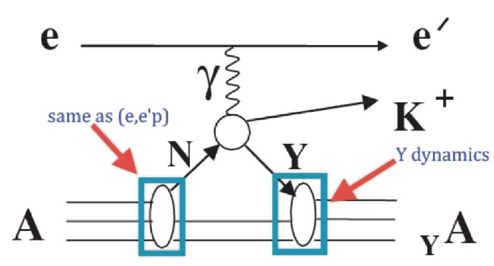
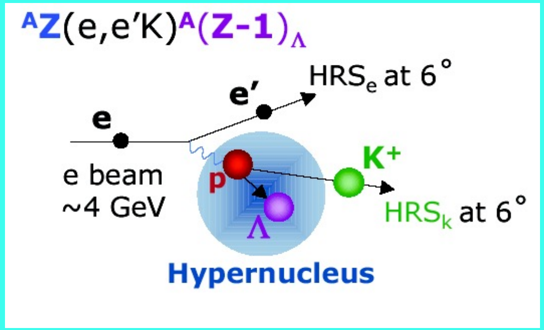
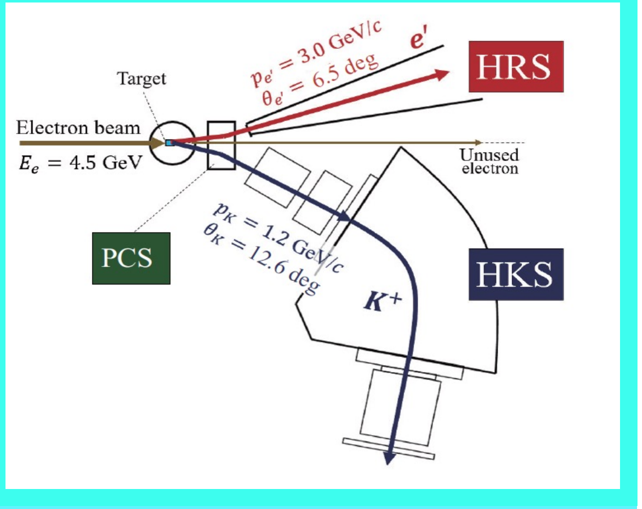
Studying Λ interactions in nuclear matter with the $^{208}Pb(e,e'K^{+})^{208}_{\Lambda}Tl$

F. Garibaldi – Jlab- hypernuclear-collaboration-meeting-07-12-2021

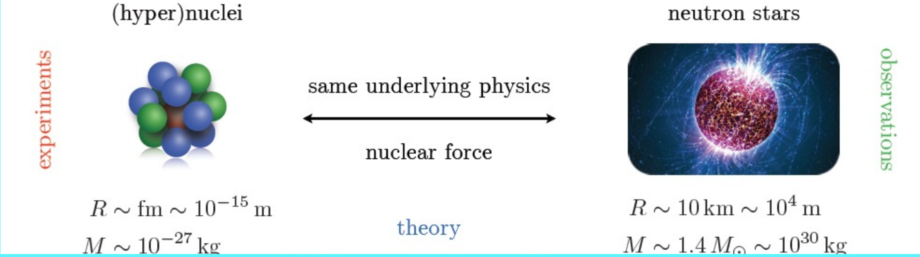
- The physics
- Why $^{208}\mathrm{Pb}(\mathrm{e},\mathrm{e}'\mathrm{K}^{+})^{208}_{\Lambda}\mathrm{Tl}$?
  - Hyperon puzzle
  - The experiment
- Summary and conclusions







The hyperon puzzle

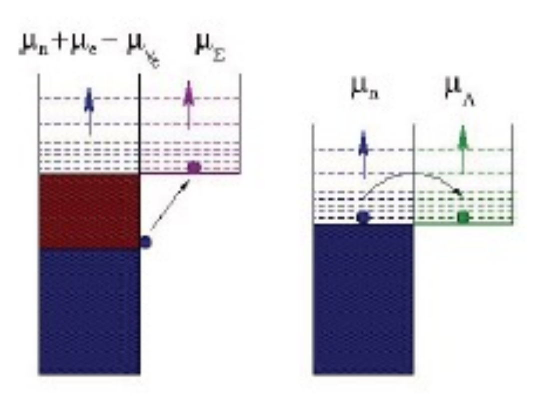


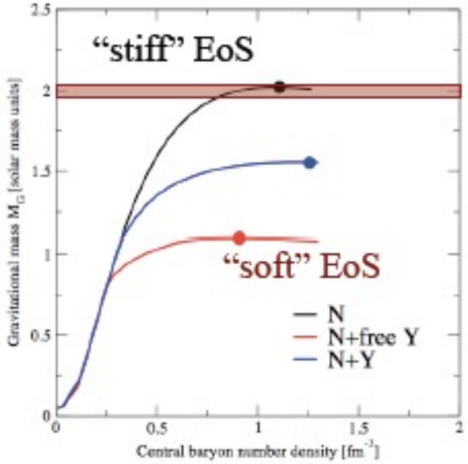
Neutron stars are remnants of the gravitational collapse of massive stars having masses of (1-2 Mo ~ 2 x 10^{33} Kg)

They 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 $\rho \sim (2\text{-}3)\rho_o$ when μ_N is large enough to make conversion of N to Y energetically favorable

but



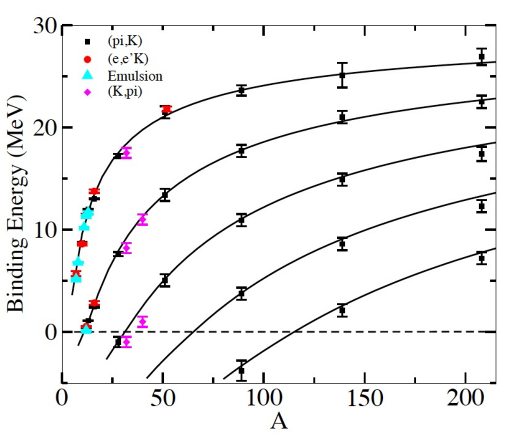


The relief of the Fermi pressure due to its appearance → EoS stiffer → reduction of the mass to values incompatible with observation (~ 2 Mo that requires much stiffer EoS)

Strong softening of the EoS of dense matter due to the appearance of hyperons which leads to maximum masses of compact stars that are not compatible with the observations.

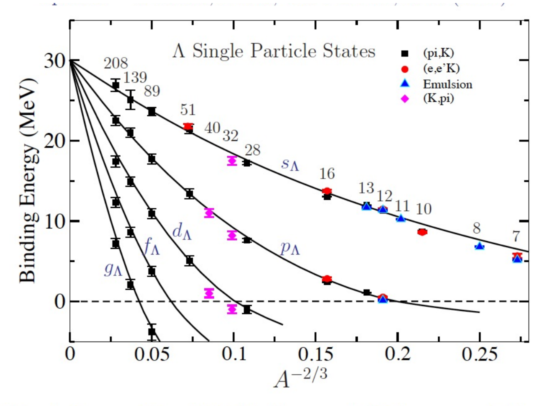
The present understanding of the nuclear interactions involving hyperons is far from being complete. The reason is in a combination of an incomplete knowledge of the forces governing the system (in the hypernuclear case both two- and three-body forces), and in the concurrent use of approximated theoretical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

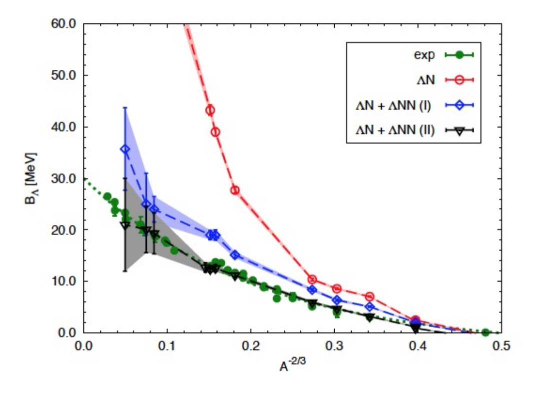


Millener

the spacings of the single-particle energies as a function of As put more constraints on the theoretical fits. Skyrme includes 3-body

