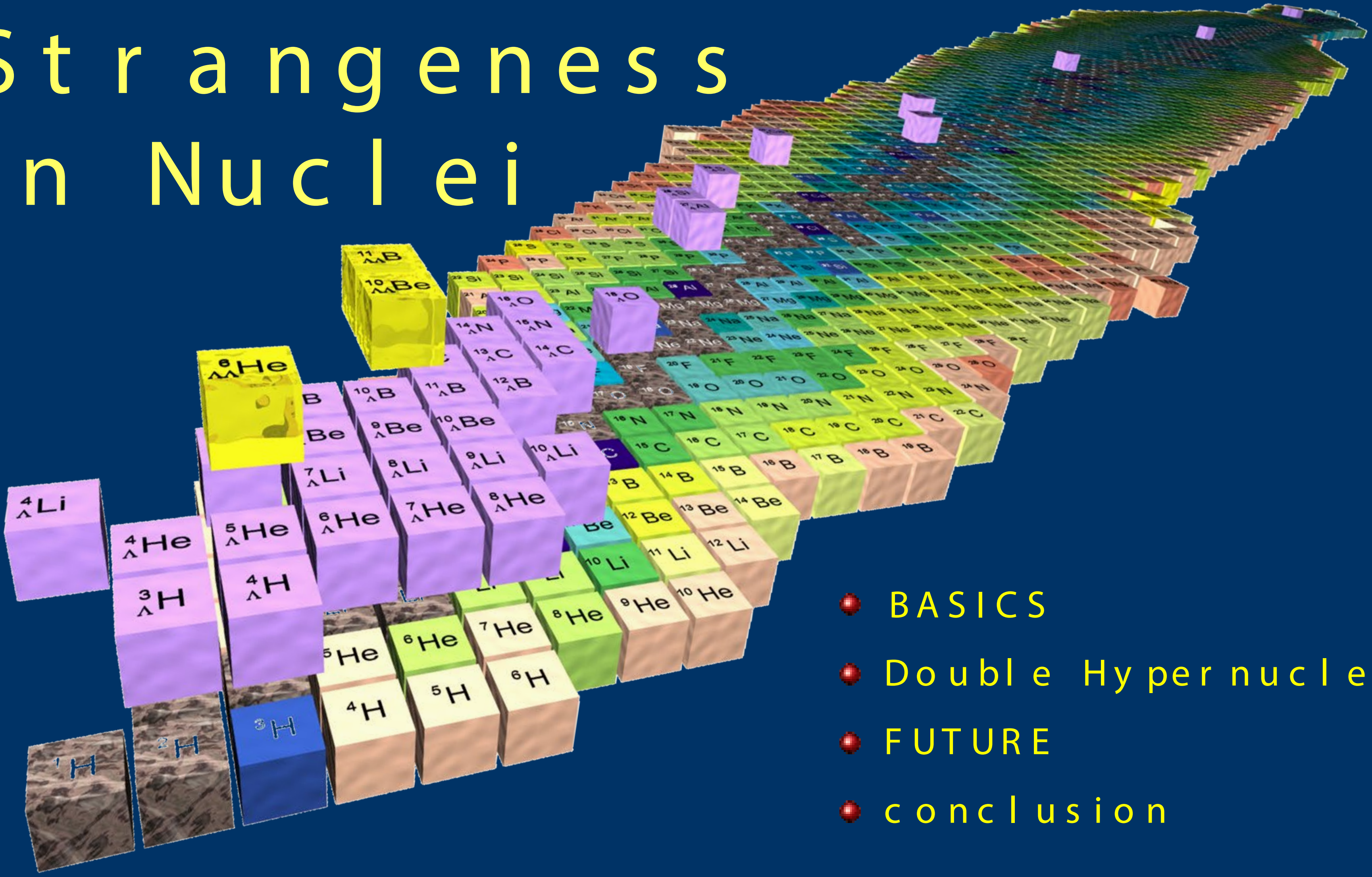
TWo and more units of Strangeness in Nuclei



- BASICS
- Double Hypernuclei
- FUTURE
- conclusion

BASICS

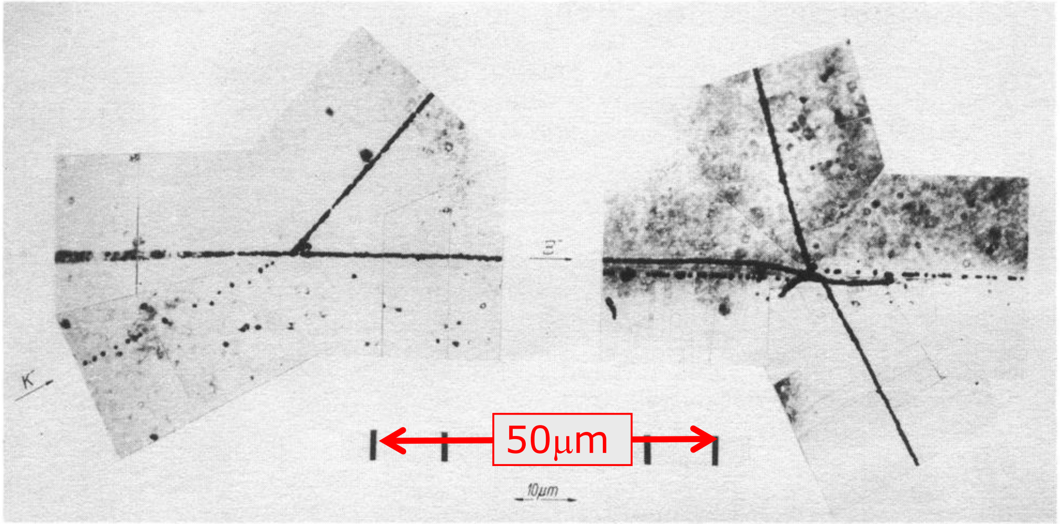
The first event

- 1.3-1.5 GeV/c K⁻+Emulsion; 31000 K⁻
- carefully reanalyzed
  - ≈1963 by P.H. Fowler, V.M. Mayes and E.R.Fletcher
  - Dalitz *et al.*, Proc. R. Soc. Lond. A426, 1 (1989)

VOLUME 11, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1963

OBSERVATION OF A DOUBLE HYPERFRAGMENT

M. Danysz, K. Garbowska, J. Pniewski, T. Pniewski, and J. Zakrzewski
Institute of Experimental Physics, University of Warsaw, Warsaw, Poland
and Institute for Nuclear Research, Warsaw, Poland
and



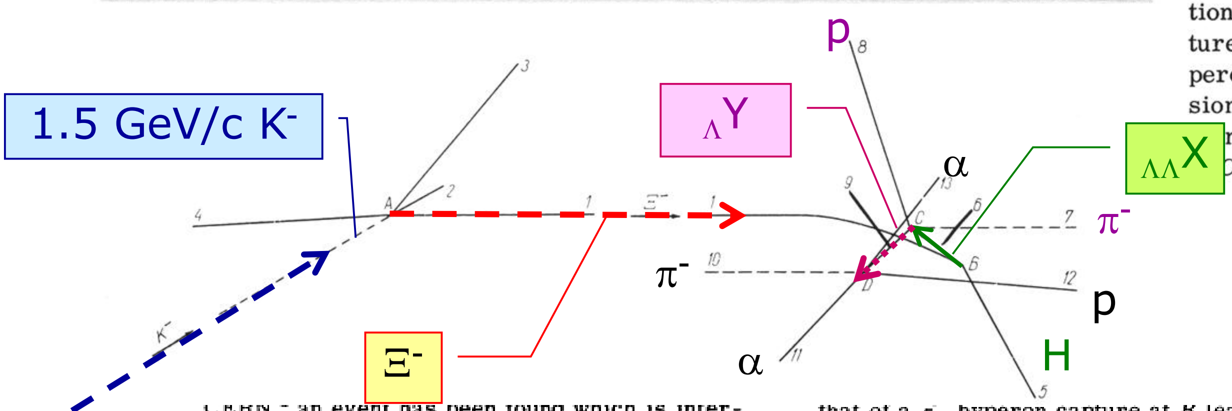


FIG. 1. A photomicrograph and a schematic drawing of the production of a Ξ⁻ hyperon in a 1.5-GeV/c K⁻-meson interaction at A followed by capture at rest of the Ξ⁻ hyperon at B with the emission of a double hyperfrag- nt decaying in cascade C and D.

CERN,¹ an event has been found which is inter- preted as the production and subsequent mesonic

that of a Ξ⁻ hyperon capture at B leading to the emission of a double hyperfragment, have been

Analysis of the Danysz-Event

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

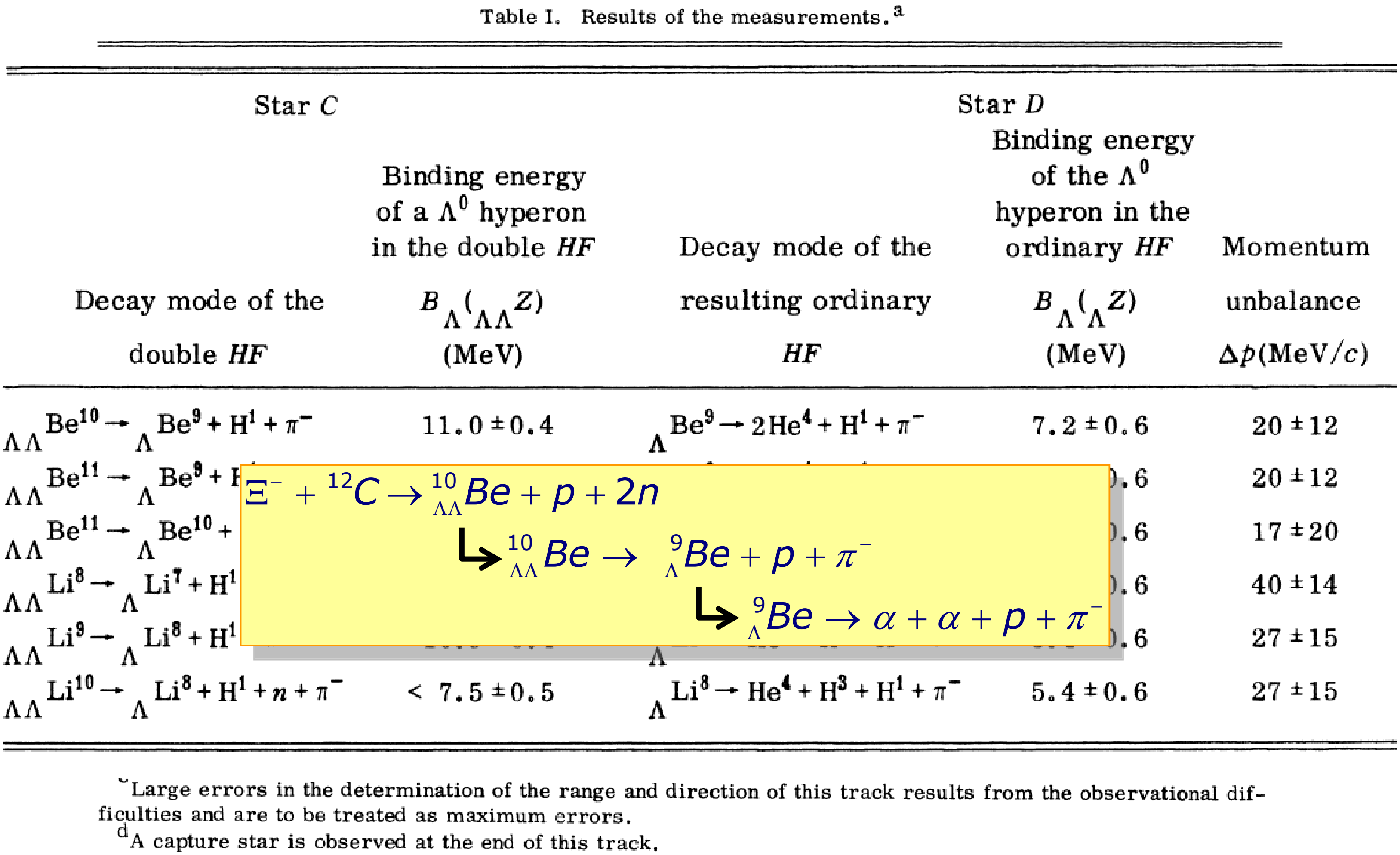


Table I. Results of the measurements.[a]

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

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

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

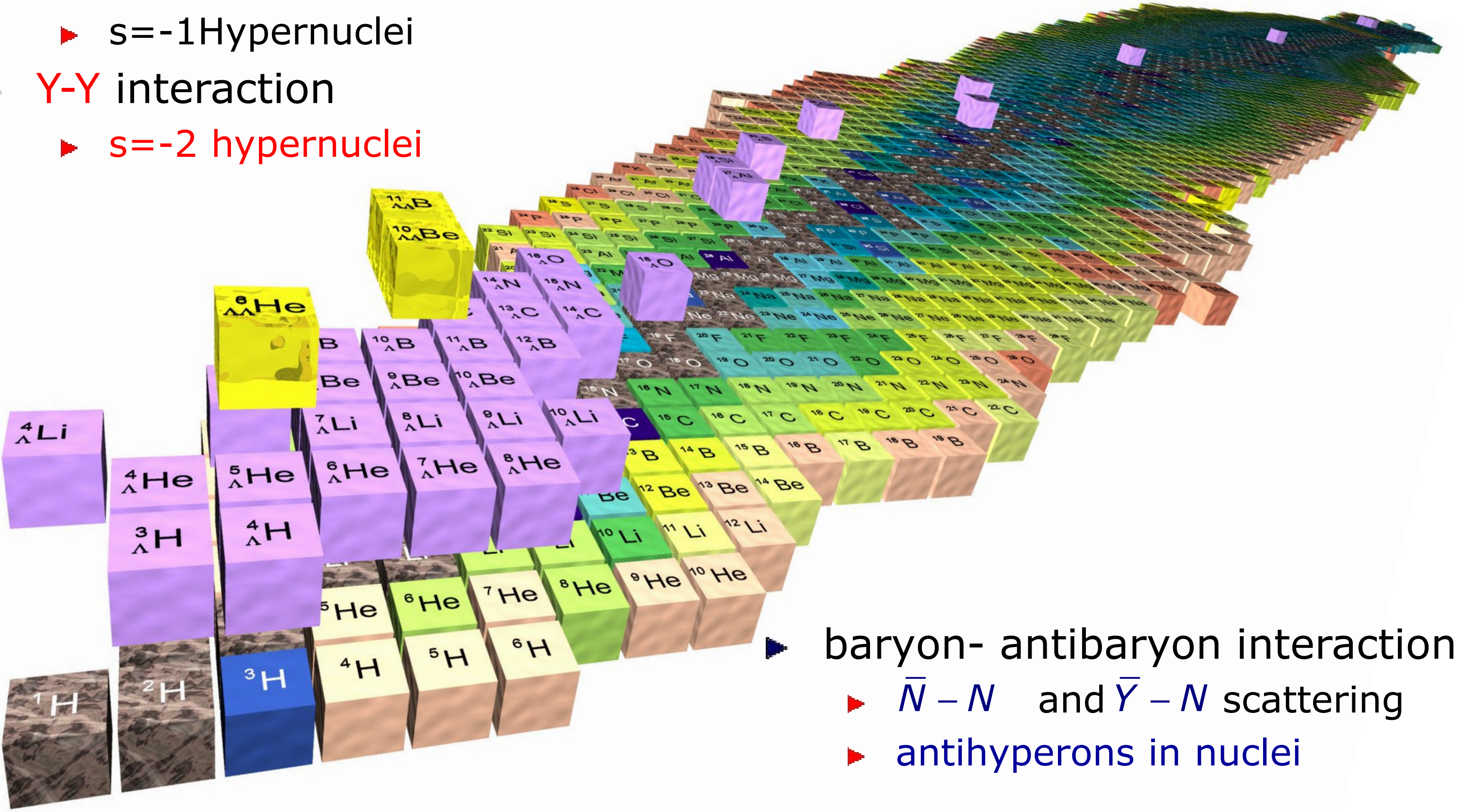
$$\hookrightarrow {}^{9}_{\Lambda}Be \to \alpha + \alpha + p + \pi^{-}$$

ˇLarge 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.

