The FINUDA experiment: a new powerful laboratory for studies of strangeness in nuclear matter

Maurizio Palomba

Physics Department of Bari University and I.N.F.N. Bari, Italy

on behalf of the FINUDA Collaboration:

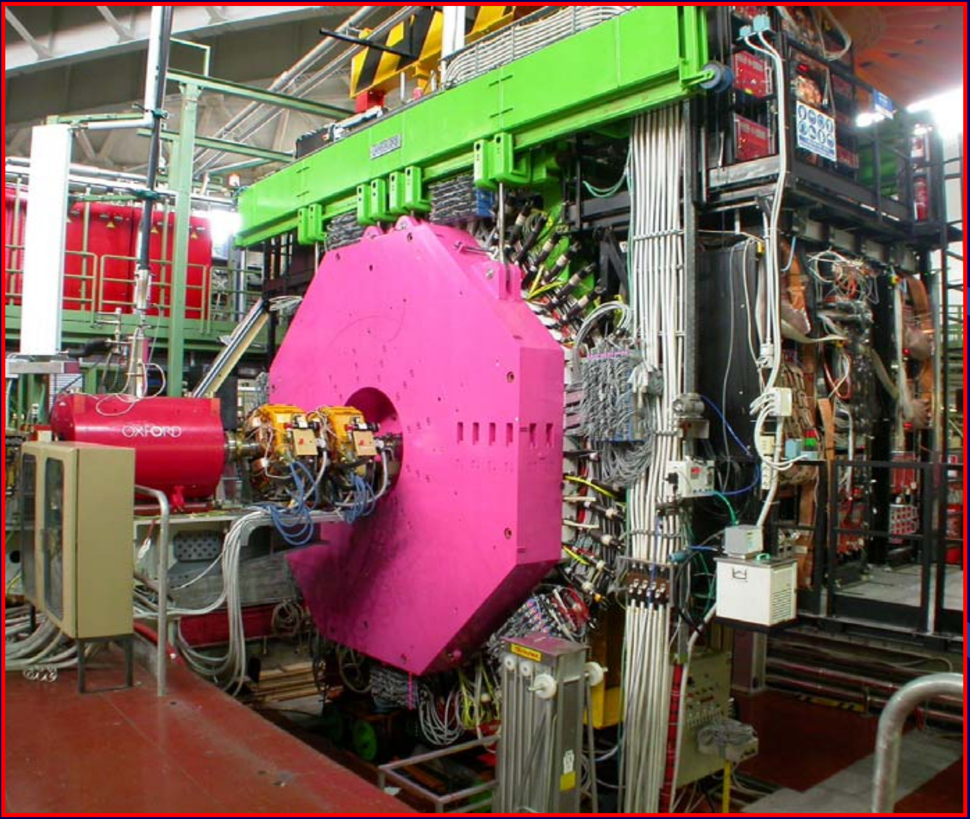
- ***Bari* University and I.N.F.N., Italy**
- ***Brescia* University, Italy**
- ***KEK*, Tsukuba, Ibaraki, Japan**
- ***LNF* (Laboratori Nazionali di Frascati) / I.N.F.N., Italy**
- ***Pavia* University and I.N.F.N., Italy**
- ***RIKEN*, Wako, Saitama, Japan**
- ***Seoul* National University, South Korea**
- ***Teheran* Shahid Beheshty University, Iran**
- ***Tokyo* University, Japan**
- ***Torino* University, Polytechnic and I.N.F.N., Italy**
- ***Trieste* University and I.N.F.N., Italy**
- ***TRIUMF*, Vancouver, Canada**

PANIC05 XVIIth Particles And Nuclei International Conference

Santa Fe, NM, United States - October 24th-28th, 2005

Outline

- The FINUDA experiment @ DAΦNE collider
- Detector description and performance
- Physics program
- Data analysis and results from the first data taking:
  1) Hypernuclear spectroscopy
  2) Search for neutron-rich hypernuclei
  3) Search for deeply bound $\overline{K}$-nucleus states
- Conclusions and future developments



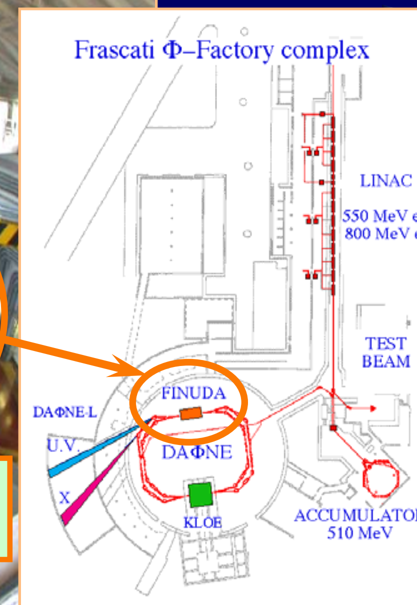
FINUDA: Fisica NUcleare a DAΦNE

The very first example of a *(hyper)nuclear physics* fixed-target experiment carried on at a *collider* (DAΦNE @ LNF)

