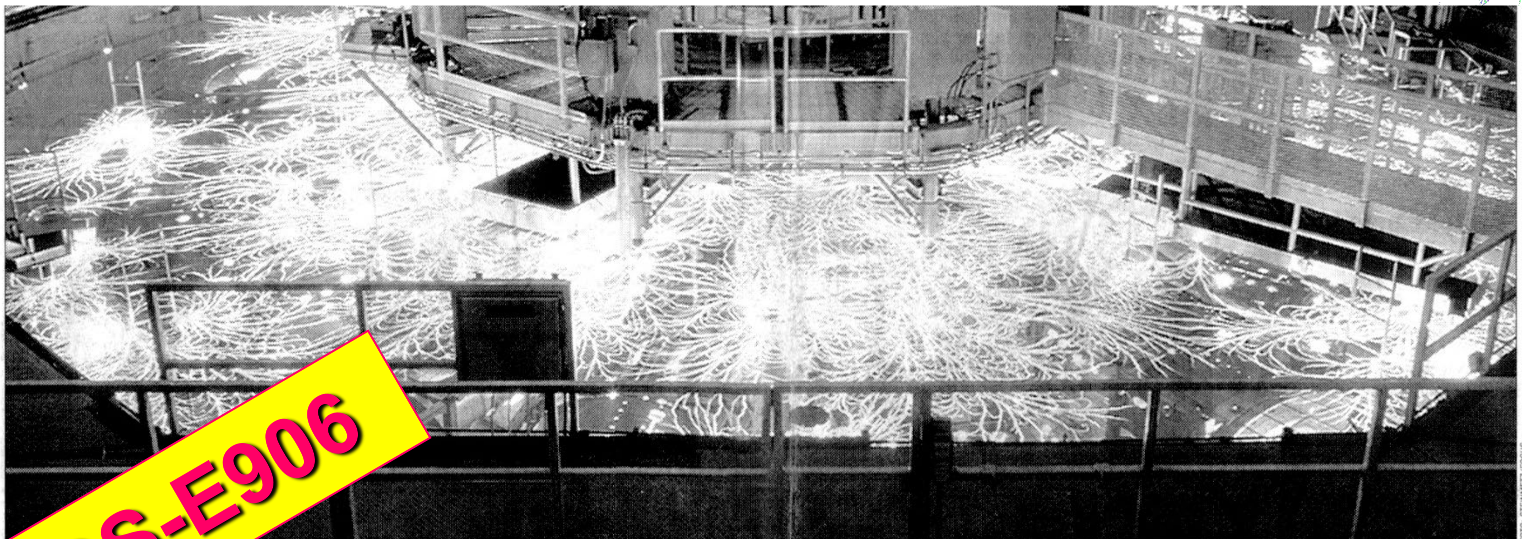


FOTO: STEINMETZ/FOCUS

AGS-E906

ein die modernen Alchimisten Materie ineinander um oder erzeugen gar Materieformen, die es auf der Erde überhaupt nicht gibt. Das Foto zeigt eine Kernfusionsanlage in Neu-Mexiko

Doppelt seltsame Atomkerne synthetisiert

Nach 40 Jahren gelingt Physikern in den USA die Herstellung von exotischer Neutronenstern-Materie

VON BRIGITTE RÖTHLEIN

Brookhaven – Drei Jahre nach Abschluss einer Serie von Experimenten konnten Forscher im Brookhaven National Lab auf Long Island bei der Auswertung der Ergebnisse eine bisher nicht bekannte Art von Materie nachweisen. Sie entstand 1998 bei Zusammenstößen von Wolframatomen mit superschnellen Protonen.

Die Physiker sprechen von „doppelt seltsamen Kernen" und bringen damit zum Ausdruck, dass sich bei den Kollisionen im Beschleuniger ein Komplex aus mehreren Teilchen gebildet hat, der normalen Atomkernen nicht unähnlich ist. Das Besondere daran ist jedoch, dass diese Gebilde je zwei „seltsame" Teilchen enthalten.

Die Experimente von Teilchenforschern laufen in Sekundenbruchteilen ab. Man lässt dabei beschleunigte Elementarteilchen auf Ziele prallen und untersucht mit Hilfe großer Detektoren, welche Bruchstücke dabei entstehen. Die Vielzahl der in den letzten Jahrzehnten auf diese Weise entdeckten Teilchen hat gezeigt, dass sich unsere „normale" Materie auf zwei so genannte Quarks (mit den Namen „up" und „down") und Elektronen zurückführen lässt.

Daneben gib es aber auch noch exotische Arten von Materie, die aus schwereren Teilchen bestehen und auf der Erde üblicherweise nicht vorkommen. Zur Unterscheidung erhielten die Quarks dieser Materie die willkürlich gewählten Namen „strange" (seltsam) und „charme".

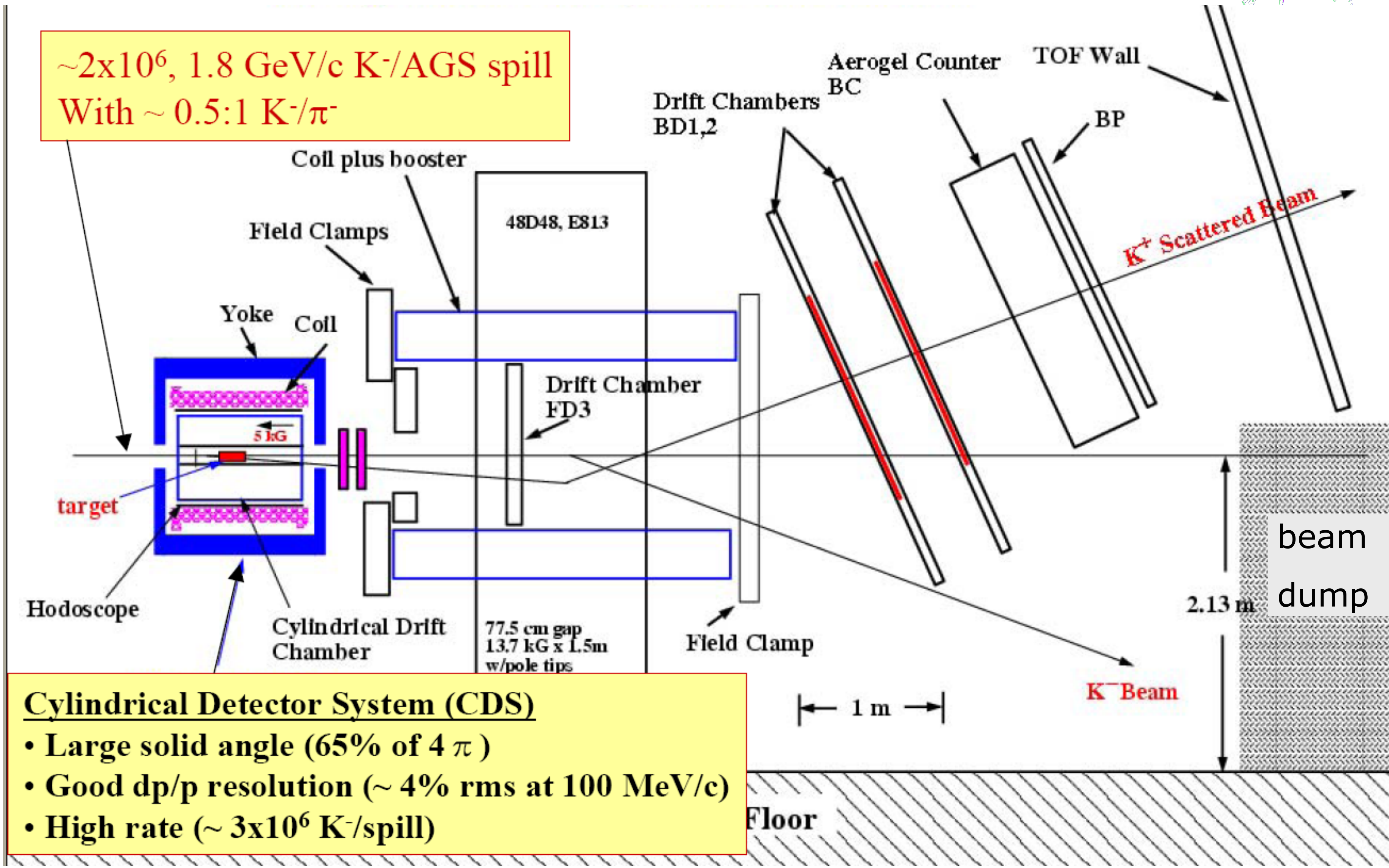
Aus den Millionen von Daten, die während einer Messkampagne entstehen, müssen die Physiker am Ende die wirklich relevanten „Ereignisse" herausfinden, die sprichwörtliche Nadel im Heuhaufen. In Brookhaven hat sich die Mühe offenbar gelohnt; aus 100 Millionen infrage kommenden Ereignissen filterten Computer zunächst 100 000 heraus, unter denen man dann 30 bis 40 mit den gesuchten Eigenschaften fand. „Hier wurde zum ersten Mal eine größere Anzahl von seltsamen Atomkernen erzeugt", erklärt Adam Rusek, der stellvertretende Sprecher der 50 beteiligten Physiker aus sechs Ländern.

40 Jahre lang hatte man in den USA, Europa und Japan nach den Gebilden gesucht, aber nur je eines davon gefunden, zum Teil mit zweifelhafter Sicherheit. Nun gelang es nachzuweisen, dass über einen mehrstufigen Zerfallsprozess Strukturen entstanden waren, die aus einem Neutron, einem Proton und zwei Lambda-Teilchen bestanden. Diese enthalten je ein up- und ein down-Quark und ein seltsames (strange) Quark. Die Lambda-Paare sind nun die bejubelten „doppelt seltsamen Kerne". Es ist allerdings sehr schwierig, sie näher zu untersuchen, da sie bereits nach weniger als einer Milliardstel Sekunde wieder zerfallen.

Die Forscher erhoffen sich vom Studium der seltsamen Kerne Erkenntnisse über jene Kräfte, die zwischen den Teilchen wirken. Daraus wollen sie Rückschlüsse auf die Prozesse in so genannten Neutronensternen ziehen. Diese Himmelskörper entstehen, wenn heiße Sterne am Ende ihres Lebens ausgebrannt sind und in sich zusammenstürzen. Man vermutet, dass sie große Mengen seltsamer Teilchen enthalten und dass sie der einzige Ort im All sind, wo seltsame Materie stabil existiert.

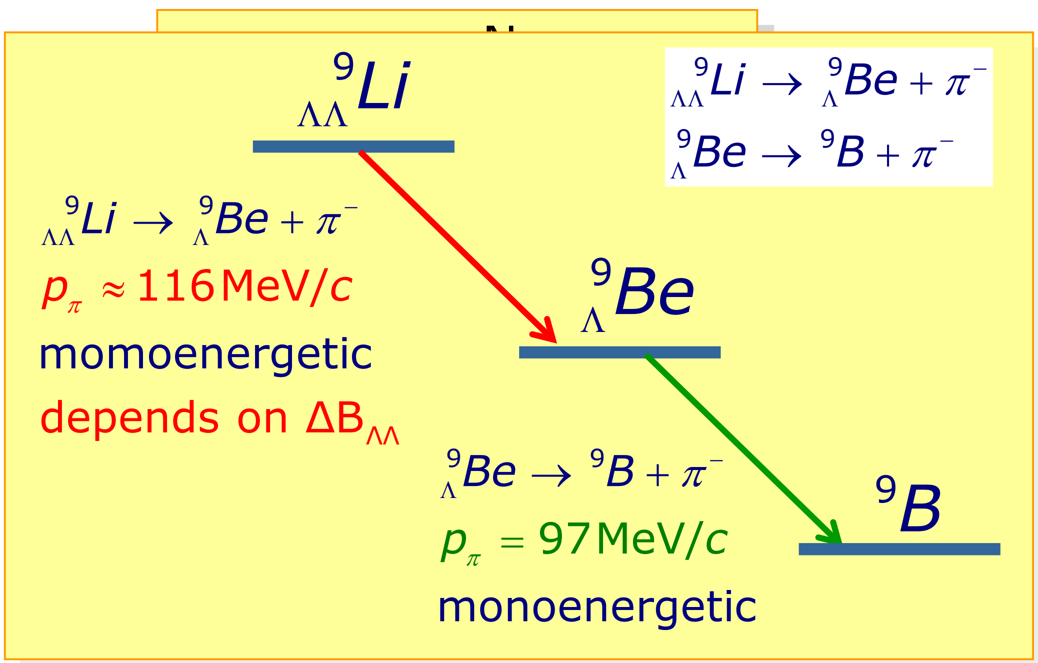
Weitere Informationen im Web: **www.bnl.gov**

