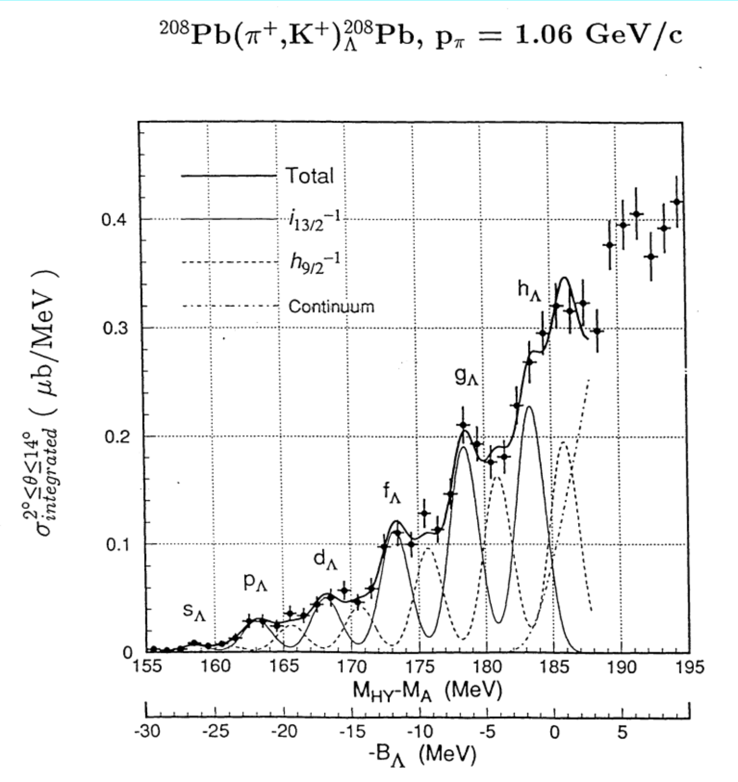
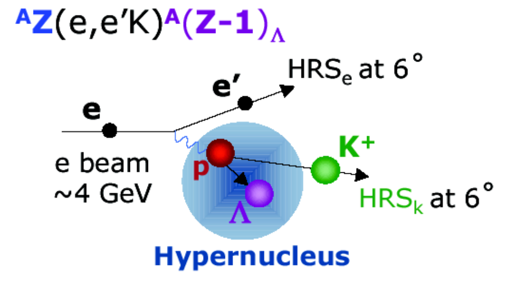
Studying Λ interactions in nuclear matter with the $^{208}Pb(e,e'K^{+})^{208}_{\Lambda}Tl$

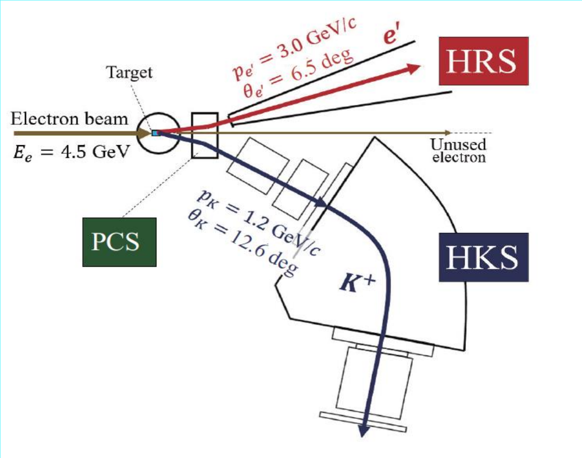
F. Garibaldi – HYP 2022 – Prague – June 30 - 2022

Is there strangeness in the neutron stars?

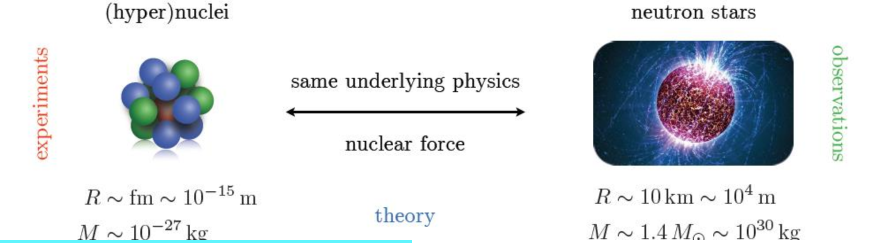
Existing data on ^{208}Pb







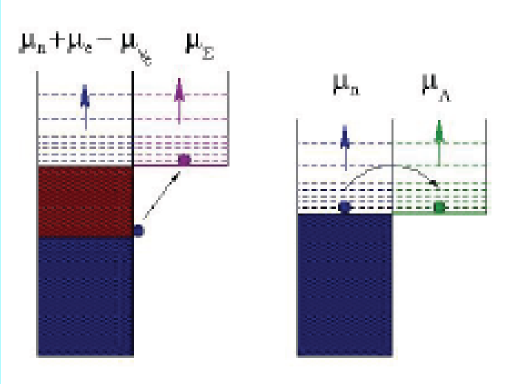
The hyperon dynamics

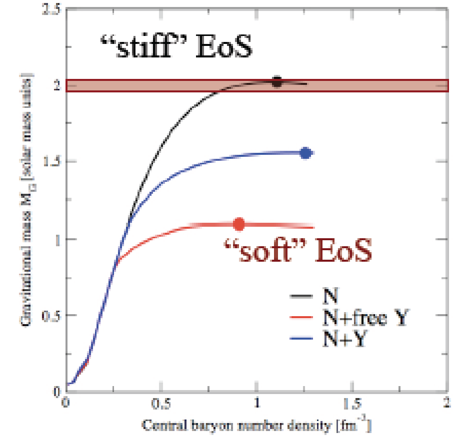


Neutron stars are remnants of the gravitational collapse of massive stars having masses of (1-2 Mo ~ 2 x 10^{33} Kg)

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 ρ ~ (2-3)ρ_o when μ_N is large enough to make conversion of N to Y energetically favorable



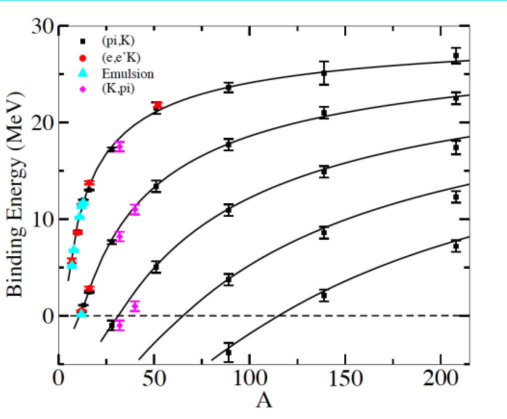


but

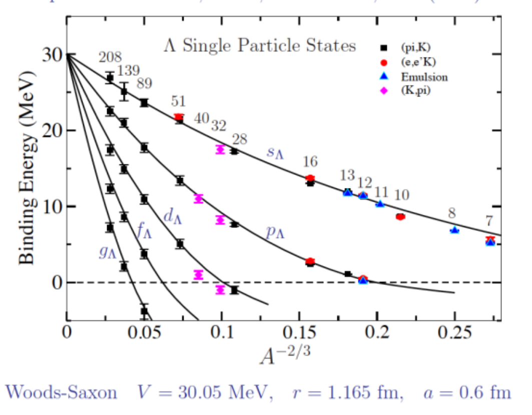
The relief of the Fermi pressure due to its appearance → EoS stiffer → reduction of the mass to values incompatible with observation (~ 2 Mo that requires much stiffer EoS)

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.

