FIRST OBSERVATION OF THE HYPER HEAVY-HYDROGEN $^{6}_{\Lambda}H$

Elena Botta

INFN-Torino and Torino University

for the FINUDA Collaboration

Outline

- Introduction to neutron-rich hypernuclei:
  physics interest, state of the art
- Neutron-rich hypernuclei production in FINUDA
- Data analysis description and results:
  - ✓ Previous results (partial statistics)
  - ✓ Present results (global statistics): preliminary
- Conclusions

n-rich hypernuclei: physics motivations

Hypernuclei with a large neutron excess (Dalitz et al., N. Cim. 30 (1963) 489 (6_ΛHe, 7_ΛHe, 8_ΛHe, 9_ΛLi observed in emulsion experiments) L. Majling, NPA 585 (1995) 211c, Y. Akaishi et al., Frascati Physic Series XVI (1999) 59.)

The Pauli principle does not apply to the Λ inside the nucleus + *extra binding energy (Λ "glue-like" role) ⇒ a larger number of neutrons can be bound with respect to ordinary nuclei.*

Hypernuclear physics:

ΛN interactions at low densities, the role of 3-body forces

nuclear core compression ($^{7}_{\Lambda}$Li vs ^{6}Li: H.Tamura et al., Phys.Rev. Lett. 84 (2000) 5963)

Λ extra binding energy

Neutron drip-line:

response of neutron halo on embedding of Λ hyperon, hypernuclear species with unstable nuclear core

T. Yu. Tretyakova and D. E. Lanskoy, Nucl. Phys. ***A 691: 51c, 2001.***

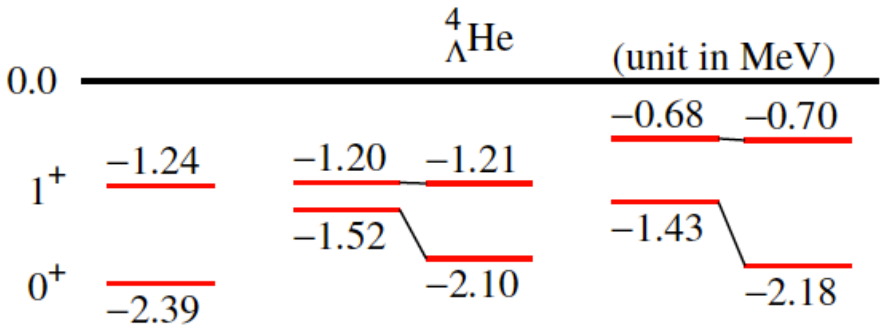
Astrophysics:

Feedback with the astrophysics field: phenomena related to *high-density nuclear matter in neutron stars.*

S. Balberg and A. Gal, Nucl. Phys. ***A 625: 435, 1997.***

Coherent Λ−Σ coupling

- The splitting of the 1^+ and 0^+ states of ${}^4_\Lambda$H and ${}^4_\Lambda$He has long been recognized as a problem to describe simultaneously the binding energies of the *s*-shell hypernuclei with a central Λ*N* interaction. R. H. Dalitz *et al.*, NPB47 (1972) 109.
- Akaishi *et al.* suggested the importance of a coherent Λ-Σ coupling in the study of He Λ hypernuclei. Khin Swe Myint *et al.*, FBS. Suppl. 12 (2000) 383. Y. Akaishi *et al.*, PRL84 (2000) 3539.



The problem might be solved by the Λ-Σ coupling which strongly affects the 0^+ states of the A = 4 hypernuclei.
It is expected that the attraction by the coherent Λ-Σ coupling enhances in a neutron-rich environment.

n-rich hypernuclei: production

- (K^-_{stop}, π^+)

$K^- + p \rightarrow \Lambda + \pi^0$	$\pi^0 + p \rightarrow n + \pi^+$	(2-step)	S-EX + C-EX
$K^- + p \rightarrow \Sigma^- + \pi^+$	$\Sigma^- + p \leftrightarrow n + \Lambda$	(1-step)	S-EX

K.Kubota et al, NPA 602 (1996) 327.

${}^{9}_{\Lambda}He$ (${}^{9}Be$) U.L.=2.3 $10^{-4}/K^-_{stop}$; ${}^{12}_{\Lambda}Be$(${}^{12}C$) U.L.=6.1 $10^{-5}/K^-_{stop}$;
${}^{16}_{\Lambda}C$(${}^{16}O$) U.L.=6.2 $10^{-5}/K^-_{stop}$

T.Y.Tretyakova et al., Nucl. Phys. A 691 (2001) 51c (10^{-6}-$10^{-7}/K^-_{stop}$)

- (π^-, K^+)

$\pi^- + p \rightarrow \pi^0 + n$	$\pi^0 + p \rightarrow \Lambda + K^+$	(2-step)	AP + C-EX
$\pi^- + p \rightarrow K^0 + \Lambda$	$K^0 + p \rightarrow n + K^+$	(2-step)	
$\pi^- + p \rightarrow K^+ + \Sigma^-$	$\Sigma^- + p \leftrightarrow n + \Lambda$	(1-step)	AP

P.K.Saha et al., PRL 94 (2005) 052502: ${}^{10}_{\Lambda}Li$ (${}^{10}B$) $d\sigma/d\Omega$ = 11.3±1.9 nb/sr

