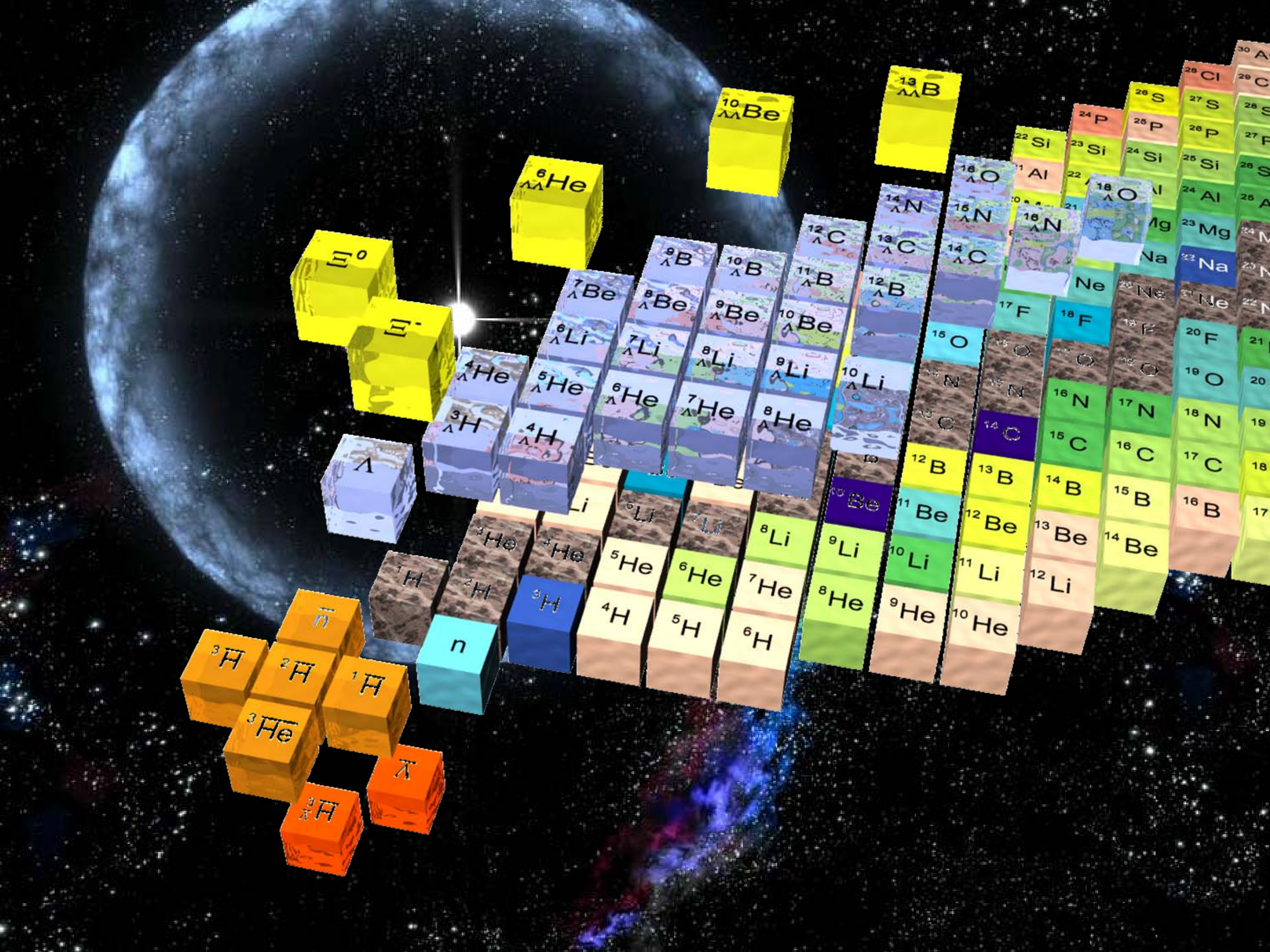

$^{13}_{\Lambda\Lambda}$B
$^{10}_{\Lambda\Lambda}$Be
$^{6}_{\Lambda\Lambda}$He
Ξ^0
Ξ^-
Λ
$^{3}_{\Lambda}$H
$^{4}_{\Lambda}$H
$^{4}_{\Lambda}$He
$^{5}_{\Lambda}$He
$^{6}_{\Lambda}$He
$^{7}_{\Lambda}$He
$^{8}_{\Lambda}$He
$^{6}_{\Lambda}$Li
$^{7}_{\Lambda}$Li
$^{8}_{\Lambda}$Li
$^{9}_{\Lambda}$Li
$^{10}_{\Lambda}$Li
$^{7}_{\Lambda}$Be
$^{8}_{\Lambda}$Be
$^{9}_{\Lambda}$Be
$^{10}_{\Lambda}$Be
$^{9}_{\Lambda}$B
$^{10}_{\Lambda}$B
$^{11}_{\Lambda}$B
$^{12}_{\Lambda}$B
$^{12}_{\Lambda}$C
$^{13}_{\Lambda}$C
$^{14}_{\Lambda}$C
$^{14}_{\Lambda}$N
$^{15}_{\Lambda}$N
$^{16}_{\Lambda}$N
$^{16}_{\Lambda}$O
$^{18}_{\Lambda}$O
$\bar{n}$
$^{3}\bar{H}$
$^{2}\bar{H}$
$^{1}\bar{H}$
$^{3}\overline{He}$
$\bar{\Lambda}$
$^{3}_{\bar{\Lambda}}\bar{H}$
n
^{1}H
^{2}H
^{3}H
^{4}H
^{5}H
^{6}H
^{3}He
^{4}He
^{5}He
^{6}He
^{7}He
^{8}He
^{9}He
^{10}He
^{6}Li
^{7}Li
^{8}Li
^{9}Li
^{10}Li
^{11}Li
^{12}Li
^{10}Be
^{11}Be
^{12}Be
^{13}Be
^{14}Be
^{12}B
^{13}B
^{14}B
^{15}B
^{16}B
^{14}C
^{15}C
^{16}C
^{17}C
^{16}N
^{17}N
^{18}N
^{15}O
^{19}O
^{17}F
^{18}F
^{20}F
^{21}Ne
^{22}Ne
^{22}Na
^{23}Mg
^{21}Al
^{24}Al
^{25}Al
^{22}Si
^{23}Si
^{24}Si
^{25}Si
^{24}P
^{25}P
^{26}P
^{27}P
^{26}S
^{27}S
^{28}S
^{28}Cl
^{30}Ar

Double Hypernuclei

an experimental challenge

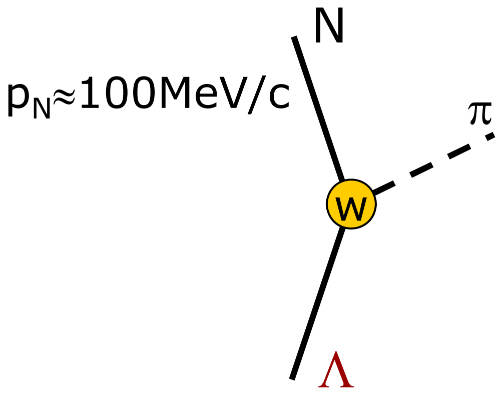
Josef Pochodzalla
XXIInd Indian-Summer School
and SPHERE School on Strangenes Nuclear Physics

- introduction/reminder
- present data
  - emulsion data
  - hybrid emulsion experiments
  - E906 - a fully electronic experiment
- future options
  - PANDA
  - $\Lambda\Lambda$ Hypernuclei in central RHIC ?
- summary

HadronPhysics2
Study of Strongly Interacting Matter
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
MAMI MAINZER MIKROTRON
Bundesministerium für Bildung und Forschung

Weak decay of hypernuclei

free Λ decay



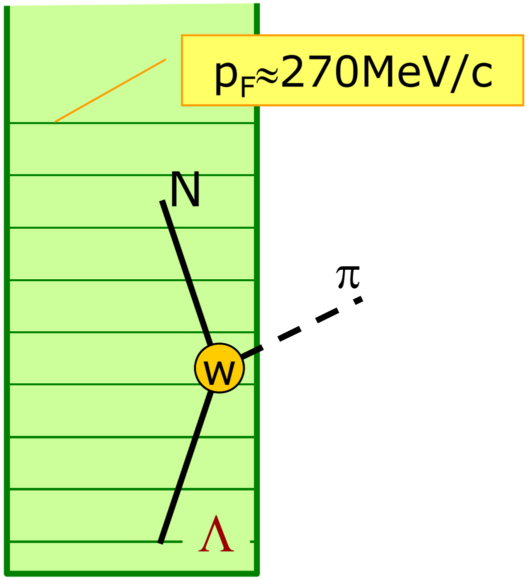
$\Lambda \rightarrow p\pi^- + 38MeV$ (64%)

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

$\tau_\Lambda = 263ps$

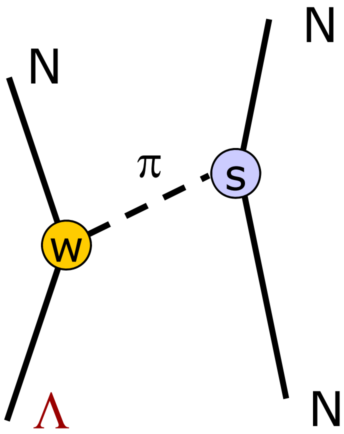
ΔI=1/2 rule

mesonic decay of hypernuclei



suppressed by Pauli blocking

non-mesonic decay of hypernuclei



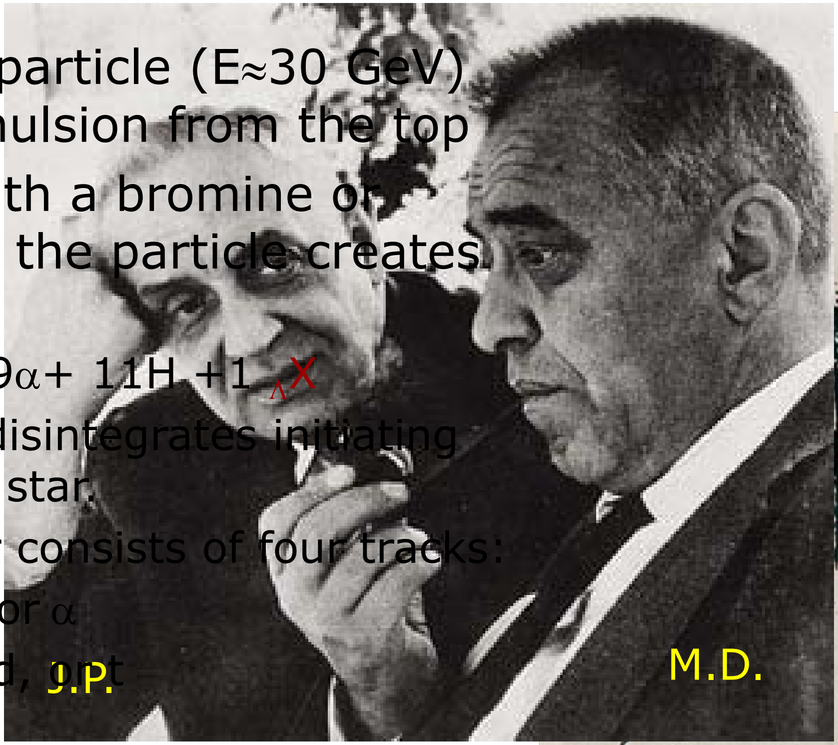
$\Lambda p \rightarrow np + 176MeV$

$\Lambda n \rightarrow nn + 176MeV$

dominant in all but the lightest hypernuclei

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)
  received 1. December 1952

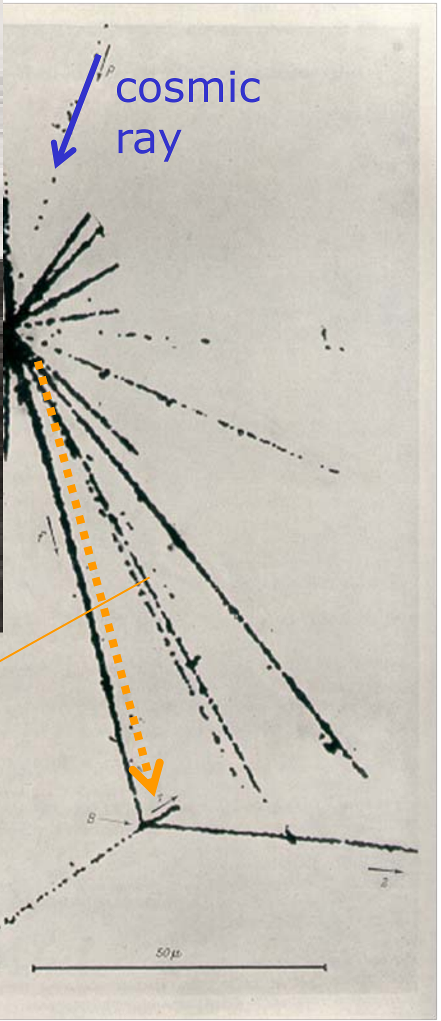


- A cosmic ray particle (E≈30 GeV) enters the emulsion from the top
- Interacting with a bromine or silver nucleus the particle creates an upper star.
  - 21 tracks: $9\alpha + 11H + 1\ {}_{\Lambda}X$
  - Finally, ${}_{\Lambda}X$ disintegrates initiating the bottom star.
  - second star consists of four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

$$t > \frac{s}{c/10} \sim \frac{80\mu m}{30000 km/s} \approx 2.6 \cdot 10^{-12} s$$

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

$\Rightarrow$ typical for weak decay



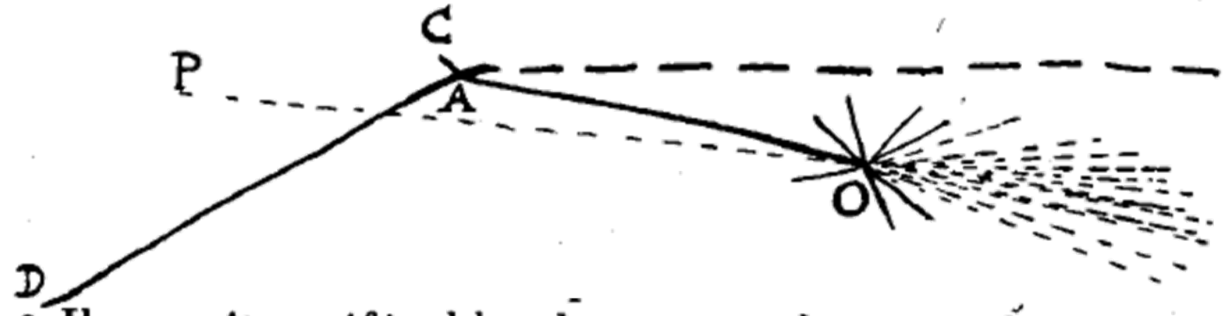
The second event

COMPTES RENDUS
HEBDOMADAIRES
DES SÉANCES
DE L'ACADÉMIE DES SCIENCES,
PUBLIÉS,
CONFORMÉMENT A UNE DÉCISION DE L'ACADÉMIE
EN DATE DU 13 JUILLET 1835,

PHYSIQUE NUCLÉAIRE. — *Émission probable d'un fragment nucléaire contenant une particule* V°. Note de MM. **Jean Crussard** et **Daniel Morellet**, présentée par M. Louis Leprince-Ringuet.

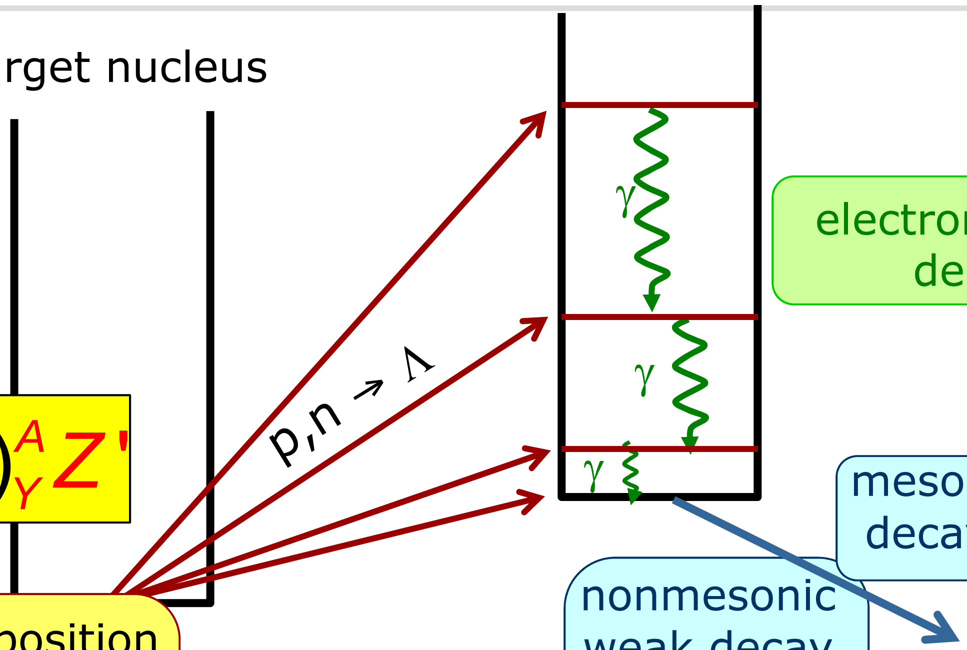
SÉANCE DU 5 JANVIER 1953. 65

probable. Un méson π est exclu (scattering trop faible). Un noyau lourd plus rapide est impossible (absence de rayons δ). On ne peut affirmer que la particule s'arrête en A, mais sa vitesse résiduelle y est en tous cas très faible.



2° Il paraît préférable de rapprocher ce phénomène d'un cas observé récemment par Danysz (⁷), dans lequel un fragment lourd ($Z \geq 8$), émis

Birth, life and death of a hypernucleus



$^{A}Z(a_{in},b_{out})^{A}_{Y}Z'$

electromagnetic decays

mesonic decays
$\Lambda \rightarrow p\pi^{-}$
$\Lambda \rightarrow n\pi^{0}$

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

hadronic decay in emulsion, heavy ion recations

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

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

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

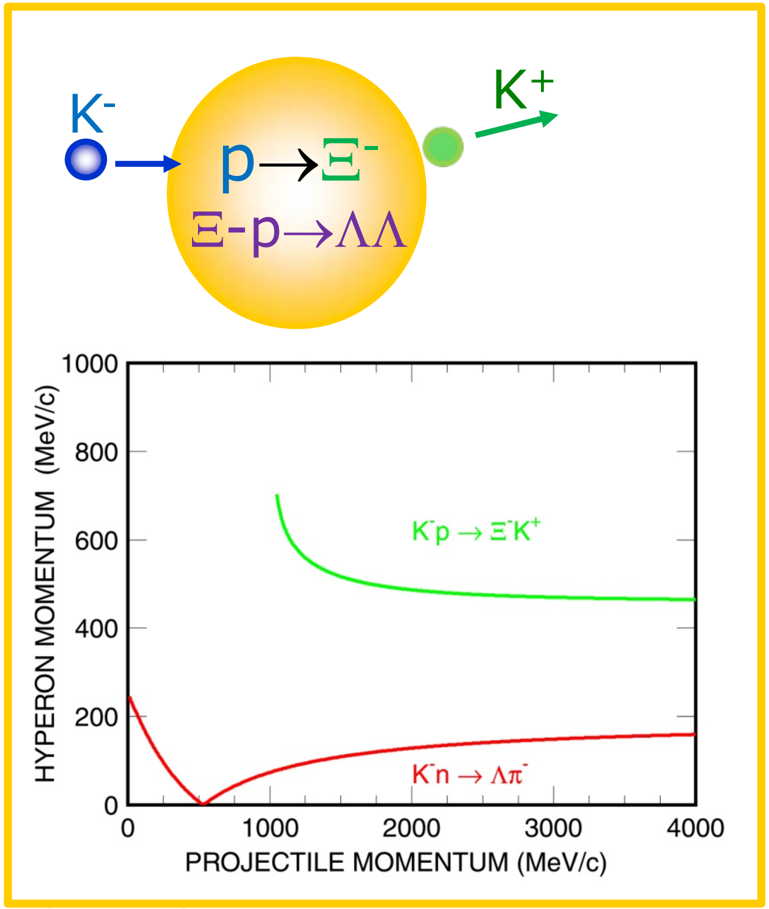
electroproduction
$(e,e' K^{+})$, (γ,K^{+})
Jlab, MAMI-C

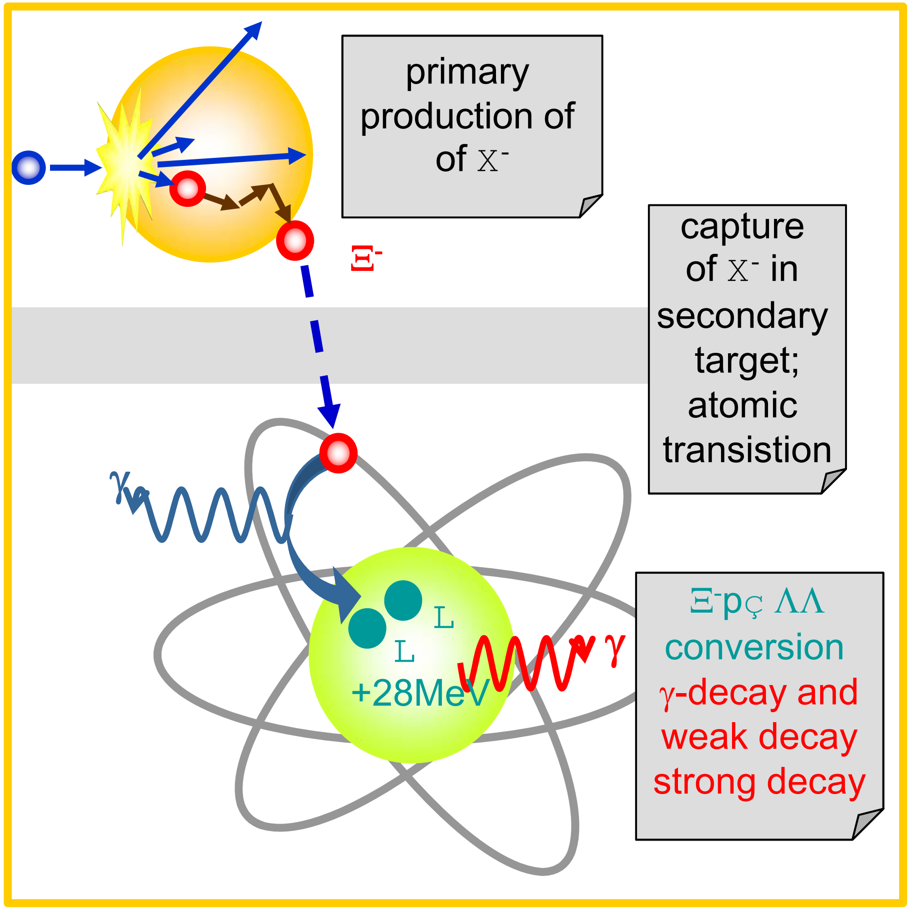
$$^{A}_{Y}Z \rightarrow \pi^{-} + {}^{A}(Z+1)$$

Production of ΛΛ Hypernuclei

- simultaneous implantation of two Λ's impossible
- Ξ^- conversion in 2Λ: $\Xi^- + p \rightarrow \Lambda + \Lambda$ + 28MeV

⇒large probability that two Λ's stick to same nucleus





primary production of of Χ-

capture of Χ- in secondary target; atomic transition

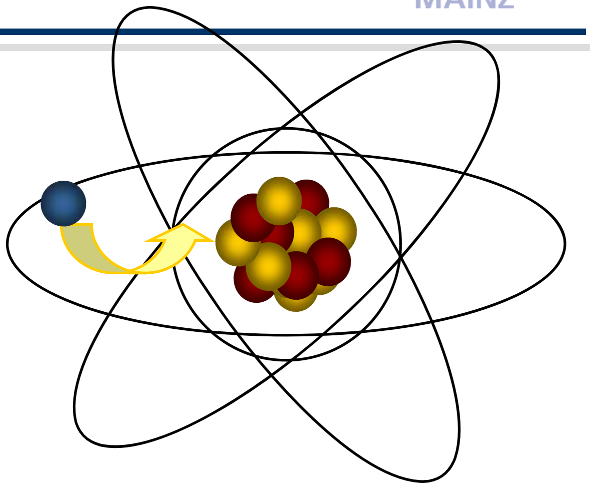
Ξ-pç ΛΛ conversion
γ-decay and weak decay strong decay

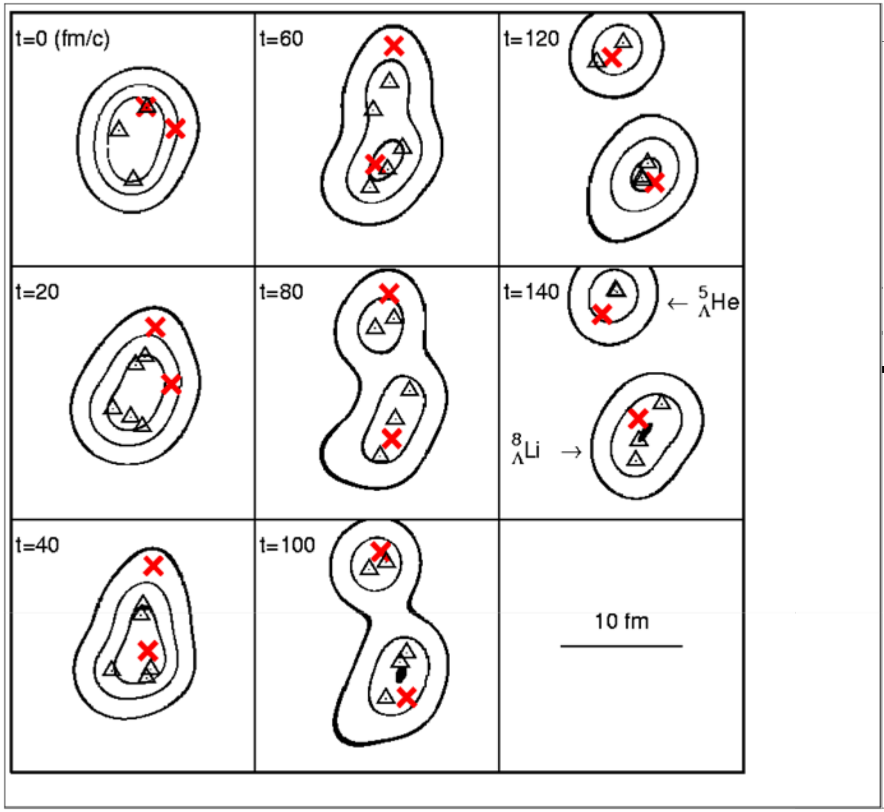
- two-step process

⇒ spectroscopic studies only via the decay products

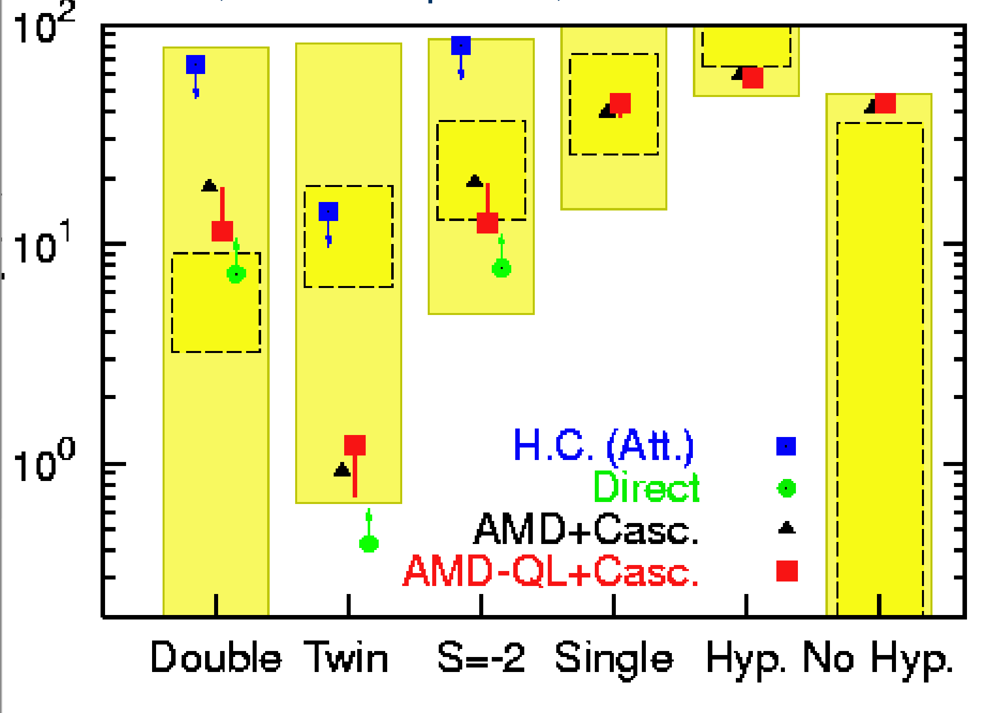
Ξ^- capture

- Ξ^--atoms: x-rays
- conversion
  - Ξ^-**(dss)** p**(uud)** → Λ**(uds)** Λ**(uds)**
  - ΔQ = 28 MeV
- Conversion probability few %



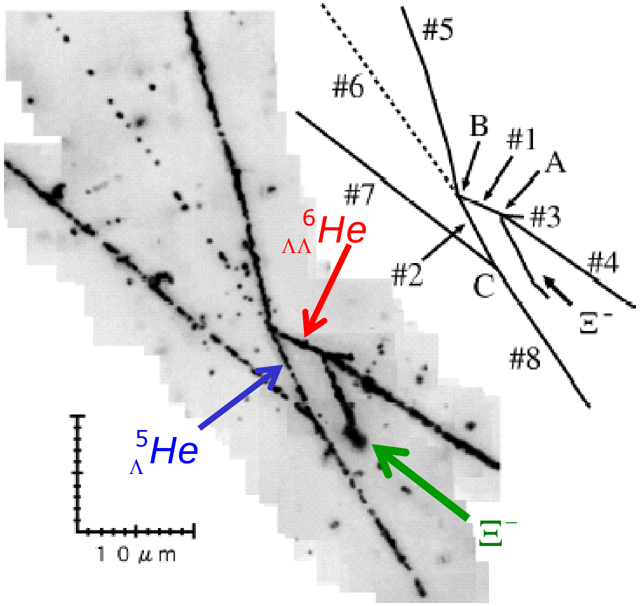


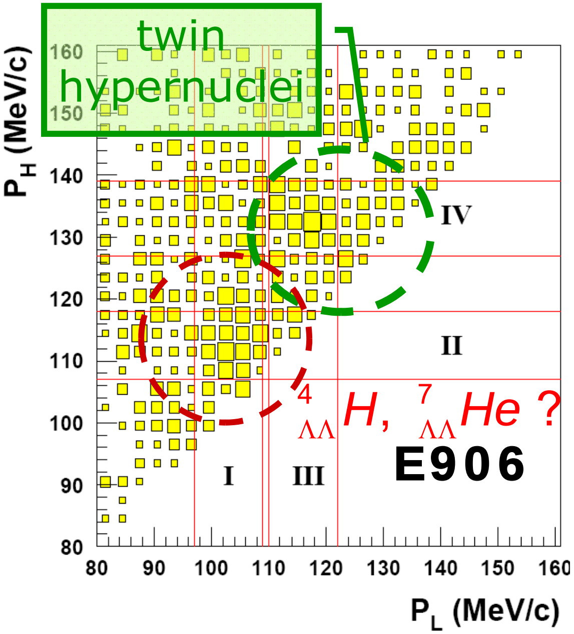
Y. Hirata, J. Randrup *et al.*,

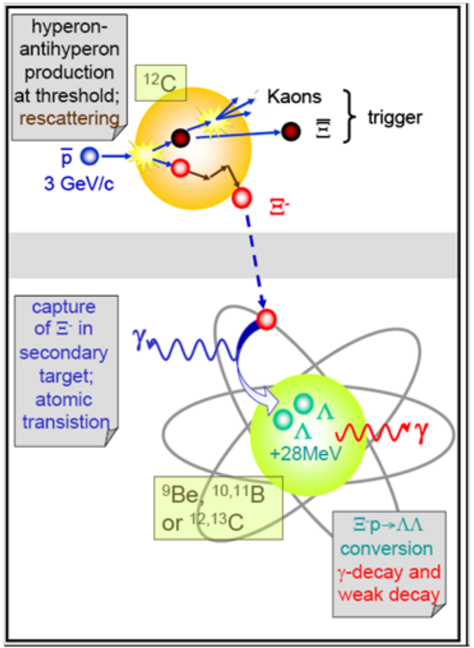


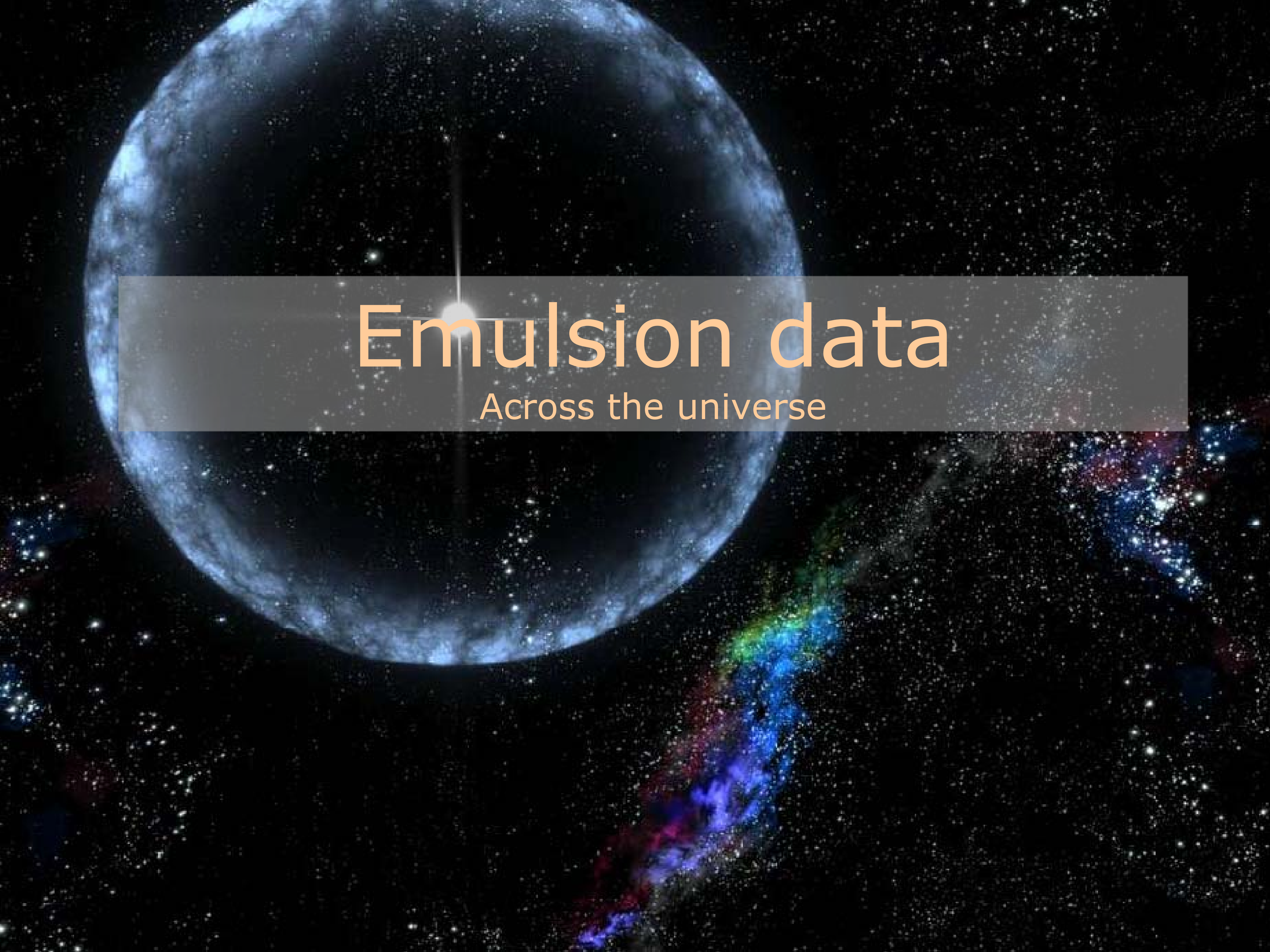
Decay Products of ΛΛ Hypernuclei

- nuclear fragments after weak decay ⇒ emulsion   hadron+nucleus
  - detection of charged products only
  - limited to light nuclei
- weak decay products (pions)   ⇒ BNL-AGS E906 $^{9}Be(K^{-},K^{+})X$
  - Electronic experiment but resolution limited
  - no information on excited states
  - interpretation not unique because π momenta are similar
- γ- spectroscopy prior weak decay   ⇒ PANDA $\bar{p}+A$
  - no excited states observed yet, but theoretically predicted
  - How to identify the nucleus ?