Millener

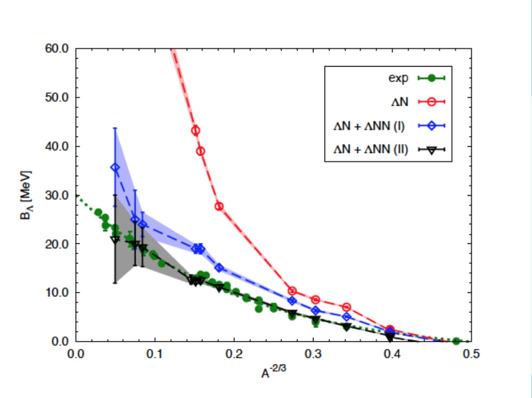


the spacings of the single-particle energies as a function of A put more constraints on the theoretical fits. Skyrme includes 3-body

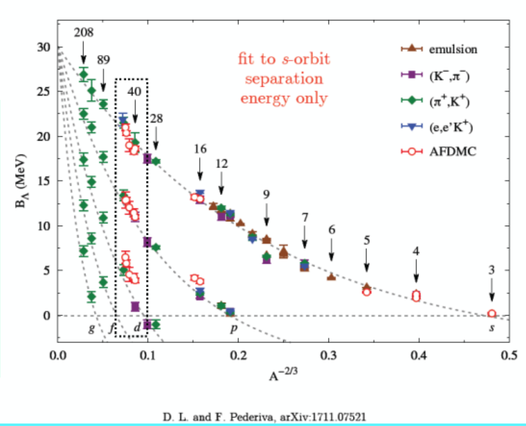


Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm

Lonardoni

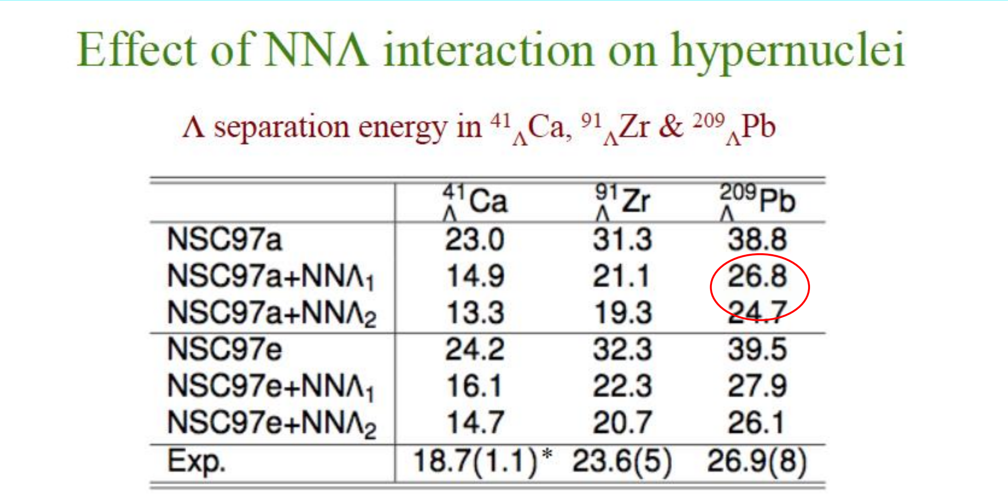


the effect of including the ΛNN termin in the Hamiltonian is very strong. It provides the repulsion necessary to realistically reproduce the limiting value of B_Λ



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

Vidana



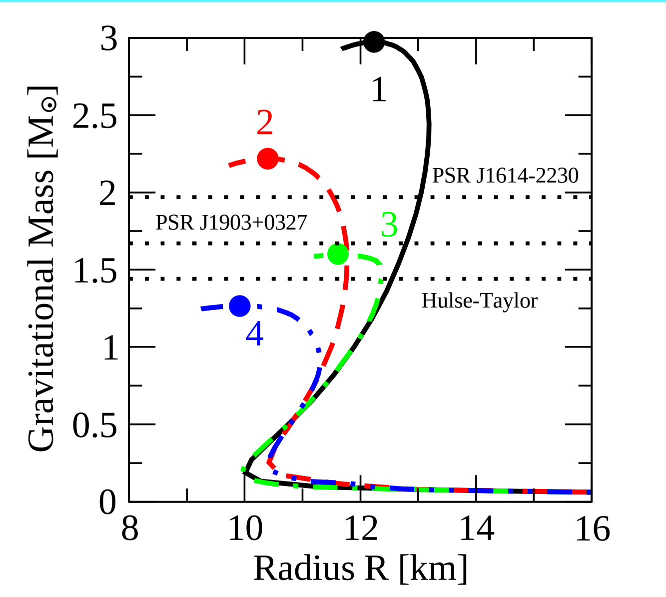
Effect of NNΛ interaction on hypernuclei

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

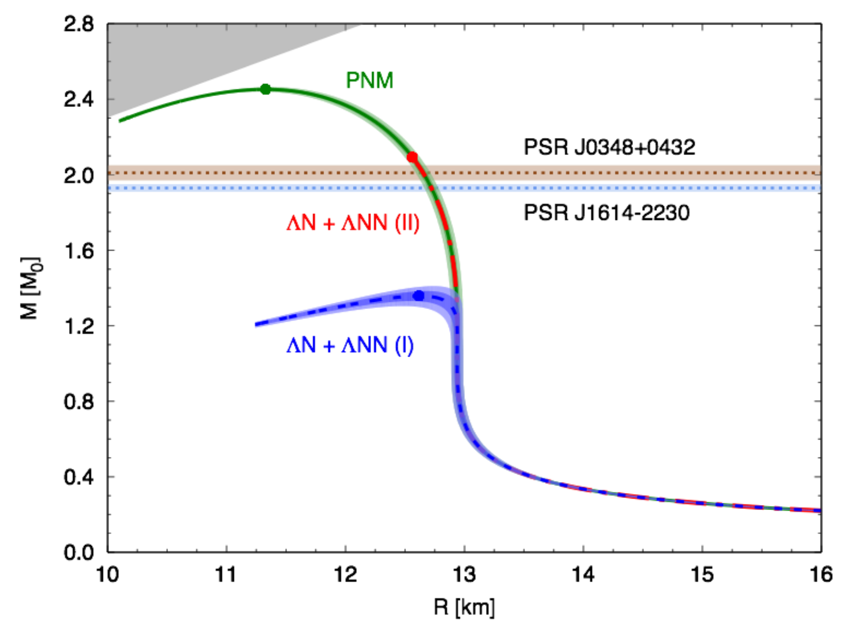
Inclusion of ΛNN improves the agreement with data for ^{91}ΛZr & ^{209}ΛPb.