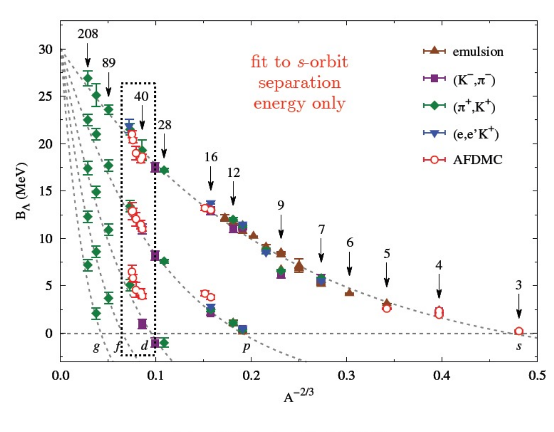


Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm



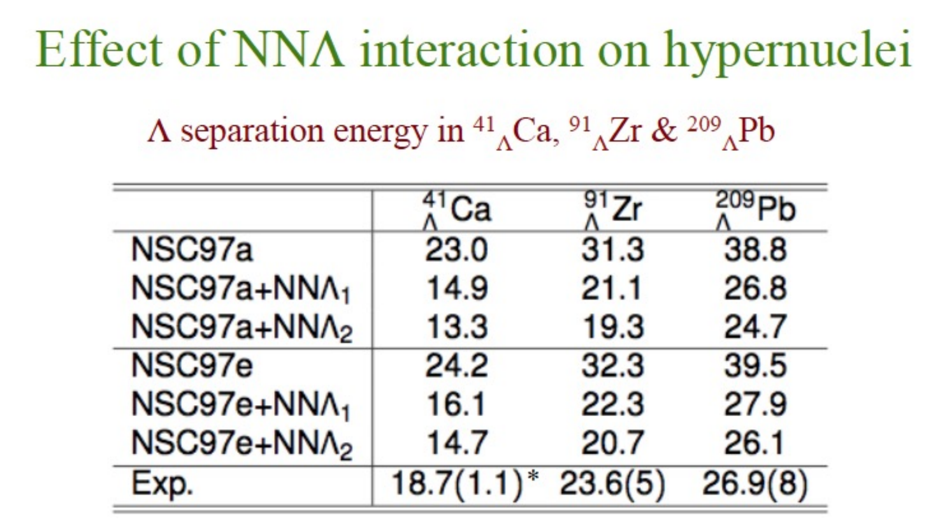
Lonardoni

the effect of including the ΛNN termin the Hamiltonian is very strong. It provides the repulsion necessary to realistically reproducethe limiting value of B_Λ



D. L. and F. Pederiva, arXiv:1711.07521

Vidana



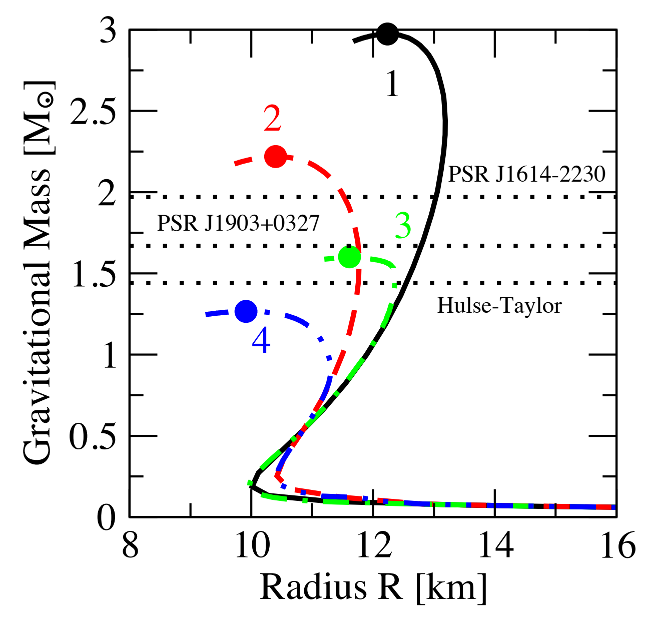
Effect of NNΛ interaction on hypernuclei

Λ separation energy in $^{41}_\Lambda$Ca, $^{91}_\Lambda$Zr & $^{209}_\Lambda$Pb

	$^{41}_\Lambda$Ca	$^{91}_\Lambda$Zr	$^{209}_\Lambda$Pb
NSC97a	23.0	31.3	38.8
NSC97a+NNΛ$_1$	14.9	21.1	26.8
NSC97a+NNΛ$_2$	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NNΛ$_1$	16.1	22.3	27.9
NSC97e+NNΛ$_2$	14.7	20.7	26.1
Exp.	18.7(1.1)*	23.6(5)	26.9(8)

Only hypernuclei described as a closed shell nuclear core + a Λ sitting in a s.p. state are considered. Comparison with the closest hypernucleus for which exp. data is available

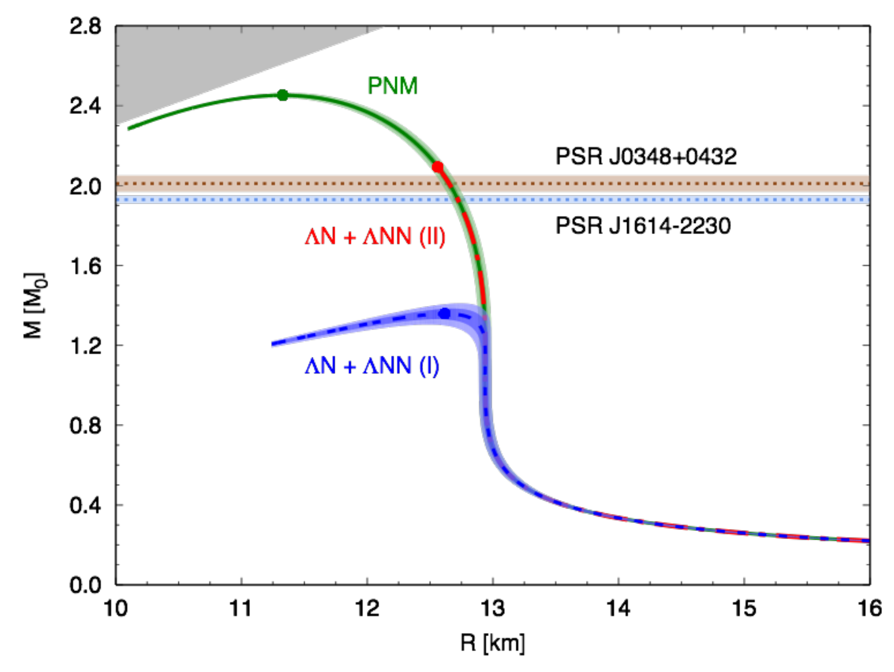
Inclusion of NNΛ improves the agreement with data for $^{91}\Lambda$Zr & $^{209}\Lambda$Pb.



It clearly appears that the inclusion of YNN forces (curve 3) leads to a large increase of the maximum mass, although the resulting value is still below the two solar mass line.