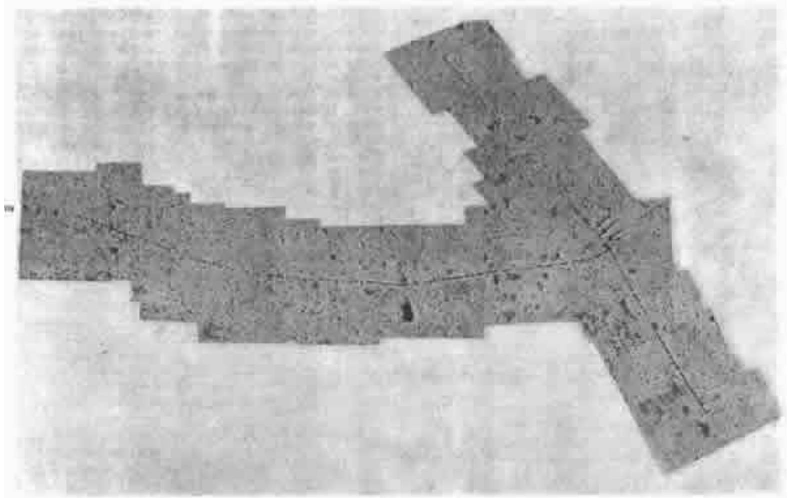




Emulsion data

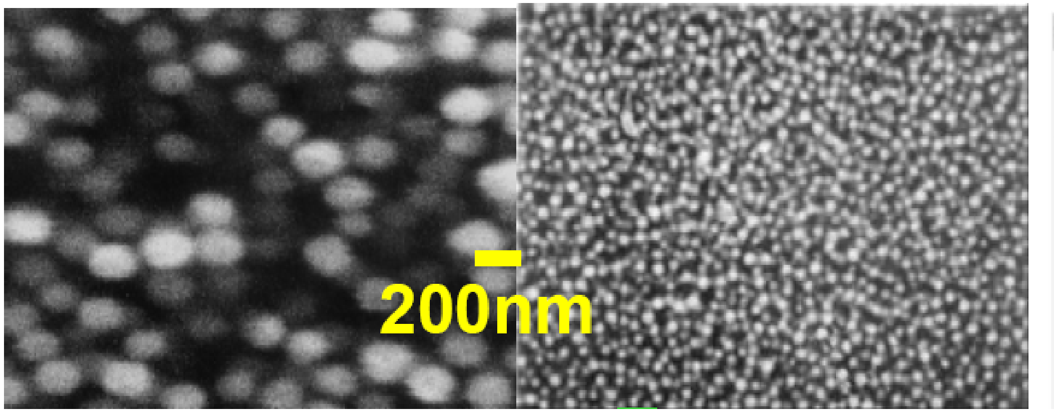
Across the universe

Nuclear Emulsion



- Cecil Frank Powell (1903-1969)
  - Nobel Prize in Physics 1950
- 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 (today: 40nm)
  - during developement excited grains are reduced to elemental silver
  - density 3g/cm^3
- Data acquisition by automated means (e.g. by scanning the film with a CCD camera) is now possible.

Composition of Emulsions



E373 emulsion (ET-7C,D)

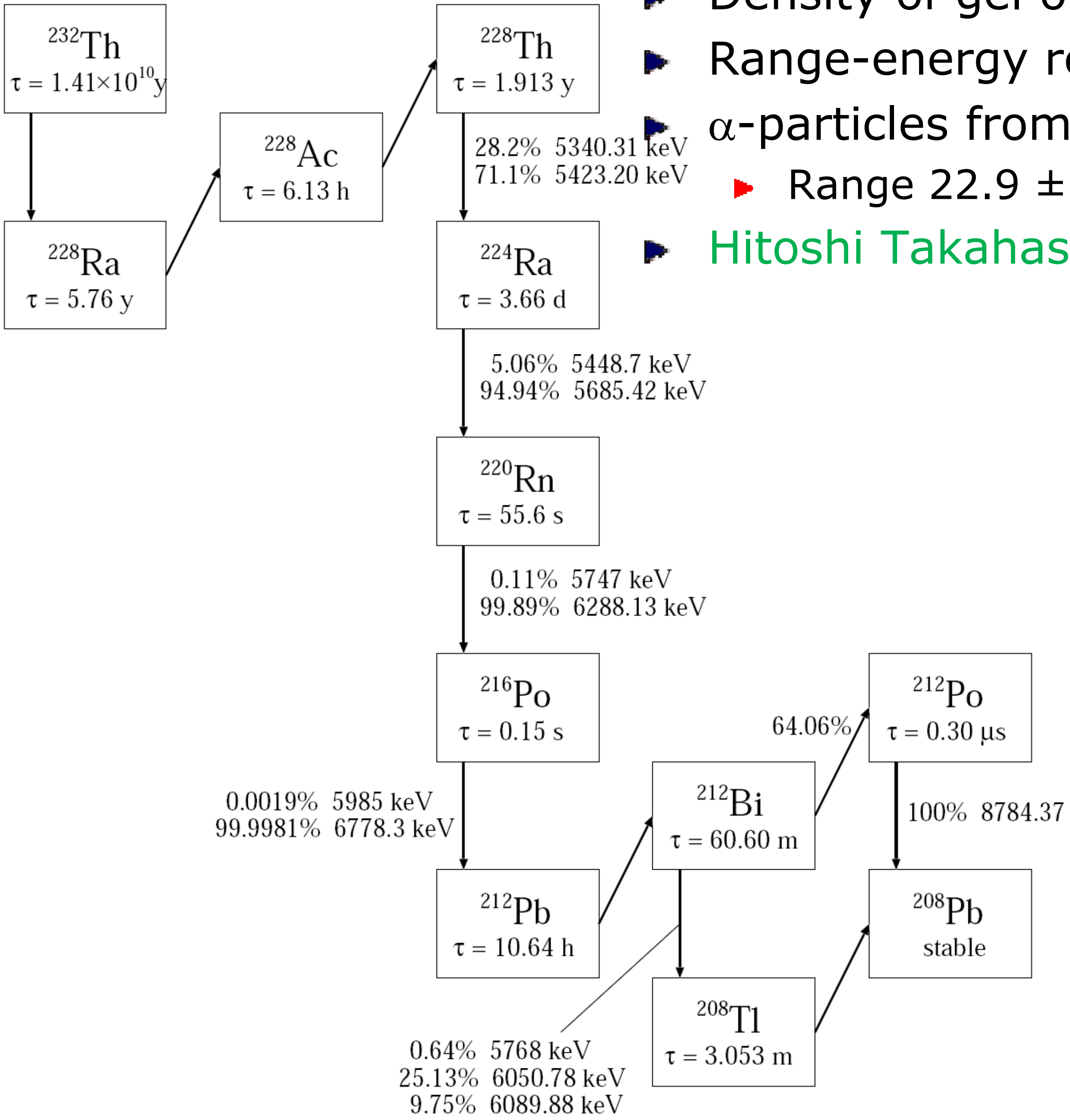
NIT(Nano Image Tracker
developed by Nagoya

Table 2.6: The composition of the Fuji ET-7C and ET-7D emulsion.

material	weight ratio (%)	mol ratio (%)	
I	0.3	0.06	heavy elements
Ag	45.4	11.2	
Br	33.4	11.1	
S	0.2	0.2	
O	6.8	11.3	light elements
N	3.1	5.9	
C	9.3	20.6	
H	1.5	40.0	

Emulsion - calibration

- Density of gel of emulsion may vary
- Range-energy relation needs to be calibrated
- α-particles from ^{212}P and ^{228}Th;
  - Range 22.9 ± 0.3 μm for 5.4MeV α from ^{228}Th
- Hitoshi Takahashi, thesis 2003



^{232}Th
$\tau = 1.41\times10^{10}$ y

^{228}Ra
$\tau = 5.76$ y

^{228}Ac
$\tau = 6.13$ h

^{228}Th
$\tau = 1.913$ y

28.2% 5340.31 keV
71.1% 5423.20 keV

^{224}Ra
$\tau = 3.66$ d

5.06% 5448.7 keV
94.94% 5685.42 keV

^{220}Rn
$\tau = 55.6$ s

0.11% 5747 keV
99.89% 6288.13 keV

^{216}Po
$\tau = 0.15$ s

0.0019% 5985 keV
99.9981% 6778.3 keV

^{212}Pb
$\tau = 10.64$ h

^{212}Bi
$\tau = 60.60$ m

0.64% 5768 keV
25.13% 6050.78 keV
9.75% 6089.88 keV

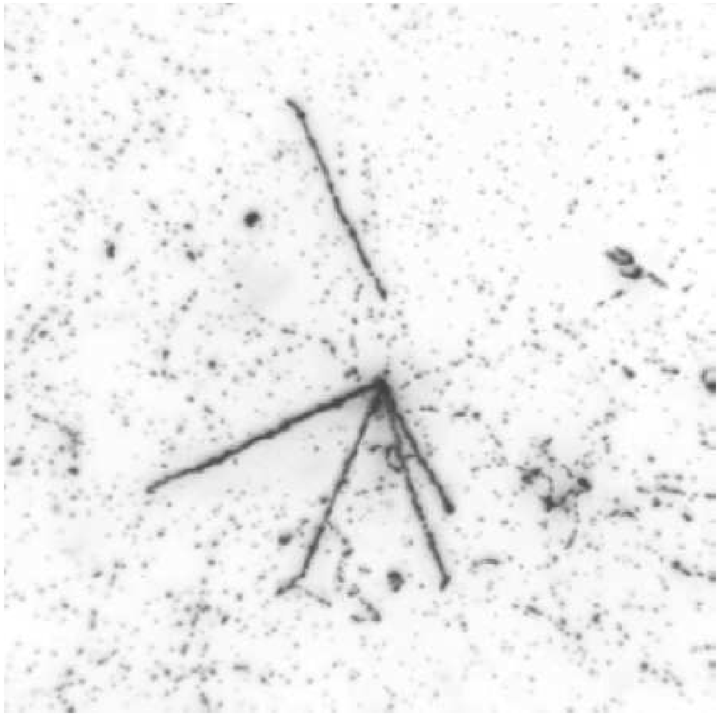
64.06%

^{212}Po
$\tau = 0.30$ μs

100% 8784.37

^{208}Tl
$\tau = 3.053$ m

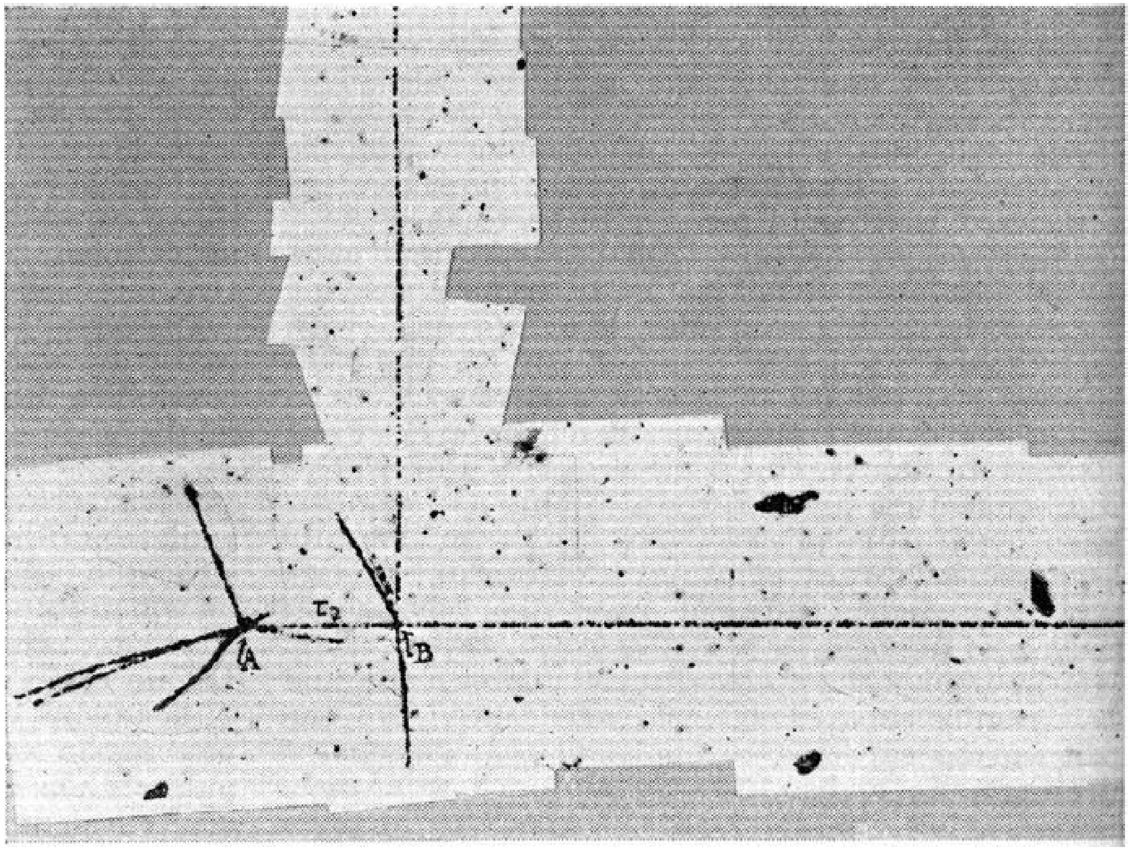
^{208}Pb
stable



168 NATURE July 31, 1948 Vol. 162

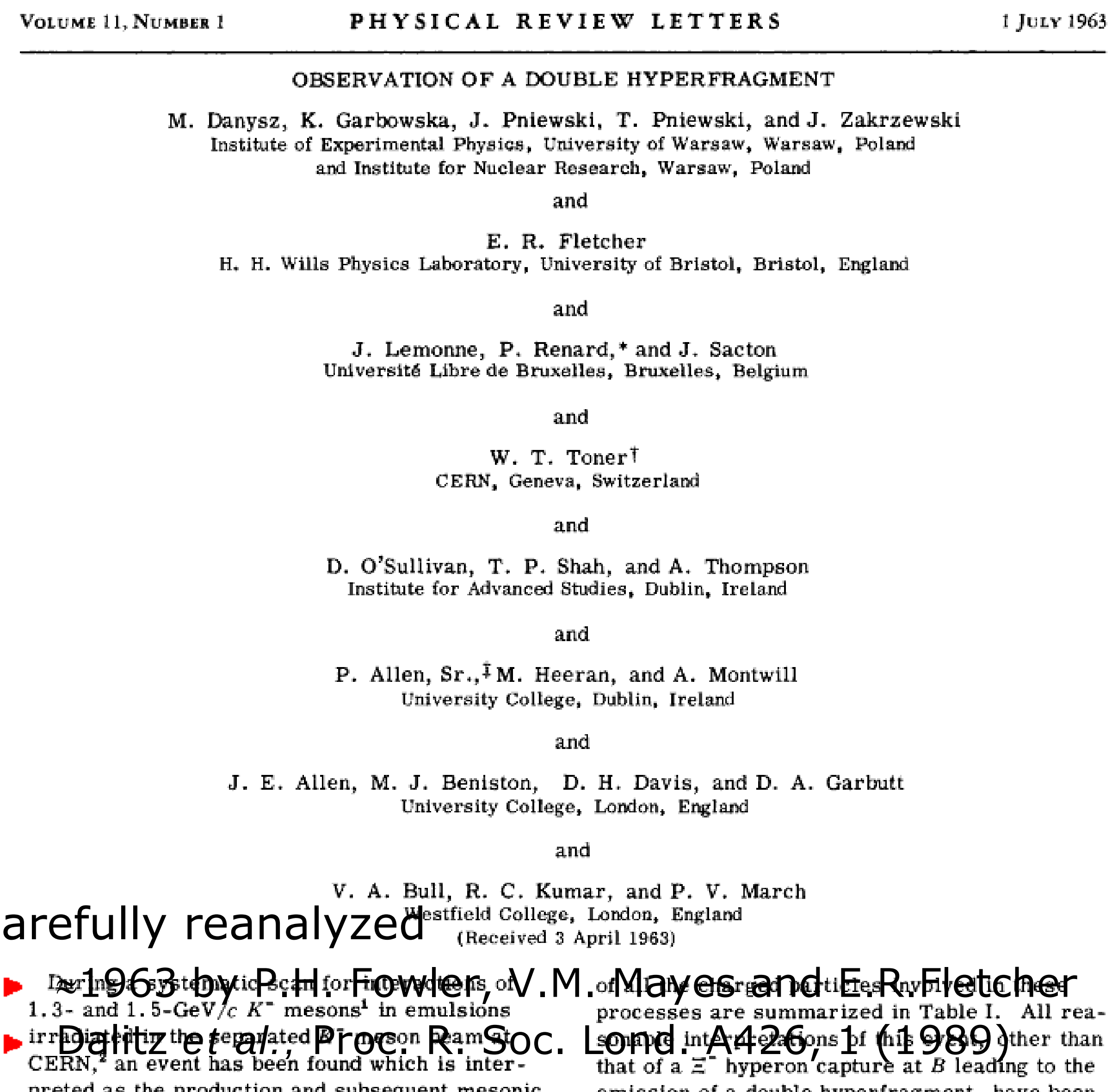
OBSERVATIONS ON THE PRODUCTION OF MESONS BY COSMIC RADIATION

By DR. G. P. S. OCCHIALINI
AND
DR. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol



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

W. T. Toner†
CERN, Geneva, Switzerland

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 emission of a double hyperfragment, have been

- 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 observed first event

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\text{MeV}$$

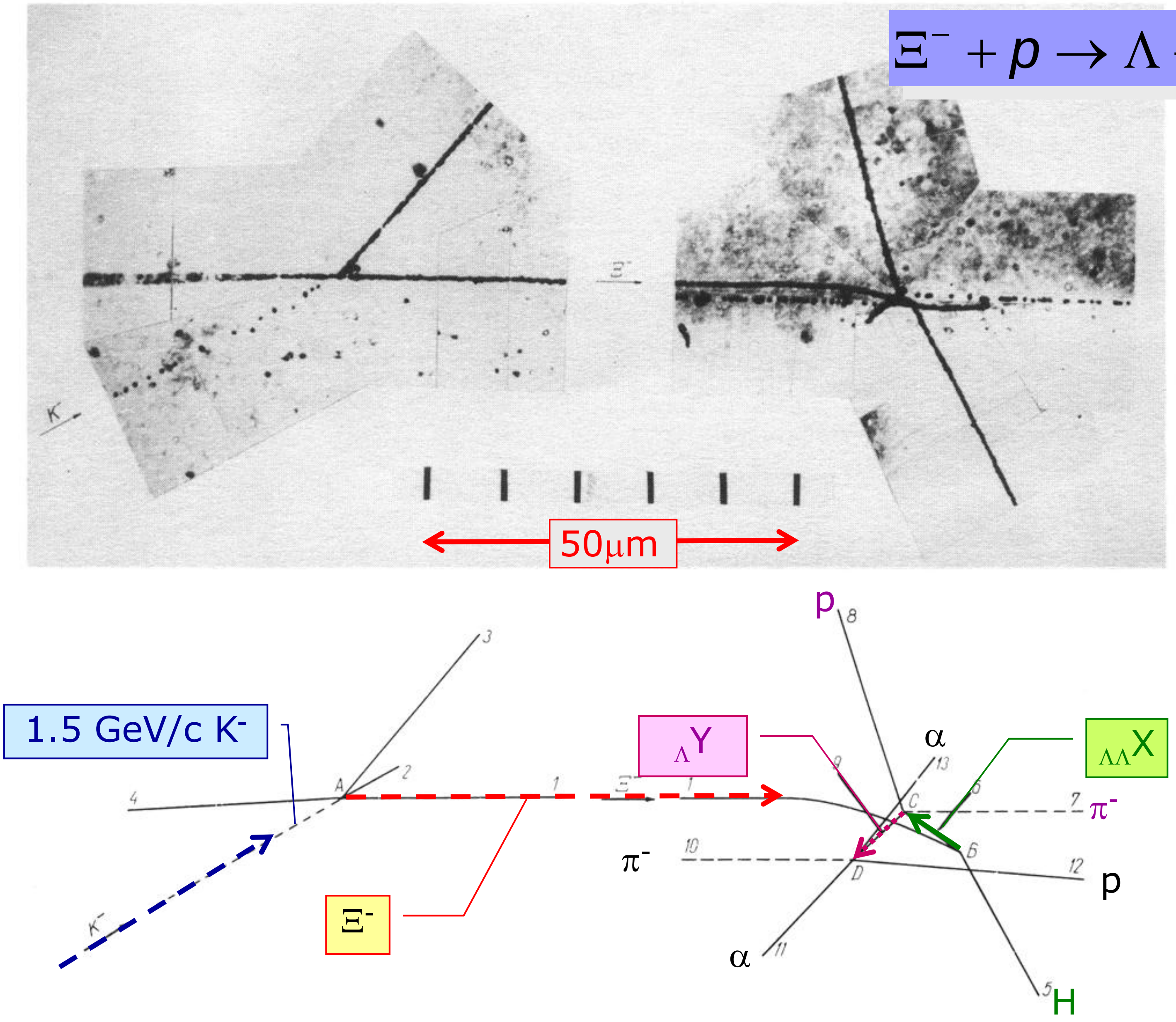


FIG. 1. A photomicrograph and a schematic drawing of the production of a Ξ^- hyperon in a 1.5-GeV/*c* K^--meson interaction at *A* followed by capture at rest of the Ξ^- hyperon at *B* with the emission of a double hyperfragment decaying in cascade at *C* and *D*.

Analysis of the Danysz-Event

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

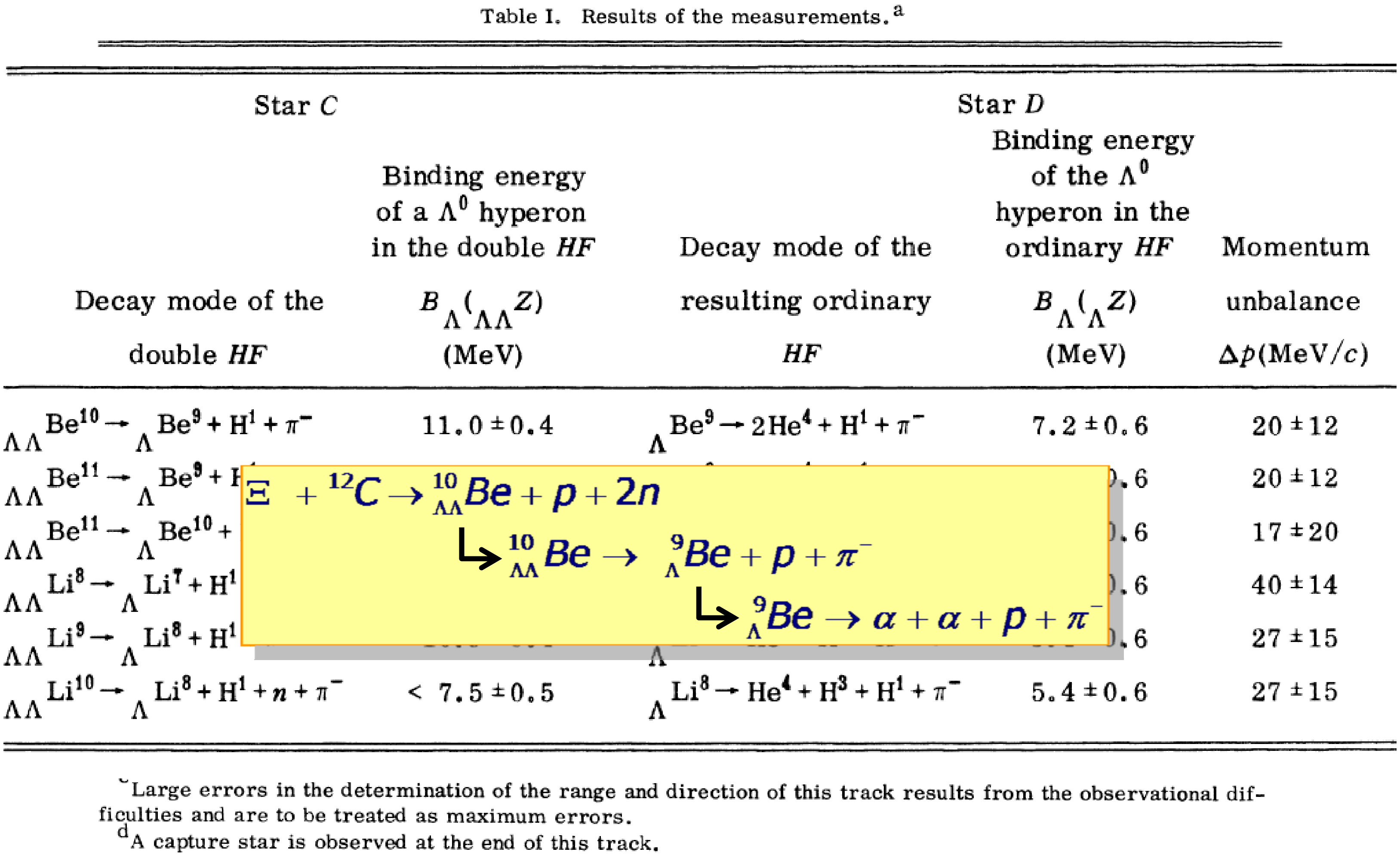


Table I. Results of the measurements.[a]

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

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

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

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

---

[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 of the decay products at point C
  - for example

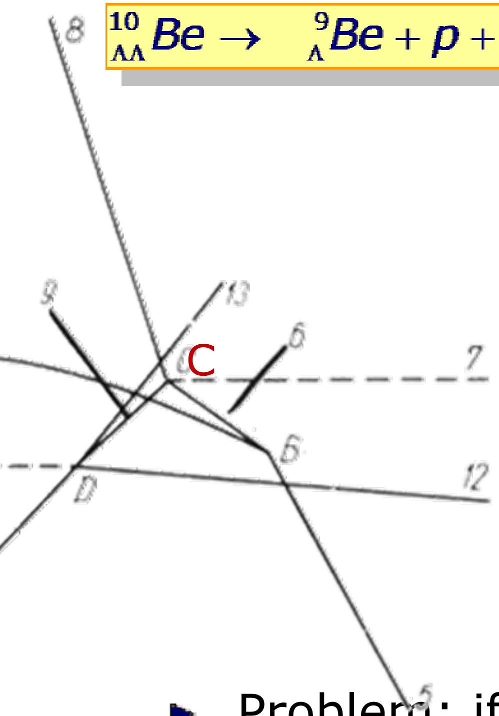
$${}^{9}_{\Lambda}Be \rightarrow \alpha + \alpha + p + \pi^-$$

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

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

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

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



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

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

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

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

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

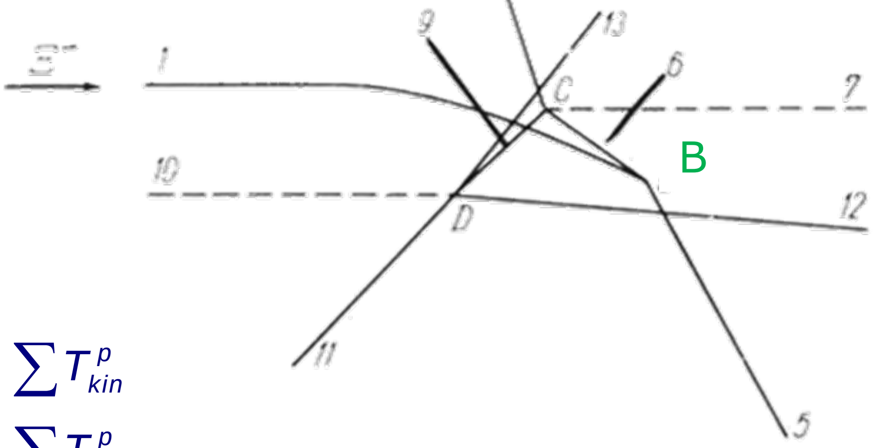
$$= m\left({}^{8}Be\right) + 2m(\Lambda) - m\left({}^{9}_{\Lambda}Be\right) - m(p) - m(\pi^-) - \sum T'_{kin}$$

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

- Problem: if excited states in ${}^{9}_{\Lambda}Be$ involved → $B_{\Lambda\Lambda}$ overestimated
- Result: $B_{\Lambda\Lambda} = 17.5 \pm 0.4\,\mathrm{MeV}$

Production analysis

- Capture of the negative Ξ by an atom
- Ξ^- Binding energy B_Ξ
- $B_{\Lambda\Lambda}$ from point B



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

$$m(\Xi) - B_\Xi + m({}^{12}C) = m\left({}^{10}_{\Lambda\Lambda}Be\right) + m({}^3H) + \sum T^p_{kin}$$

$$m\left({}^{10}_{\Lambda\Lambda}Be\right) = m(\Xi) - B_\Xi + m({}^{12}C) - m({}^3H) - \sum T^p_{kin}$$

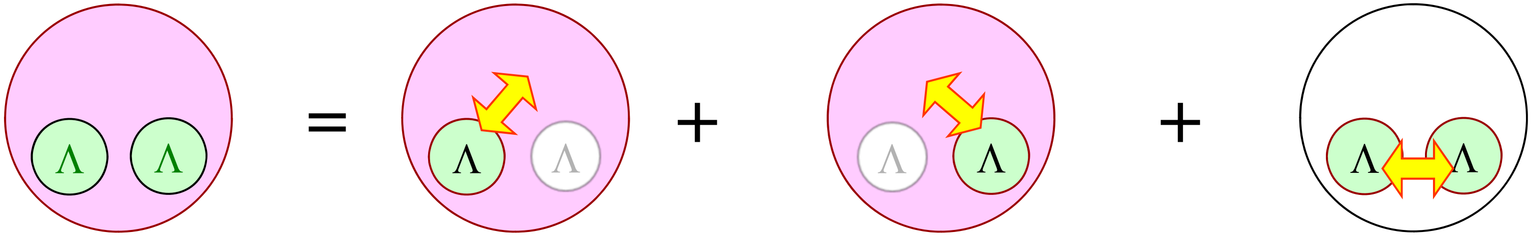
$$B_{\Lambda\Lambda}\left({}^{10}_{\Lambda\Lambda}Be\right) = m\left({}^8Be\right) + 2m(\Lambda) - m\left({}^{10}_{\Lambda\Lambda}Be\right)$$

$$= m\left({}^8Be\right) + 2m(\Lambda) - m(\Xi) + B_\Xi - m({}^{12}C) + m({}^3H) + \sum T^p_{kin}$$

- $B_{\Lambda\Lambda} = 10.9 \pm 0.6$ MeV
- Lower limit

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

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

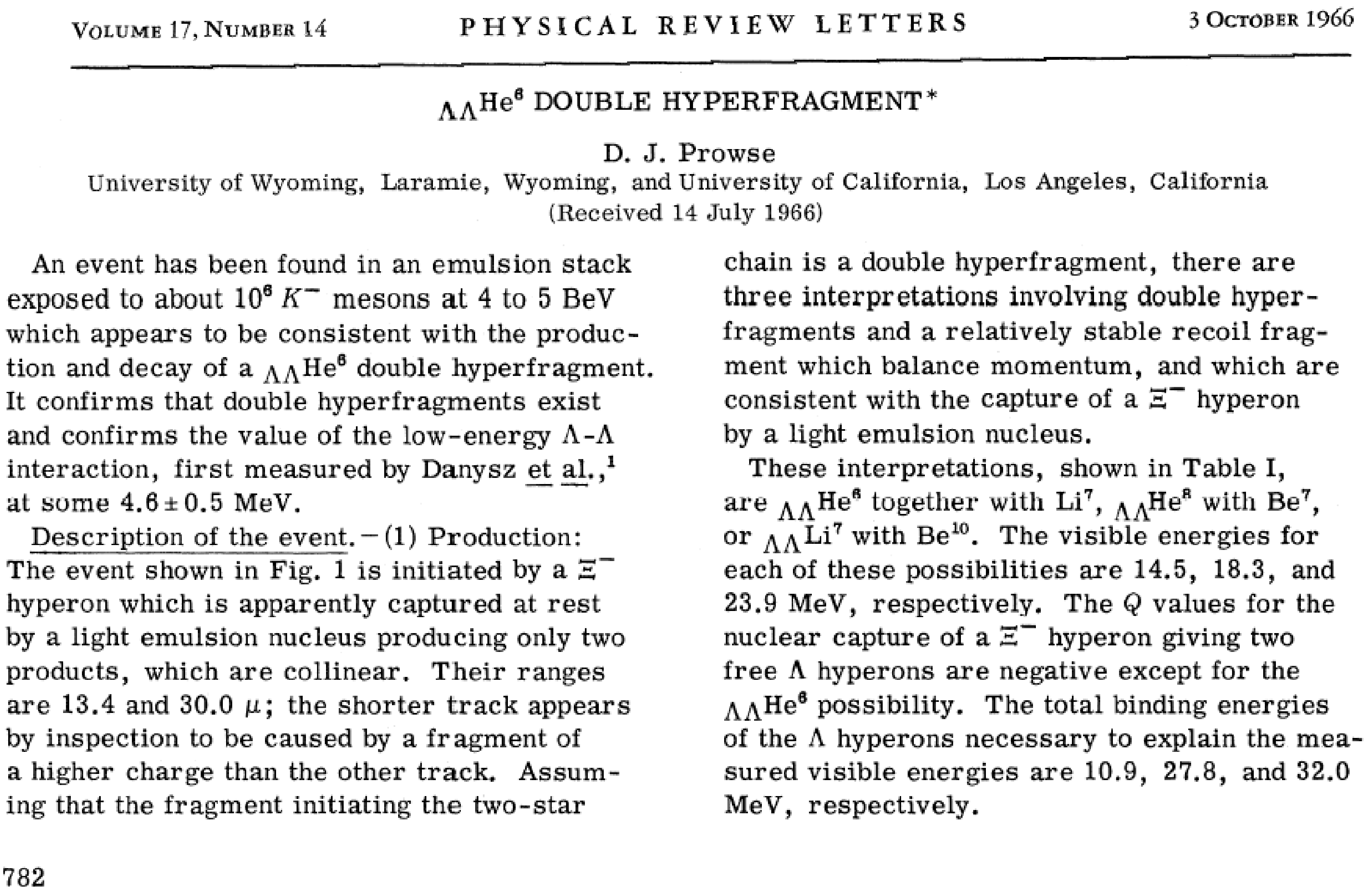
$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (4.3 \pm 0.4)\mathrm{MeV}$$