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.

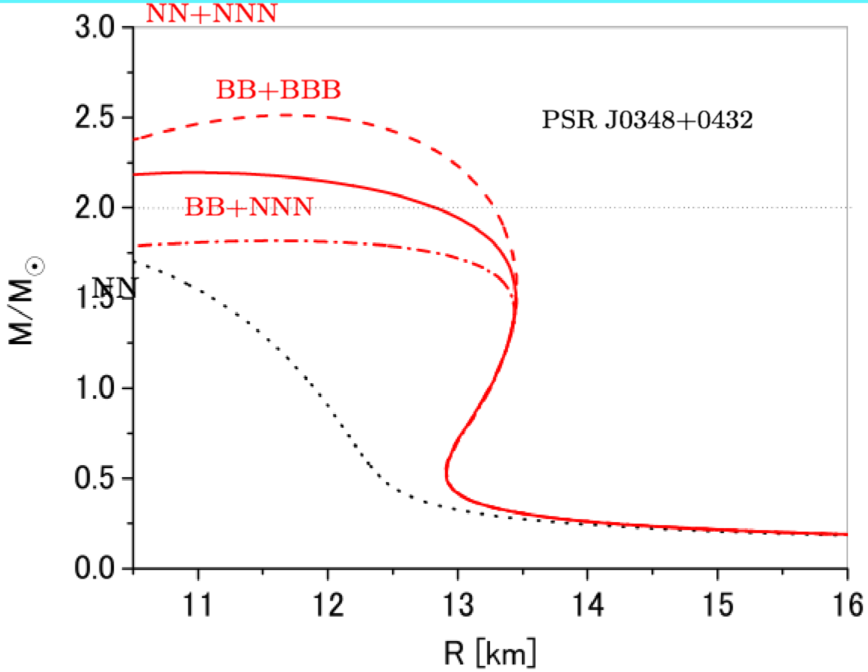
1. **Nucleons without 3 body forces**
2. **Nucleons with 3 body forces**
3. **Λ and N with 3 body forces(ΛNN)**
4. **Λ and N without 3 body force**

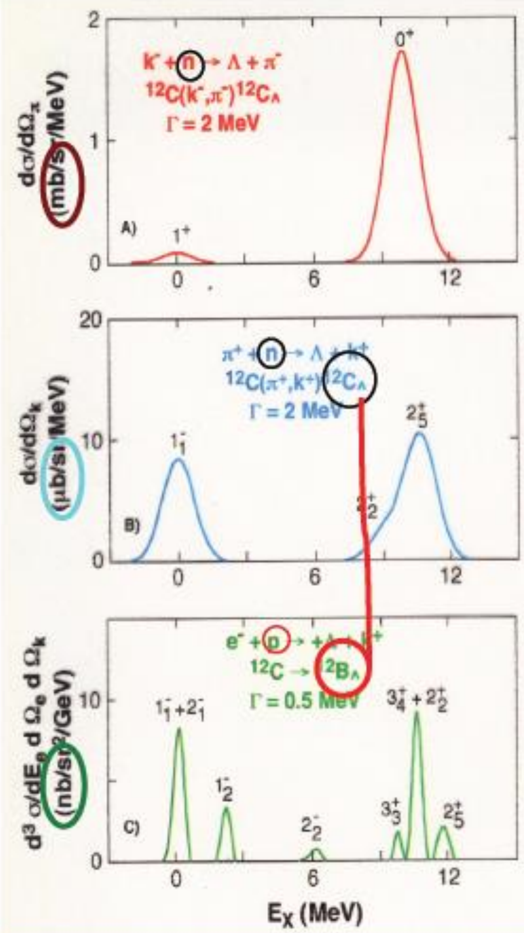
D.Lonardoni *et al.*, Phys. Rev. Lett. 114, 092301 (2015) (AFDMC)



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

G-Matrix: ESC08 + MPa

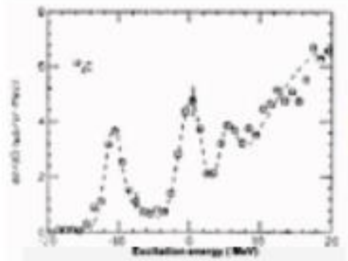




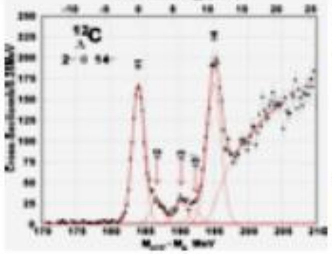
q ≈ 100 MeV/c --> Δℓ = 0
---> substitutional states
Δs = 0 --> no spin flip
---> natural parity
(J = 0^+)
absorption

q ≈ 300 MeV/c --> Δℓ = 1,2
spin flip (weak for $\Theta_K < 10°$)
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

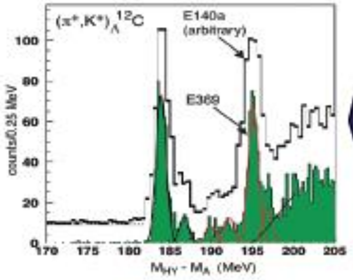


BNL 3 MeV



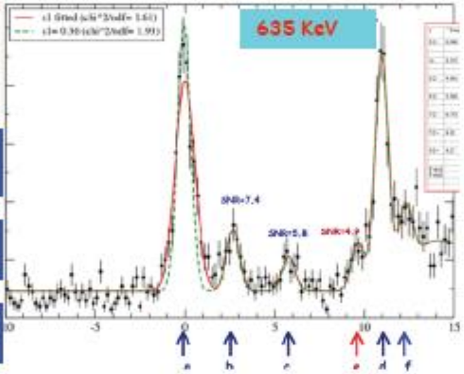
KEK336 2 MeV

Improving energy resolution



~ 1.5 MeV

and



using electromagnetic probe

High resolution, high yield, and systematic study is essential

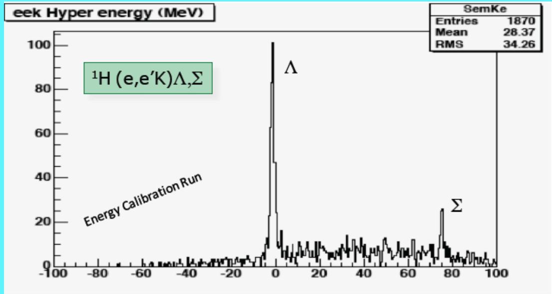
new aspects of hyernuclear structure

production of mirror hypernuclei

energy resolution ~ 500 KeV

(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 (Vidana)

