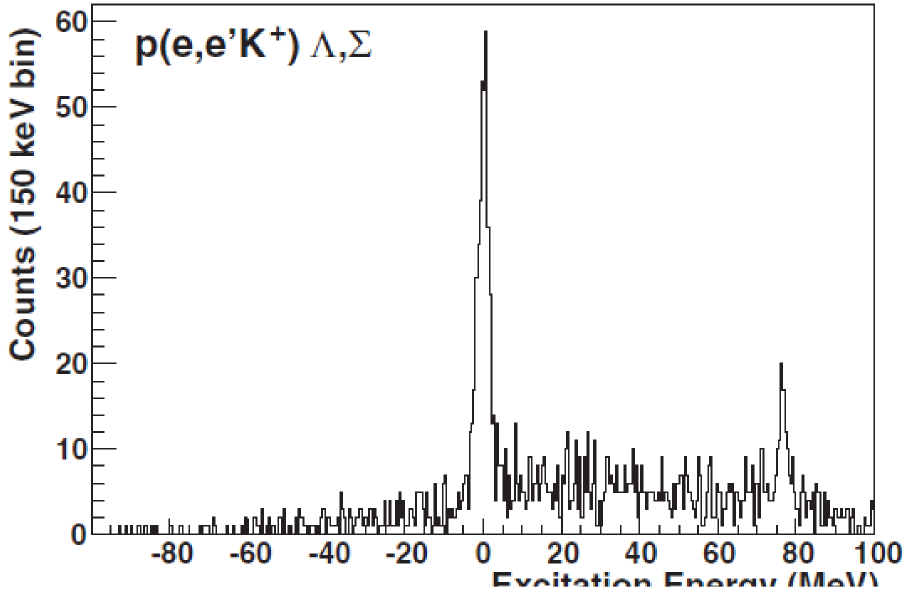
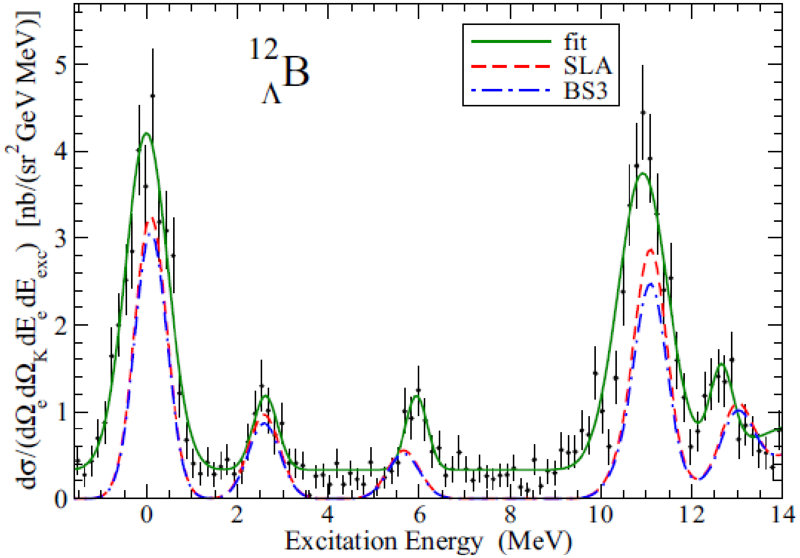
Hypernuclear spectroscopy experiments at Jlab with the HKS spectrometer.

G. M Urciuoli

Features of hypernuclear spectroscopy performed through ${}^{A}Z(e,e'K^{+})^{A}_{\Lambda}(Z-1)$ reactions:





Energy calibration

Energy resolution

Thanks to the availability of Hydrogen targets and hence to the possibility to determine the missing mass spectrum of the reaction: ${}^{1}H(e,e'K^{+})\Lambda,\Sigma$ it is possible to obtain very good energy calibration and hence to determine very precisely Binding energies (only possible at Jlab!)

The hypernuclear spectroscopy program at Jlab has two main goals:

1) Study of Charge Symmetry Breaking in the Hyperon-Nucleon interaction

2) Solving the hyperon puzzle in order to understand the neutron star structure

Study of Charge Symmetry Breaking

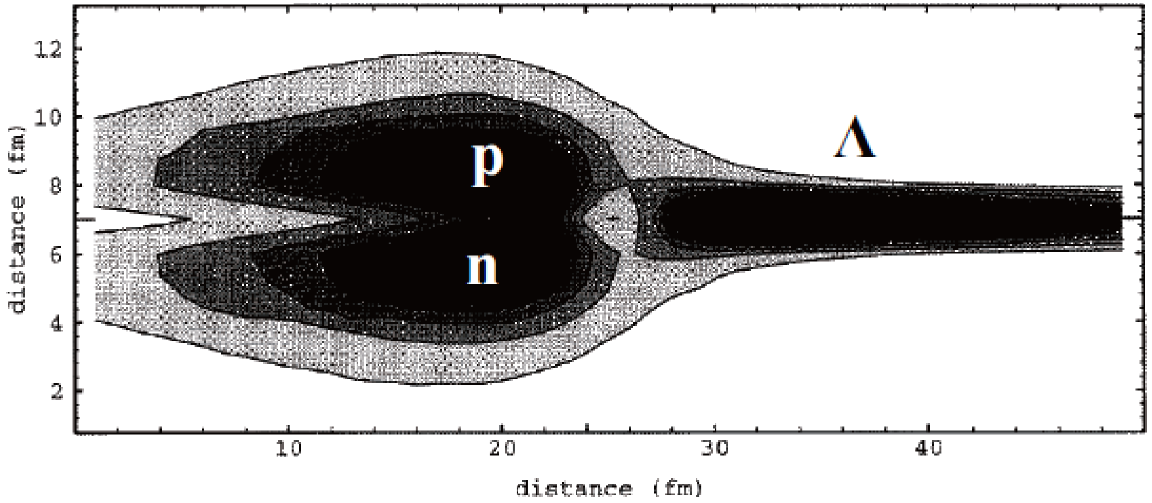
- Two experiments were approved by Jlab PAC on this topic:

1) **Fully approved: Experiment E12-19-002: high accuracy measurement of nuclear masses of hyperhydrogens.**

2) **Conditionally approved: Experiment E12-20-003, extension request for E12-17-003: determining the unknown Λ-n interaction by investigating the Λnn resonance. About its physics case: see Gogami's talk at this meeting.**

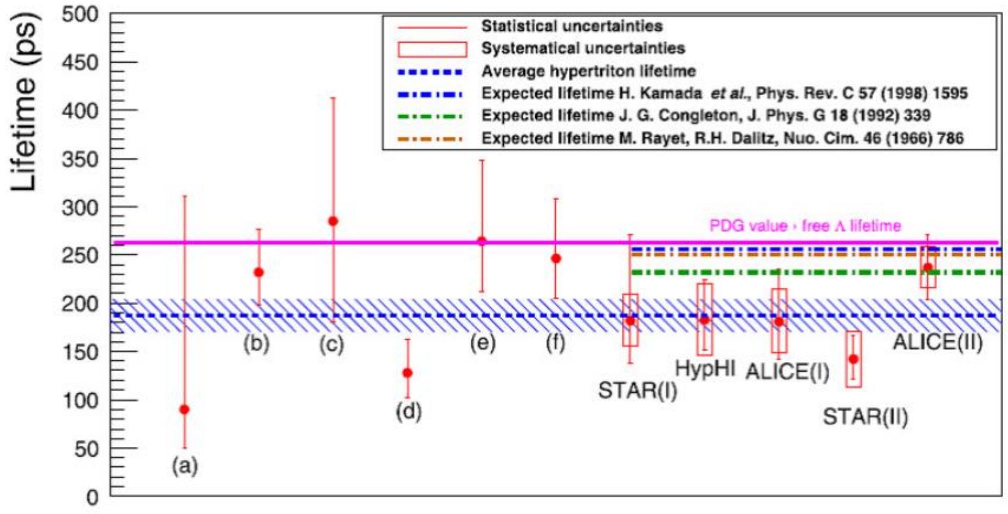
Experiment E12-19-002:

A precise measurement of the ground state binding energy of ${}^{3}_{\Lambda}H$ through the ${}^{3}He(e,e'K^{+}){}^{3}_{\Lambda}H$ reaction is urgently needed



Theoretical calculated probability distribution of a proton, a neutron and a Λ in hypertriton (A. Cobis *et al.*, *J. Phys. G: Nucl. Part. Phys.* **23**, 401{421 (1997)).