Optimized to produce hypernuclei $^{A}_{\Lambda}Z$ in a completely new way

DAΦNE: Double Annular e^+- e^- Φ-factory for Nice Experiments

e+ e- Beam Energy	510 MeV
Design Luminosity	$5 \cdot 10^{32}$ cm^{-2} s^{-1}
σ_X (rms)	2.11 mm
σ_Y (rms)	0.021 mm
σ_Z (rms)	35 mm
Bunch Length	30 mm
$e^+ e^-$ Crossing Angle	12.5 mrad
Frequency (max)	368.25 MHz
Bunch / Ring	Up to 120
Particles / Bunch	$8.9 \cdot 10^{10}$
Current / Ring (max)	5.2 A



Hypernuclei production in FINUDA

- DAΦNE is a high-luminosity Φ-factory
- 2003-2004 data taking:
  $\mathcal{L} \sim 5 \cdot 10^{31}$ cm^{-2}s^{-1}: ~ 250 ϕ mesons / s
- to be increased of a factor ~ 10 with the next machine upgrade

$e^+ e^- \rightarrow \phi(1020) \rightarrow$

- $K^+ K^-$ (49%)
- $K^0_S K^0_L$ (34%)
- ρ π (13%)

Intense source of $K^+ K^-$ pairs:

1) Monochromatic with low energy (T ~ 16 MeV, p ~ 127 MeV/c)
2) Collinear and tagged
3) Hadronic background free

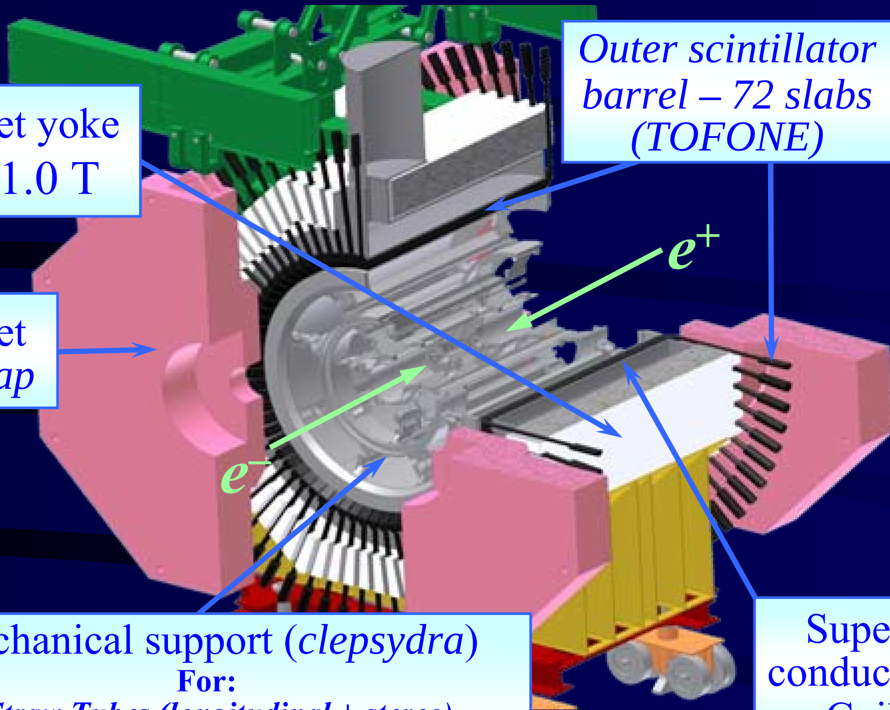
→ ***"clean" low-energy K⁻ beam***

- K⁻'s are stopped inside *thin targets* (~ 0.2 ÷ 0.3 g cm^{-2}):
  2×^{6}Li, ^{7}Li, 3×^{12}C, ^{27}Al, ^{51}V

- *Strangeness exchange* reaction on target nuclei:
  $$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

- The π^- is tracked in the detector
- π^- momentum →
  → ${}^{A}_{\Lambda}Z$ hypernucleus *energy level*

The FINUDA detector



Mechanical support (*clepsydra*)
For:

- ***2424 Straw Tubes (longitudinal + stereo)***
- ***16 Low-Mass Drift Chambers***
- ***18 μ-strip vertex detectors (ISIM/OSIM)***
- ***Inner scintillator barrel – 12 slabs (TOFINO)***
- ***8 Targets***

Detector capabilities:

- ***Selective trigger*** **based on fast scintillation detectors (TOFINO, TOFONE)**
- ***Clean*** **K^-** ***vertex identification*** **(ISIM P.ID.+ *x,y,z* resolution + K^+ tagging)**
- **π, K, p, d, … P.ID. (OSIM d*E*/d*x*)**
- ***High momentum resolution*** **(6‰ FWHM) (tracker resolution + He bag + thin targets)**
- ***Neutron detection*** **(TOFONE)**
- **Time-Of-Flight (TOFONE–TOFINO)**

Apparatus designed for a typical *collider experiment*:

- **Cylindrical geometry**
- **large solid angle (~ 3π sr)**
- **multi-tracking analysis**

Simultaneous study of formation and decay of strange hadronic systems by *full event reconstruction*

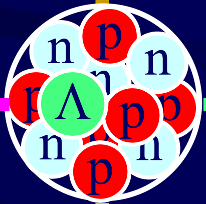
FINUDA: a new opportunity to investigate strange nuclear matter

Low-energy NY strong interaction

- Neutron-rich Λ hypernuclei
- Σ hypernuclei
- Deeply-bound kaonic nuclei

- 4-Baryons NΛ→NN weak interaction
- ΔI = 1/2 rule

Hypernuclear spectroscopy



Hypernuclear weak decay

- NY potentials
- SP nuclear models
- Many-body dynamics
- Bound states with S≠0

Impurity nuclear physics:
- Λ "*glue-like*" role
- Changes in nuclear *size* and *shape*
- …

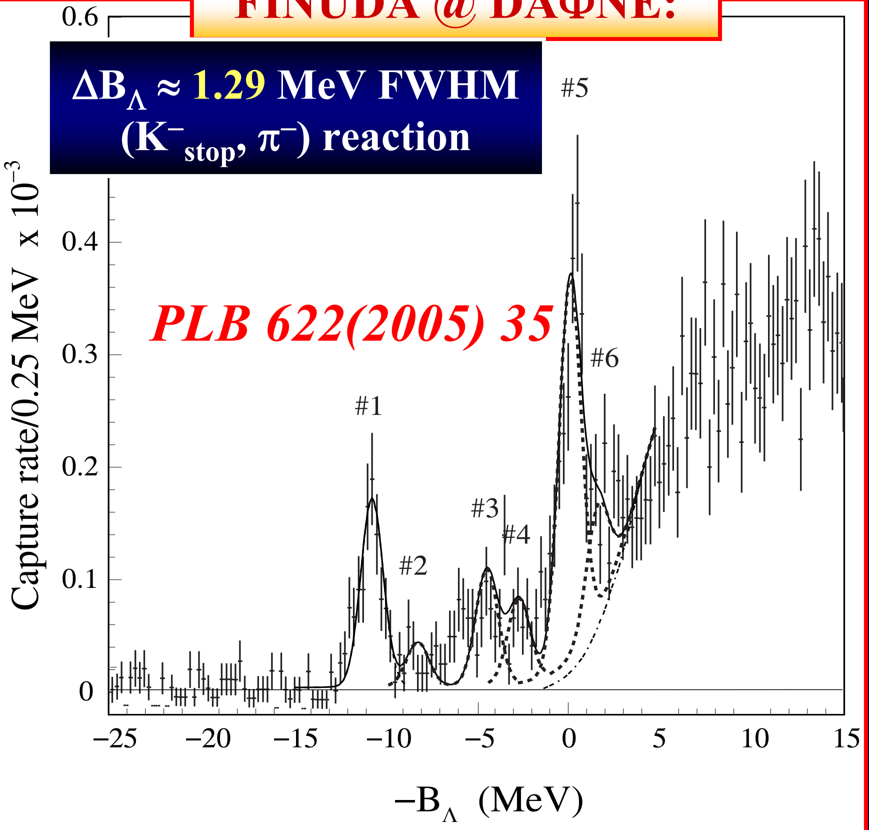
Quark degrees of freedom in nuclear medium

Hypernuclear spectroscopy

- First results on $^{12}_{\Lambda}C$ hypernucleus (first 2003-2004 data taking): very good agreement with the best previously published ones (***6 peaks fit***)