Baryon-baryon interaction

- N-N interaction
  - N-N scattering
  - ordinary nuclei
- Y-N interaction
  - low momentum hyperon-proton scattering
  - s=-1Hypernuclei
- Y-Y interaction
  - s=-2 hypernuclei

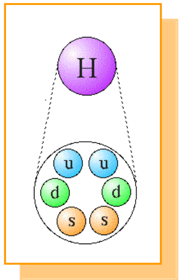


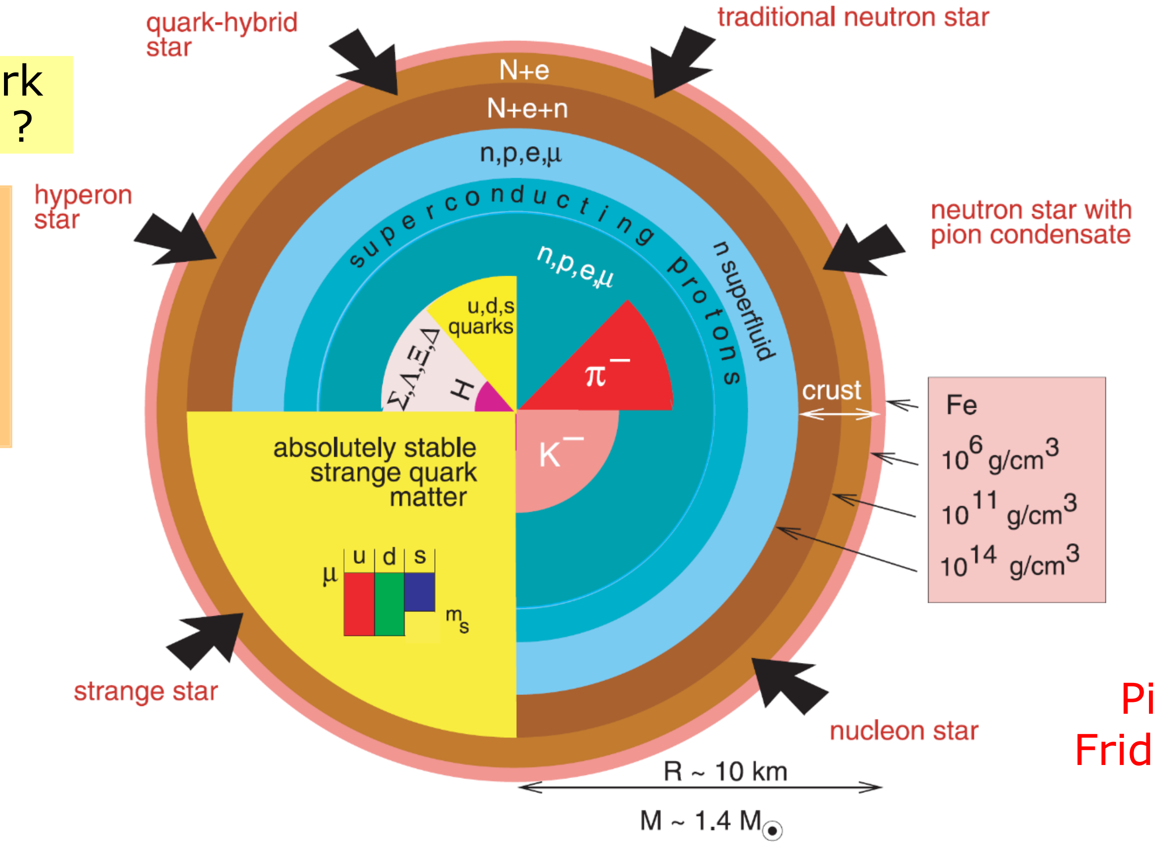
- baryon- antibaryon interaction
  - $\bar{N}-N$ and $\bar{Y}-N$ scattering
  - antihyperons in nuclei

Exotic Hypernuclei

- „Neutronstars“:
  - at about $2\rho_0$ hyperons may play a role in neutron stars
  - consequence: softer EOS $\Rightarrow$ lower mass and smaller radii

exotic quark structures ?



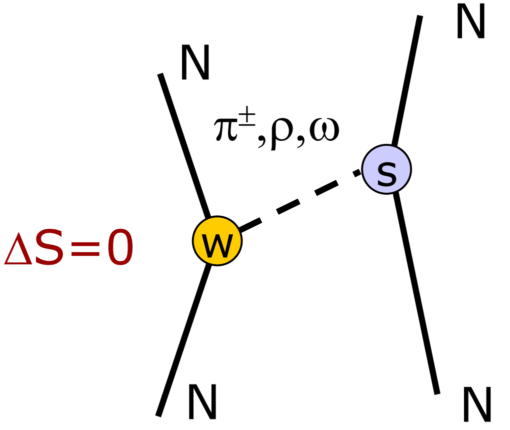


Picture from Fridolin Weber

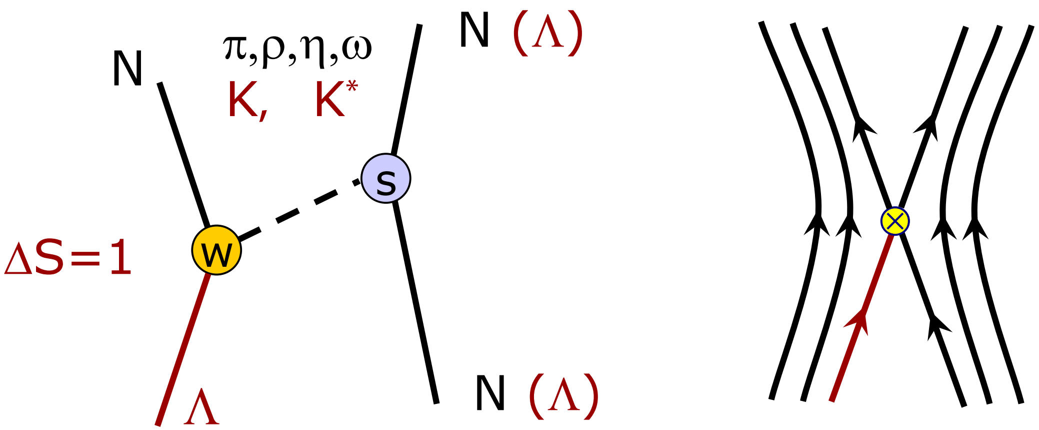
- Isospin dependence of Y-N and Y-Y interaction?
- $\Rightarrow$ Information on hyperons in neutron rich matter/nuclei needed

Weak decay in double Hypernuclei

N-N scattering



$\Lambda N \to N N$ and $\Lambda\Lambda \to Y N$



- 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

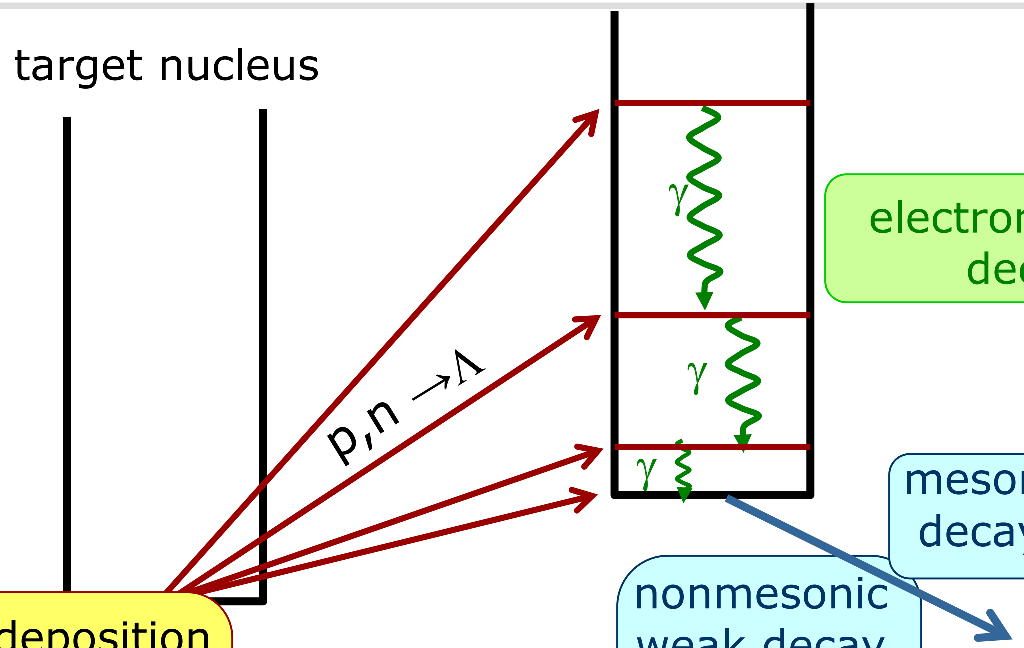
- Interesting theoretical developments:
  - Effective Field Theories in S=-1 sector

    A. Parreno, C. Bennhold and B.R. Holstein, nucl-th/0308074 & 0308056
  - [illegible]

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

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

Birth, life and death of a hypernucleus



electromagnetic decays

mesonic decays $\Lambda \to p\pi^-$ $\Lambda \to n\pi^0$

nonmesonic weak decay
$\Lambda p \to np$
$\Lambda n \to nn$
$\Lambda\Lambda \to YN$

hadronic decay in emulsion

strangeness deposition
$e^+ + e^- \to \Phi \to K^+ + K^-$
$K^-_{stopped} + {}^A Z \to {}^A_\Lambda Z + \pi^-$
FINUDA

strangeness production
(π^+, K^+), (π^-, K^0)
BNL,KEK,(GSI)

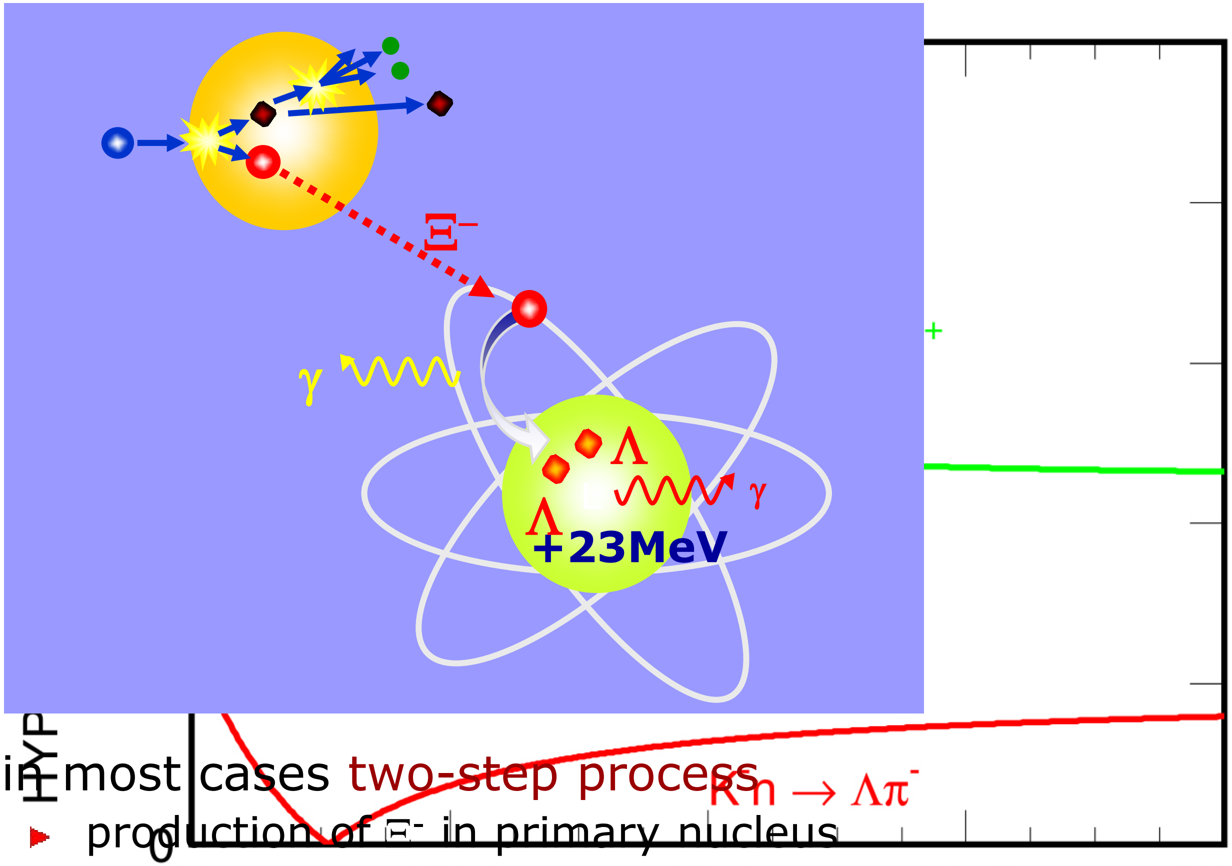
strangeness exchange
(K^-, π^-) , (K^-, π^0)
BNL,KEK,JPARC

electroproduction
$(e,e'K^+)$, (γ,K^+)
Jlab, MAMI-C

$\Sigma^- p \to \Lambda n$	$\Sigma^+ n \to \Lambda p$	$(Q \simeq 78MeV)$
$\Xi^- p \to \Lambda\Lambda$	$\Xi^0 n \to \Lambda\Lambda$	$(Q \simeq 26MeV)$
$\Omega^- p \to \Lambda\Xi^0$	$\Omega^- n \to \Lambda\Xi^-$	$(Q \simeq 178MeV)$

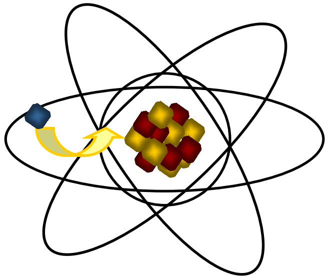
Production of ΛΛ–Hypernuclei

- simultaneous implantation of two Λ is not feasible (→ RHIC?)
- 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



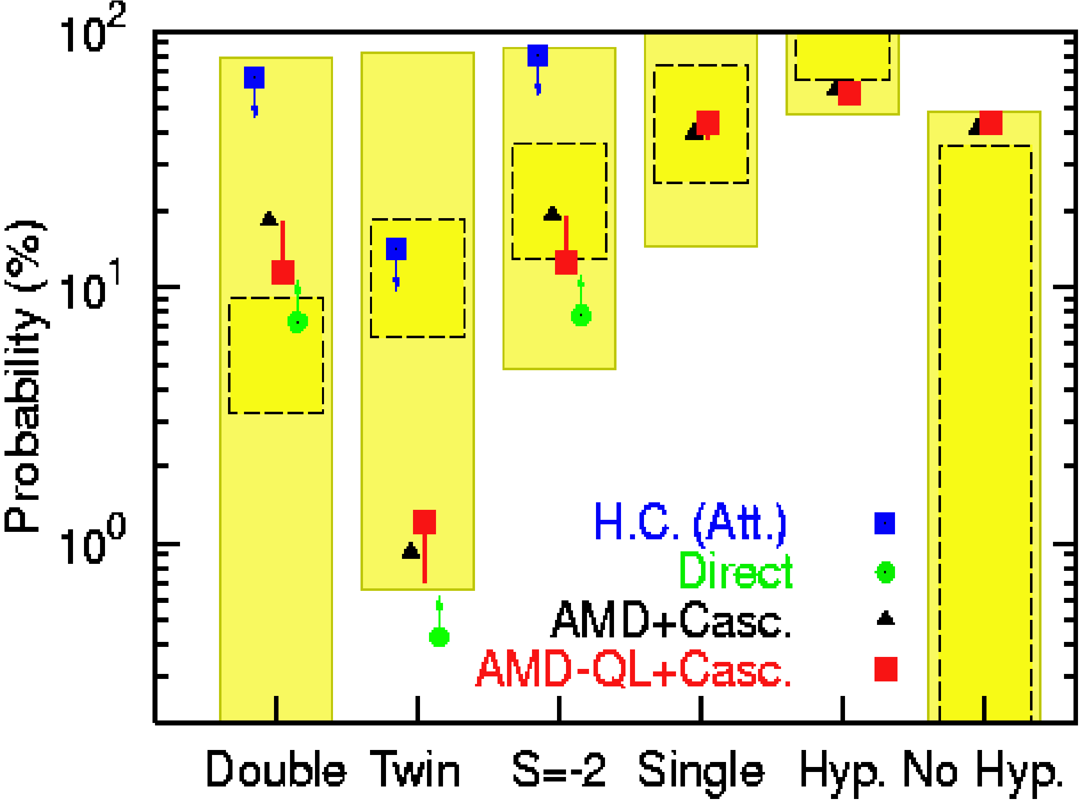
- in most cases two-step process
  - production of Ξ^- in primary nucleus
  - slowing down and capture in a secondary target nucleus
- spectroscopic studies only possible via the decay products

Ξ^- capture



- Ξ^- -atoms: x-rays
- conversion
  - Ξ^-**(dss)** p**(uud)** → Λ**(uds)** Λ**(uds)** ΔQ = 28 MeV
- Conversion probability approximatly ~10-20%
- individual nuclei may be populated with a probability of a few %

Y. Hirata, J. Randrup *et al.*



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

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

  but: usually we can only detect charged decay products

  ⇒ only light nuclei which decay exclusively in charged particles

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

  ⇒ need sub-μm resolution

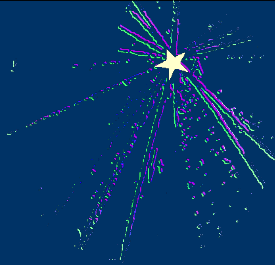
  ⇒ emulsion
- interesting: $\Lambda\Lambda$-interaction in nuclear medium ⇒ heavy nuclei
  - $\Lambda\Lambda$-hypernuclei and intermediate Λ-nuclei are produced in excited states
    - ▹ Q-value difficult to determine
    - ▹ nuclear fragments difficult to identify (neutrons!) with emulsion technique
  - non-mesonic weak decay dominates
    - ▹ non-mesonic: mesonic $\approx$ 5

$$\begin{aligned} \Lambda + n &\rightarrow n + n + 176\,\mathrm{MeV} \\ \Lambda + p &\rightarrow n + p + 176\,\mathrm{MeV} \end{aligned}$$

- new approach
  - high resolution spectroscopy of γ-rays from particle stable, excited states