The binding energy of hypertriton ${}^{3}_{\Lambda}H$ was measured to be B_{Λ} = 130 ± 50 keV (M. Juric et al., Nucl. Phys. B **52**, 1{30 (1973)). Consequently, according to the equation $\sqrt{<r^2>} \gtrsim \frac{\hbar}{\sqrt{4\mu B_{\Lambda}}}$, the root mean square radius of the hypertriton should be equal to about 10 fm. The overlap between the core nucleus and Λ is hence small, and the Λ is almost free from interactions



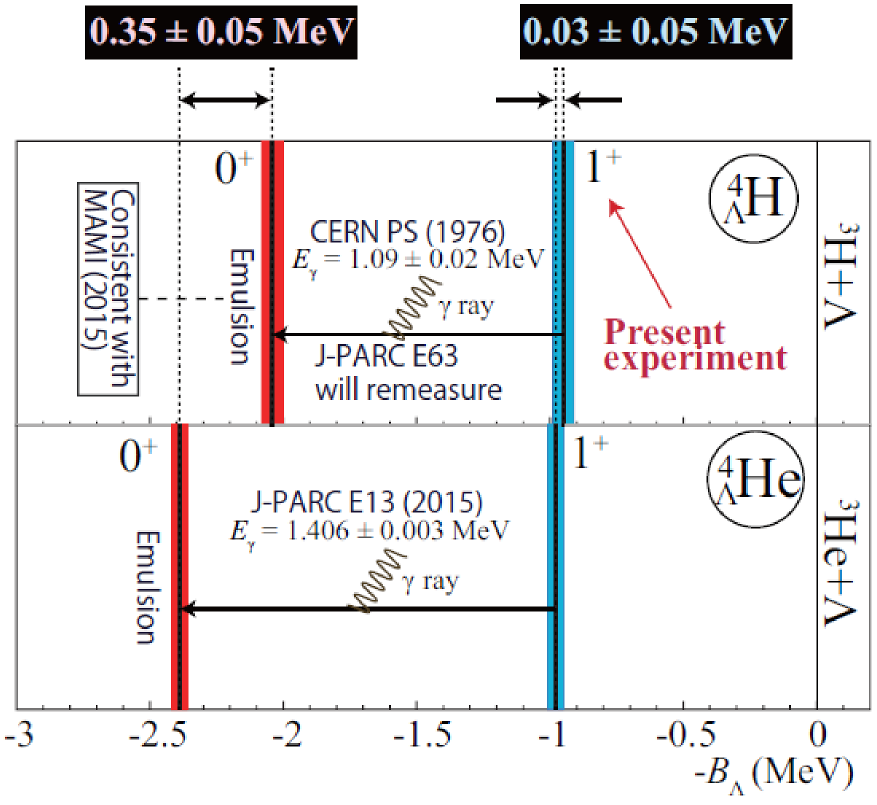
Experiments shows that the hypertriton lifetime is shorter by 30 ± 8% than expected.

Consequently

However

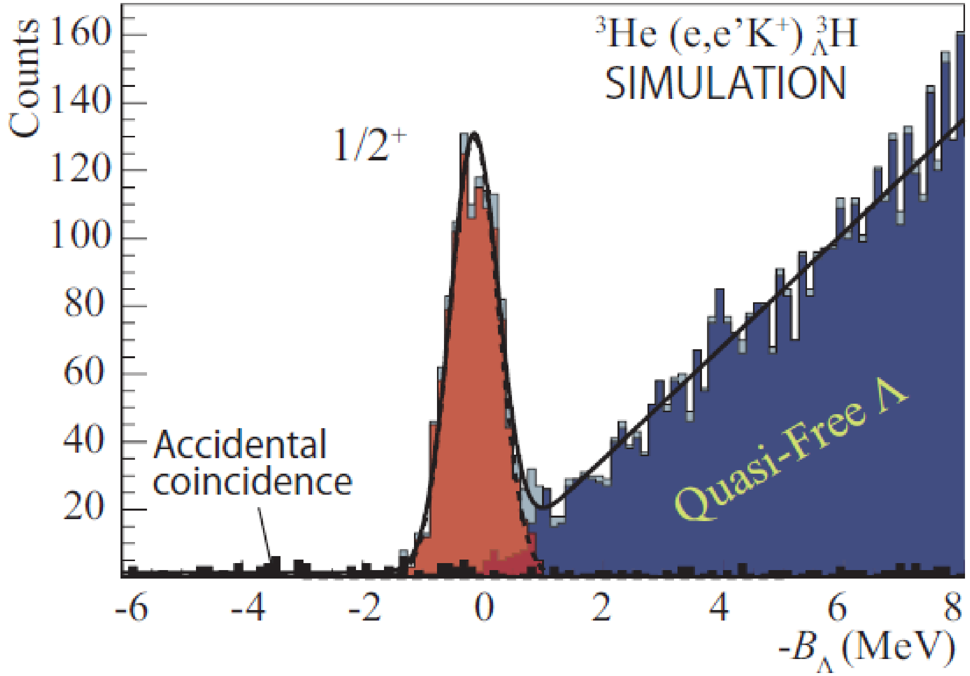
The hypertriton lifetime is naively expected to be similar to that of a free Λ hyperon.

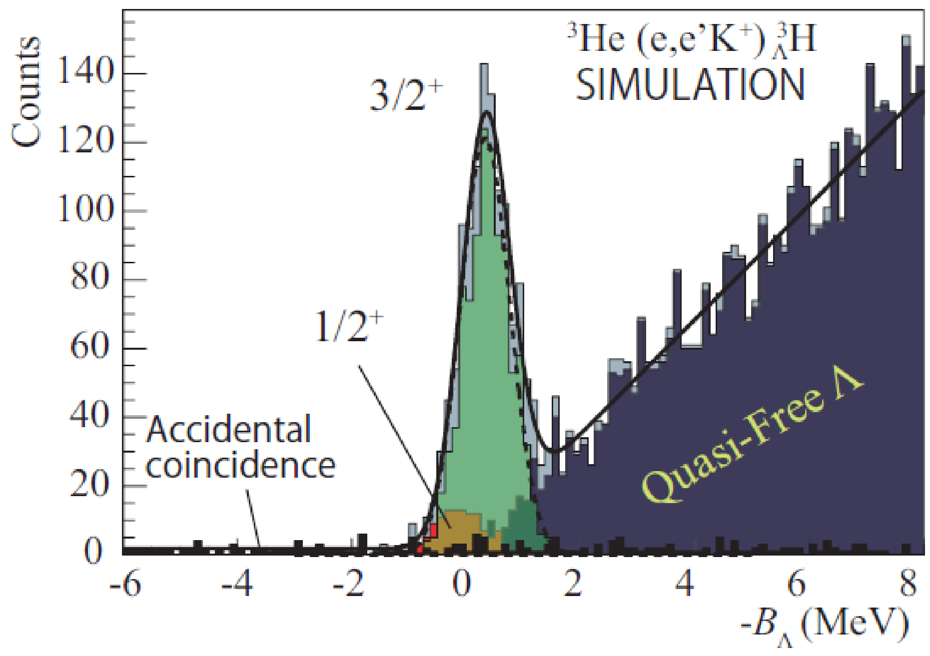
The first direct measurement of the absolute binding energy of ${}^{4}_{\Lambda}H$ (1^{+}) through the ${}^{4}He(e,e'K^{+}){}^{4}_{\Lambda}H$ reaction is needed too.