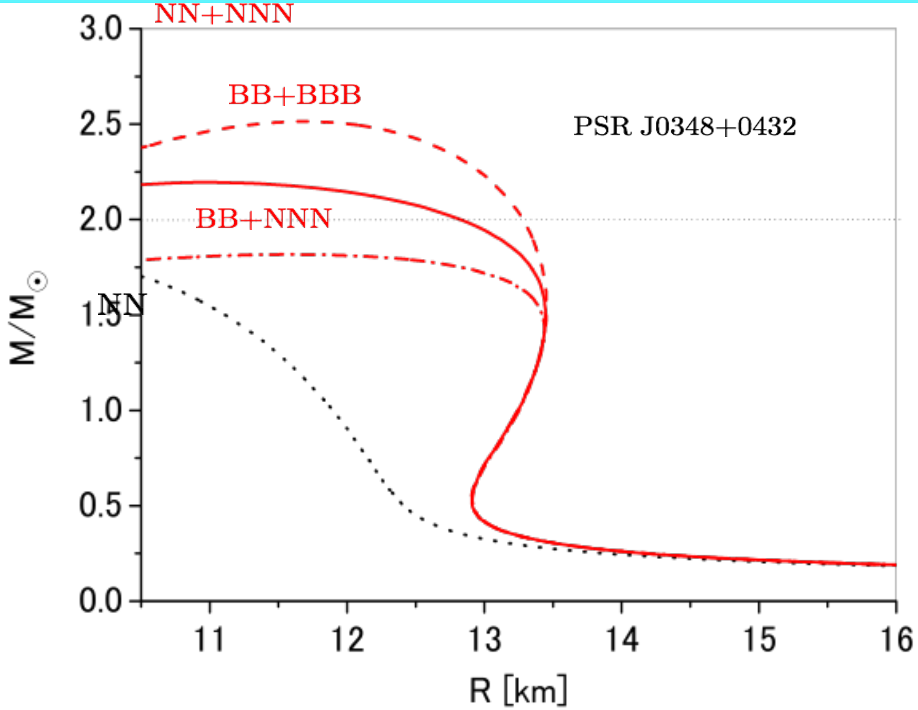
1. Nucleons without 3 body forces
2. Nucleons with 3 body forces
3. Λ and N with 3 body forces(ΛNN)
4. Λ and N without 3 body force

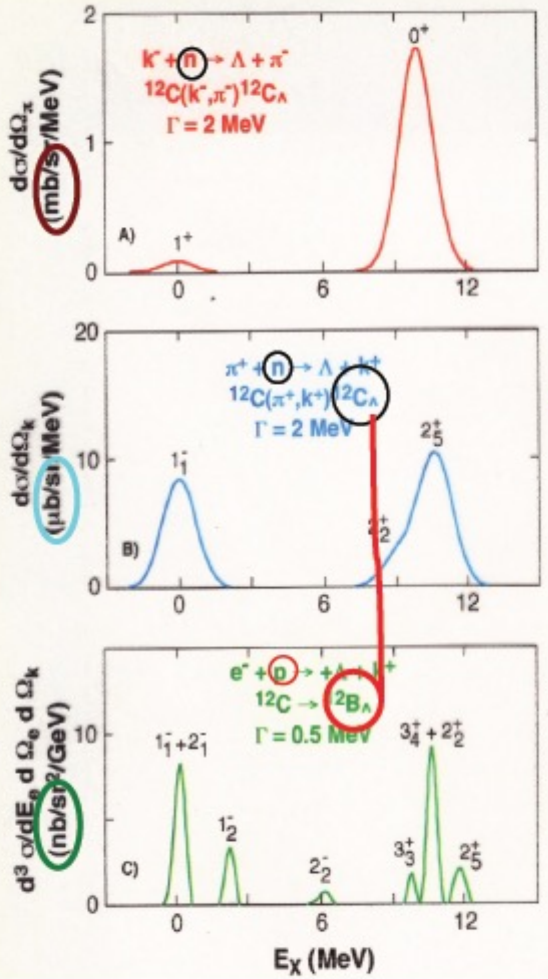
D.Lonardoni *et al.*, Phys. Rev. Lett. 114, 092301 (2015) (AFDMC)



Y. Yamamoto *et al.*, Phys. Rev. C 90, 045805 (2014)

G-Matrix: ESC08 + MPa





q ≈ 100 MeV/c --> Δℓ = 0
---> substitutional states
Δs = 0 --> no spin flip
---> natural parity
(J = 0⁺)
absorption

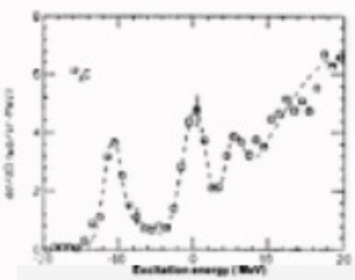
q ≈ 300 MeV/c --> Δℓ = 1,2
spin flip (weak for ΘK < 10°)
Δs = 0 ---> natural parity
(J = 1⁻ , J = 2⁺)
absorption

q ≈ 300 MeV/c --> Δℓ= 1,2
--> non substitutional statesd
Δs = 0,1 (spin flip)
---> unnatural parity
(J = 2⁻ , J = 3⁺)
no absorption

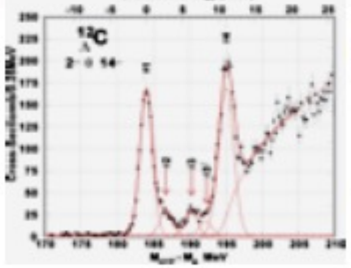
new aspects of hyernuclear structure

production of mirror hypernuclei

energy resolution ~ 500 KeV

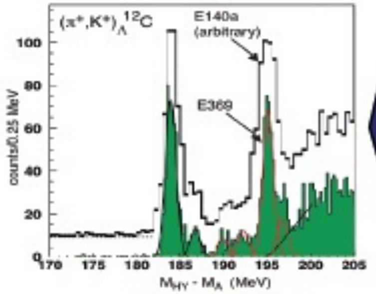


BNL 3 MeV



KEK336 2 MeV

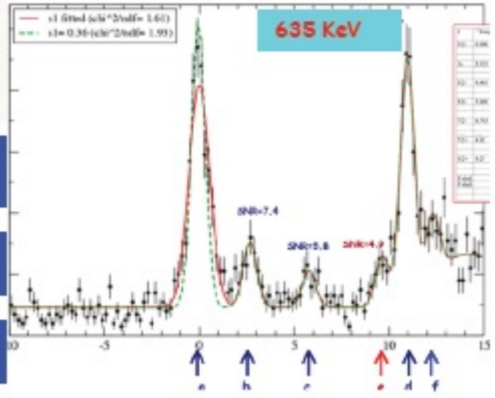
Improving energy resolution



~ 1.5 MeV

and

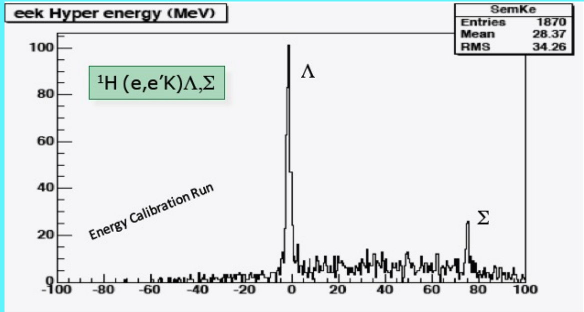
using electromagnetic probe



High resolution, high yield, and systematic study is essential

(e,e'K+) hypernuclear spectroscopy provides information on the cross section as well as on the binding energy. These information are complementary to the information obtained by decay product studies such as gamma and decay-pion spectroscopies

Hypernuclear spectroscopy is the only method that can measure the absolute binding energy for ground and excited states with an high accuracy (~ 70 KeV)



Energy calibration IS important !

We are proposing to extend the experimental study of kaon electroproduction to the $^{208}Pb(e,e'K^+)^{208}{}_{\Lambda}Tl$ reaction.