- 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

$_{\Lambda\Lambda}\mathrm{He}^6$ 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 $_{\Lambda\Lambda}\mathrm{He}^6$ 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 $_{\Lambda\Lambda}\mathrm{He}^6$ together with Li^7, $_{\Lambda\Lambda}\mathrm{He}^8$ with Be^7, or $_{\Lambda\Lambda}\mathrm{Li}^7$ 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 $_{\Lambda\Lambda}\mathrm{He}^6$ 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

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

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

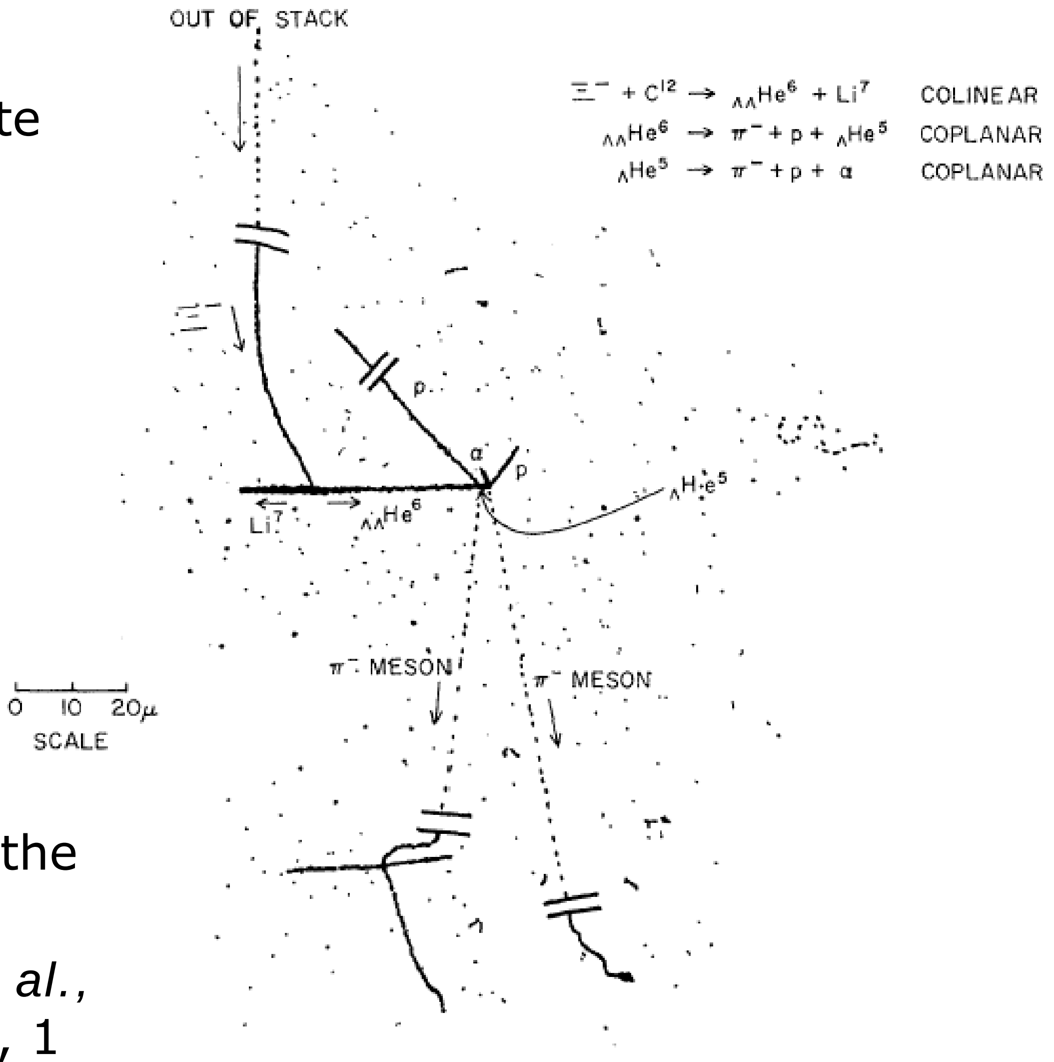
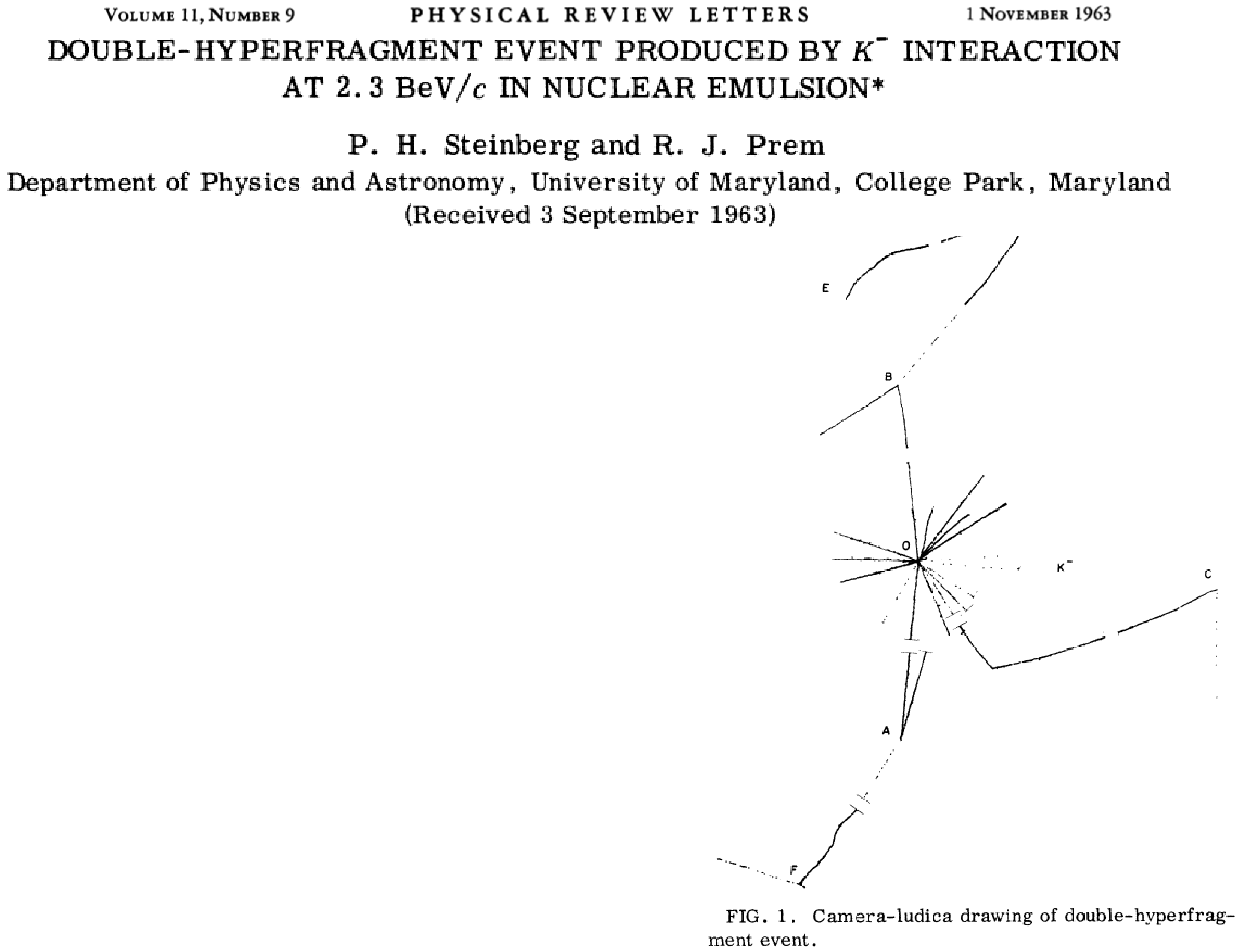


FIG. 1. Drawing of the event.

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

The first twin nuclei



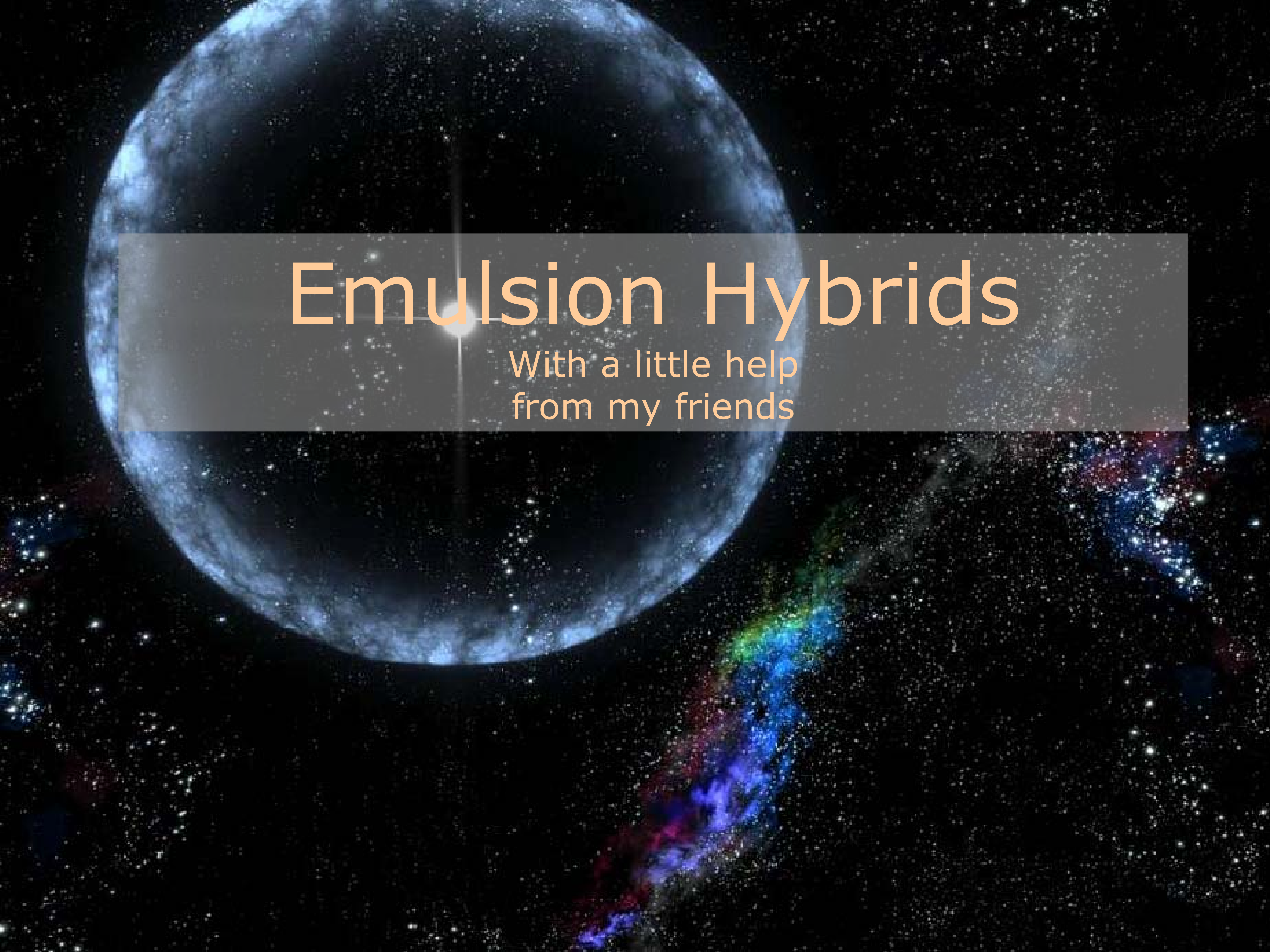
VOLUME 11, NUMBER 9 PHYSICAL REVIEW LETTERS 1 NOVEMBER 1963

DOUBLE-HYPERFRAGMENT EVENT PRODUCED BY K^- INTERACTION AT 2.3 BeV/c IN NUCLEAR EMULSION*

P. H. Steinberg and R. J. Prem
Department of Physics and Astronomy, University of Maryland, College Park, Maryland

(Received 3 September 1963)

FIG. 1. Camera-ludica drawing of double-hyperfragment event.



Emulsion Hybrids

With a little help
from my friends

Pros and Cons of Emulsion Technique

+ excellent track resolution

- 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*.

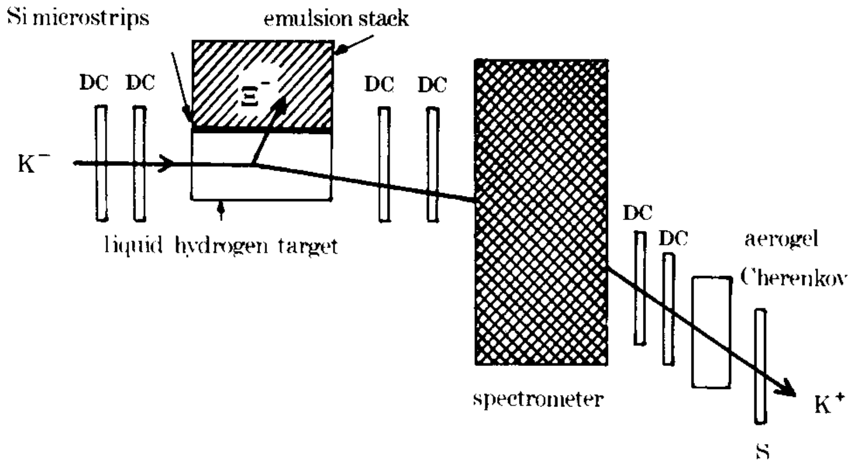
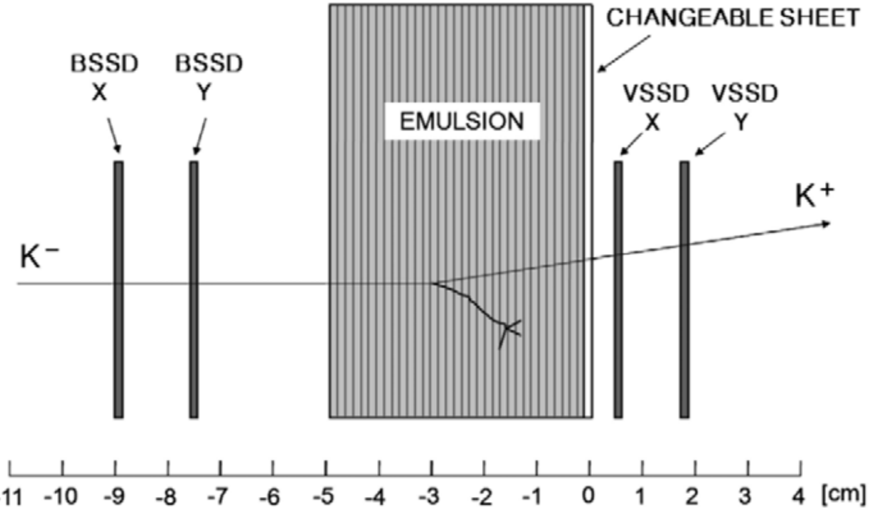


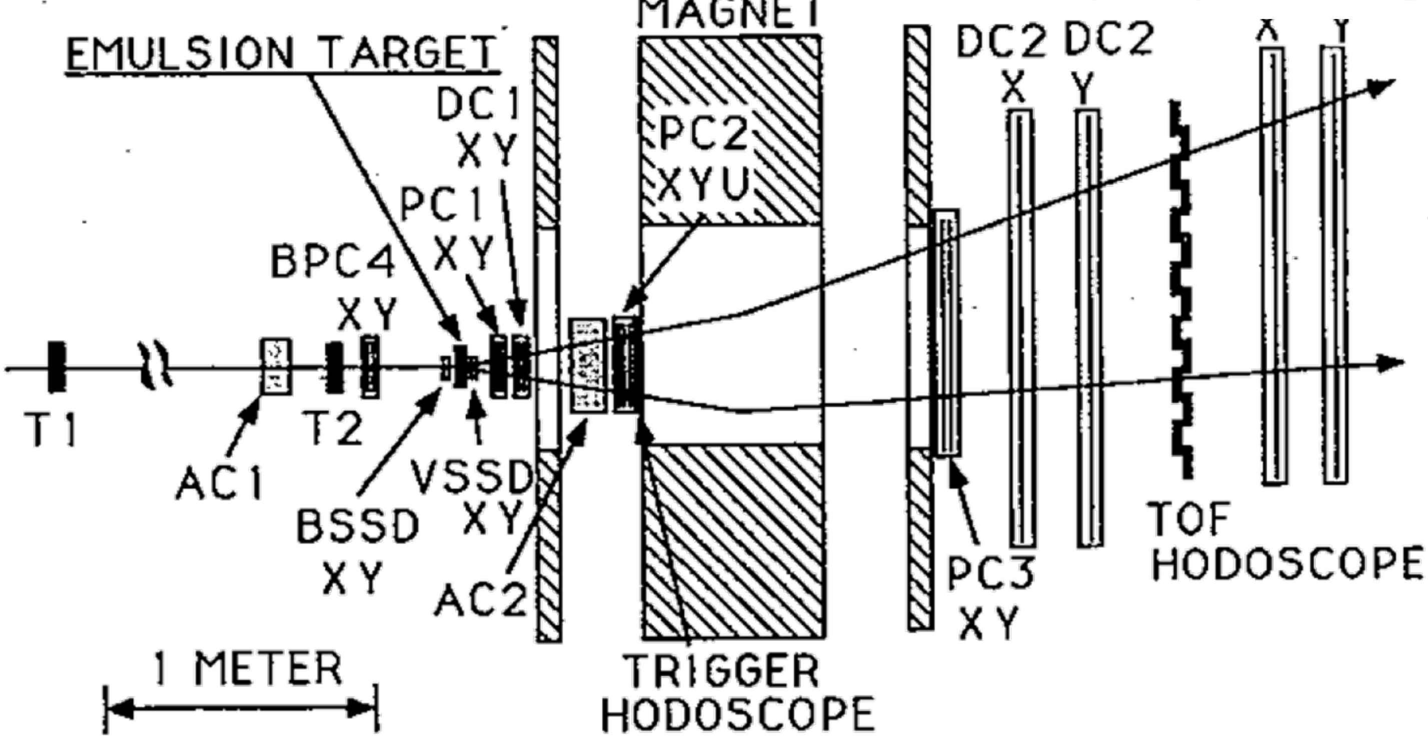
FIGURE 3. Schematic diagram of proposed hybrid emulsion experiment to study double hypernuclei. (DC is drift chamber and S is scintillator.)

- applied by KEK-E176 and KEK-E373 collaboration

KEK-E176 Experiment

- Ξ^- stops: 77.6±5.1 events
- Captured
  - 43.3% by light elements
  - 57.7% by heavy elements





The KEK-E176Event (Aoki-event)

- 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)

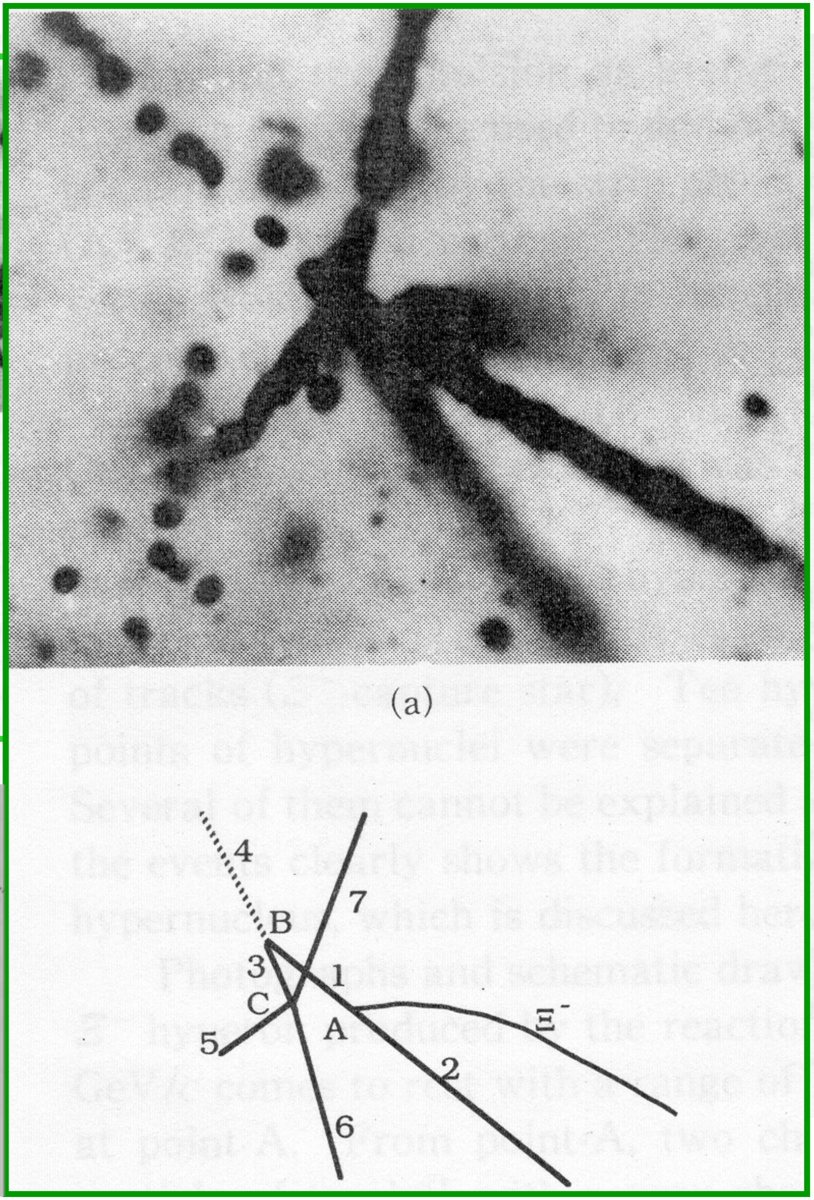
at point A: $\Xi^- + {}^{14}N \rightarrow n + {}^{14}_{\Lambda\Lambda}C^* \rightarrow n + p + {}^{13}_{\Lambda\Lambda}B$

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

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



Reanalysis of E176 Event

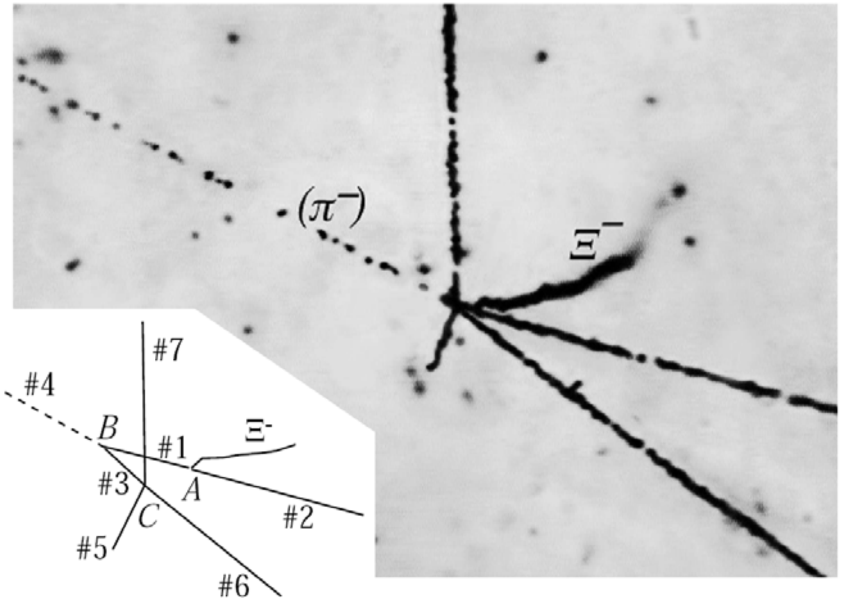
- Hitoshi Takahashi, thesis 2003; S. Aoki *et al.*, Nucl. Phys. **A828** (2009) 191;
- Allow for excited state
- Use recalibrated range-energy relation
- Updated values of hyperon and meson mases
  - PDG 2006: M(Ξ^-)= 1321.31±0.13 MeV
  - PDG 2008: M(Ξ^-)= 1321.71±0.07
- B_Ξ=0.17MeV (atomic 3D state in ^{14}N+Ξ system)

$$^{14}N + \Xi^- \rightarrow {}^{13}_{\Lambda\Lambda}B + p + n$$

$$^{13}_{\Lambda\Lambda}B \rightarrow {}^{13}_{\Lambda}C^*_{4.9MeV} + \pi^-$$

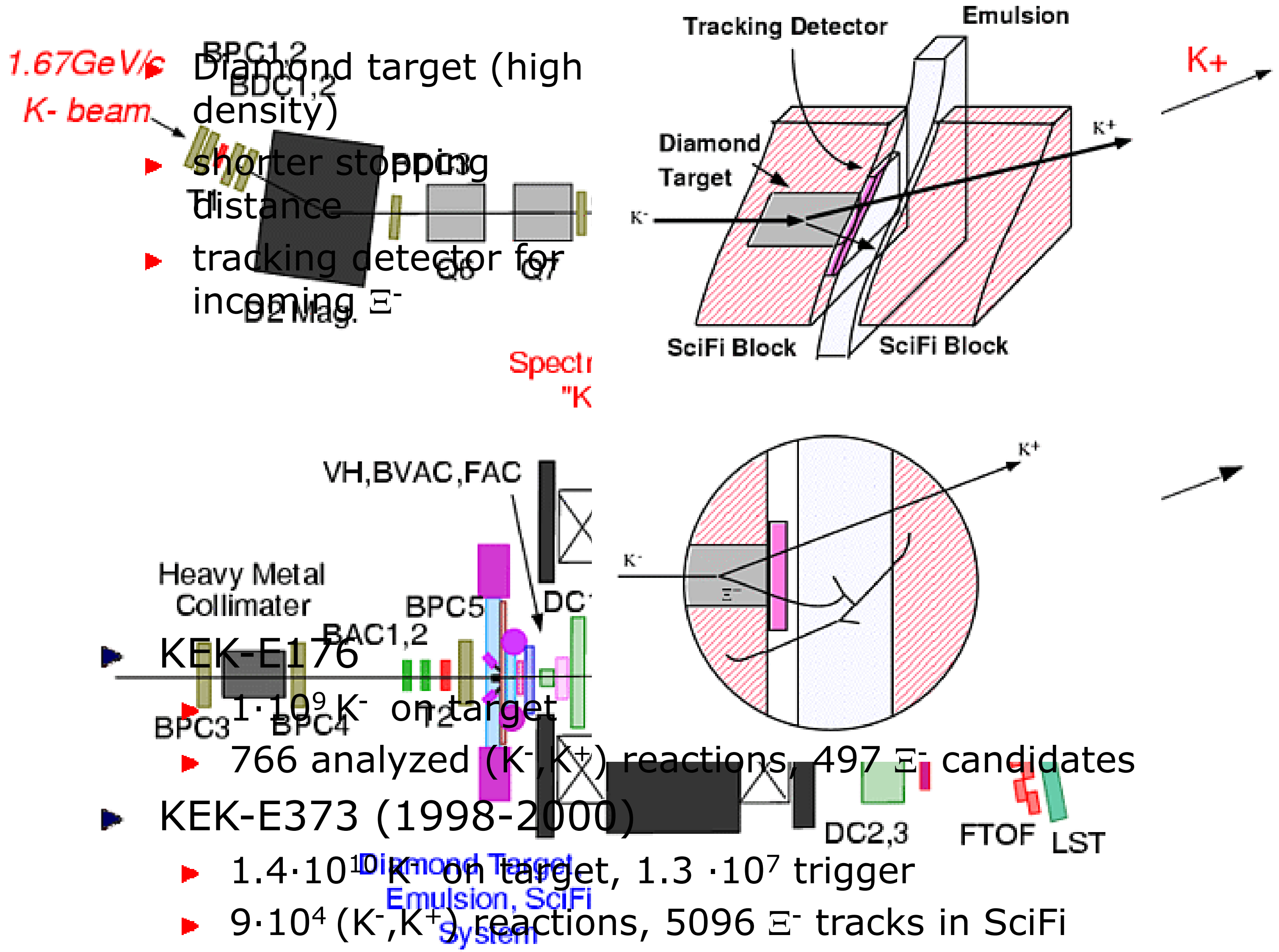
$$B_{\Lambda\Lambda} = 23.3 \pm 0.7 MeV$$

$$\Delta B_{\Lambda\Lambda} = 0.6 \pm 0.8 MeV$$



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

KEK-E373: the NAGARA event

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

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

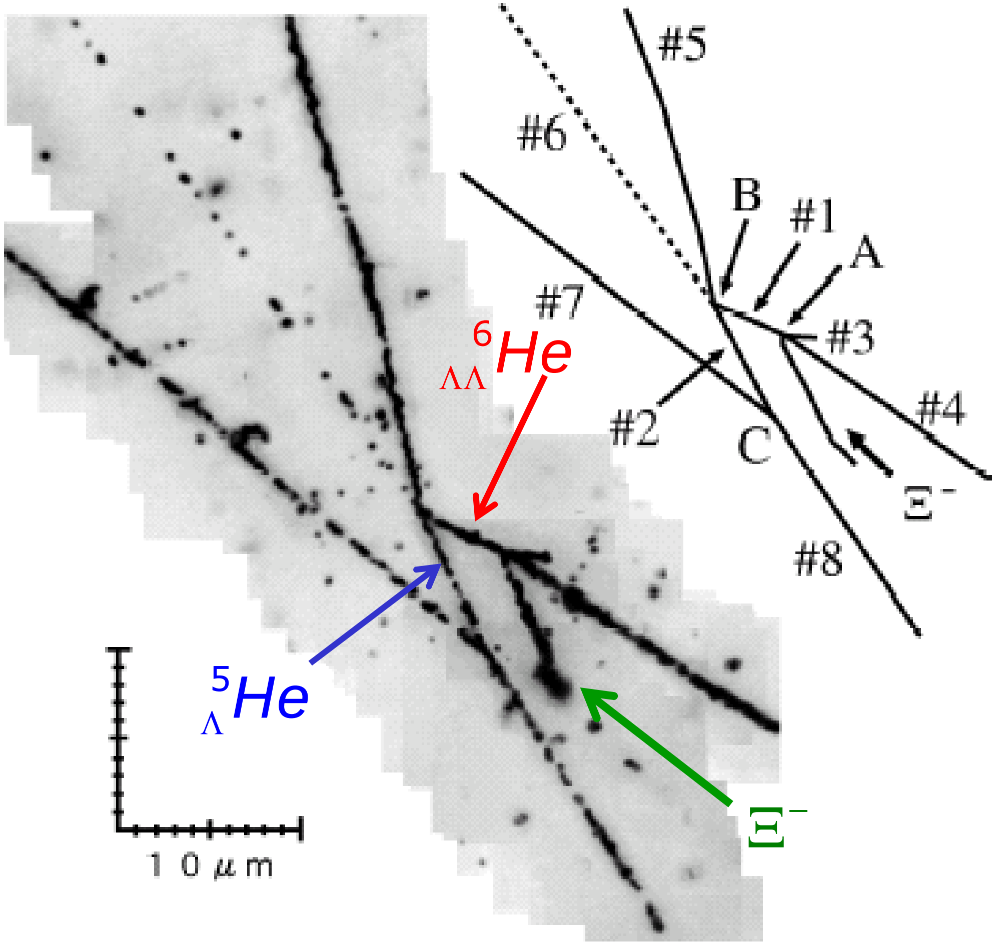
$${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi$$

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

2009:

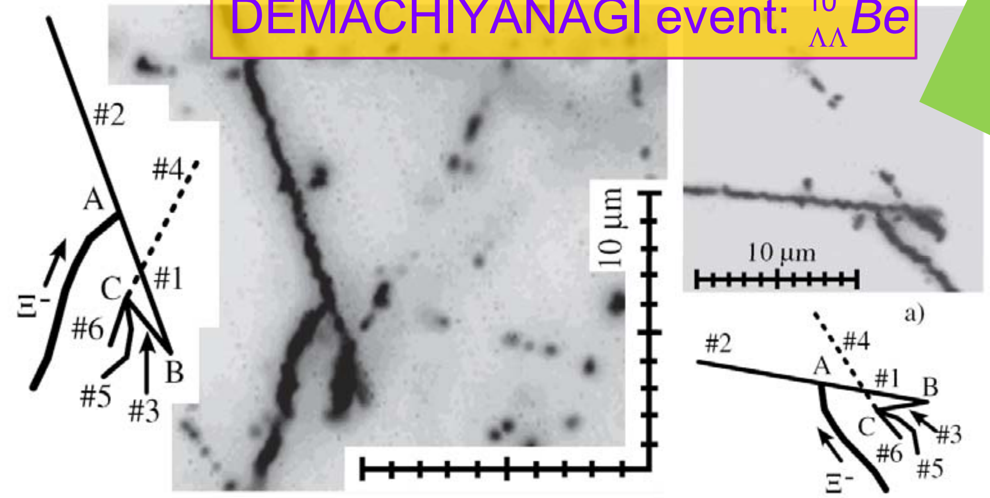
$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$$

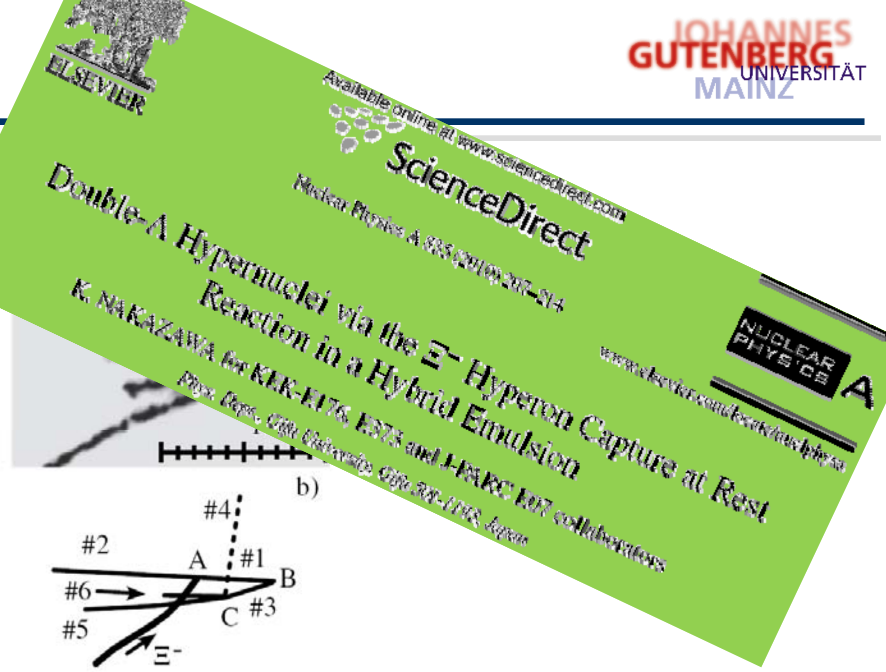
  - inconsistent with Prowse event



After HYP-X 2009

DEMACHIYANAGI event: $^{10}_{\Lambda\Lambda}Be$





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Nuclear Physics A 835 (2010) 207–214