T.Y.Tretyakova et al., Phys. At. Nucl. 66 (2003) 1651

Production by DCX reaction

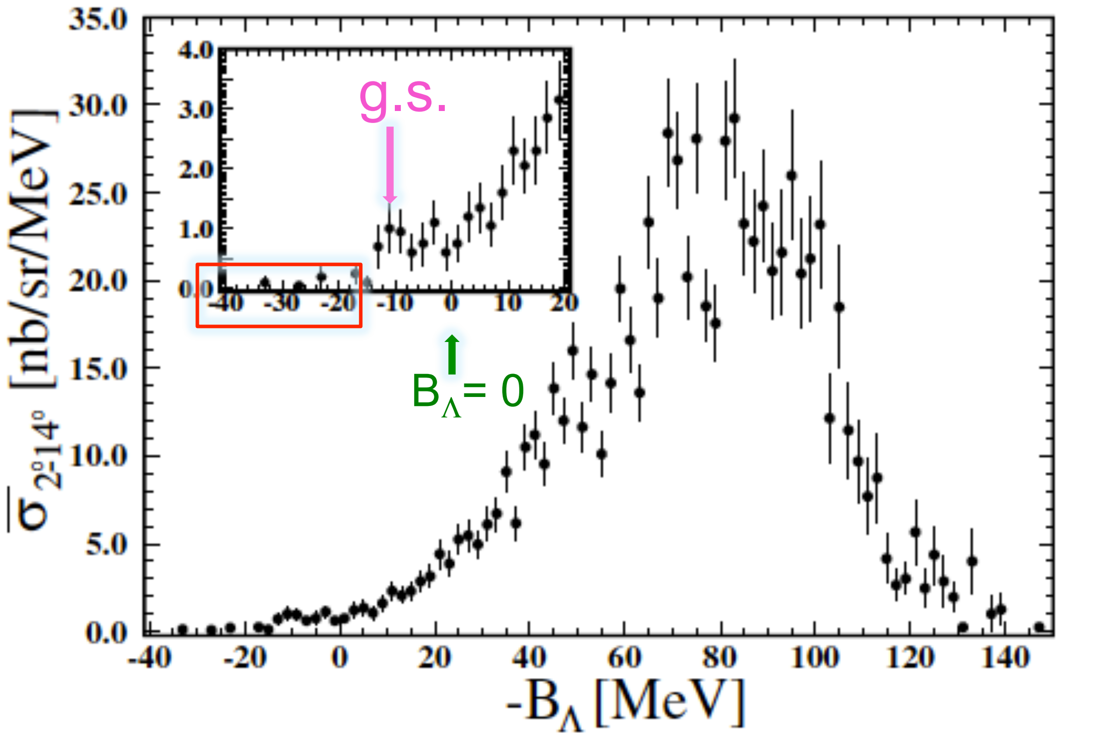
P.K.Saha et al., PRL 94 (2005) 052502

KEK-E521 experiment:

- $^{10}B(\pi^-,K^+)^{10}{}_{\Lambda}Li$ reaction
- Clean reaction

K6 beam line @ KEK-PS
1.2 GeV/c
SKS spectrometer

Good energy resolution
σB=2.5 MeV (FWHM)
ΔB: ±0.23 MeV



47 events in bound region
$d\sigma/d\Omega$ = 11.3±0.9 nbr/sr
(10^{-3} of Non Charge Exchange)

Increased yield x 10 at
J-PARC E10

Neutron-rich hypernuclei production in FINUDA

(K^-_{stop}, π^+) reaction

- Global reactions:
  A. ^{12}C target: $K^- + {}^{12}C \rightarrow {}^{12}_{\Lambda}Be + \pi^+$
  B. ^{6}Li target: $K^- + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + \pi^+$
  C. ^{7}Li target: $K^- + {}^{7}Li \rightarrow {}^{7}_{\Lambda}H + \pi^+$

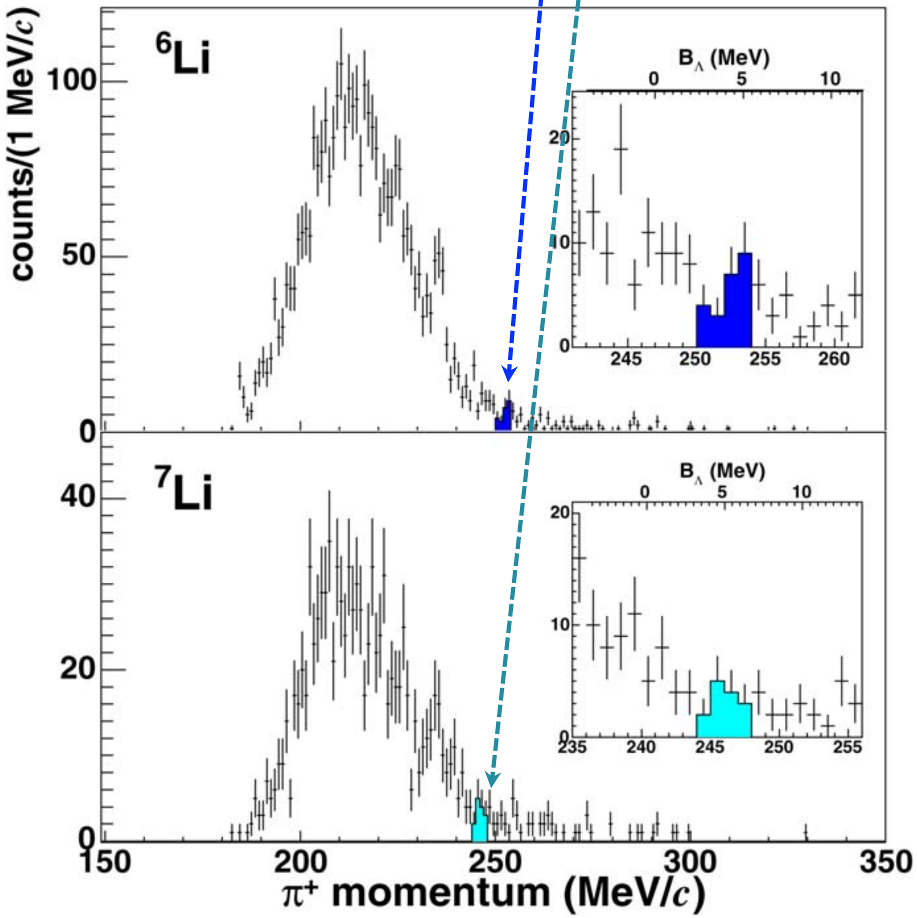
- π^+ is produced in the final state
- the π^+ momentum contains the information on the Λ binding energy B_Λ inside the neutron-rich hypernucleus
- π^+ inclusive momentum spectra observed in the ~ 250 MeV/c region (where the NRH peaks are expected)
- Candidates: positive high quality tracks coming out from K^- vertex

n-rich hypernuclei search with FINUDA: previous results

$K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+$

$K^-_{stop} + {}^7Li \rightarrow {}^7_\Lambda H + \pi^+$

M.Agnello et al., PLB 640 (2006) 145



2003-2004 data sample
190 pb^{-1}

background:

- $K^-_{stop} + p \rightarrow \Sigma^+ + \pi^-$
  $\Sigma^+ \rightarrow n\,\pi^+$ (~130-250 MeV/c)

- $K^-_{stop} + pp \rightarrow \Sigma^+ + n$
  $\Sigma^+ \rightarrow n\,\pi^+$ (~100-320 MeV/c)

cut on K^-/π^+ distance

N R Λ H	Rate / stopped K- (90% C.L. Upper Limit)	
	FINUDA (10^{-5})	Previous best published value
${}^6_\Lambda H$	$2.5 \pm 0.4(stat)_{-0.1}^{+0.4}(sys)$	NEW
${}^7_\Lambda H$	$4.5 \pm 0.9(stat)_{-0.1}^{+0.4}(sys)$	NEW
${}^{12}_\Lambda Be$	$2.0 \pm 0.4(stat)_{-0.1}^{+0.3}(sys)$	$6.1 \cdot 10^{-5}$

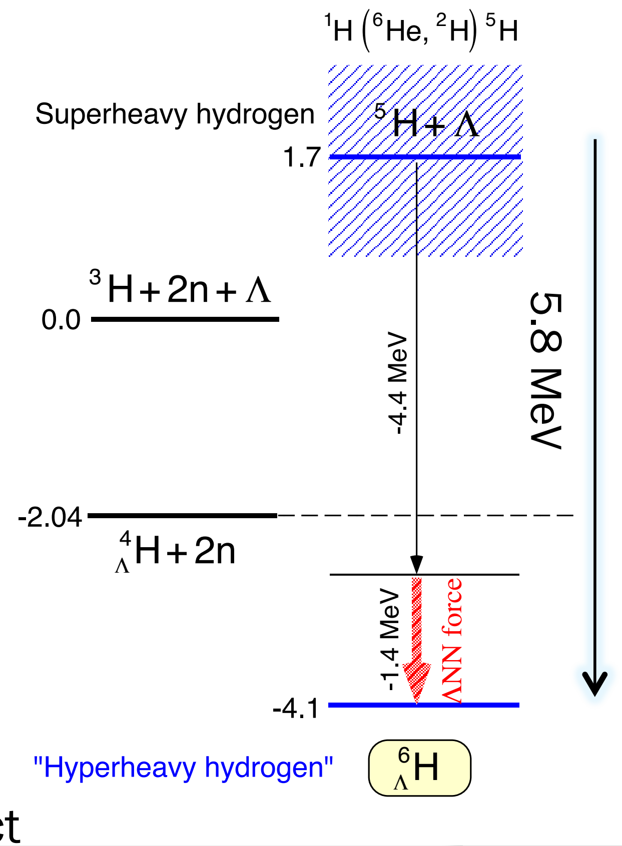
n-rich hypernuclei: $^{6}_{\Lambda}H$

Dalitz et al., N. Cim. 30 (1963) 489 (binding energy 4.2 MeV)

B $^{4}_{\Lambda}He$ 2.39 Λ	$^{5}_{\Lambda}He$ 3.12 Λ	◇ $^{6}_{\Lambda}He$ 4.18 n 0.17 xxx	◇ $^{7}_{\Lambda}He$ 5.23 n 2.92 halo	$^{8}_{\Lambda}He$ 7.16 n 1.49 xxx	♠ $^{9}_{\Lambda}He$ (8.5) n 3.9 halo
$^{3}_{\Lambda}H$ 0.13 Λ	◇ $^{4}_{\Lambda}H$ 2.04 Λ	$^{5}_{\Lambda}H$ (3.1) *n -1.8* xxx	♠ $^{6}_{\Lambda}H$ (4.2) *2n -5* xxx	♠ $^{7}_{\Lambda}H$ (5.2) 3n 0.4 xxx	

4.2 MeV

L. Majling, NPA 585 (1995) 211c
- binding energy
- prod. rate ~ 10^{-2} * hyp. prod. rate in (K^{-}_{stop}, π^{-})

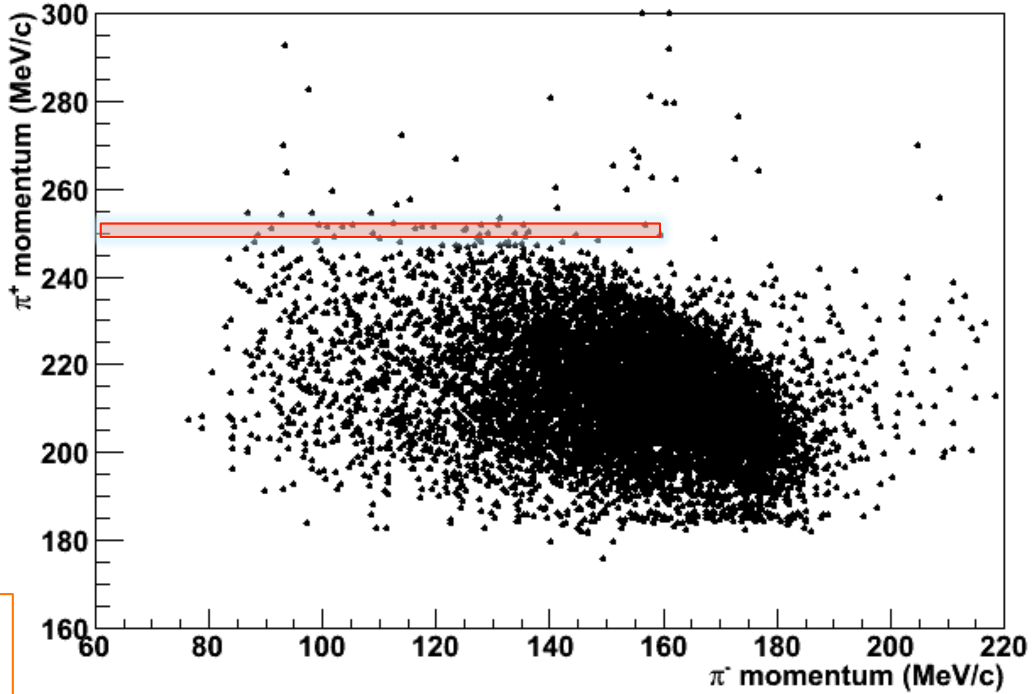


Y. Akaishi et al., AIP Conf. Proc. 1011 (2008) 277
K.S. Myint, et al., Few Body Sys. Suppl. 12 (2000) 383
Y. Akaishi et al., Frascati Phys. Series XVI (1999) 16

