Hypernuclei at SIS18 energies

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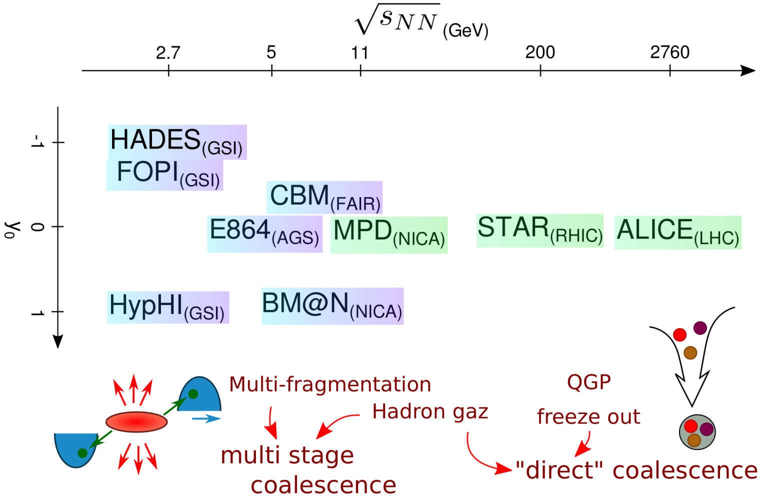
3rd EMMI Workshop:
Antimatter, hypermatter and exotica production at the LHC
5 December 2019

Outline

Outline

hypernuclei with ion beam



Observables on hypernuclei in ion collisions

Spectroscopy study:

- Production of exotic system
- Ground states via invariant mass measurement
- $\rightarrow$ Lifetime estimation.
- Binding energy when high measurement resolution
  - Useful for structure models $\rightarrow$ YN / YY interactions

Reaction study:

- Yields, Cross section, Multiplicity of observed hypernuclei
- Yield ratios : to Λ yield, to nuclear yield, double ratios
  - Useful to probe the dynamics of the reaction
  - sensitive to the overlap region participant / spectator

Outline

Hypernuclei with ion beam

SIS18 Energy range : The HypHI project

- Results on ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H
- Result on d+π^- and t+π^-

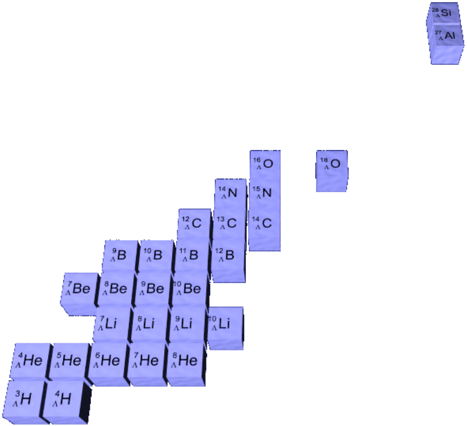
Next at SIS18 : WASA@FRS

Further perspective at SIS energy range

Summary & Perspectives

Several phases

Current knowledge:

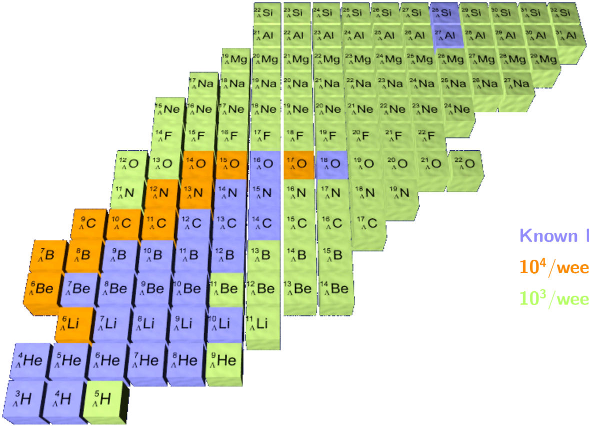


Known Hypernuclei

Several phases

Ideal outcome of the HypHI[1] project started in 2006:

(1) **Hyp**ernuclei with **H**eavy **I**on



Known Hypernuclei

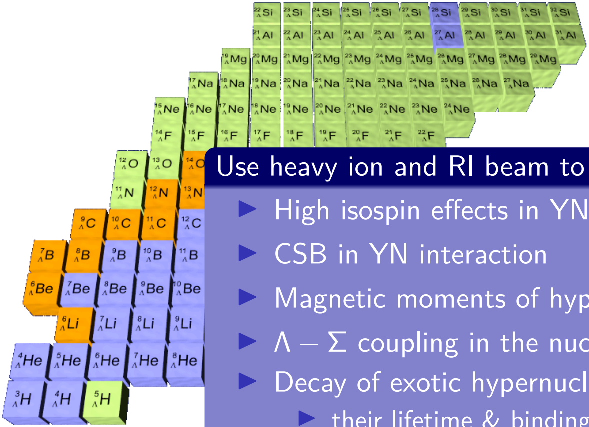
10^4/week

10^3/week

Several phases

Ideal outcome of the HypHI[1] project started in 2006:

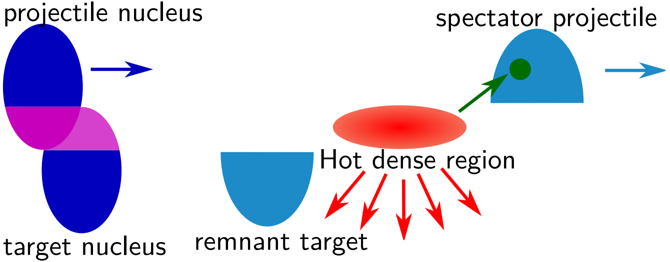
(1) **Hyp**ernuclei with **H**eavy **I**on



Use heavy ion and RI beam to study

- High isospin effects in YN interaction
- CSB in YN interaction
- Magnetic moments of hypernuclei
- $\Lambda - \Sigma$ coupling in the nuclear matter
- Decay of exotic hypernuclei
  - their lifetime & binding energy
- Multistrangeness hypernuclei

Heavy Ion : Properties of the production mechanism



- $NN \rightarrow \Lambda KN$ Energy threshold ~ 1.6 GeV.
- Beam energy $> \mathrm{E}_{th}$: available at GSI (2 A GeV)
- Coalescence of Λ or (π^+, K^+) reaction in spectator fragment.

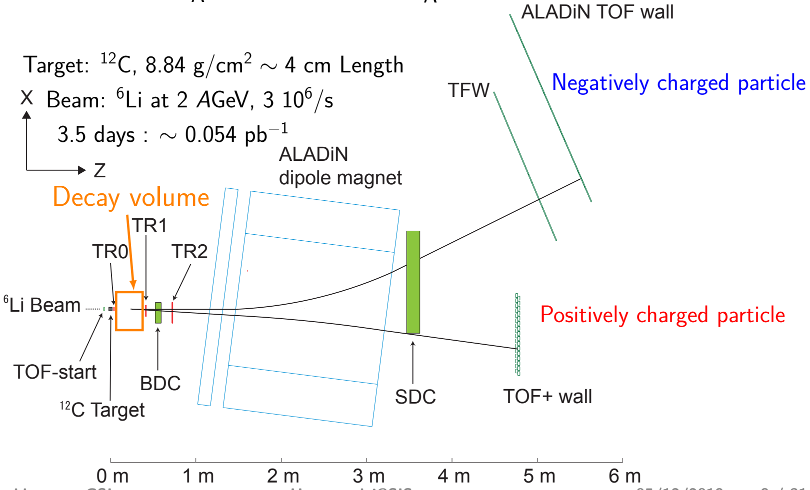
  $\Rightarrow$ same velocity than projectile: Lorentz Boosted
- Effective lifetime longer:
  - 200 ps $\rightarrow$ 600 ps ($\gamma \sim 3$) at GSI: $c\tau \sim$ 15 to 20 cm.

  $\Longrightarrow$ study Hypernuclei in flight
  - Lifetime measurement via decay vertex reconstruction.