The Charge Symmetry Breaking (CSB) was experimentally observed in the A = 4 iso-doublet, as a large binding energy difference of 350 ± 50 keV was measured by emulsion experiments between the binding energies of the ground states of ${}^{4}_{\Lambda}He$ (0^{+}) and ${}^{4}_{\Lambda}H$ (0^{+}). After the Coulomb correction, this energy difference is about 400 keV. Before J-PARC E13 experiment, it was believed that CSB held true also for the ${}^{4}_{\Lambda}He$ (1^{+}) and ${}^{4}_{\Lambda}H$ (1^{+}) states, because old measurements provided a value of 290 ± 60 keV for the difference between the binding energies of these states. However, J-PARC E13 experiment reduced this difference to a value of 30 ± 50 keV . Apparently it turns out that CSB is spin dependent! A precise measurement of the binding energy of ${}^{4}_{\Lambda}H$ (1^{+}) Is hence absolutely needed.

Experiment E12-19-002 expected results:





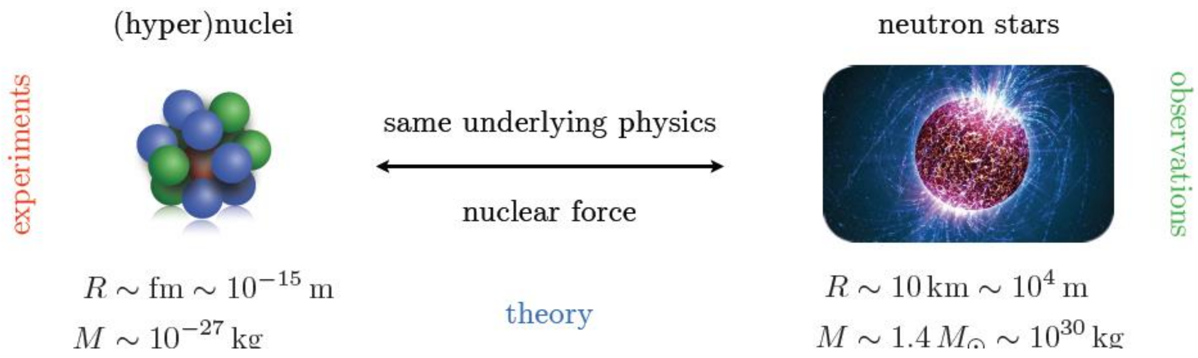
Expected uncertainties: $\left|\Delta B_{\Lambda}^{stat}\right| \leq$ 20 keV; $\left|\Delta B_{\Lambda}^{stat}\right| \leq$ 70 keV (possibly 55 keV)

Experiment E12-19-002 requested beam time

Mode	Hypernucleus	Target (mg/cm^2)	Beam current (μA)	Beamtime (day)	Yield
Physics	$^{3}_{\Lambda}$H	^{3}He (168)	50	10	1050 ($1/2^+$, $3/2^+$)
	$^{4}_{\Lambda}$H	^{4}He (312)	50	1	587 (1^+)
	Subtotal			**11**	-
Calibration	Λ Σ^0	LH_2 (174)	20	0.5	3900 1300
	$^{12}_{\Lambda}B^{g.s.}$	Multi foil (100×3)	50	1	300×3
	-	Multi foil + Sieve slit	20	0.2	-
	-	Empty cell	20	0.1	-
	-	Empty cell + Sieve slit	20	0.2	-
	Subtotal			**2**	-
Total				**13**	-

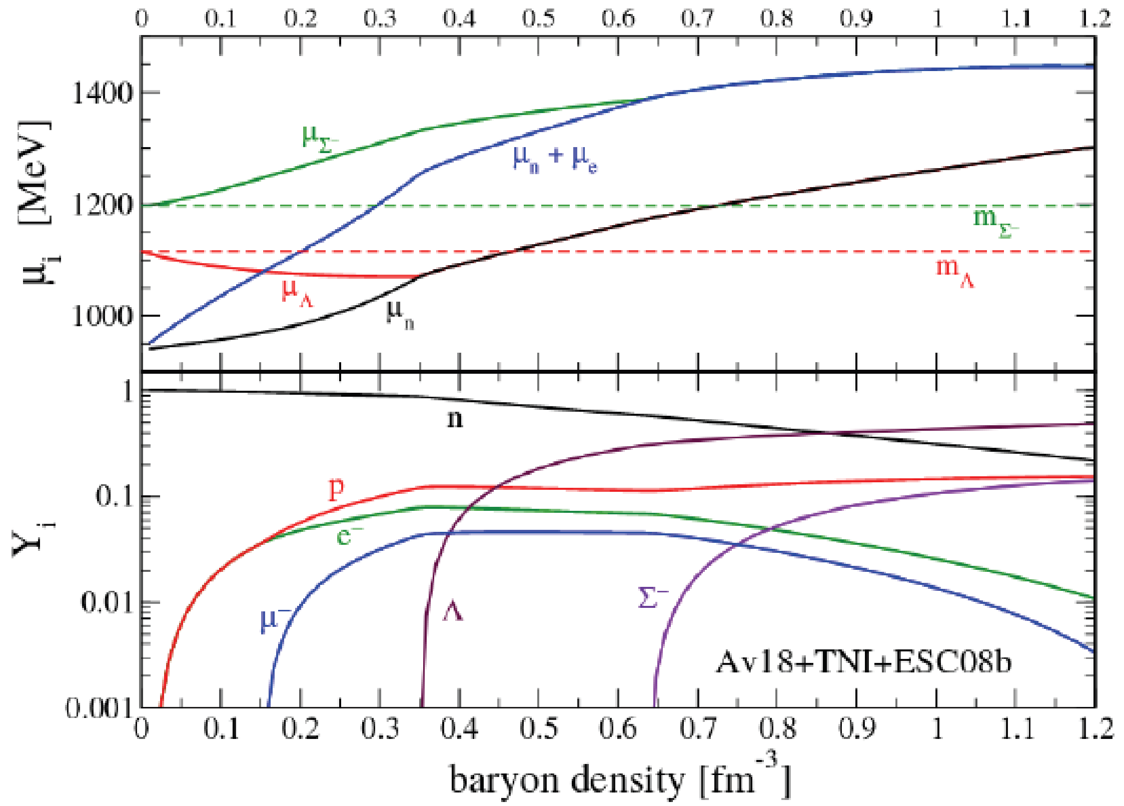
Solving the «Hyperon puzzle»

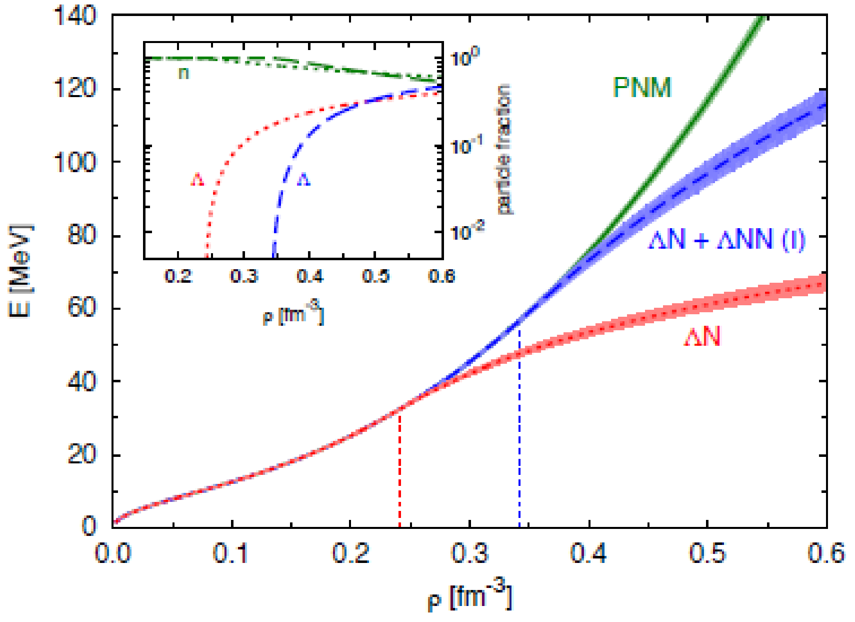
(understanding neutron star structure)