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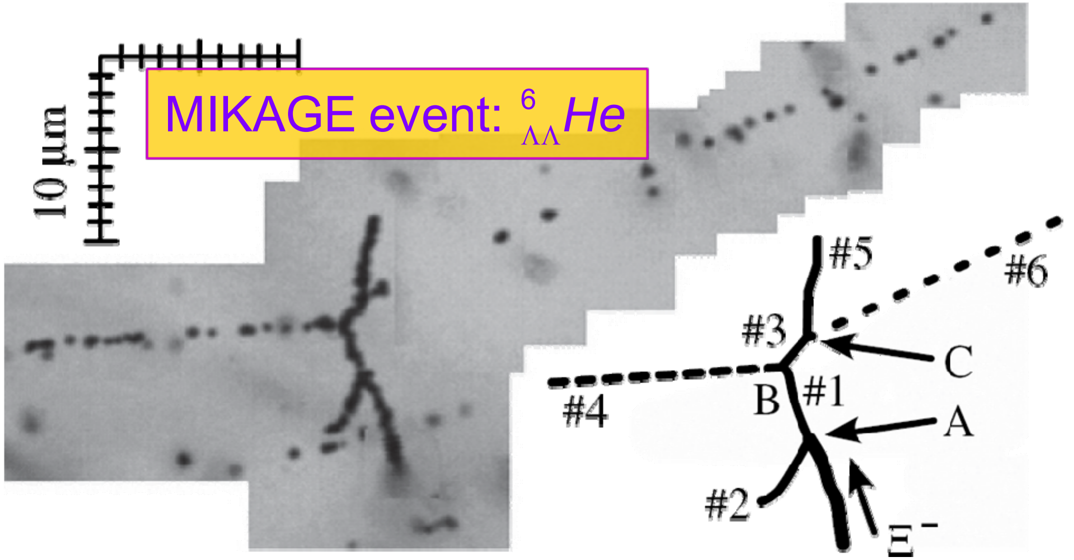
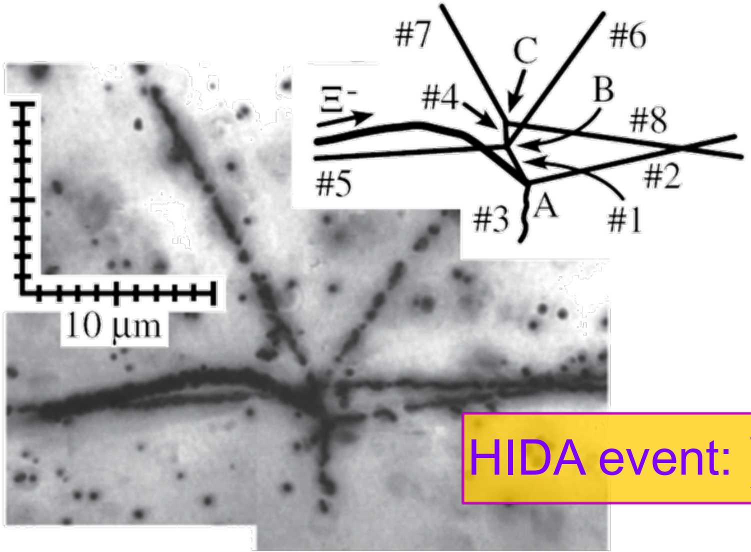
Double-Λ Hypernuclei via the Ξ⁻ Hyperon Capture at Rest Reaction in a Hybrid Emulsion

K. NAKAZAWA for KEK-E176, E373 and J-PARC E07 collaborators

Phys. Dept., Gifu University, Gifu 501-1193, Japan

MIKAGE event: $^{6}_{\Lambda\Lambda}He$

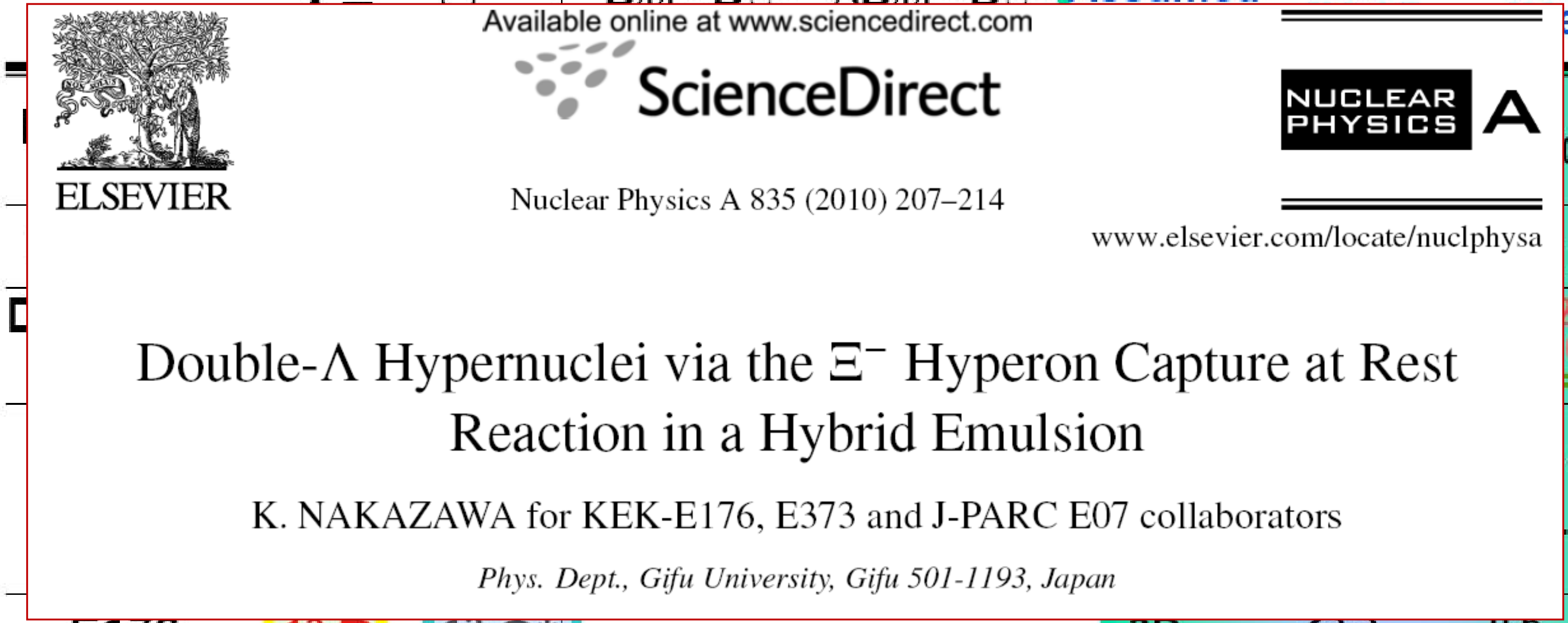




HIDA event: $^{11}_{\Lambda\Lambda}Be$ or $^{12}_{\Lambda\Lambda}Be$

Summary and perspective (1)

By checking consistency of $\Delta B_{\Lambda\Lambda}$ (NAGARA) within 3 STD. errors,



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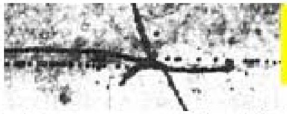
Double-Λ Hypernuclei via the Ξ^- Hyperon Capture at Rest Reaction in a Hybrid Emulsion

K. NAKAZAWA for KEK-E176, E373 and J-PARC E07 collaborators

Phys. Dept., Gifu University, Gifu 501-1193, Japan

		Ξ^-	$B_{\Lambda\Lambda}$ - B_{Ξ^-}	$\Delta B_{\Lambda\Lambda}$ - B_{Ξ^-}	Assumed	$B_{\Lambda\Lambda}$	$\Delta B_{\Lambda\Lambda}$ eV]
							0.17
							.72
							2 0.15 = 3.0
							1.23
							--
E176	$^{13}_{\Lambda\Lambda}$B -> $^{13}_{\Lambda}$C*	*Ex* = 4.9	------	-------	3D	23.3 +/- 0.7	0.6 +/- 0.8
	$^{10}_{\Lambda\Lambda}$Be -> $^{9}_{\Lambda}$Be*	*Ex* = 3.0	------	-------	not checked, yet.	14.7 +/- 0.4	1.3 +/- 0.4

M.Danysz et al., PRL.11(1963)29;
R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

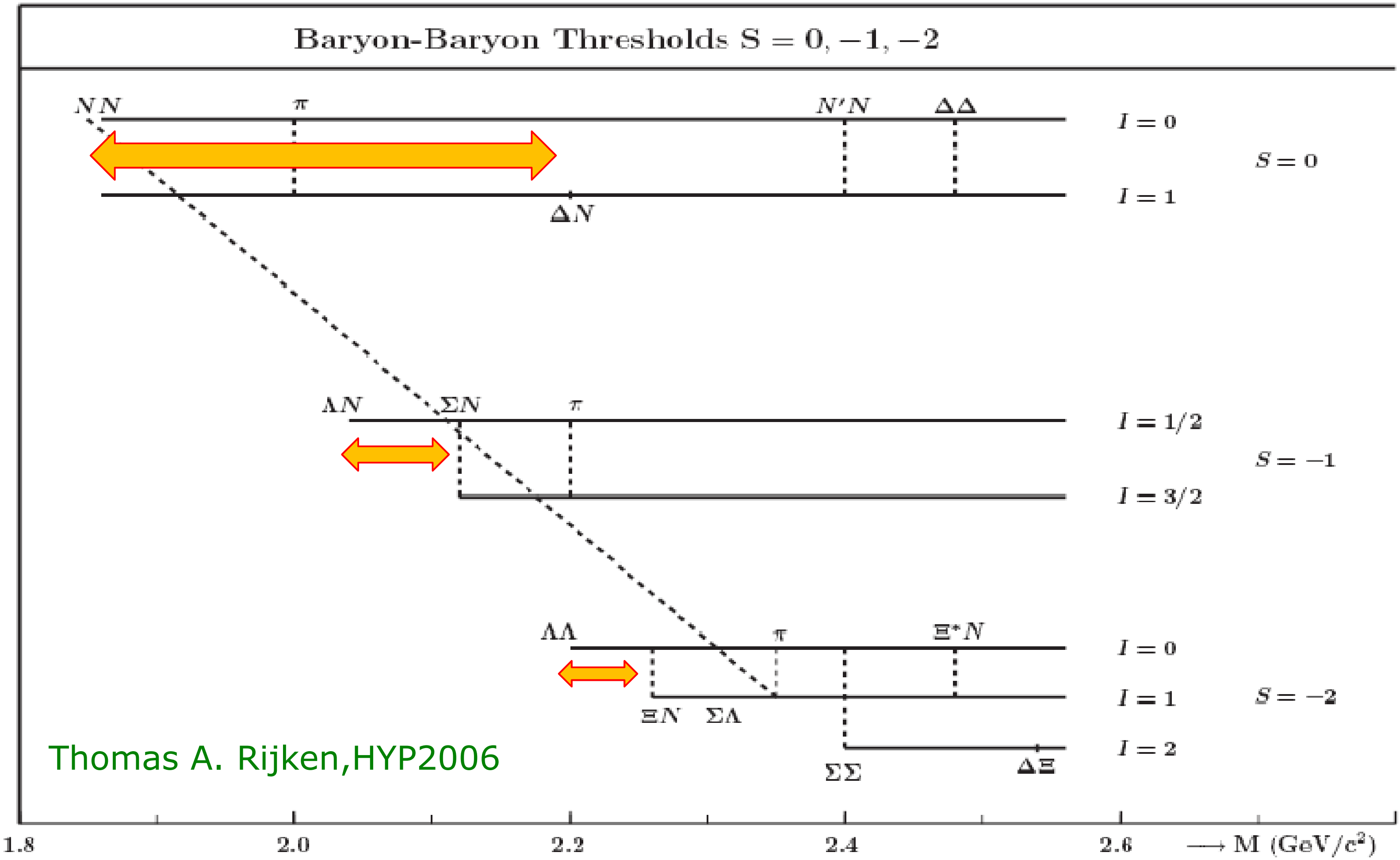
B_{Ξ^-} (atomic 3D) = 0.13 MeV [^{12}C- Ξ^-], 0.17 MeV [^{14}N- Ξ^-], 0.23 MeV [^{16}O- Ξ^-].

Experiment	**Observed stopped Ξ-**	**Double Hypernuclei**
Emulsion		~1
KEK E176	~100	1
KEK E373	~1000	4
AGS-E906		
Future Experiments		
J-PARC E07	~10000	
FAIR-PANDA		

Tulio Bressani:
„One event contains all (physics)“

Y-N or Y-Y Interaction in Hypernuclei

- Mass difference between Σ and Λ in single hypernuclei and $\Lambda\Lambda$, ΞN, $\Lambda\Sigma$ in double hypernuclei are small
    - $m(\Xi^0 n)-m(\Lambda\Lambda)=23$MeV $m(\Sigma^0\Lambda)-m(\Lambda\Lambda)=77$MeV
- $\Rightarrow$ mixing important



Thomas A. Rijken,HYP2006

PHYSICAL REVIEW C **70**, 024306 (2004)

ΛΛ bond energy from the Nijmegen potentials

I. Vidaña*
Dipartimento di Fisica "Enrico Fermi," Università di Pisa and INFN Sezione di Pisa, Via Buonarroti 2, I-56127 Pisa, Italy

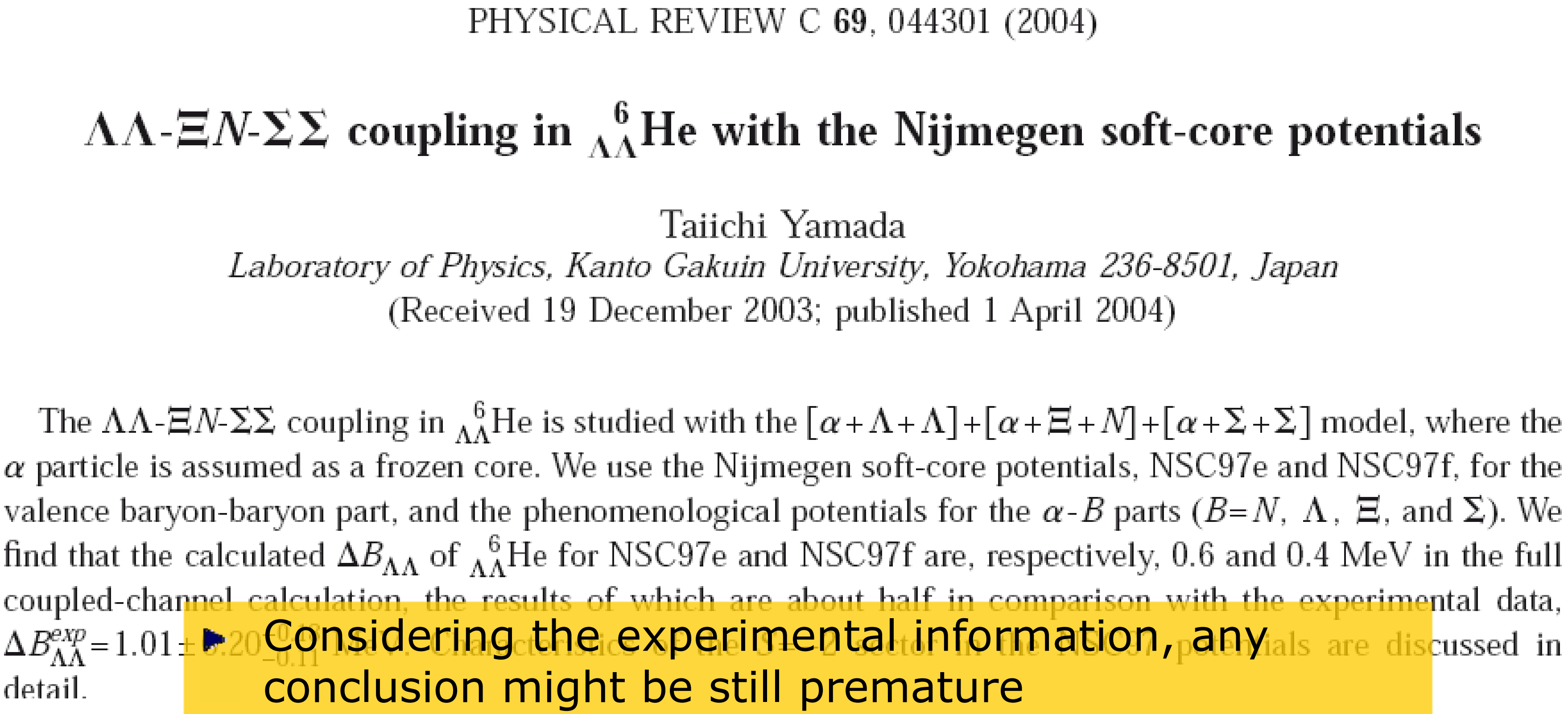
A. Ramos and A. Polls
Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain

(Received 23 July 2003; revised manuscript received 18 May 2004; published 16 August 2004)

The ΛΛ bond energy $\Delta B_{\Lambda\Lambda}$ in ΛΛ hypernuclei is obtained from a G-matrix calculation which includes the coupling between the ΛΛ, ΞN, and ΣΣ channels, as well as the effect of Pauli blocking to all orders. The Nijmegen NSC97e model is used as bare baryon-baryon interaction in the strangeness $S=-2$ sector. The ΛΛ-ΞN coupling increases substantially the bond energy with respect to the uncoupled ΛΛ case. However, the additional incorporation of the ΣΣ channel, which couples simultaneously to ΛΛ and ΞN states, has a surprisingly drastic effect and reduces the bond energy down to a value closer to that obtained in an uncoupled calculation. We find that a complete treatment of Pauli blocking reduces the repulsive effect on the bond energy to about half of what was claimed before.

TABLE II. ΛΛ scattering length and ΛΛ bond energy in ${}^{6}_{\Lambda\Lambda}\mathrm{He}$, for various channel couplings. Results within brackets ignore Pauli blocking effects.

	$a_{\Lambda\Lambda}$ [fm]	$\Delta B_{\Lambda\Lambda}$ [MeV]
ΛΛ	−0.25	0.16 (0.16)
ΛΛ, ΞN	−0.84	0.78 (1.02)
ΛΛ, ΞN, ΣΣ	−0.49	0.28 (0.54)



PHYSICAL REVIEW C **69**, 044301 (2004)

$\Lambda\Lambda$-ΞN-$\Sigma\Sigma$ coupling in ${}^{6}_{\Lambda\Lambda}$He with the Nijmegen soft-core potentials

Taiichi Yamada
Laboratory of Physics, Kanto Gakuin University, Yokohama 236-8501, Japan

(Received 19 December 2003; published 1 April 2004)

The $\Lambda\Lambda$-ΞN-$\Sigma\Sigma$ coupling in ${}^{6}_{\Lambda\Lambda}$He is studied with the $[\alpha+\Lambda+\Lambda]+[\alpha+\Xi+N]+[\alpha+\Sigma+\Sigma]$ model, where the α particle is assumed as a frozen core. We use the Nijmegen soft-core potentials, NSC97e and NSC97f, for the valence baryon-baryon part, and the phenomenological potentials for the α-B parts ($B=N$, Λ, Ξ, and Σ). We find that the calculated $\Delta B_{\Lambda\Lambda}$ of ${}^{6}_{\Lambda\Lambda}$He for NSC97e and NSC97f are, respectively, 0.6 and 0.4 MeV in the full coupled-channel calculation, the results of which are about half in comparison with the experimental data, $\Delta B^{exp}_{\Lambda\Lambda}=1.01\pm0.20^{+0.18}_{-0.11}$ MeV. Characteristics of the $S=-2$ sector in the NSC97 potentials are discussed in detail.

- Considering the experimental information, any conclusion might be still premature
- More precission data are needed

NSC97e and NSC97f Nijmegen potential describe single hypernuclei reasonably well

Potential	$\Delta B_{\Lambda\Lambda}(MeV)$	$P_{\Lambda\Lambda}(\%)$	$P_{\Xi N}(\%)$	$P_{\Sigma\Sigma}(\%)$
NSC97e	0.61	99.77	0.21	0.01
NSC97f	0.36	99.81	0.18	0.01

Predictive Power

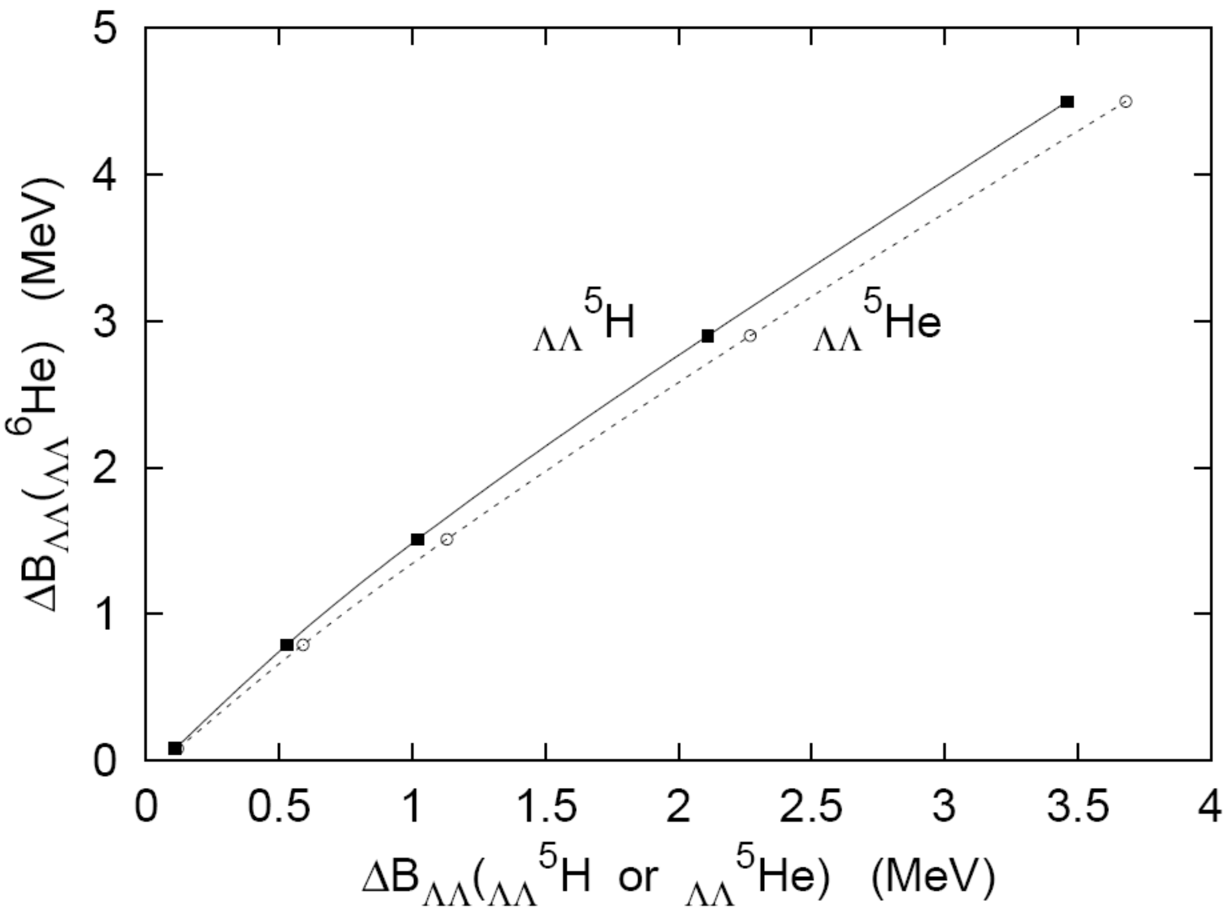
PHYSICAL REVIEW C **68**, 024002 (2003)

Faddeev calculations for the $A=5,6$ $\Lambda\Lambda$ hypernuclei

I. N. Filikhin,[1,2] A. Gal,[3,*] and V. M. Suslov[1]

[1]*Department of Mathematical and Computational Physics, St. Petersburg State University, 198504 Petrodvorets, St. Petersburg, Russia*
[2]*Department of Physics, North Carolina Central University, Durham, North Carolina 27707, USA*
[3]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

(Received 13 March 2003; published 22 August 2003)



PHYSICAL REVIEW C **69**, 054003 (2004)

Variational Monte Carlo calculation of ${}^{6}_{\Lambda\Lambda}$He and other *s*-shell hypernuclei

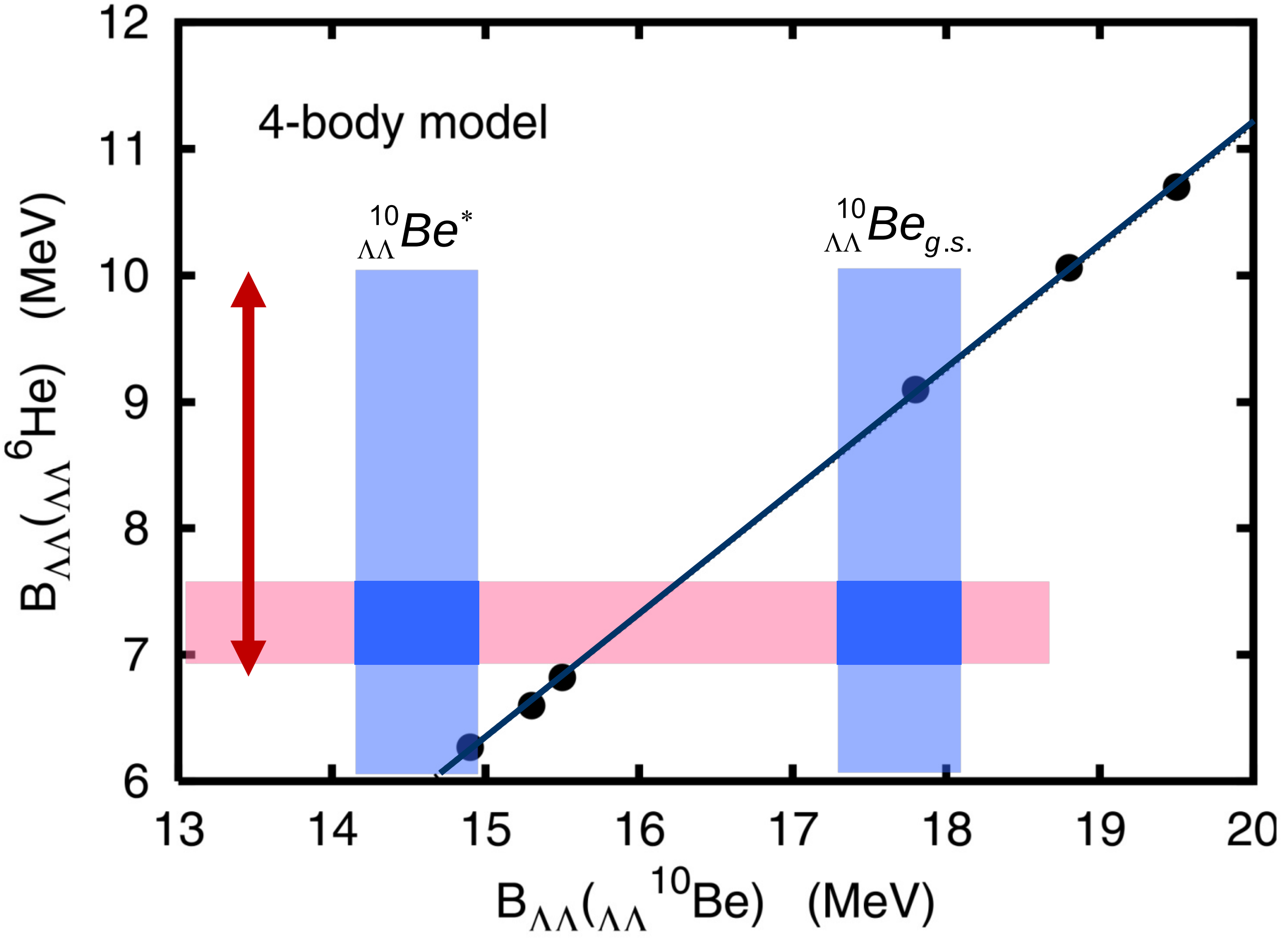
Mohammad Shoeb*
Department of Physics, Faculty of Science, Addis Ababa University, P. O. Box No. 1176, Addis Ababa, Ethiopia

(Received 23 July 2003; published 26 May 2004)

A variational Monte Carlo analysis of recent binding energy data of the hypernucleus ${}^{6}_{\Lambda\Lambda}$He has been made treating this as a six-body problem. A phenomenological central Urbana-type $\Lambda\Lambda$ potential which fits the new data, predicts a bound state for the charge symmetric pair ${}^{5}_{\Lambda\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$He and just or weakly bound state for ${}^{4}_{\Lambda\Lambda}$H is obtained. A three-range Gaussian $\Lambda\Lambda$ potential phase equivalent to the Nijmegen model D over estimates by 25–80 % the binding energy of ${}^{6}_{\Lambda\Lambda}$He and pair ${}^{5}_{\Lambda\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$He compared to an Urbana potential. The simulated potential predicts bound ${}^{4}_{\Lambda\Lambda}$H. The incremental $\Delta B_{\Lambda\Lambda}$ value, leaving ${}^{4}_{\Lambda\Lambda}$H, for the above potentials is about half of that found in recent cluster model calculation which uses a $\Lambda\Lambda$ potential phase equivalent to the ND type in the Faddeev method.

Consistent Description - not yet!

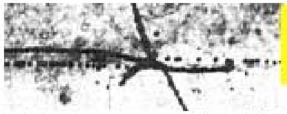
- I.N. Filikhin, A. Gal, Phys. Rev. C 65, 041001 (R) (2002)
  - Faddeev-Yakubovsky calculation



- no convincing consistent description possible so far

Summary and perspective (1)

By checking consistency of $\Delta B_{\Lambda\Lambda}$ (NAGARA) within 3 STD. errors,

	$^{A}_{\Lambda\Lambda}Z$	Ξ^- Captured	$B_{\Lambda\Lambda} - B_{\Xi^-}$ [MeV]	$\Delta B_{\Lambda\Lambda} - B_{\Xi^-}$ [MeV]	Assumed level	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
NAGARA	$^{6}_{\Lambda\Lambda}$He	^{12}C	$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-}$ (+/- 0.16) $\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-}$ (+/- 0.17) $B_{\Xi^-} < 1.86$		3D	6.91 +/- 0.16	0.67 +/- 0.17
MIKAGE	$^{6}_{\Lambda\Lambda}$He	^{12}C	9.93 +/- 1.72	3.69 +/- 1.72	3D	10.06 +/- 1.72	3.82 +/- 1.72
DEMACHI-YANAGI	$^{10}_{\Lambda\Lambda}$Be*	^{12}C	11.77 +/- 0.13	-1.65 +/- 0.15 *cf.* Ex = 3.0	3D	11.90 +/- 0.13	-1.52 +/- 0.15 *cf.* Ex = 3.0
HIDA	$^{11}_{\Lambda\Lambda}$Be	^{16}O	20.26 +/- 1.15	2.04 +/- 1.23	3D	20.49 +/- 1.15	2.27 +/- 1.23
	$^{12}_{\Lambda\Lambda}$Be	^{14}N	22.06 +/- 1.15	------	3D	22.23 +/- 1.15	------
E176	$^{13}_{\Lambda\Lambda}$B -> $^{13}_{\Lambda}$C*		------ Ex = 4.9	-------	3D	23.3 +/- 0.7	0.6 +/- 0.8
	$^{10}_{\Lambda\Lambda}$Be -> $^{9}_{\Lambda}$Be*		------ Ex = 3.0	-------	not checked, yet.	14.7 +/- 0.4	1.3 +/- 0.4

M.Danysz et al., PRL.11(1963)29;
R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

B_{Ξ^-} (atomic 3D) = **0.13** MeV [^{12}C- Ξ^-], **0.17** MeV [^{14}N- Ξ^-], **0.23** MeV [^{16}O- Ξ^-].

JPARC: E07 experiment

- 1.7GeV K- beam
- $3 \cdot 10^5$ K^-/4.8s
- 3 times larger emulsion volume
- Ξ atomic transisions?
- Factor of 10

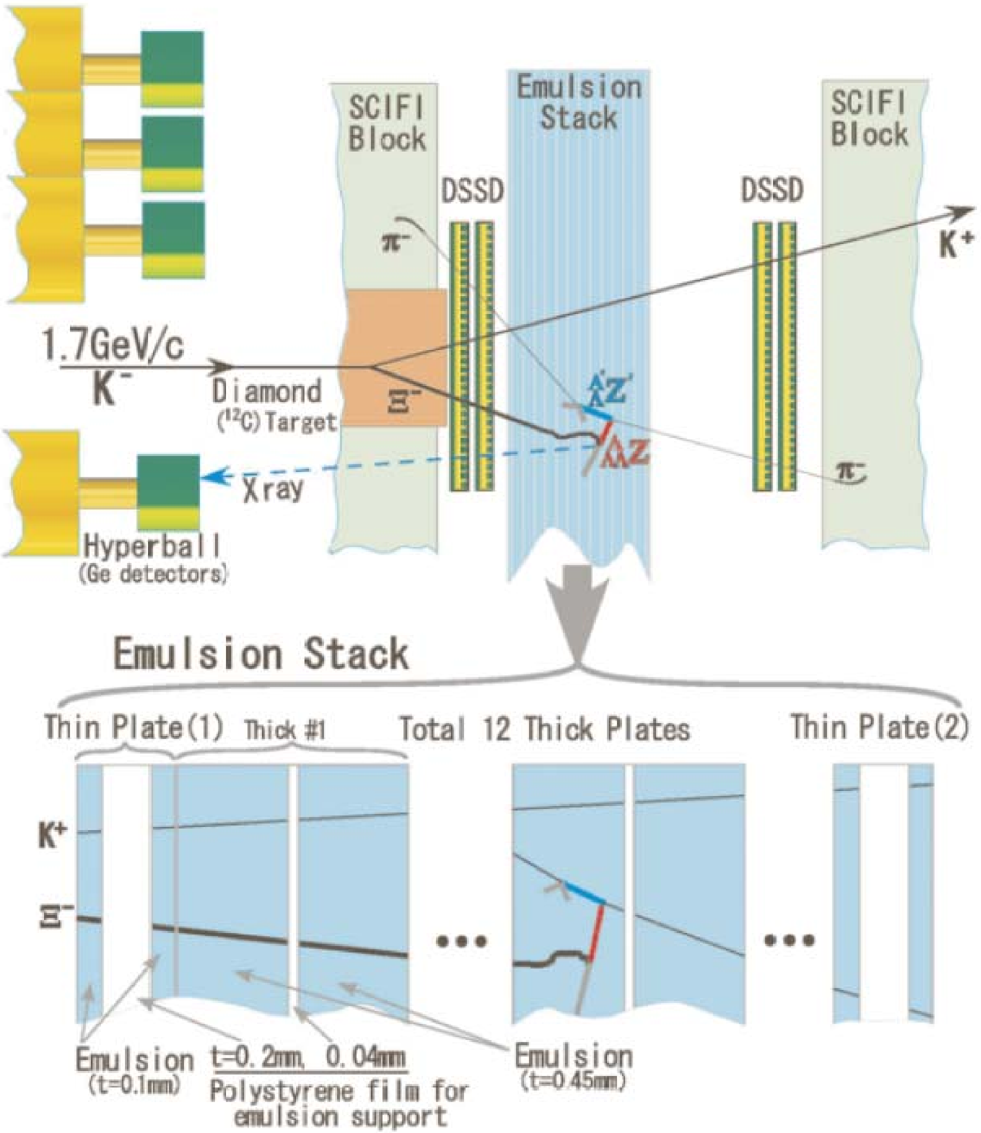


Figure 6: Setup of the E07 experiment at J-PARC.

