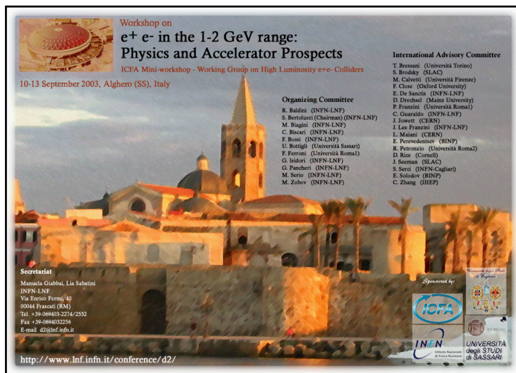
High resolution spectroscopy of Hypernuclei with γ-detectors at DAΦNE2



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Outline

- Discovery potential of the strangeness nuclear physics
  - recent experimental results
  - unexpected effects

- Need of sub-MeV resolution apparatuses
  - γ-ray spectroscopy

- Ideas for detectors for DAΦNE2 (FINUDA2, "YKLOE", …)

Open questions

- (low-energy) YN (YY) interaction
  - detailed knowledge of the hypernuclear fine structure
    - → evaluation of the spin dependent terms of the ΛN interaction
  - measurement of angular distribution and polarization of γ-rays
    - → determination of spin and parity of each observed level

- Impurity nuclear physics
  - measurement of transition probability B(E2)
    - → information on the size and deformation of hypernuclei
    - → measurement of nucleus core shrinking → glue role of Λ

- Properties of hyperons in nuclear matter (medium effect)
  - measurement of transition probability B(M1)
    - → g-factor value for Λ in nuclear matter

Spin-dependent forces

The simple structure of light hypernuclear system can be described in the frame of the shell model

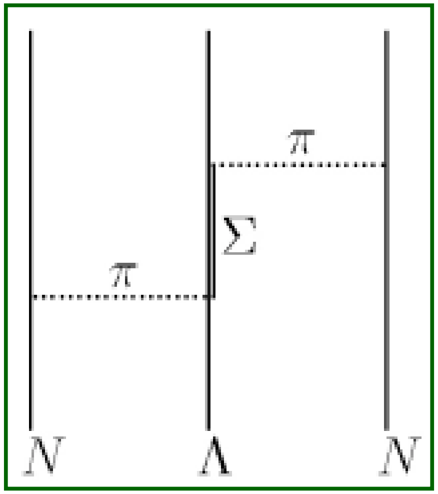
$$V_{\Lambda-N}(r) = V_0(r) + V_\sigma(r)\vec{s}_N \cdot \vec{s}_\Lambda + V_\Lambda(r)\vec{l}_{N\Lambda} \cdot \vec{s}_\Lambda + V_N(r)\vec{l}_{N\Lambda} \cdot \vec{s}_N + V_T(r)[3(\vec{\sigma}_N \cdot \vec{r})(\vec{\sigma}_\Lambda \cdot \vec{r} - \vec{\sigma}_N \cdot \vec{\sigma}_\Lambda)]$$

Each of the 5 terms (V, Δ, S_Λ, S_N, T) correspond to a radial integral that can be phenomelogically determined from the low-lying level structure of *p*-shell hypernuclei

The knowledge of these characteristics of the ΛN interaction allows to improve baryon-baryon interaction models and to discriminate between the ones based on meson exchange picture and those including quark-gluon degree

3-body force

The energy spectrum of hypernuclei cannot be completely reproduced by a simplified 2-body effective interaction scheme



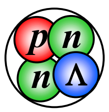
Study of ΛNN 3-body and of ΛN 2-body forces is of great importance to understand the structure of hypernuclei

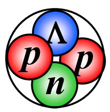
- $\Delta m_{\Sigma\text{-}\Lambda} \ll \Delta m_{\Delta\text{-}N} \rightarrow \Lambda NN \gg NNN$
- $\Lambda NN > \Lambda N$

Charge symmetry breaking

$$\Lambda \begin{cases} I = 0 \\ q = 0 \end{cases} \Longrightarrow \Lambda p = \Lambda n$$

if the charge symmetry holds exactly

${}^4_\Lambda H$ 

${}^4_\Lambda He$ 

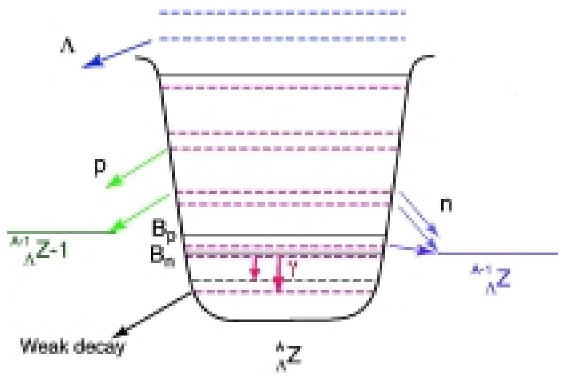
$$B_\Lambda({}^4_\Lambda H) \neq B_\Lambda({}^4_\Lambda He)$$