    ⇒ need of high statistics

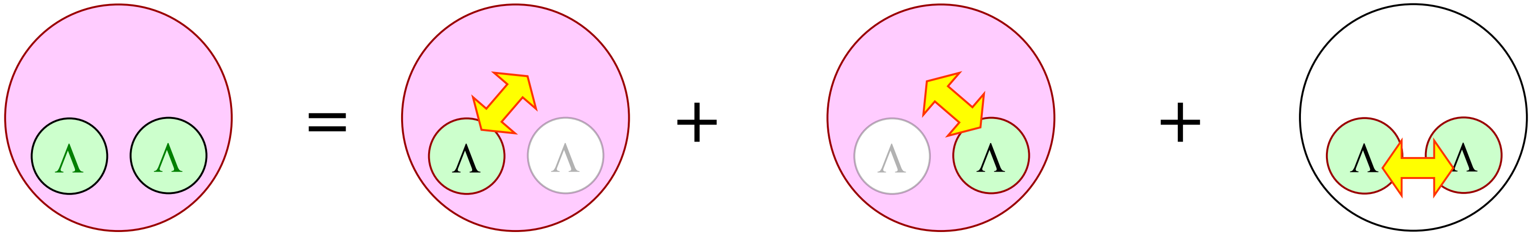
    ⇒ fully electronic detectors



DOUBLE Hypernuclei

First approach to the ΛΛ interaction

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



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

- in the case of the Danysz-event one obtains

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

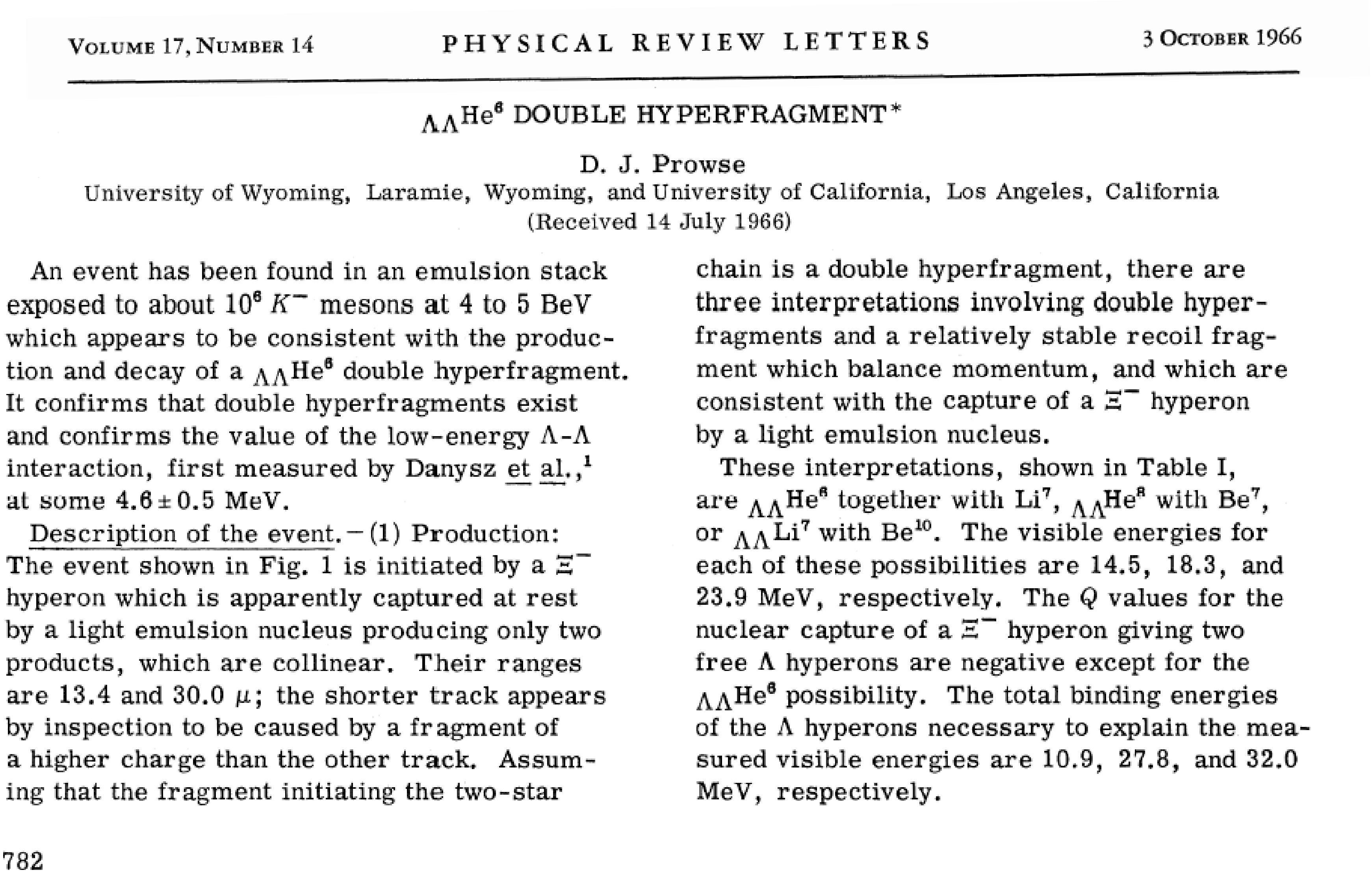
$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (4.3 \pm 0.4)\,\mathrm{MeV}$$

- positive ⇒ attractive interaction
- this is the net ΛΛ 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*

D. J. Prowse
University of Wyoming, Laramie, Wyoming, and University of California, Los Angeles, California

(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

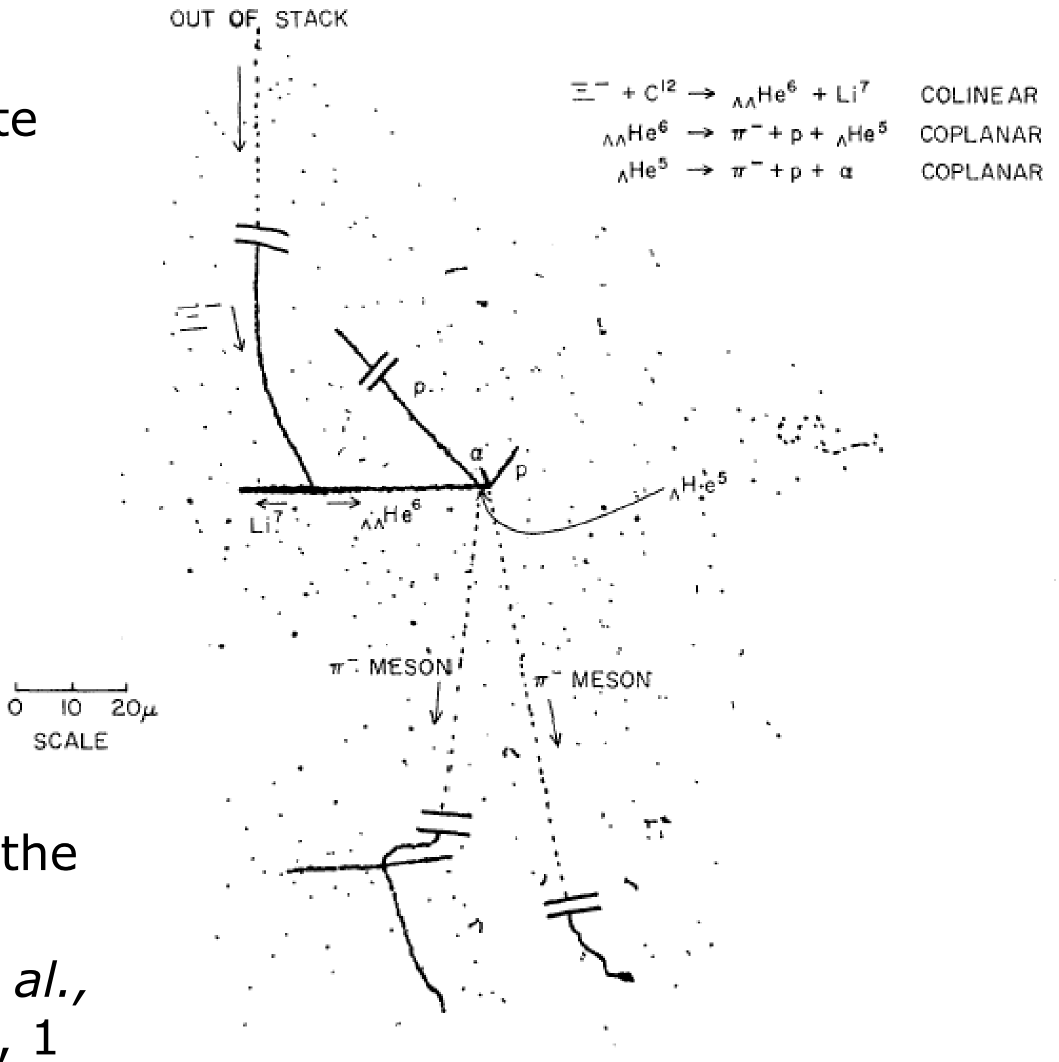


FIG. 1. Drawing of the event.

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*.

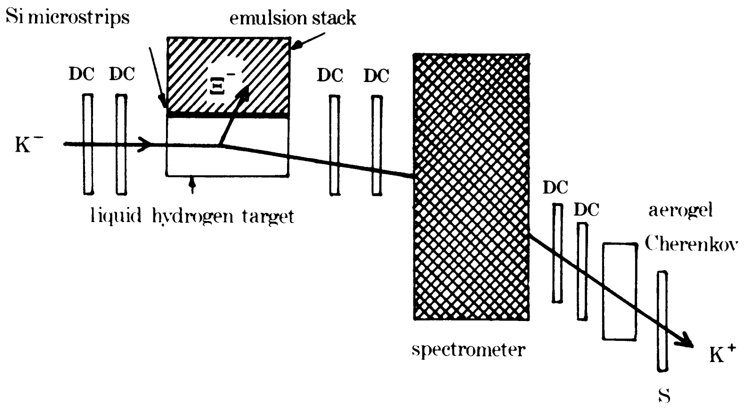


FIGURE 3. Schematic diagram of proposed hybrid emulsion experiment to study double hypernuclei. (DC is drift chamber and S is scintillator.)

- applied by KEK-E176 and KEK-E373 collaboration

The Aoki-Event (KEK-E176)

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

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

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

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

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

- repulsive $\Lambda\Lambda$ interaction!?

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

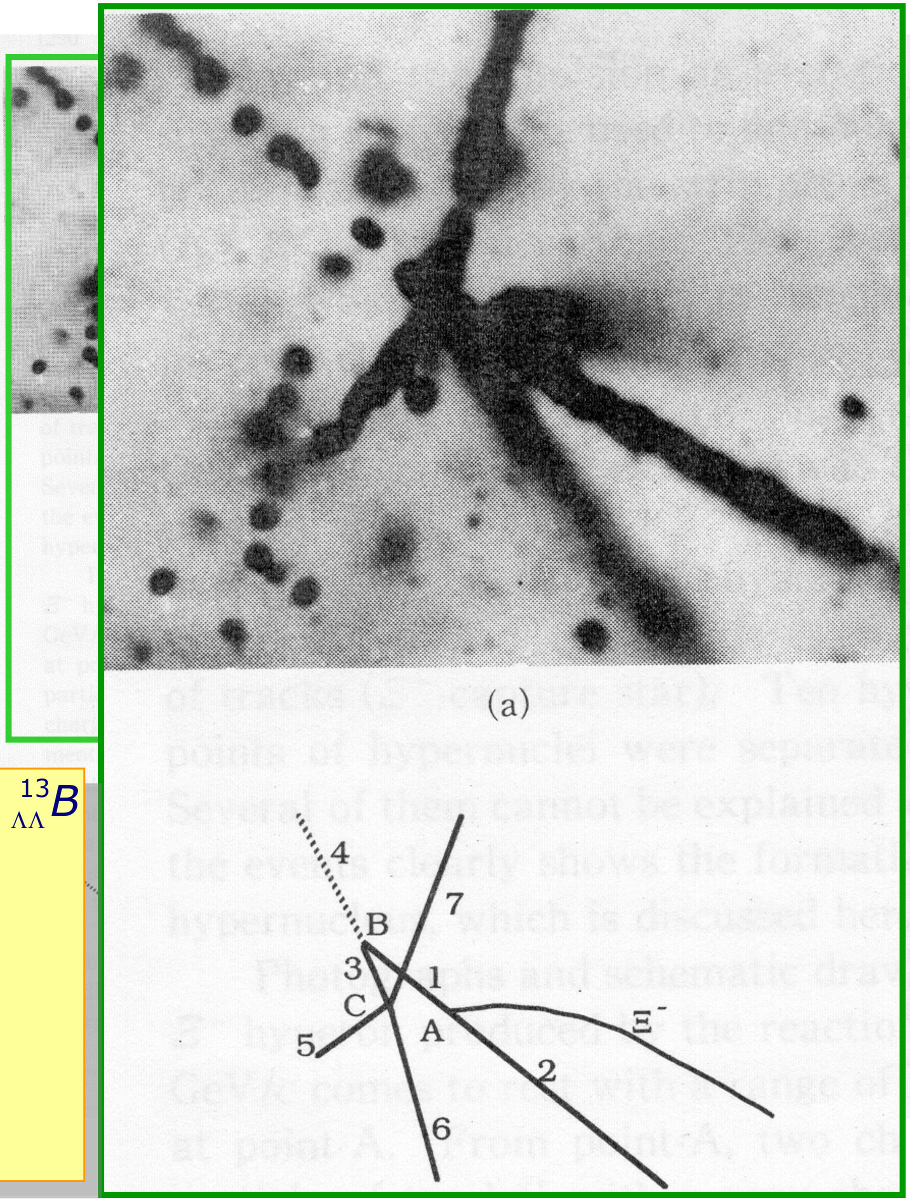
at point A: $\Xi^- + {}^{14}N \to n + {}^{14}_{\Lambda\Lambda}C^* \to n + p + {}^{13}_{\Lambda\Lambda}B$

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

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

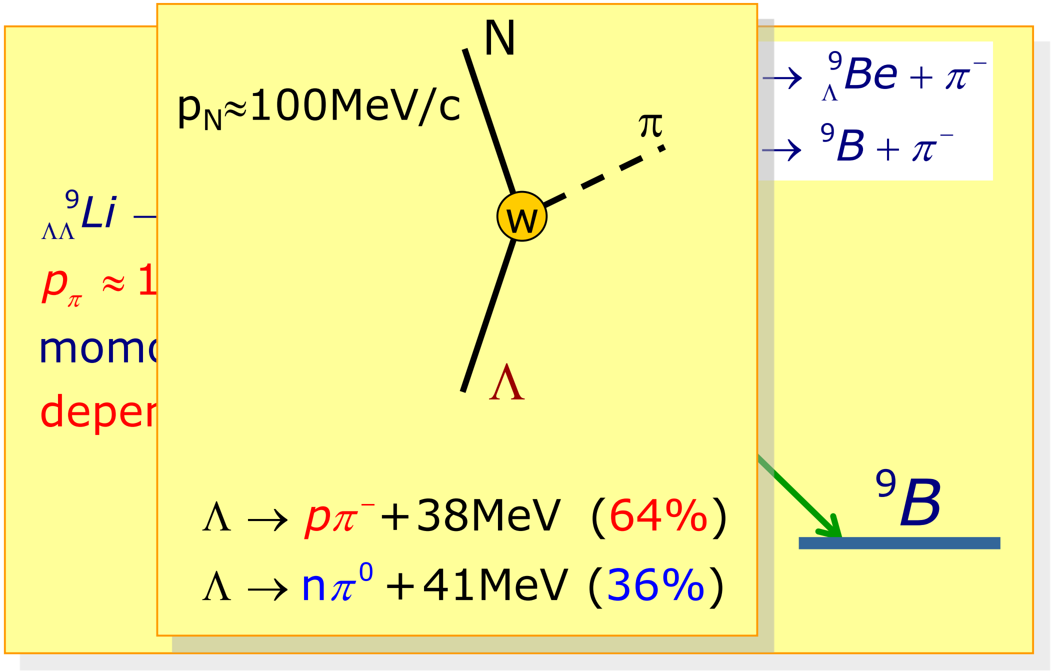
or $\to {}^{6}Li + {}^{4}He + p + 2n$

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



The E906 strategy

- fully electronic detector
- use p(K$^-$,K$^+$)Ξ^- 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