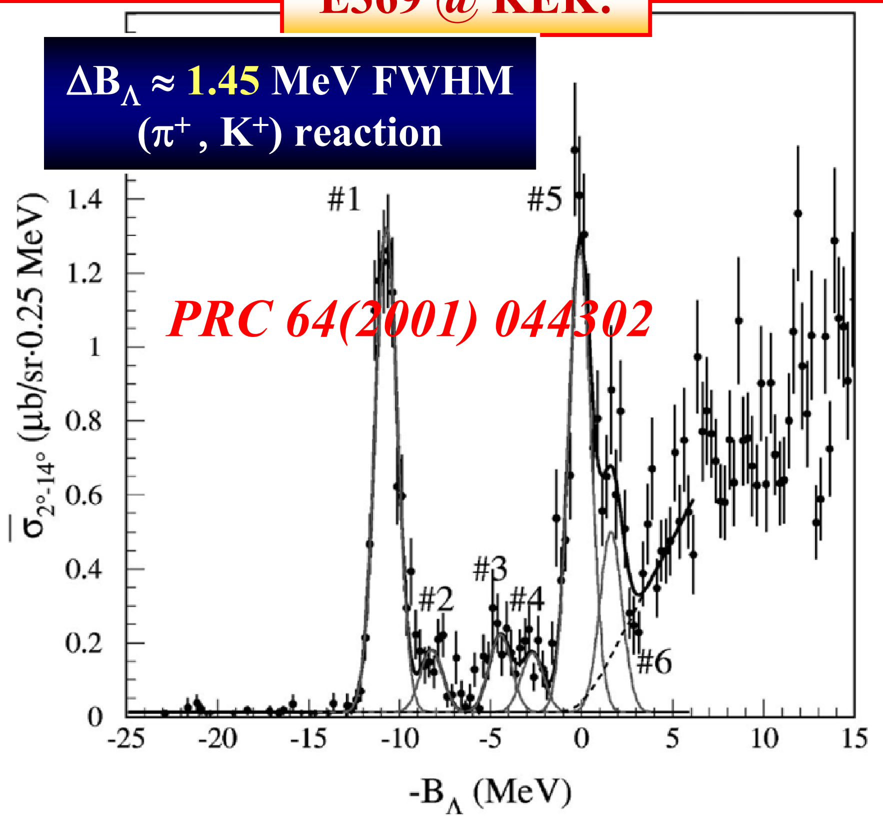
FINUDA @ DAΦNE:

$\Delta B_{\Lambda} \approx$ 1.29 MeV FWHM
(K^{-}_{stop}, π^{-}) reaction



E369 @ KEK:

$\Delta B_{\Lambda} \approx$ 1.45 MeV FWHM
(π^{+} , K^{+}) reaction



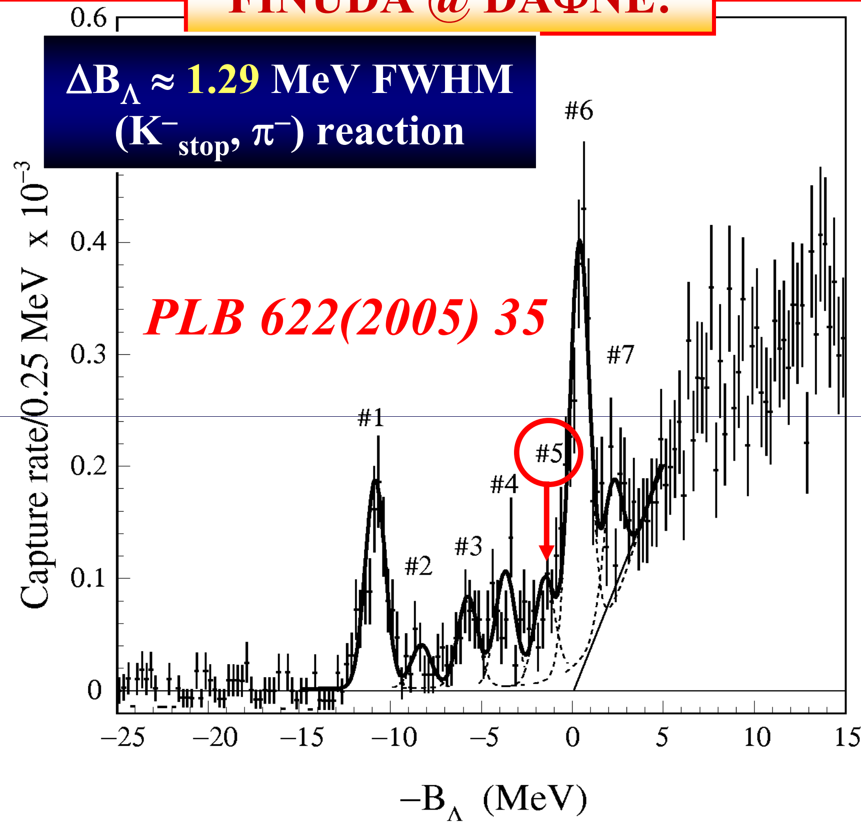
Hypernuclear spectroscopy (2)