The E906 experiment



The E906 strategy

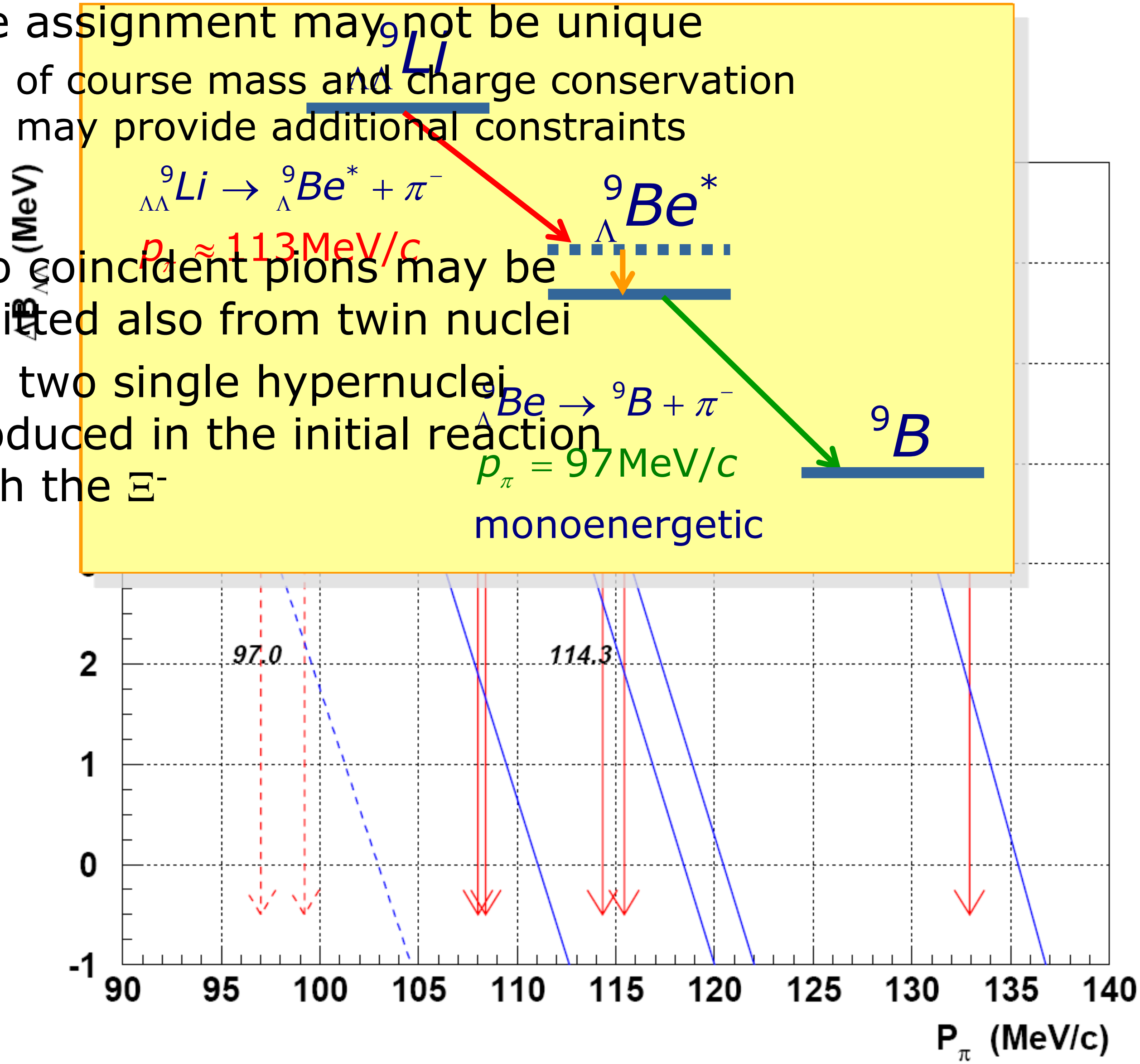
- fully electronic detector
- use $p(K^-,K^+)\Xi^-$ to produce Ξ^- on a nuclear target
- $\Xi^- p \rightarrow \Lambda\Lambda$ conversion after capture by another target
- Identification of $\Lambda\Lambda$ hypernucleus through sequential weak decay via π^- emission
  - in light nuclei the pionic weak decay dominates
  - the pion kinetic energy is proportional to $\Delta B_{\Lambda\Lambda}$
  - coincidences between two pions help to trace the decay of the $\Lambda\Lambda$-nucleus
- example



…but life is not so easy

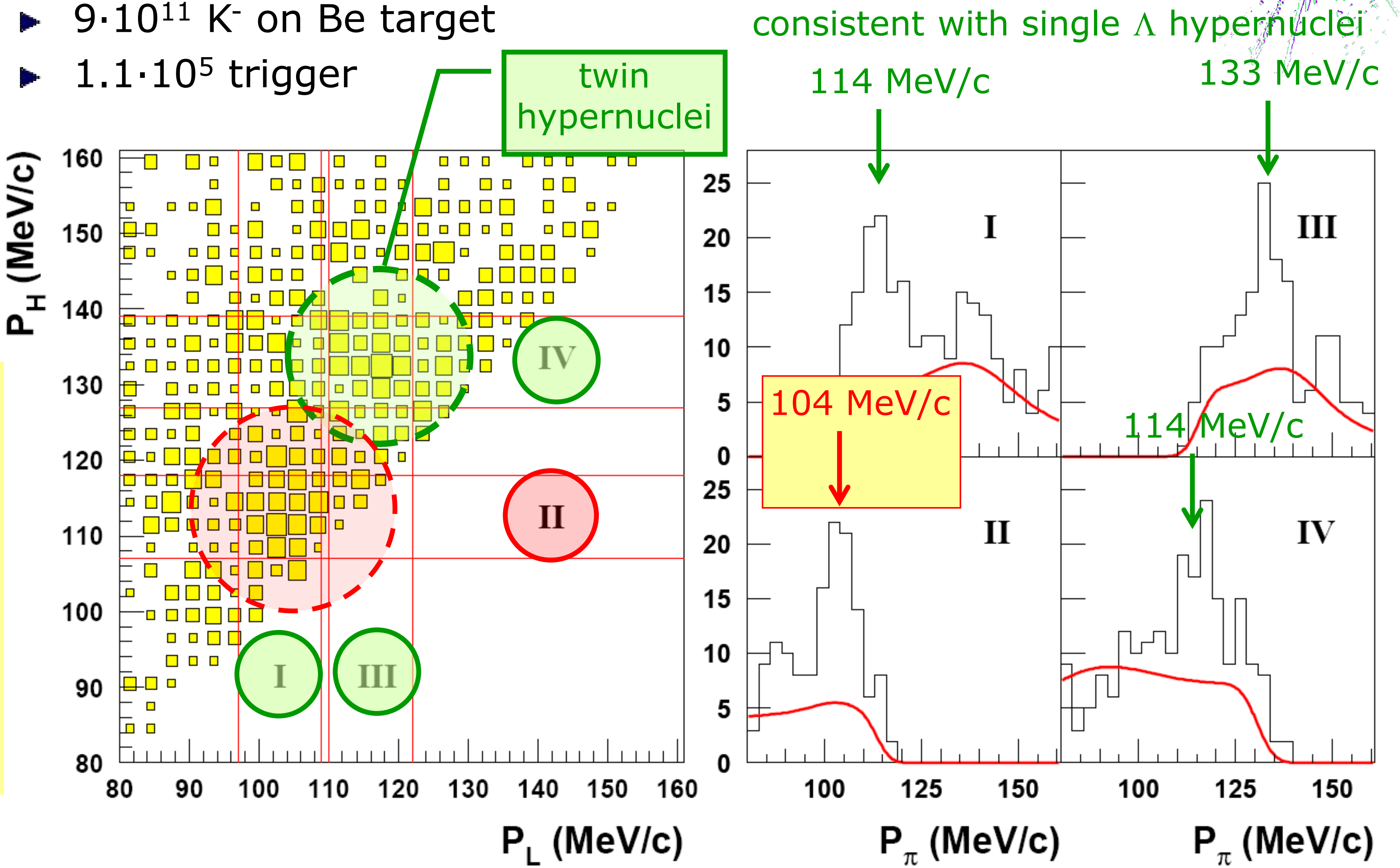
- there may be excited states involved
- the assignment may not be unique
  - of course mass and charge conservation may provide additional constraints
- two coincident pions may be emitted also from twin nuclei

  i.e. two single hypernuclei produced in the initial reaction with the Ξ^-



E906

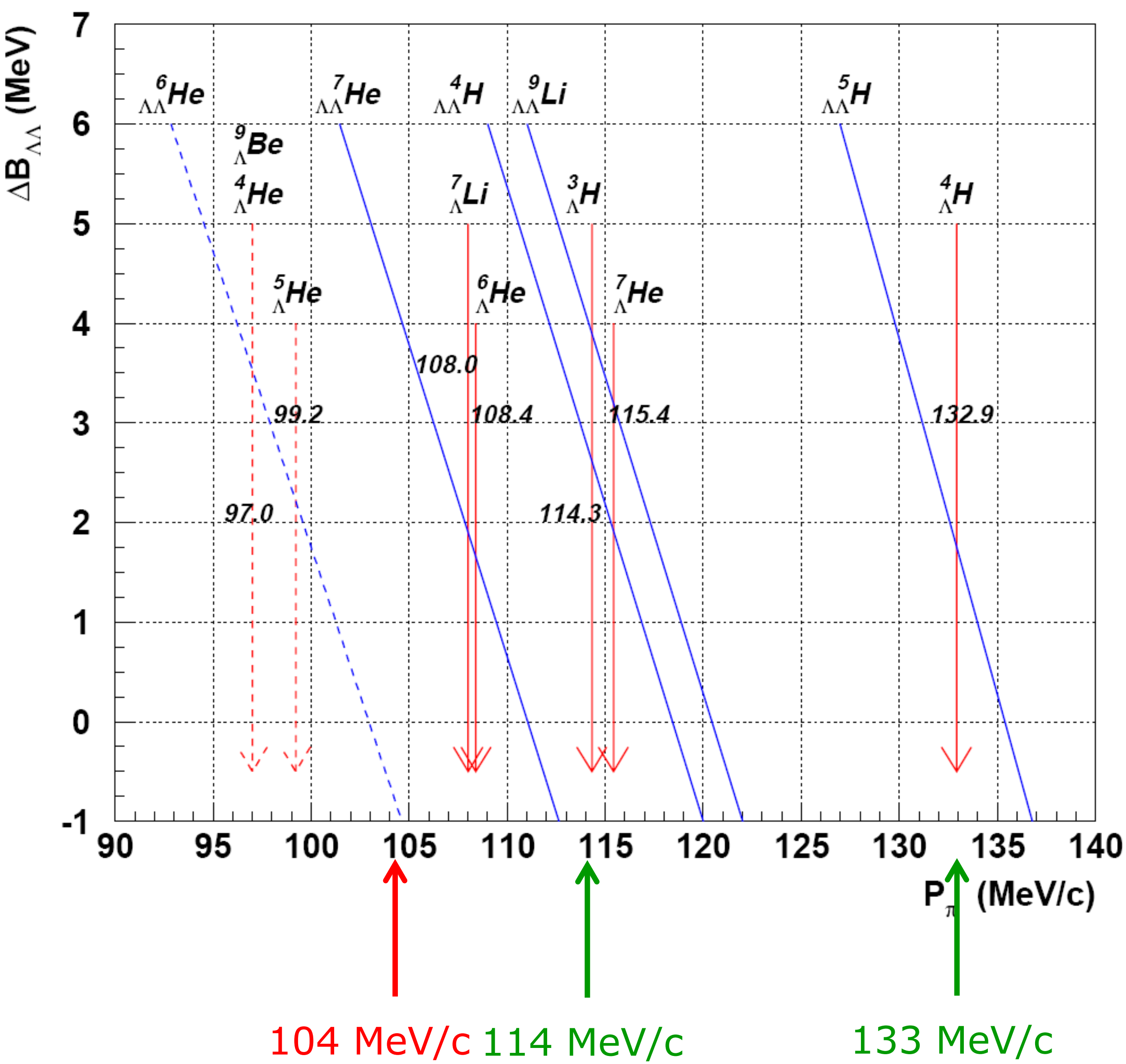
- $9 \cdot 10^{11}$ K^- on Be target
- $1.1 \cdot 10^5$ trigger