The E906 Experiment

The magical mystery tour

DIE WELT 4. September 2001

AGS-E906

FOTO: STEINMETZ/FOCUS

n 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“.

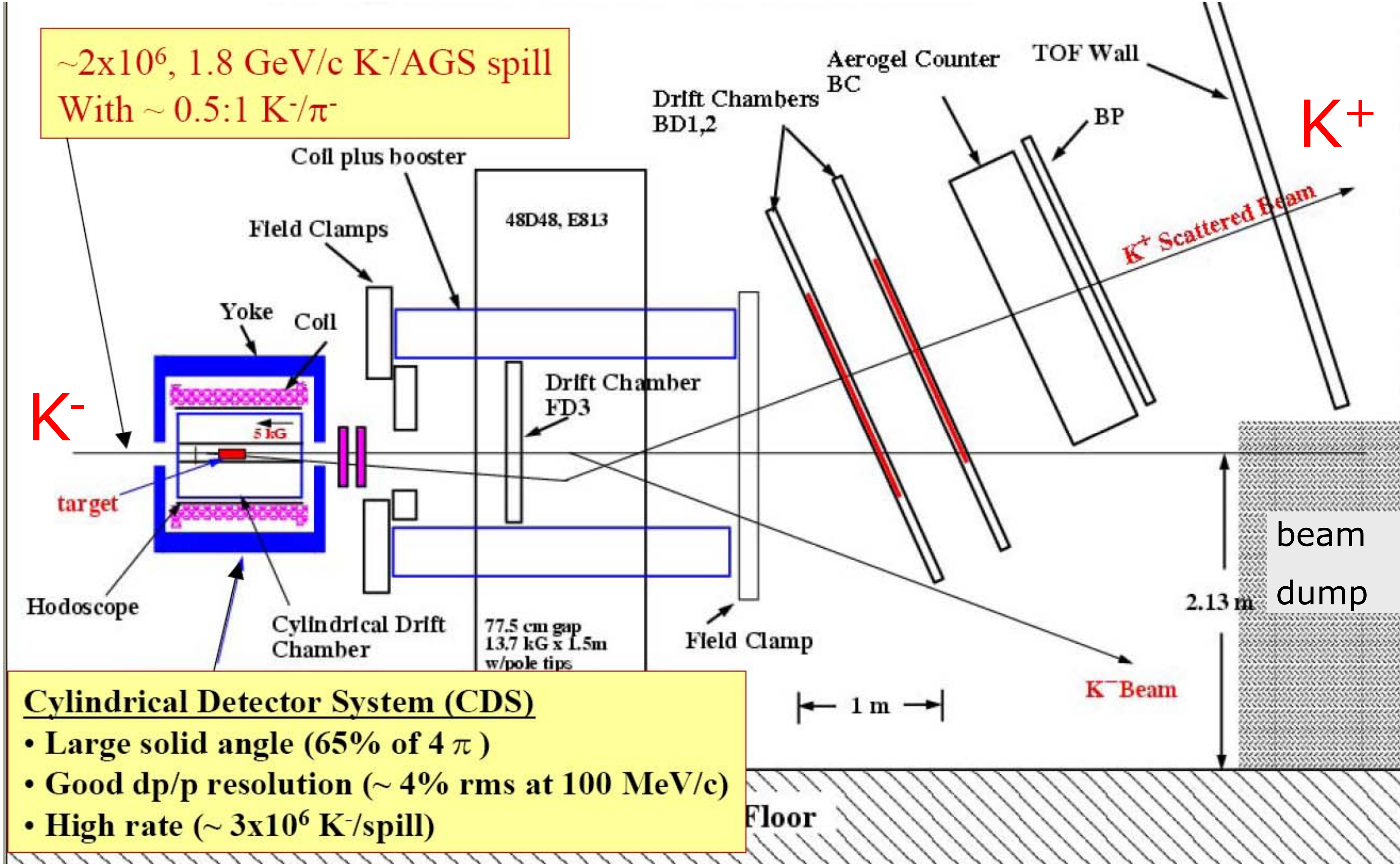
Aus den Millionen von Daten, die während einer Messkampagne entstehen, müssen die Physiker am Ende die wirklich relevanten „Ereignisse“ herausfinden, die sprichwörtliche Nadel im Heuhaufen. In Brookhaven hat sich die Mühe offenbar gelohnt; aus 100 Millionen infrage kommenden Ereignissen filterten Computer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



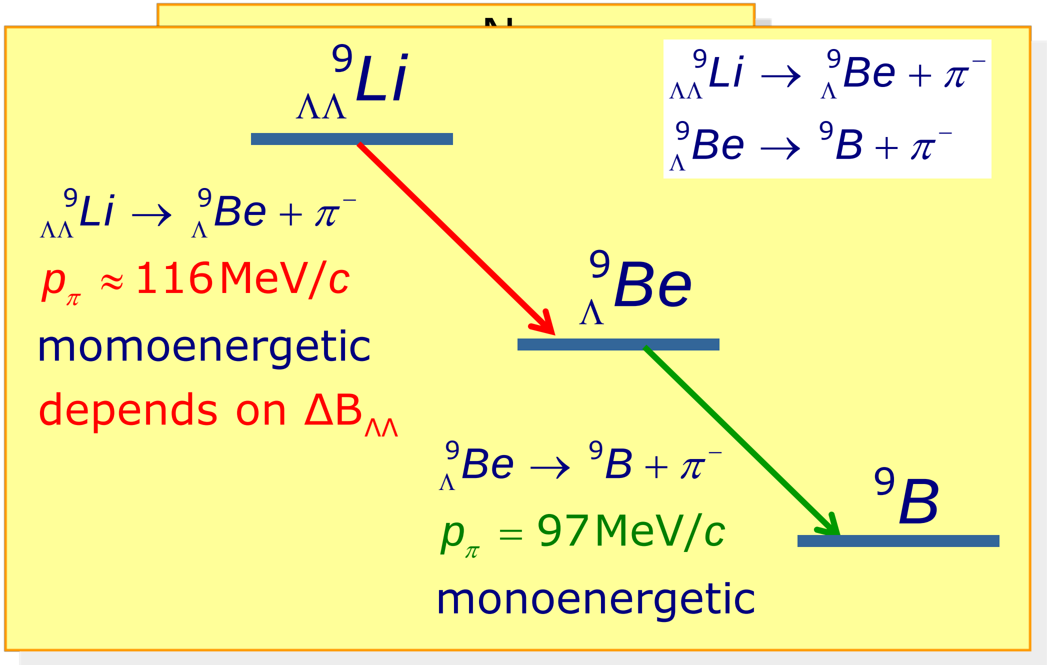
~2×10^6, 1.8 GeV/c K^-/AGS spill
With ~ 0.5:1 K^-/π^-

Cylindrical Detector System (CDS)

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

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 (^{9}Be)
- Identification of $\Lambda\Lambda$ hypernucleus through sequential weak decay via π^- emission
  - in light nuclei the pionic weak decay significant
  - 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



$^{9}_{\Lambda\Lambda}Li$

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

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

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

$p_\pi \approx 116\,\mathrm{MeV}/c$

momoenergetic

depends on $\Delta B_{\Lambda\Lambda}$

$^{9}_{\Lambda}Be$

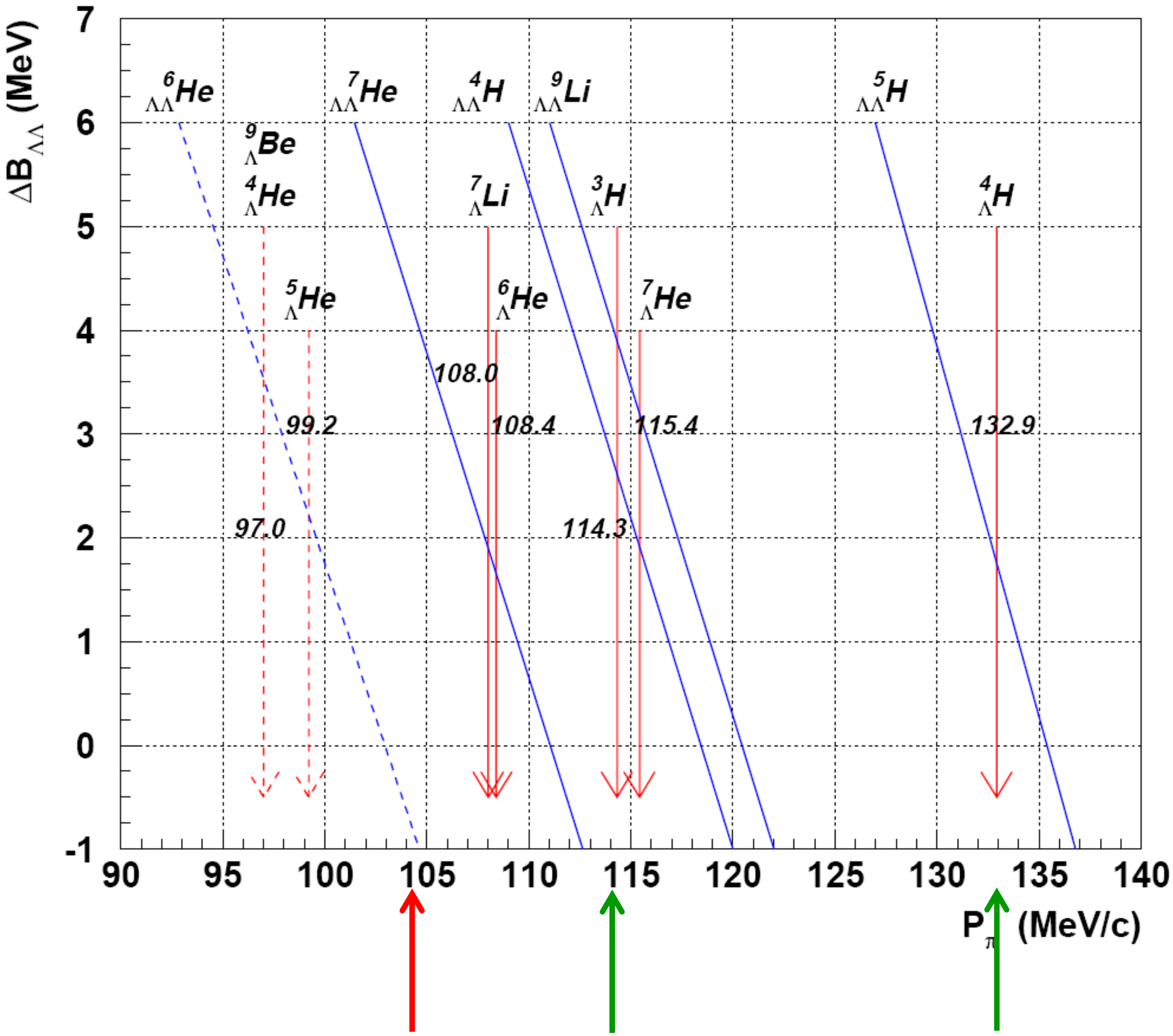
$$^{9}_{\Lambda}Be \rightarrow {}^{9}B + \pi^-$$

$p_\pi = 97\,\mathrm{MeV}/c$

monoenergetic

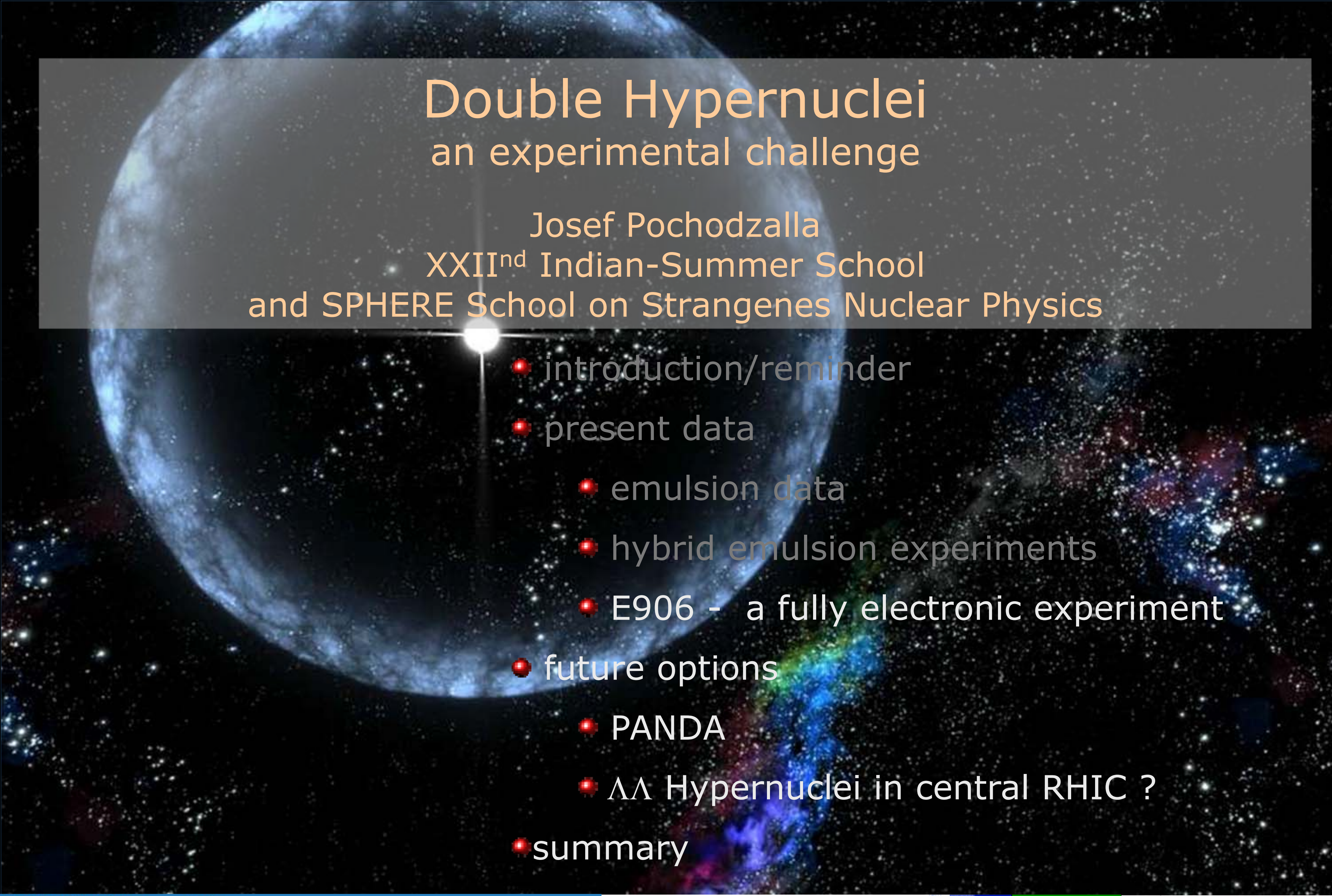
^{9}B

Assignement of pion momenta



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

- …is not straight forward



Double Hypernuclei

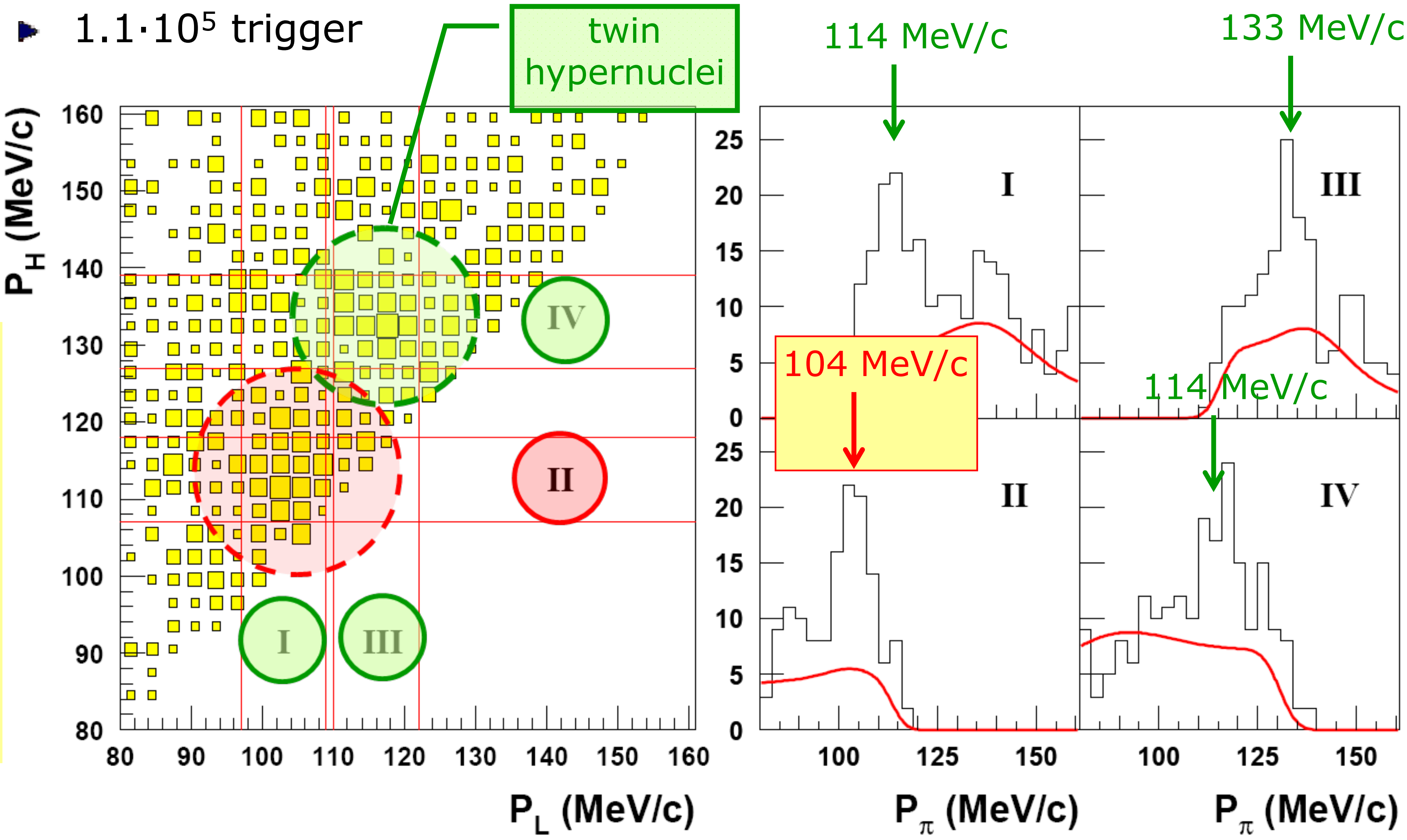
an experimental challenge

Josef Pochodzalla
XXIInd Indian-Summer School
and SPHERE School on Strangenes Nuclear Physics

- introduction/reminder
- present data
  - emulsion data
  - hybrid emulsion experiments
  - E906 - a fully electronic experiment
- future options
  - PANDA
  - $\Lambda\Lambda$ Hypernuclei in central RHIC ?
- summary

E906

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



twin hypernuclei

consistent with single Λ hypernuclei

114 MeV/c

133 MeV/c

104 MeV/c

114 MeV/c

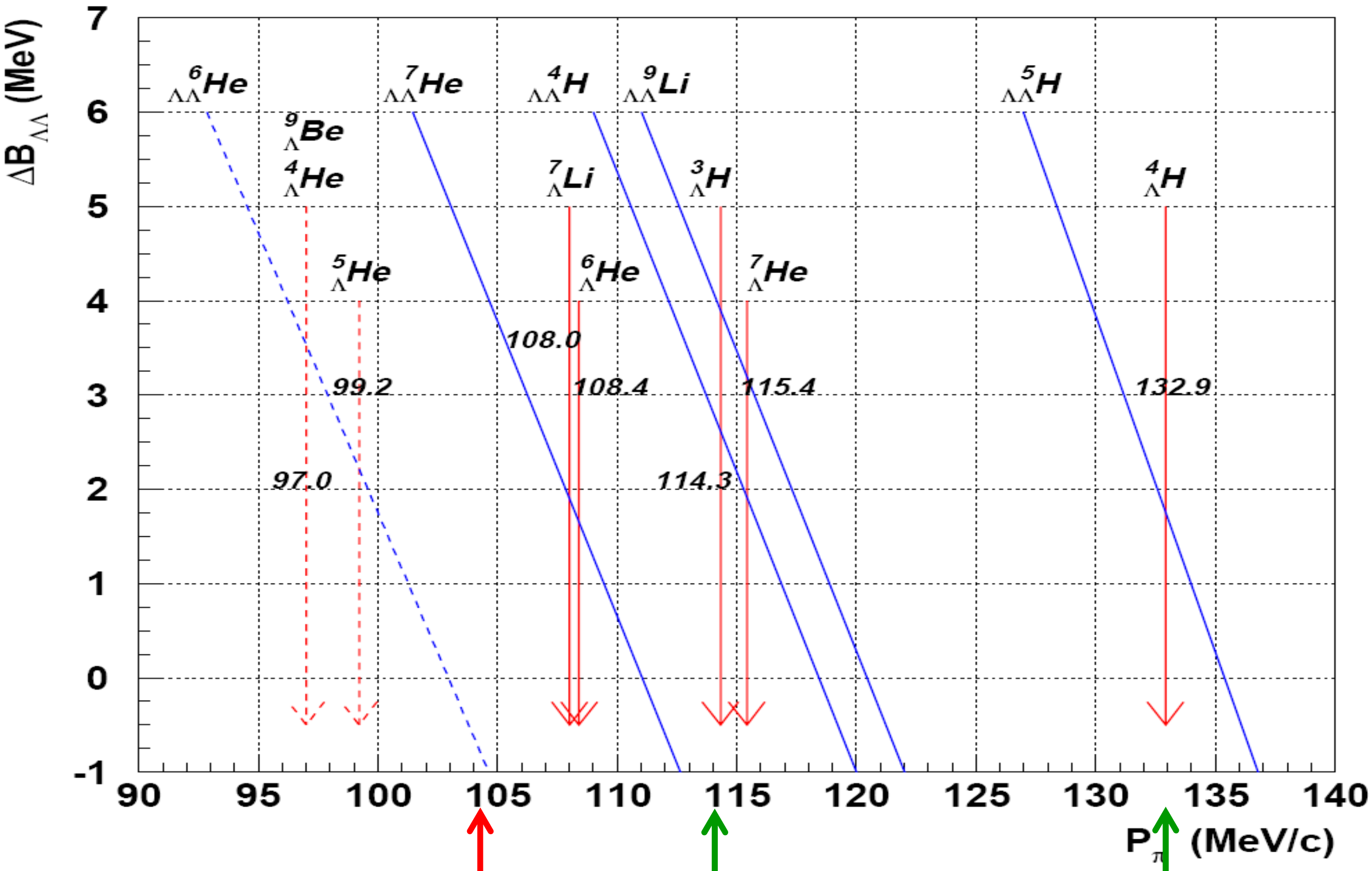
momentum of the pion with lower momentum

momentum of the pion
with lower momentum

9Be(K^-,K^+) at E906

- Two options Ξ^- Stopping & Fusion: $\Xi^- + {}^9Be \rightarrow {}^{10}_{\Lambda\Lambda}Li^*$

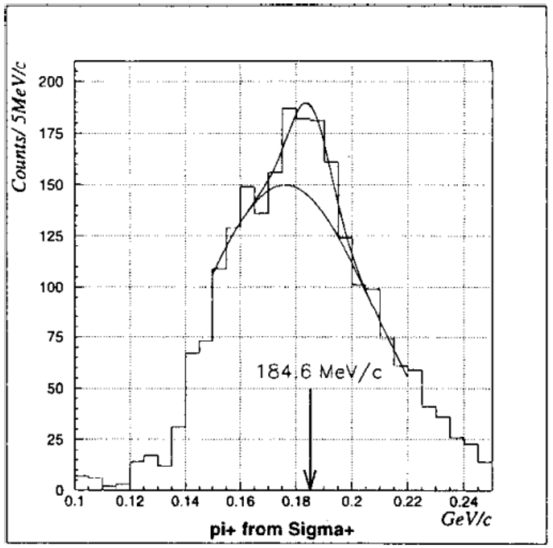
  $p(K^-,K^+)\Xi^-$ & nucleon kickout $\Rightarrow {}^8_{\Lambda\Lambda}He^*$ or ${}^8_{\Lambda\Lambda}H^*$

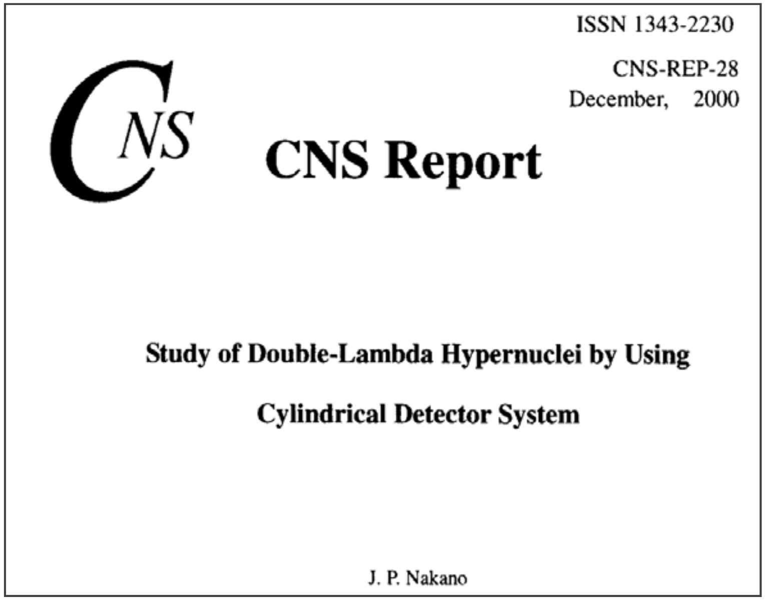


104 MeV/c 114 MeV/c 133 MeV/c

- Correlated pion momenta
  - (104,114) ⇒ ?
  - (114,133) ⇒ ${}^3_{\Lambda}H + {}^4_{\Lambda}H$

Momentum Calibration of E906 CDC




ISSN 1343-2230

CNS-REP-28
December, 2000

CNS Report

Study of Double-Lambda Hypernuclei by Using Cylindrical Detector System

J. P. Nakano

Figure 4.8: A histogram of the π^+ momentum from Σ^+ decay

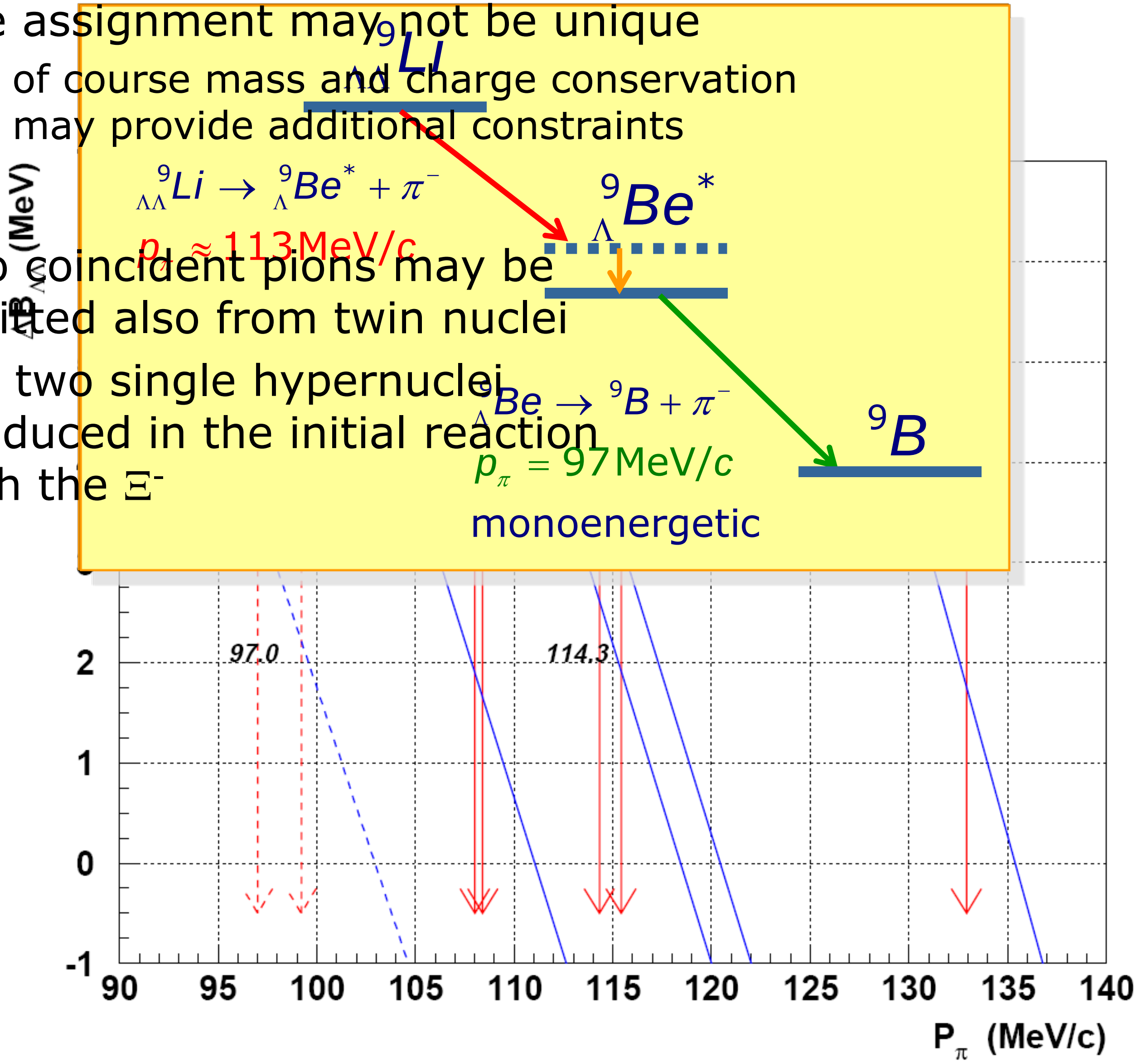
It consists of a peak of the stopped-Σ^+ and a broad bump from in-flight decay. The component of in-flight decay shows a slightly asymmetric shape with a tail to higher momentum, which is caused by the CDS acceptance. When the histogram from 0.14 to 0.22 GeV/c was fitted with two gaussians, it gives a centroid of stopped Σ^+peak; 184.7 ± 1.9 MeV/c and the width; 7.07 ± 1.91 MeV/c, whereas the momentum of π^+ from Σ^+ decay is known to be 184.6 MeV/c.

In searching for $\Lambda\Lambda$ hypernuclei among $2\pi^-$ data, a large enhancement is observed, which corresponds to the decay from the twin hypernuclear production, ${}^4_\Lambda$H and ${}^3_\Lambda$H; This gives two more calibration points for the π^- momentum. The details will be described in the Chapter 5.

…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

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

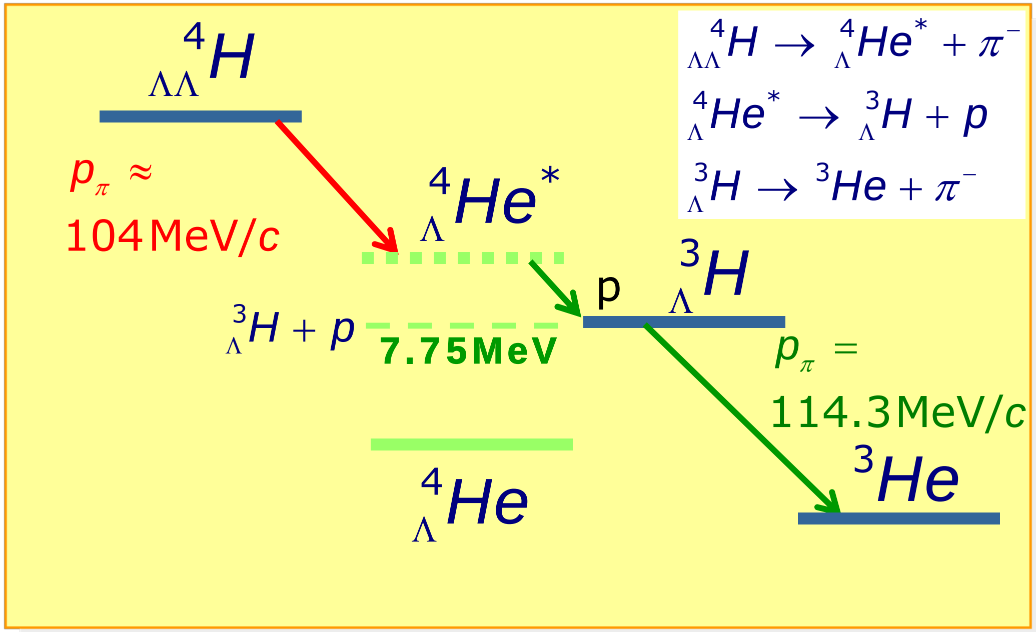
$p_{\pi} = 97$ MeV/c

monoenergetic

Suggested decay mode (104/114)

- 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

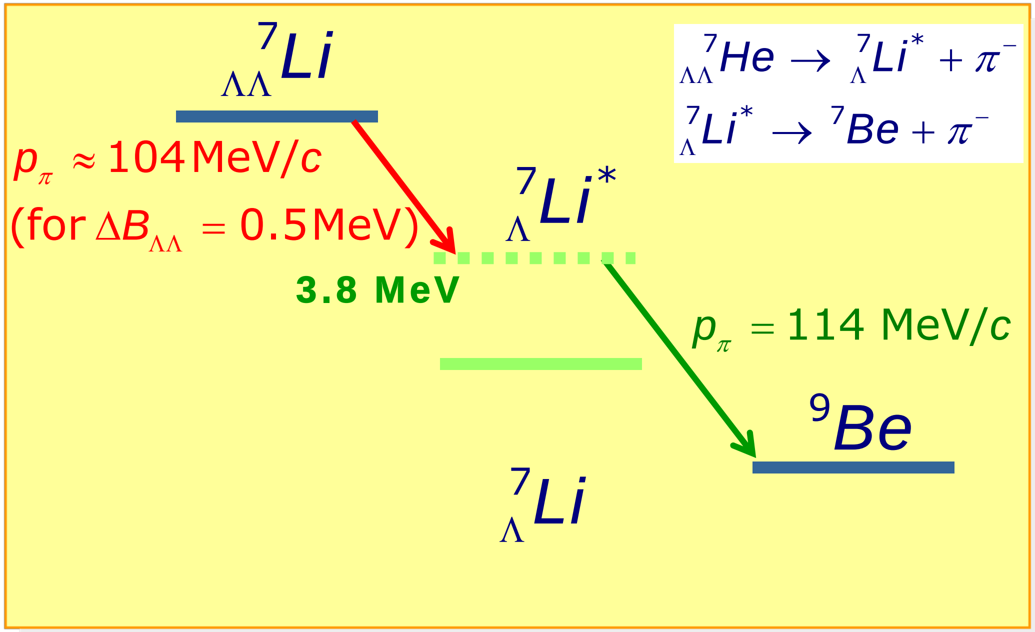


- Hungerford (HYP03)
  - requires isomeric state at 3.8MeV
- Gal (HYP03)

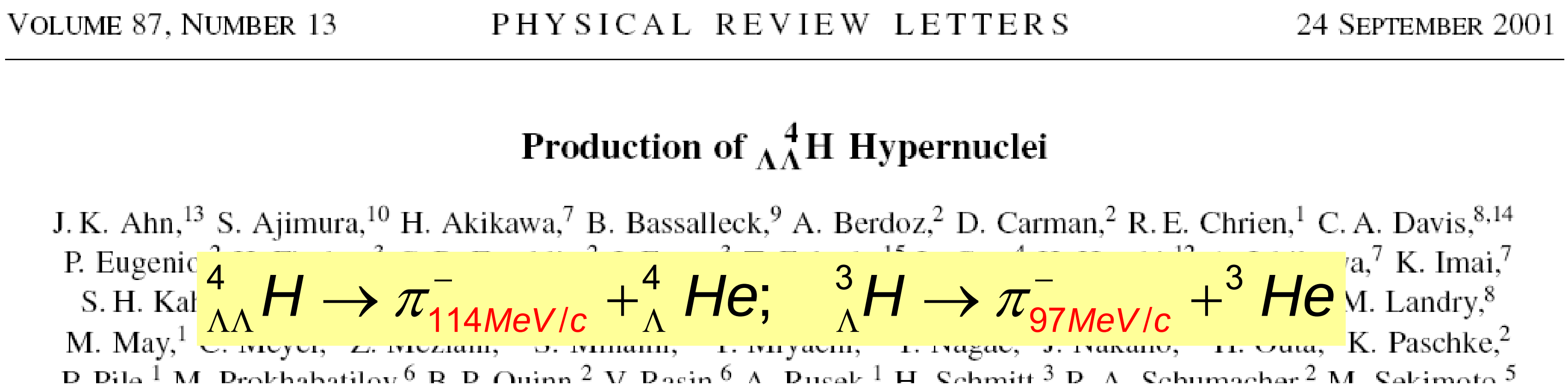
$^{3}_{\Lambda\Lambda}n \rightarrow {}^{3}_{\Lambda}H + \pi^{-}$(104MeV/c)

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

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



104/114 Structure – What is it?