⇓

Λp more attractive than Λn

Possible explanations:
- $\Lambda\Sigma^0$ mixing
- $\Lambda N - \Sigma N$ coupling

Odd-state interaction



even-states ΛN (*s*-wave)
odd-states ΛN (*p*-wave) } interactions

$$\frac{s\text{-wave}}{p\text{-wave}} = ?$$

- ND model: attractive odd-state force
- NSC97 model: repulsive odd-state force

in contrast with data on $^{13}_{\Lambda}C$!

odd-states are usually particle unbound for light (A < 50) hypernuclei
→ best candidate hypernuclei $^{89}_{\Lambda}Y$ and $^{208}_{\Lambda}Pb$

Impurity nuclear physics

A hypernucleus can be considered the outcome of a genetic engineering manipulation applied to the nuclear physics domain

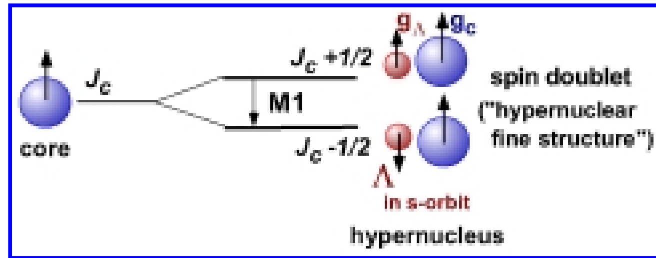
The introduction of 1 (or 2) hyperons in a nucleus may give rise to various changes of the nuclear structure

- changes of the size and of the shape
- changes of the cluster structure
- manifestation of new symmetries
- change of collective motions
- …

study of hypernucleus level schemes and B(E2) ⇒ Doppler-shift attenuation method

Medium effect

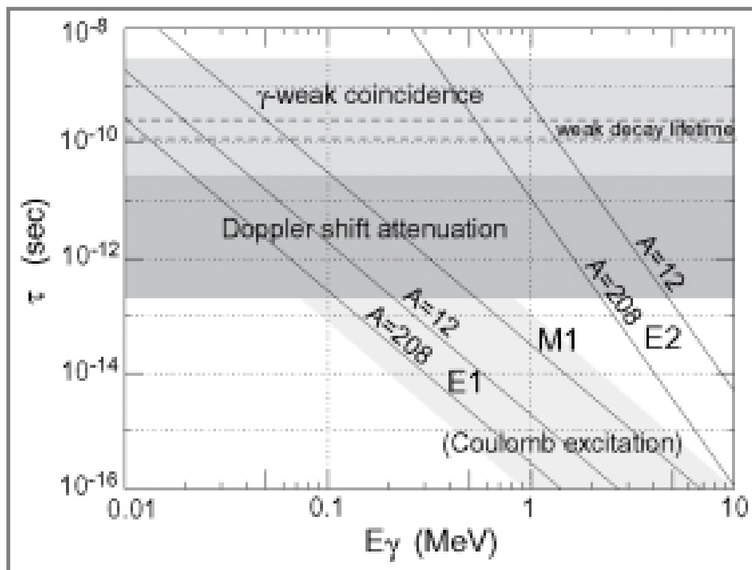
If the mass or the size of a hyperon is modified in a nucleus, its magnetic moment may be changed



$$B(M1) \propto \left| \left\langle \phi_{lo} \middle| \mu^z \middle| \phi_{up} \right\rangle \right|^2 = \left| \left\langle \phi_{lo} \middle| g_N J_N^z + g_\Lambda J_\Lambda^z \middle| \phi_{up} \right\rangle \right|^2$$
$$\propto (g_N - g_\Lambda)^2$$

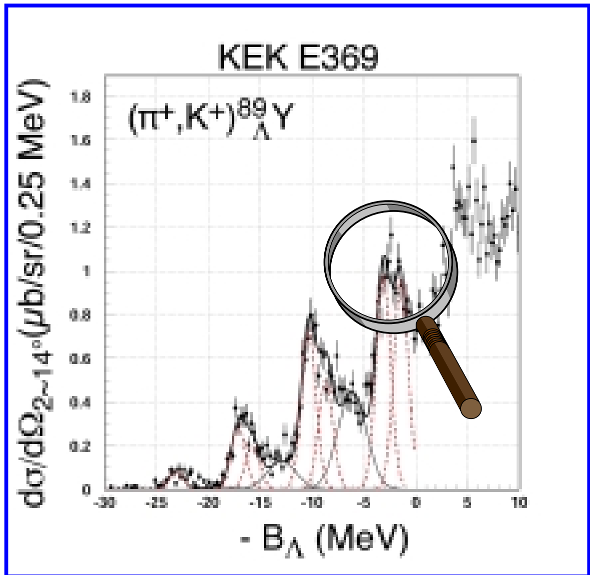
B(M1) can be derived from excited states lifetimes