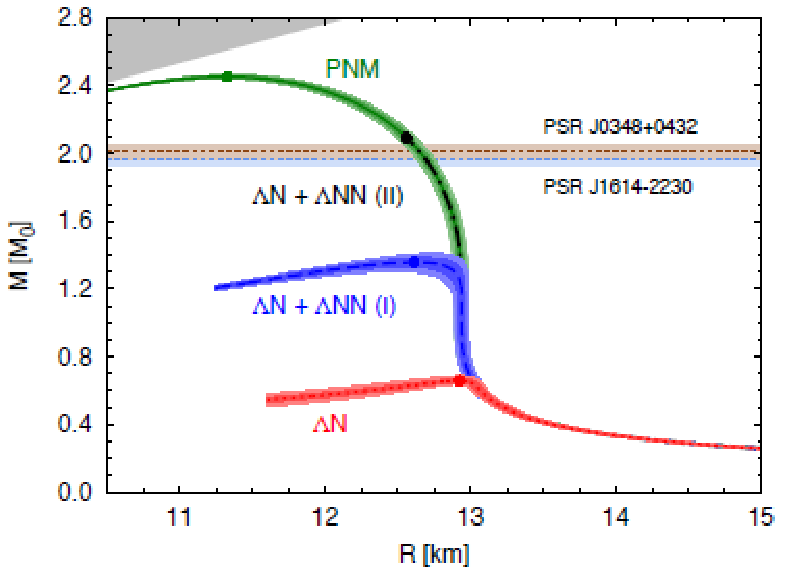


Neutron stars are remnants of the gravitational collapse of massive stars having masses of (1-2 Mo ~ 2 x 10^{33} Kg) and are excellent observatories to test fundamental properties of nuclear matter under extreme conditions and offer interesting interplay between nuclear processes and astrophysical observables

Hyperons are expected to appear in their core at density $\rho \sim (2\text{-}3)\rho_o$. In fact, at these densities, the chemical potential μ_N is large enough to match the chemical potential of a hyperon. This makes conversion of N to Y energetically favorable. However, this results in a reduction of the Fermi pressure exerted by the baryons and a softening of the equation of state (EOS). Consequently, the maximum mass determined by the equilibrium condition between gravitational and nuclear forces is reduced. Most of EOS matter containing strangeness predict a maximum neutron star mass of about 1.5 solar mass. However the recent measurements of neutron star masses as big as 2 solar mass require a much stiffer EOS to be explained (Hyperon puzzle).







The hyperon puzzle shows that the present understanding of the nuclear interactions involving hyperons is far from being complete. The reason is in a combination of an incomplete knowledge of the forces governing the system (in the hypernuclear case both two- and three-body forces), and in the concurrent use of approximated theoretical many-body techniques.

It has been suggested that three body forces could provide additional repulsion making the EOS stiffer enough to help solving the hyperon puzzle

D.Lonardoni *et al.*, Phys. Rev. Lett. 114, 092301 (2015) (AFDMC)

Two complementary experiments already approved by Jlab PAC aim at solving the “hyperon puzzle”:

1) Experiment E**12-15-008**

An isospin dependence study of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei with electron beam

(it will investigate the isospin dependence of the NΛ interaction)

2) Experiment **12-20-013**

Studying Λ interactions in nuclear matter with the $^{208}Pb(e,e'K^{+})^{208}_{\Lambda}Tl$ reaction

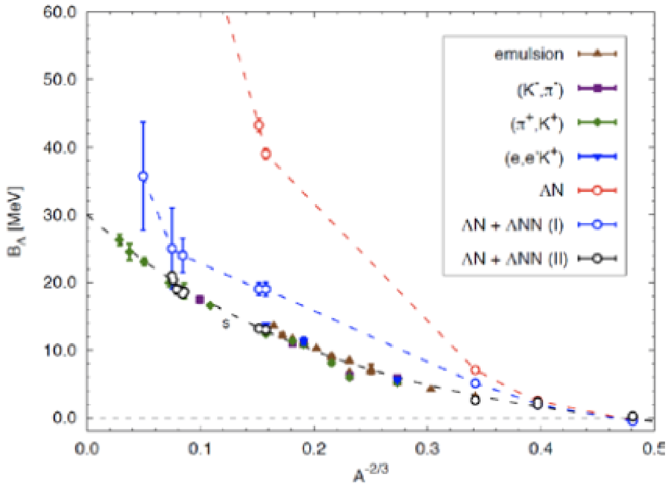
(it will investigate the *A* dependence of NNΛ and Λ interactions in an uniform nuclear medium)

Experiment E12-15-008

Study of the isospin dependence of the ΛN interaction through the high precision spectroscopy of Λ-hypernuclei obtained through the $^{40}Ca(e,e'K^{+})^{40}_{\Lambda}K$ and the $^{48}Ca(e,e'K^{+})^{48}_{\Lambda}K$ reactions

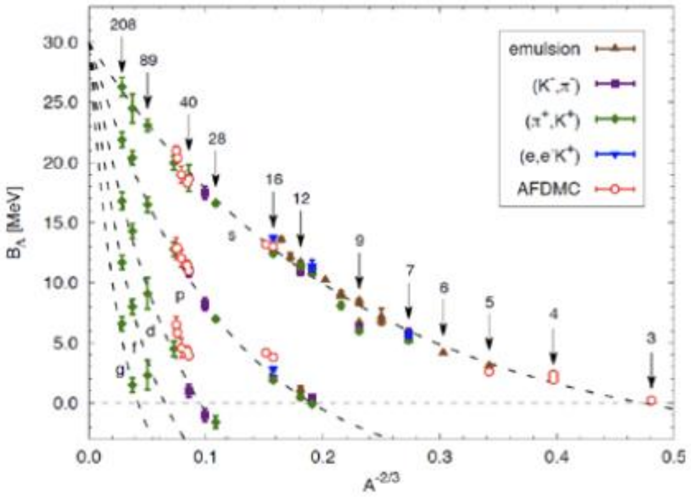
- In neutron matter or in matter at beta-equilibrium the contribution of the isospin triplet channel (T=1) in the hyperon-nucleon interaction becomes quite relevant.
- Nuclei/hypernuclei with A ≈ 50 are the most similar to the infinite medium for which ab-initio many-body calculations are feasible.
- Heavy asymmetric hypernuclei are the most sensitive to the strength and the sign of the isospin triplet component of the ΛNN potential.
- $^{48}_{\Lambda}K$ has a large dependence on the ΛNN triplet, while $^{40}_{\Lambda}K$ has not (for symmetric hypernuclei the Pauli principle suppresses any strong contribution from the Λnn or Λpp channels). A comparison of $^{48}_{\Lambda}K$ and $^{40}_{\Lambda}K$ Λ separation energies will clarify the role of the isospin asymmetry in the 3-body hyperon-nucleon interaction.

The importance of the inclusion of the three-body ΛNN force



(updated from D. Lonardoni, F. Pederiva, and S. Gandolfi, Phys. Rev. C 89, 014314 (2014)).