$_{\Lambda\Lambda}^{9}Li$ –

$p_\pi \approx 1$

mom

deper

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

$\rightarrow\ ^{9}B+\pi^-$

p$_N$≈100MeV/c

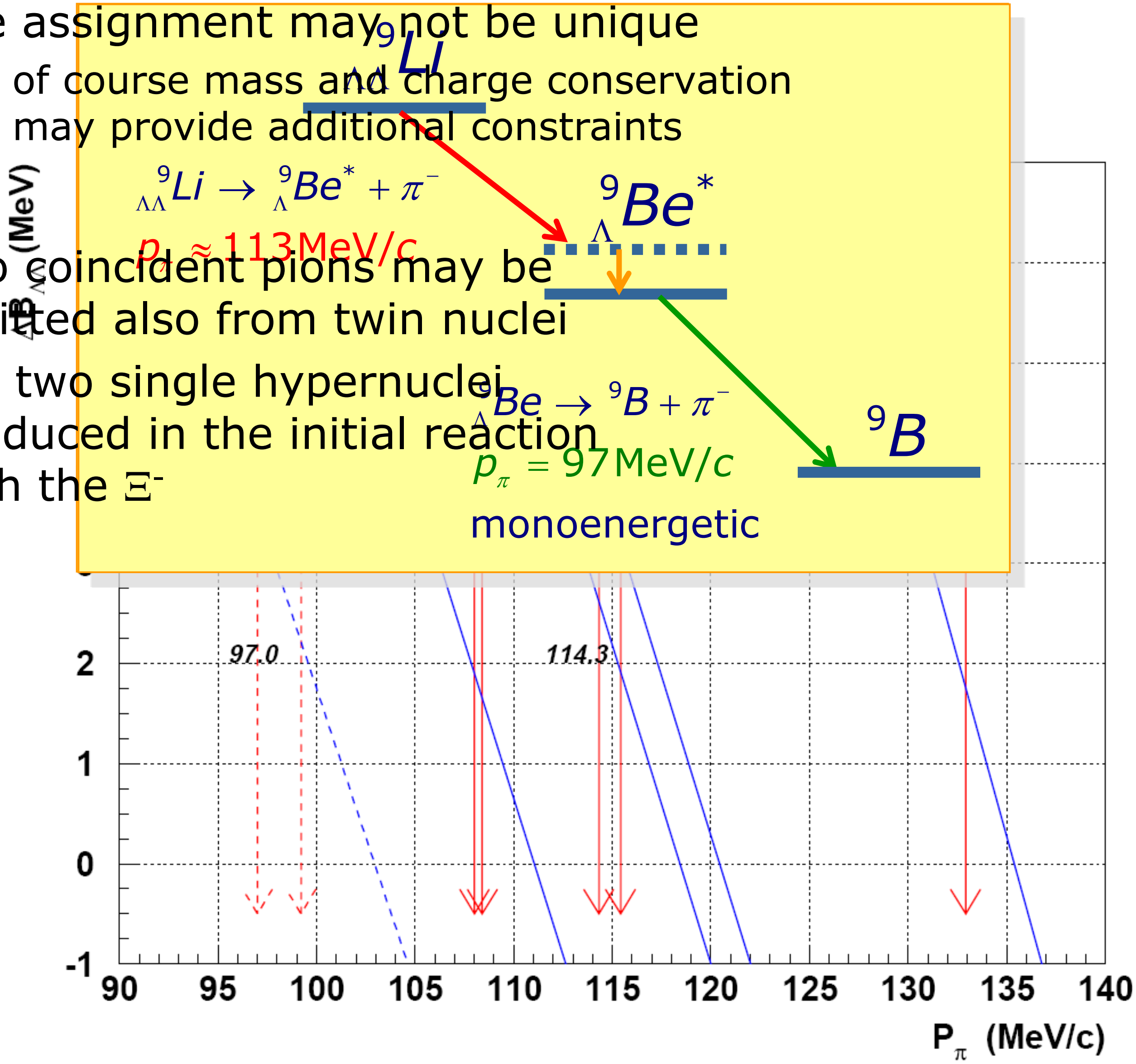
$\Lambda\rightarrow p\pi^-$+38MeV (64%)

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

…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^-



$^{9}_{\Lambda\Lambda}Li \rightarrow {}^{9}_{\Lambda}Be^{*} + \pi^{-}$

$p_\pi \approx 113$ MeV/c

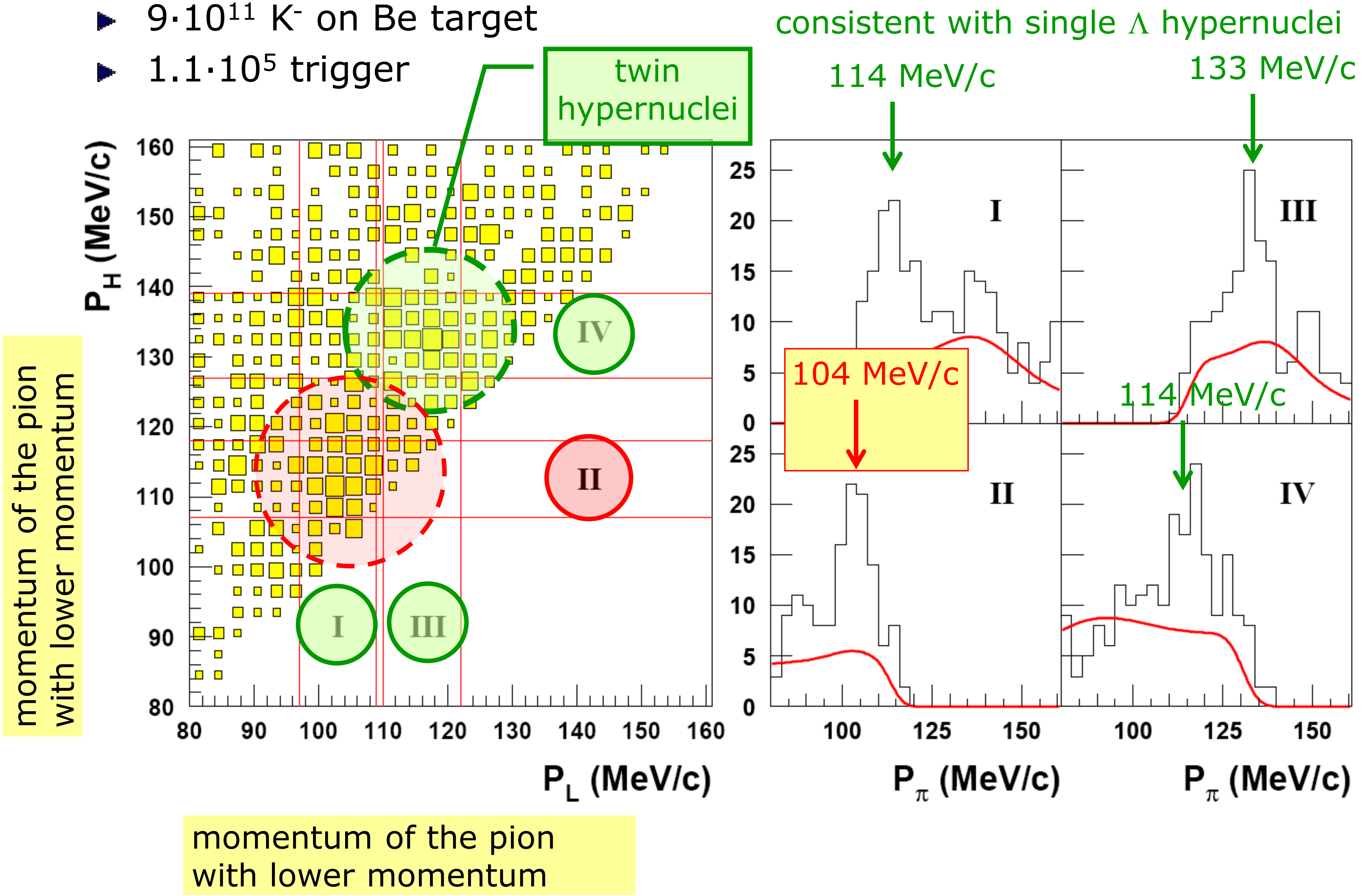
$^{9}_{\Lambda}Be \rightarrow {}^{9}B + \pi^{-}$

$p_\pi = 97$ MeV/c

monoenergetic

E906

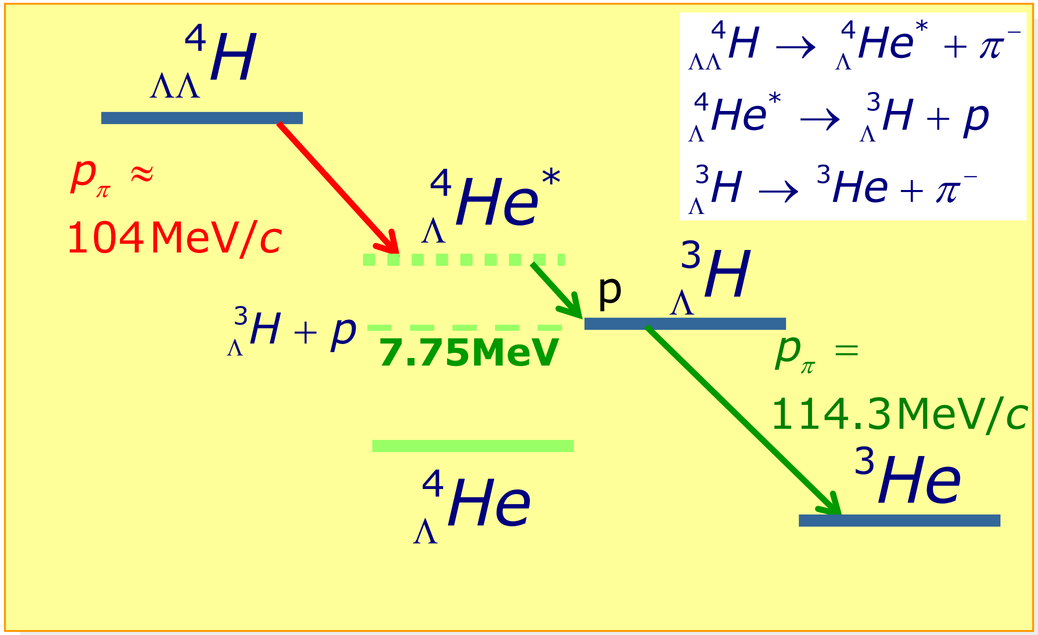
- $9 \cdot 10^{11}$ K^- on Be target
- $1.1 \cdot 10^5$ trigger



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



$${}^{4}_{\Lambda\Lambda}H \rightarrow {}^{4}_{\Lambda}He^{*} + \pi^{-}$$

$${}^{4}_{\Lambda}He^{*} \rightarrow {}^{3}_{\Lambda}H + p$$

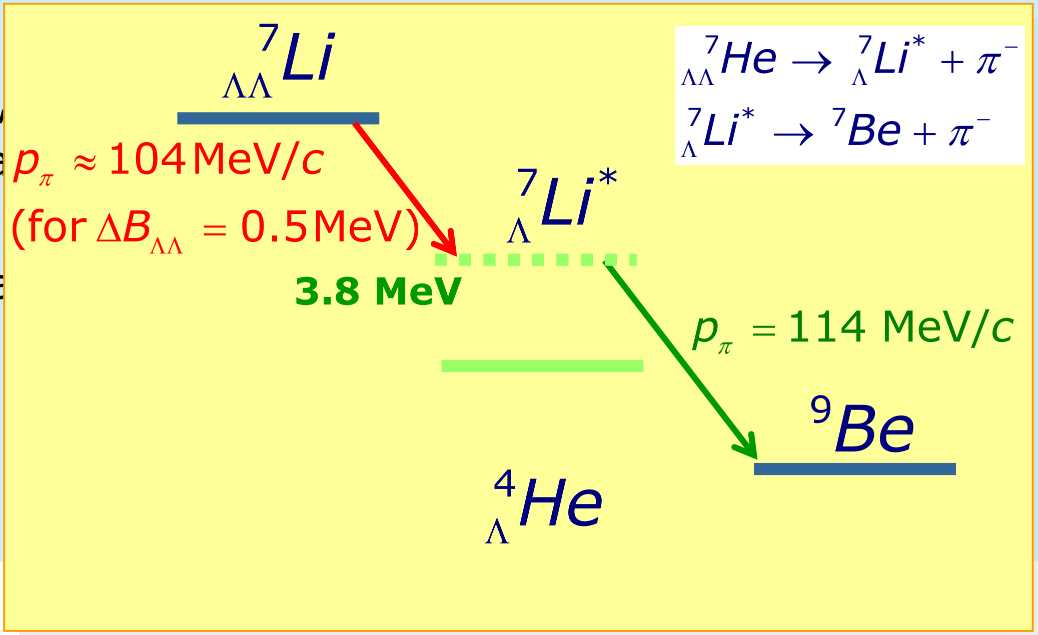
$${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

- Properties of ${}^{4}_{\Lambda\Lambda}H$
  - Hungerford (HYP03)
  - I.N. Filikhin, A. Gal, PRL 89,
    - requires isomeric state at 3.8MeV
    - Faddeev-Yakubowsky ca
  - H. Nemura, Y. Akaishi, Khin
    - Stochastic variational ca
  - Gal (HYP03)
  - M. Shoeb, PRC 71, 024004
  - lo

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

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

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



$${}^{7}_{\Lambda\Lambda}He \rightarrow {}^{7}_{\Lambda}Li^{*} + \pi^{-}$$

$${}^{7}_{\Lambda}Li^{*} \rightarrow {}^{7}Be + \pi^{-}$$

KEK-E373: the NAGARA event

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

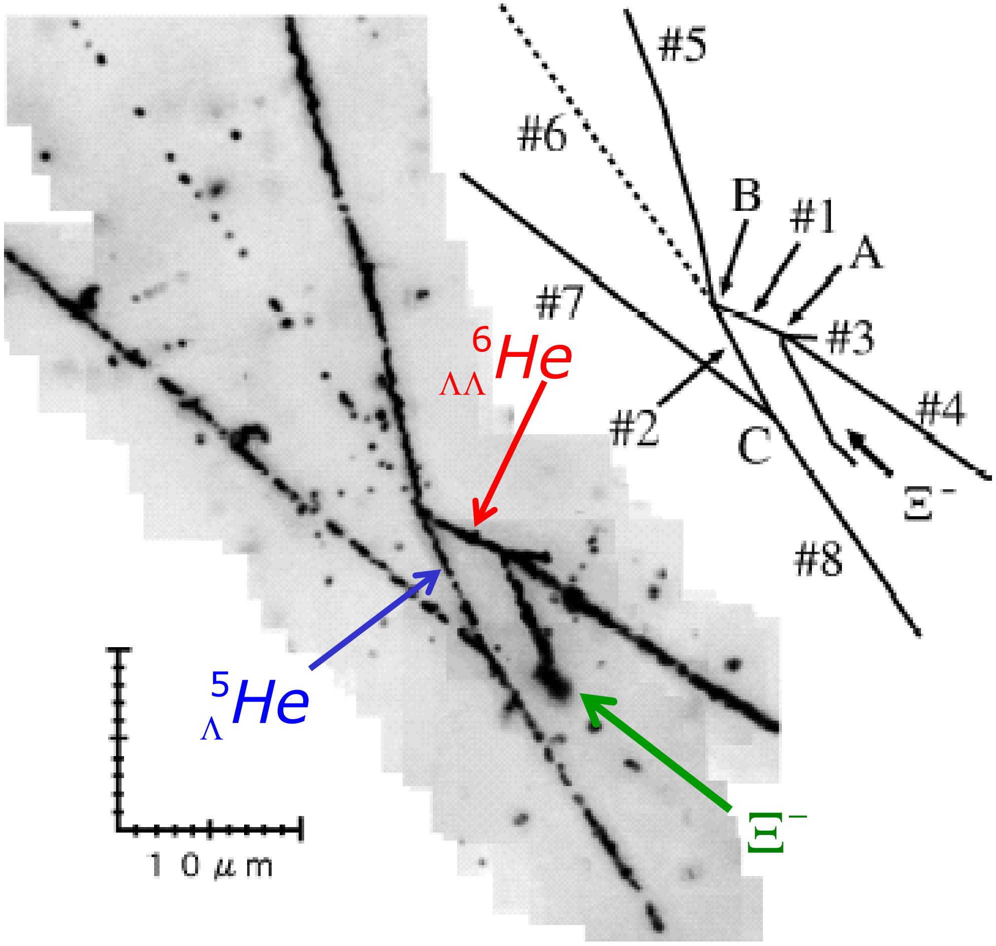
$$\Xi^- + {}^{12}C \rightarrow {}^{4}He + t + {}^{6}_{\Lambda\Lambda}He$$