"coherent" Λ−Σ coupling in 0+ states
→ΛNN three body force
→ precise measurement of B.E.: estimation of mixing effect

$^{6}{}_{\Lambda}H$ search with FINUDA

2006-2007 data sample: 5x statistics
966 pb^{-1}



$K^-_{stop} + {}^6Li \rightarrow {}^6_{\Lambda}H + \pi^+$ (250-254 MeV/c)
INCLUSIVE MEASUREMENT

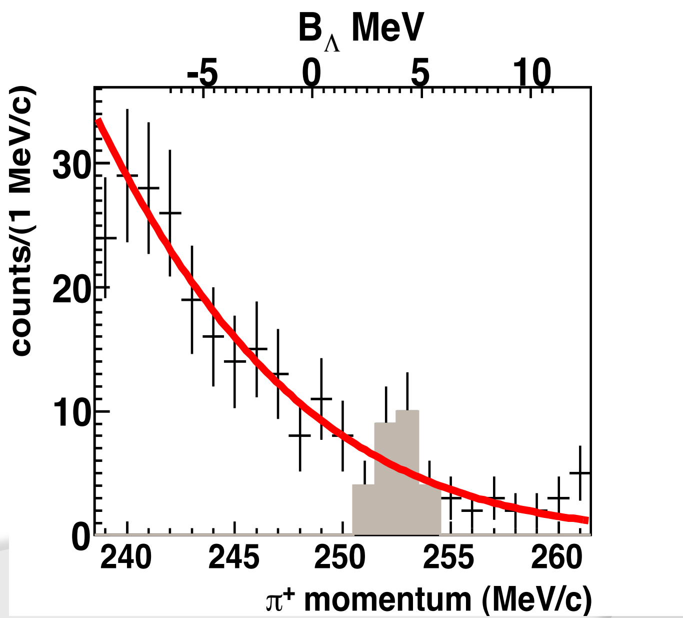
${}^6_{\Lambda}H \rightarrow {}^6He + \pi^-$ (60-160 MeV/c)
COINCIDENCE MEASUREMENT

$K^- + p \rightarrow \Sigma^+ + \pi^-$ (<190 MeV/c)
$\Sigma^+ \rightarrow n\,\pi^+$ (~130-250 MeV/c)

no evident signal/structure

low production rate

→ new strategy



$^{6}_{\Lambda}H$ search with FINUDA

$K^-_{stop} + {}^6Li \rightarrow {}^6_{\Lambda}H + \pi^+$

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

independent reactions: decay at rest

$$M(K^-) + 3\,M(n) + 3M(p) - B({}^6Li) = M({}^6_{\Lambda}H) + T({}^6_{\Lambda}H) + M(\pi^+) + T(\pi^+)$$

$$M({}^6_{\Lambda}H) = 4\,M(n) + 2M(p) - B({}^6He) + T({}^6He) + M(\pi^-) + T(\pi^-)$$

$$\sqrt{M^2({}^6He) + p^2(\pi^-)} - M({}^6He)$$

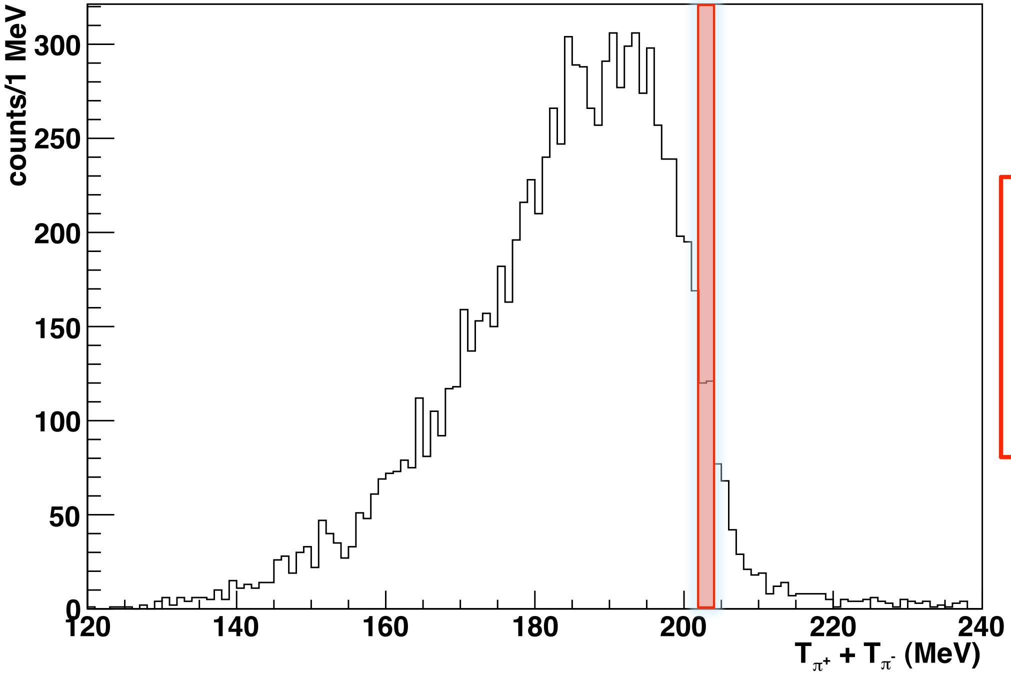
$$\sqrt{M^2({}^6{}_{\Lambda}H) + p^2(\pi^+)} - M({}^6{}_{\Lambda}H)$$

$$M({}^6{}_{\Lambda}H) = M({}^5H) + M(\Lambda) - B(\Lambda)$$

$$T(\pi^+) + T(\pi^-) = M(K^-) + M(p) - M(n) - B({}^6Li) + B({}^6He) - T({}^6He) - T({}^6_{\Lambda}H) - M(\pi^+) - M(\pi^-)$$