momentum of the pion with lower momentum

momentum of the pion with lower momentum

Interpretation

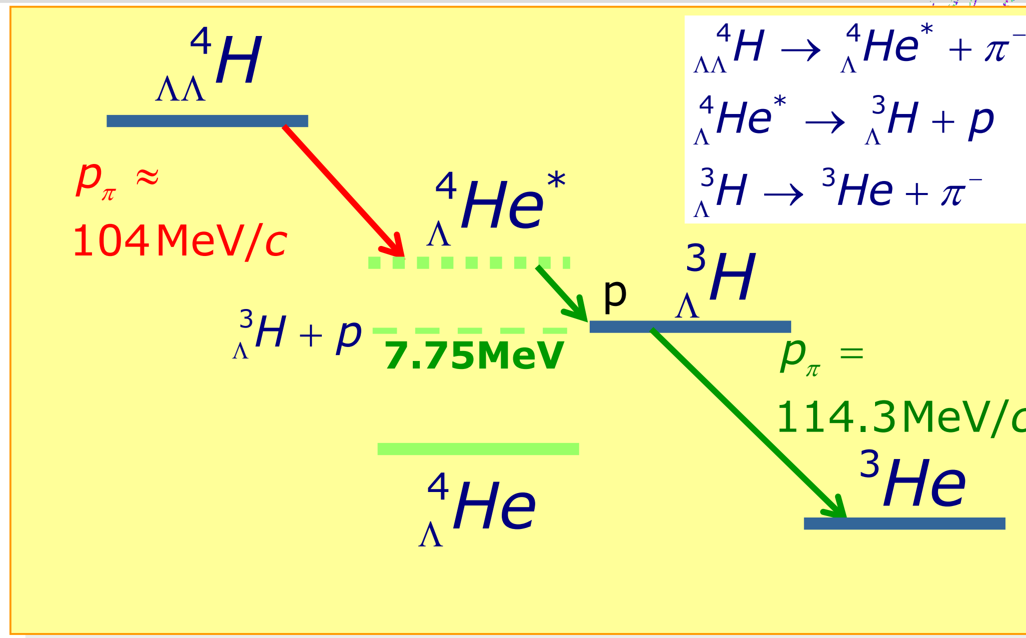


- …is not straight forward

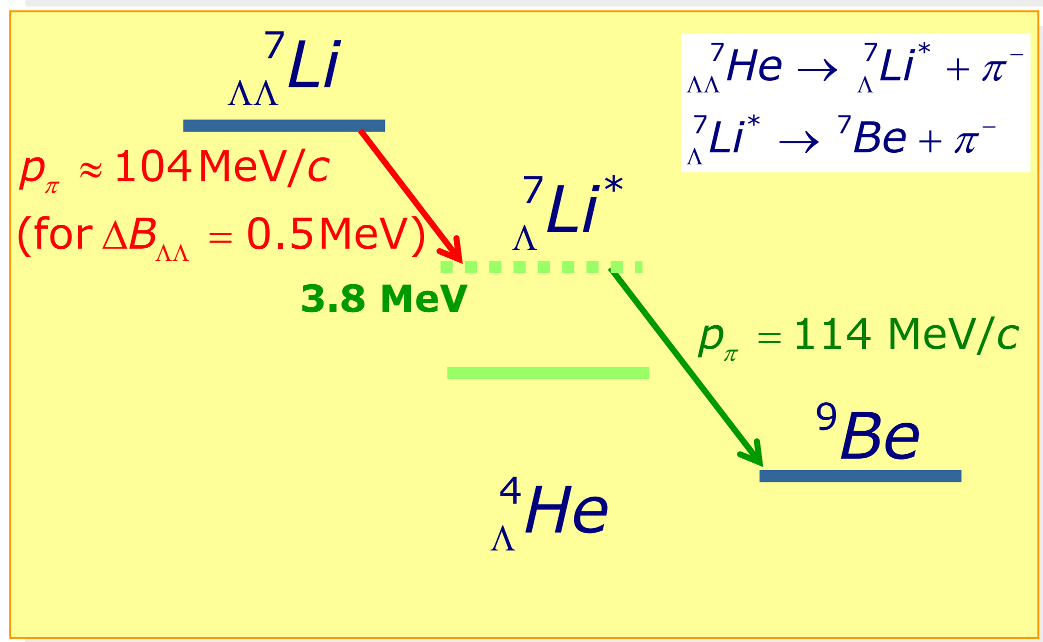
Suggested decay mode

- PRL 87, 132504-1 (2001)
  - $\Delta B_{\Lambda\Lambda}$ depends then on excitation energy

E_x (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)
7.75	1.8
8.75	0.8
9.84	-0.26



- Hungerford (HYP03)
  - requires isomeric state at 3.8MeV



- Gal (HYP03)

$${}^{3}_{\Lambda\Lambda}n \rightarrow {}^{3}_{\Lambda}H + \pi^{-} (104\mathrm{MeV/c})$$

for $\Delta B_{\Lambda\Lambda}$=4MeV

$${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} (114.3\mathrm{MeV/c})$$

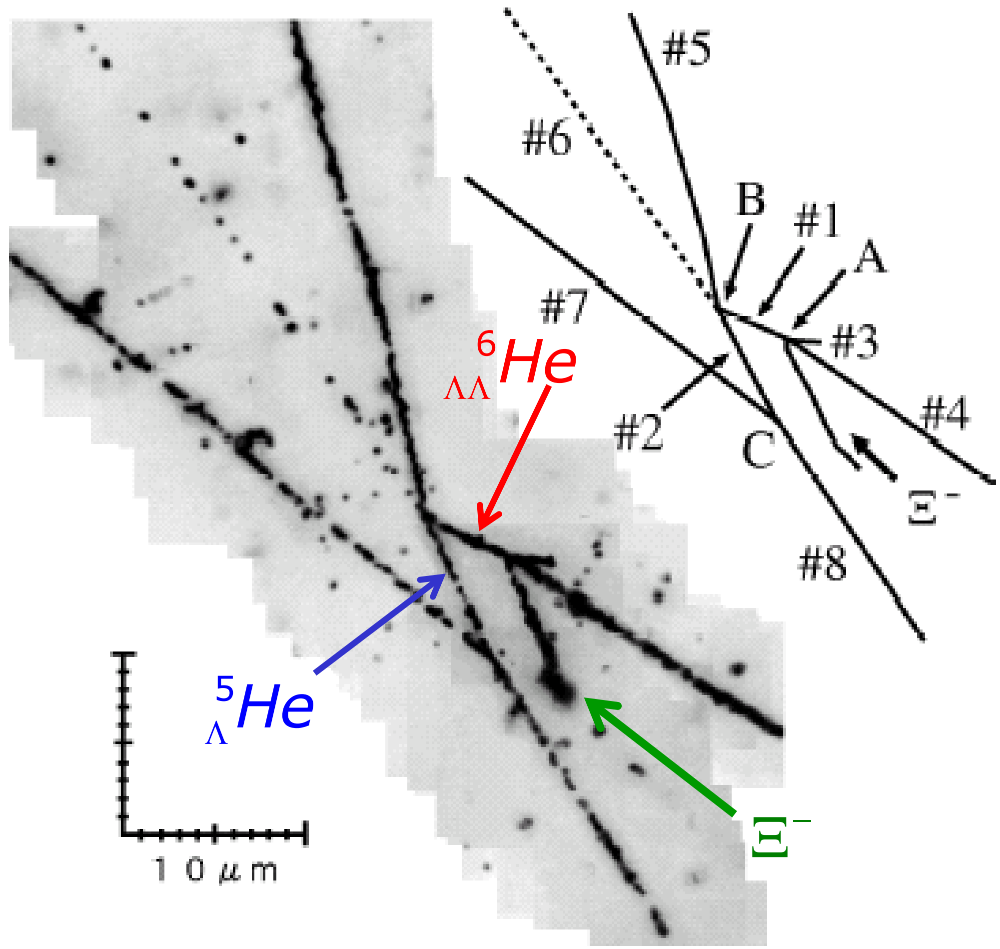
KEK-E373: the NAGARA event

- H. Takahashi *et al*., PRL 87, 212502-1 (2001)
  - hybrid emulsion technique
  - cleanest event so far (also theoretically)

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

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

$$\Rightarrow \Delta B_{\Lambda\Lambda} = +1.01 \pm 0.2^{+0.18}_{-0.11}\,\mathrm{MeV}$$



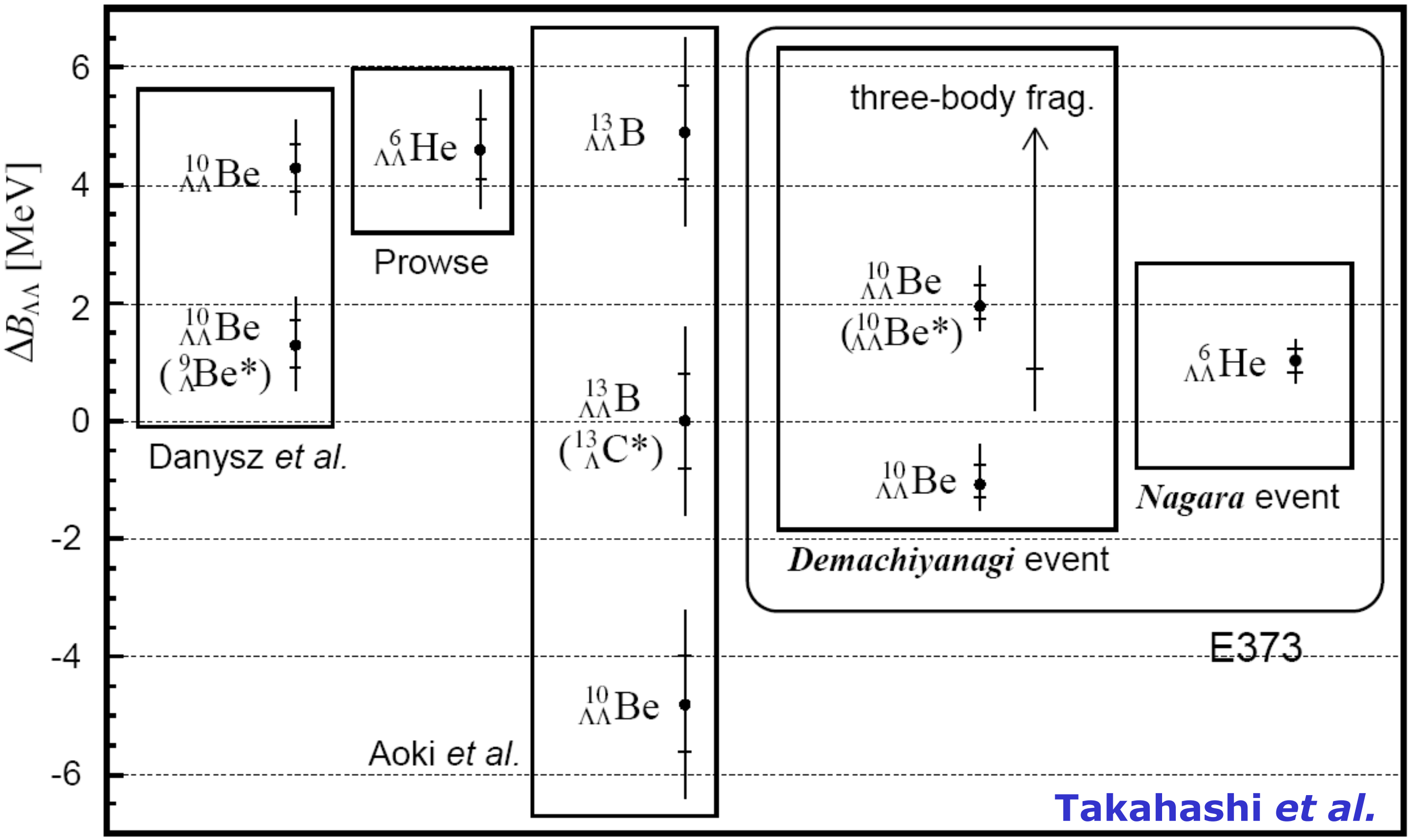
  - inconsistent with Prowse event
- one additional event
  - Demachiyanagi-event:

$${}^{10}_{\Lambda\Lambda}Be$$

what we know …

- mass production of double hypernuclei is in principle possible! provided we have a Ξ^- factory
- γ-spectroscopy is in principle possible since very likely particle stable, excited states exist

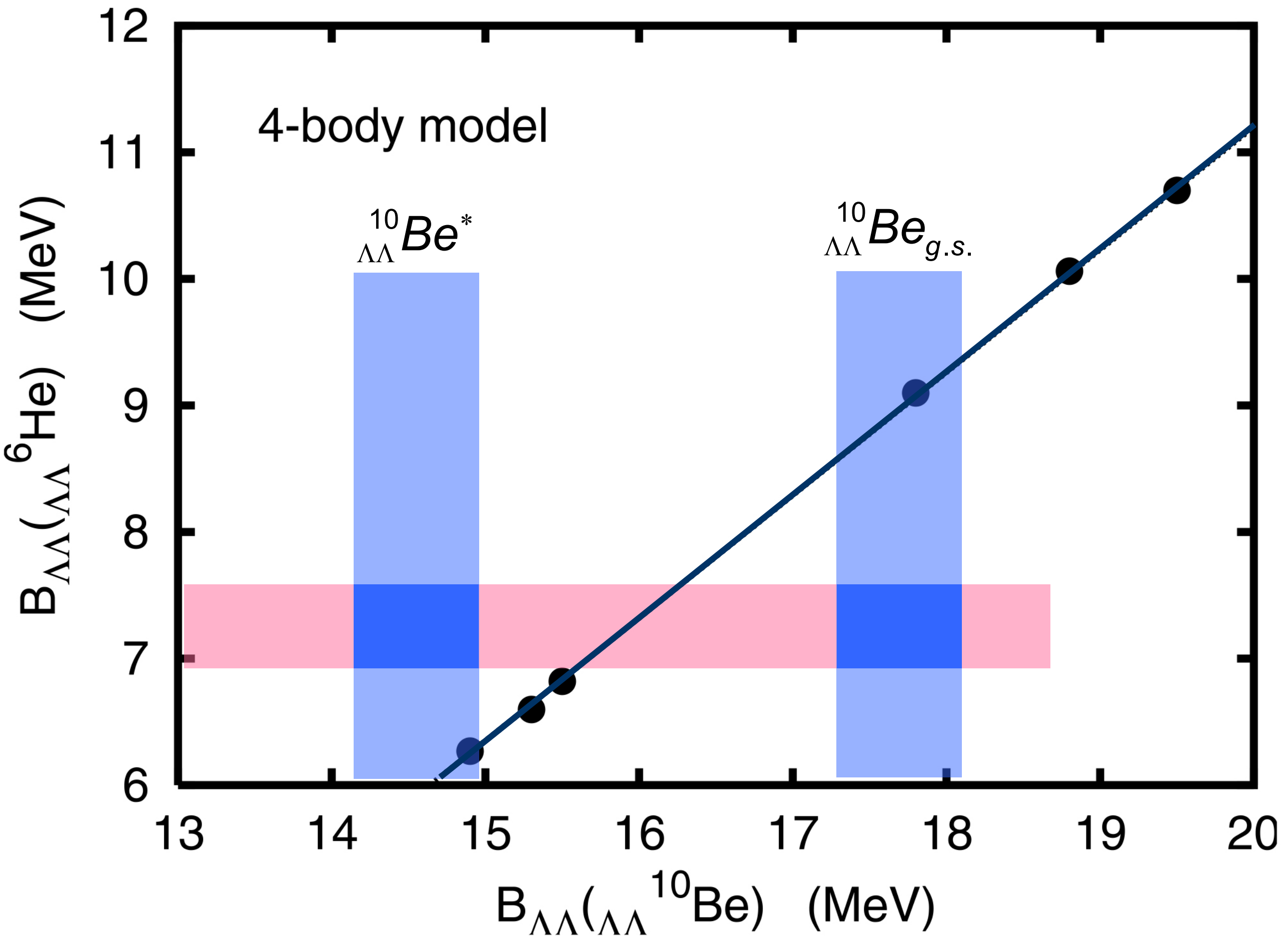
Summary



- 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
  - $\Lambda\Lambda$-ΞN-$\Sigma\Sigma$ coupling
  - excited states possible, but have not been clearly identified so far

Consistent Description - not yet!