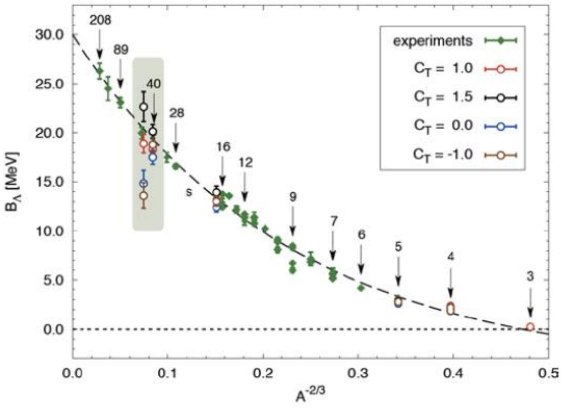
when only the two-body ΛN force is considered, calculated hyperon separation energies tend to disagree with the experimental data as the density increases.



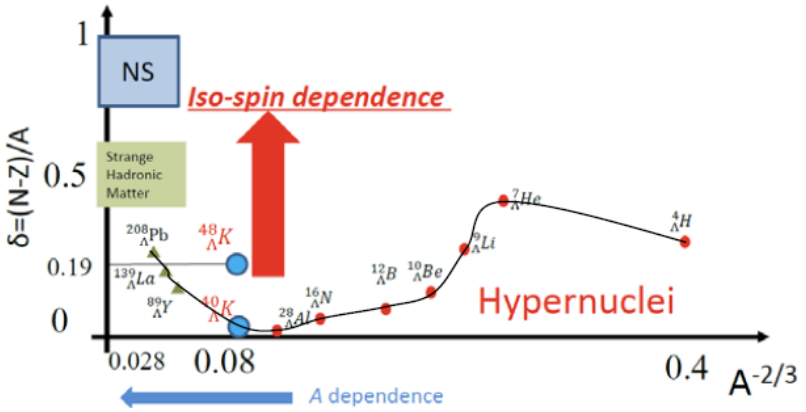
(F. Pederiva, F. Catalano,D. Lonardoni, A. Lovato , and S. Gandolfi's calculations)

The inclusion of the three-body ΛNN force leads to a satisfactory description of the hyperon separation energies in a wide mass range and for the Λ occupying different single particle state orbitals (s, p and d wave)

Heavy asymmetric hypernuclei sensitiveness to the strength and the sign of the isospin triplet component as made evident by ab-initio many-body calculations. The importance of the comparison of ${}^{48}_{\Lambda}K$ and ${}^{40}_{\Lambda}K$ Λ separation energies



(F. Pederiva, F. Catalano,D. Lonardoni, A. Lovato , and S. Gandolfi's calculations)



Behavior of the asymmetry parameter δ as a function of $A^{-2/3}$. The blue closed circles represent the case for ${}^{40}_{\Lambda}K$ (δ=0.025) and ${}^{48}_{\Lambda}K$ (δ=0.188).

The contribution of the isospin triplet channel in the hyperon-nucleon interaction is visible only in the medium-mass region

(CT is a parameter that gauges the strength and the sign of the isospin triplet component)

Relatively small differences in the Λ separation energies of hypernuclei give dramatically different results as for the properties of the infinite medium!

Experiment E12-13-008 beam time request

Target and objective hypernucleus	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected Yield (/hour)	Num. of events	Req. beamtime (hours)	B.G. Rate (/MeV/h)	S/N (±1σ)	Comments
CH_2	2	500	200	19	1000	54	0.05	252	Calibration
$^{6,7}Li$	50	100	10	5.4	150	28	1.3	4.9	Calibration
^{9}Be	100	100	10	36	300	9	4.7	8.8	Calibration
$^{10,11}B$	25	100	10	16	150	19	0.29	33	Calibration
^{12}C	100	100	100	54	2000	37	4.4	17	Calibration
Subtotal for calibration targets						**147**			
^{40}Ca ($^{40}{}_{\Lambda}K$)	50	50	10	0.9	200	230	0.43	4.0	
^{48}Ca ($^{48}{}_{\Lambda}K$)	50	50	10	0.7	200	278	0.42	3.5	
Subtotal for heavier targets						**508**			
Total						**655**			

Experiment E12-20-013

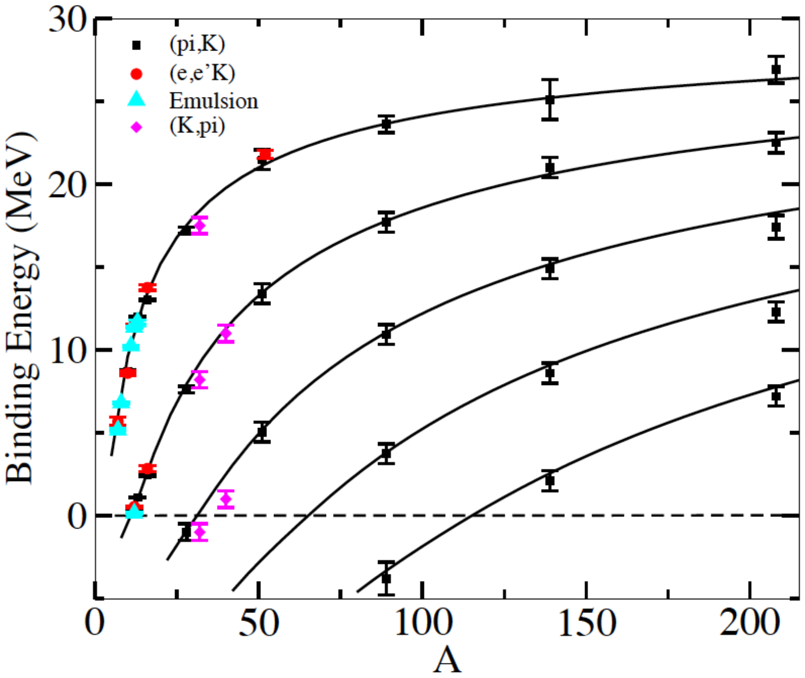
Study of $^{208}_{\Lambda}Tl$ spectroscopy through the $^{208}Pb(e,e'K^{+})^{208}_{\Lambda}Tl$ reaction

- Three-body ΛNN forces are known to be strongly A-dependent.

- A ^{208}Pb target is the best suited to obtain information on Λ interactions in a uniform nuclear medium with large neutron excess.

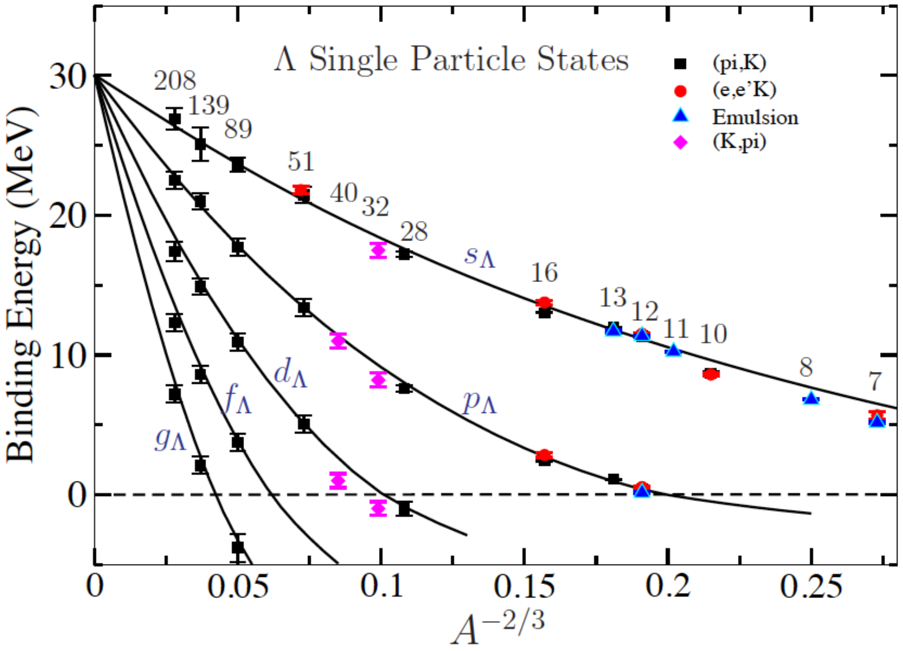
- $^{208}Pb(e,e'p)^{207}Tl$ data will provide the baseline needed to extract information, in a model independent way, on hyperon binding energies

A-dependence



The spacings of the single-particle energies as a function of *A* put more constraints on the theoretical fits.