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

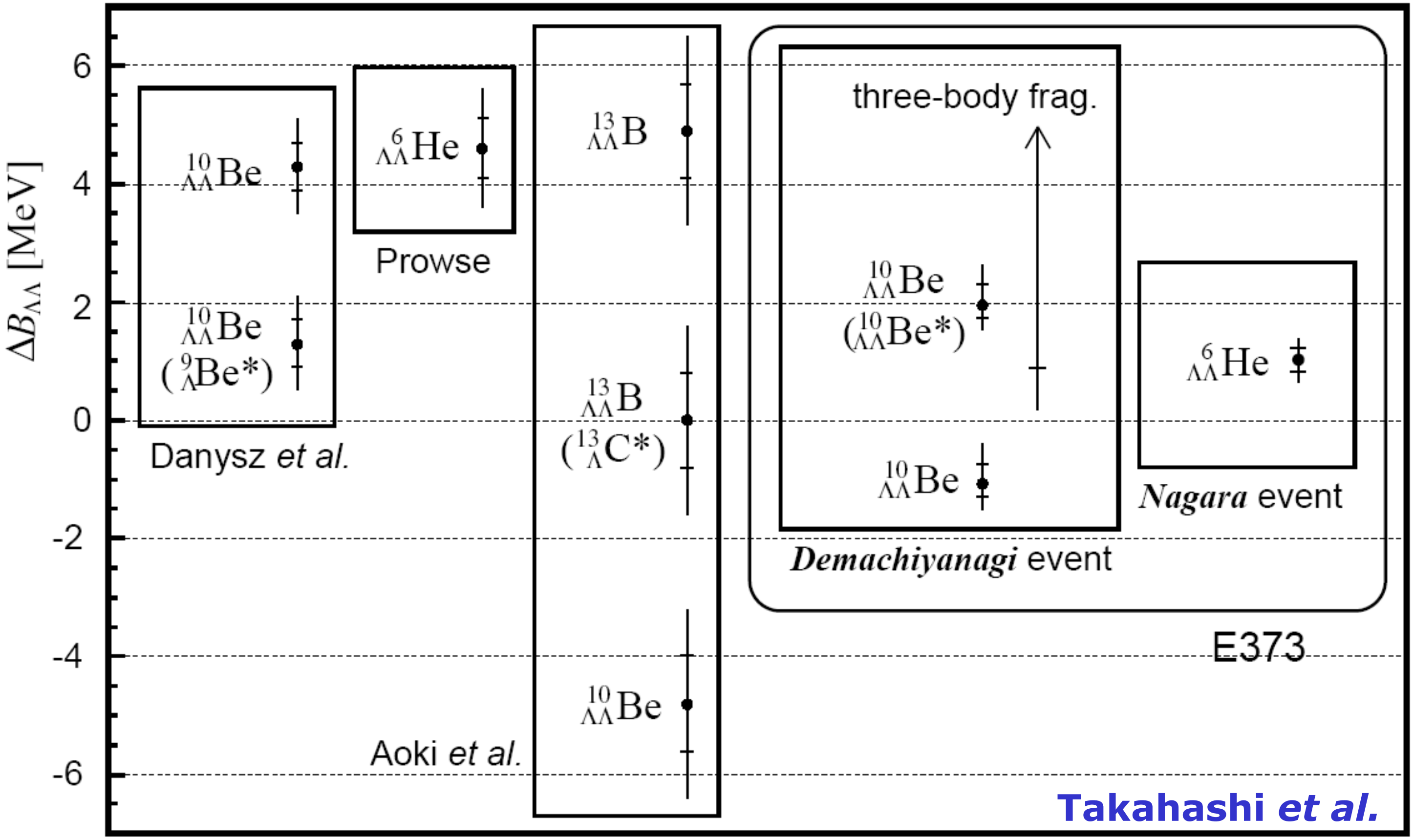
$$\Rightarrow \Delta B_{\Lambda\Lambda} = +1.01 \pm 0.2^{+0.18}_{-0.11}\,\text{MeV}$$

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

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



Summary



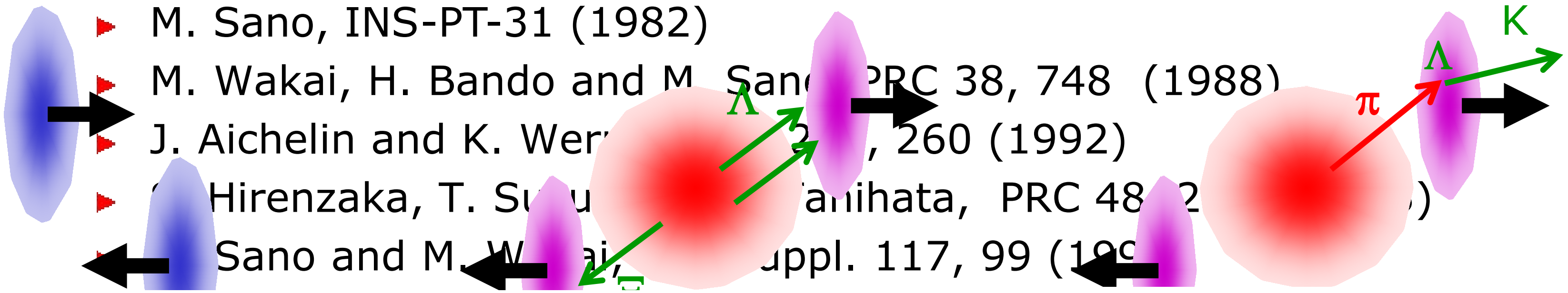
Takahashi *et al.*

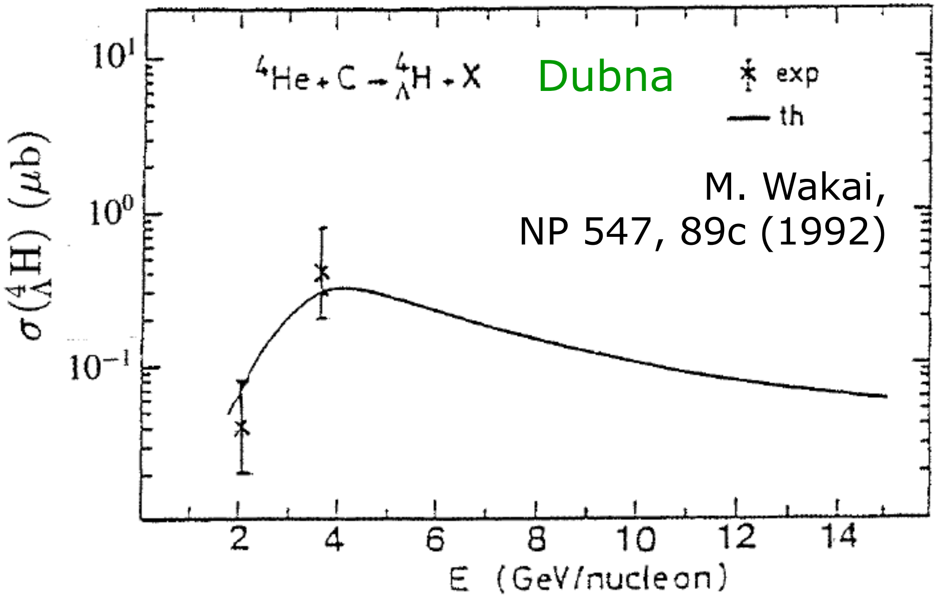
- Interpreting $\Delta B_{\Lambda\Lambda}$ as $\Lambda\Lambda$ bond energy one has to consider e.g.
  - dynamical change of the core nucleus
  - ΛN spin-spin interaction for non-zero spin of core
  - $\Lambda\Lambda$–ΞN-$\Sigma\Sigma$ coupling
  - excited states possible, but have not been clearly identified so far

Future of Double Hypernuclei

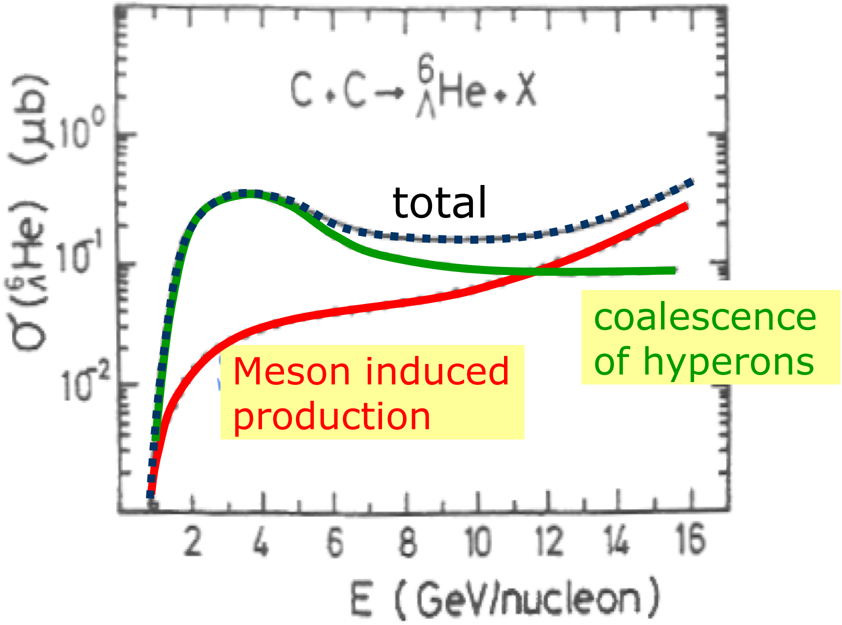
Relativistic Hypernuclei

- Production of hypernuclei in relativistic heavy ion collisions
  - Production of many hyperons
  - Multiple Coalescence of hyperons with fragments
  - (π,K), (K,π) and (K^-,K^+) reactions on fragments
- Many predictions based on coalescence model
  - M. Sano, INS-PT-31 (1982)
  - M. Wakai, H. Bando and M. San PRC 38, 748 (1988)
  - J. Aichelin and K. Wer 2 , 260 (1992)
  - Hirenzaka, T. Su u anihata, PRC 48 2)
  - Sano and M. W ai, uppl. 117, 99 (19





M. Wakai, NP 547, 89c (1992)



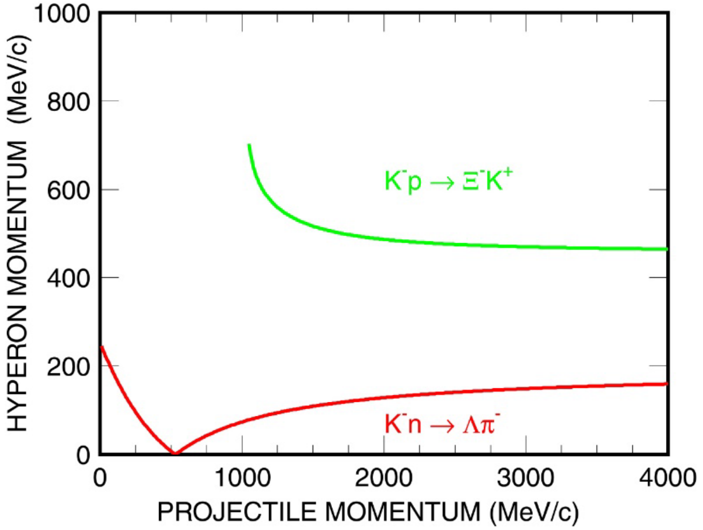
Meson induced production

coalescence of hyperons

Production of Ξ^-

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

- Ξ- production
  - $p(K^-,K^+)\Xi^-$
    - needs K^- beam ($c\cdot\tau$=3.7cm)
    - recoil momentum >460 MeV/c
  - KEK-E176: 10^2 stopped Ξ
  - KEK- E373: 10^3 stopped Ξ } per week(s)
  - AGS-E885: 10^4 stopped Ξ



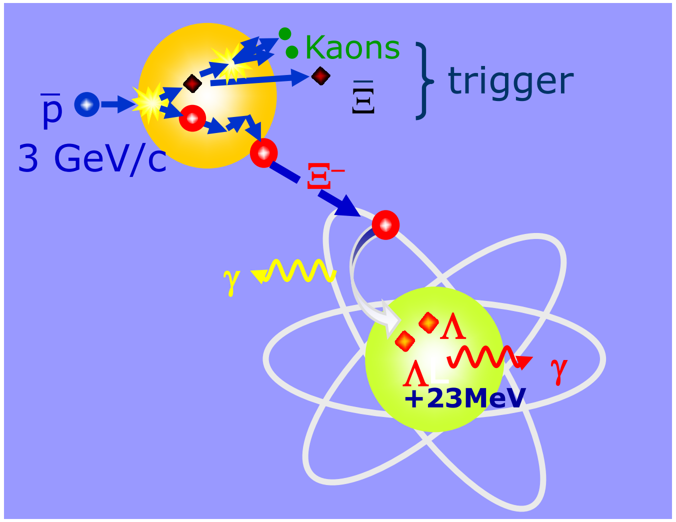
- antiproton storage ring HESR

$$p + \bar{p} \to \Xi^- + \bar{\Xi}^+$$

$$p + \bar{p} \to \Omega^- + \bar{\Omega}^+$$

- few times 10^5 stopped Ξ per day

$\Rightarrow$ γ-spectroscopy feasible



The Discovery of the anti-Xi

- discovered simulataniously at CERN and SLAC

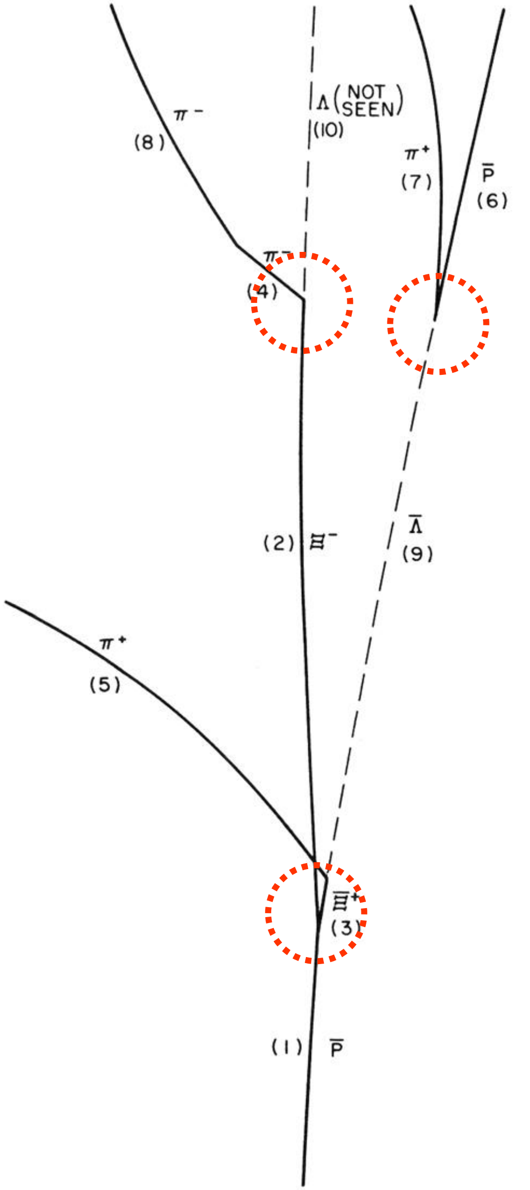
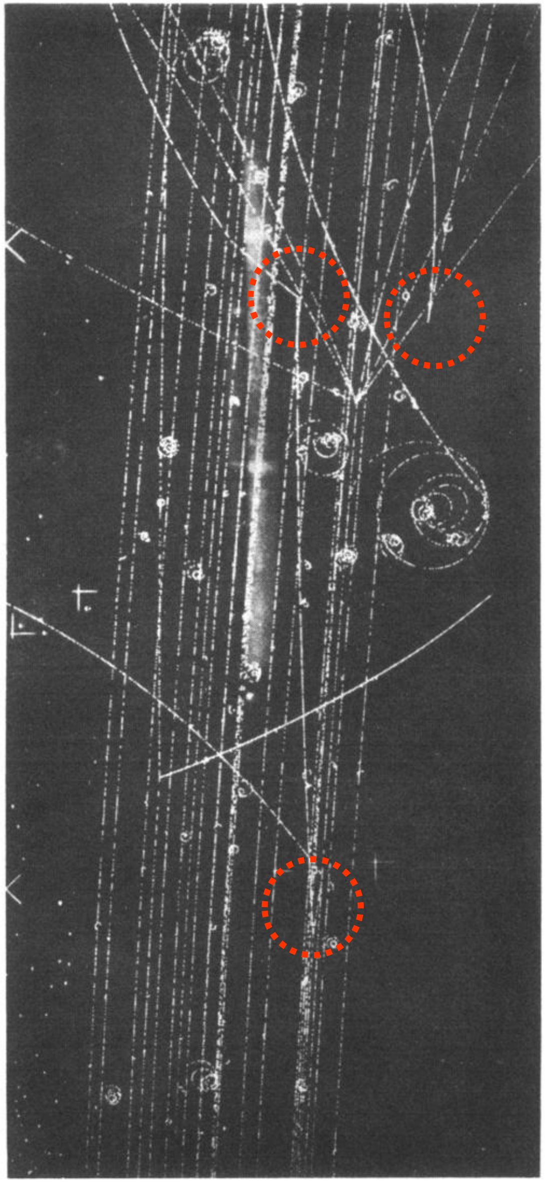
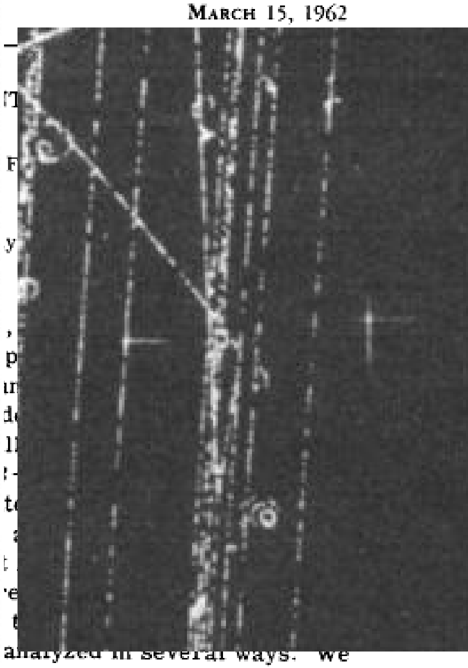


FIG. 1. A print of the event $\bar{p}+p\to\Xi^-+\bar{\Xi}^+$ as photographed in the BNL 20-in. liquid hydrogen bubble chamber is shown. The sketch of the event as shown is labelled according to the most likely mass interpretation for each observed track. The numbers on each track are those used in Table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