It is a complementary (to the $^{40}{}_{\Lambda}K$ and $^{48}{}_{\Lambda}K$ experiment that was approved by PAC 45) way to address the same problem ("hyperon puzzle").
In fact E12-15-008 will allow us to extract isospin dependence of the 3-body ΛNN force

Three-body ΛNN forces are known to be strongly A-dependent, making the ^{208}Pb target uniquely suited to study Λ interaction in a uniform nuclear medium with large neutron excess

The contribution of three-nucleon forces, which is known to be large and repulsive in nuclear matter at equilibrium density, is believed to be much smaller and attractive in ^{40}Ca

Theoretical framework

Exploiting K^+ electroproduction data to constrain the models of hyperon dynamics requires a quantitative understanding of the nucleon sector

A framework has been developed (O.Benhar*, P. Bydzowsky**, I.Vidana***) to carry out calculations of the nuclear (e,e'K^+) cross section within the formalism of nuclear many-body theory, which has been extensively and successfully employed to study the proton knockout, (e,e'p) reaction. In fact, the clear connection between (e,e'p) and (e,e'K^+) processes that naturally emerges from the proposed analysis, shows that the missing energy spectra measured in (e,e'p) experiments provide the baseline for a model-independent determination of the hyperon binding energies

** New Elementary calculations have been performed

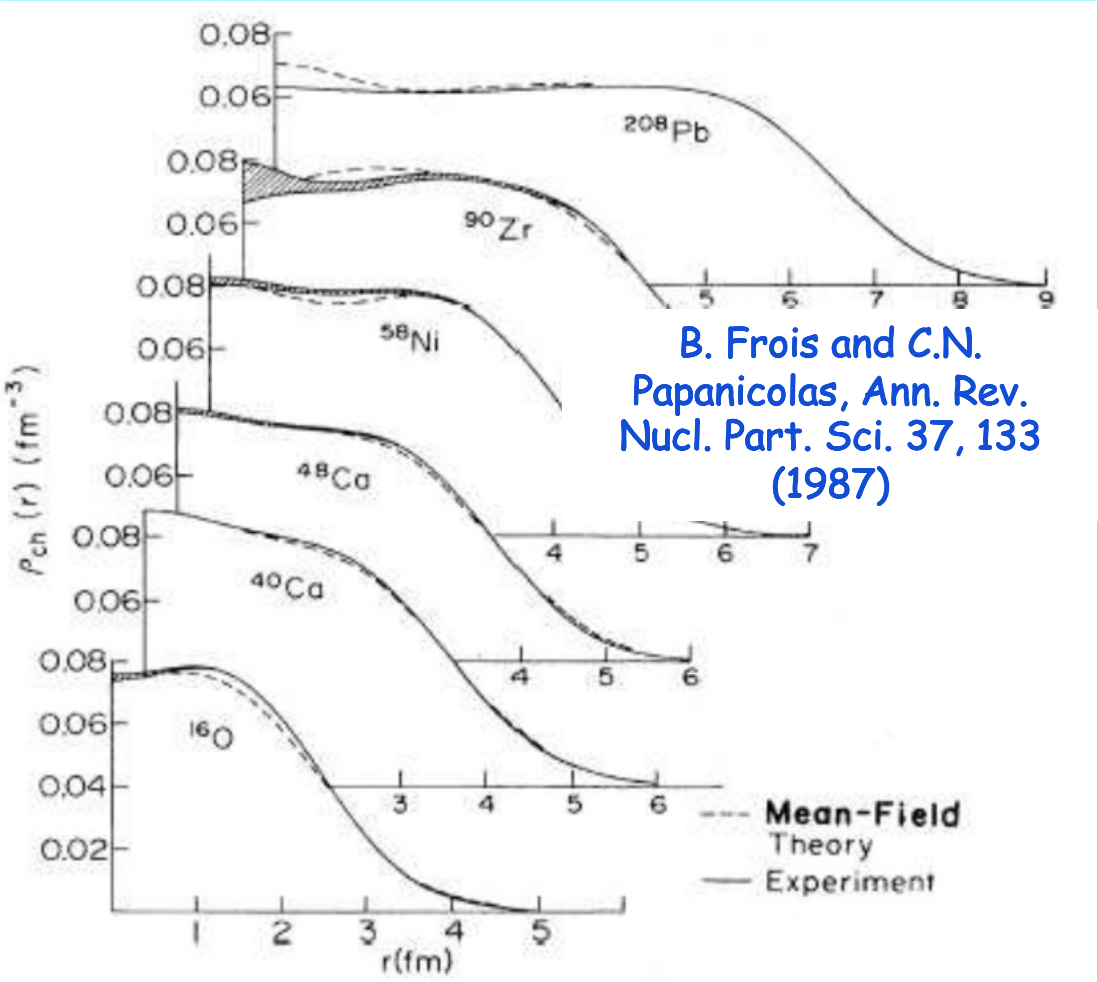
*** Microscopic calculations of the Λ spectral function in a variety of nuclei, ranging from ^{5}He to ^{208}Pb, have been recently carried out (Lonardoni)

**** Cross sections for the new kinematics have been calculated by T. Motoba

***** and J. Millener

******* Calculations by Millener, Vidana, Lonardoni et al for A dependence

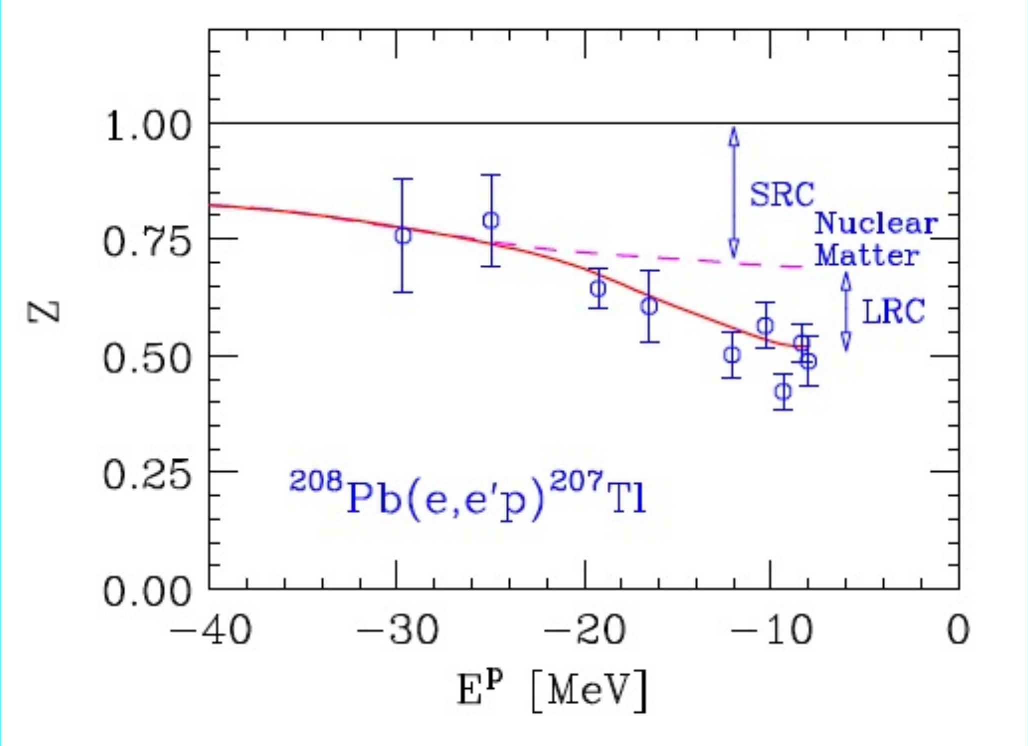
******** G-matrix calulations by Y. Yamamoto *et al.*