- Doppler-shift attenuation method
- γ-weak coincidence method

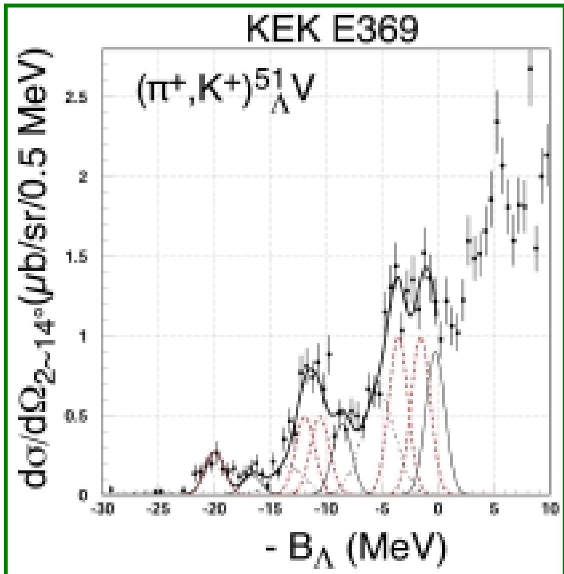


The status of the art

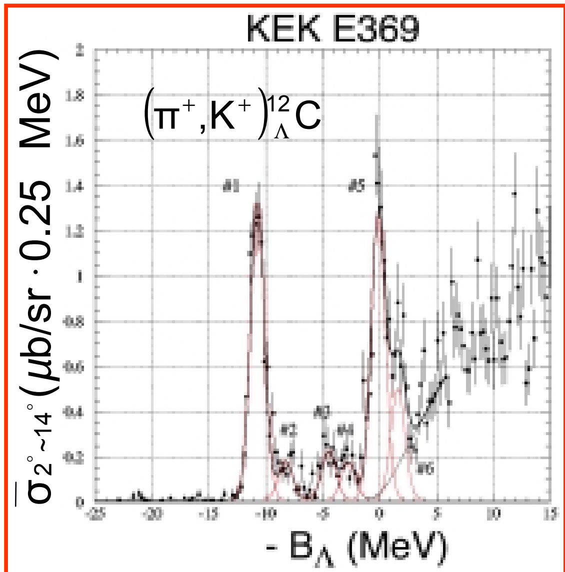
ΔE ~ 1.65 MeV FWHM



ΔE ~ 1.95 MeV FWHM



ΔE ~ 1.45 MeV FWHM

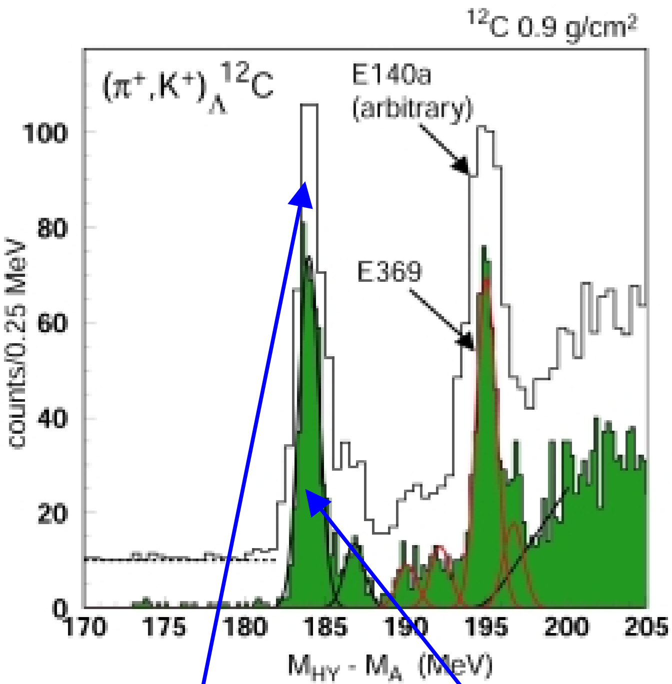


f-orbit splitting
into two peaks observed?