- I.N. Filikhin, A. Gal, Phys. Rev. C 65, 041001 (R) (2002)
  - Faddeev-Yakubovsky calculation



- no consistent description possible so far

Future ideas

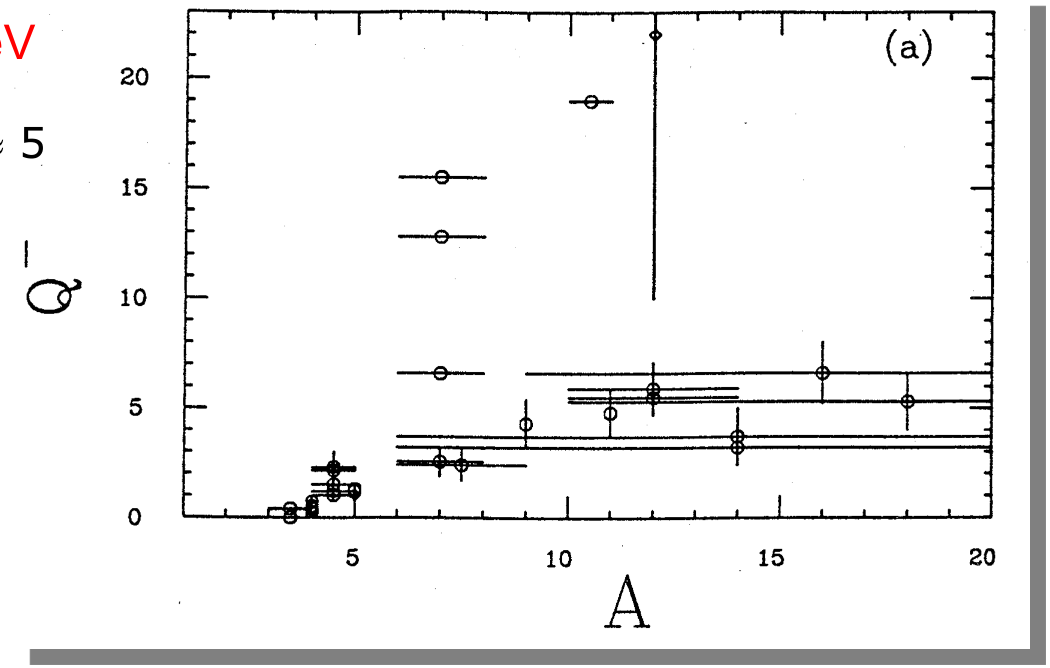
What about Heavy Nuclei?

- interesting: $\Lambda\Lambda$-interaction in nuclear medium
- $\Lambda\Lambda$-hypernuclei and intermediate Λ-nuclei are produced in excited states
  - Q-value difficult to determine
  - nuclear fragments difficult to identify (neutrons!)

  with usual emulsion technique
- non-mesonic weak decay dominates

$$\Lambda + n \rightarrow n + n + 176\,\text{MeV}$$
$$\Lambda + p \rightarrow n + p + 176\,\text{MeV}$$

  - non-mesonic: mesonic $\approx$ 5



- new concept required!

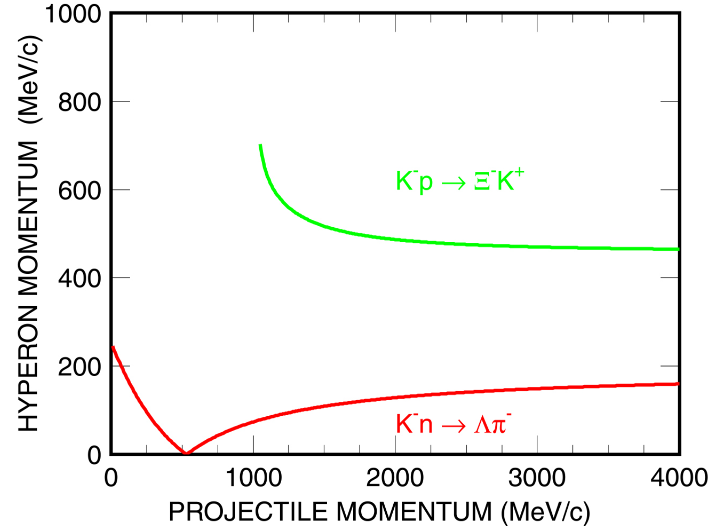
high resolution
γ-spectroscopy !

Production of Ξ^-

- Ξ^- conversion in 2 Λ: $\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\text{MeV}$

- Ξ- production
  - p(K$^-$,K$^+$)Ξ^-
    - needs K$^-$ beam (c·τ=3.7cm)
    - recoil momentum >460 MeV/c
  - KEK-E176: 10^2 stopped Ξ
  - $\Rightarrow$ E373: 10^3 stopped Ξ
  - AGS-E885: 10^4 stopped Ξ

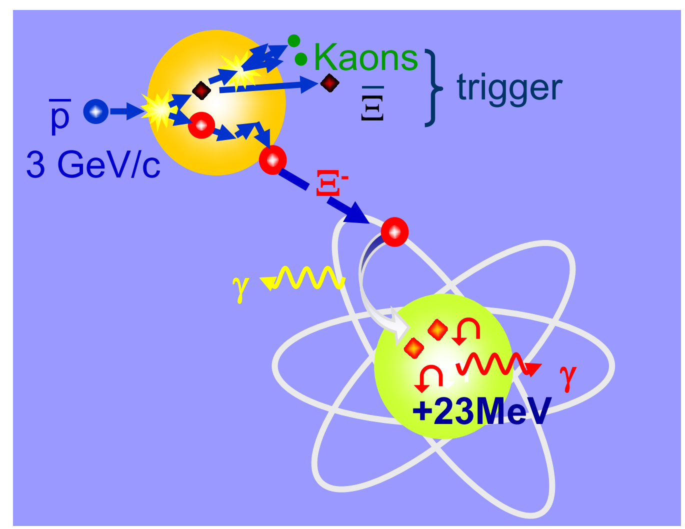
  } per week(s)



- PANDA@HESR

$$p + \bar{p} \rightarrow \Xi^- + \bar{\Xi}^+$$
$$p + \bar{p} \rightarrow \Omega^- + \bar{\Omega}^+$$

- few times 10^5 stopped Ξ per day
- $\Rightarrow$ γ-spectroscopy feasible



The Discovery of the anti-Xi

- discovered simulataniously at CERN and SLAC

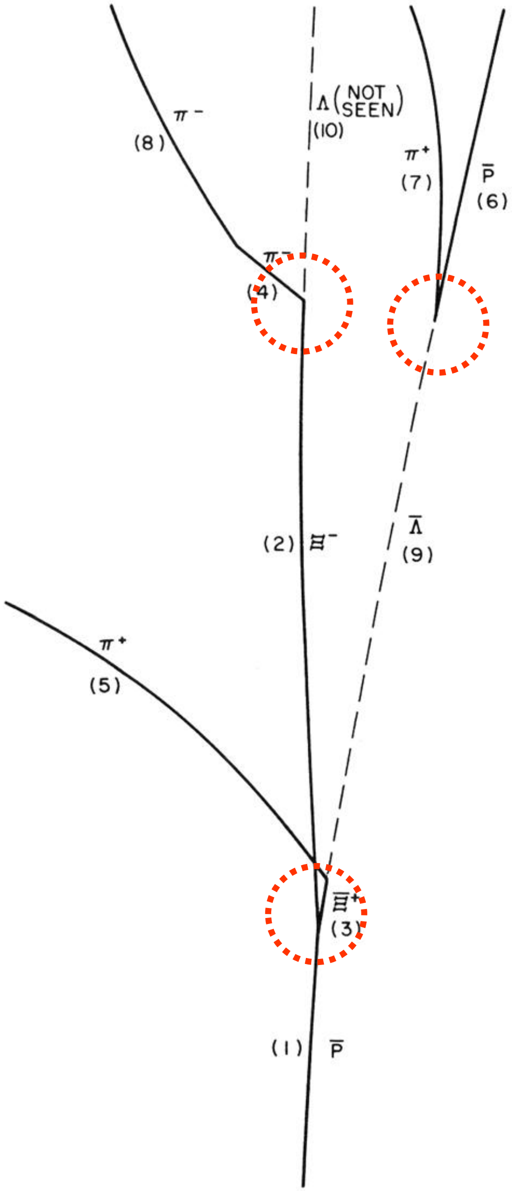
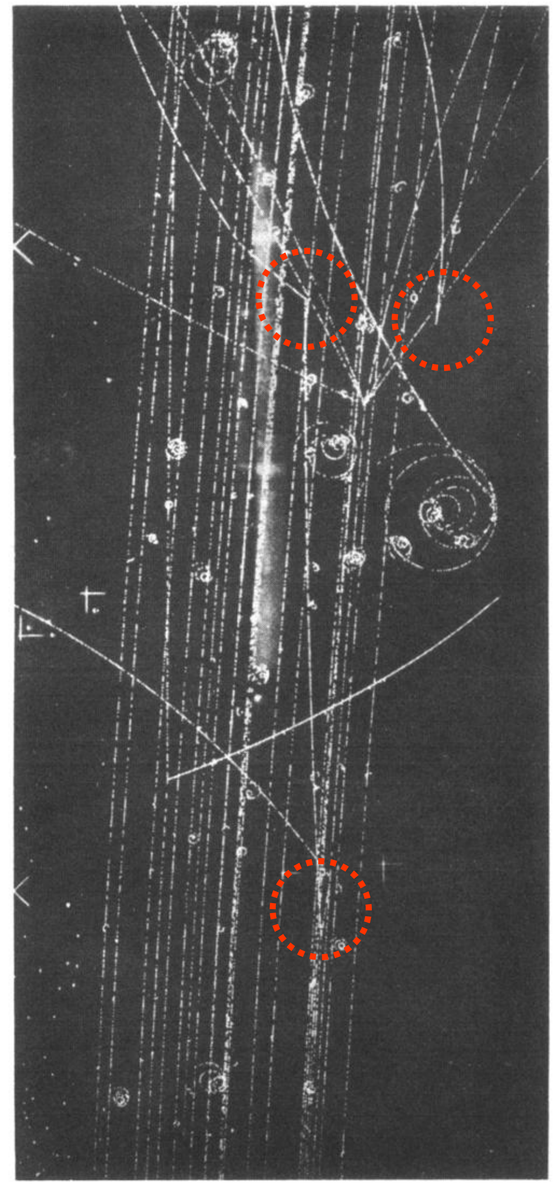
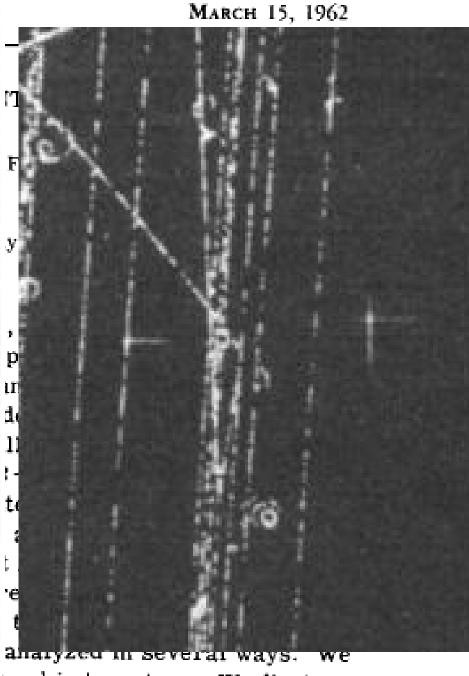