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

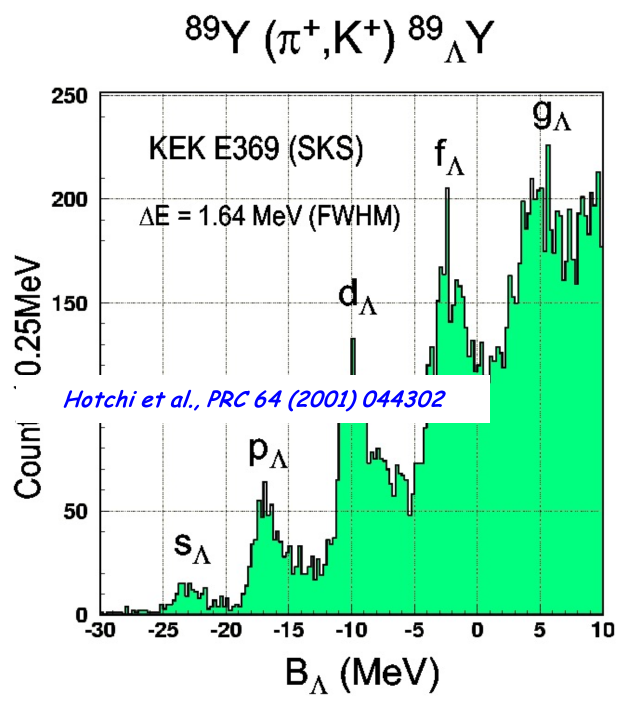
→ behave as if they were in nuclear matter

The hyperon binding energies are given by the difference between the missing energies measured in (e,e´K$^+$) and the proton binding energies obtained from the (e,e´p) cross sections. Hence, (e,e´p) data will provide the baseline needed to extract information, in a model independent way, on hyperon binding energies

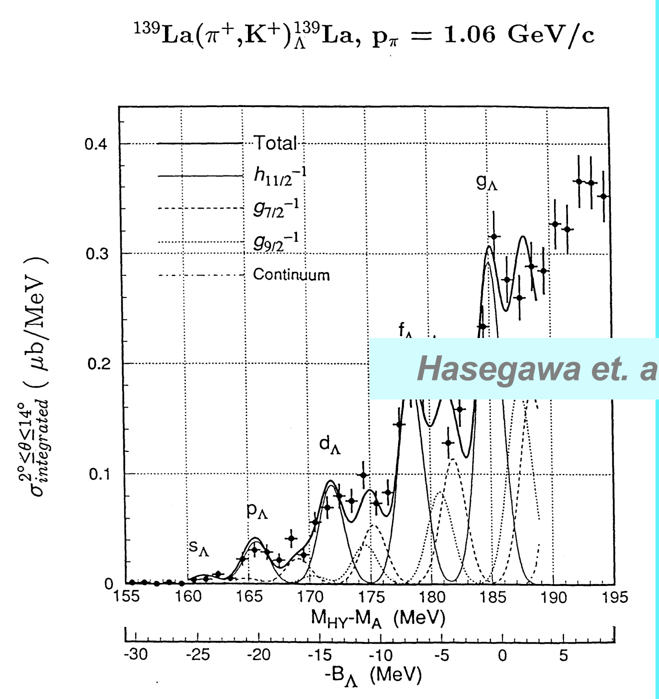
→ The use of a ^{208}Pb target appears to be uniquely suited to study Λ interactions in a uniform nuclear medium with large neutron excess
Jlab is the only lab where to make this experiment

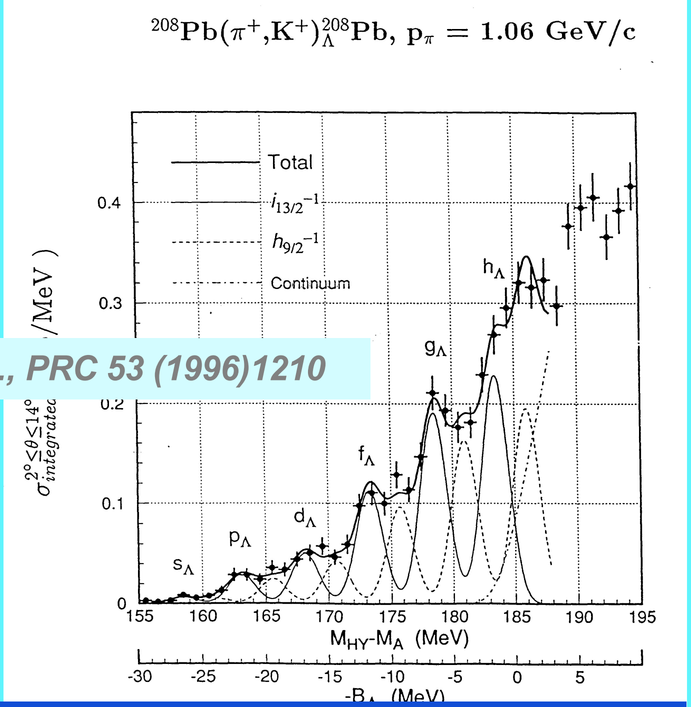
Hyperon in heavy nuclei – ^{208}(e,e'K+)$^{208}{}_{\Lambda}$Ti