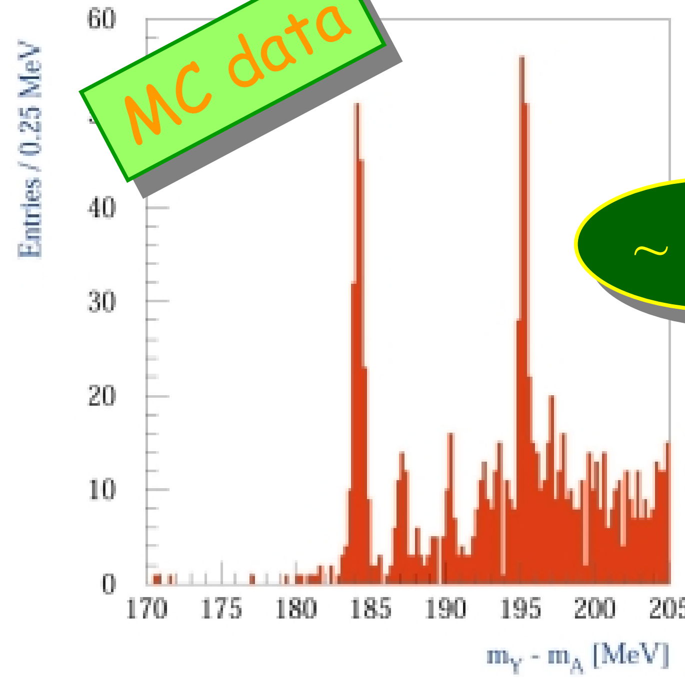
The answer of FINUDA

KEK data

ΔE ~ 0.75 MeV FWHM



MC data



~ 5 pb^{-1}

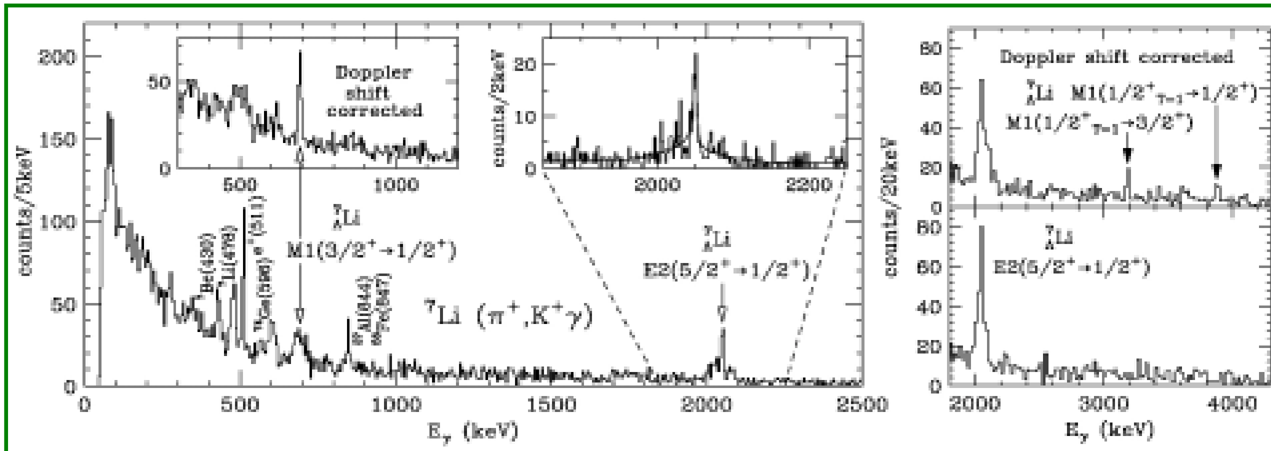
ΔE = 1.9 MeV FWHM

ΔE ~ 1.5 MeV FWHM

$^{12}C(K^-_{stop}, \pi^-)^{12}_{\Lambda}C$

One step beyond

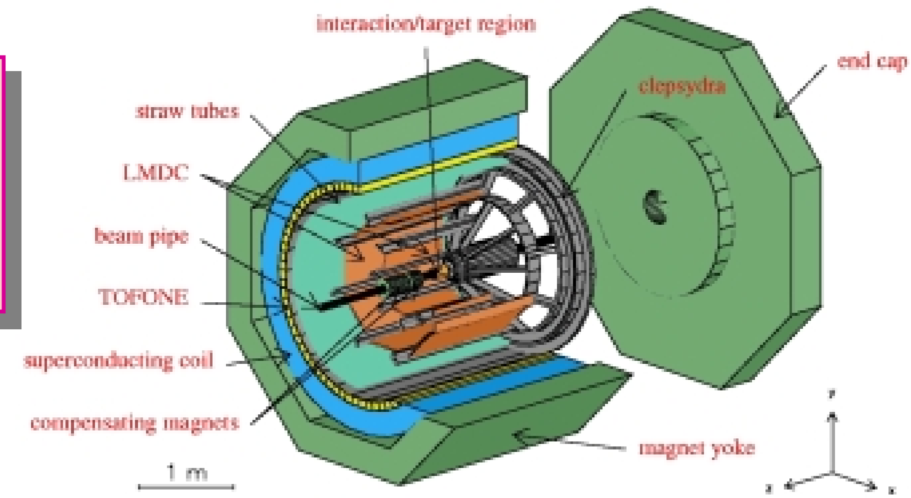
KEK E419