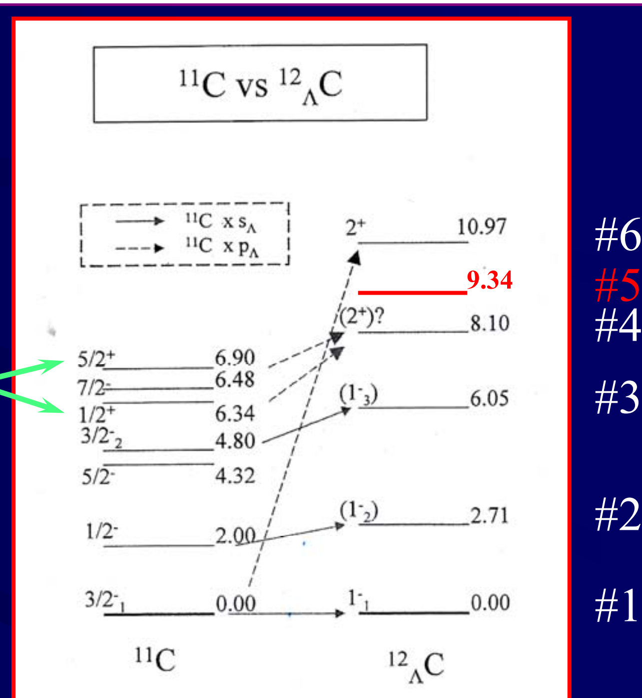
- A better fit may be obtained taking into account a seventh peak (#5 in the figure) → a new hypernuclear state found on $^{12}{}_{\Lambda}C$?

FINUDA @ DAΦNE:

$\Delta B_{\Lambda} \approx$ 1.29 MeV FWHM
(K^{-}_{stop}, π^{-}) reaction

PLB 622(2005) 35





Peaks #4 and #5 could be explained as $|^{11}C; J^{+}\rangle \otimes |1s^{\Lambda}\rangle$ states, in an extended shell model including inter-shell couplings [*T. Motoba, NP A 639 (1998) 135c*]

Search for neutron-rich hypernuclei

- Hypernuclei with a large neutron excess
- Their existence has been theoretically predicted (*L. Majling, NP A 585 (1995) 211c*) but not experimentally observed yet

The Pauli principle does not apply to the Λ inside the nucleus

→ A larger number of neutrons may occupy the bound nuclear levels

→ *extra* binding energy (Λ "*glue-like*" role)

- Study of the hypernuclear structure properties (size, shape, …) at <u>very high *N/Z*</u>;
- Feedback with the astrophysics field: phenomena related to *high-density nuclear matter* in neutron stars

HYPER-NUCLEUS	HYPERNUCL. STATE	B_Λ (MeV)	PRODUCTION RATE / K^-_{stop}	REFERENCES
${}^{12}_{\Lambda}$Be	1^- (g.s.)	11.4 &	$< 6.1 \cdot 10^{-5}$ + $1.8 \cdot 10^{-5}$ °	+ *MEASURED* (90% C.L. *Upper Limit*) K. Kubota et al., *NP A 602 (1996) 327* ° *THEORETICAL EVALUATION* T. Tretyakova, D. Lanskoy, *NP A 691 (2001) 351c*
	0^+ (exc.s.)	?	$6.0 \cdot 10^{-6}$ °	
${}^{6}_{\Lambda}$H	0^+ (g.s.)	4.1 * 4.2 &	?	* *THEORETICAL EVALUATION* Y. Akaishi, *Frascati Phys. Series, Vol. XVI (1999) 59*
${}^{7}_{\Lambda}$H	0^+ (g.s.)	5.2 &	?	& *EXTRAPOLATION FROM DATA* L. Majling, *NP A 585 (1995) 211c*

Neutron-rich production in FINUDA

Reaction mechanisms:

1) Double charge exchange:
   $K^- + p \rightarrow \Lambda + \pi^0$; $\pi^0 + p \rightarrow n + \pi^+$
2) Strangeness exchange & Σ–Λ coupling:
   $K^- + p \rightarrow \Sigma^- + \pi^+$ $(\Sigma^- + p \leftrightarrow \Lambda + n)$