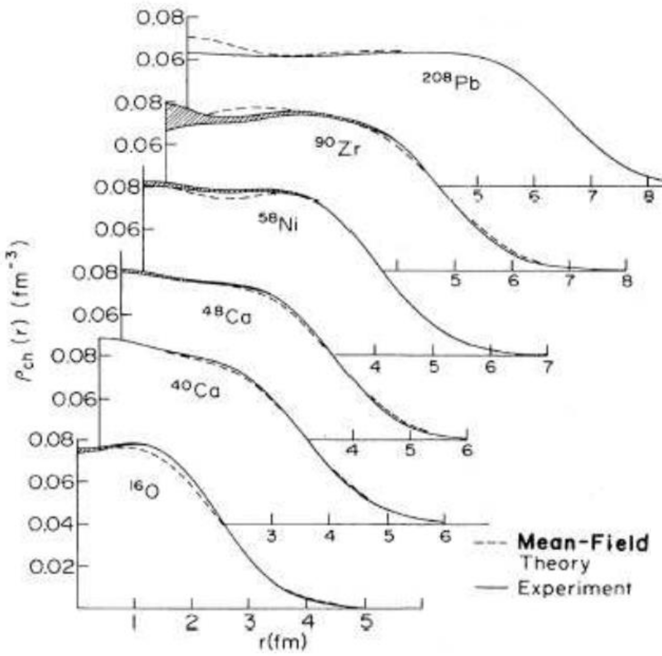
Update: Millener, Dover, Gal PRC 38, 2700 (1988)



Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

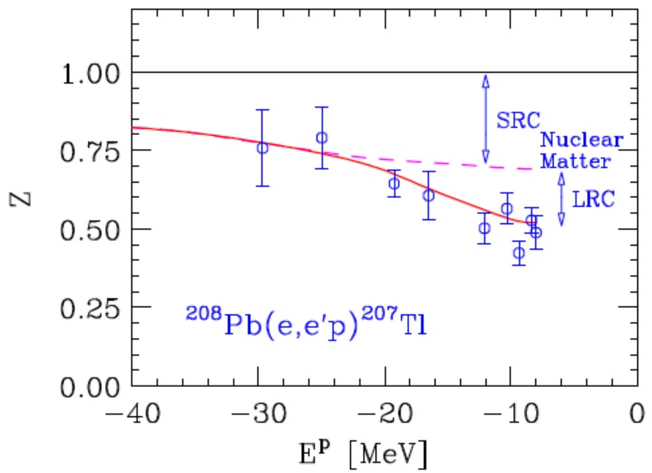
To understand Hyperon puzzle we need the binding energies and spacings of Lambda single-particle levels for a number of hypernuclei widely spaced in A.

Λ interactions in a uniform nuclear medium



B. Frois and C.N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37, 133 (1987)

The measured charge density distribution of ^{208}Pb clearly shows that the region of nearly constant density accounts for a very large fraction (~70 %) of the nuclear volume, thus suggesting that its properties largely reflect those of uniform nuclear matter in the neutron star
The validity of this conjecture has been long established by a comparison between the results of theoretical calculations and the data extracted from the ^{208}Pb(e,e´p)^{207}Tl cross sections measured at NIKHEF in the 1990s

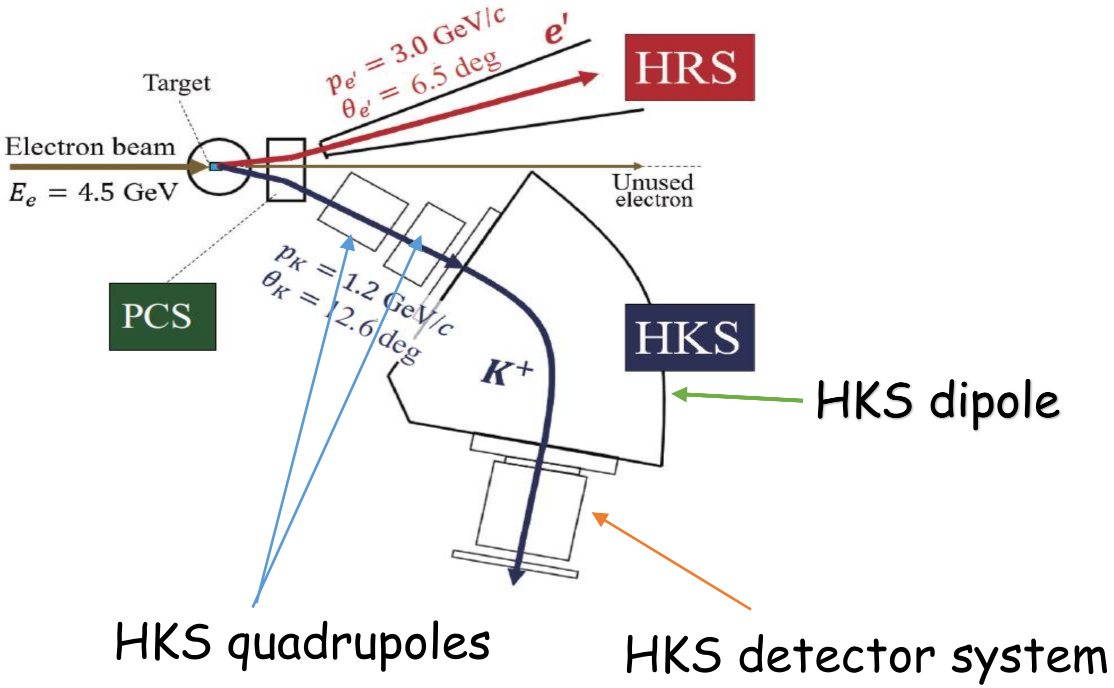


Short-range correlations appear to be the most important mechanism leading to the observed quenching of the spectroscopic factor, while surface and shell effects only play an important role in the vicinity of the Fermi surface ➔Deeply bound protons in the ^{208}Pb ground state largely unaffected by finize size and shell effect behave as if they were in nuclear matter

Experiment E12-20-013 beam time request

Target and objective hypernucleus	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/hour)	Number of events	Requested beam time (hours)	B. G. rate (/Mev/hour)	S/N	Comments
CH_2	2	500	200	19	1000	54	0.05	252	Calibration
$^{6,7}Li$	50	100	10	5.4	150	28	1.3	4.9	Calibration
^{9}Be	100	100	10	36	300	9	4.7	8.8	Calibration
$^{10,11}B$	25	100	10	16	150	19	0.29	33	Calibration
^{12}C	100	100	100	54	2000	37	4.4	17	Calibration
Subtotal for calibration						147			
^{208}Pb	25	100	80 (g.s.)	0.3	145	480	0.1	21	Production