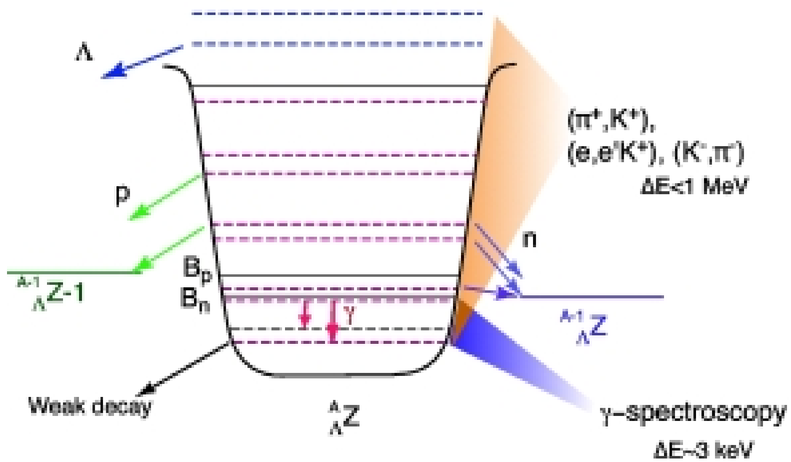


Precise hypernuclear γ-spectroscopy has been established as new frontier in strangeness nuclear physics

The γ-ray spectroscopy domain

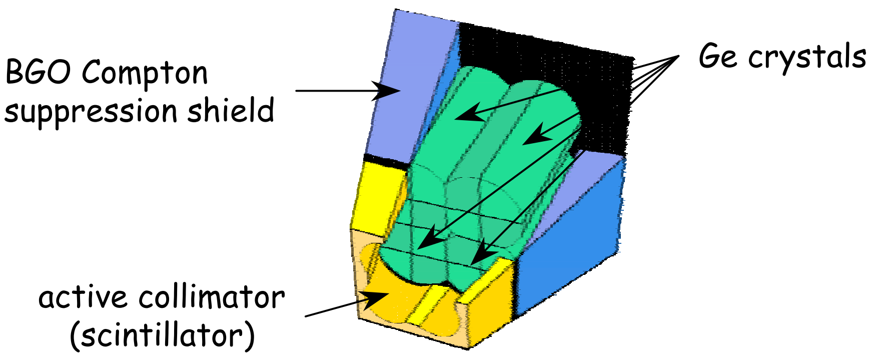
The region of high excitation energy
in heavy Λ-hypernuclei
cannot be explored
with γ-spectroscopy