✓ Mass spectroscopy to its extreme



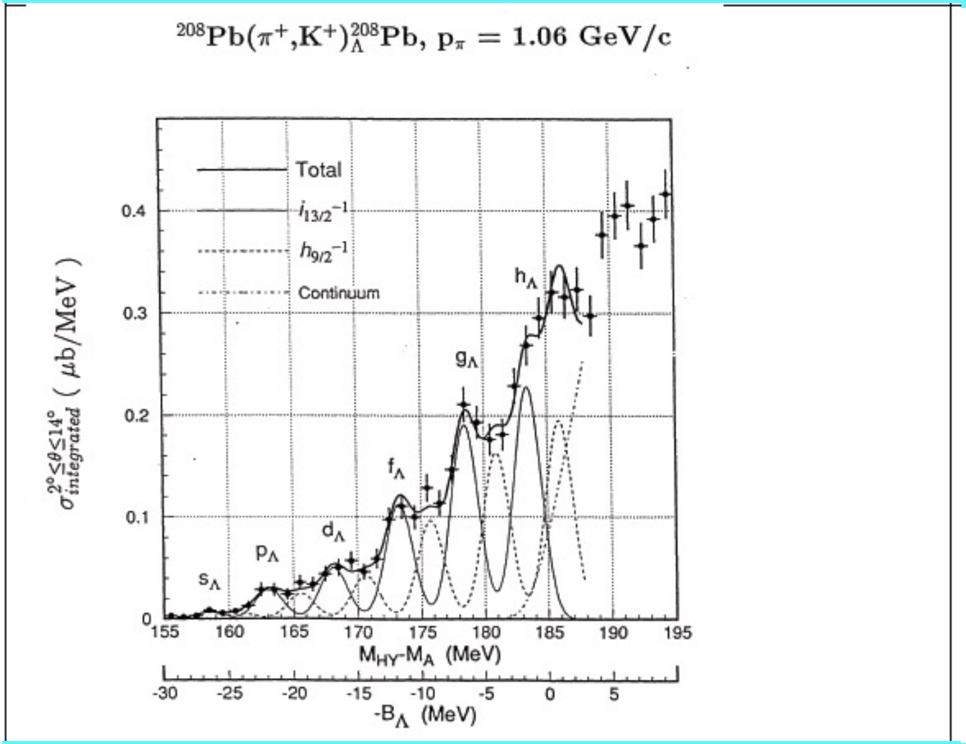
Hotchi et al., PRC 64 (2001) 044302

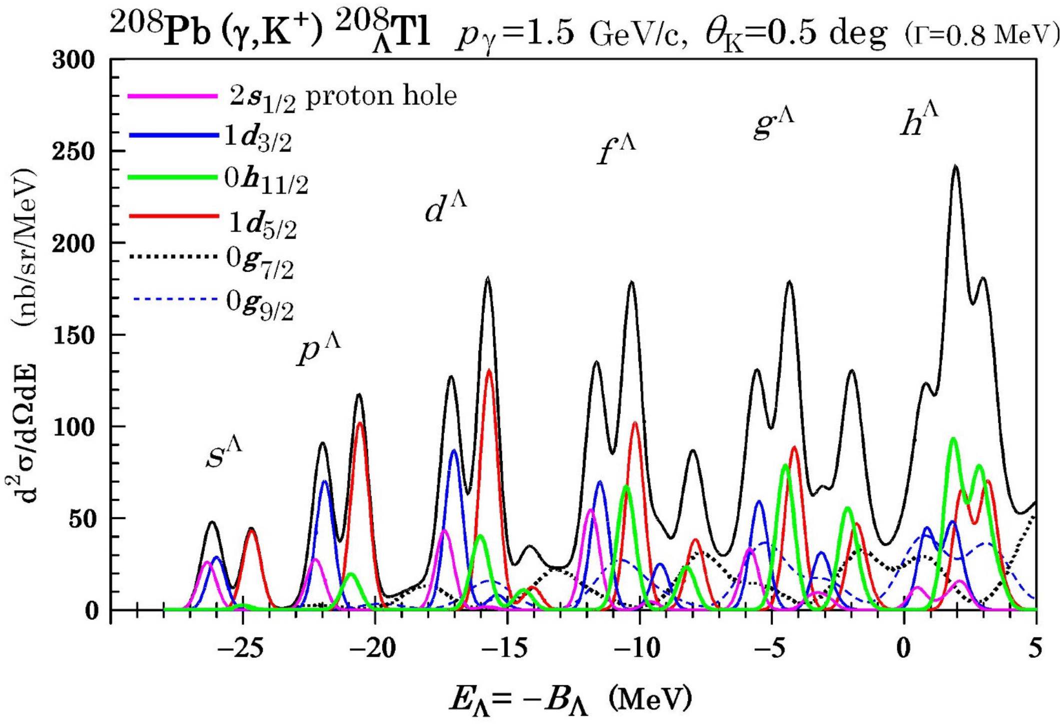




Hasegawa et. al., PRC 53 (1996)1210

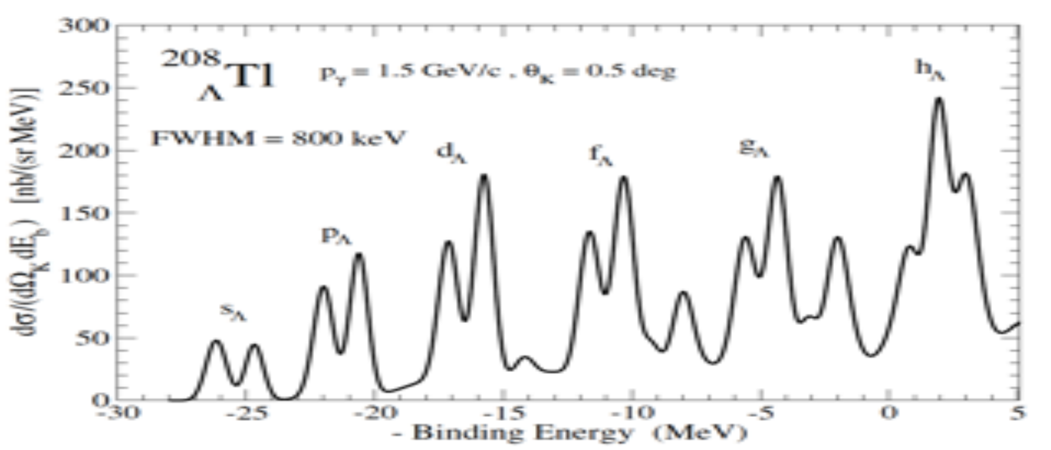
"Therefore is of vital importance to perform precision spectroscopy of heavy Λ hypenuclei with mass resolution comparable to or better than the energy differences of core excited states, in order to further investigate the structure of the Λ hyperon deeply bound states in heavier nuclei. (e,e'K) spectroscopy is a promising approach to this problem

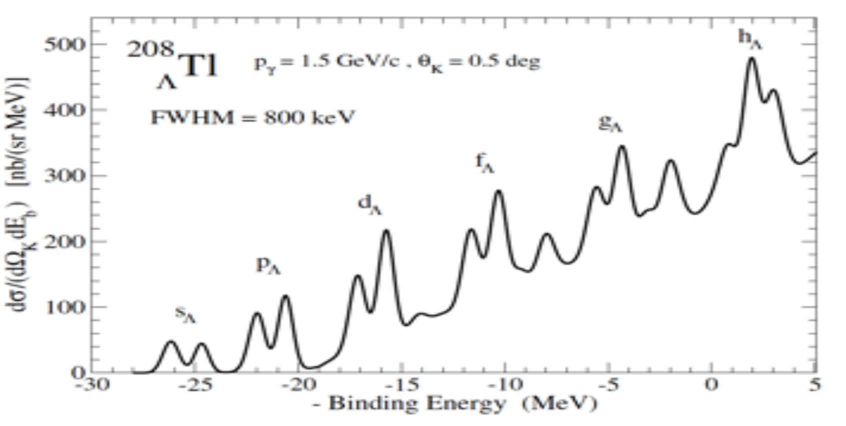


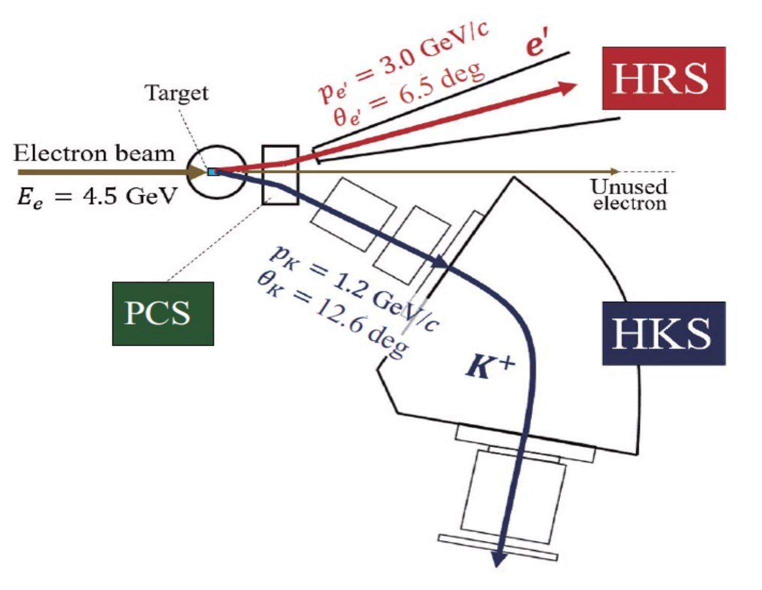


Millener-Motoba calculations

- Particle hole calculation, weak-coupling of the Λ hyperon to the hole states of the core (i.e. no residual Λ-N interaction). One can extract Λ single-particle energies from each of the observed peaks. Each peak does correspond to several levels based on two closely-spaced proton-hole states





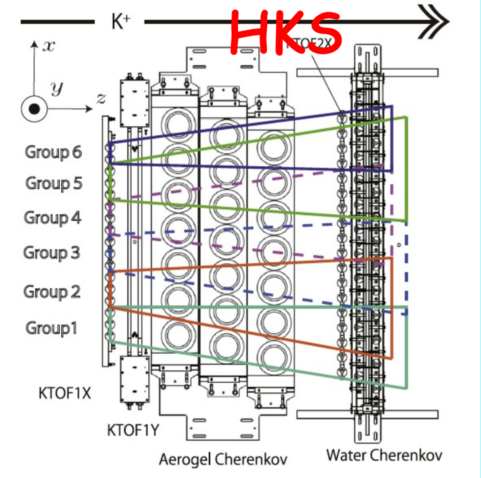


Beam	$\Delta p/p$	$< 1 \times 10^{-4}$ FWHM
	E_e	4.5 GeV
PCS + HRS (e')	D(PCS) + QQDQ	
	$\Delta p/p$	2.6×10^{-4} FWHM
	$p_{e'}$	3.0 GeV/$c \pm 4.5\%$
	$\theta_{ee'}$	6.5 ± 1.5 deg
	Solid angle $\Omega_{e'}$	2.4 msr
PCS + HKS (K^+)	D(PCS) + QQD	
	$\Delta p/p$	4.2×10^{-4} FWHM
	p_K	1.2 GeV/$c \pm 10\%$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