<u>In FINUDA we are searching for</u>:

${}^{12}_{\Lambda}\mathrm{Be}$ $(N/Z = 7/4)$ from ${}^{12}\mathrm{C}(K^-_{stop}, \pi^+){}^{12}_{\Lambda}\mathrm{Be}$

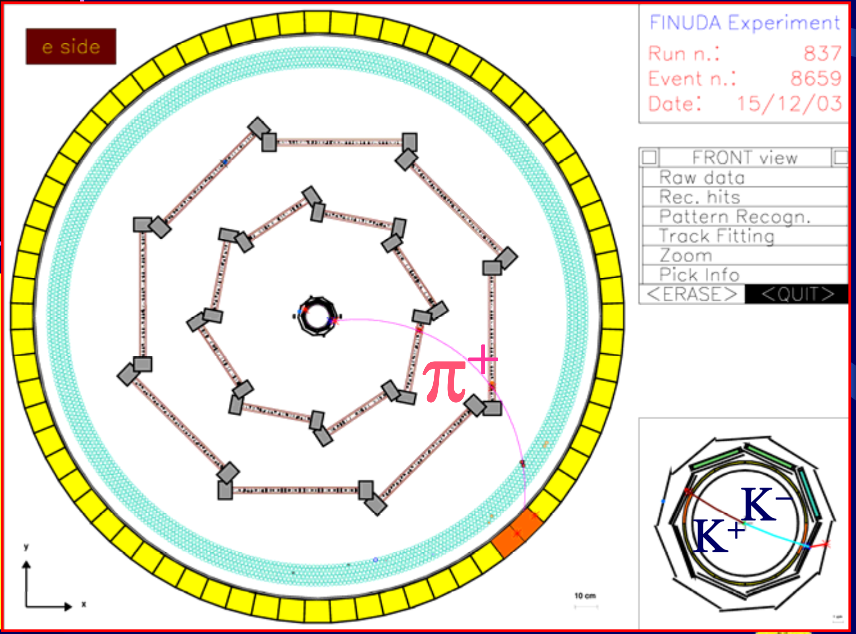
${}^{6}_{\Lambda}\mathrm{H}$ $(N/Z = 4)$ from ${}^{6}\mathrm{Li}(K^-_{stop}, \pi^+){}^{6}_{\Lambda}\mathrm{H}$

${}^{7}_{\Lambda}\mathrm{H}$ $(N/Z = 5)$ from ${}^{7}\mathrm{Li}(K^-_{stop}, \pi^+){}^{7}_{\Lambda}\mathrm{H}$

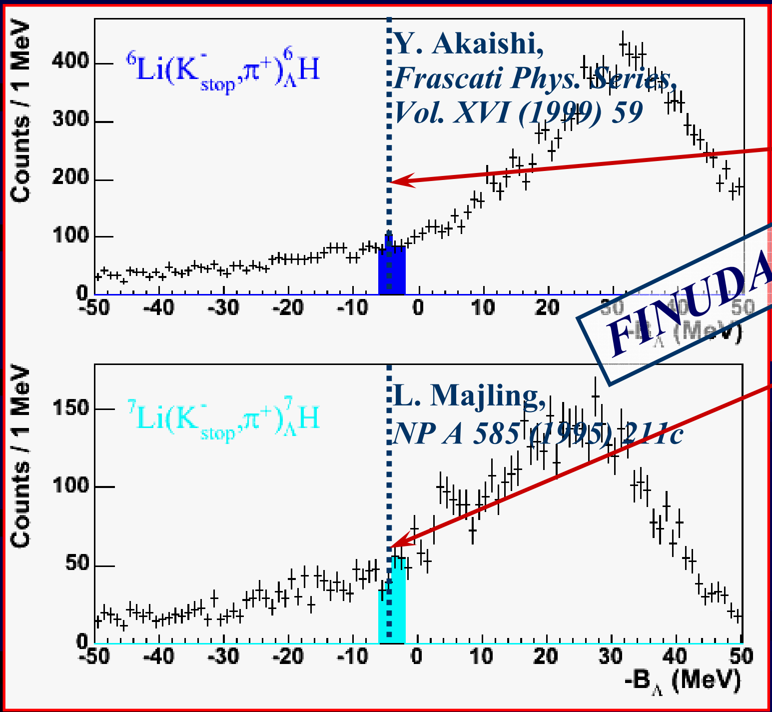
- ΔQ (NUCLEUS) = –2
- π^+ in the final state