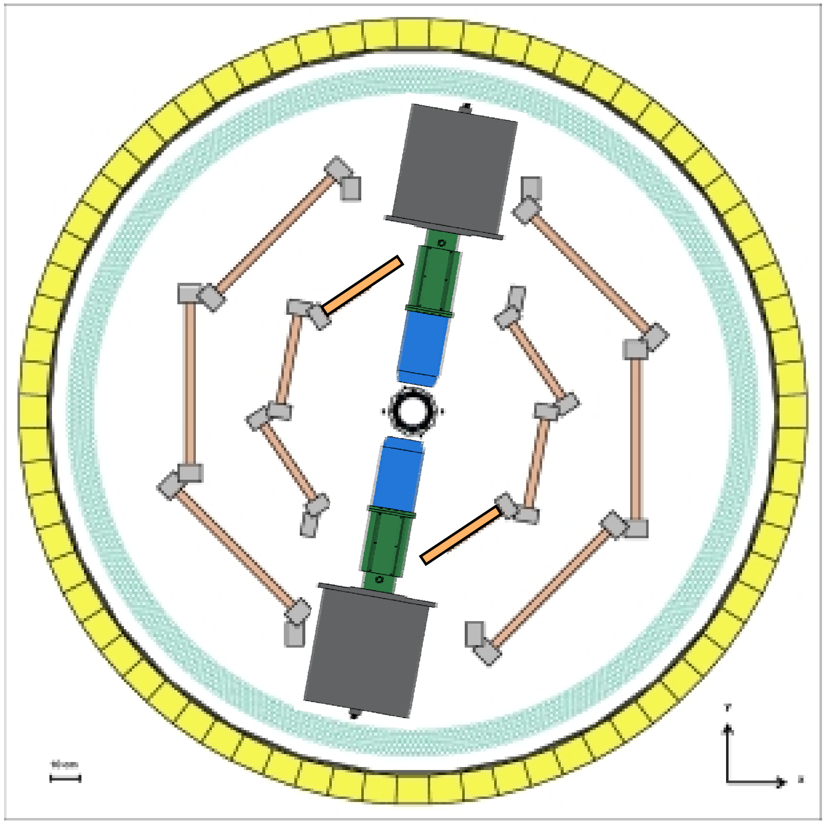




FINUDA2

The Segmented Clover Detector





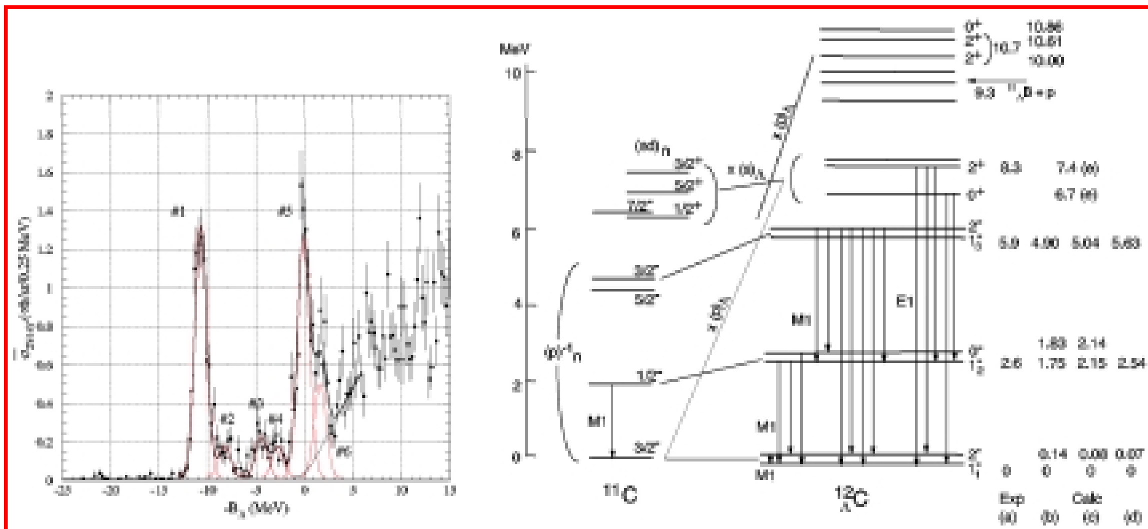
Geometrical acceptance reduced to 72%

Spectroscopy of light hypernuclei

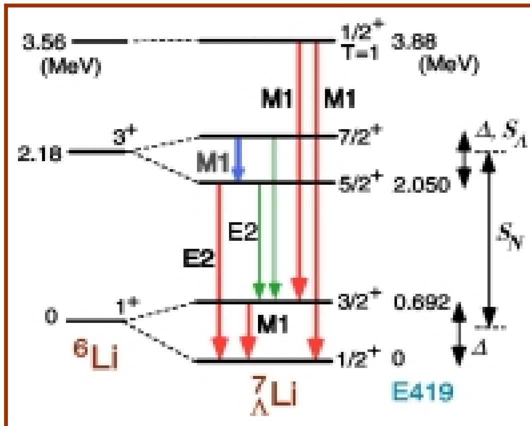
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

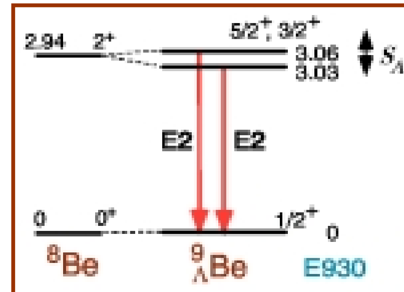
survey of hypernuclei with A < 30:

$${}^{7}_{\Lambda}Li,\ {}^{9}_{\Lambda}Be,\ {}^{10}_{\Lambda}B,\ {}^{11}_{\Lambda}B,\ {}^{12}_{\Lambda}C,\ {}^{13}_{\Lambda}C,\ {}^{23}_{\Lambda}Na,\ {}^{27}_{\Lambda}Al,\ {}^{28}_{\Lambda}Si$$

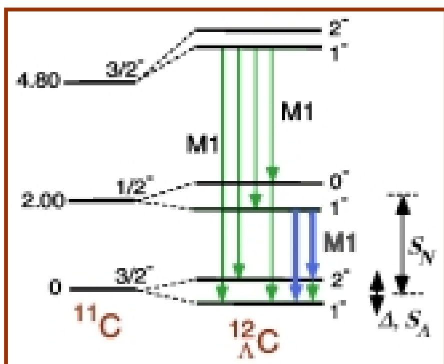


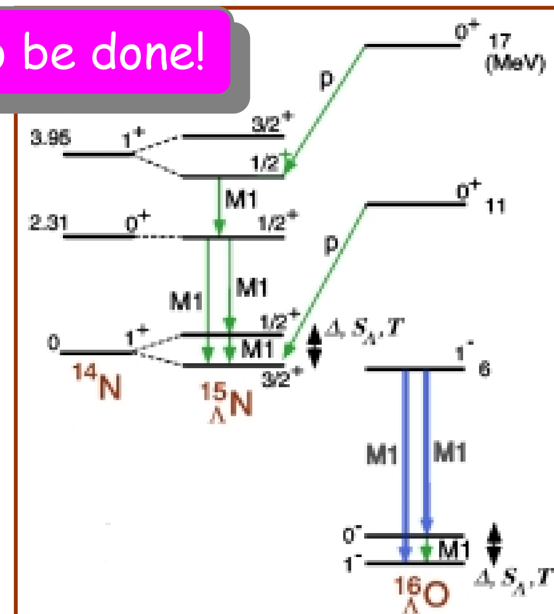
Spectroscopy of light hypernuclei





A lot of work remains to be done!