	Momentum/Energy Resolution (%)	Angle resolution (mrad)	Contribution to the missing mass resolution (keV)
PCS + HKS	4.2×10^{-4}	0.6	500
PCS + HRS	2×10^{-4}	1.5	600
Beam	5×10^{-5}	-	250
Missing Mass Resolution			850

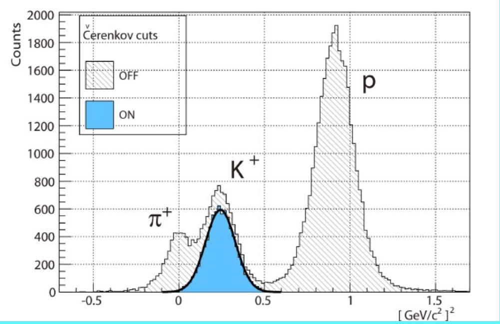
Target and objective hypernucleus	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected Yield (/hour)	Num. of events	Req. beamtime (hours)	B.G. Rate (/MeV/h)	S/N (±4 σ)	Comments
CH_2	2	500	200	19	1000	54	0.05	252	Calibration
^{6,7}Li	50	100	10	5.4	150	28	1.3	4.9	Calibration
^{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**

PID



3 TOF, 2 water Cherenkov, three aerogel Cerenkov

pK=1.2 GeV/c)

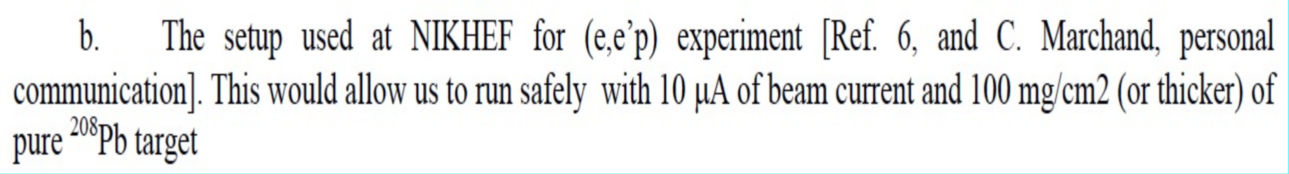


(π/k rejection ratio: 4.7 x 10^{-4})

(T. Gogami et al, NIM (2018) 69-83)

We will add up the RICH detector if needed

Target



b. The setup used at NIKHEF for (e,e'p) experiment [Ref. 6, and C. Marchand, personal communication]. This would allow us to run safely with 10 µA of beam current and 100 mg/cm2 (or thicker) of pure ^{208}Pb target

Water - 15° - 60—70 l/h

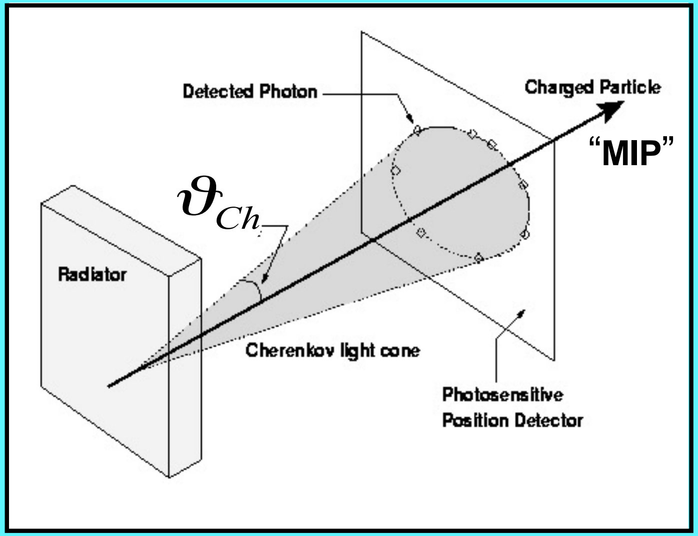
Heath transfer calculation show that the conduction cooling becomes competitve as compared to increase radiation cooling by rotating the target for thick target

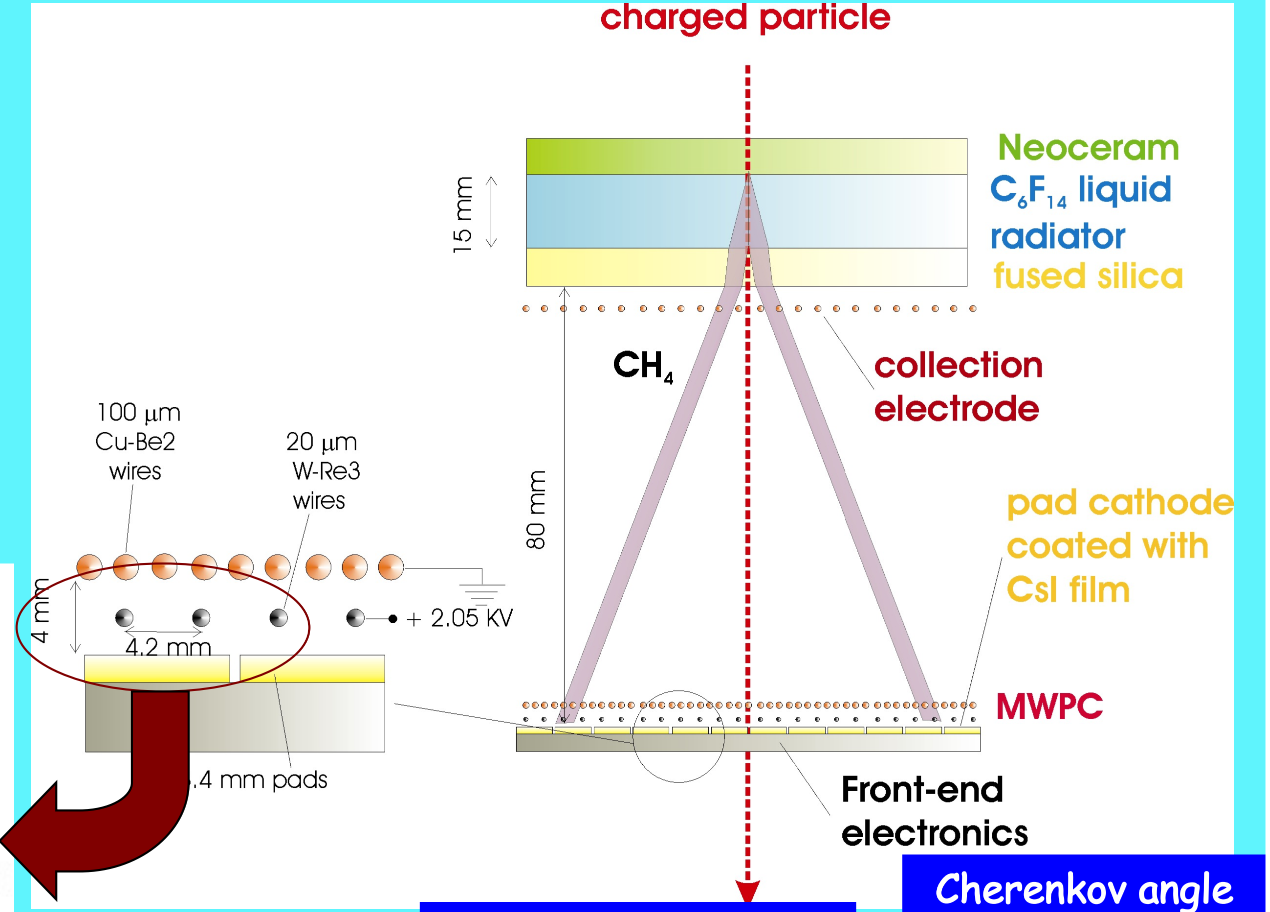
$$< i_{max} > = 2\pi k \, (T_{melting} - T_0)/\{[\ln(r_1/r_0) + \tfrac{1}{2}] \, \rho \, dE/dx\}$$