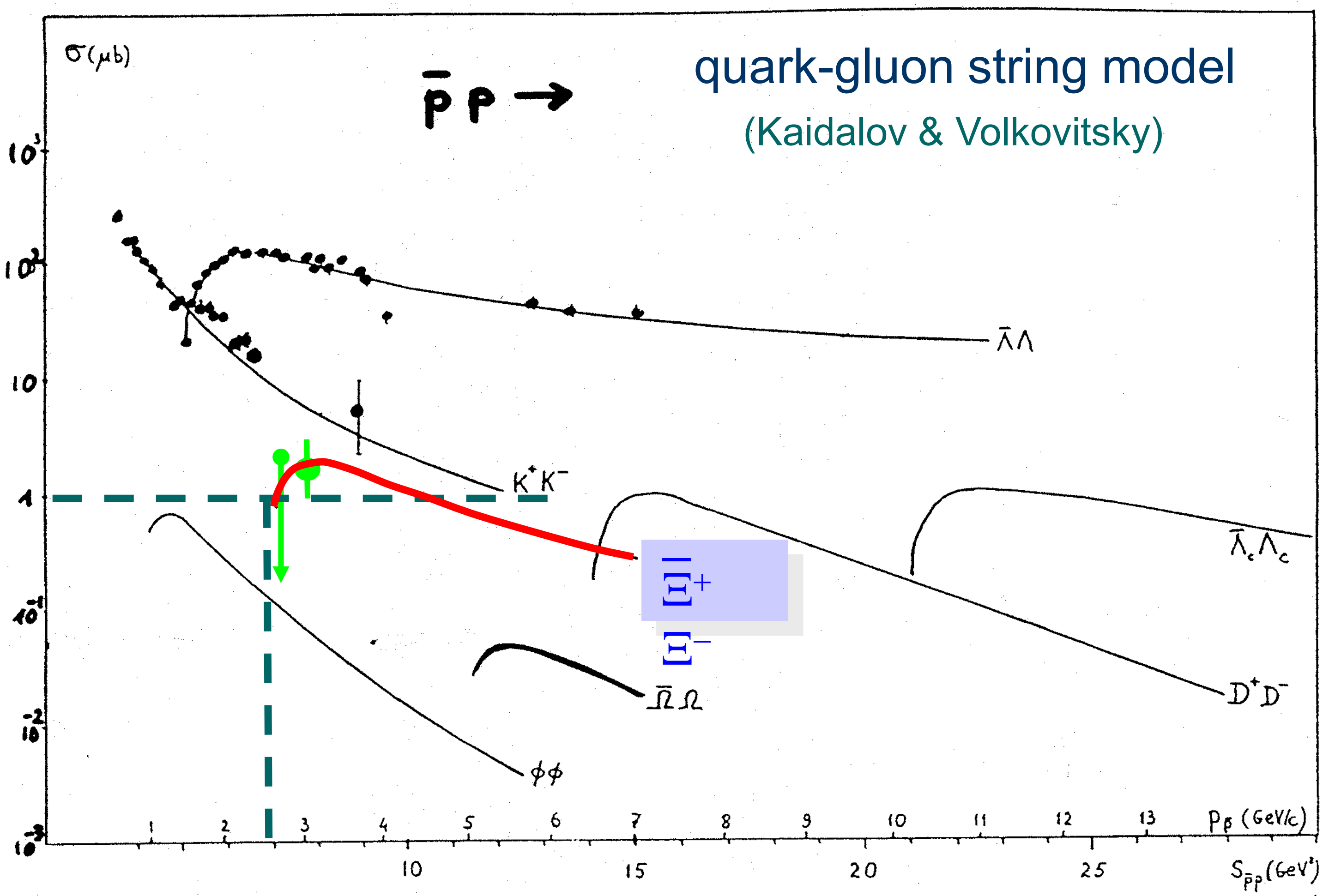
FIG. 1. A print of the event $\bar{p}+p\rightarrow\Xi^{-}+\bar{\Xi}^{+}$ as photographed in the BNL 20-in. liquid hydrogen bubble chamber is shown. The sketch of the event as shown is labelled according to the most likely mass interpretation for each observed track. The numbers on each track are those used in Table I.

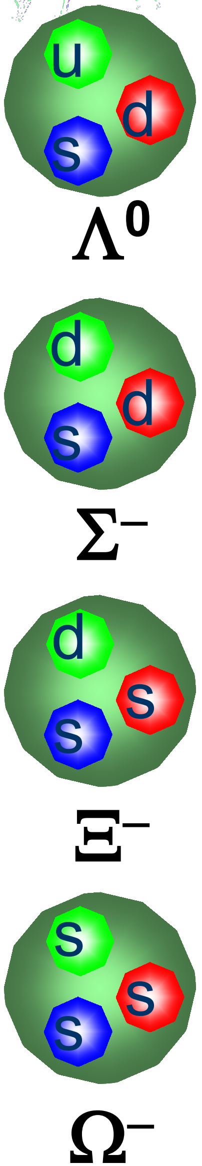




General Idea

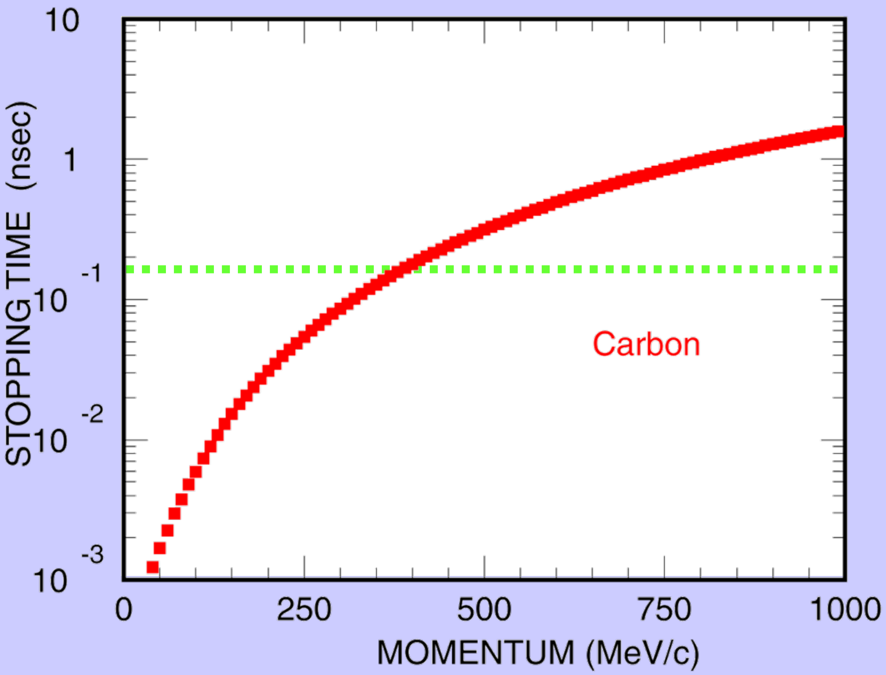
- Use p$\bar{p}$ Interaction to produce a hyperon "beam" (t~10^{-10} s) which is tagged by the antihyperon or its decay products
  - Data: B. Mugrave et al., Il Nuovo Cimento, Vol. XXXV, 735 (1965)

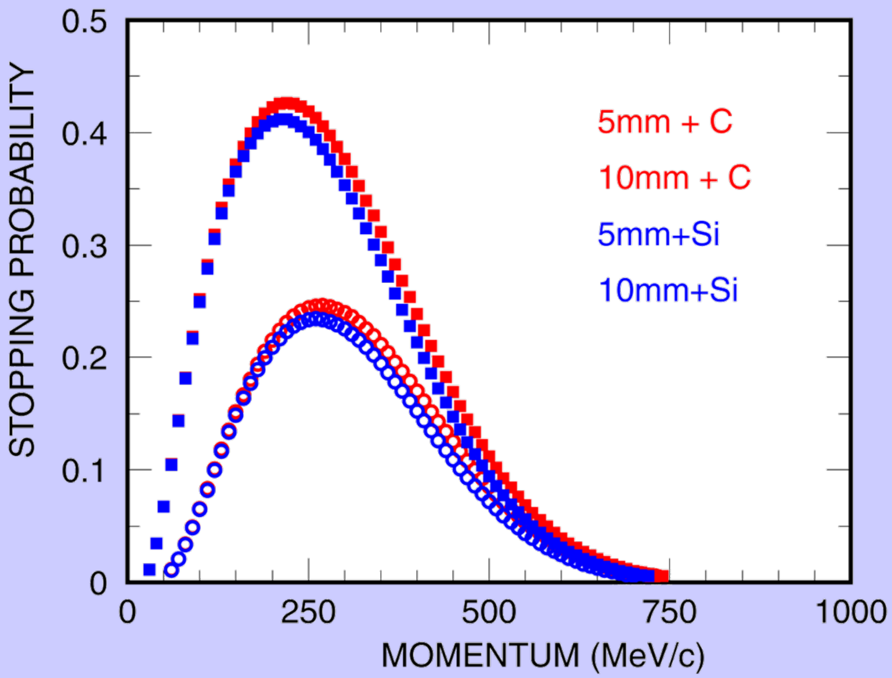




Ξ⁻ properties

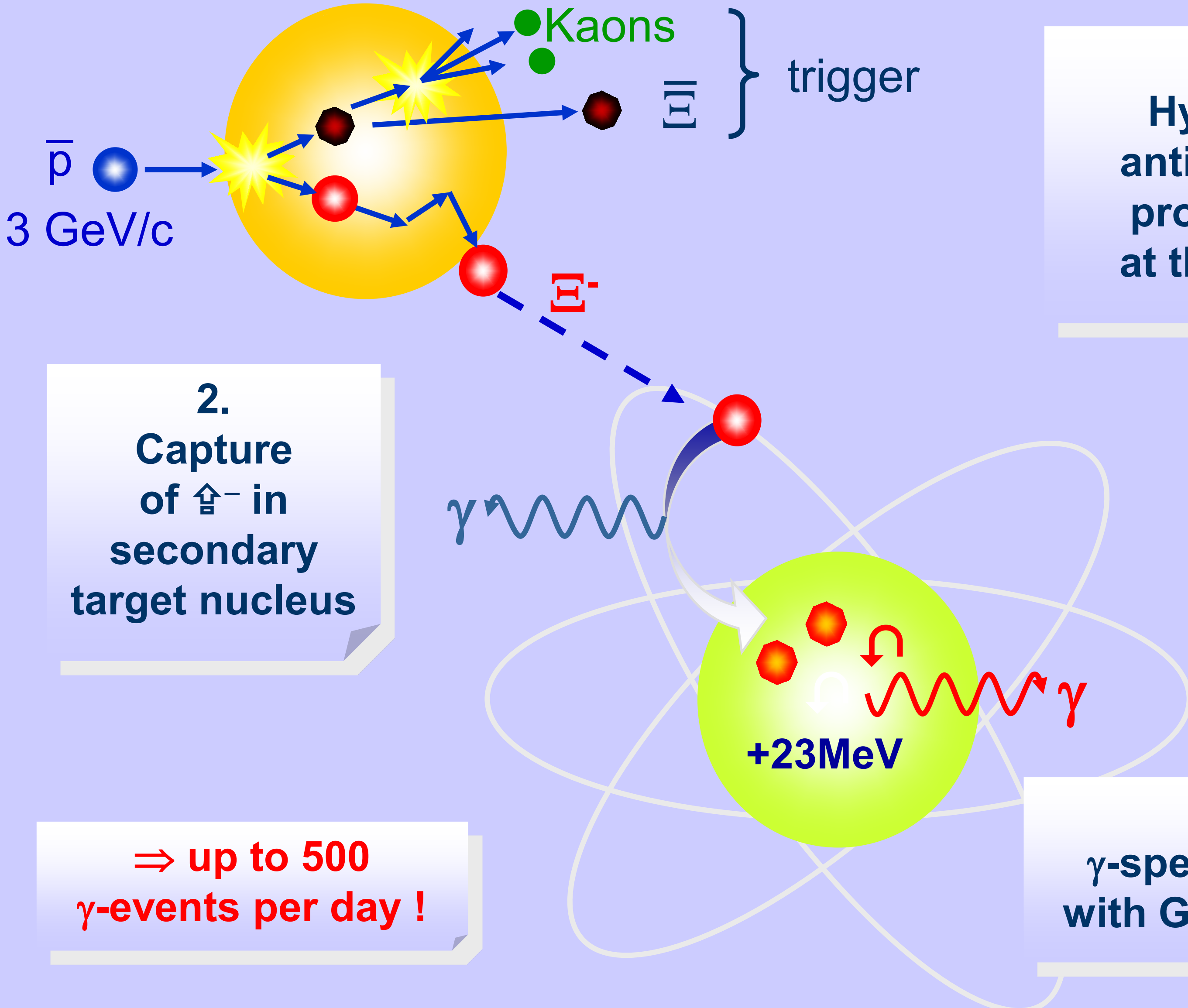
- Ξ^- mean lifetime 0.164 ns





- minimal distance production ⇔ capture
- initial momentum 100-500 MeV/c → range ~ few g/cm²

Production of Double Hypernuclei



1.
Hyperon-antihyperon production at threshold

2.
Capture of Ξ^- in secondary target nucleus

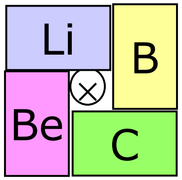
3.
γ-spectroskopy with Ge-detectors

⇒ up to 500 γ-events per day !