= **203.0 ± 1.3 MeV** (variation ~0.3 MeV with B_{Λ}= 0÷6 MeV)

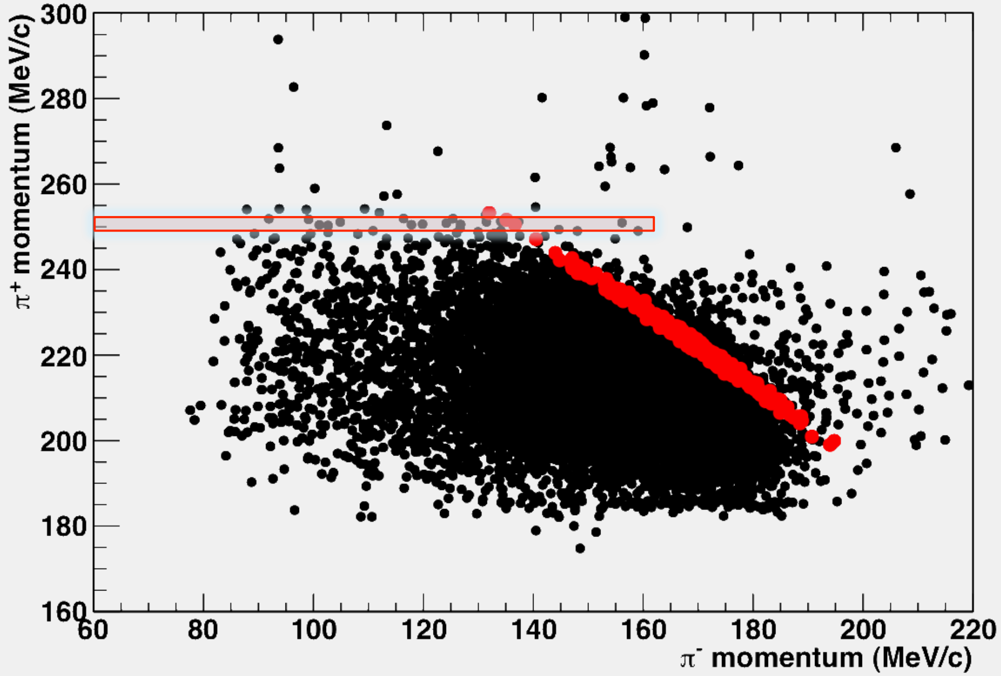
cut on $T(\pi^+) + T(\pi^-)$: 202÷204 MeV



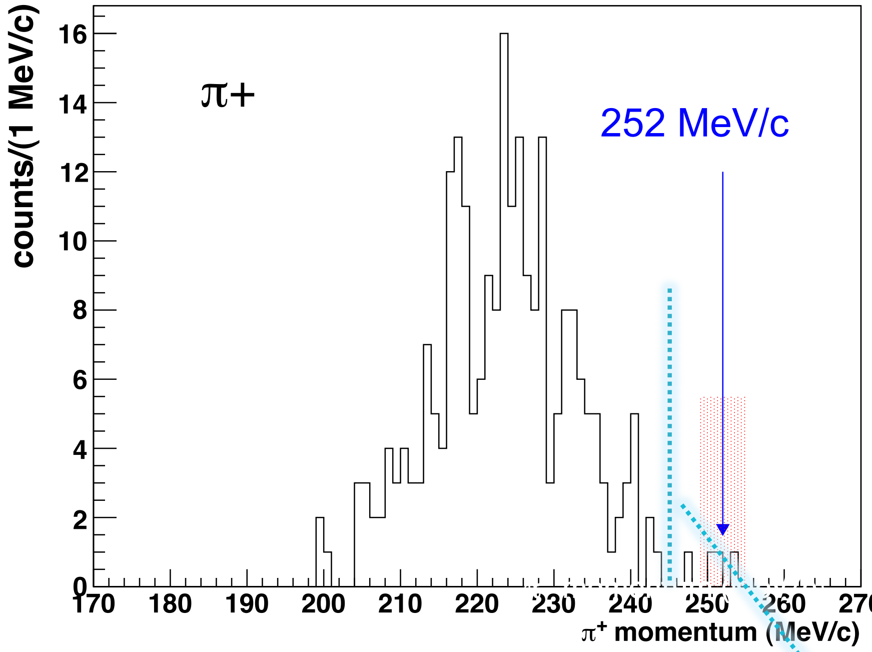
selection:
$T(\pi^+)+T(\pi^-)$ =
202÷204 MeV

absolute energy scale:
μ+(235.6 MeV/c) from $K_{\mu 2}$
Δ_p< 0.12 MeV/c → π+: Δ_T < 0.1 MeV

π- (133 MeV/c) from $^4{}_\Lambda H$ MWD
Δ_p< 0.2 MeV/c, Δ_T < 0.14 MeV

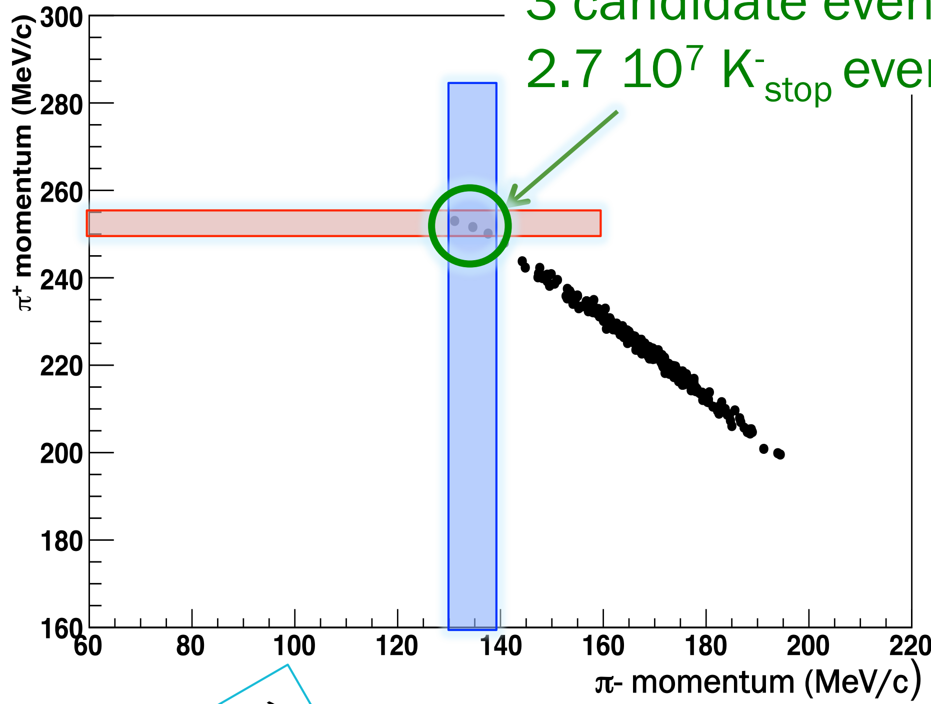


250÷255 MeV/c (σ_p=1.1 MeV/c)