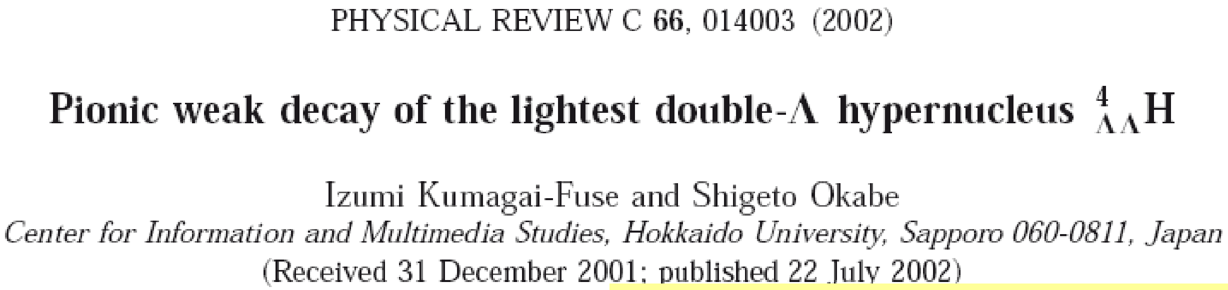


VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 2001

Production of $^{4}_{\Lambda\Lambda}$H Hypernuclei

J. K. Ahn,[13] S. Ajimura,[10] H. Akikawa,[7] B. Bassalleck,[9] A. Berdoz,[2] D. Carman,[2] R. E. Chrien,[1] C. A. Davis,[8,14]
P. Eugenic a,[7] K. Imai,[7]
S. H. Kal M. Landry,[8]
M. May,[1] C. Meyer, Z. Meziani, S. Minami, T. Miyachi, T. Nagae, J. Nakano, H. Outa, K. Paschke,[2]
P. Pile,[1] M. Prokhabatilov,[6] R. P. Quinn,[2] V. Rusin,[6] A. Rusek,[1] H. Schmitt,[3] R. A. Schumacher,[2] M. Sekimoto,[5]

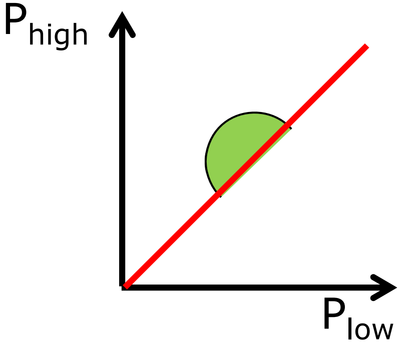
$$^{4}_{\Lambda\Lambda}H \rightarrow \pi^{-}_{114MeV/c} + ^{4}_{\Lambda}He; \quad ^{3}_{\Lambda}H \rightarrow \pi^{-}_{97MeV/c} + ^{3}He$$



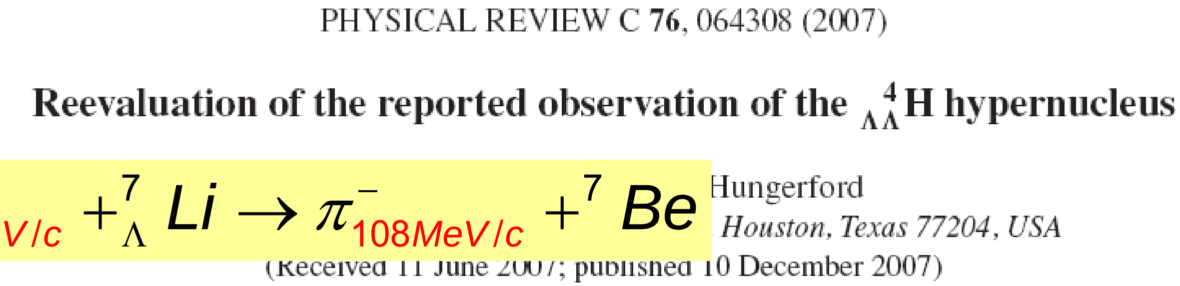
PHYSICAL REVIEW C **66**, 014003 (2002)

Pionic weak decay of the lightest double-Λ hypernucleus $^{4}_{\Lambda\Lambda}$H

Izumi Kumagai-Fuse and Shigeto Okabe
Center for Information and Multimedia Studies, Hokkaido University, Sapporo 060-0811, Japan
(Received 31 December 2001; published 22 July 2002)



$$^{3}_{\Lambda}H + ^{6}_{\Lambda}He : 114MeV/c \text{ and } 108MeV/c$$



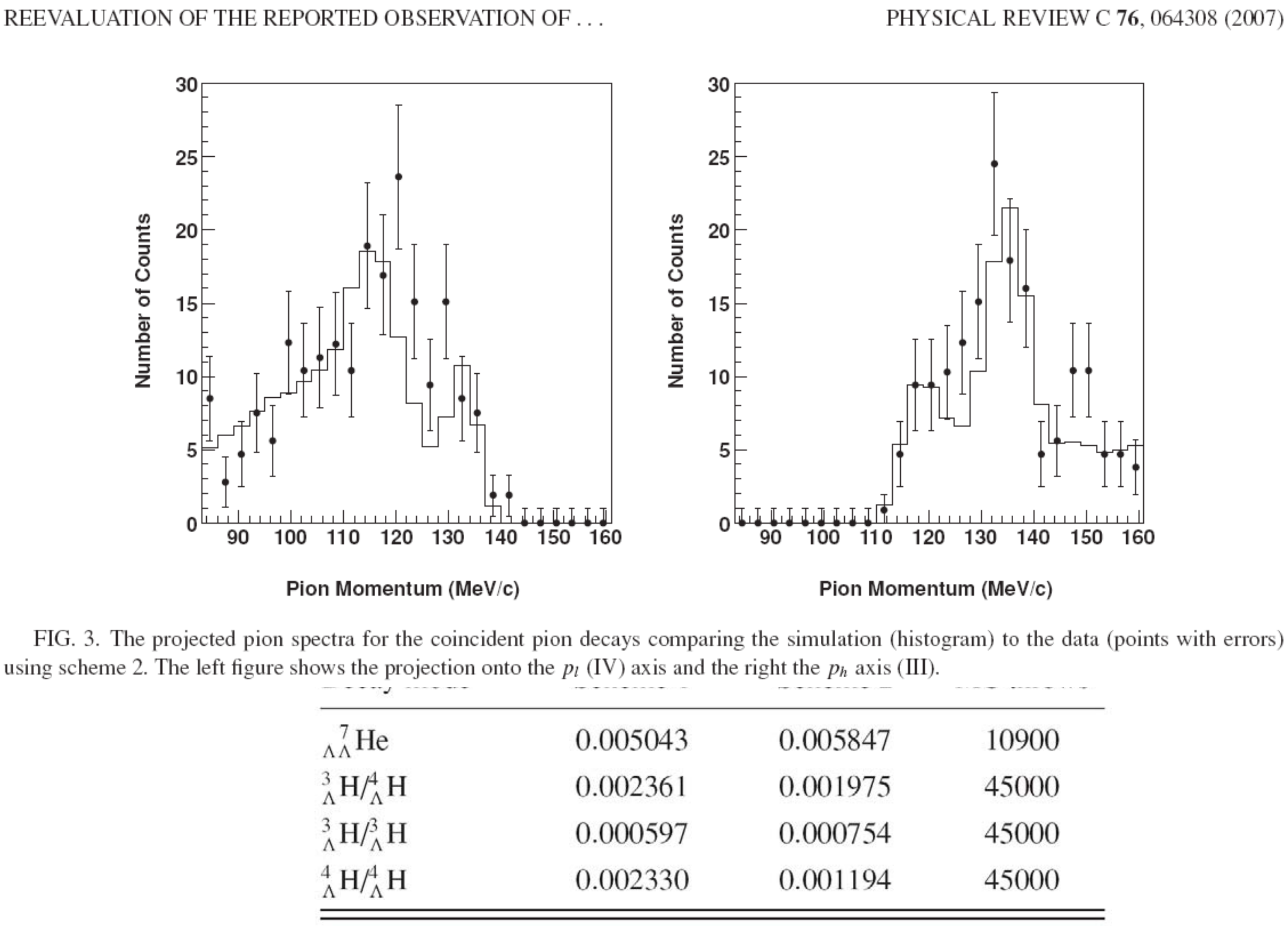
PHYSICAL REVIEW C **76**, 064308 (2007)

Reevaluation of the reported observation of the $^{4}_{\Lambda\Lambda}$H hypernucleus

Hungerford
Houston, Texas 77204, USA
(Received 11 June 2007; published 10 December 2007)

$$^{7}_{\Lambda\Lambda}He \rightarrow \pi^{-}_{109MeV/c} + ^{7}_{\Lambda}Li \rightarrow \pi^{-}_{108MeV/c} + ^{7}Be$$

Hungerford: $^{7}_{\Lambda\Lambda}He \rightarrow \pi^{-}_{109MeV/c} + ^{7}_{\Lambda}Li \rightarrow \pi^{-}_{108MeV/c} + ^{7}Be$



REEVALUATION OF THE REPORTED OBSERVATION OF . . .

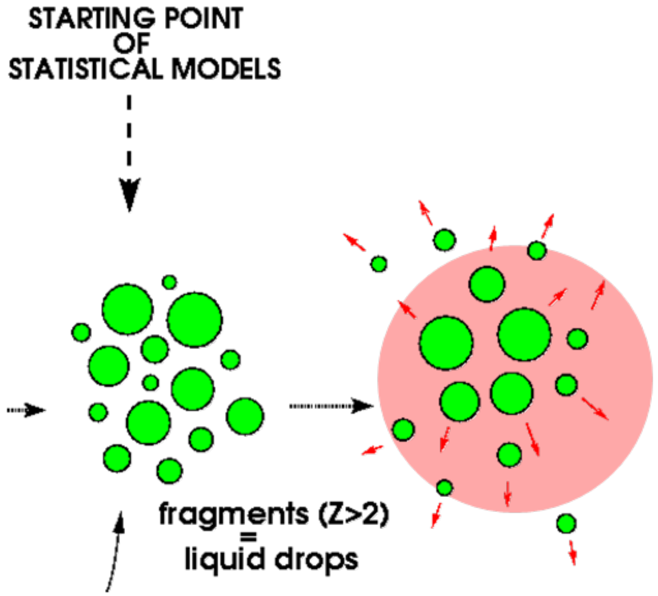
PHYSICAL REVIEW C **76**, 064308 (2007)

FIG. 3. The projected pion spectra for the coincident pion decays comparing the simulation (histogram) to the data (points with errors) using scheme 2. The left figure shows the projection onto the p_l (IV) axis and the right the p_h axis (III).

$^{7}_{\Lambda\Lambda}$He	0.005043	0.005847	10900
$^{3}_{\Lambda}$H/$^{4}_{\Lambda}$H	0.002361	0.001975	45000
$^{3}_{\Lambda}$H/$^{3}_{\Lambda}$H	0.000597	0.000754	45000
$^{4}_{\Lambda}$H/$^{4}_{\Lambda}$H	0.002330	0.001194	45000

Multifragmentation

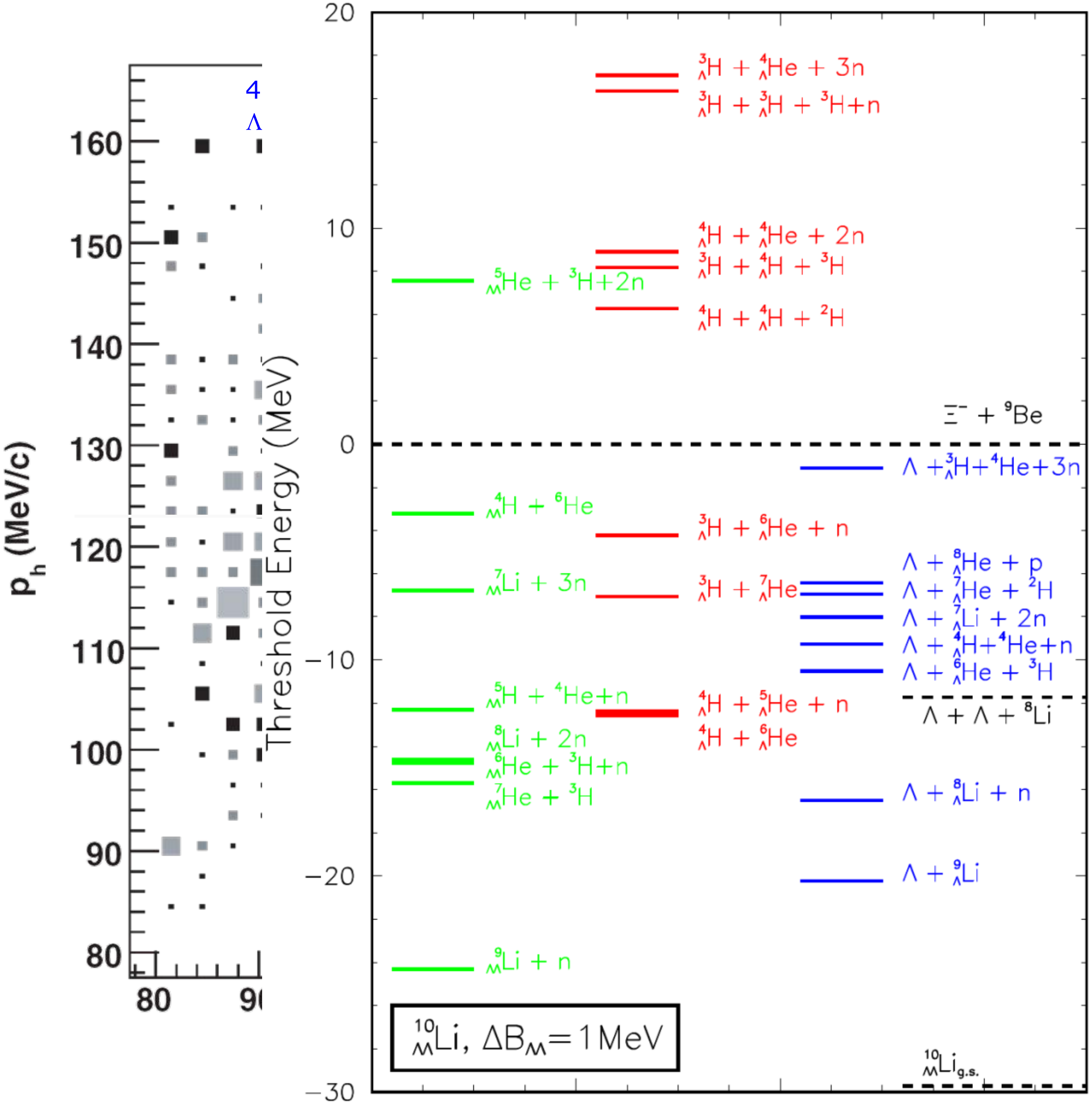
- conversion width $\Xi + p \rightarrow \Lambda\Lambda$ around $\Gamma = 1$MeV
- excitation energy ~ 40MeV/12≈ 3MeV/nucleon
  - fragmentation of excited projectile remnants are well understood in that regime
- ⇒ Statistical decay models may work ***(E. Fermi; J.P. Bondorf et al.)***
  - De-excitation of light nuclei via Fermi break-up process
  - Conservation of A, Z, H, Energy and momentum
- Input
  - All normal bound nuclei (p,d,t,3He…) and their particle stable escited states
  - All known stable single hypernuclei and their particle stable states
  - All bound double hypernuclei and their excited states
    - $\Delta B_{\Lambda\Lambda} = 1$MeV
    - Theoretically predicted states + core excited states



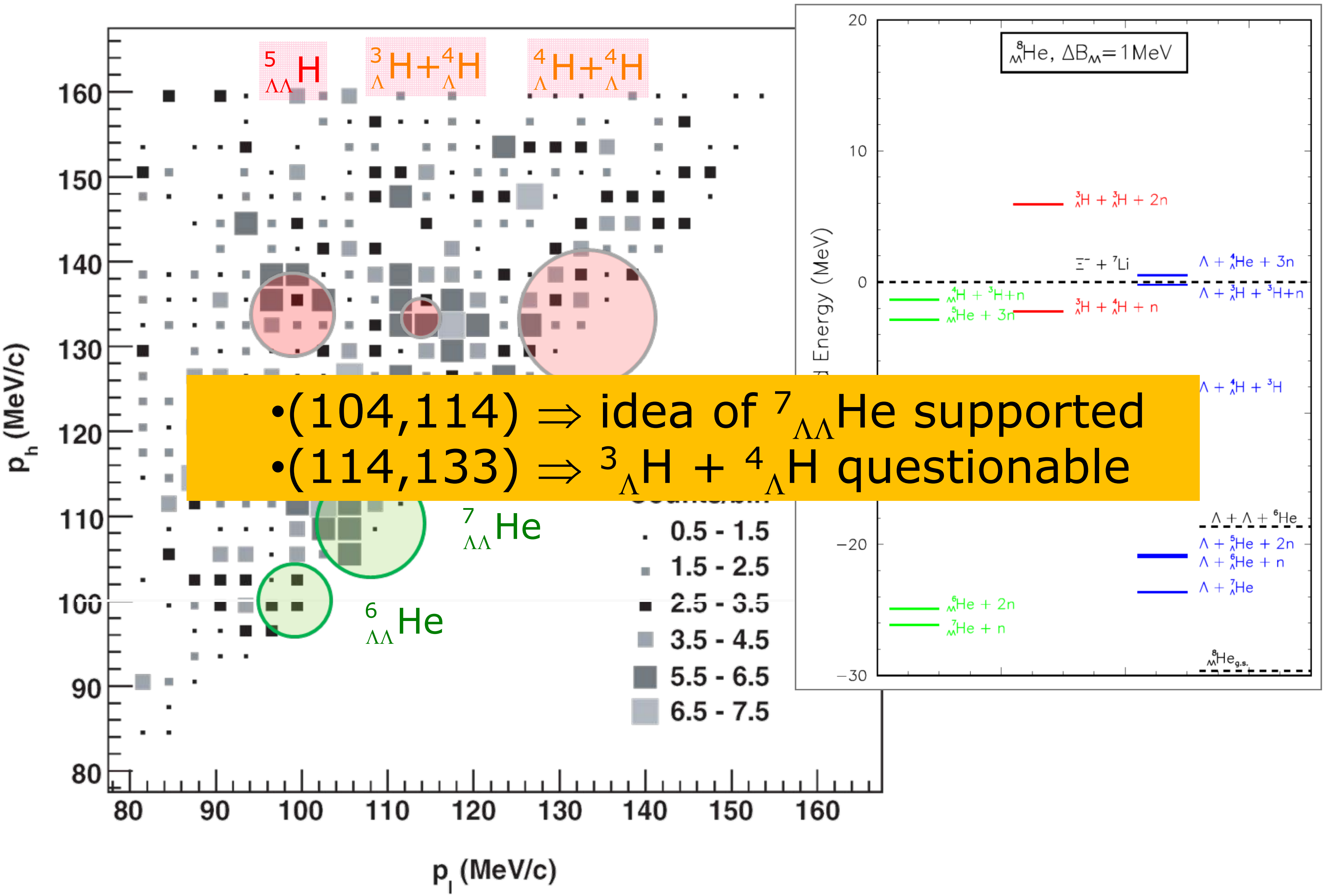
$$\Xi^- \text{ Stopping \& Fusion: } \Xi^- + {}^{9}Be \rightarrow {}^{10}_{\Lambda\Lambda}Li^*$$

$$p(K^-,K^+)\Xi^- \text{ \& nucleon kickout} \Rightarrow {}^{8}_{\Lambda\Lambda}He^* \text{ or } {}^{8}_{\Lambda\Lambda}H^*$$

Ξ^- Stopping & Fusion: $\Xi^- + {}^9Be \rightarrow {}^{10}_{\Lambda\Lambda}Li^*$



$p(K^-,K^+)\Xi^-$ & N kickout $\Rightarrow {}^{8}_{\Lambda\Lambda}He^*$ or ${}^{8}_{\Lambda\Lambda}H^*$



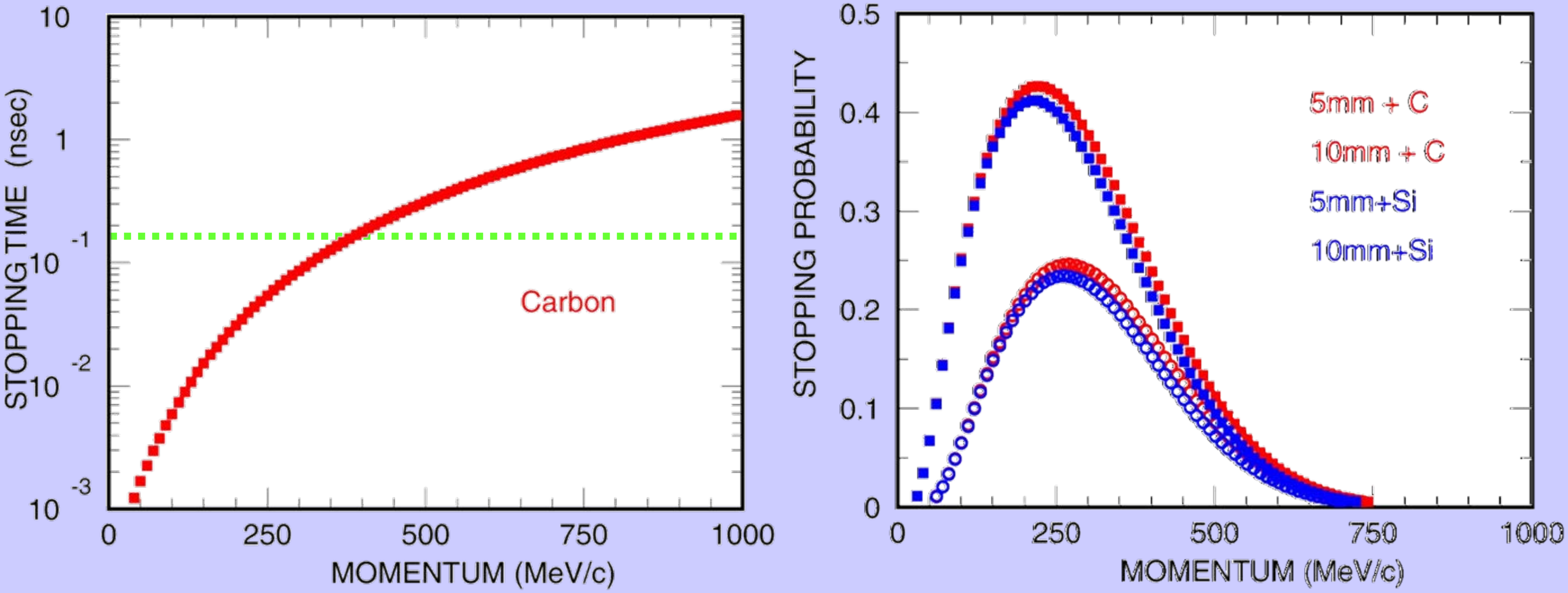
- (104,114) ⇒ idea of ${}^{7}_{\Lambda\Lambda}He$ supported
- (114,133) ⇒ ${}^{3}_{\Lambda}H$ + ${}^{4}_{\Lambda}H$ questionable

The PANDA Experiment

The long and winding road
or
When I´m sixty four

Ξ^- properties

- Ξ^- mean lifetime 0.164 ns

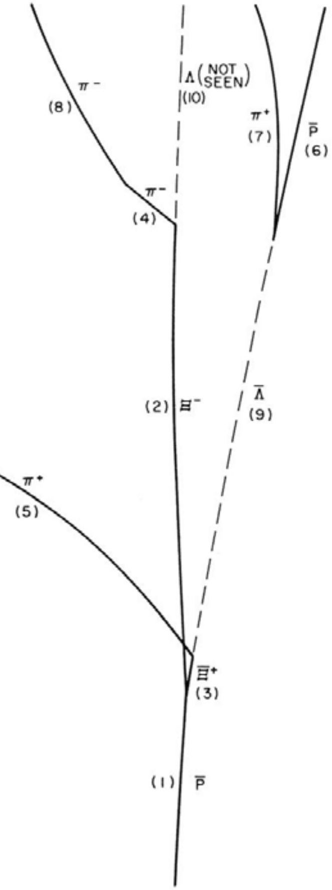


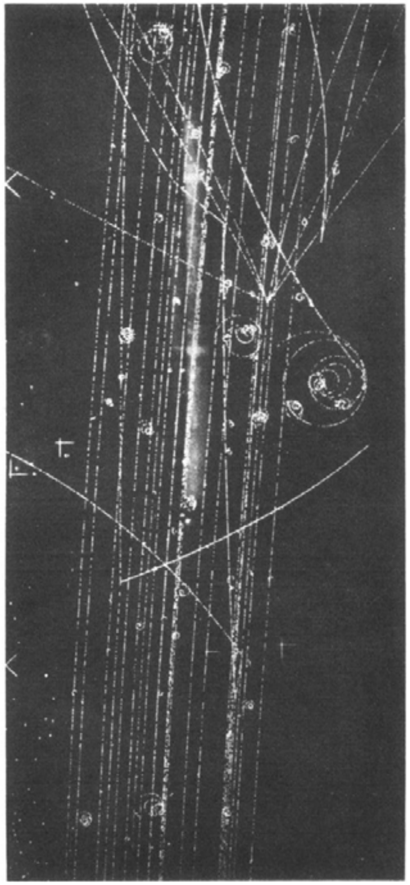
- minimal distance production ⇔ capture
- initial momentum 100-500 MeV/c → range ~ few g/cm^2

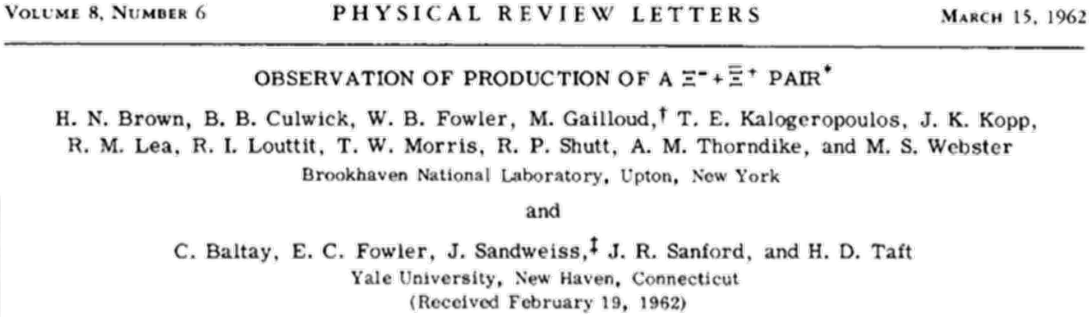
The Discovery of the anti-Xi

- discovered simultaneously at CERN and SLAC

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



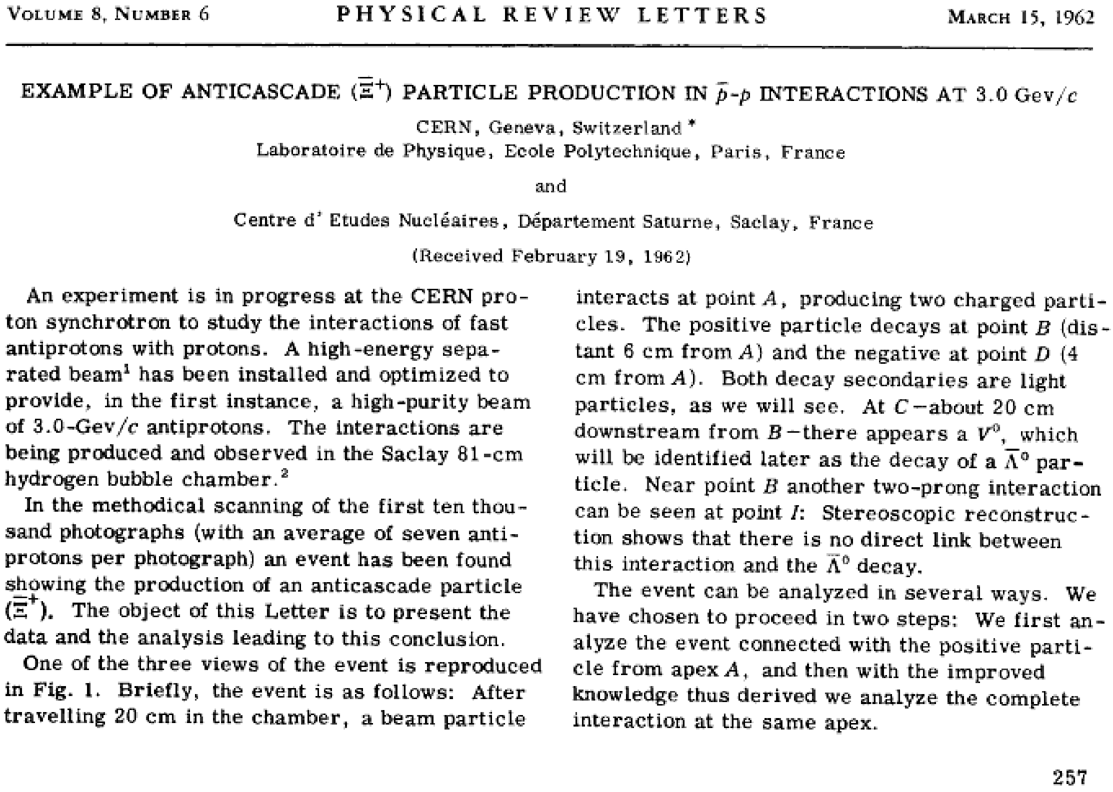




Volume 8, Number 6 PHYSICAL REVIEW LETTERS March 15, 1962

OBSERVATION OF PRODUCTION OF A $\Xi^- + \bar{\Xi}^+$ PAIR[*]

H. N. Brown, B. B. Culwick, W. B. Fowler, M. Gailloud,[†] T. E. Kalogeropoulos, J. K. Kopp,
R. M. Lea, R. I. Louttit, T. W. Morris, R. P. Shutt, A. M. Thorndike, and M. S. Webster
Brookhaven National Laboratory, Upton, New York
and
C. Baltay, E. C. Fowler, J. Sandweiss,[‡] J. R. Sanford, and H. D. Taft
Yale University, New Haven, Connecticut
(Received February 19, 1962)



Volume 8, Number 6 PHYSICAL REVIEW LETTERS March 15, 1962

EXAMPLE OF ANTICASCADE ($\bar{\Xi}^+$) PARTICLE PRODUCTION IN $\bar{p}$-p INTERACTIONS AT 3.0 Gev/c

CERN, Geneva, Switzerland[*]
Laboratoire de Physique, Ecole Polytechnique, Paris, France
and
Centre d' Etudes Nucléaires, Département Saturne, Saclay, France
(Received February 19, 1962)

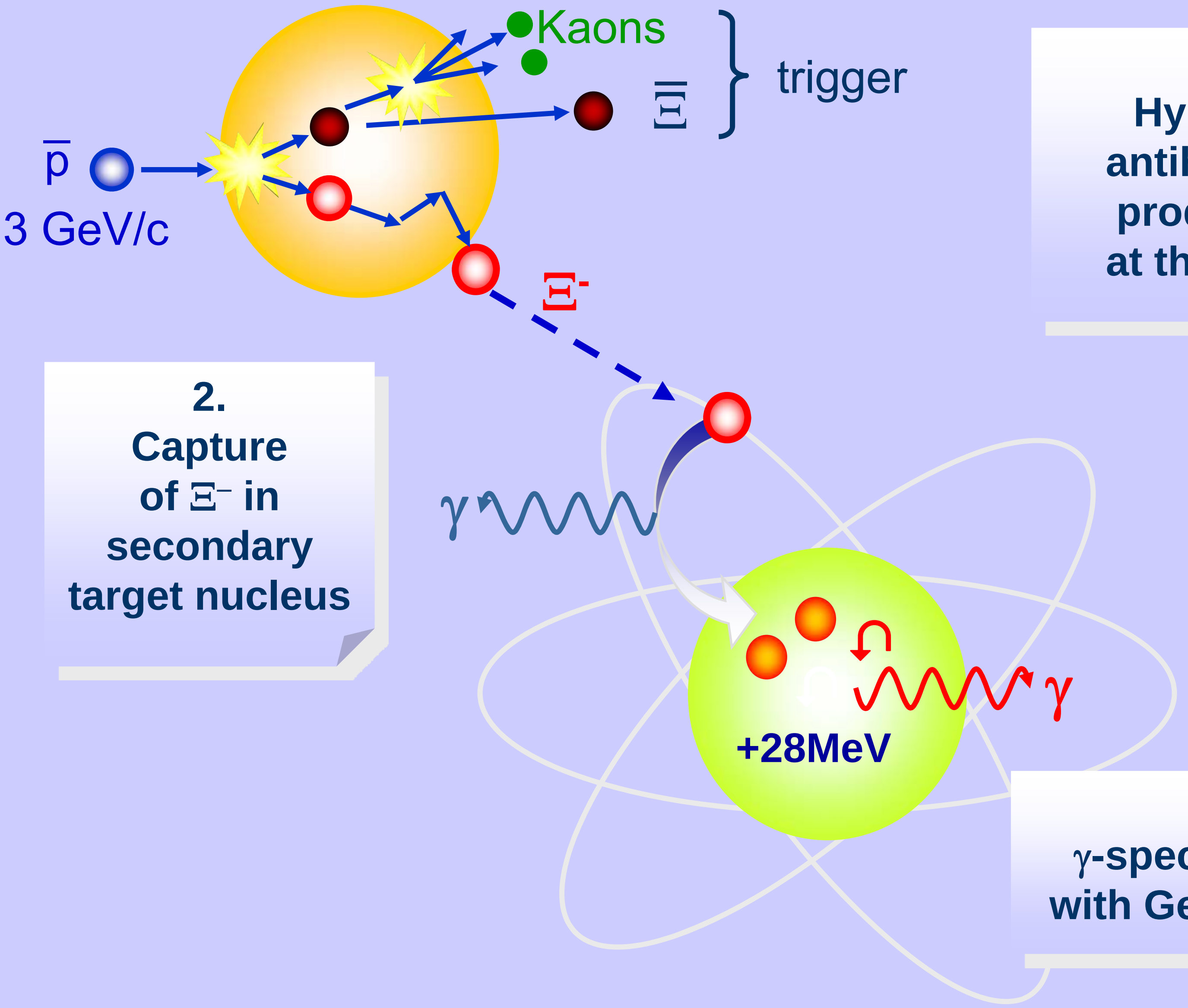
An experiment is in progress at the CERN proton synchrotron to study the interactions of fast antiprotons with protons. A high-energy separated beam[1] has been installed and optimized to provide, in the first instance, a high-purity beam of 3.0-Gev/c antiprotons. The interactions are being produced and observed in the Saclay 81-cm hydrogen bubble chamber.[2]

In the methodical scanning of the first ten thousand photographs (with an average of seven antiprotons per photograph) an event has been found showing the production of an anticascade particle ($\bar{\Xi}^+$). The object of this Letter is to present the data and the analysis leading to this conclusion.