Strategy

- Fully electronic detector for high luminosity
  - tag primary reaction by Ξ^+ or $2K^+$ in forward direction $\Rightarrow$ trigger
  - use primary target nucleus as a degrader
  - measure incoming track of Ξ^- by active secondary target $\Rightarrow$ background
  - measure secondary decay star(s) by displaced vertices $\Rightarrow$ background
  - measure emitted γ-rays with high resolution $\Rightarrow$ resolution
- antiproton momentum close to threshold (3GeV/c)
  - only few open channel with double strangeness production:

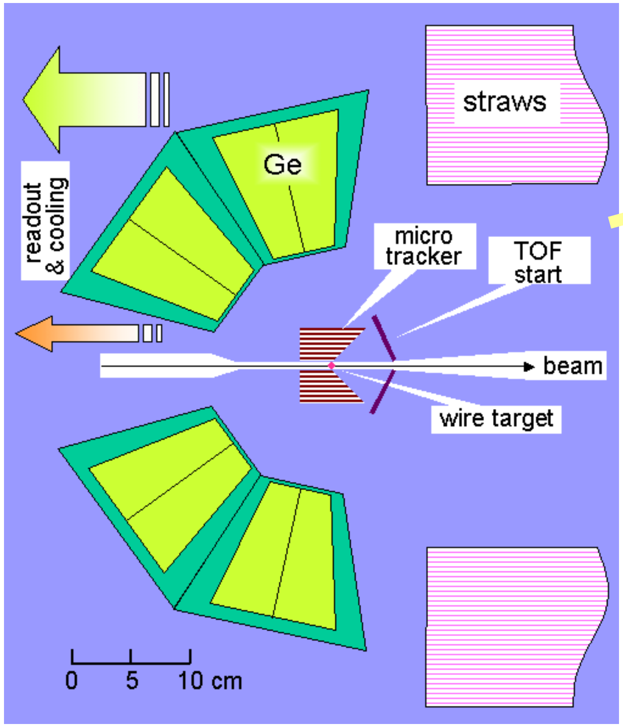
$$\bar{p} + p \rightarrow \begin{cases} \bar{\Xi}^+ + \Xi^- & \text{that's what we want} \\ K^+K^+K^-K^- + \text{pions} & \text{phase space!} \end{cases}$$

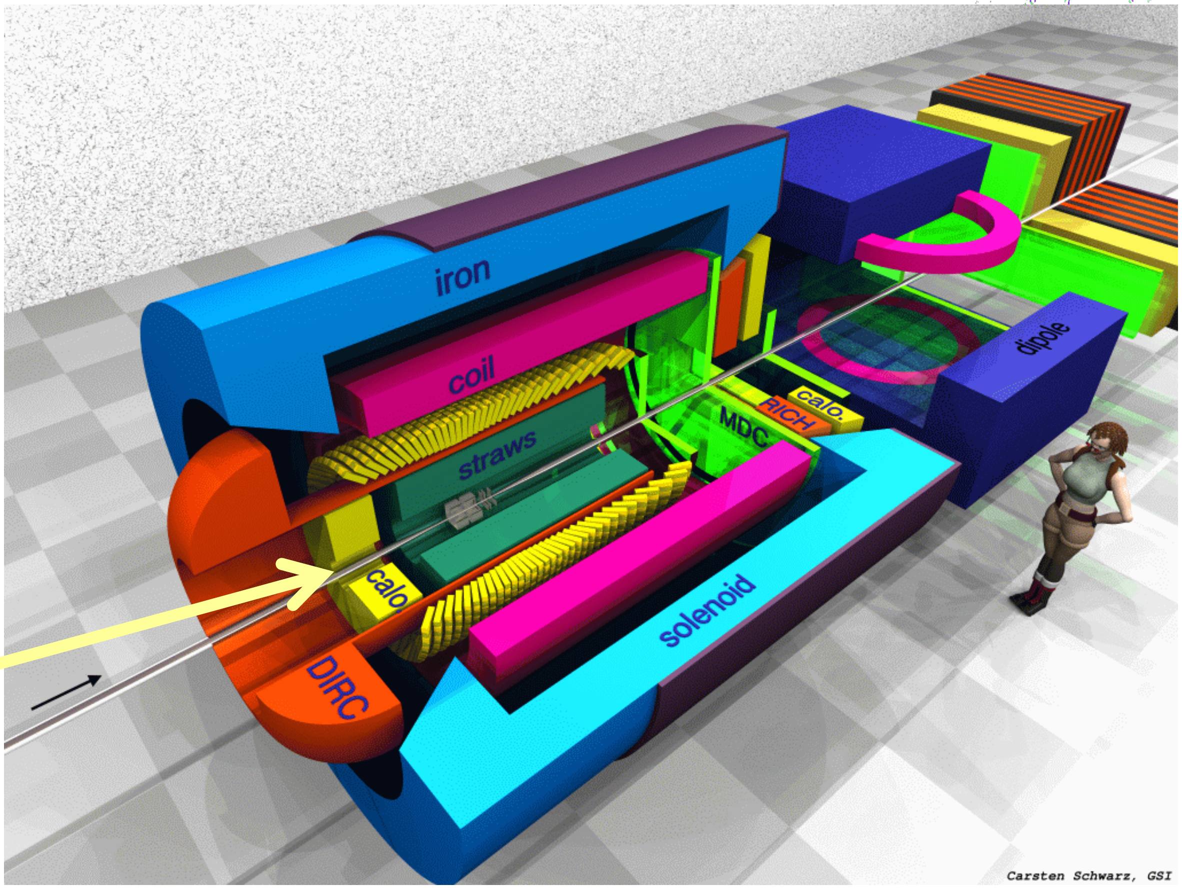


- low secondary masses (Li,Be,B,C) in four separated sections
  - identification can rely on existing information on single hypernuclei
  - low γ-ray absorption
  - no x-ray background

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

Expected Count Rate

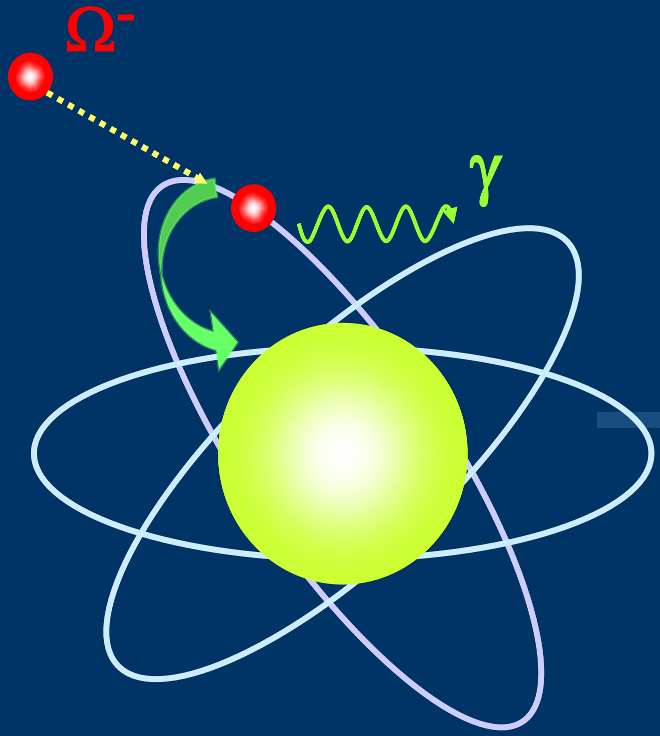
- Ingredients (golden events: Ξ^+ trigger)
  - luminosity $2 \cdot 10^{32}\ cm^{-2}s^{-1}$
  - $\Xi^+\Xi^-$ cross section 2mb for pp Þ 700 Hz
  - p(100-500 MeV/c) $p_{500} \approx 0.0005$
  - Ξ^+ reconstruction probability 0.5
  - stopping and capture probability $p_{CAP} \approx 0.20$
  - total captured Ξ^- Þ 3000 / day

  - Ξ^- to $\Lambda\Lambda$–nucleus conversion probability $p_{\Lambda\Lambda} \approx 0.05$
  - total $\Lambda\Lambda$ hyper nucleus production Þ 4500 / month

  - gamma emission/event, $p_\gamma \approx 0.5$
  - γ-ray peak efficiency $p_{GE} \approx 0.1$

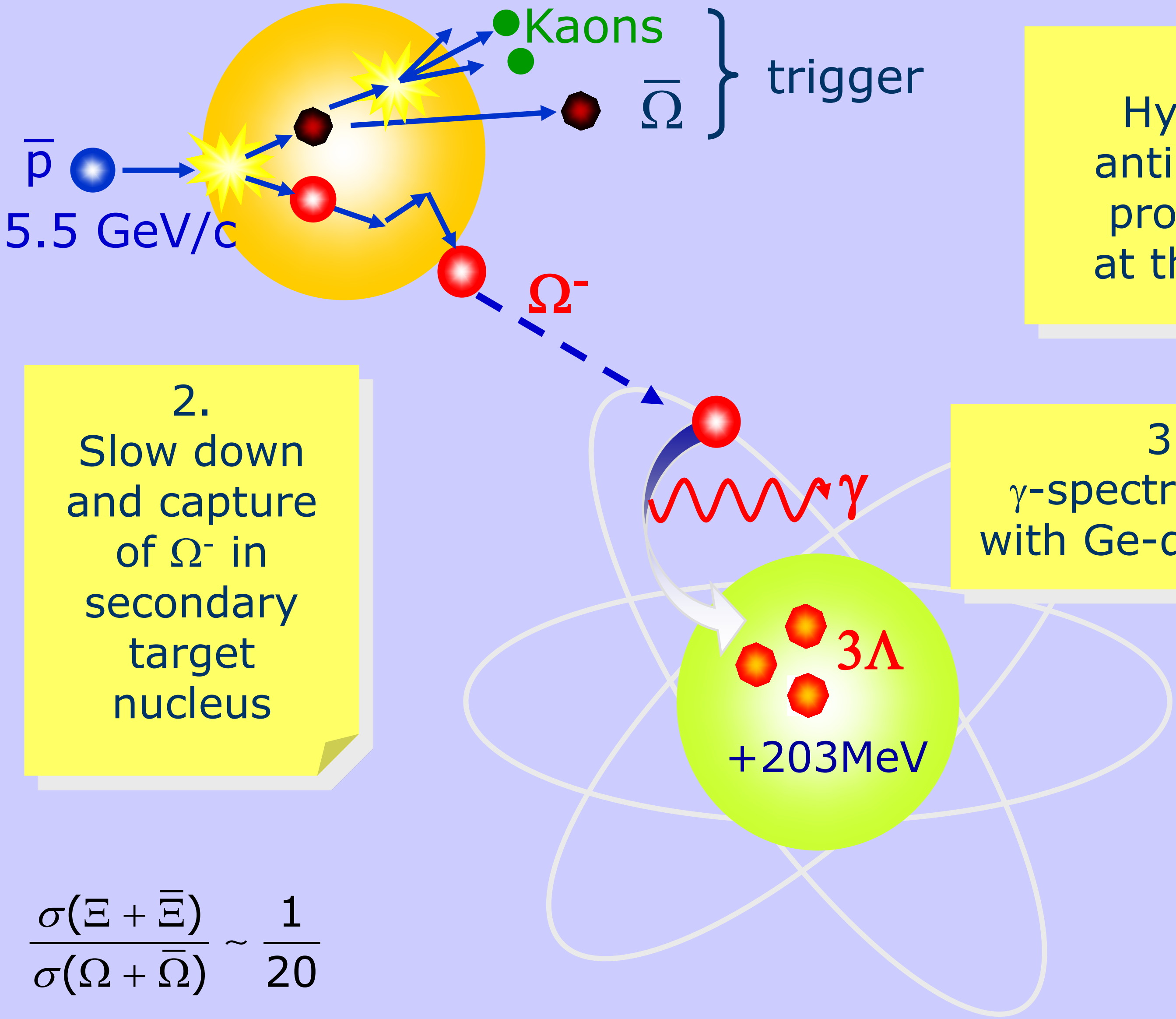
- ~7/day „golden“ γ-ray events
- ~ several 100/day with *KK* trigger

high resolution γ-spectroscopy of double hypernuclei will be feasible



Hyperatoms

Production of Ω-Atoms



1.
Hyperon-antihyperon production at threshold

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

3.
γ-spectroskopy with Ge-detectors

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

Deformation of a Baryon

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

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

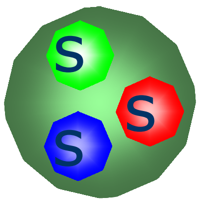
$$Q_s \propto (3J_z^2 - J(J+1)) \xrightarrow[J_z=1/2]{J=1/2} 0$$

- The Ω^- Baryon is the only „elementary" particle whose quadrupole moment can be measured
  - J=3/2
  - long mean lifetime $0.82 \cdot 10^{-10}$ s

- Contributions to *intrinsic* quadrupole moment of baryons
  - General: One-gluon exchange and meson exchange
  - Ω: only one-gluon contributions to quadrupole moment

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

  - e.g. within SU(3) limit $m_u/m_s=1$



$$Q_\Omega = Q_\Delta(gluon)$$

A very strange Atom

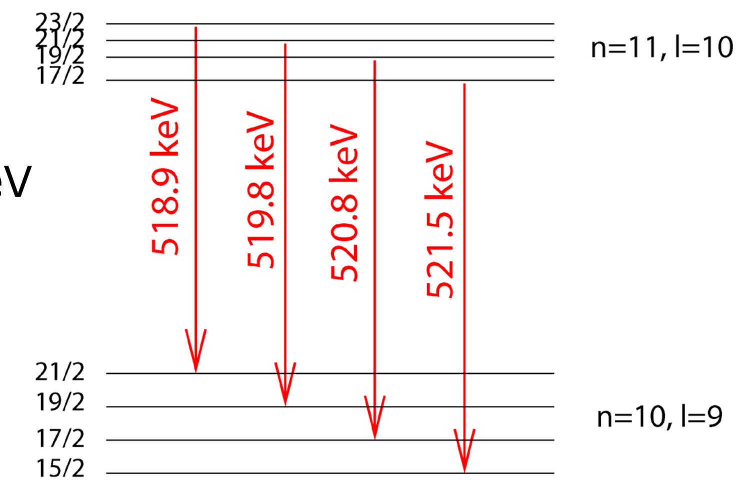
- hyperfine splitting in Ω-atom
  $\Rightarrow$ electric quadrupole moment of Ω

spin-orbit	$\Delta E_{ls} \sim (aZ)^4\, l \cdot m_\Omega$
quadrupole	$\Delta E_\Theta \sim (aZ)^4 Q m^3_\Omega$

R.M. Sternheimer, M. Goldhaber, Phys. Rev. A 8, 2207 (1973)

M.M. Giannini, M.I. Krivoruchenko, Phys. Lett. B 291, 329 (1992)

- prediction $Q_\Omega = (0 - 3.1)\ 10^{-2}\ \mathrm{fm}^2$
  - $E(n=11, l=10 \rightarrow n=10, l=9) \sim 520$ keV
    - calibration with 511keV line!
  - $\Delta E_\Theta \sim$ few tenth of keV for Pb



$Q_\Omega = 0.02\,\mathrm{fm}^2$

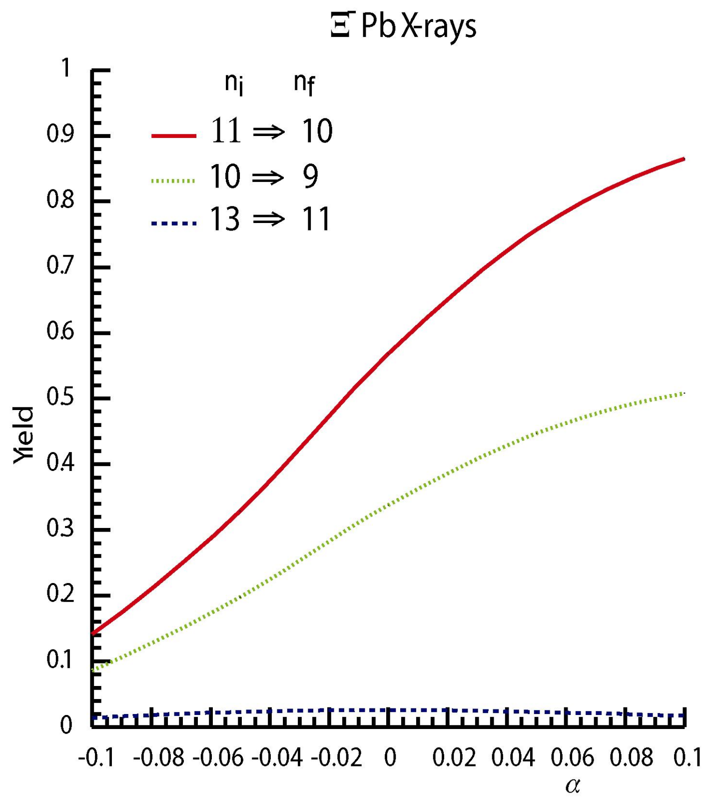
Experimental details

- 4000 stopped Ω per day
- Yield(Σ-Pb)≈Yield(Ξ-Pb)

  C.J.Batty, E. Friedman, A. Gal, PRC 59, 295 (1999)
- capture probability ~10%
- X-ray detection efficiency ~5%

~10 X-rays/day

- antiprotonic atoms at FLAIR
  will be an ideal testground!