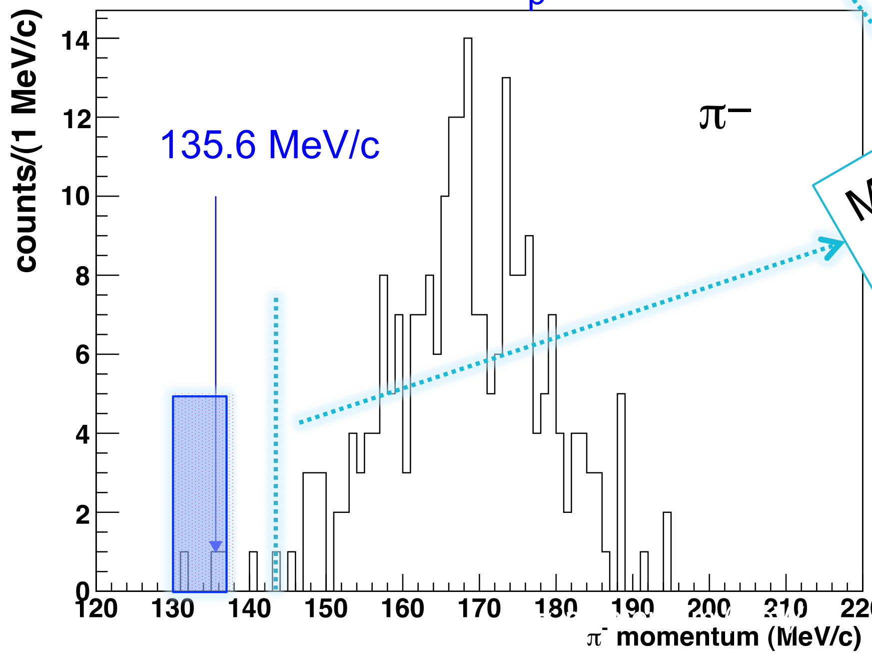


3 candidate events

2.7 10^7 K^-_{stop} events

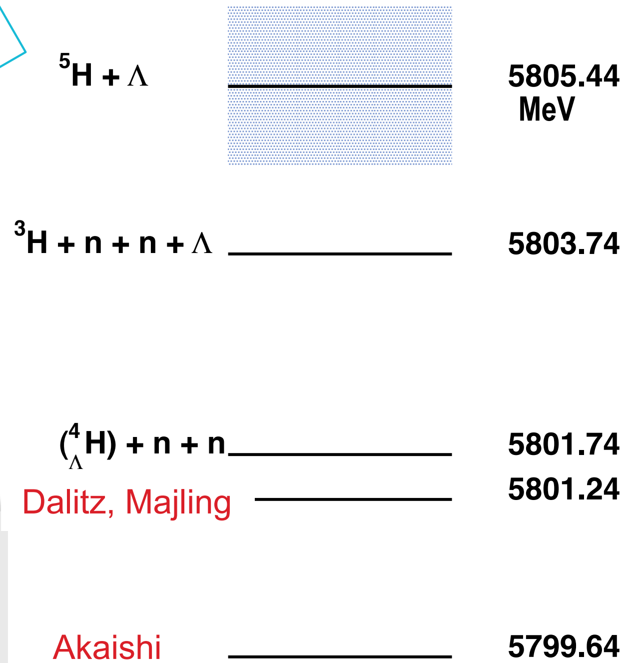


130÷138 MeV/c (σ_p=1.2 MeV/c)



$M(^6_\Lambda H) > M(\Lambda + {}^3H + 2n)$
$M(\Lambda + {}^5H)$

no systematics from cuts



${}^{6}_{\Lambda}H/K^{-}_{stop}$ production rate

Background sources:

- fake coincidences: π+(250÷255 MeV/c) & π^{-}(130÷138 MeV/c)

- $K^{-}_{stop} + {}^{6}Li \rightarrow \Sigma^{+} + \pi^{-} + {}^{4}He + n$ (end point ~190 MeV/c)
  - $\Sigma^{+} \rightarrow n + \pi^{+}$ (end point ~282 MeV/c)

- $K^{-}_{stop} + {}^{6}Li \rightarrow {}^{4}_{\Lambda}H + n + n + \pi^{+}$ (end point ~252MeV/c)
  - ${}^{4}He + \pi^{-}$ ($p(\pi^{-})$ = 133 MeV/c)

- $K^{-}_{stop} + {}^{6}Li \rightarrow \pi^{0} + {}^{6}_{\Lambda}He$
  - ${}^{6}_{\Lambda}He \rightarrow {}^{6}Li + \pi^{-}$ ($p(\pi$-) = 108.5 MeV/c)

  $\pi^{0} + {}^{6}Li \rightarrow {}^{6}_{\Lambda}He + \pi$+ (end point 280 MeV/c)

  different ${}^{6}Li$ nuclei ($\tau(\pi^{0})$)

- $K^{-}_{stop} + {}^{6}Li \rightarrow {}^{3}_{\Lambda}H + \pi^{+} + n + n + n$ (end point 242 MeV/c)
  - ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ ($p(\pi$-) = 115 MeV/c)

- $K^{-}_{stop} + {}^{6}Li \rightarrow {}^{3}He + n + n + \Lambda + \pi$+ ($T_{tot}$ < 182 MeV)
  - $\Lambda \rightarrow n\ \pi$-

- $K^{-}_{stop} + {}^{6}Li \rightarrow {}^{3}He + \Sigma^{+} + n + n + \pi$ (T_{tot} < 180 MeV)
  - $\Sigma^{+} \rightarrow n + \pi^{+}$

${}^{6}_{\Lambda}H/K^{-}_{stop}$ production rate

Background evaluation:

- fake coincidences:

T_{tot}(202÷204 MeV) & π^{+}(250÷255 MeV/c) & π^{-}(130÷138 MeV/c) for targets other than ^{6}Li (T_{tot}< 199 MeV)

1 event for all other targets → 0.27±0.27 bgd events on ^{6}Li = BGD1

- K^{-}_{stop} + ^{6}Li → Σ^{+} + π^{-} + "^{4}He" + n (end point 190 MeV/c)

  ⟶ Σ^{+}→ n + π^{+} (end point 282 MeV/c)

Preliminary !!