One of the three views of the event is reproduced in Fig. 1. Briefly, the event is as follows: After travelling 20 cm in the chamber, a beam particle interacts at point A, producing two charged particles. The positive particle decays at point B (distant 6 cm from A) and the negative at point D (4 cm from A). Both decay secondaries are light particles, as we will see. At C—about 20 cm downstream from B—there appears a V^0, which will be identified later as the decay of a $\bar{\Lambda}^0$ particle. Near point B another two-prong interaction can be seen at point I: Stereoscopic reconstruction shows that there is no direct link between this interaction and the $\bar{\Lambda}^0$ decay.

The event can be analyzed in several ways. We have chosen to proceed in two steps: We first analyze the event connected with the positive particle from apex A, and then with the improved knowledge thus derived we analyze the complete interaction at the same apex.

Production of Double Hypernuclei



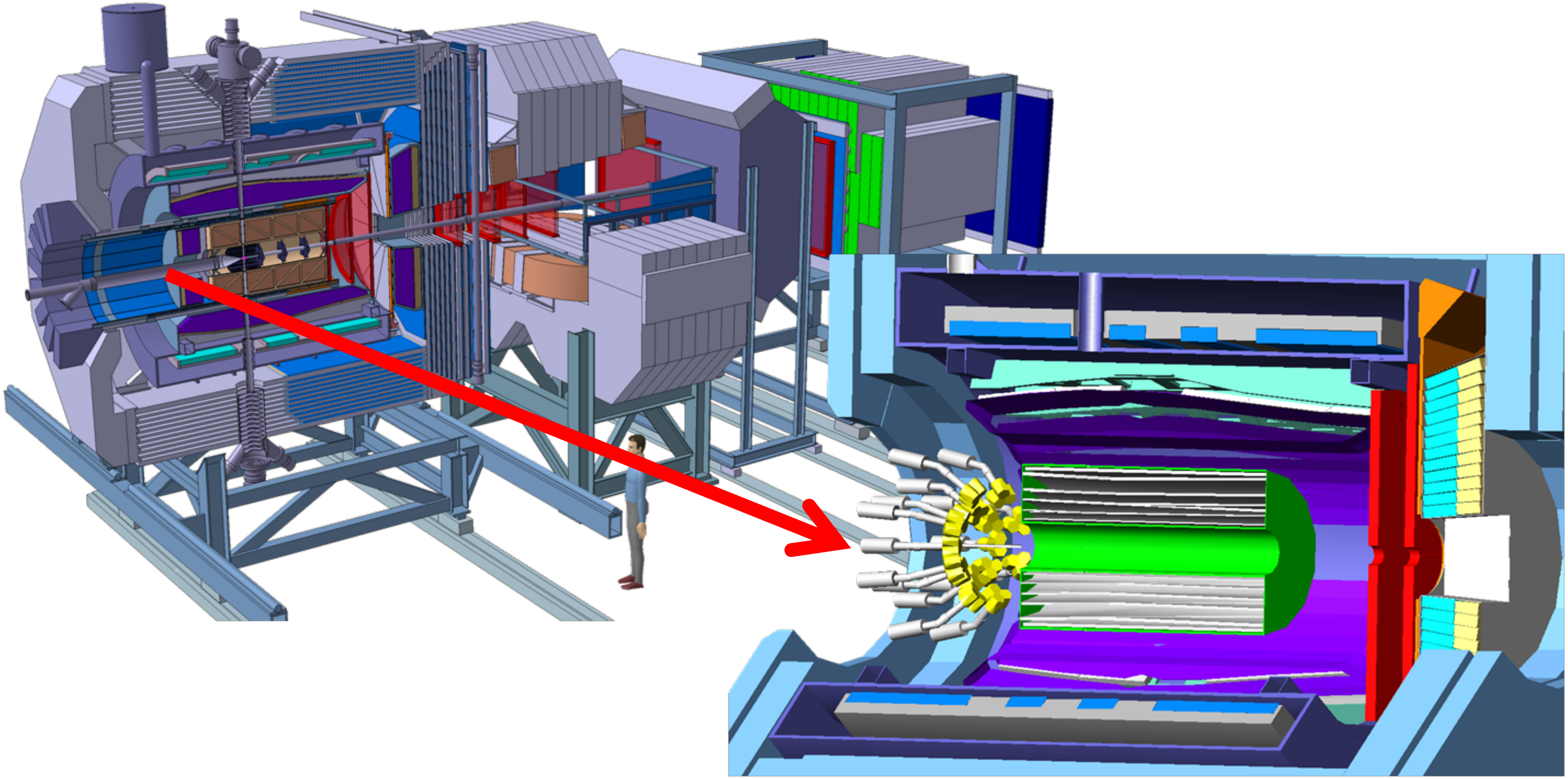
1.
Hyperon-antihyperon production at threshold

2.
Capture of Ξ^- in secondary target nucleus

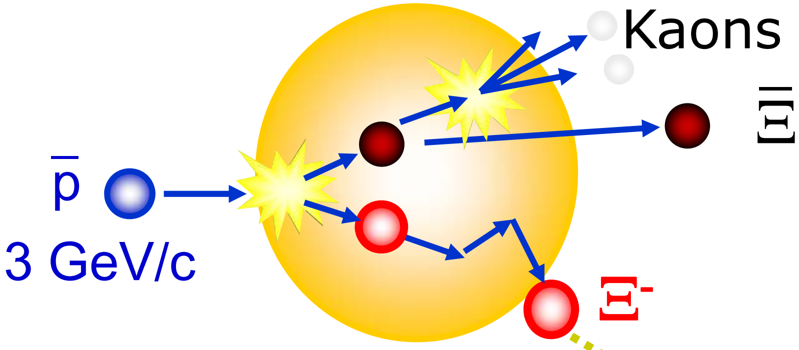
3.
γ-spectroskopy with Ge-detectors

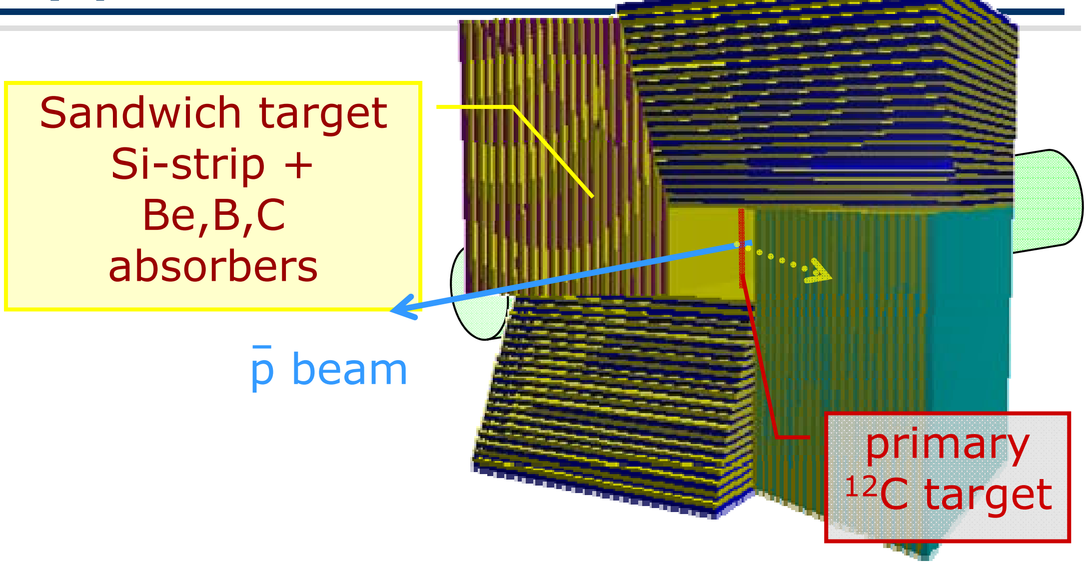
PANDA Setup

- θ_{lab}< 45°: Ξ–, K- trigger (PANDA)
- θ_{lab}= 45°-90°: Ξ-capture, hypernucleus formation
- θ_{lab}>90°: γ-detection Euroball (?) at backward angles

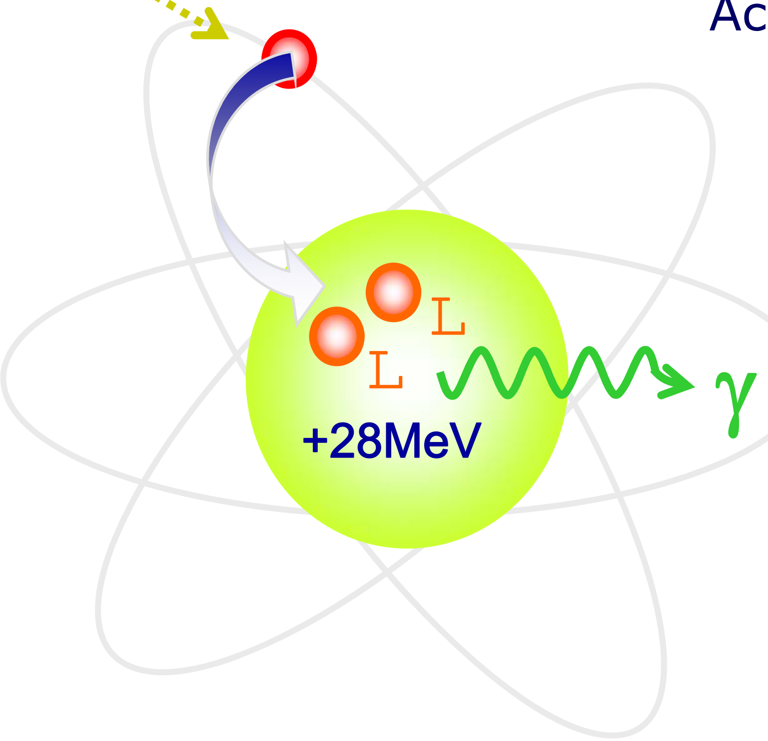


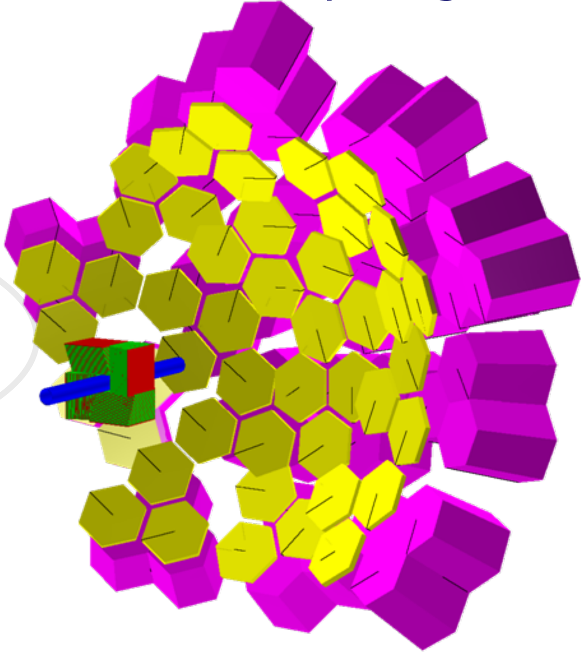
Production of ΛΛ Hypernuclei at PANDA





Active secondary target

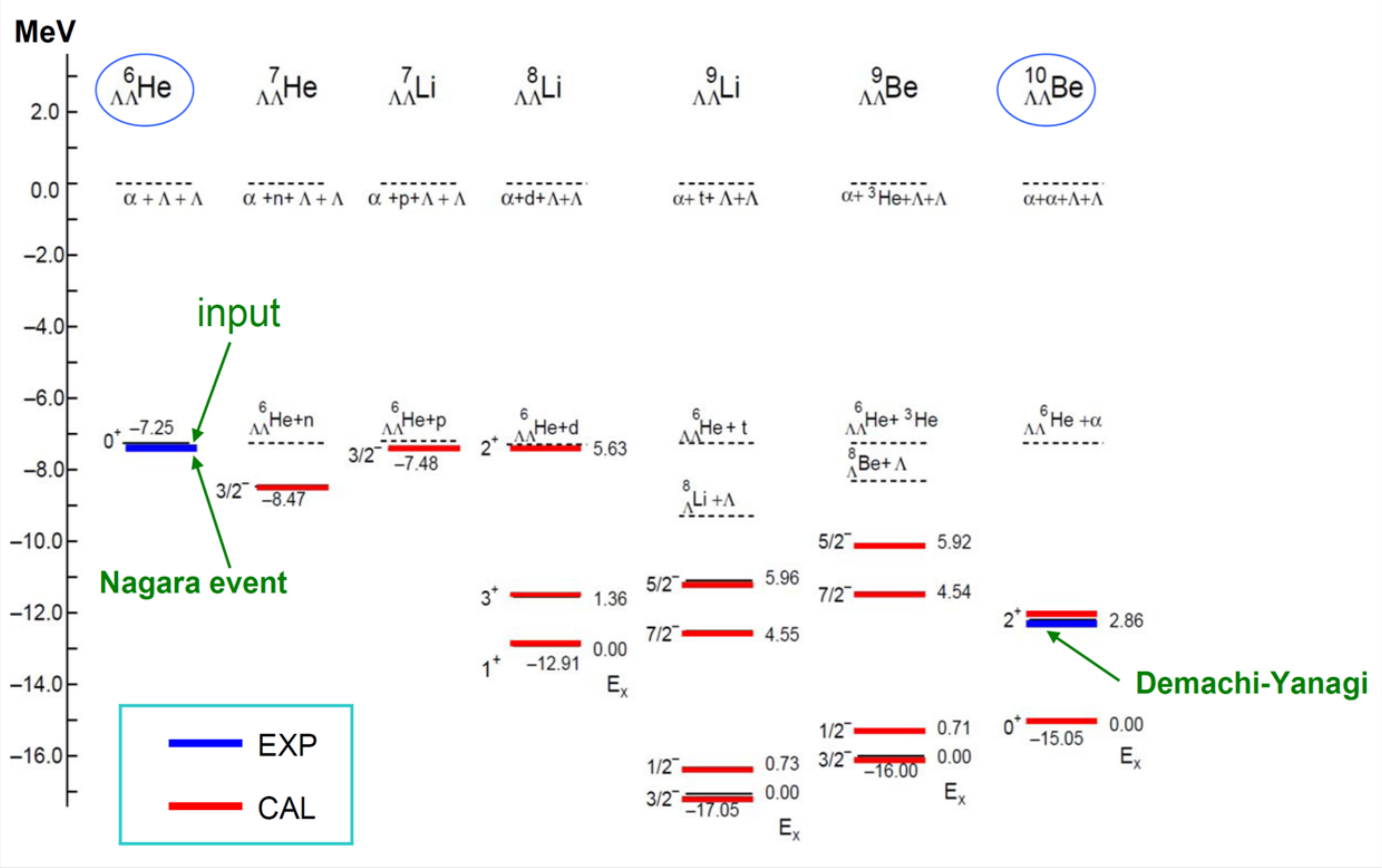




Array of HPGe

Spectroscopy of ΛΛ-hypernuclei

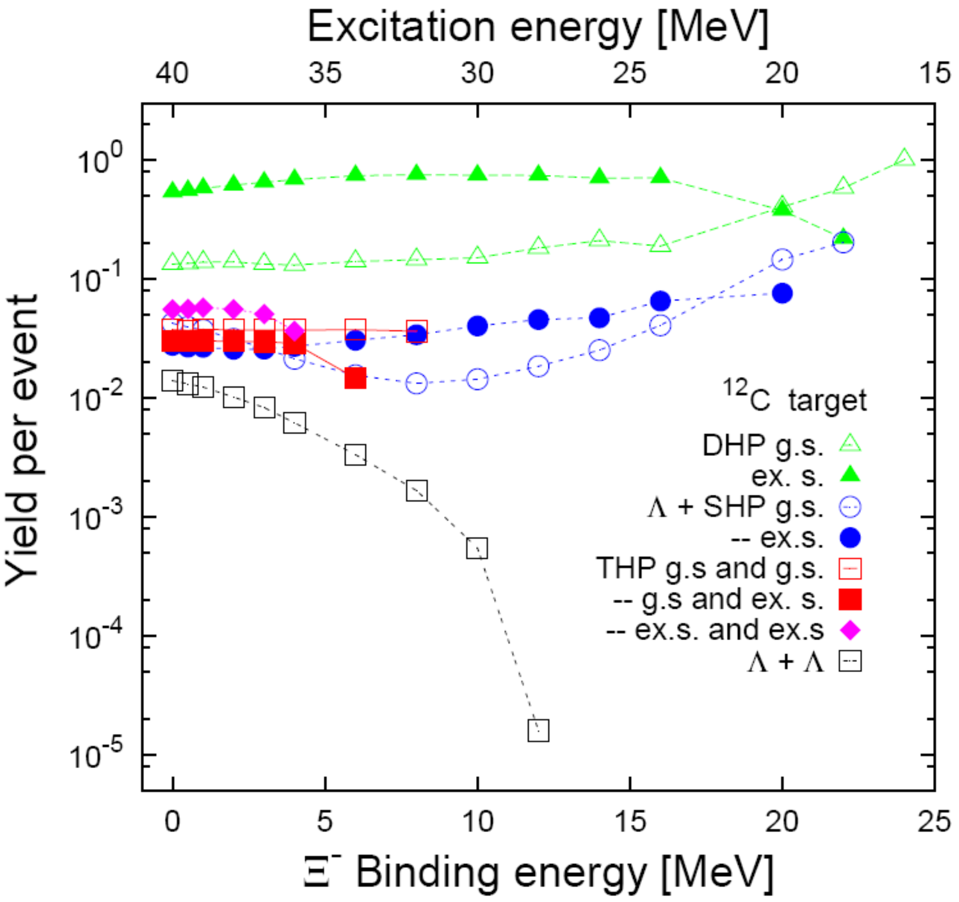
E. Hiyama, M. Kamimura, T.Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002) , 024007



- many excited, particle stable states in double hypernuclei predicted
- level structure reflects levels of core nucleus

Excitation Function for $^{13}_{\Lambda\Lambda}B^*$ decays

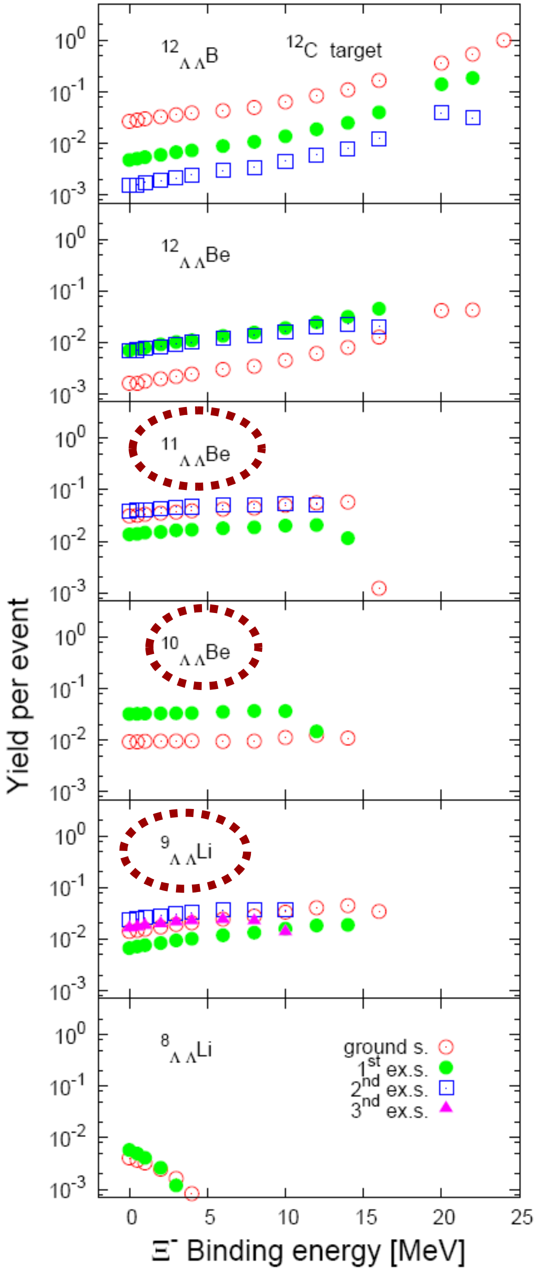
- DHP ▼△: double hypernuclei dominates
- SHP ●○ : single hypernuclei below B_Ξ=-12MeV only $^{12}{}_\Lambda B$ states
- THP □▲○: twin hypernuclei ~10%



- note: relevant range probably B_Ξ≈0MeV

Population of individual states for ^{12}C

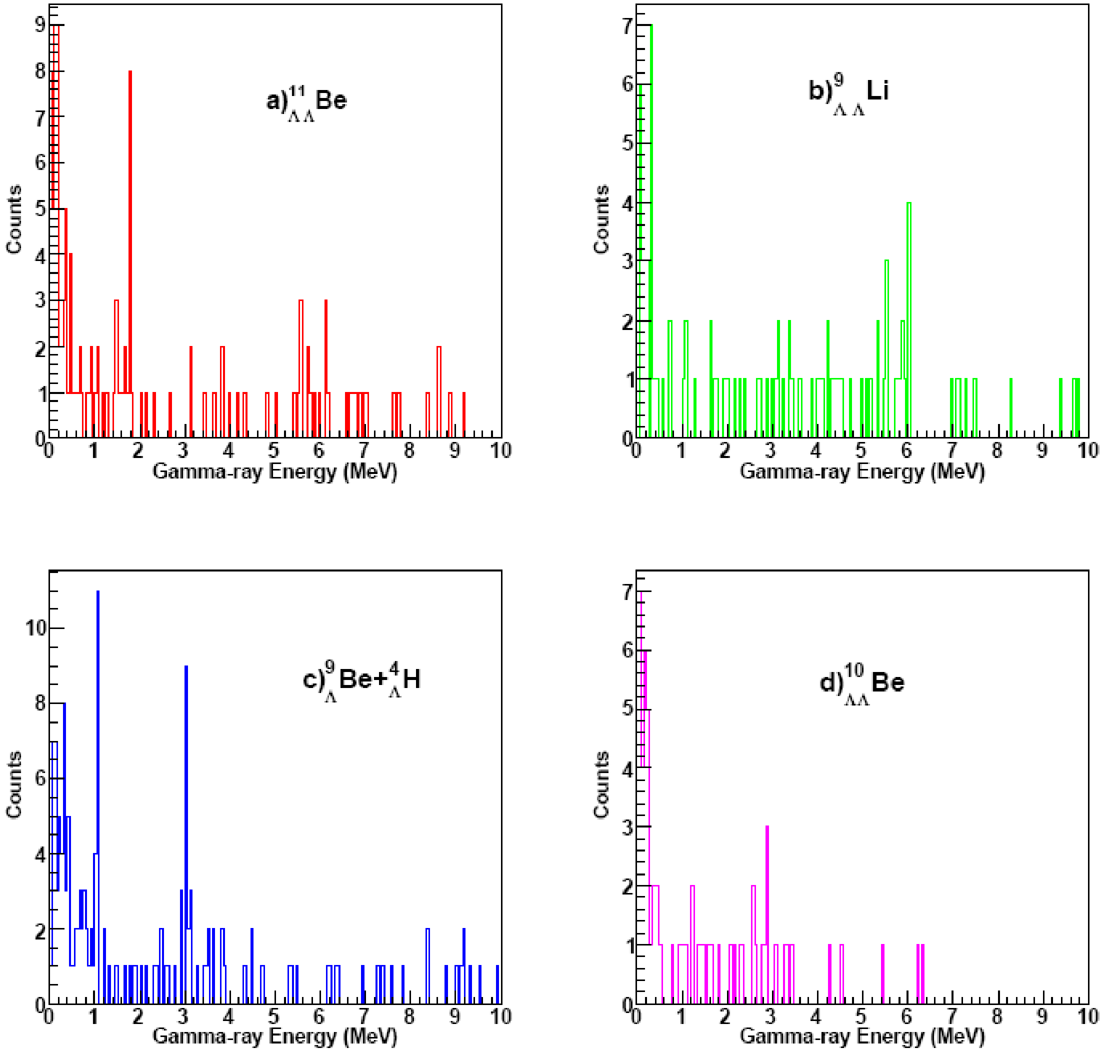
- $^{9}_{\Lambda\Lambda}$Li, $^{10}_{\Lambda\Lambda}$Be, $^{11}_{\Lambda\Lambda}$Be dominate (few percent)
- excited state in $^{10}_{\Lambda\Lambda}$Be more likely than ground state ⇒ c.f. E. Hiyama
- relative large probability (~5%) for individual *excited* states ●□



Simulation within PANDA_ROOT

- Example: secondary ^{12}C target (~2 weeks$^{*)}$)

Alicia Sanchez (Mainz)

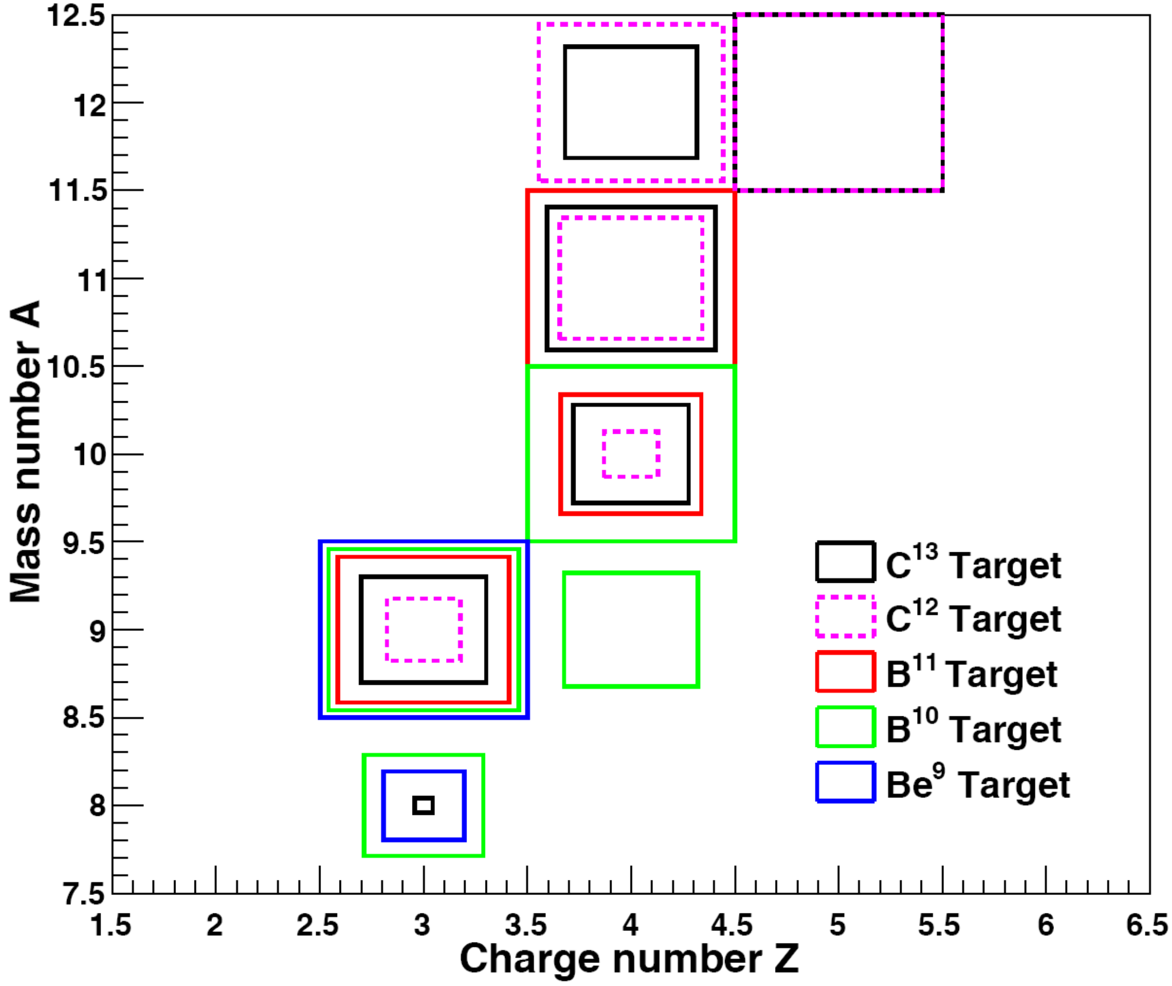


$^{*)}$In these simulations we assume a Ξ capture and conversion probability of 5%

(arXiv:0903.3905)

Identification of double hypernuclei

- PANDA will explore several targets: ^{9}Be, ^{10}B, ^{11}B, ^{12}C, ^{13}C
- Sum of dominating first and second excited state

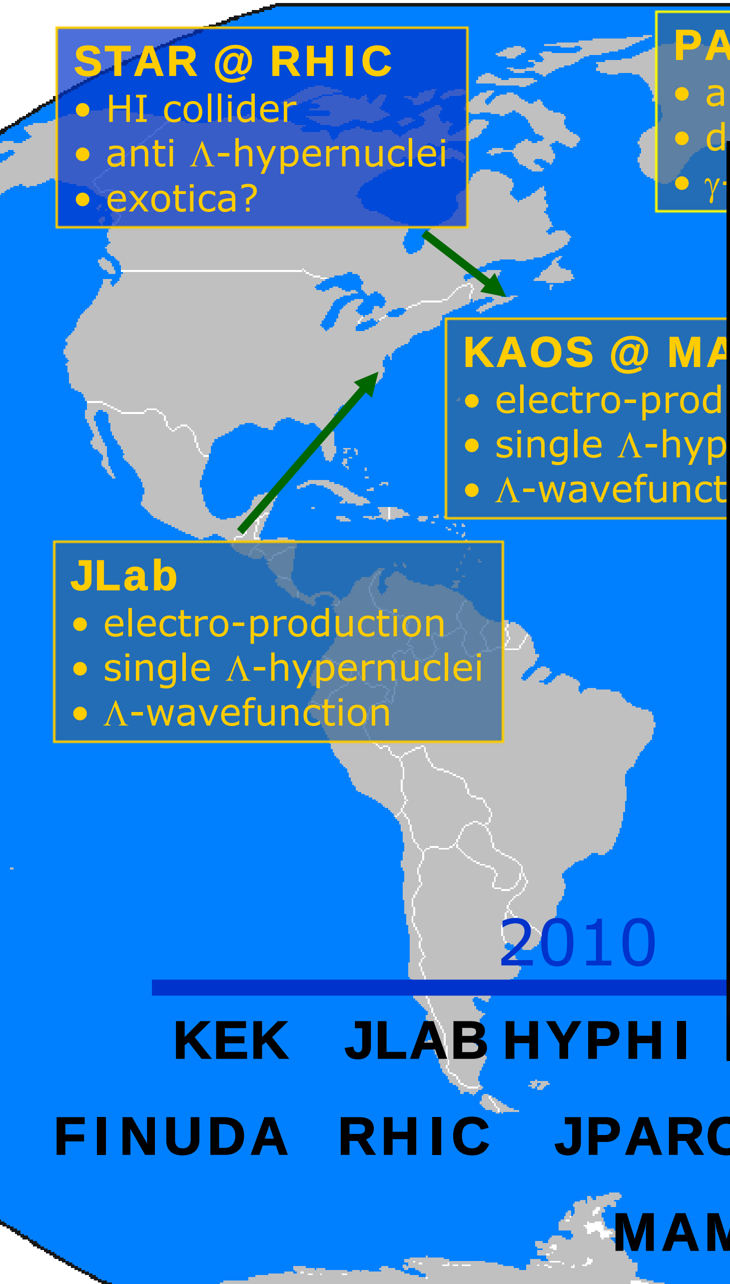


- caveat: probabilities need to be folded with efficiency

Other options

Here, there and everywhere

International Hypernuclear Network



STAR @ RHIC
- HI collider
- anti Λ-hypernuclei
- exotica?