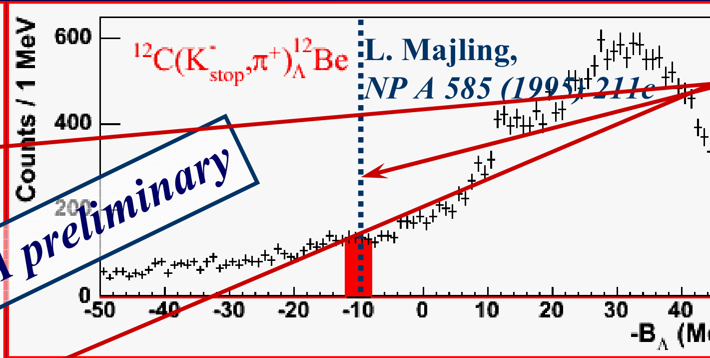
Event selection:

- Reconstruction of a π^+ with a momentum value in the hypernucleus bound region
- P.ID. Made using dE/dx from OSIM and TOF from TOFINO & TOFONE



Data analysis and preliminary results





Expected B_{Λ} for the ground state

Regions of interest width = $\pm 2\sigma$ with respect to the B_{Λ} central value

- Two independent normalization methods used to convert the count numbers to a NRH production rate (work in progress)
- Statistical analysis to estimate the background contribution in the spectra

Neutron-rich hypernucleus	Rate / stopped K^{-} (90% C.L. Upper Limit)	
	FINUDA preliminary	Best published value
$^{12}_{\Lambda}Be$	$[4.7 \pm 0.8(stat)\ _{-0.8}^{+1.3}(sys)] \cdot 10^{-5}$	$6.1 \cdot 10^{-5}$
$^{6}_{\Lambda}H$	$[2.3 \pm 0.6(stat)\ _{-0.8}^{+1.2}(sys)] \cdot 10^{-5}$	–
$^{7}_{\Lambda}H$	$[4.7 \pm 2.1(stat)\ _{-0.7}^{+1.2}(sys)] \cdot 10^{-5}$	–

Search for bound $\bar{K}$-nucleus states

Discrete nuclear bound states of $\bar{K}$ in few-body nuclear systems with S = –1

- Theoretical models in favour of their observation:

  Akaishi & Yamazaki, PLB535 (2002) 70; Akaishi & Yamazaki, PRC65 (2002) 044005
  Kaiser et al., NP A594 (1995) 325

- Deep $\bar{K}$-nucleus optical potential:

  strongly I = 0 attractive interaction → "deeply" bound $\bar{K}$-nucleus states
  - $\bar{K}$ N (*I=0*) → Σ + π channel energetically closed
  - Λ + π decay forbidden (isospin conservation)
  - *Large binding energies* (B ~ 100 MeV); *small widths* (Γ ~ 50 MeV) → detectable

- Theoretical models against their observation:

  Schaffner-Bielich et al., NP A 669 (2000); Ramos et al., NP A 671 (2000) 481
  Cieply et.al, NP A 696 (2001) 173; Oset & Toki, arXiv:nucl-th/0509048 v1 (2005)

- Shallow $\bar{K}$-nucleus optical potential: small B, large Γ values

Search methods for deeply bound $\bar{K}$ states

1) Invariant mass spectroscopy

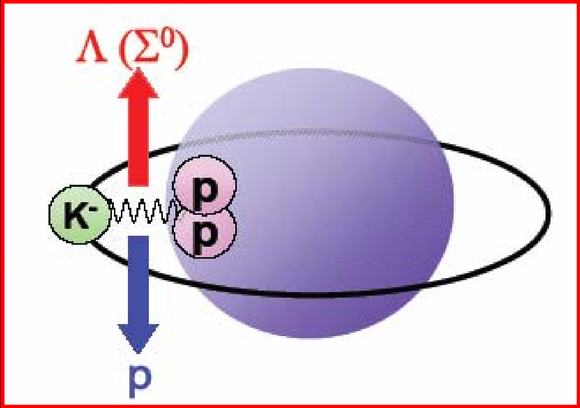
- Based on the kaonic nuclear states feature of decaying *into hyperons*:

  $^{2}_{\bar{K}}H$ ($\equiv K^{-}pp$) $\rightarrow \Lambda + p$

  with subsequent Λ decay: $\Lambda \rightarrow p + \pi^{-}$

- Full reconstruction of decay events and involved particles
- ($p\ \pi^{-}$) selection @ Λ invariant mass
- Selection of events with *back-to-back* Λ-p

FINUDA @ DAΦNE
FOPI @ GSI



2) Missing mass spectroscopy

- Measurement of the momentum of the monochromatic recoiling particle in $^{A}Z(K^{-}_{stop}, N)X$ inclusive reactions