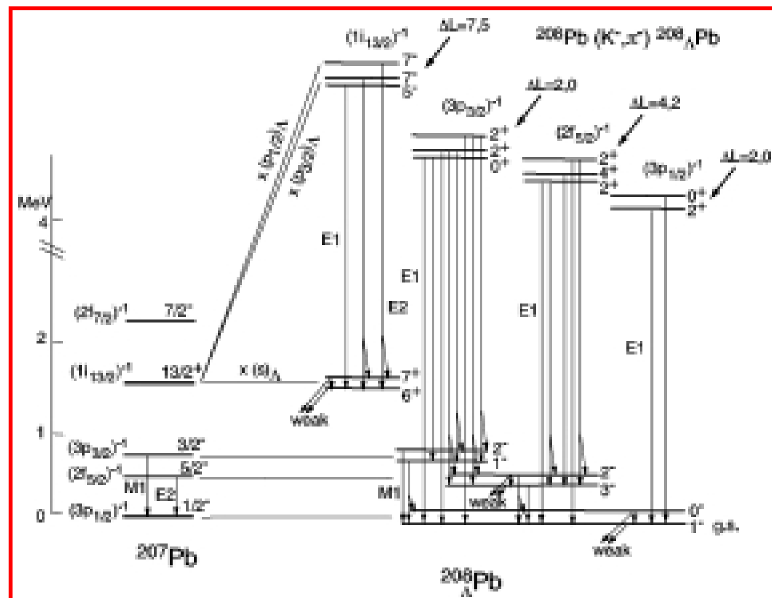
Already observed (E419,E930) | To be observed (Target of E930) | Will hopefully be observed

Spectroscopy of medium-heavy hypernuclei

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$

survey of hypernuclei with *A* > 30:

$${}^{40}_{\Lambda}Ca,\ {}^{48}_{\Lambda}Ca,\ {}^{55}_{\Lambda}Mn,\ {}^{89}_{\Lambda}Y,\ {}^{89}_{\Lambda}Nb,$$
$${}^{133}_{\Lambda}Cs,\ {}^{139}_{\Lambda}La,\ {}^{165}_{\Lambda}Ho,\ {}^{208}_{\Lambda}Pb,\ {}^{209}_{\Lambda}Bi,$$

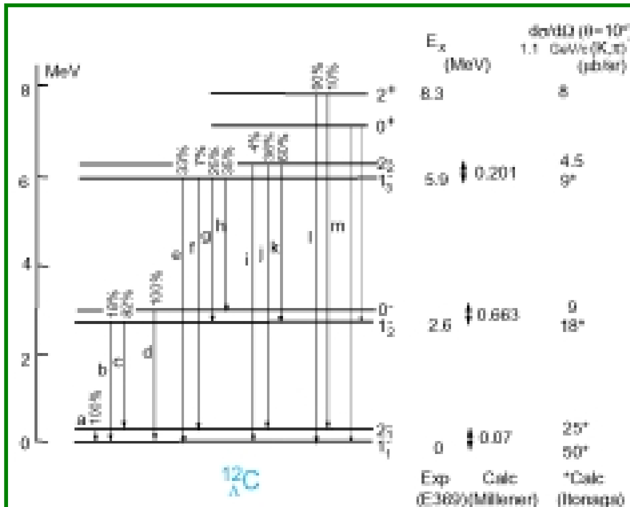


Expected rates

@ L = 10^{34} cm^{-2} s^{-1} FINUDA can observe ~ 1.6×10^{4} ev/h from YN g.s.

- machine duty cycle: 75%
- spectrometer acceptance: 72%
- Ge acceptance: ~ 30%
- ε_{Ge}: ~ 30%

~ 1.87×10^{4} ev/d



Expected Yield (5 days)

single				γγ coincidence with a		with c		with d	
a	112000	h	1700	c	1900	a	1900	h	55
b	2600	i	64	f	50	g	39		
c	12000	j	580	g	150	k	50		
d	7500	k	1400	j	94				
e	1100	l	2000	k	170				
f	240	m	230	m	31				
g	1300								