**** 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

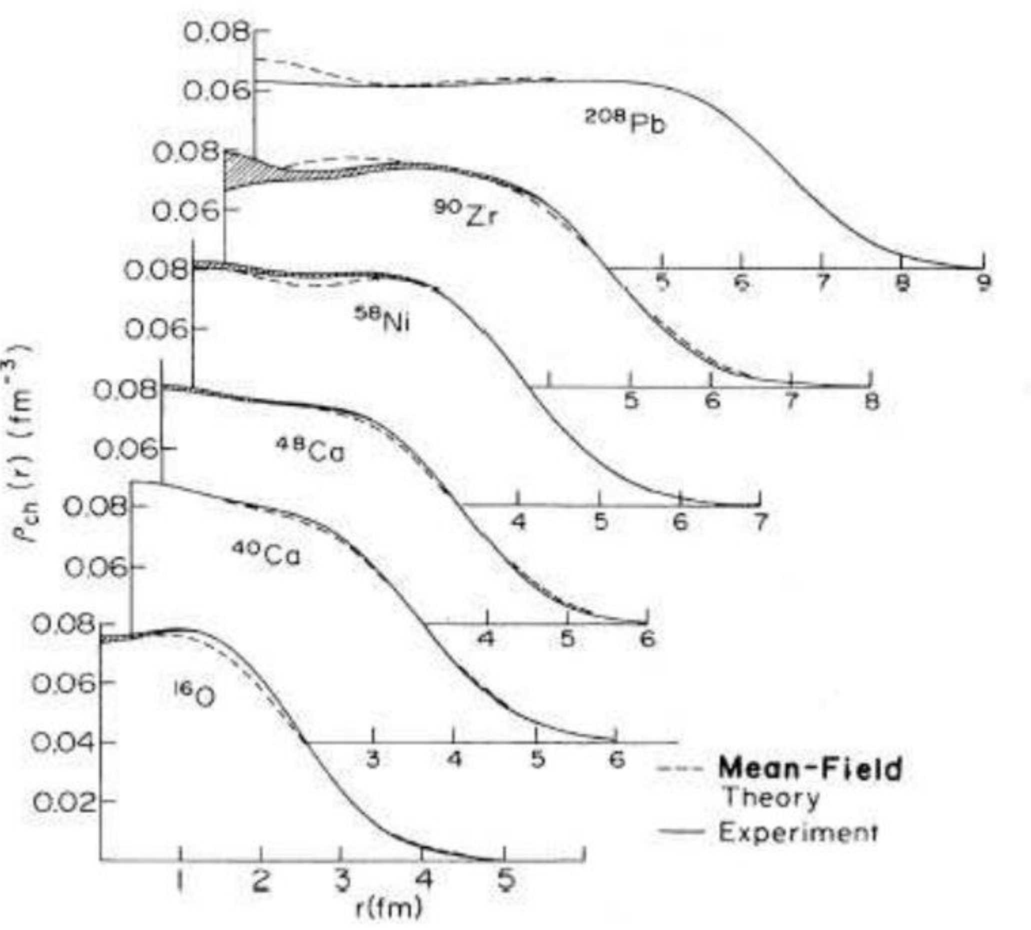
******** G-matrix calulations by Y. Yamamoto *et al.*

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.

The use of the Pb target will allow us to investigate hypernuclear dynamics in a new environment, in which three-body interactions are expected to play an important role. This will allow us, in the framework of a more general approach, 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

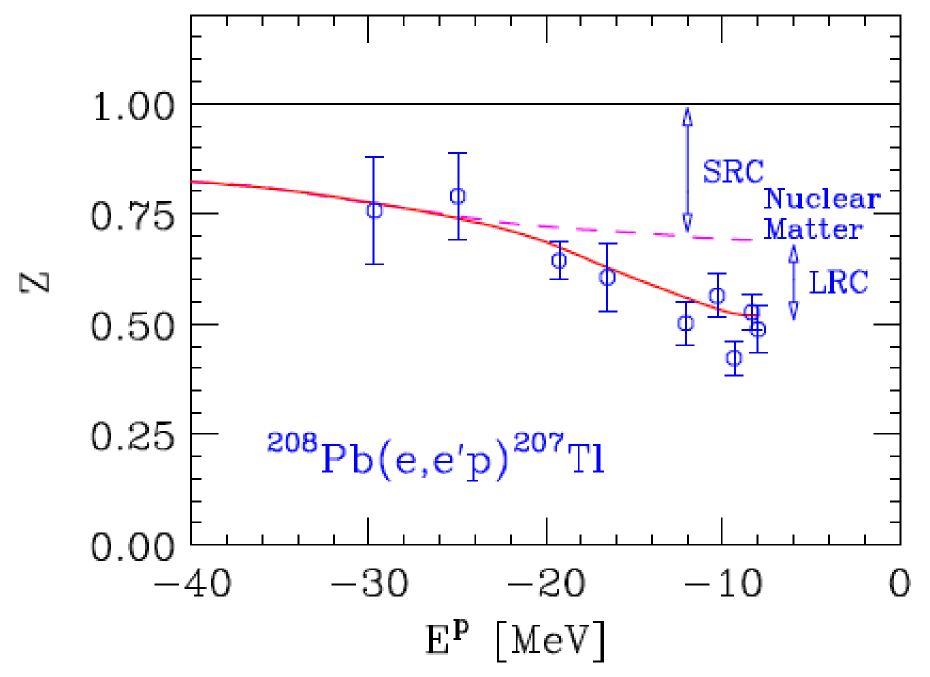
In fact it has been suggested that three body forces could provide additional repulsion making the EOS stiffer enough to help solving the hyperon puzzle

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

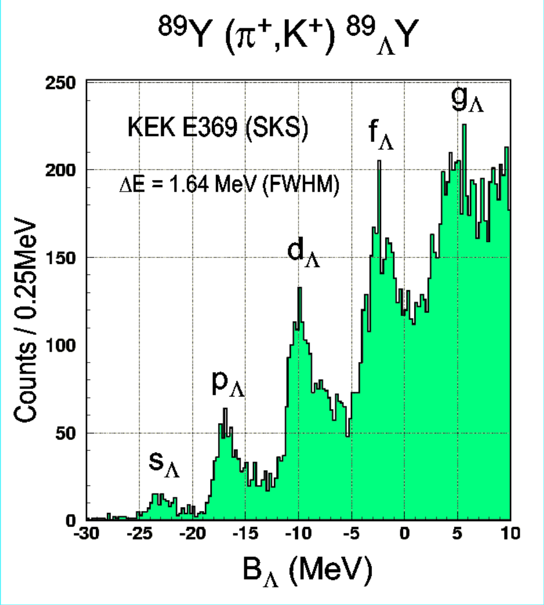
The hyperon binding energies are given by the difference between the missing energies measured in (e,e´K$^+$) and the proton binding energies obtained from the (e,e´p) cross sections. Hence, (e,e´p) data will provide the baseline needed to extract information, in a model independent way, on hyperon binding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