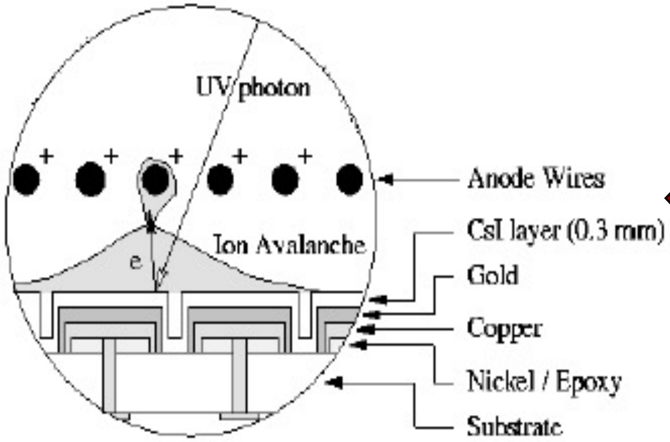
Using the right K for cryocooling brings to the conclusion that we will be able to

run safely at 25 µA

RICH detector -C_6F_{14}/CsI proximity focusing RICH







$$n_\sigma \sim \sqrt{\frac{m_A^2 - m_B^2}{2\tan\theta_c \, p \, \sigma_\theta^r}}$$

Separation Power

$$\vartheta_2 - \vartheta_1 = n_\sigma \sigma_{\vartheta_c}$$

Cherenkov angle resolution

$$\sigma_{\vartheta_c} = \frac{\sigma_\vartheta^{p.e.}}{\sqrt{N_{p.e}}}$$

N. of detected photoelectrons

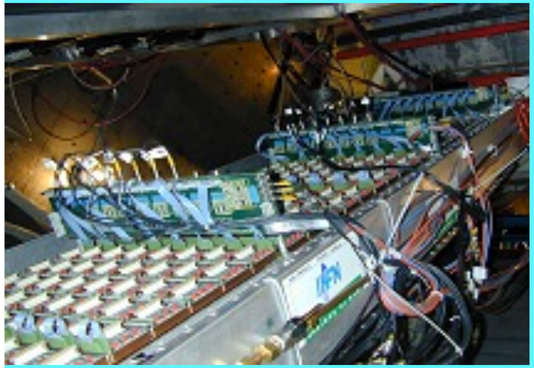
$$N_{p.e.} = 370 L \sin^2 \vartheta_c \prod_i \varepsilon_i \Delta E \approx 20 - 50$$

Performances

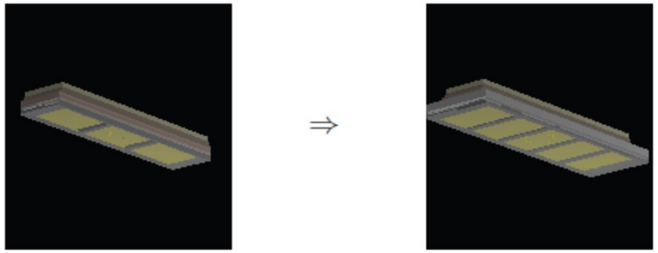
- $N_{p.e.}$ # of detected photons(p.e.) ← maximize
- and σ_θ (angular resolution) ← minimize

The RICH

RICH Detector



The RICH detector has been upgraded for the neutron Transversity experiment. Easy calculation show that the new layout would allow us to get an added factor of 10^6 as π/K rejection factor



Radiator	15 mm thick Liquid Freon (C_6F_{14}, n=1.28)
Proximity Gap	100→ 175 mm, filled with Methane at STP
Photon converter	300 nm CsI film coated on Pad Planes
Position Detector	3→ 5 × pad planes = 1940 × 403→ 2015 × 646 mm^2
	Multi Wire/Pad Proportional Chamber, HV= 1050 ÷ 1100 V
Pad Plane	403.2 × 640 mm^2 (single pad: 8.4 × 8 mm^2)
FE Electronics	11520→ 19200 analog chs. multiplexed S&H

Fig. A1. Old and new upgrated RICH layout

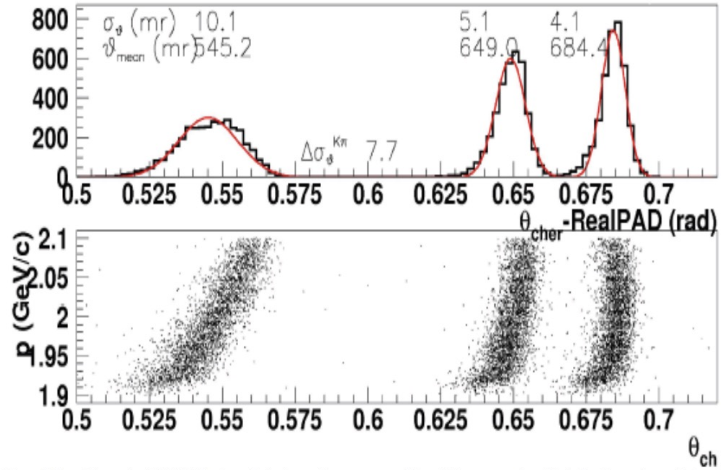


Fig. A3. Upgrated RICH simulated performance. Pion/Kaon angle distribution (equal hadrons populations) at 2 GeV/c momentum, in the HRS acceptance. The Mcarlo is tuned on Hall A hypernuclear experimental data.

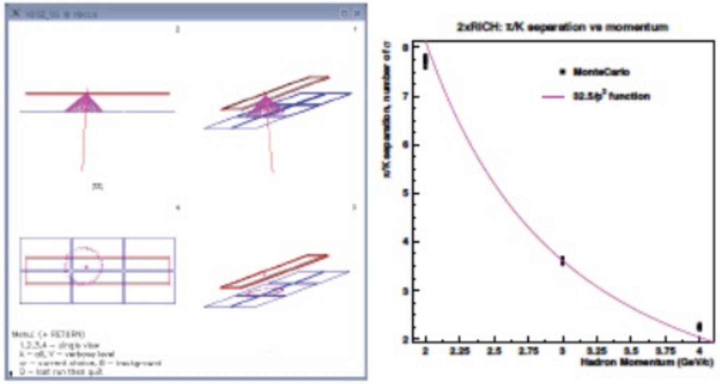


Fig. A2 Upgraded RICH simulation events (left panel) and expected performance (right panel): pion-kaon separation (number of sigmas) at different hadron momenta. The simulation is tuned to the E-94-107 hypernuclear experimental data.

Summary and conclusions

We propose to extend the experimental study of kaon electroproduction to the ^{208}Pb(e,e'K)$^{208}{}_{\Lambda}$Tl reaction to study the hyperon puzzle in a complementary way with respect to the approved proposal $^{40}{}_{\Lambda}$K and $^{48}{}_{\Lambda}$K on isospin dependence of ΛNN

ΛNN could provide additional repulsion making the EOS stiffer enough to help solving the hyperon puzzle. Moreover they rapidly increase with A, making the ^{208}Pb target uniquely suited to study Λ interaction in a uniform nuclear medium with large neutron excess

In fact, the contribution of three-nucleon forces, which is known to be large and repulsive in nuclear matter at equilibrium density, is believed to be much smaller and attractive in ^{40}Ca

The availability of accurate ^{208}Pb(e,e'p)^{207}Tl data may be exploited to achieve a largely model-independent analysis of the measured cross section, based on the well established formalism of nuclear many-body theory

In conclusion, even if the typical baryon density inside a neutron star is much higher than in a hypernucleus a precise knowledge of the ^{208}Pb level structure can, by constraining the hyperon-nucleon potential, contribute to more reliable predictions regarding the internal structure of neutrons stars, and in particular their maximum mass