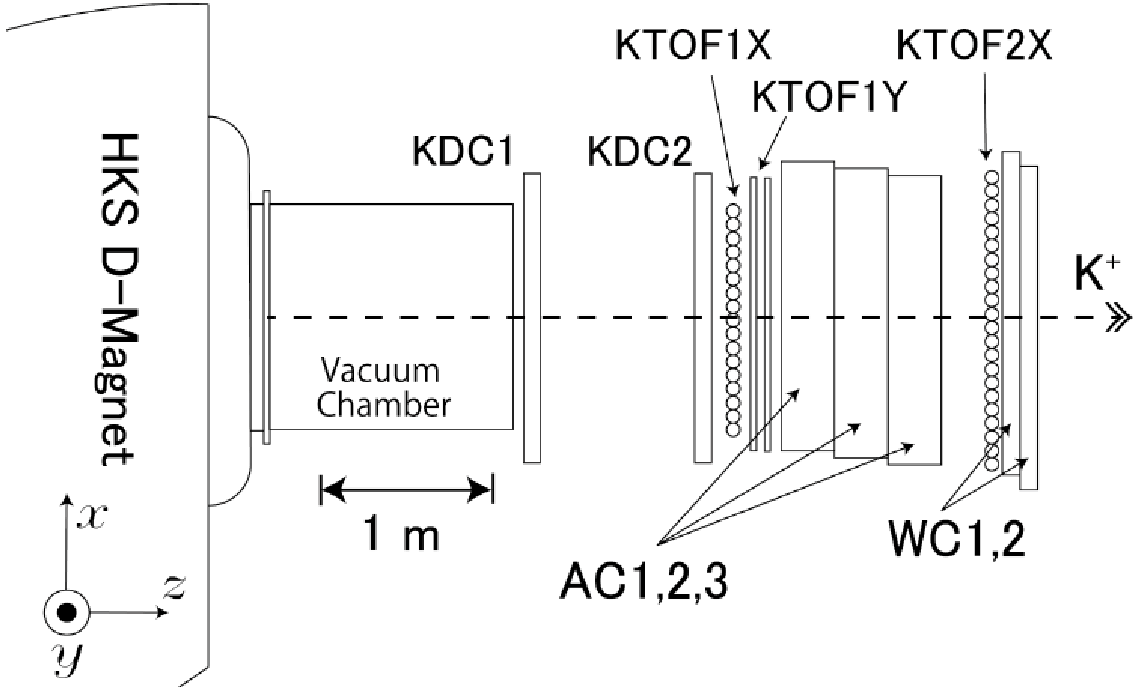
Experimental setup for all the hypernuclear spectroscopy experiments at Jlab



Beam	$\Delta p/p$	$< 1 \times 10^{-4}$ FWHM
	E_e	4.5 GeV
PCS + HRS (e')	D(PCS) + QQDQ	
	$\Delta p/p$	2.6×10^{-4} FWHM
	$p_{e'}$	3.0 GeV/$c \pm 4.5\%$
	$\theta_{ee'}$	6.5 ± 1.5 deg
	Solid angle $\Omega_{e'}$	2.4 msr
PCS + HKS (K^+)	D(PCS) + QQD	
	$\Delta p/p$	4.2×10^{-4} FWHM
	p_K	1.2 GeV/$c \pm 10\%$
	θ_{eK}	12.6 ± 4.5 deg
	Solid angle Ω_K	7 msr
	Optical length	12 m
	K^+ survival ratio	26%

Energy Resolution less than 1 MeV with solid targets

HKS Detector System:



Fujii et al., Nuclear Instruments Methods A, 795, 351 – 363 (2015)

Possible insertions:

- a scintillation fiber detector for angle calibration (active sieve slits, from Tohoku Group)

- a RICH detector (from Rome Group)

PCS magnets

Already fabricated and shipped to Jlab!

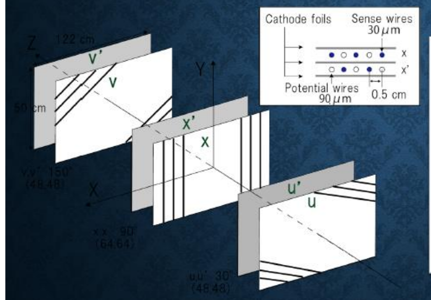
They are arriving at Jlab.

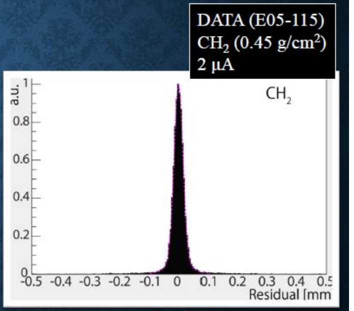
A really important
improvement for the experiment
at Hall A.

An example of the so many human and
financial resources spent for the project!

HKS Detector System components

PLANER DRIFT CHAMBER; KDC1,2
→ HAMPTON GROUP





Typical Tracking Residual

σ = 150 μm

KDC1, 2
360 × 2 = 720 channels

Three sets of KDC are stored in SBS, JLab

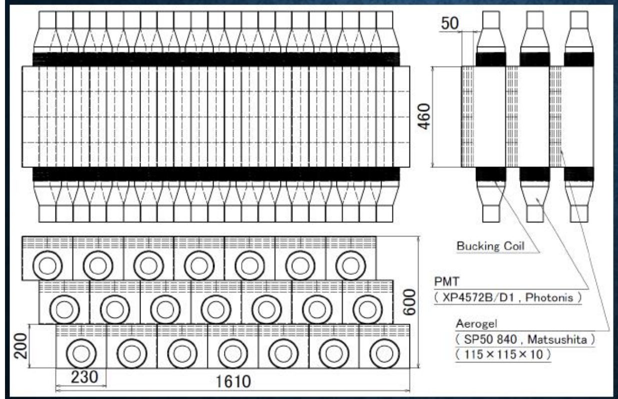
TIME-OF-FLIGHT DETECTOR; KTOF
→ TOHOKU GROUP (NUE, TG)

ID	Effective Area (mm^2) [1 seg. vol. (mm^3)]	# of channels	σ_t (ps)
1X	1275 × 300 (75 × 300 × 20^t)	17 × 2	60
1Y	1250 × 275 (1250 × 35 × 20^t)	9 × 2	70
2X	1710 × 350 (95 × 350 × 20^t)	18 × 2	60
Total number of channels		88	

PMT check was done for TOF in 2017

Scintillator: Saint Gobain BC-408
PMT: Hamamatsu H1949

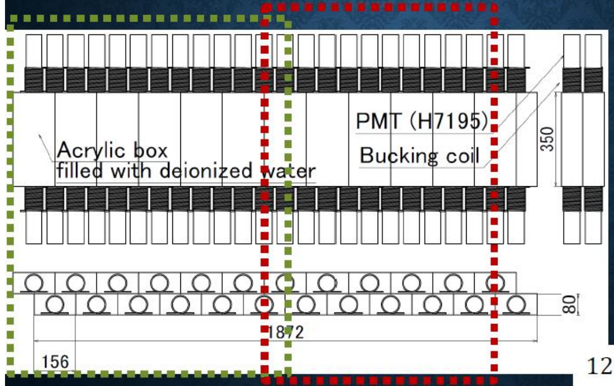
AEROGEL ČERENKOV DETECTOR; AC
→ FIU GROUP (J. REINHOLD)