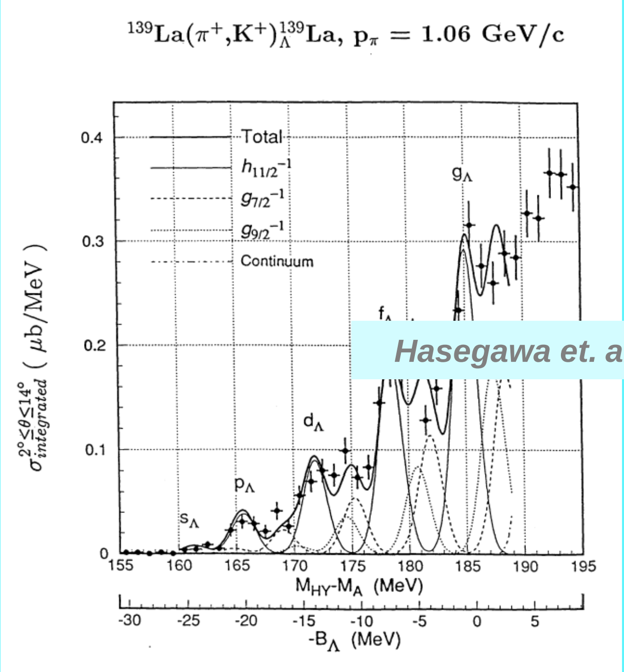
Jlab is the only lab where to make this experiment

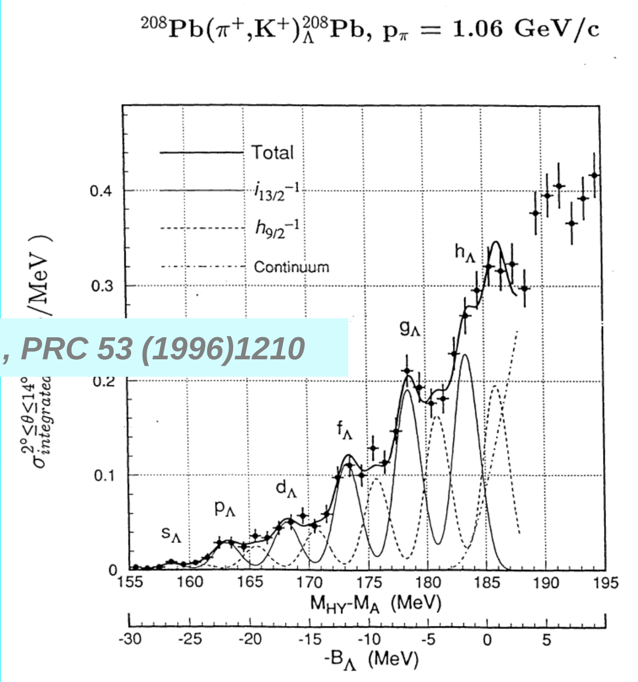
Hyperon in heavy nuclei – ^{208}(e,e'K+)$^{208}_{\Lambda}$Ti

- ✓ **Mass spectroscopy to its extreme**



Hotchi et al., PRC 64 (2001) 044302





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

"Up to now these data are the best proof ever of quasi particle motion in a strongly interacting system" (Review paper by Hashimoto and Tamura)

- ✓ **(π,k) reaction, levels barely visible for Pb**

(e,e'K) reaction can do better

Better energy resolution (*and calibration*)

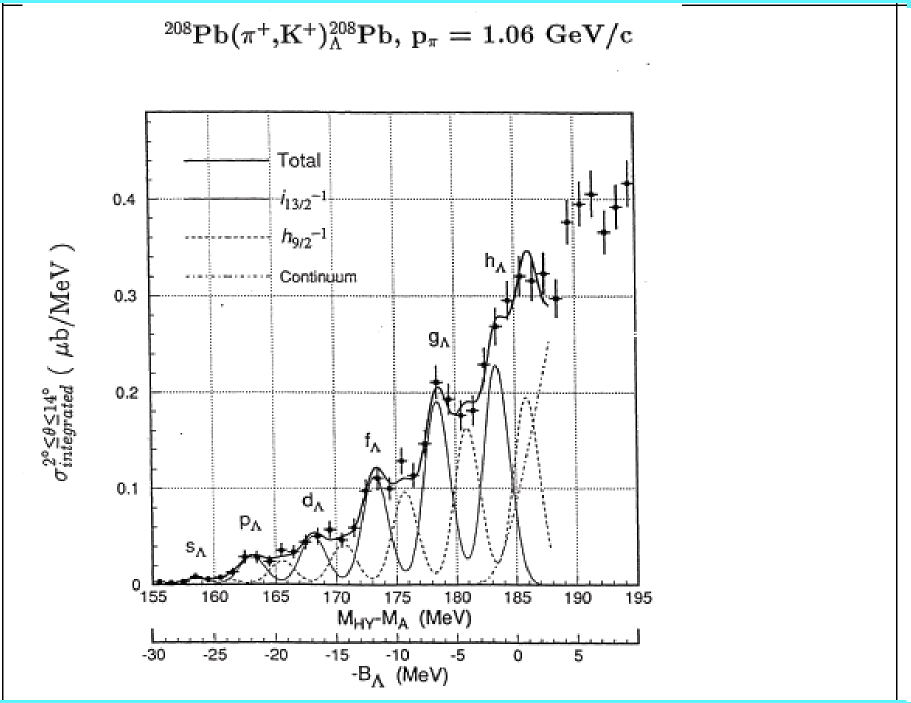
→ more precise Λ single particle energies.

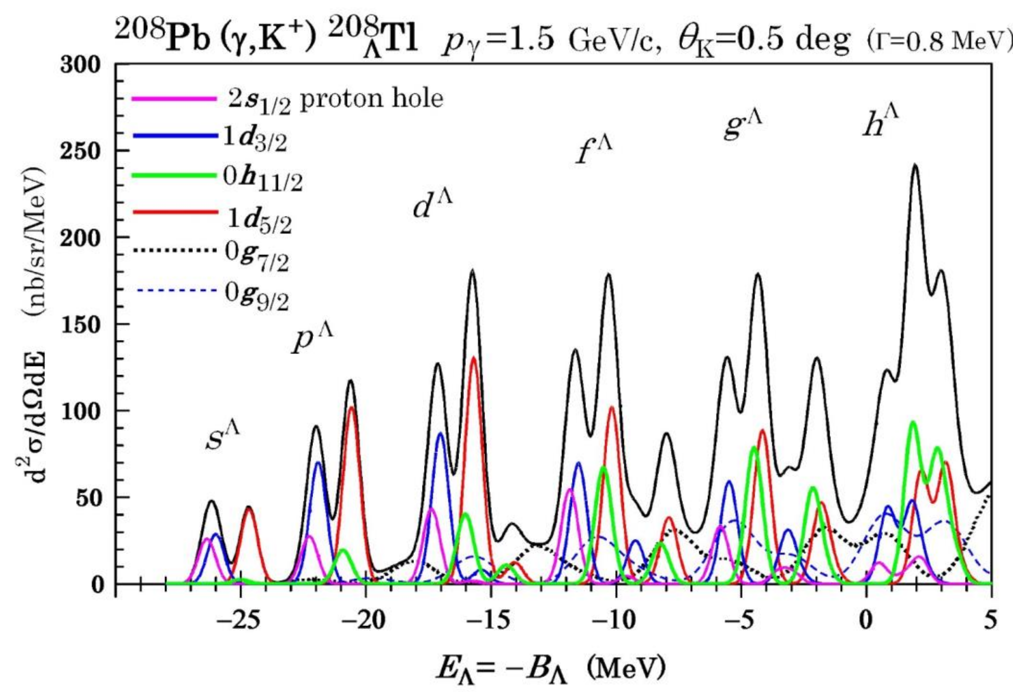
“Therefore is of vital importance to perform precision spectroscopy of heavy Λ hypenuclei with mass resolution comparable to or better than the energy differences of core excited states, in order to further investigate the structure of the Λ hyperon deeply bound states in heavier nuclei.