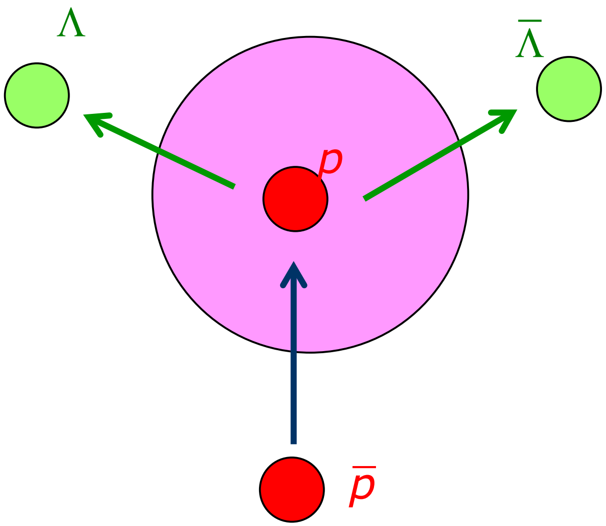
$$p_{initial}(l) = (2l+1)\cdot e^{\alpha l}$$

What else can we do?

Can we measure the potential for an $\bar{\Lambda}$?

- $p + \bar{p} \to \Lambda + \bar{\Lambda}$ close to threshold in complex nuclei
- Question: is the momentum of the Λ and anti-Λ on the average equal?
- possible answer:
  - at the point of creation inside the nucleus one has momentum conservation
  - but: Λ and anti-Λ have different mass (= different potential)
  - as soon as Λ and anti-Λ leave the nucleus they will have different asymptotic momenta
  - the momentum difference is sensitive to the potential difference
- experimental details
  - need to average over Fermi motion
  - use light nucleus to reduce rescattering (Li?)
  - use Λ and anti-Λ polarization to enhance anti-$\Lambda\Lambda$ pairs which did not encounter a rescattering on their way out

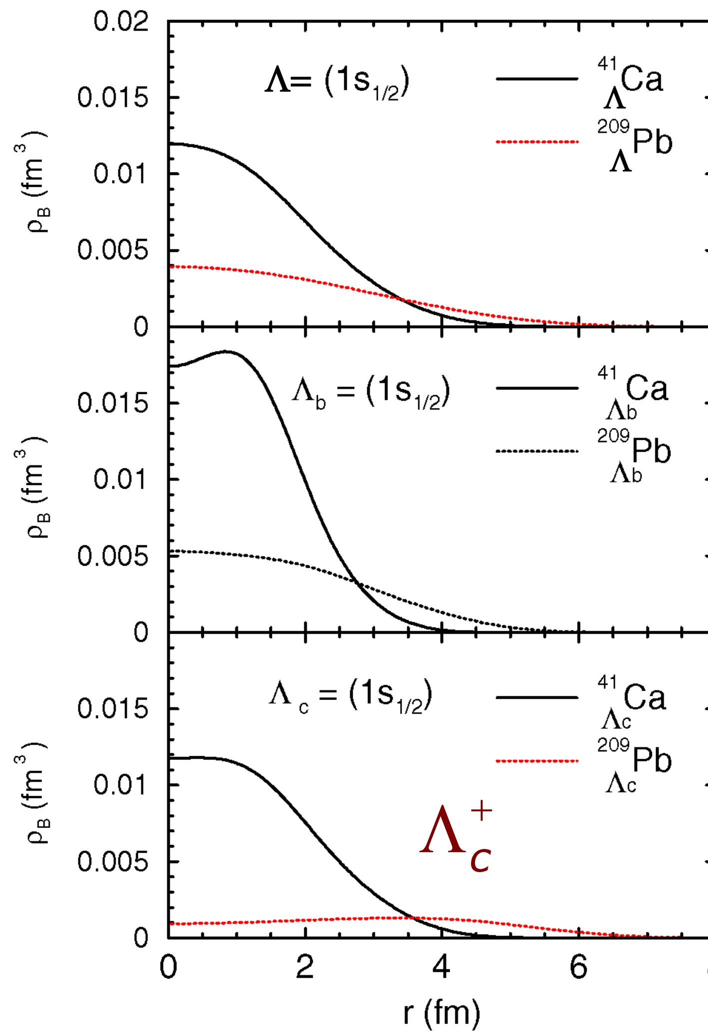
is this correct?



Λ_c Hypernuclei

- already early work predicted bound states of Λ_c
  - A.A. Tyaokin, Sov. J. Nucl. Phys. 22, 89 (1976)
  - C.B. Dover and S.H. Kahana, Phys. Rev. Lett. 39, 1506 (1977)

- Recent theoretical studies by K. Tsushima and F.C. Khanna
    - Phys.Lett. B552 (2003) 138-144
  - nucl-th/0207077
  - nucl-th/0212100



Λ_c Hypernuclei

- bound states of Λ_c hypernuclei are pedicted
  - level spacing smaller than in Λ hypernuclei but larger than in Λ_b hypernuclei $\Rightarrow$ would need dm~1MeV resolution

	${}^{16}_{\Lambda}$O (Exp.)	${}^{17}_{\Lambda}$O	${}^{17}_{\Lambda_c^+}$O	${}^{17}_{\Lambda_b}$O	${}^{40}_{\Lambda}$Ca (Exp.)	${}^{41}_{\Lambda}$Ca	${}^{41}_{\Lambda_c^+}$Ca	${}^{41}_{\Lambda_b}$Ca	${}^{49}_{\Lambda}$Ca	${}^{49}_{\Lambda_c^+}$Ca	${}^{49}_{\Lambda_b}$Ca
$1s_{1/2}$	-12.5	-14.1	-12.8	-19.6	-20.0	-19.5	-12.8	-23.0	-21.0	-14.3	-24.4
$1p_{3/2}$	-2.5	-5.1	-7.3	-16.5	-12.0	-12.3	-9.2	-20.9	-13.9	-10.6	-22.2
$1p_{1/2}$	$(1p_{3/2})$	-5.0	-7.3	-16.5	$(1p_{3/2})$	-12.3	-9.1	-20.9	-13.8	-10.6	-22.2
$1d_{5/2}$						-4.7	-4.8	-18.4	-6.5	-6.5	-19.5
$2s_{1/2}$						-3.5	-3.4	-17.4	-5.4	-5.3	-18.8
$1d_{3/2}$						-4.6	-4.8	-18.4	-6.4	-6.4	-19.5
$1f_{7/2}$									—	-2.0	-16.8

	${}^{89}_{\Lambda}$Yb (Exp.)	${}^{91}_{\Lambda}$Zr	${}^{91}_{\Lambda_c^+}$Zr	${}^{91}_{\Lambda_b}$Zr	${}^{208}_{\Lambda}$Pb (Exp.)	${}^{209}_{\Lambda}$Pb	${}^{209}_{\Lambda_c^+}$Pb	${}^{209}_{\Lambda_b}$Pb
$1s_{1/2}$	-22.5	-23.9	-10.8	-25.7	-27.0	-27.0	-5.2	-27.4
$1p_{3/2}$	-16.0	-18.4	-8.7	-24.2	-22.0	-23.4	-4.1	-26.6
$1p_{1/2}$	$(1p_{3/2})$	-18.4	-8.7	-24.2	$(1p_{3/2})$	-23.4	-4.0	-26.6
$1d_{5/2}$	-9.0	-12.3	-5.8	-22.4	-17.0	-19.1	-2.4	-25.4
$2s_{1/2}$	—	-10.8	-3.9	-21.6	—	-17.6	—	-24.7
$1d_{3/2}$	$(1d_{5/2})$	-12.3	-5.8	-22.4	$(1d_{5/2})$	-19.1	-2.4	-25.4
$1f_{7/2}$	-2.0	-5.9	-2.4	-20.4	-12.0	-14.4	—	-24.1
$2p_{3/2}$	—	-4.2	—	-19.5	—	-12.4	—	-23.2
$1f_{5/2}$	$(1f_{7/2})$	-5.8	-2.4	-20.4	$(1f_{7/2})$	-14.3	—	-24.1
$2p_{1/2}$		-4.1	—	-19.5	—	-12.4	—	-23.2
$1g_{9/2}$		—	—	-18.1	-7.0	-9.3	—	-22.6
$1g_{7/2}$					$(1g_{9/2})$	-9.2	—	-22.6

Production of Λ_c Hypernuclei

- production via primary and secondary target not possible because of short lifetime of $\tau_{\Lambda c}$ =0.2ps
- direkt production via p̄p $\rightarrow \bar{\Lambda}_c \Lambda_c$ or $\pi^- p \rightarrow \Lambda_c D^-$ difficult because of high momenta involved (low sticking probability)
- does a two-step process *within one nucleus* work?

$$\bar{p} + p \rightarrow D^+ + D^-$$

$$D^+ + p \rightarrow \Lambda_c^+ + \pi^+$$

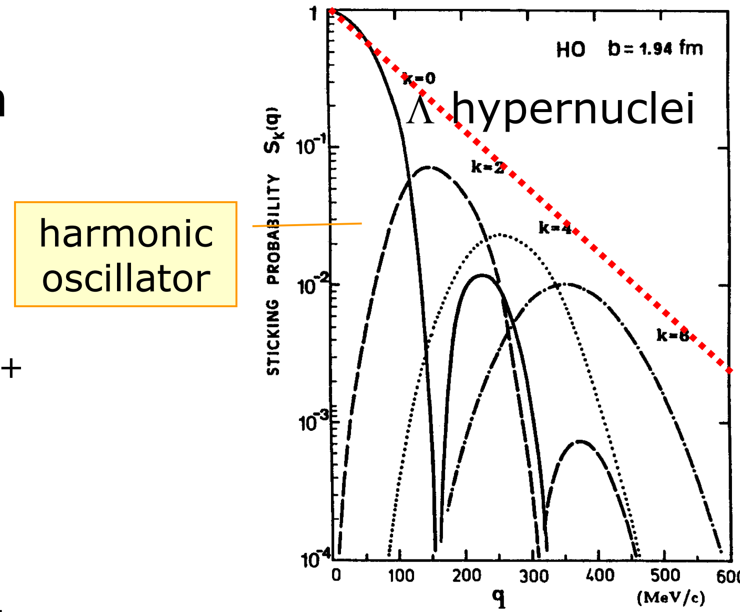
detected

captured in the nucleus A-2

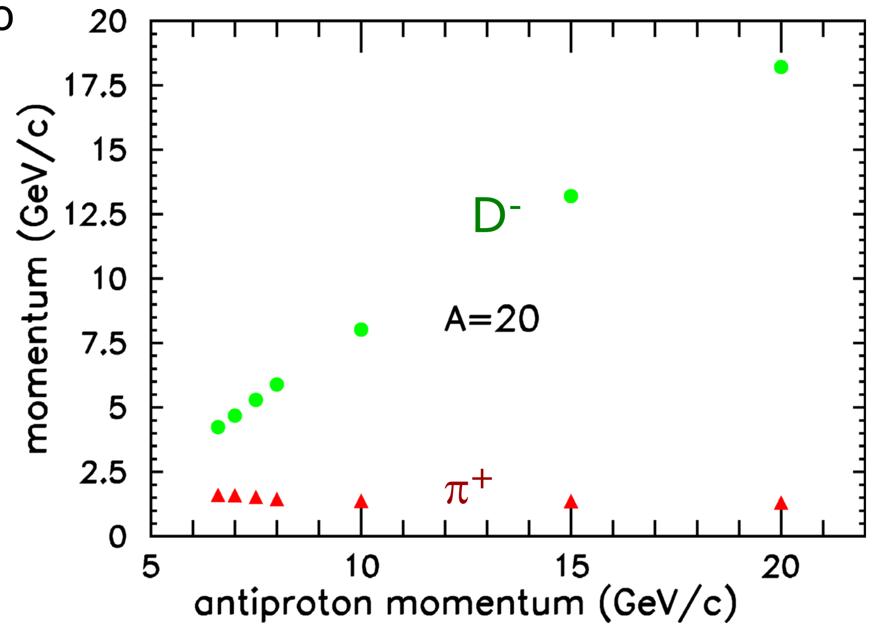
- determination of the Λ_c hypernucleus mass via missing mass
  - needs good knowledge of beam momentum (10^{-4})
  - excellent momentum resolution for π^+ and D^- (resp. decay products)