E471, E549 @ KEK-PS
FINUDA @ DAΦNE
(with *stopped* K^{-})
E930 @ BNL-AGS
E548 @ KEK-PS
(with *in-flight* K^{-})

Invariant mass method: results on ^{6}Li

- Events excess observed below the 2p + K^- mass threshold @ 2.37 GeV/c^2
- Possible mechanisms explaining the enhancement:

1) Two-nucleons absorption ← *(expected near the threshold)*

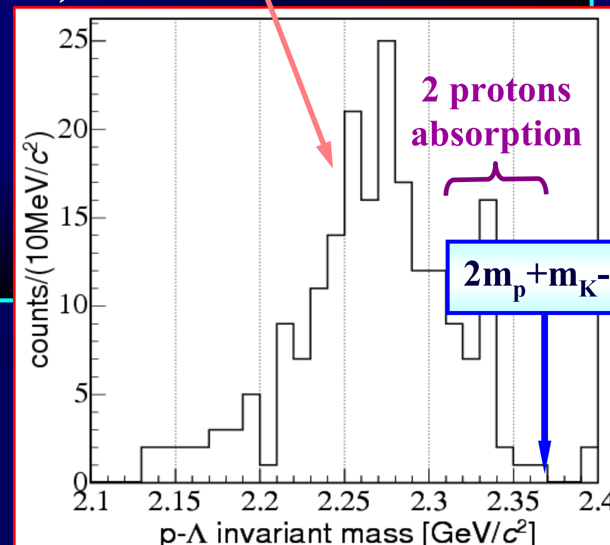
$K^- + (pp) \rightarrow Y^* N \rightarrow \Lambda + p$

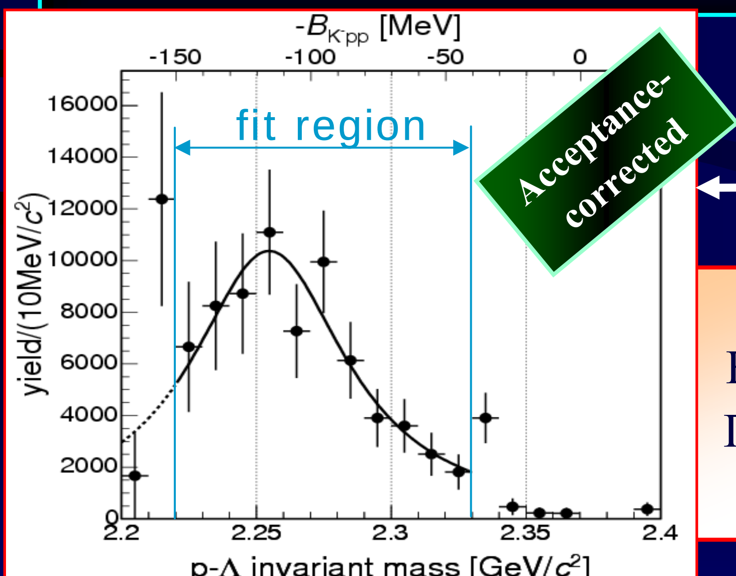
$\rightarrow \Sigma^0 + p \rightarrow \Lambda + p + \gamma$ (74 MeV)

2) Kaon bound state formation

$K^- + (pp) \rightarrow (K^- pp) \rightarrow \Lambda + p$

$\rightarrow \Sigma^0 + p \rightarrow \Lambda + p + \gamma$ (74 MeV)





FINUDA Coll. PRL 94(2005) 212303

$M = 2255 \pm 9$ MeV/c^2

$B = 115^{+6}_{-5}(stat)^{+3}_{-4}(sys)$ MeV

$\Gamma = 67^{+14}_{-11}(stat)^{+2}_{-3}(sys)$ MeV

Yield $\approx 10^{-3} / K^-_{stop}$

to know more about this analysis please see the Dr. Fujioka poster on Tuesday 25

Summary, conclusions and prospects

- FINUDA is the very first collider experiment for studying hypernuclear physics and strangeness in nuclear matter
- First data taking ended in march 2004:
  - Some interesting results on strangeness nuclear physics already found
  - Data analysis still in progress
- Next data taking scheduled in the middle of 2006

- Future prospects (after 2006):
  - DAΦNE luminosity upgrade ($\sim 5\cdot10^{32}$ $cm^{-2}s^{-1}$ foreseen) and data taking at higher statistics
  - FINUDA upgrade and hypernuclear physics at high energy resolution: study of hypernuclei spin-orbit and spin-spin fine structures