→ (e,e'K) spectroscopy is a promising approach to this problem

We know that there are plans at KEK to produce high resolution pion beams

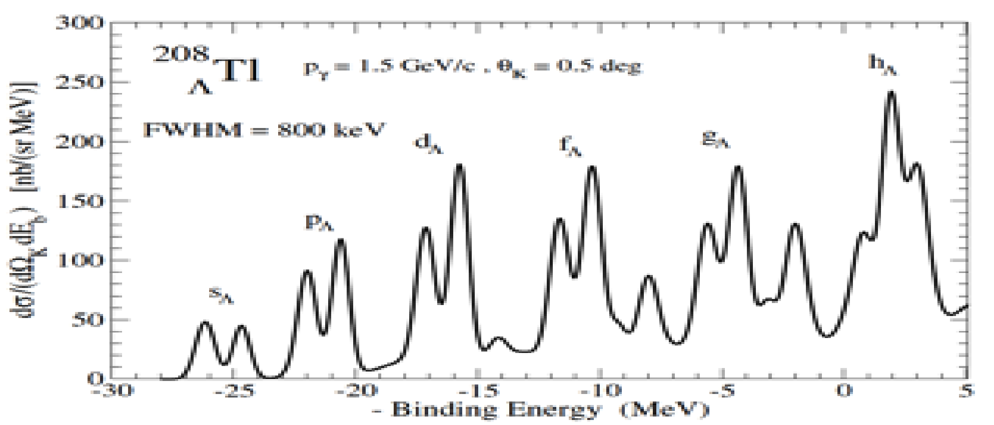
This is very good because of the complementarity of the two approaches

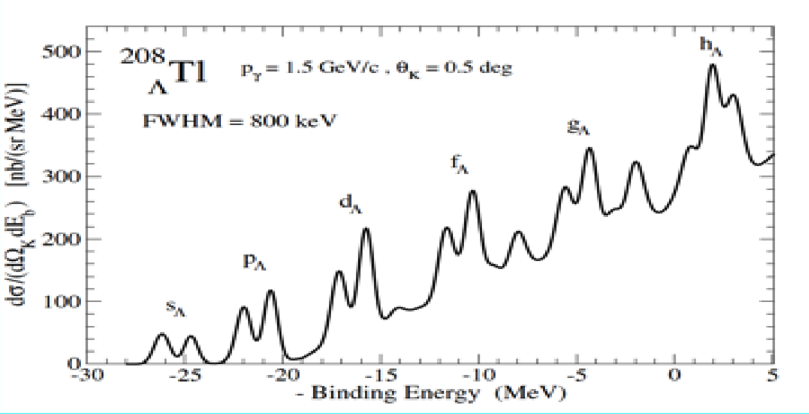


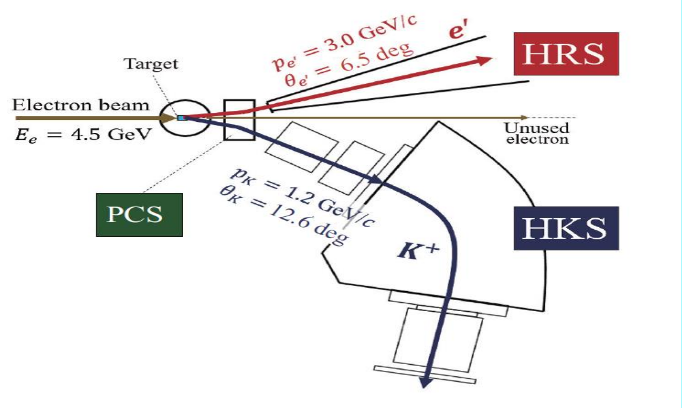


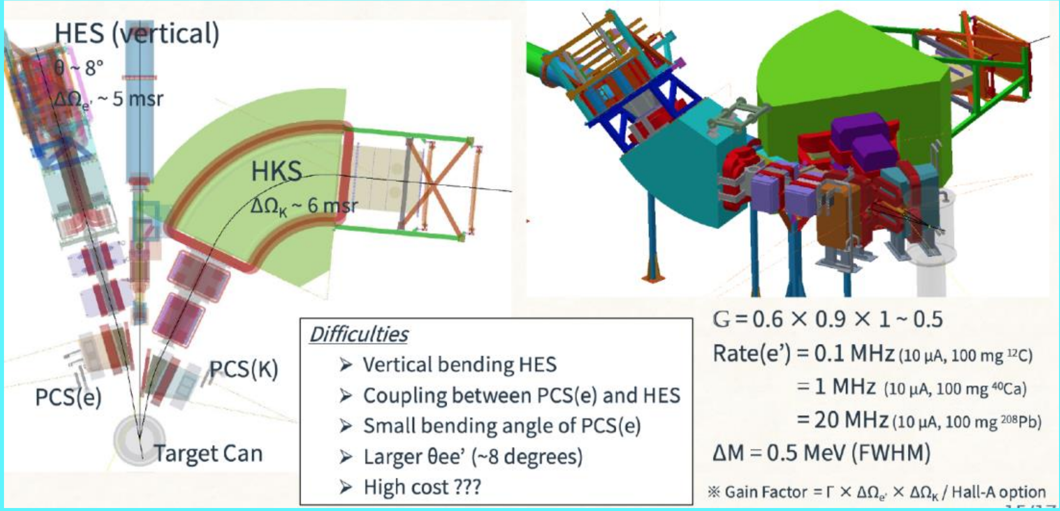
Millener-Motoba calculations

- 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









Difficulties

- Vertical bending HES
- Coupling between PCS(e) and HES
- Small bending angle of PCS(e)
- Larger θee' (~8 degrees)
- High cost ???