$7^{seg} \times 2 \times 3^{layers}$
= 42 channels

Need to check:
- ✓ Radiator
- ✓ PMTs

WATER ČERENKOV DETECTOR; WC
→ TOHOKU GROUP



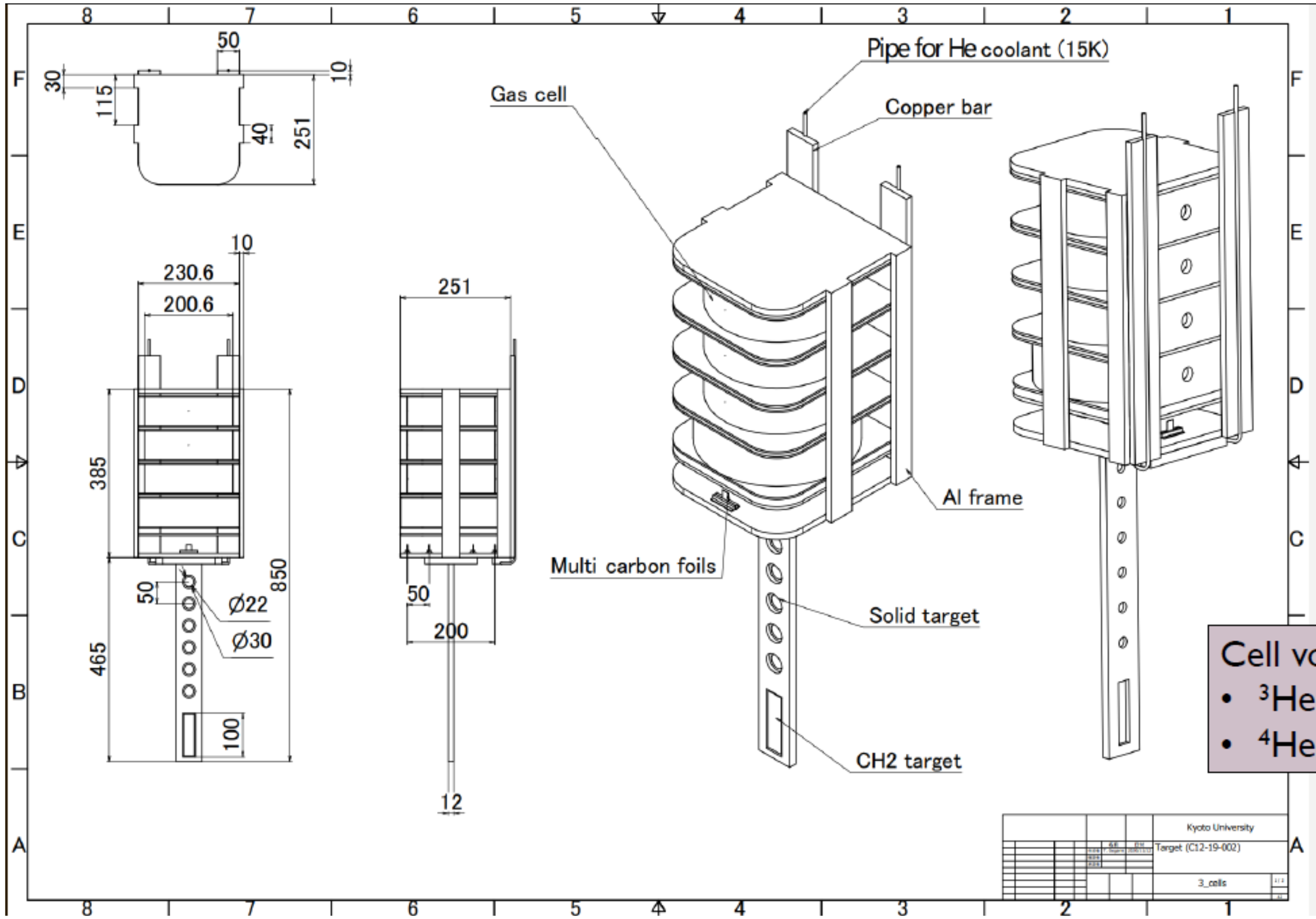
HWC   LWC

Need to check:
- ✓ Container
- ✓ PMTs

$12^{seg} \times 2 \times 2^{layers}$
= 48 channels

(Gogami's courtesy)

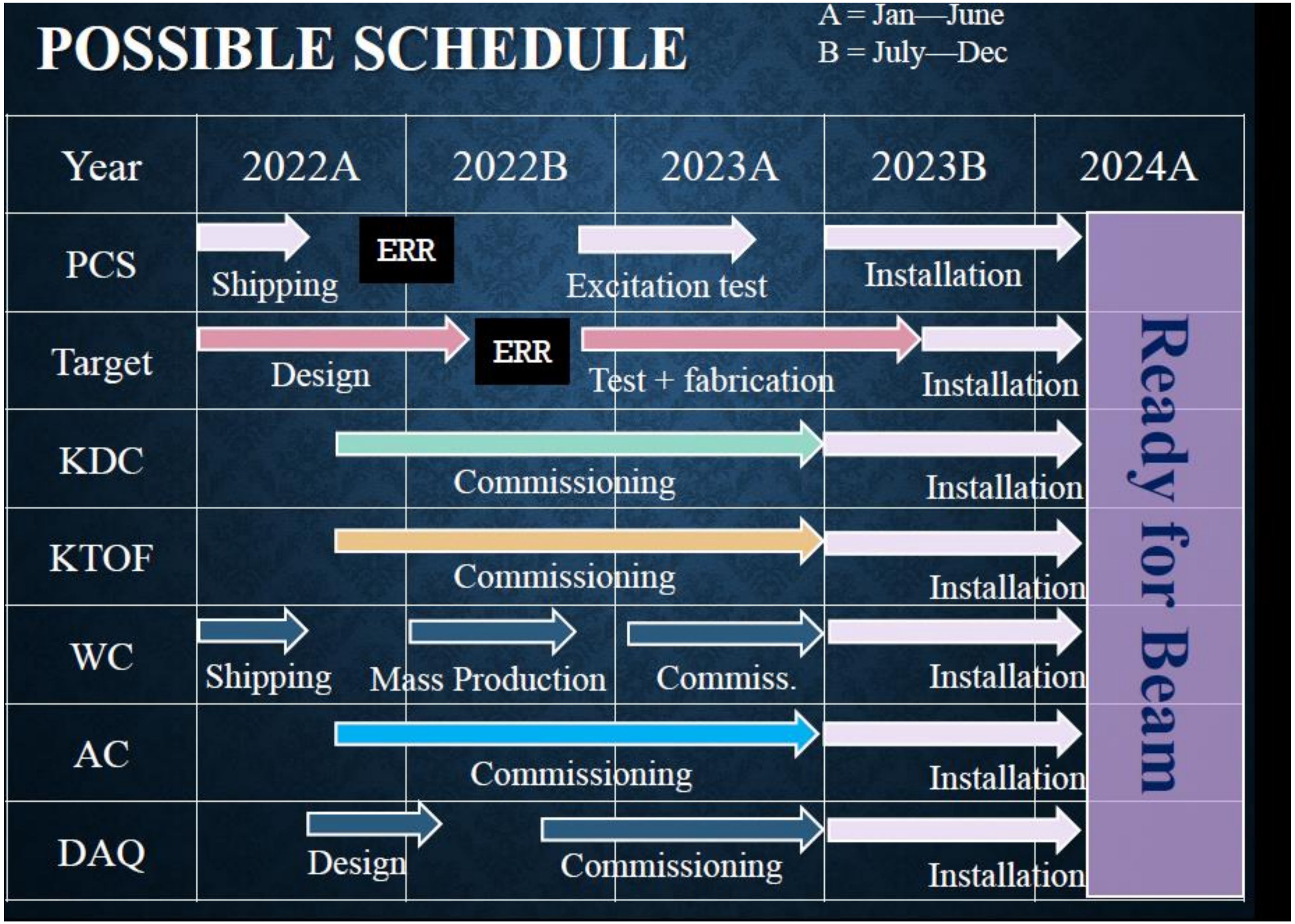
Target design status



Cell volume → 1.57 l

- ^{3}He 3.3 g
- ^{4}He 6.8 g

Computer simulations show no Lead target melting with beam intensity equal to 25 µA and raster size equal to 1.5 x 1.5 mm^2


POSSIBLE SCHEDULE
A = Jan—June
B = July—Dec
Year
2022A
2022B
2023A
2023B
2024A
PCS
Shipping
ERR
Excitation test
Installation
Target
Design
ERR
Test + fabrication
Installation
KDC
Commissioning
Installation
KTOF
Commissioning
Installation
WC
Shipping
Mass Production
Commiss.
Installation
AC
Commissioning
Installation
DAQ
Design
Commissioning
Installation
Ready for Beam

Conclusions

- Thanks to consolidated techniques only possible at Jlab , the hypernuclear spectroscopy experimental program, solving the hyperon puzzle, will allow the scientific community to have a much more clear picture of the neutron star structure. The long-standing problem of a clear identification and understanding of Charge Symmetry Breaking in the hyperon – nucleon interaction will be addressed too.
- The Hypernuclear spectroscopy experimental program will be ready to start in 2024