Monte Carlo simulation of the process (detector acceptance, trigger, PR, reconstruction, PId, selections)

quasi-free approx.:

3 events for 2.1 10^{7} K^{-}_{stop} from MC * BR(K^{-}_{stop} p→ Σ^{+} π^{-}) * [1 - (Σ^{+}n→Λp)]

- BR(Σ^{+}→nπ^{+}) → 0.14±0.08 bgd events on ^{6}Li

4-body kinematics on the whole ^{6}Li

3 events for 1.7 10^{7} K^{-}_{stop} from MC * BR(K^{-}_{stop} p→ Σ^{+} π^{-}) * [1 - (Σ^{+}n→Λp)] * BR(Σ^{+}→nπ^{+}) * BR(^{4}He + n) → 0.20±0.11 bgd events on ^{6}Li

Vander Velde-Wilchet et al., Nucl.Phys. A241 (1975) 511 ^{12}C

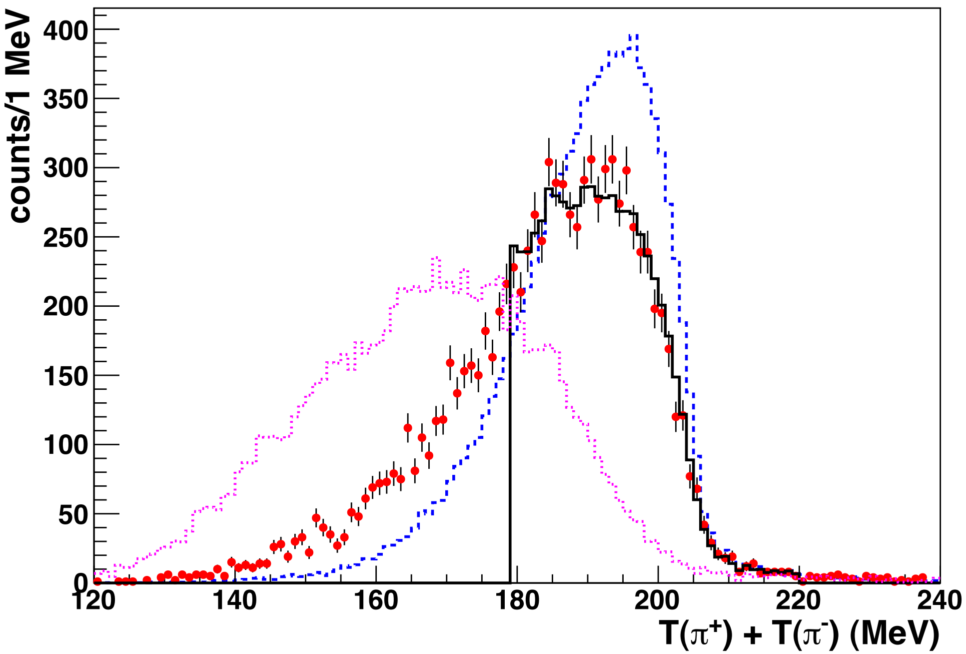
Katz et al., Phys. Rev. D 1 (1970) 1267 ^{4}He

H.Outa, Ph.D. thesis: ^{4}He BR(^{4}He + n) = 100%

Background simulation

$K^-_{stop} + {}^6Li \rightarrow \Sigma^+ + \pi^- + {}^4He + n$ $p(\pi^-) \leq 190$ MeV/c

$\Sigma^+ \rightarrow n + \pi^+$ $p(\pi^+) \leq 282$ MeV/c



Red points: experimental data

Blue-dashed: “quasi free” simulation

Violet: “4-body” simulation

Normalization to the experimental distribution area

fractions: 0.743±0.019 0.257±0.017 χ^2/NDF = 40.0/39

weight fractions
BDG2 = 0.16±0.07 events on ^{6}Li

Preliminary !!

R. Barlow and C. Beeston, Comp. Phys. Comm. 77 (1993) 219

$^{6}_{\Lambda}H/K^{-}_{stop}$ production rate

Background evaluation:

- $K^{-}_{stop} + {}^{6}Li \rightarrow {}^{4}_{\Lambda}H + n + n + \pi^{+}$ (end point ~252MeV/c)

  $\hookrightarrow {}^{4}He + \pi^{-}$ ($p(\pi^{-}) \sim 133$ MeV/c)

Calculation based on:

4-body kinematics $\rightarrow \pi^{+}$ (250÷255 MeV/c): $4 \bullet 10^{-6}$

$K^{-}_{stop} + {}^{7}Li \rightarrow {}^{4}_{\Lambda}H$ capture rate on ^{4}He and ^{7}Li $(23\pm3)\bullet10^{-3}/K^{-}_{stop}$
fraction of ${}^{4}_{\Lambda}H$ produced with π^{+}/π^{-} (0.49±0.08)
$^{4}He + \pi^{-}$ decay branching ratio: 0.49

H.Tamura et al., Phys. Rev. C 40 (1989) R479

Total probability: $2\bullet10^{-8}$

BDG3 = 0.04±0.01 events on ^{6}Li negligible vs BG1 & BGD2

Preliminary !!