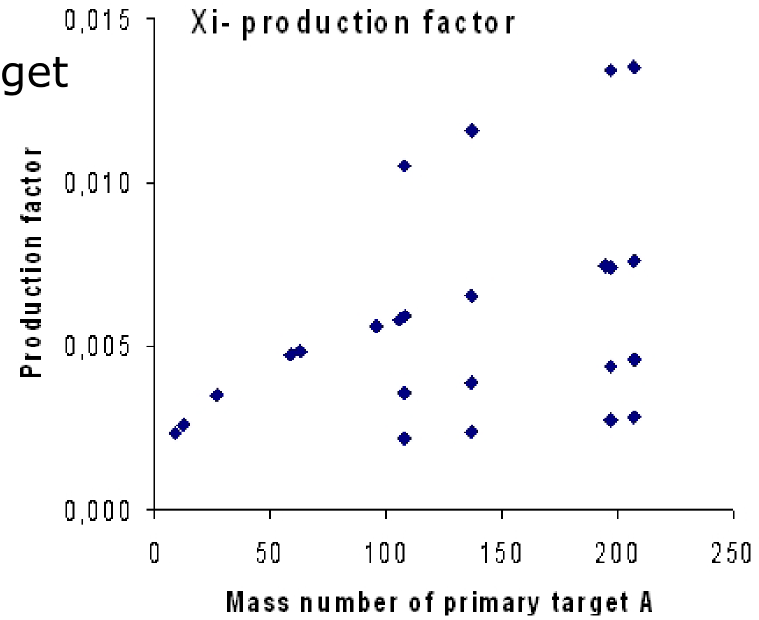


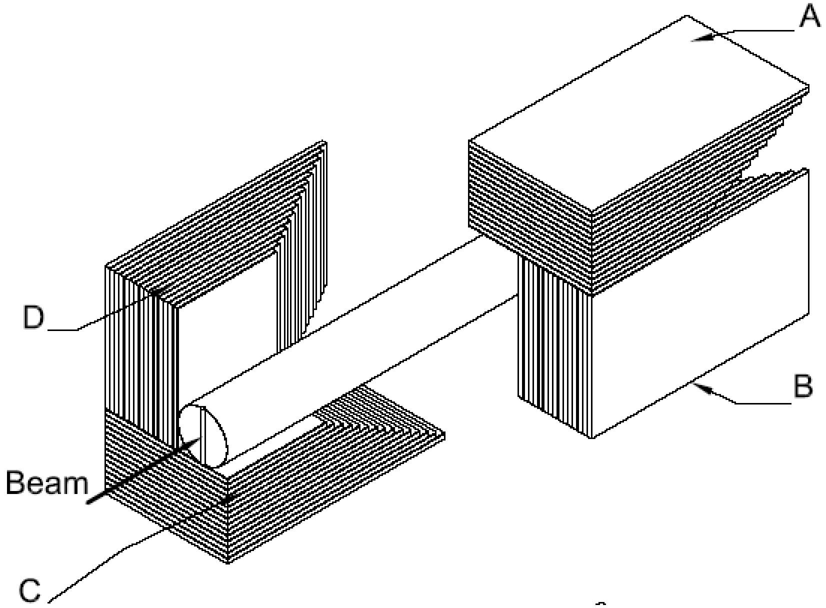
MARCH 15, 1962

analyzed in several ways. We

Target considerations

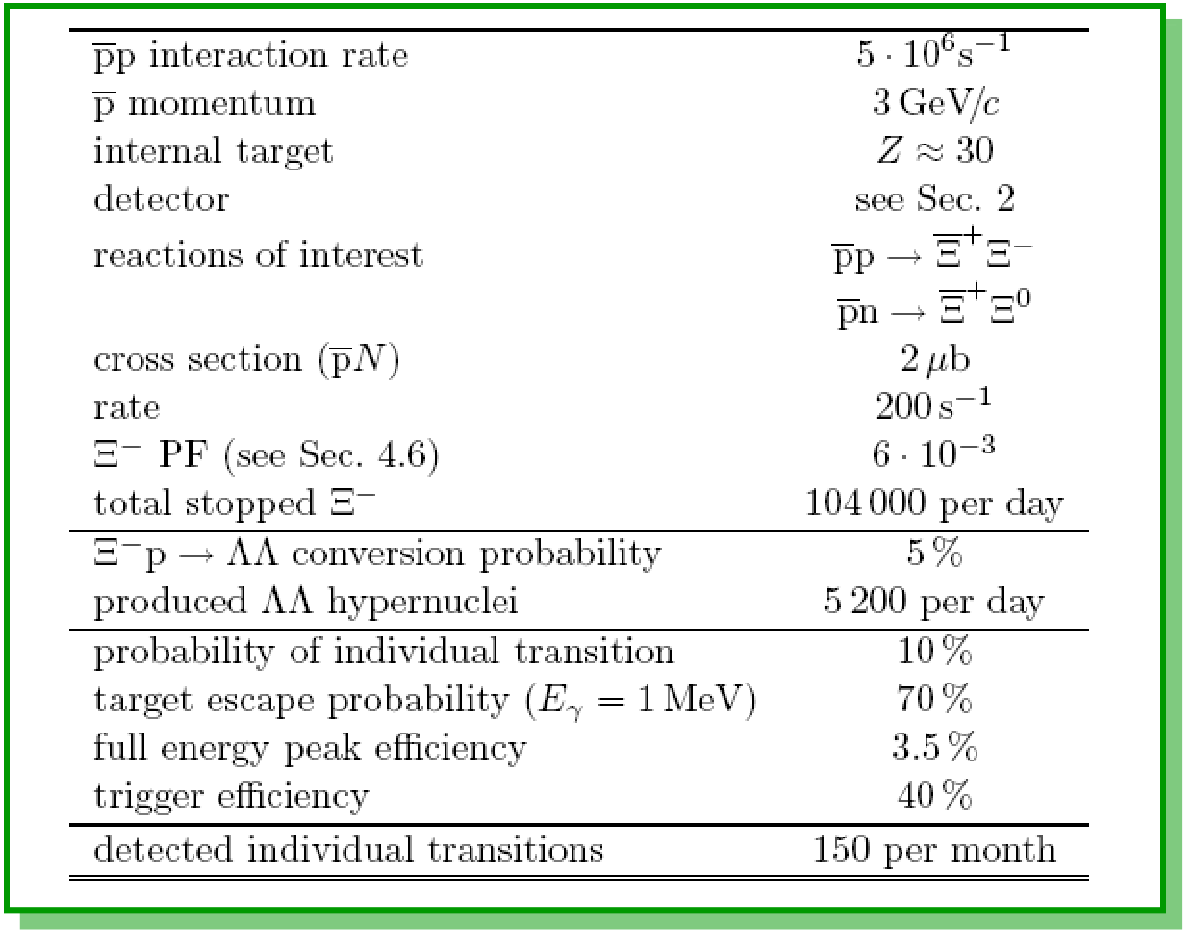
- primary reaction: Ξ-pair production
  - very limited space → nuclear wire target
  - Ξ production for given pbar rate
    → heavy target (not very critical)
  - beam scattering, neutrons
    → light target (critical)
- secondary target
  - geometry defined by Ξ- range, angle distribution and lifetime
  - thickness ~5 gr/cm² (~2.5 cm)
- 4 sectors with 4 different targets (Li,Be, B, C)+Si-strip detectors
  - identification can rely on existing information on single hypernuclei
  - low γ-ray absorption
  - no x-ray background



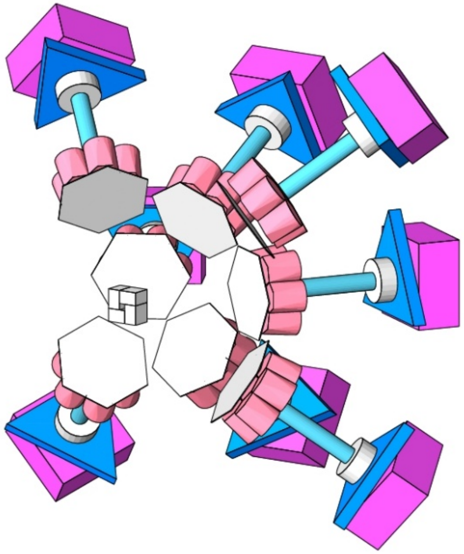


PANDA: s-baryons in complex systems

- Physics case
  - double hypernuclei (γ-spectroscopy)
  - hyper atoms (Ω^- quadrupole moment)
  - pair production of hadron – antihadron pairs in nuclei (?)



$\bar{p}p$ interaction rate	$5 \cdot 10^6 \, s^{-1}$
$\bar{p}$ momentum	$3\,GeV/c$
internal target	$Z \approx 30$
detector	see Sec. 2
reactions of interest	$\bar{p}p \to \bar{\Xi}^+\Xi^-$
	$\bar{p}n \to \bar{\Xi}^+\Xi^0$
cross section ($\bar{p}N$)	$2\,\mu b$
rate	$200\,s^{-1}$
Ξ^- PF (see Sec. 4.6)	$6 \cdot 10^{-3}$
total stopped Ξ^-	104 000 per day
$\Xi^- p \to \Lambda\Lambda$ conversion probability	5 %
produced $\Lambda\Lambda$ hypernuclei	5 200 per day
probability of individual transition	10 %
target escape probability ($E_\gamma = 1\,MeV$)	70 %
full energy peak efficiency	3.5 %
trigger efficiency	40 %
detected individual transitions	150 per month



CONCLUSION

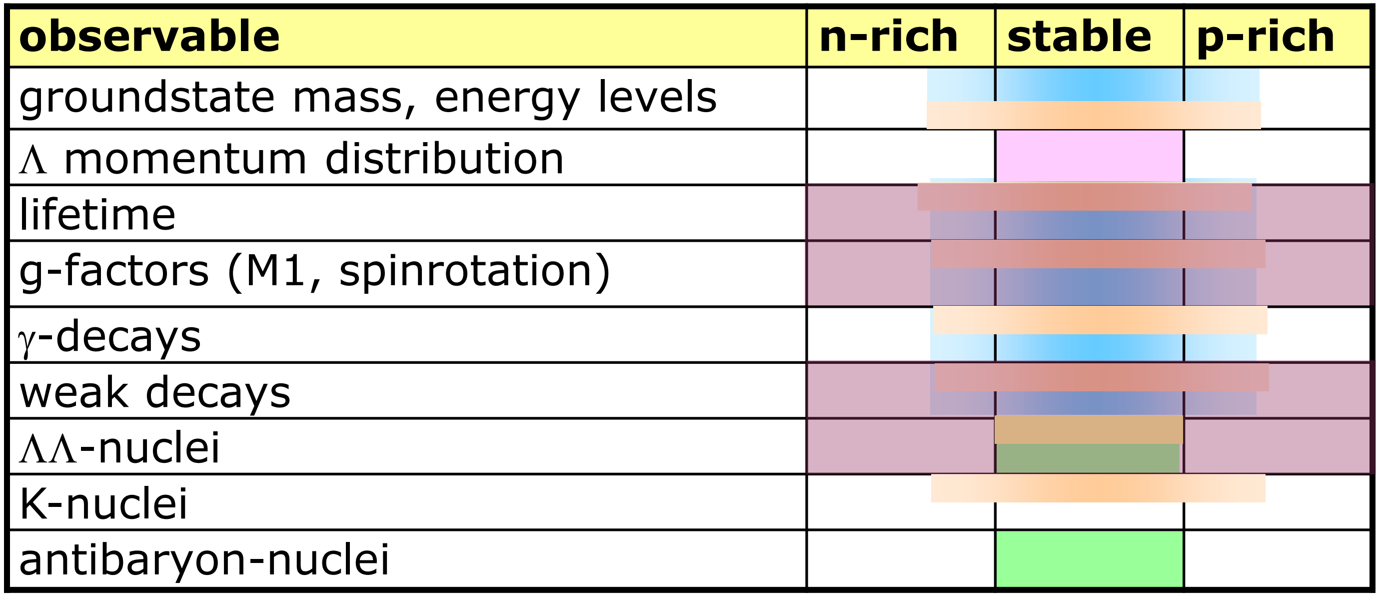
Conclusion

- Double hypernuclei exist
- Double Hypernuclei offer a wide range of unique opportunities to study strong interaction in a multi-body environment n
    - baryon-baryon interaction
    - weak decays
    - new nuclear structure effects
    - baryons in nuclear medium
- New production schemes seem to be very promising

- Finally: There are many more things
    - …next year HYP2006 in Mainz

discussion

Hypernuclei – Phase IV



observable	n-rich	stable	p-rich
groundstate mass, energy levels			
Λ momentum distribution			
lifetime			
g-factors (M1, spinrotation)			
γ-decays			
weak decays			
$\Lambda\Lambda$-nuclei			
K-nuclei			
antibaryon-nuclei			

- (π,K), (K,π) → JPARC
- (K^-,K^+) → JPARC
- K_{stop} → FINUDA
- (e,e’) → MAMI-C
- HI → HypHi, JPARC
- pbar-p → PANDA

Questions concerning (not only) HypHI

- What information is most wanted?
- How important are low energy hyperon-nucleon scattering experiments ? Can we live without them?

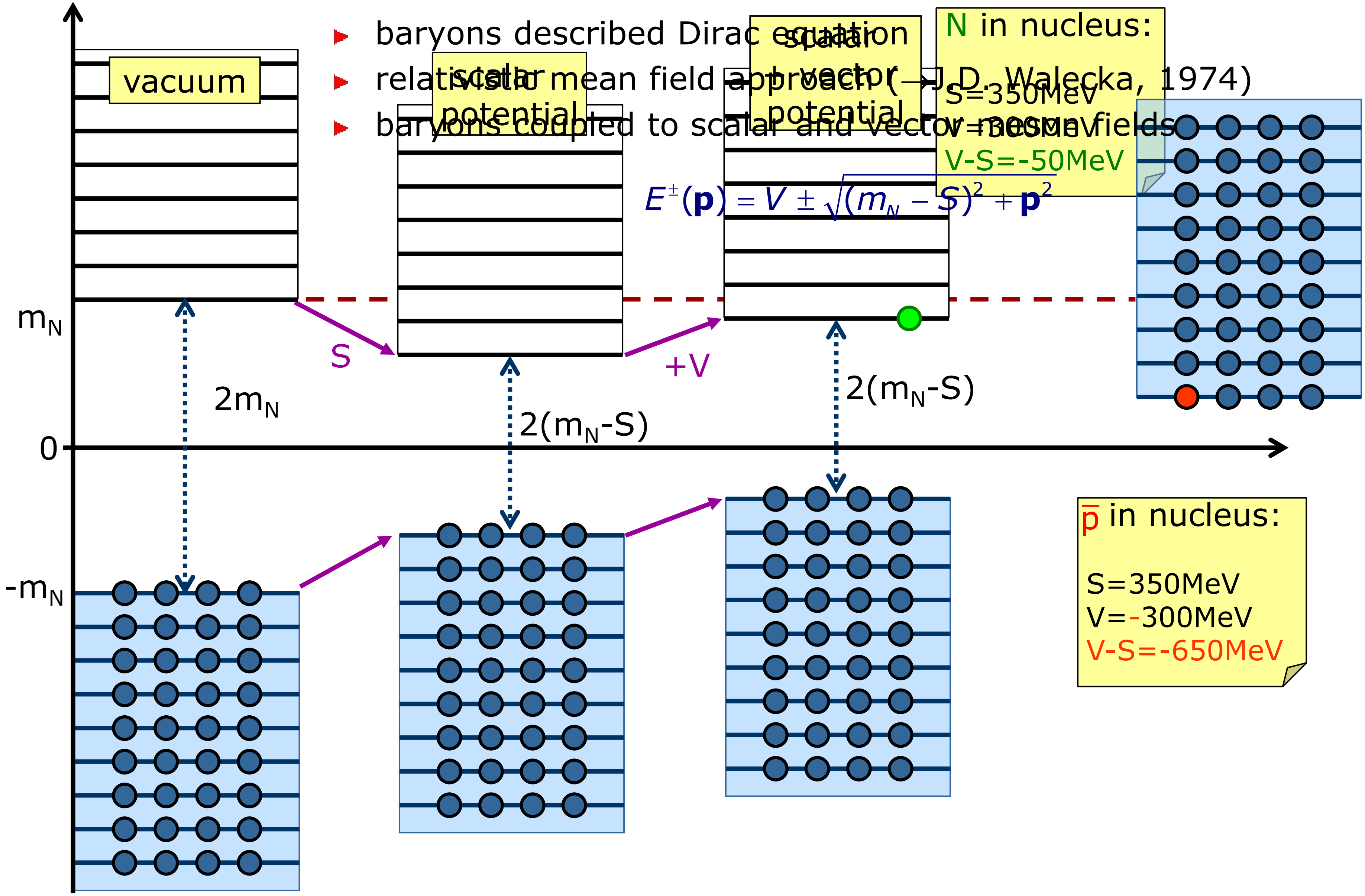
- What nuclei to study ? (YN-interaction, n-stars,…)
- How well does coalescence work ?
- What can be said about stability of exotic^2 nuclei ?

- Is the H-particle still relevant?
- Are hyperons relevant for nova explosions, element formation,….?
- Are there excited states in kaonic nuclei ?