MC data

5 day data taking

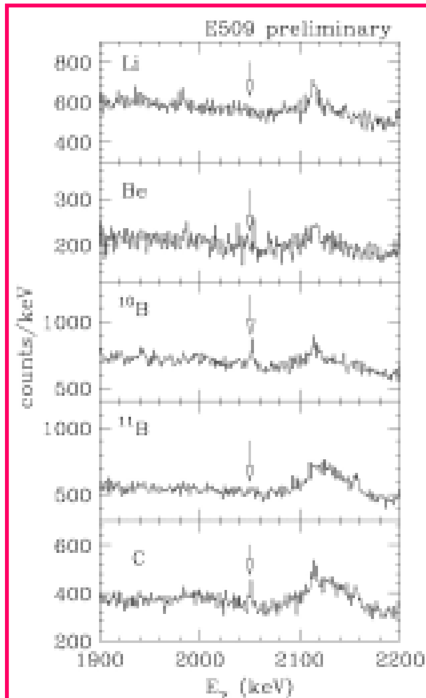
~ 9.33×10^{4} ev

Spectroscopy of hyperfragments

hypernuclear species are limited by target availability

stopped K^- induced reactions are the most efficient way to produce hypernuclei

high level of background



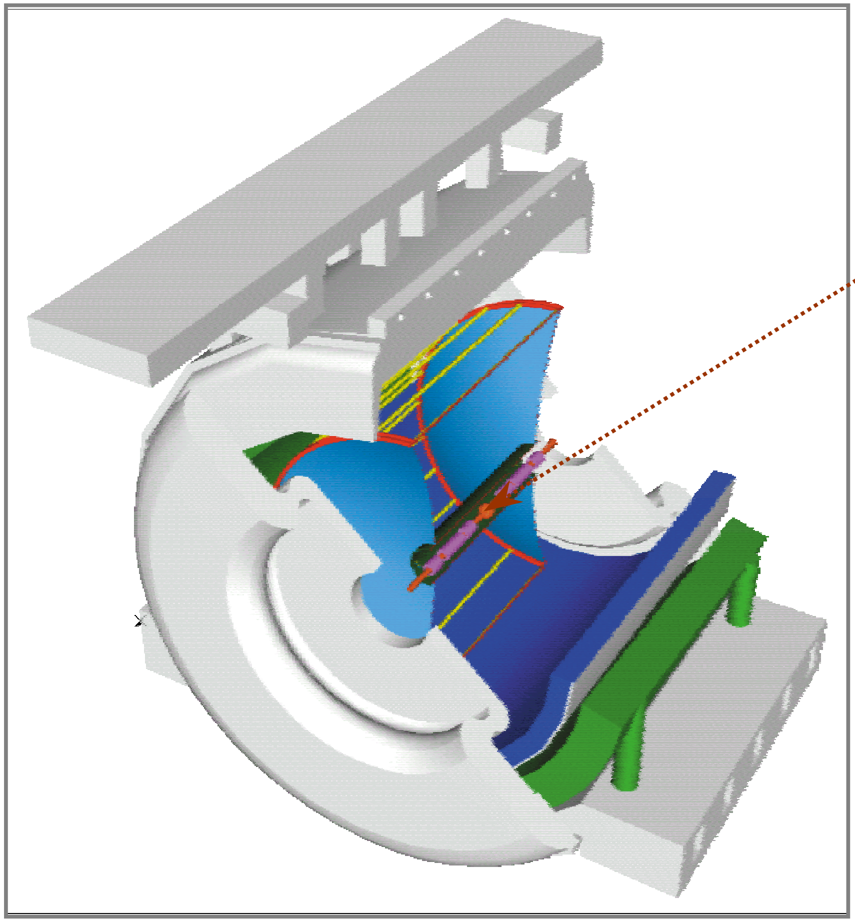
high resolution spectrometer no longer needed in order to identify the hypersystem produced ($\rightarrow$ low or no magnetic field required)

spectrum of experimental solutions

- modified FINUDA apparatus
- modified KLOE apparatus (+ t.o.f. + Ge array)
- dedicated apparatus

Production of hyperfragments extends the possibility of hypernuclear γ-ray measurements

"YKLOE"



Ge
detector(s)
+
t.o.f.

Expected hyperfragments yelds

@ DAΦNE2 (L = 10^{34} cm^{-2} s^{-1})

- ϕ/d = 2.85×10^9
- K^-/d = 1.40×10^9
- *stopped* K^-/d = 0.9 · 1.40×10^9 = 1.26×10^9
- YN/d = 0.1 · 1.26×10^9 = 1.26×10^8

3.77×10^8

@ JPARC (K1.1 line)

* initial conditions

- K^-/d = 6.67×10^8
- *stopped* K^-/d = 0.2 · 6.68×10^8 = 1.33×10^8
- YN/d = 0.1 · 1.33×10^8 = 1.33×10^7

4.00×10^7 *

3 day data taking

Summary

✓ The fifty-year-old field of strangeness nuclear physics is still alive and has a great discovery potential

☞ An intensive and exhaustive program for new generation experiments, based on γ-ray spectroscopy, is in preparation @ JPARC (Japan) with the hope to observe new phenomena in deeply-bound many-body systems

☞ By exploiting the new potentialities of DAΦNE2, FINUDA2 can perform some selected high-resolution measurements in coincidence, in better experimental conditions and with counting rates comparable (or even better) with the ones of the present and future facilities