PANDA @ FAIR
- anti-proton beam
- double Λ-hypernuclei
- γ-

Dubna
- heavy ion beam

KAOS @ MA
- electro-prod
- single Λ-hyp
- Λ-wavefunct

JLab
- electro-production
- single Λ-hypernuclei
- Λ-wavefunction

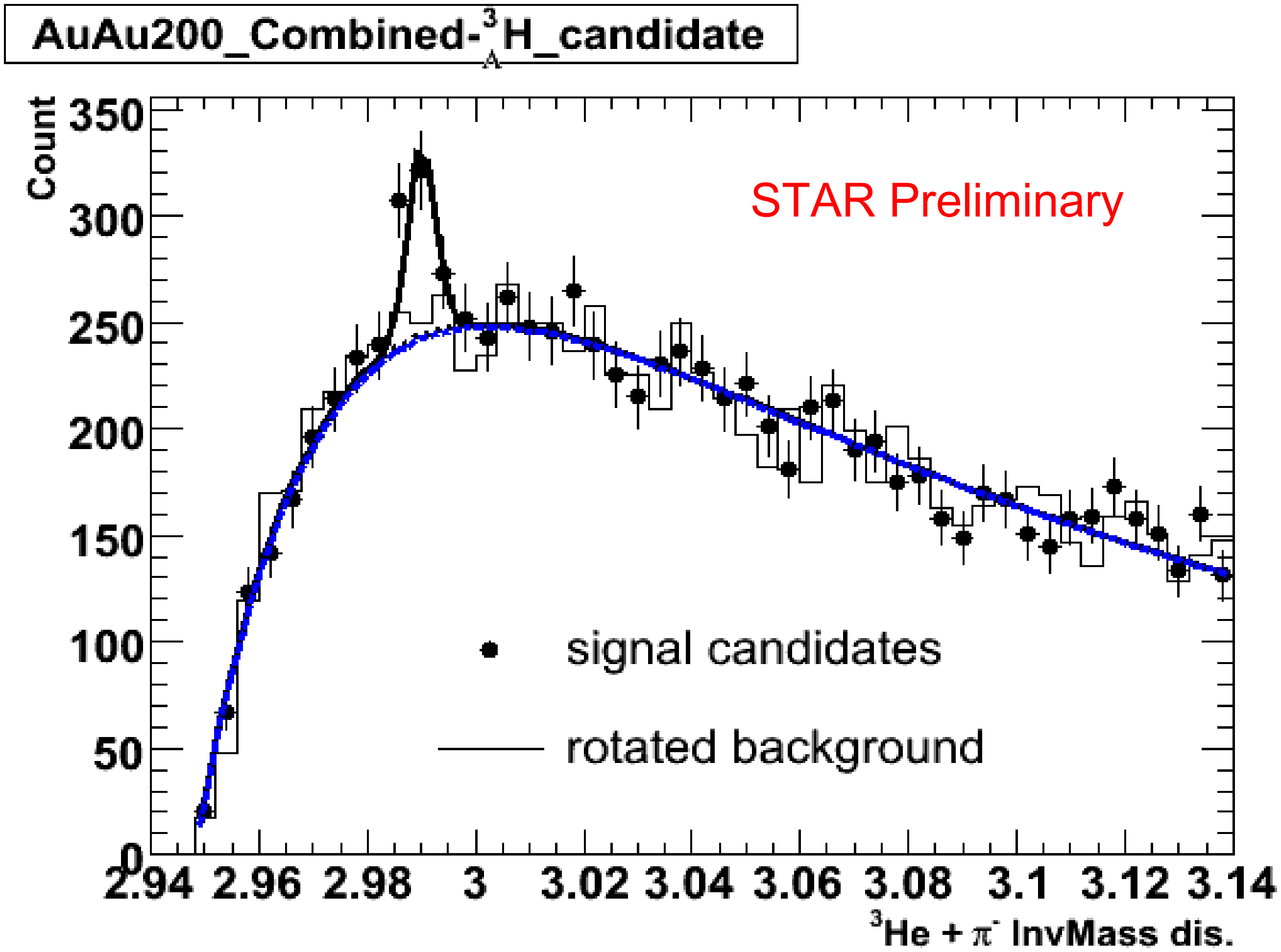
2010

KEK **JLAB** **HYPHI**

FINUDA **RHIC** **JPARC**

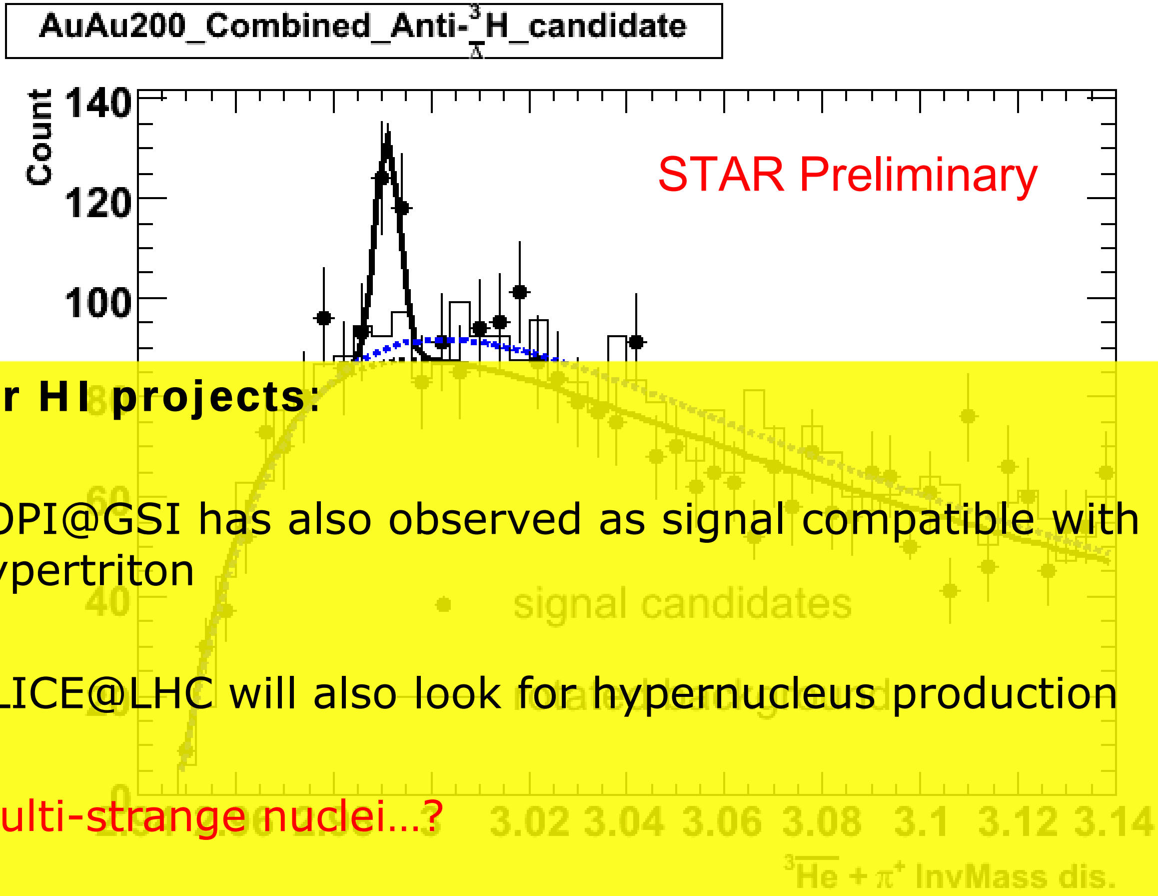
MAMI

${}^{3}_{\Lambda}H$ at STAR



- background shape determined from rotated background analysis
- Signal observed from the data (bin-by-bin counting): 177 ± 30
- Mass: 2.990 ± 0.001 GeV; Width (fixed): 0.0025 GeV.

The first antihypernucleus: $^{3}_{\bar{\Lambda}}\bar{H}$ @ STAR

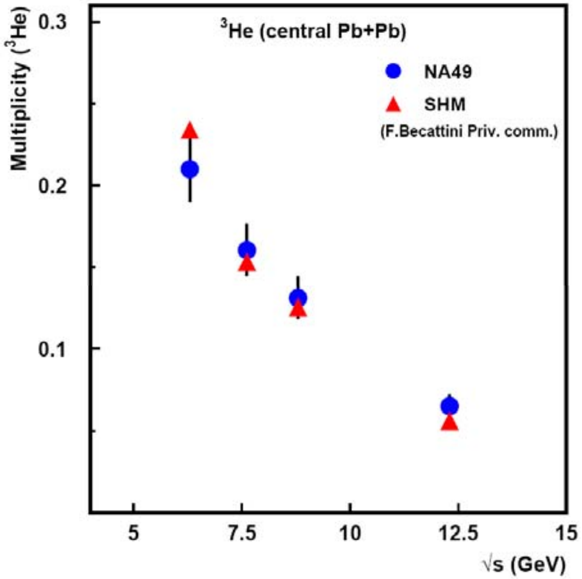


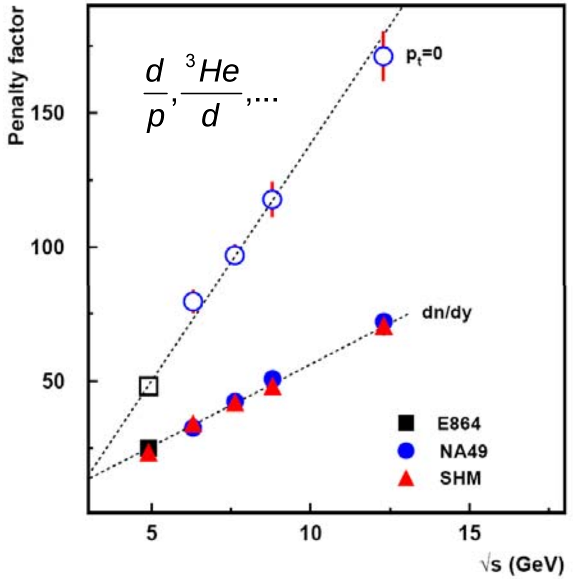
Other HI projects:

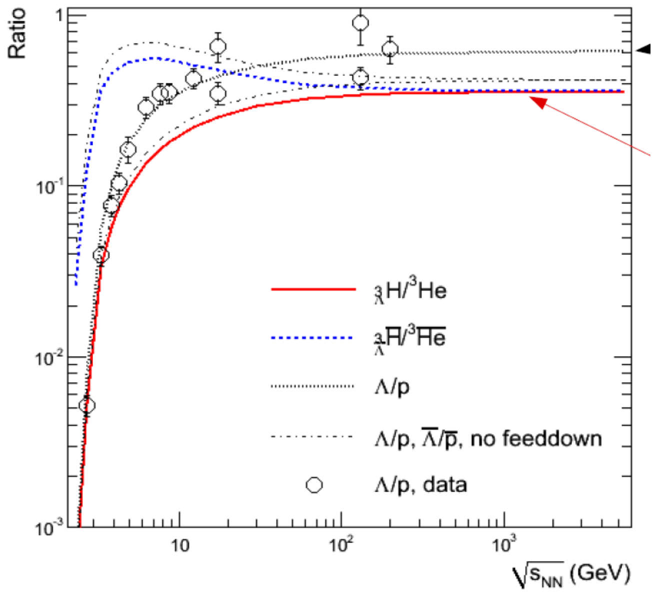
- FOPI@GSI has also observed as signal compatible with hypertriton
- ALICE@LHC will also look for hypernucleus production
- multi-strange nuclei…?

- Signal observed from the data (bin-by-bin counting): 68±18
- Mass: 2.991±0.001 GeV; Width (fixed): 0.0025 GeV

$^{6}_{\Lambda\Lambda}$He Production in central RHIC







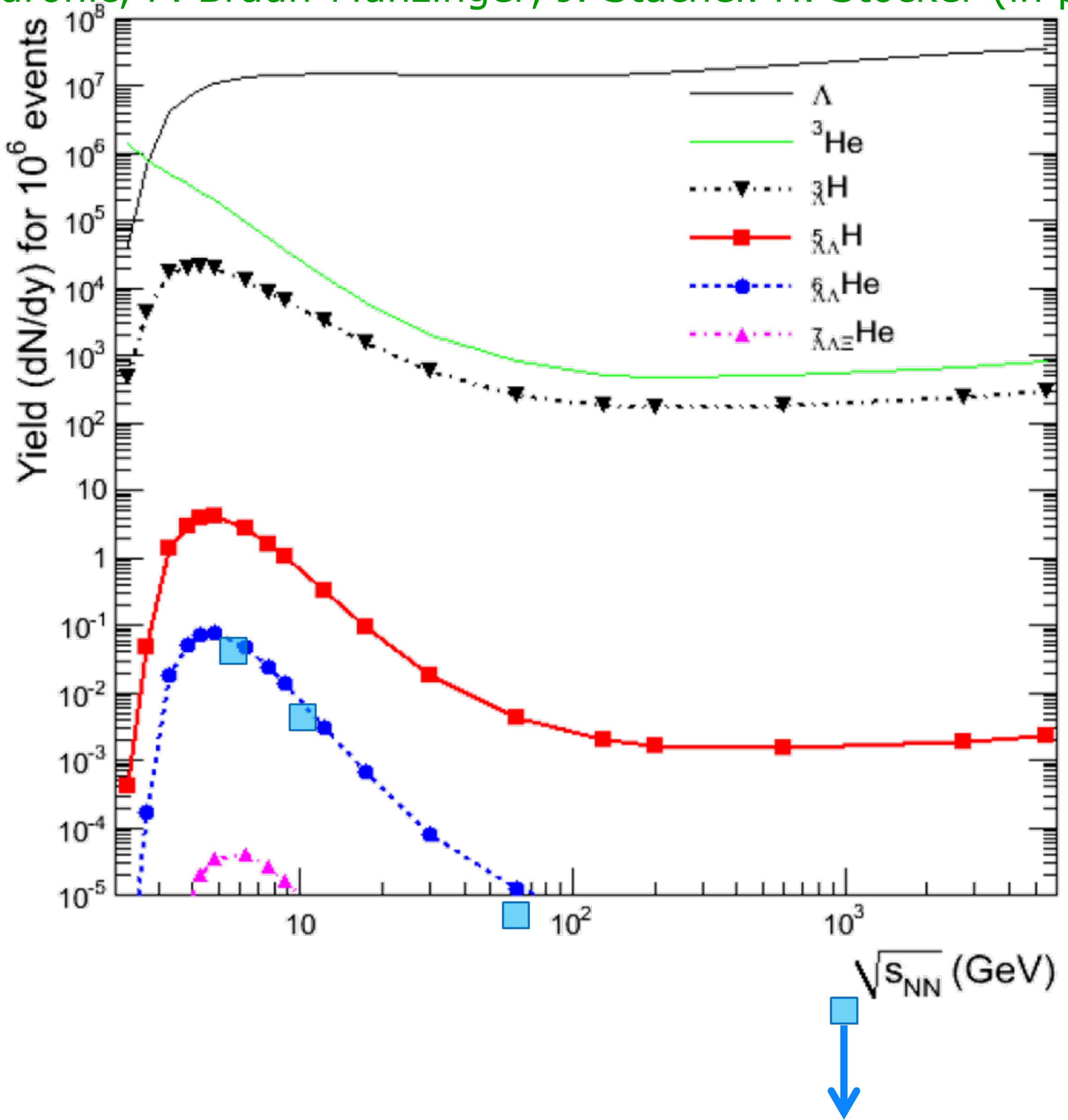
$$M(^{6}_{\Lambda\Lambda}He) = M(^{3}He) \times penalty^{3}_{nucleon} \times penalty^{2}_{\Lambda}$$

$$= M(^{3}He) \times \left(\frac{d}{p}\right)^{3} \times \left(\frac{\Lambda}{p}\right)^{2}$$

	AGS	*SPS*		*STAR*	*ALICE*
$\sqrt{s}$	5	10	60	100	1000
$M(^{6}_{\Lambda\Lambda}He)$	$5 \cdot 10^{-8}$	$2 \cdot 10^{-9}$	$1.5 \cdot 10^{-12}$	$1 \cdot 10^{-13}$	10^{-18}

Statistical model – central Pb+Pb

- A. Andronic, P. Braun-Munzinger, J. Stachel. H. Stöcker (in preparation)



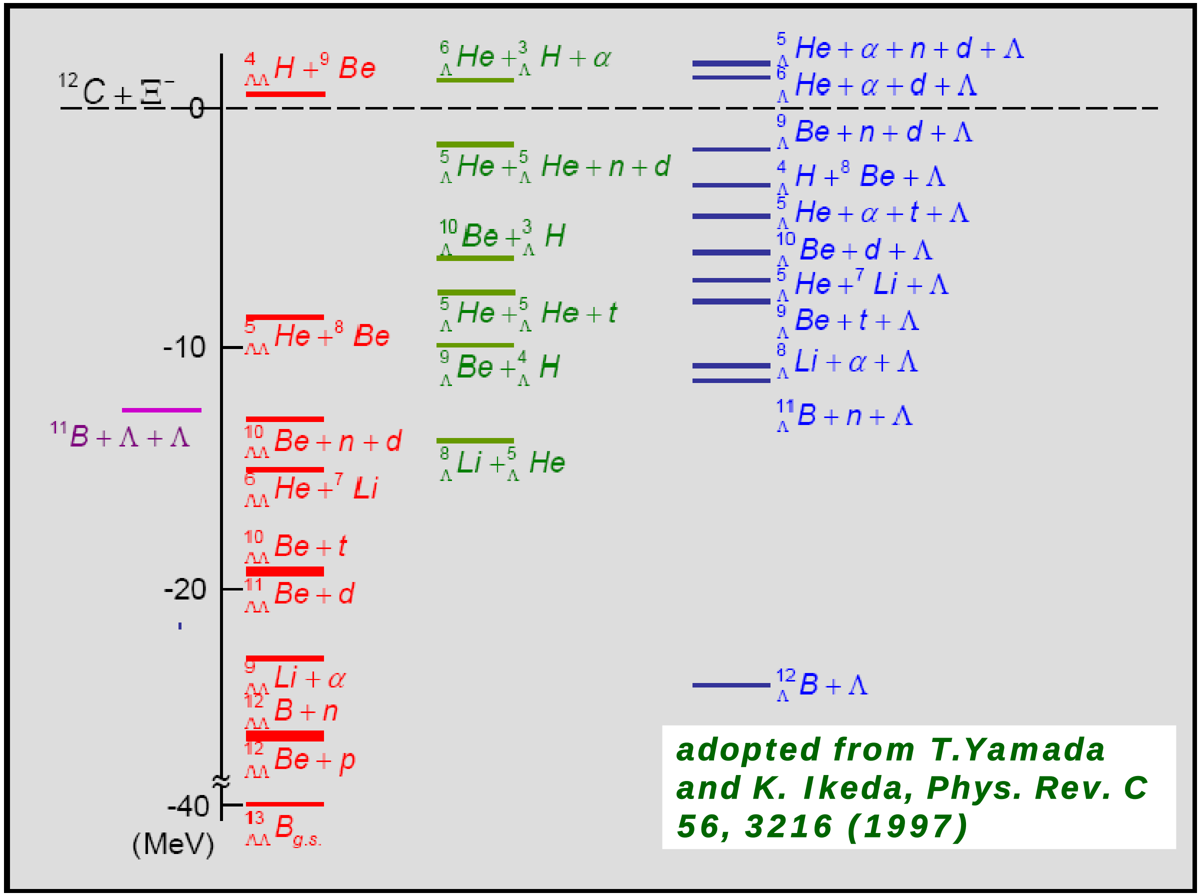
THANK YOU

Energy Balance for Ξ conversion

- Maximum energy available with respect to $^{13}_{\Lambda\Lambda}B_{g.s.}$ ≈40 MeV

$$E_x = m(^{12}C) + m(\Xi^-) + B_\Xi - m(^{13}_{\Lambda\Lambda}B)$$

- Ξ^- binding energy unknown
  - Theoreticals calculations on Ξ nuclear potential leads to 0.6 – 3.7 MeV
    (C.J Batty et al, Aoki et al.,…)



adopted from T.Yamada and K. Ikeda, Phys. Rev. C 56, 3216 (1997)

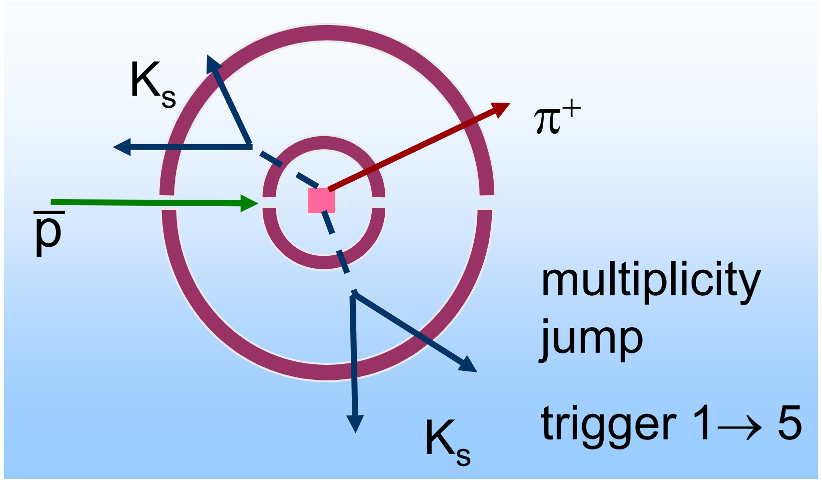
$\bar{p}$ – Annihilation at Rest

- K. Kilian (1987)

$p\bar{p} \rightarrow K^*\bar{K}^*$ $\quad p(K^*(892)) = 285$ MeV/c

$\hookrightarrow \bar{K}^*pn \rightarrow \pi^+ K\, H$

$p\,^3He \rightarrow KK\pi^+H$



multiplicity jump

trigger 1 → 5

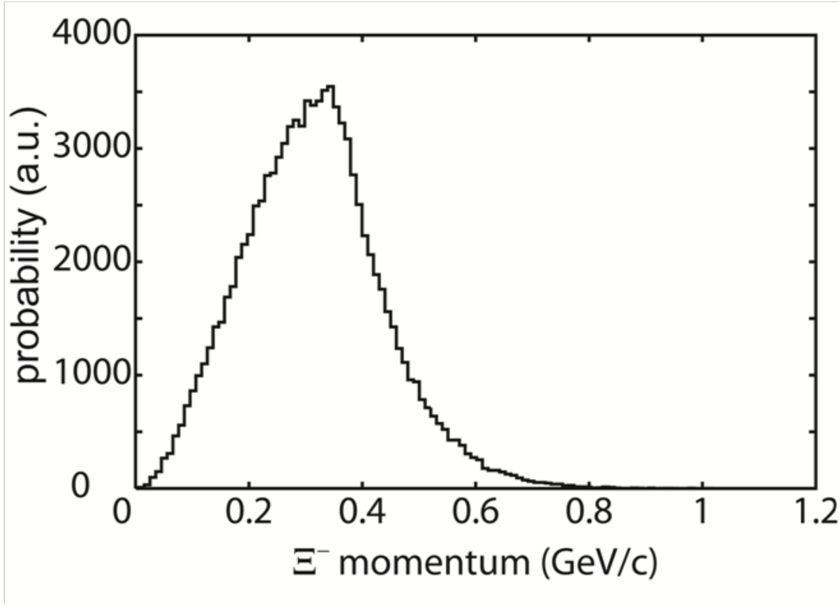
- ...FLAIR

$p\bar{p} \rightarrow K^*\bar{K}^*$ $\qquad p(K^*) = 285$ MeV/c

$\hookrightarrow \bar{K}^*N \rightarrow K\,\Xi$

- count rate
  - $1.5 \cdot 10^{-3}$ probability for $\bar{p}p \rightarrow K^*\bar{K}^*$
  - 20% survival probability of K^* prior interaction
  - 10^{-3} probability for $\bar{K}^*N \rightarrow K^+\Xi^-$
  - stopping probability 20%
  - 10^6 antiprotons/s

⇒ 5000 stopped Ξ^- per day



(104,114), (114,133)

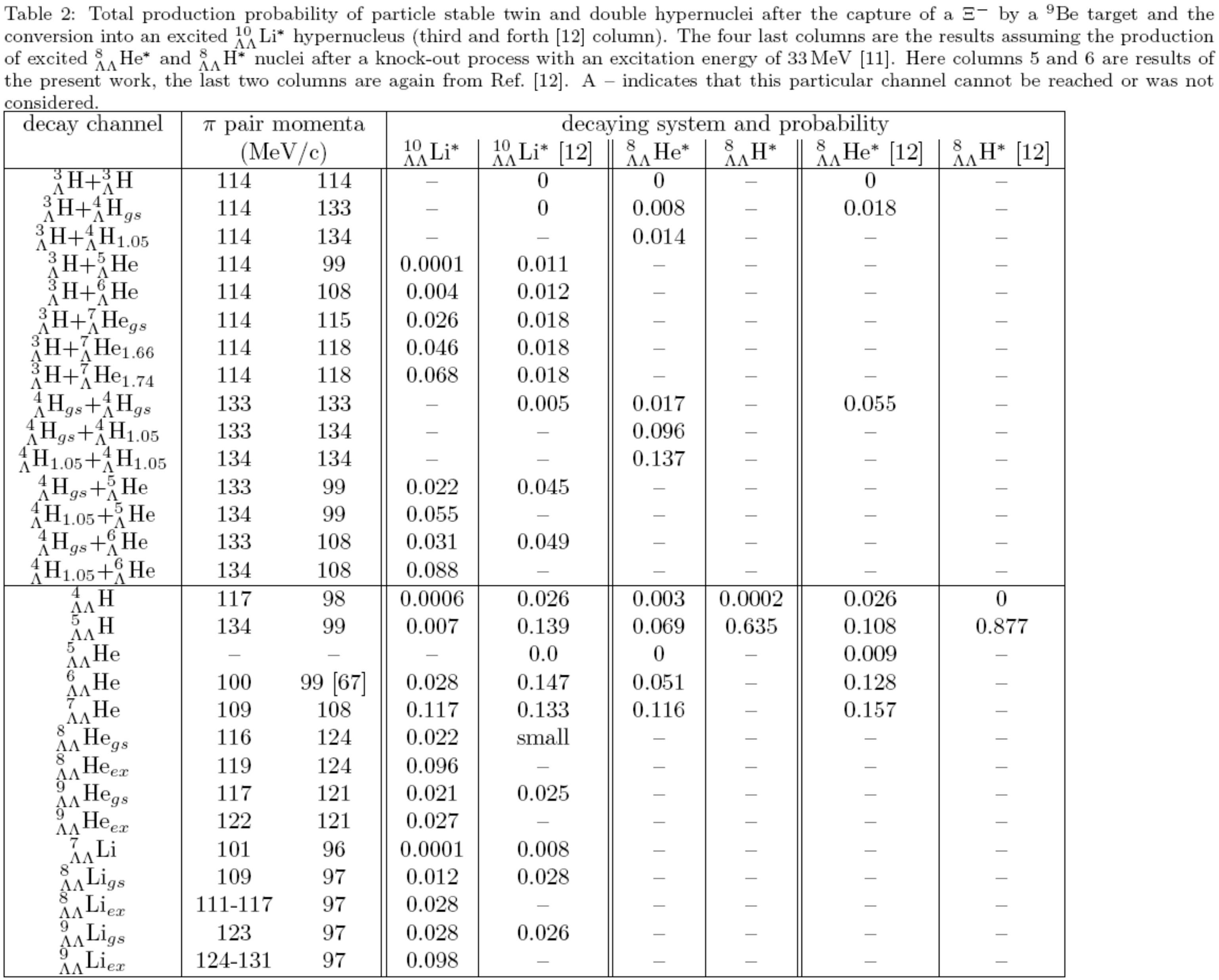
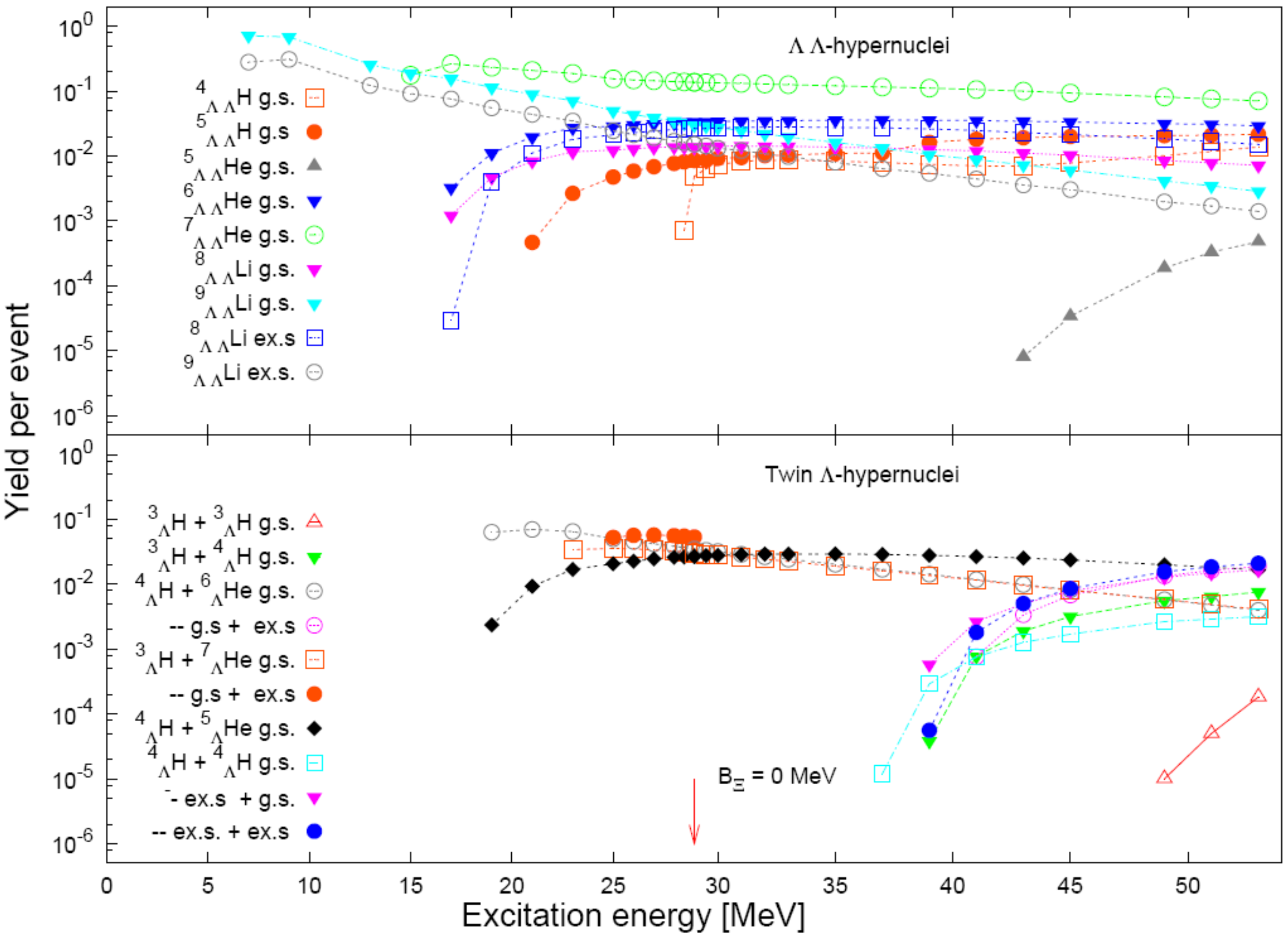


Table 2: Total production probability of particle stable twin and double hypernuclei after the capture of a Ξ^- by a ^{9}Be target and the conversion into an excited ${}^{10}_{\Lambda\Lambda}\mathrm{Li}^*$ hypernucleus (third and forth [12] column). The four last columns are the results assuming the production of excited ${}^{8}_{\Lambda\Lambda}\mathrm{He}^*$ and ${}^{8}_{\Lambda\Lambda}\mathrm{H}^*$ nuclei after a knock-out process with an excitation energy of 33 MeV [11]. Here columns 5 and 6 are results of the present work, the last two columns are again from Ref. [12]. A – indicates that this particular channel cannot be reached or was not considered.

decay channel	π pair momenta (MeV/c)		decaying system and probability					
			${}^{10}_{\Lambda\Lambda}\mathrm{Li}^*$	${}^{10}_{\Lambda\Lambda}\mathrm{Li}^*$ [12]	${}^{8}_{\Lambda\Lambda}\mathrm{He}^*$	${}^{8}_{\Lambda\Lambda}\mathrm{H}^*$	${}^{8}_{\Lambda\Lambda}\mathrm{He}^*$ [12]	${}^{8}_{\Lambda\Lambda}\mathrm{H}^*$ [12]
${}^{3}_{\Lambda}\mathrm{H}+{}^{3}_{\Lambda}\mathrm{H}$	114	114	–	0	0	–	0	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{4}_{\Lambda}\mathrm{H}_{gs}$	114	133	–	0	0.008	–	0.018	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{4}_{\Lambda}\mathrm{H}_{1.05}$	114	134	–	–	0.014	–	–	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{5}_{\Lambda}\mathrm{He}$	114	99	0.0001	0.011	–	–	–	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{6}_{\Lambda}\mathrm{He}$	114	108	0.004	0.012	–	–	–	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{7}_{\Lambda}\mathrm{He}_{gs}$	114	115	0.026	0.018	–	–	–	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{7}_{\Lambda}\mathrm{He}_{1.66}$	114	118	0.046	0.018	–	–	–	–
${}^{3}_{\Lambda}\mathrm{H}+{}^{7}_{\Lambda}\mathrm{He}_{1.74}$	114	118	0.068	0.018	–	–	–	–
${}^{4}_{\Lambda}\mathrm{H}_{gs}+{}^{4}_{\Lambda}\mathrm{H}_{gs}$	133	133	–	0.005	0.017	–	0.055	–
${}^{4}_{\Lambda}\mathrm{H}_{gs}+{}^{4}_{\Lambda}\mathrm{H}_{1.05}$	133	134	–	–	0.096	–	–	–
${}^{4}_{\Lambda}\mathrm{H}_{1.05}+{}^{4}_{\Lambda}\mathrm{H}_{1.05}$	134	134	–	–	0.137	–	–	–
${}^{4}_{\Lambda}\mathrm{H}_{gs}+{}^{5}_{\Lambda}\mathrm{He}$	133	99	0.022	0.045	–	–	–	–
${}^{4}_{\Lambda}\mathrm{H}_{1.05}+{}^{5}_{\Lambda}\mathrm{He}$	134	99	0.055	–	–	–	–	–
${}^{4}_{\Lambda}\mathrm{H}_{gs}+{}^{6}_{\Lambda}\mathrm{He}$	133	108	0.031	0.049	–	–	–	–
${}^{4}_{\Lambda}\mathrm{H}_{1.05}+{}^{6}_{\Lambda}\mathrm{He}$	134	108	0.088	–	–	–	–	–
${}^{4}_{\Lambda\Lambda}\mathrm{H}$	117	98	0.0006	0.026	0.003	0.0002	0.026	0
${}^{5}_{\Lambda\Lambda}\mathrm{H}$	134	99	0.007	0.139	0.069	0.635	0.108	0.877
${}^{5}_{\Lambda\Lambda}\mathrm{He}$	–	–	–	0.0	0	–	0.009	–
${}^{6}_{\Lambda\Lambda}\mathrm{He}$	100	99 [67]	0.028	0.147	0.051	–	0.128	–
${}^{7}_{\Lambda\Lambda}\mathrm{He}$	109	108	0.117	0.133	0.116	–	0.157	–
${}^{8}_{\Lambda\Lambda}\mathrm{He}_{gs}$	116	124	0.022	small	–	–	–	–
${}^{8}_{\Lambda\Lambda}\mathrm{He}_{ex}$	119	124	0.096	–	–	–	–	–
${}^{9}_{\Lambda\Lambda}\mathrm{He}_{gs}$	117	121	0.021	0.025	–	–	–	–
${}^{9}_{\Lambda\Lambda}\mathrm{He}_{ex}$	122	121	0.027	–	–	–	–	–
${}^{7}_{\Lambda\Lambda}\mathrm{Li}$	101	96	0.0001	0.008	–	–	–	–
${}^{8}_{\Lambda\Lambda}\mathrm{Li}_{gs}$	109	97	0.012	0.028	–	–	–	–
${}^{8}_{\Lambda\Lambda}\mathrm{Li}_{ex}$	111-117	97	0.028	–	–	–	–	–
${}^{9}_{\Lambda\Lambda}\mathrm{Li}_{gs}$	123	97	0.028	0.026	–	–	–	–
${}^{9}_{\Lambda\Lambda}\mathrm{Li}_{ex}$	124-131	97	0.098	–	–	–	–	–


Λ Λ-hypernuclei
Twin Λ-hypernuclei
Yield per event
Excitation energy [MeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
5
10
15
20
25
30
35
40
45
50
$^{4}_{\Lambda\Lambda}$H g.s.
$^{5}_{\Lambda\Lambda}$H g.s
$^{5}_{\Lambda\Lambda}$He g.s.
$^{6}_{\Lambda\Lambda}$He g.s.
$^{7}_{\Lambda\Lambda}$He g.s.
$^{8}_{\Lambda\Lambda}$Li g.s.
$^{9}_{\Lambda\Lambda}$Li g.s.
$^{8}_{\Lambda\Lambda}$Li ex.s
$^{9}_{\Lambda\Lambda}$Li ex.s.
$^{3}_{\Lambda}$H + $^{3}_{\Lambda}$H g.s.
$^{3}_{\Lambda}$H + $^{4}_{\Lambda}$H g.s.
$^{4}_{\Lambda}$H + $^{6}_{\Lambda}$He g.s.
-- g.s + ex.s
$^{3}_{\Lambda}$H + $^{7}_{\Lambda}$He g.s.
-- g.s + ex.s
$^{4}_{\Lambda}$H + $^{5}_{\Lambda}$He g.s.
$^{4}_{\Lambda}$H + $^{4}_{\Lambda}$H g.s.
- ex.s + g.s.
-- ex.s. + ex.s
B_{Ξ} = 0 MeV