ANTI-HYPERONS
in Nuclei

Antibaryons in nuclei

- Hans-Peter Dürr and Edward Teller, Phys. Rev. **101**, 494 (1956)
  - baryons described Dirac equation
  - relativistic mean field approach (→J.D. Walecka, 1974)
  - baryons coupled to scalar and vector meson fields



$$E^{\pm}(\mathbf{p}) = V \pm \sqrt{(m_N - S)^2 + \mathbf{p}^2}$$

N in nucleus:
S=350MeV
V=300MeV
V-S=-50MeV

$\overline{\text{p}}$ in nucleus:

S=350MeV
V=-300MeV
V-S=-650MeV

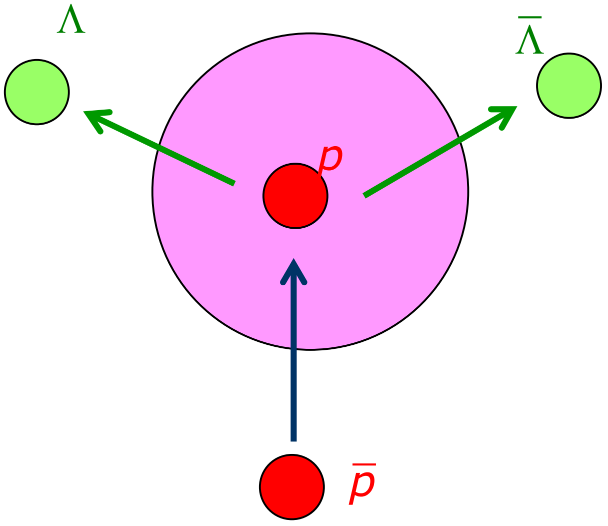
Why do antihyperons in matter matter?

- antibaryons in nuclei allow in principle to determine S and V separately
- because of the strong cold compression color degrees of freedom might become very important
- allow to study the formation of a baryon antibaryon pair inside a nucleus ⇒ study formation time $t \sim \hbar/E_F \sim 5\,\mathrm{fm}/c$

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

- $p + \bar{p} \rightarrow \Lambda + \bar{\Lambda}$ 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 effective 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

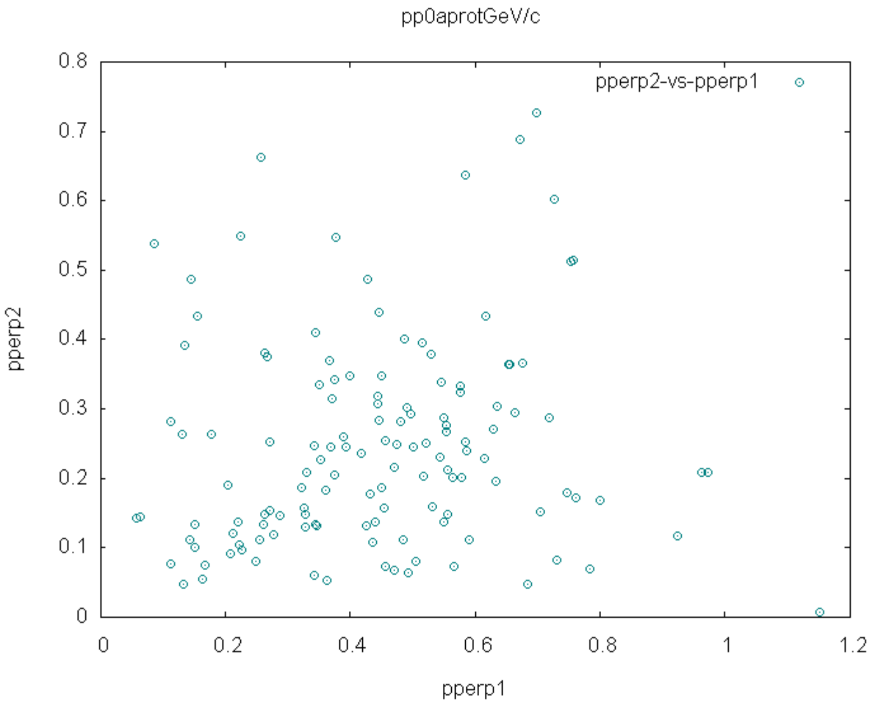
is this correct?



Simple MC: 1.6 GeV/c pbar-C

$$E_H(\vec{p}) = V + \sqrt{(m_H - S)^2 + \vec{p}^2}$$

- proton: S=350MeV V=300MeV (V-S=-50MeV)
- antiproton: S=350MeV V=-300MeV (V-S=-650MeV)
- C target
- Λ potential=2/3 of nucleons
- Fermi motion
- leading effect
  - lambda: 0.445 GeV/c
  - antilambda: 0.244 GeV/c



- can be extended to every hadron-antihadron production ($\Lambda_c\bar{\Lambda}_c$...)

Some open questions

- different absorption of hyperon and antihyperon

- rescattering
  - influence of nuclear mass ⇒ use light nucleus to reduce rescattering
  - but: coherence length of Λ antiΛ pair: $t \sim \hbar/E_F \sim 5\text{fm}/c$ ⇒ need large nucleus

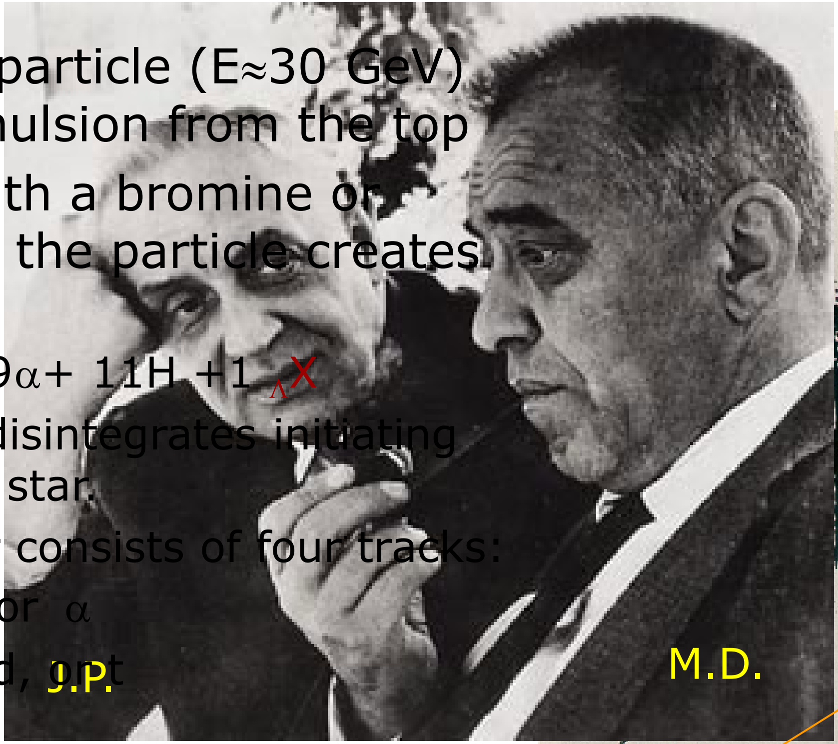
- use Λ and anti-Λ polarization to enhance anti-$\Lambda\Lambda$ pairs which did not encounter a rescattering on their way out

- if method is successful: can be extended to any hadron-antihadron production (even $\Lambda_c\bar{\Lambda}_c$…)

BACK UP

How it began

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



- A cosmic ray particle (E≈30 GeV) enters the emulsion from the top
- Interacting with a bromine or silver nucleus the particle creates an upper star.
  - 21 tracks: 9α+ 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

$$t > \frac{s}{c} \sim \frac{80\mu m}{300000 km/s} \approx 2.6 \cdot 10^{-13} s$$

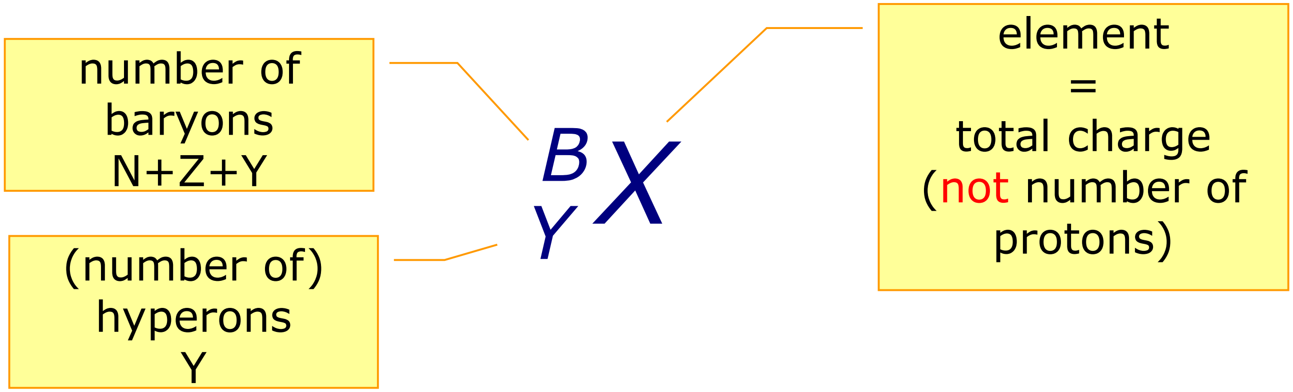
$$\tau(\Lambda) = 2.6 \cdot 10^{-10} s$$

$$\Rightarrow \text{typical for weak decay}$$

- many associated particles in primary reaction

Nomenclature

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



number of baryons N+Z+Y

(number of) hyperons Y

element = total charge (not number of protons)

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

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

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

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

Ξ^-(dss)p(uud) Þ Λ(uds)Λ(uds)

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

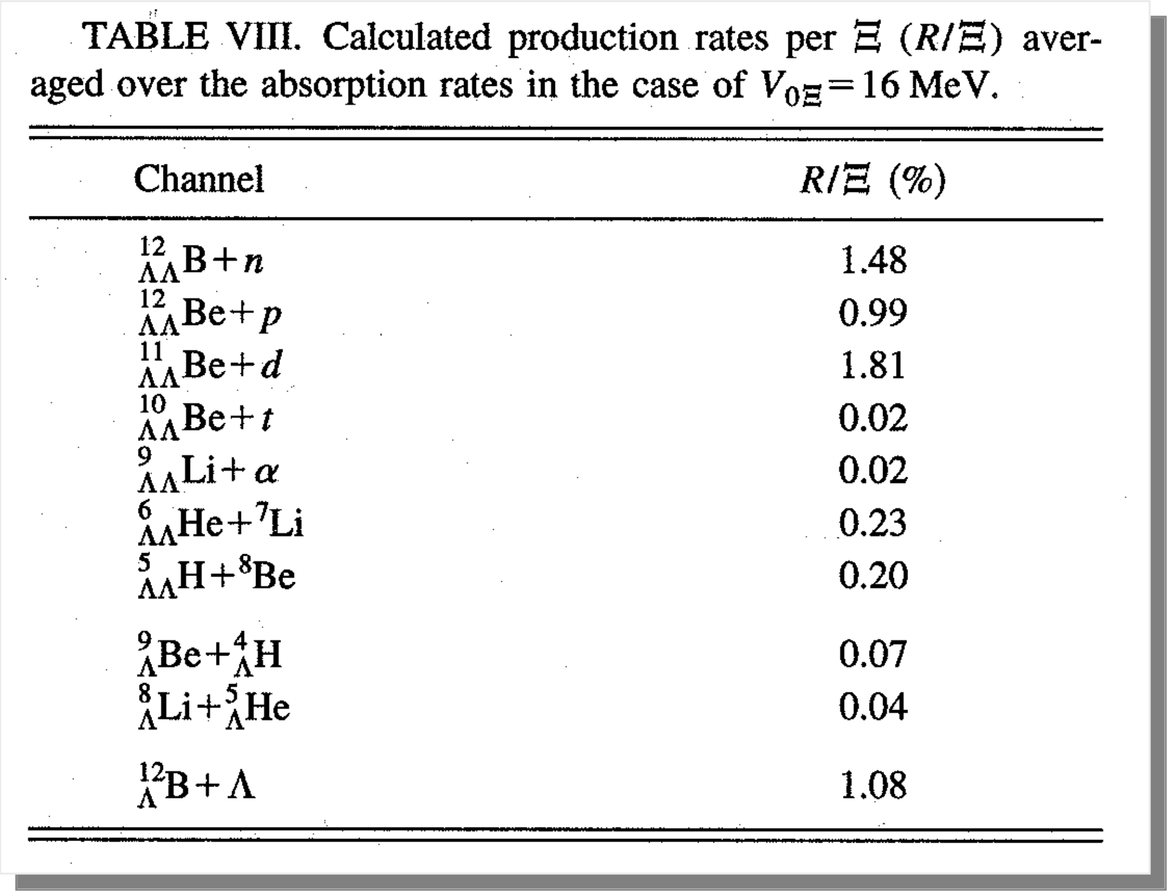


TABLE VIII. Calculated production rates per Ξ (R/Ξ) averaged over the absorption rates in the case of $V_{0\Xi}=16$ MeV.

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

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

Can we determine the $\Lambda\Lambda$ interaction?

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

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

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

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

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

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

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

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

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

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

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

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

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

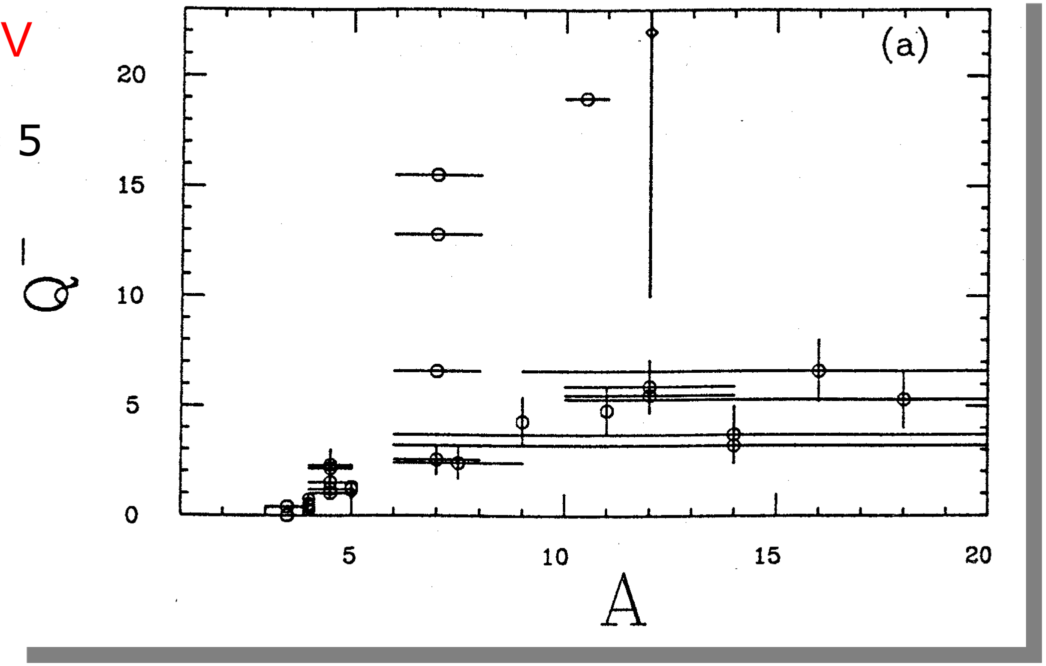
What about Heavy Nuclei?

- 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

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

  - non-mesonic: mesonic ≈ 5



- new concept required
  - high resolution γ-spectroscopy

DIE WELT 4. September 2001

AGS-E906

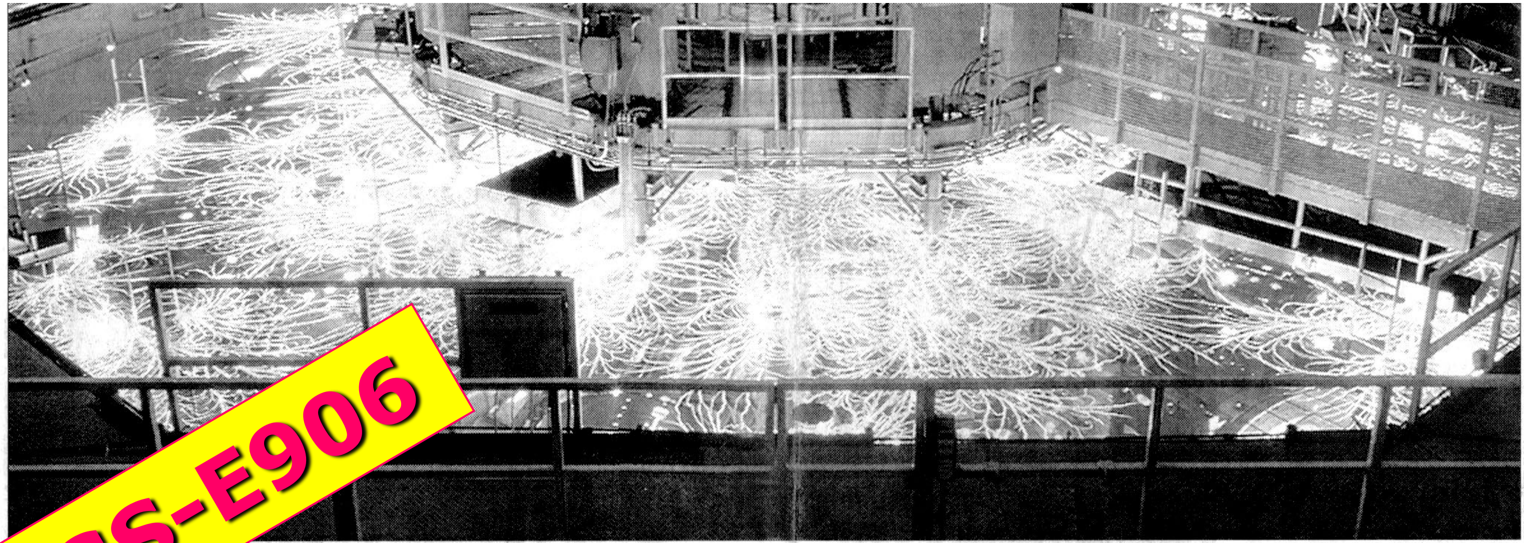


FOTO: STEINMETZ/FOCUS

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“.