$G = 0.6 \times 0.9 \times 1 \sim 0.5$

Rate(e') = 0.1 MHz (10 μA, 100 mg ^{12}C)

= 1 MHz (10 μA, 100 mg ^{40}Ca)

= 20 MHz (10 μA, 100 mg ^{208}Pb)

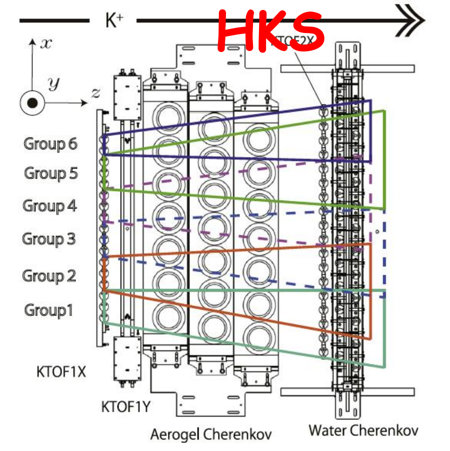
ΔM = 0.5 MeV (FWHM)

※ Gain Factor = $\Gamma \times \Delta\Omega_{e'} \times \Delta\Omega_K$ / Hall-A option

Target	Beam Current (μA)	Target thickness (mg/cm^2)	Assumed cross section (Nb/Sr)	Expected yield (/hour)	Number of events	Rquested beam time (hours)	B.G. Rate (MeV/h)	S/N
^{208}Pb	25	100	80 (g.s.)	0.24	115	480	0.084	18.5

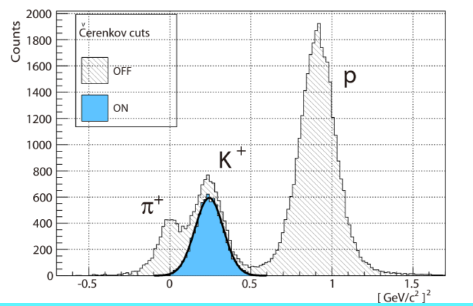
preliminary

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)

Target

The target comes from the expertise gained with the PREX one (Silviu Covrig)

- A water cooled target at room temperature could sustain a beam current in the range of 10 microA with a beam spot at least 16 mm^2 in area.

- If the target is cooled down to at least 15 K, then the beam current can be increased by a factor of at least 2x compared with RT cooling (minimum beam spot/raster area of 9 mm^2), in the range of 20 μA.

If the target is cooled down to 15 K and also rotated (or oscillated in one direction), then the beam current can be increased another factor of 2x, in the range of at least 40 microA.

So, for PR12-20-013, cryo-cooling the target is enough to achieve its goals. No rotation of the target would be needed for beam currents less than 30 microA

For PR12-20-013 we need 25 μA

We migh add up the RICH detector

Conclusions

This experiment will extend the study of (e,e'K) to the ^{208}Pb(e,e'K)$^{208}_{\Lambda}$Tl reaction. The use of the Pb target will allow us to investigate hypernuclear dynamics in a new environment, in which three-body interactions are expected to play an important role. This will allow us, in the framework of a more general approach, to study the hyperon puzzle in a complementary way with respect to the $^{40}_{\Lambda}$K and $^{48}_{\Lambda}$K experiment on isospin dependence of ΛNN

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.

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

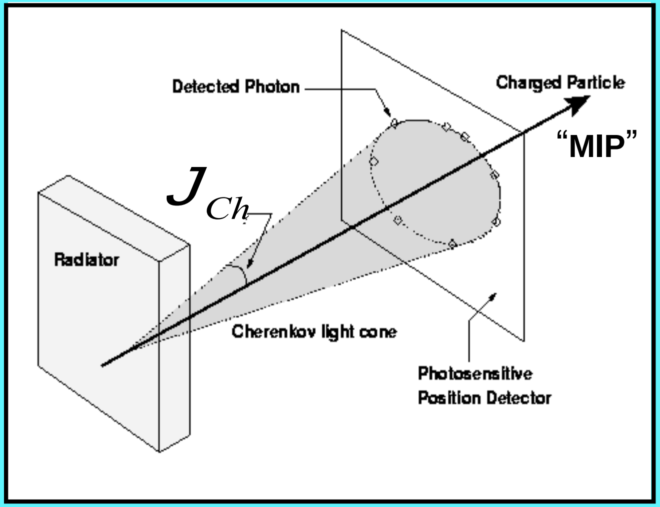
Even if the typical baryon density inside a neutron star is much higher than in a hypernucleus a precise knowledge of the ^{208}Pb level structure can, by constraining the hyperon-nucleon potential, contribute to more reliable predictions regarding the internal structure of neutrons stars, and in particular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

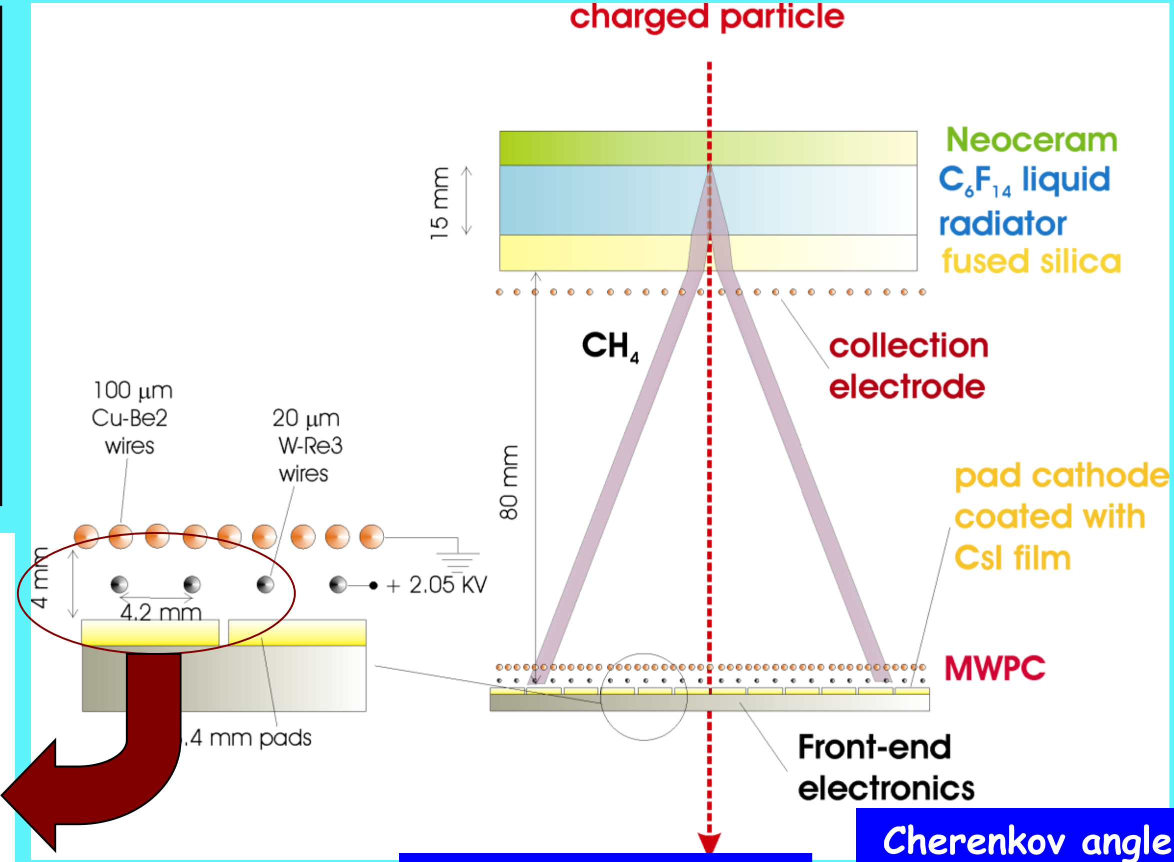
The proposed measurements, along with those on lighter hypernuclei, will provide valuable information on YN and YNN interactions