Kinematics

- sticking of Λ_c requires low momentum ~ Fermi momentum



- low momentum of Λ_c if D^- and π^+ emitted forward
- example: consider events with $m_{hyp}-m_\pi-m_{\Lambda c}<100$ MeV
  - D^-momentum rises proporional to antiproton momentum
  - mass resolution of ~1MeV would require momentum resolution of better then 10^{-4} for $p(\bar{p})$ >10GeV/c
  - rather narrow distribution: typical width ~0.6GeV/c



Rate estimate

- probability that a Λ_c is captured and that D^- and π^+ are emitted without further interaction (i.e. no rescattering; see later)
- Ingredients
  - luminosity: $2 \cdot 10^{32}$, max. 10^7 antiprotons/s
  - $\sigma(D^+D^-)$: empirical fit to Sibirtsev *et al.*, Eur. phys. J. A6, 351 (1999)
    - interpolated between A=12 and A=197 with $A^{2/3}$
  - probability for *no* scattering of D^-: $\sigma(D^-N \to D^-N)=20$mb
  - charme exchange cross section (Sibirtsev *et al.*)

$$\sigma_{D^+N\to\Lambda_c\pi}(s) = \frac{const.}{16\pi s}\sqrt{\frac{(s-m_{\Lambda_c}^2-m_\pi^2)^2-4m_{\Lambda_c}^2 m_\pi^2}{(s-m_D^2-m_N^2)^2-4m_N^2 m_D^2}}$$

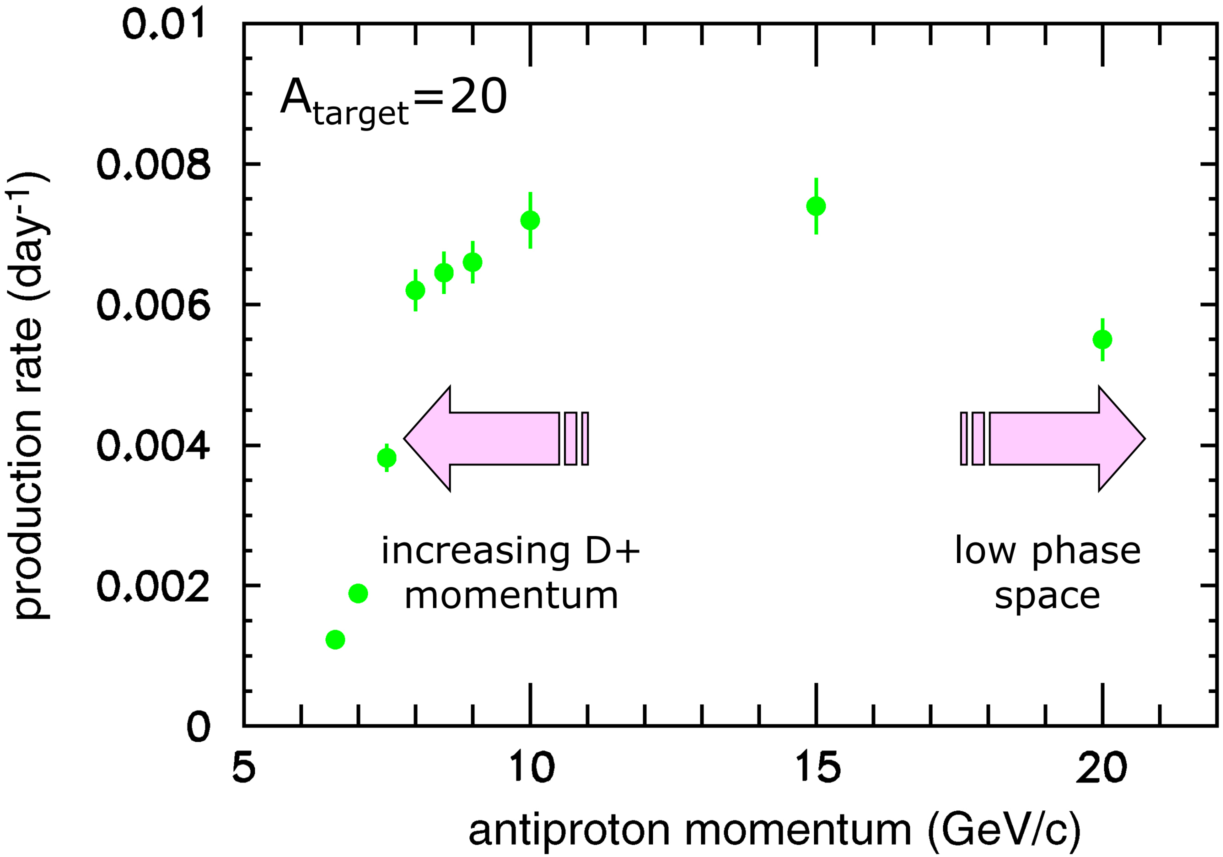
  - total π^+N cross section ~25 mb (neglected momentum dependence)
  - branching ratio $\Gamma(D^- \to K^+\pi^-\pi^-)/\Gamma_{tot}=9\%$
  - reconstruction and detection probability of D^- and π^+: 50%
  - Fermi momentum of nucleons
  - Sticking probability

$$p_{capture} = e^{-q_\Lambda/(0.1GeV/c)}$$

dominant factor!

Rate n

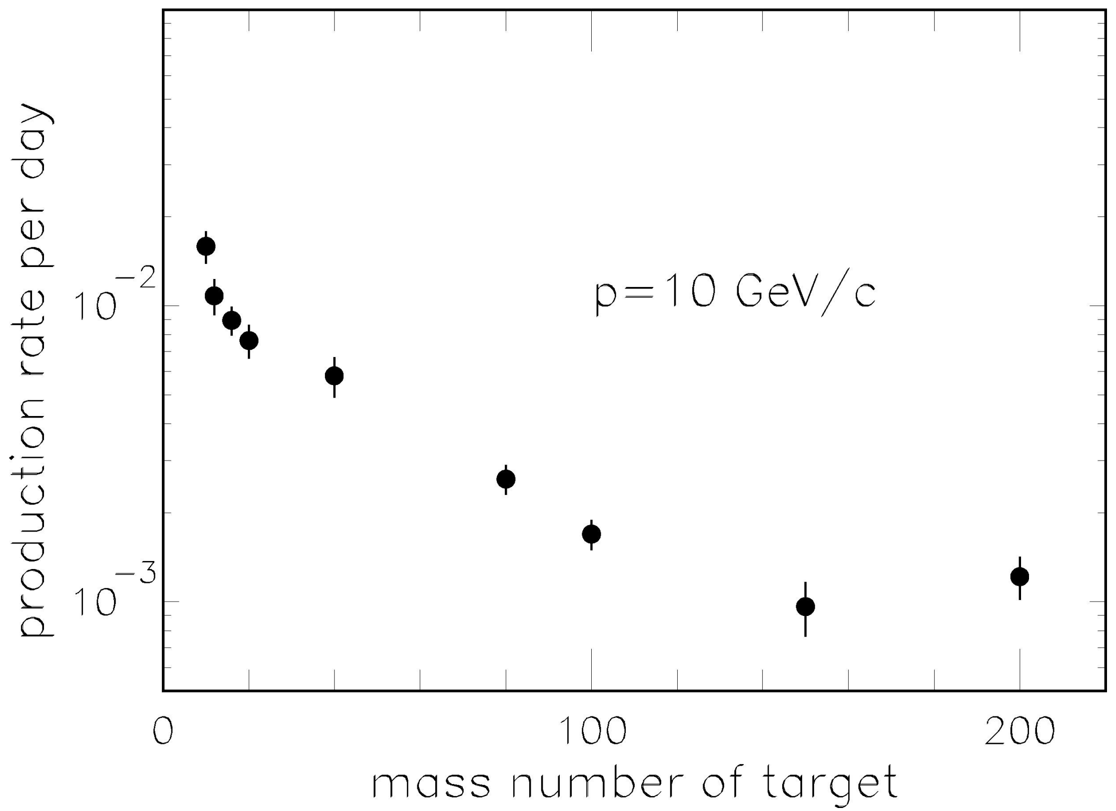
- with increasing antiproton momentum decreasing *minimum* D^+ momentum
- smaller phase space at larger antiproton momenta



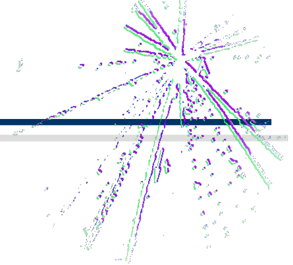
- production rate ~0.01 day^{-1}....*hopeless!?*

Target dependence

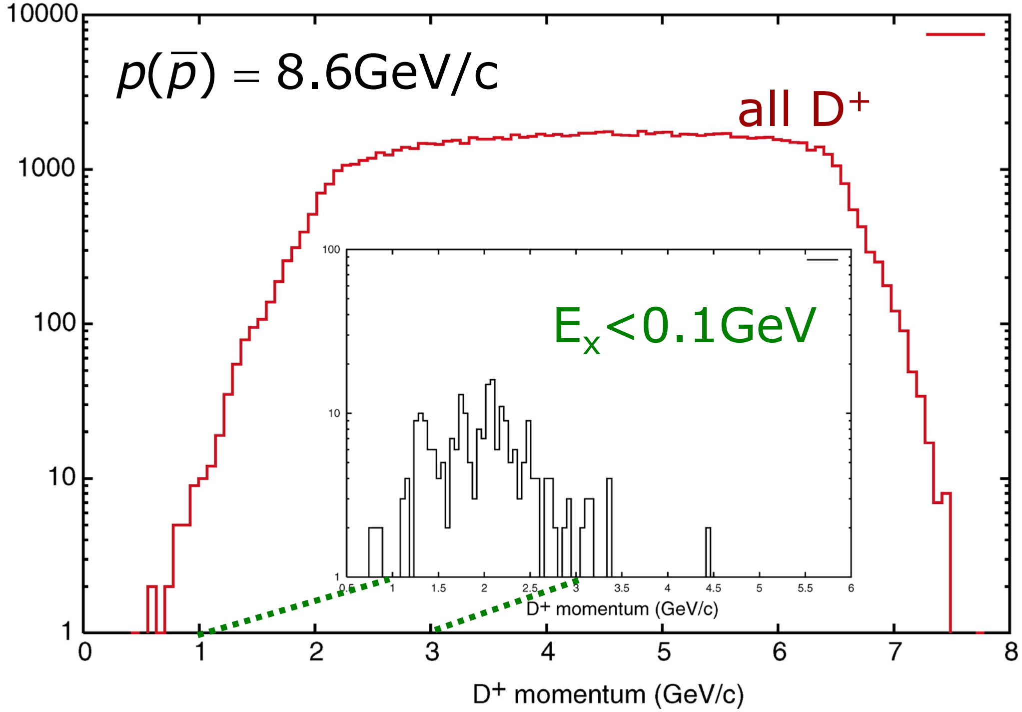
- limited by production rate
- absorption larger for larger nuclei



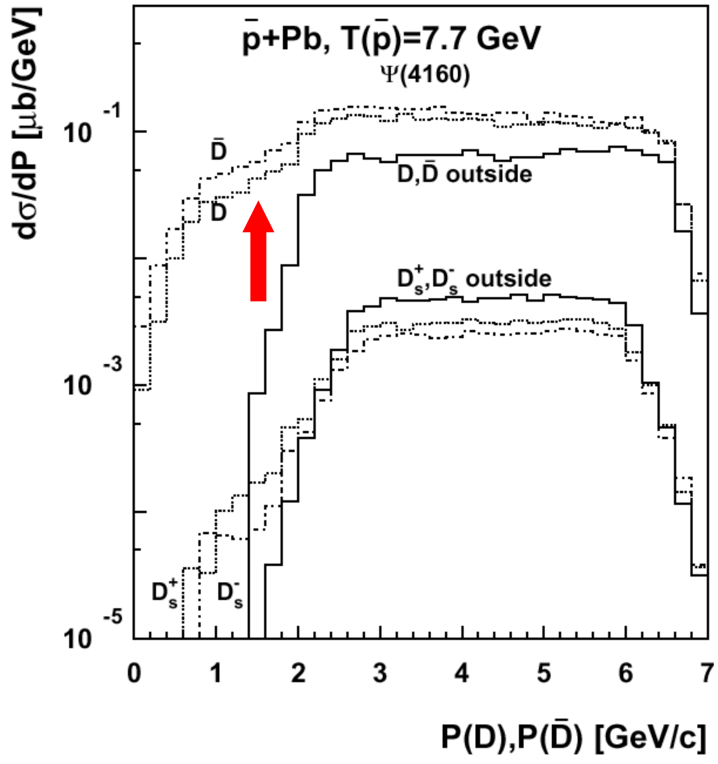
Is there still a happy end possible?



- relevant for Λ_c production are D^+ momenta < 1-2 GeV/c



- significant broadening by rescattering
  - Ye.S. Golubeva *et al.*, Eur. Phys. J. A14, 255 (2002)
  - increase of yield by order(s) of magnitude may be possible



Conclusion

- the measurement of Λ_c hypernuclei requires excellent momentum resolution ($dp/p < 10^{-3}$) in forward direction
- optimal antiproton momentum around 8-10 GeV/c
- without rescattering production rate rather low (<0.01/day)
- need to consider in more detail
  - rescattering in more detailed calculations
  - sticking probability