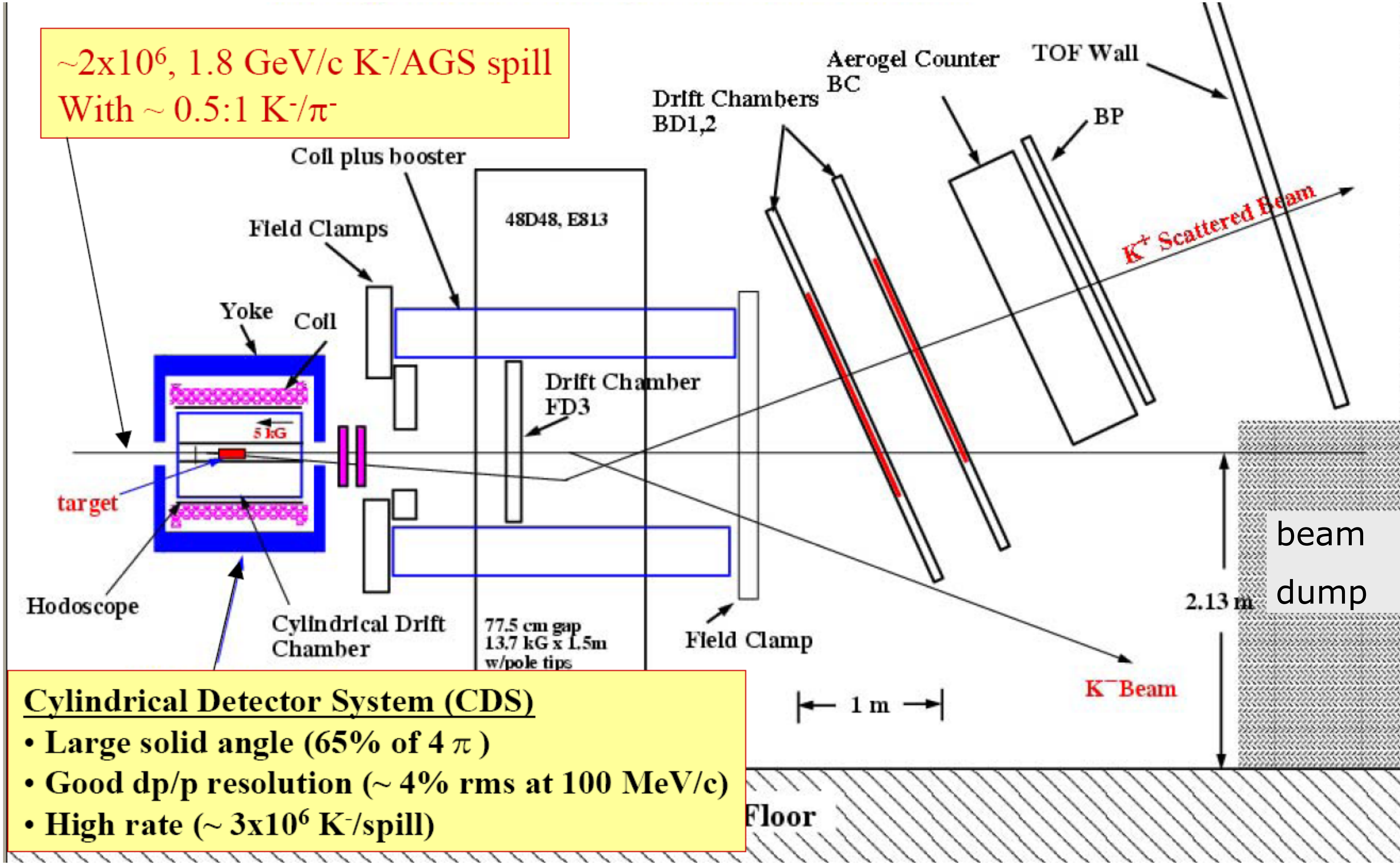
Aus den Millionen von Daten, die während einer Messkampagne entstehen, müssen die Physiker am Ende die wirklich relevanten „Ereignisse“ herausfinden, die sprichwörtliche Nadel im Heuhaufen. In Brookhaven hat sich die Mühe offenbar gelohnt; aus 100 Millionen infrage kommenden Ereignissen filterten Computer 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



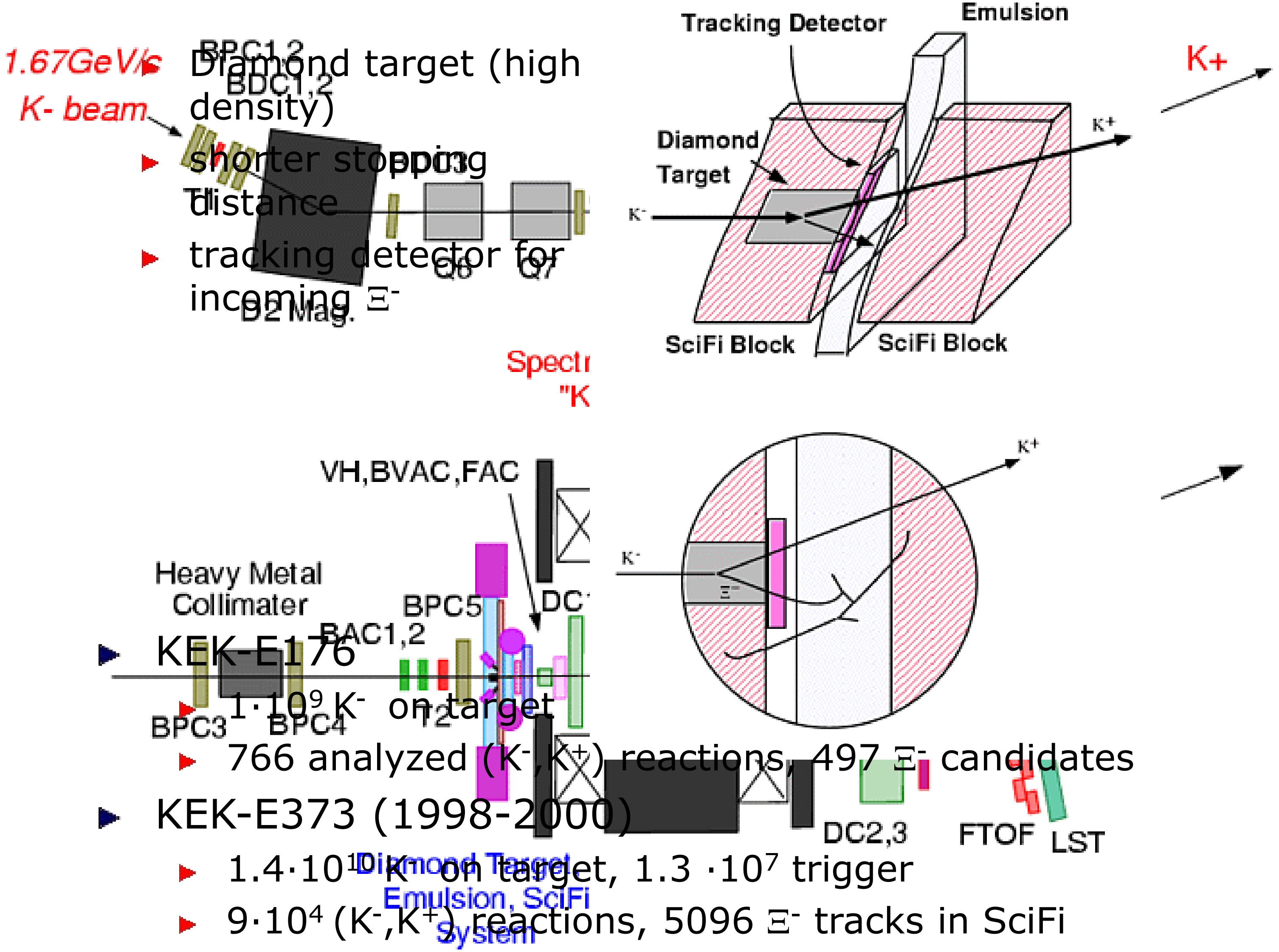
~$2\text{x}10^6$, 1.8 GeV/c K^-/AGS spill
With ~ 0.5:1 K^-/π^-

Cylindrical Detector System (CDS)

- **Large solid angle (65% of 4 π)**
- **Good dp/p resolution (~ 4% rms at 100 MeV/c)**
- **High rate (~ $3\text{x}10^6$ K^-/spill)**

The KEK-E373 Experiment

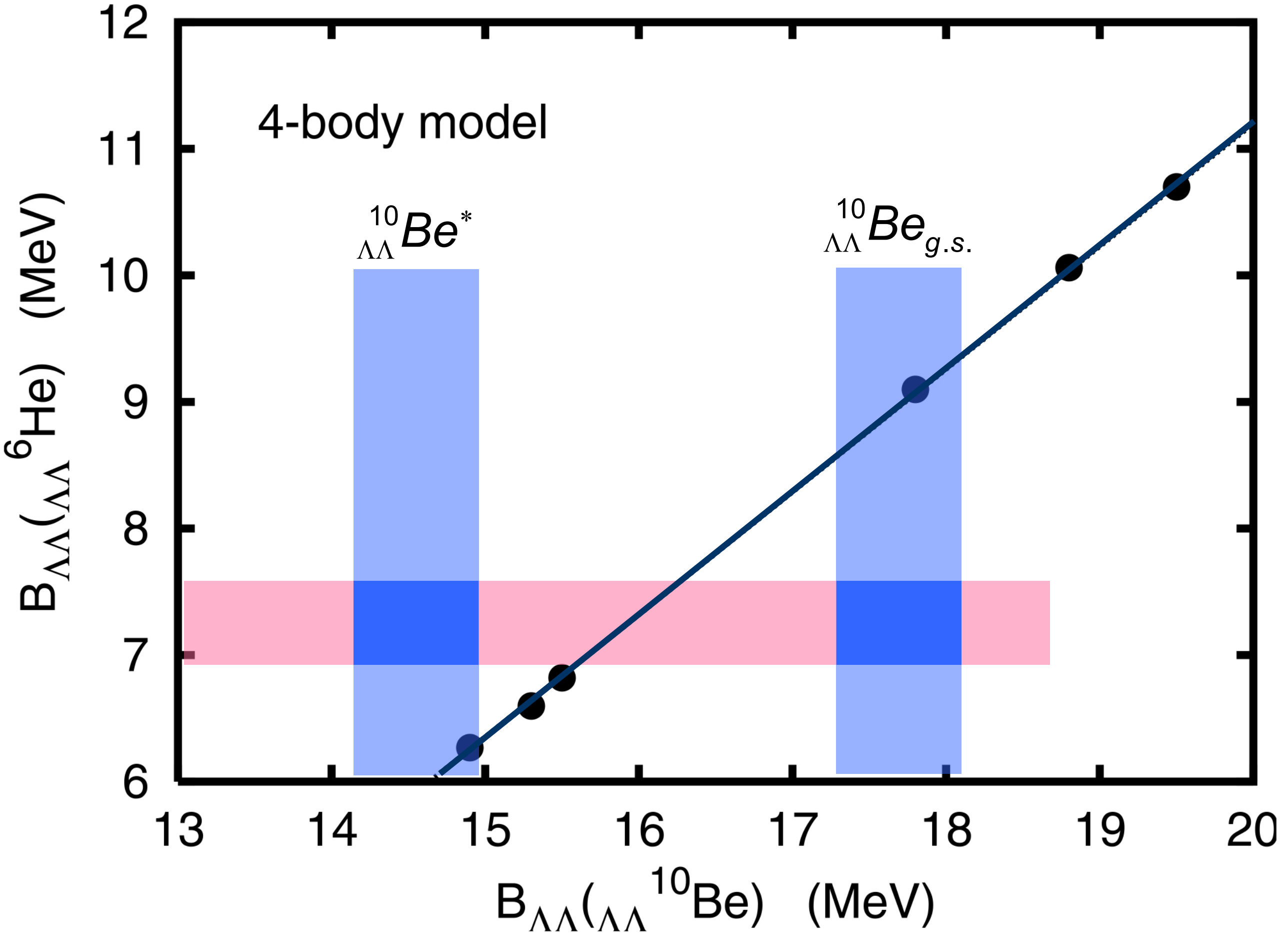
- KEK proton synchrotron
- 1.66 GeV/c K$^-$ beam
  - Diamond target (high density)
  - shorter stopping distance
  - tracking detector for incoming Ξ^-



- KEK-E176
  - $1\cdot10^9$ K$^-$ on target
  - 766 analyzed (K$^-$,K$^+$) reactions, 497 Ξ^- candidates
- KEK-E373 (1998-2000)
  - $1.4\cdot10^{10}$ K$^-$ on target, $1.3\cdot10^7$ trigger
  - $9\cdot10^4$ (K$^-$,K$^+$) reactions, 5096 Ξ^- tracks in SciFi

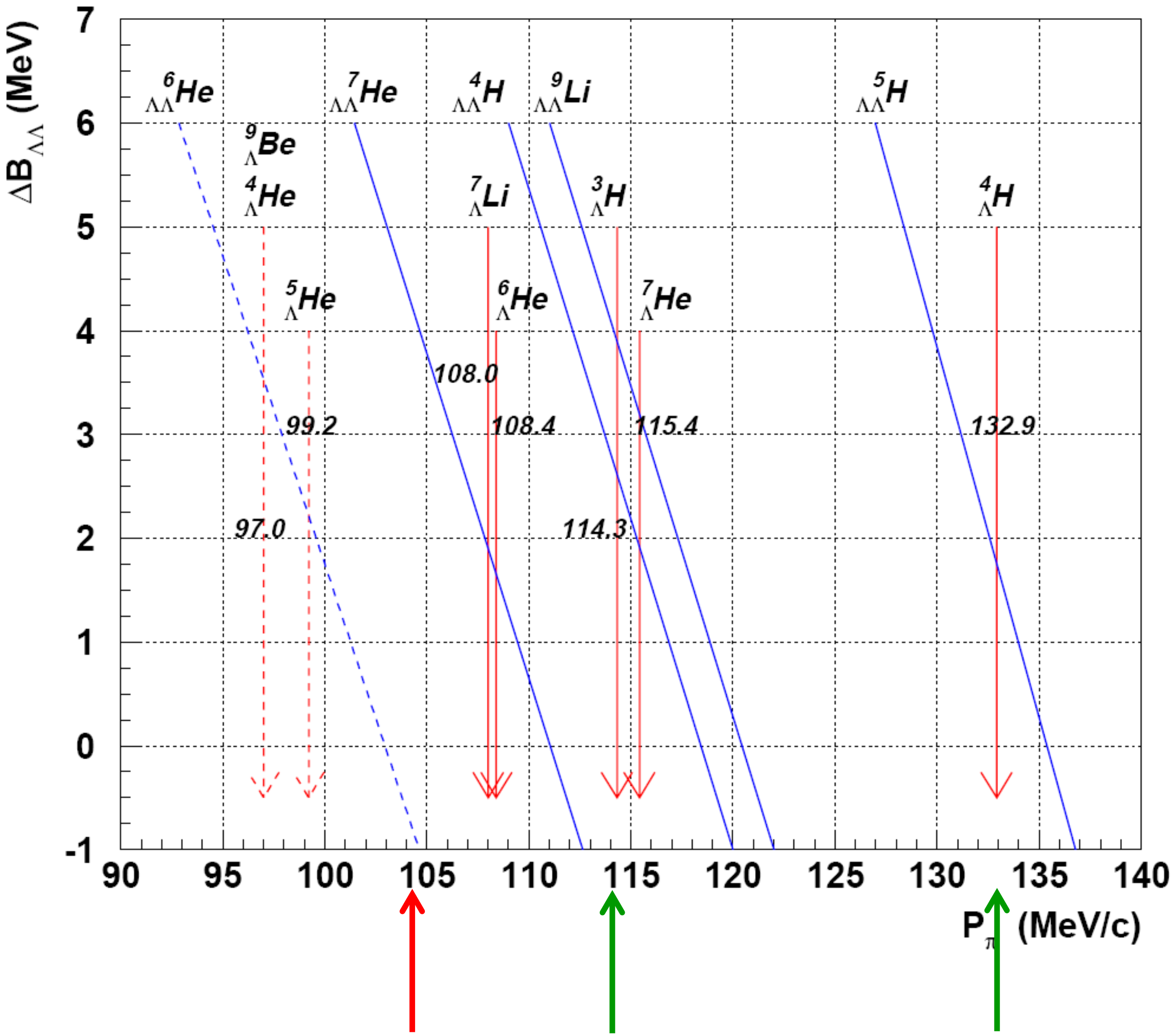
Consistent Description - not yet!

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



- no consistent description possible so far

Interpretation



104 MeV/c 114 MeV/c 133 MeV/c

- …is not straight forward