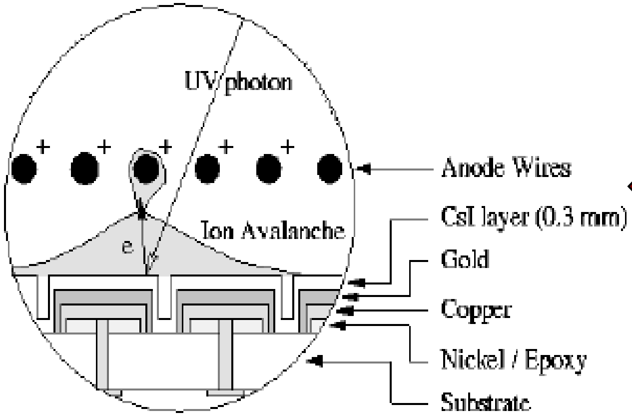
They are well positioned theoretically and experimentally in the framework of the hypercnulear collaboration proposals: the C12-15-008 (^{40}Ca and ^{48}Ca) and C12-19-002 (High accuracy measurement of nuclear masses of Λ hyperhydrogens) and «Determining the unknown Λ-n interaction by investigating the Λ-nn resonance (L. Tang talk last Monday)

All of them will give contribution on the best knowledge of the ΛN and ΛNN interactions and their impact on astrophysics

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







Separation Power

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

$$- J_1 = n_s s_{J_c}$$

Cherenkov angle resolution

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

N. of detected photoelectrons

$$N_{p.e.} = 370 L \sin^2 J_c \prod_i e_i DE \approx 20 - 50$$

Performances

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

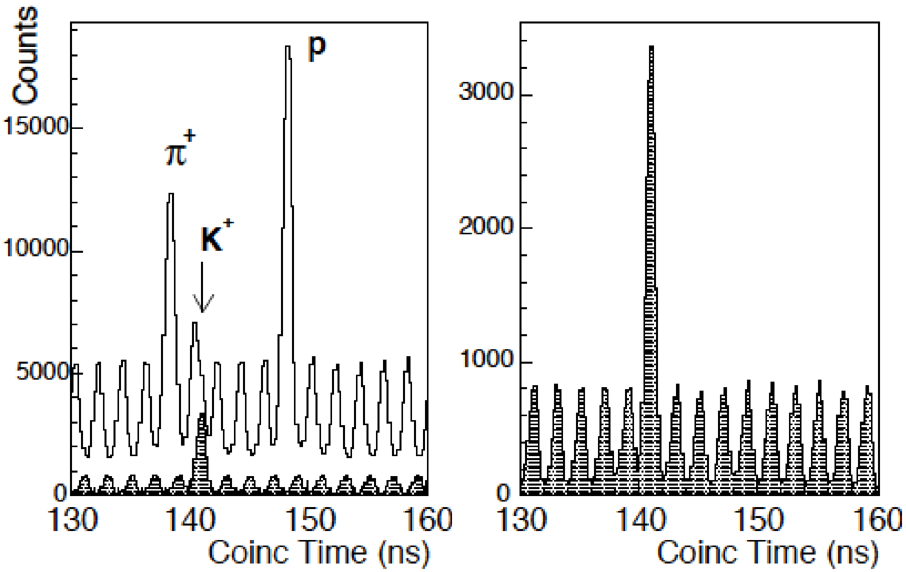


FIG. 10. Hadron plus electron arm coincidence time spectra. Left panel: the unfilled histogram is obtained by selecting kaons with only the threshold aerogel Cherenkov detectors. The filled histogram (expanded in the right panel) also includes the RICH kaon selection. The remaining contamination is due to accidental $(e,e')\otimes(e,K^+)$ coincidences. The π and p contamination is clearly reduced to a negligible contribution.

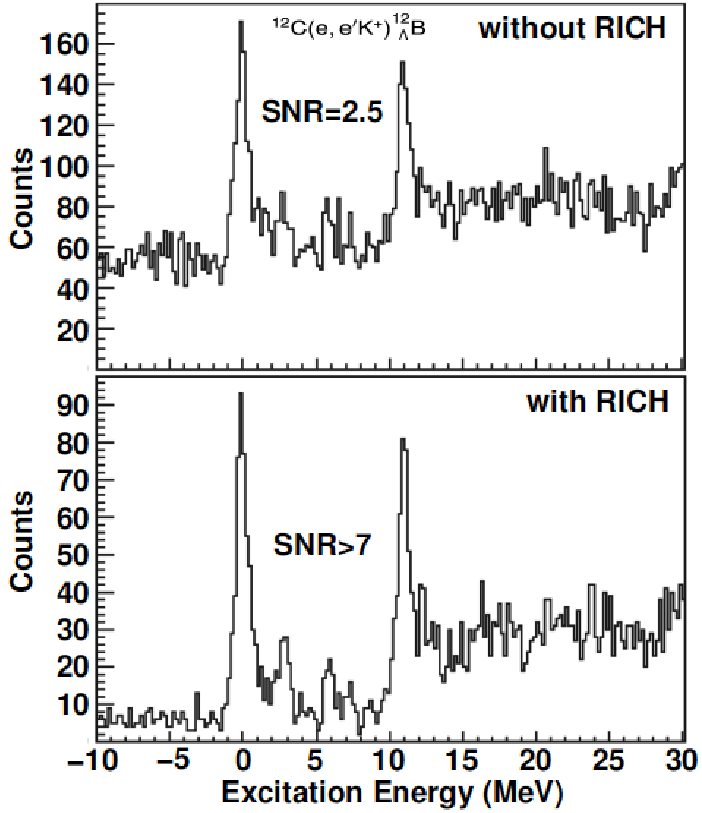


FIG. 11. Excitation energy spectra of $^{12}_{\Lambda}$B using, for kaon identification, only the aerogel (upper plot) or also the RICH (lower plot). The counts are for 200 keV bins.