${}^{6}_{\Lambda}H/K^{-}_{stop}$ production rate

Total background: BGD1 + BGD2 = 0.43 ± 0.28 events on ^{6}Li

Poisson statistics: 3 events DO NOT belong to pure background: C.L.= 99%

$R * BR(\pi-) = (\text{events} - BGD1 - BGD2 - \text{~~BGD3~~}) (\varepsilon(\pi-))^{-1} (\varepsilon(\pi+))^{-1} / (n.\ K^{-}_{stop} \text{ on } {}^{6}Li)$

$\varepsilon(\pi) = \varepsilon_D\ \varepsilon_{MC}$

$$R * BR(\pi-) = (1.3 \pm 0.9)\ 10^{-6}/K^{-}_{stop}$$

- ^{6}Li target purity ~ 90% → $R * BR(\pi-) = (1.4 \pm 1.0)\ 10^{-6}/K^{-}_{stop}$
- sel. cut vs T res.→ $R * BR(\pi-) = (2.6 \pm 1.8)\ 10^{-6}/K^{-}_{stop}$

$$\mathbf{R * BR(\pi-) = (2.6 \pm 1.8)\ 10^{-6}/K^{-}_{stop}}$$

Preliminary !!

H.Tamura et al., Phys. Rev. C 40 (1989) R479: $BR(\pi-)=0.49$

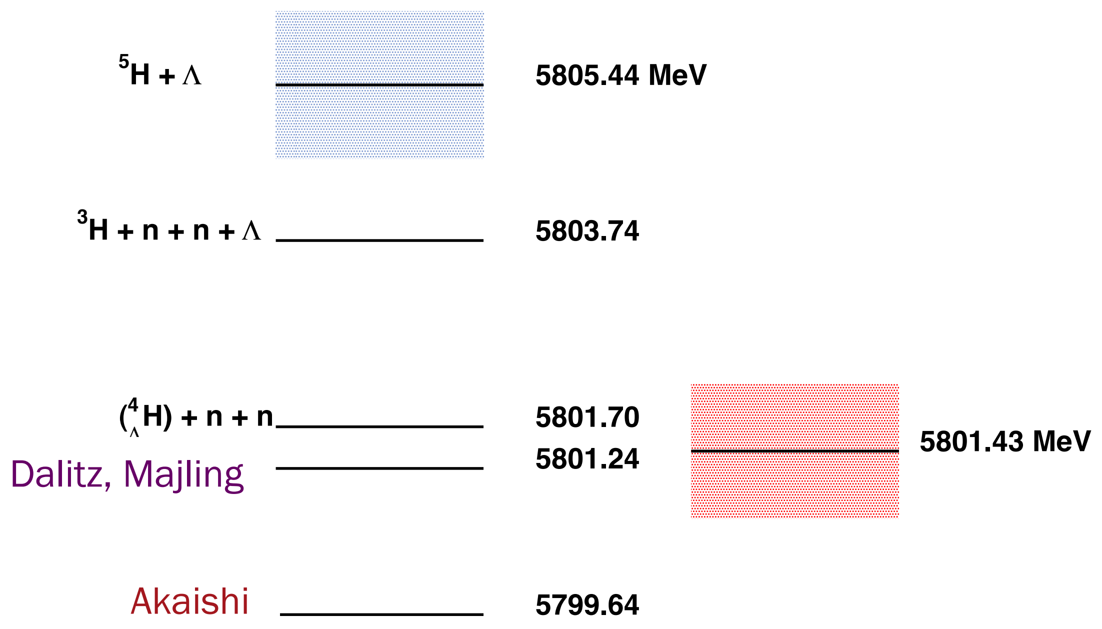
$$R = 5.2 \pm 3.6\ \ 10^{-6}/K^{-}_{stop}$$

$(2.5 \pm 0.4^{+0.4}_{-0.1})\ 10^{-5}/K^{-}_{stop}$

Agnello et al., *PLB 640 (2006) 145*

kinematics

T_{tot} (MeV)	$T(\pi^+)$ (MeV)	$T(\pi^-)$ (MeV)	$p(\pi^+)$ (MeV/c)	$p(\pi^-)$ (MeV/c)	$M(^6_\Lambda H)$ formation (MeV/c^2)	$M(^6_\Lambda H)$ decay (MeV/c^2)
202.5±1.3	147.86±0.96	54.67±0.84	251.3±1.1	135.1±1.2	5802.33±0.96	5801.41±0.84
202.7±1.3	146.79±0.96	55.94±0.84	250.0±1.1	136.9±1.2	5803.45±0.96	5802.73±0.84
202.1±1.3	150.11±0.96	52.01±0.84	253.8±1.1	131.2±1.2	5799.97±0.96	5798.66±0.84



mean value = 5801.43±0.74

B_Λ = 2.31±0.74 MeV (^{3}H + 2n + Λ)
= 4.01±0.74 MeV (^{5}He + Λ)

B_Λ = 4.1 MeV (^{3}H + 2n + Λ)
= 5.8 MeV (^{5}He + Λ)
ΛNN force: 1.4 MeV

Preliminary !!

…… thank you!

$^{12}_{\Lambda}$Be, $^{6}_{\Lambda}$H, $^{7}_{\Lambda}$H: known data

- At present our knowledge about neutron-rich hypernuclei on the experimental side is rather poor:

HYPER-NUCLEUS	STATE	B_{Λ} (MeV)	p_{π} (MeV/c)	PRODUCTION RATE / K^{-}_{stop}	REFERENCES
$^{12}_{\Lambda}$Be	1- (gs)	11.4$^{\&}$	262.9	$< 6.1 \cdot 10^{-5}$ (EXP)$^{+}$ $1.8 \cdot 10^{-5}$ (TH)°	$^{+}$K. Kubota et al., Nucl. Phys, A602 (1996) 327 °T. Tretyakova et al., Nucl. Phys, A691 (2001) 351c
	0+ (es)	?	?	$6.0 \cdot 10^{-6}$ (TH)°	
$^{6}_{\Lambda}$H	0+ (gs)	5.8 (TH)* 4.2$^{\&}$	249.1 247.5	?	*Y. Akaishi, Frascati Phys. Ser., Vol. XVI (1999) 59
$^{7}_{\Lambda}$H	0+ (gs)	5.2$^{\&}$	246.4	?	$^{\&}$L. Majling, Nuclear Physics A 585 (1995) 211c