Results from HypHI experiment: Phase 0 @ GSI

Fixed target, Reaction : ^{6}Li+^{12}C @ 2 *A*GeV or $\sqrt{s_{NN}} = 2.7$ GeV

$^{3}_{\Lambda}$H→ π^-+^{3}He $^{4}_{\Lambda}$H→ π^-+^{4}He $^{5}_{\Lambda}$He→ π^-+^{4}He+p

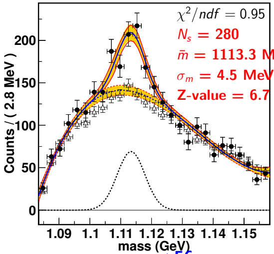


Hypernuclear spectroscopy from ^{6}Li+^{12}C @ 2 *A* GeV

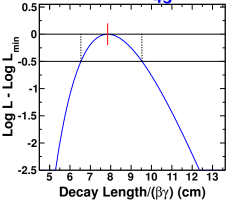
[C. Rappold *et al.*, Nucl. Phys. A. **913**, 170 (2013)]

Evidence of Λ, ${}^{3}_{\Lambda}$H et ${}^{4}_{\Lambda}$H & Lifetime measurements

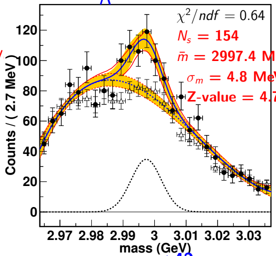
$\Lambda \to p + \pi^-$



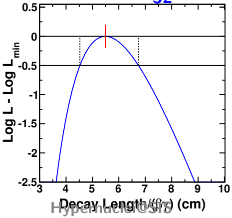
$\tau = 262^{+56}_{-43} \pm 45$ ps



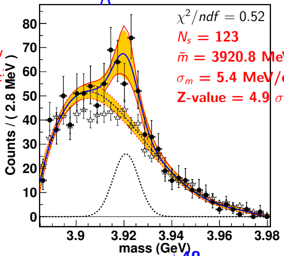
${}^{3}_{\Lambda}H \to {}^{3}He + \pi^-$



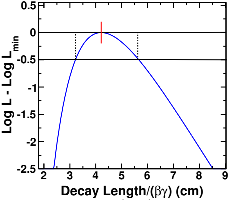
$\tau = 183^{+42}_{-32} \pm 37$ps



${}^{4}_{\Lambda}H \to {}^{4}He + \pi^-$

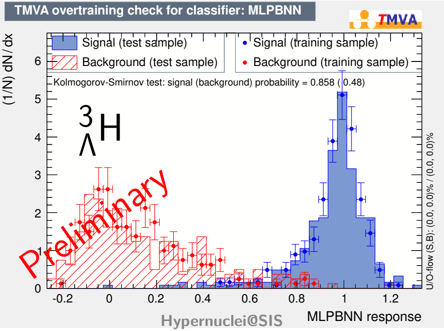


$\tau = 140^{+48}_{-33} \pm 35$ps



New perspective: ML for hypernuclear discrimination

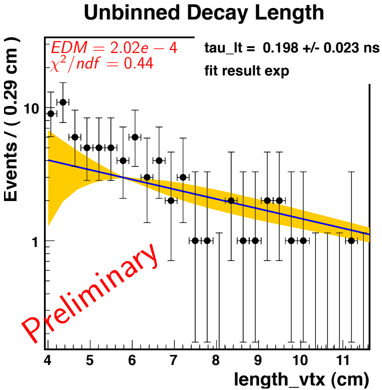
- Since [C. Rappold *et al.*, Phys. Lett. B **728**, 543 (2014)]
- Average lifetime in 2013: ${}^{3}_{\Lambda}\mathrm{H}$: 216^{+19}_{-16} ps & ${}^{4}_{\Lambda}\mathrm{H}$: 192^{+20}_{-18} ps
- Average in 2019 : ${}^{3}_{\Lambda}\mathrm{H}$: 206^{+15}_{-13} ps
- Revisiting the data with machine learning techniques to improve the S/B ratio.
- Training and testing data set: directly the experimental data

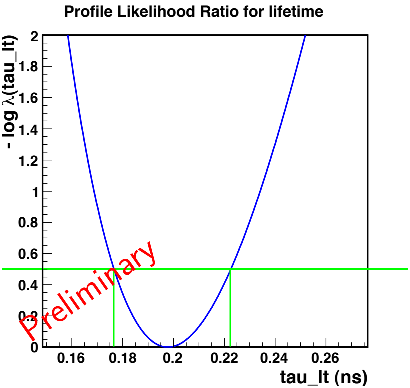


New perspective: ML for hypernuclear discrimination

Applying ML discrimination for $^{3}_{\Lambda}$H lifetime :

- Preliminary statistical error: $198\ ^{+25}_{-21}$ ps
- Need more detailed analysis before publishing.

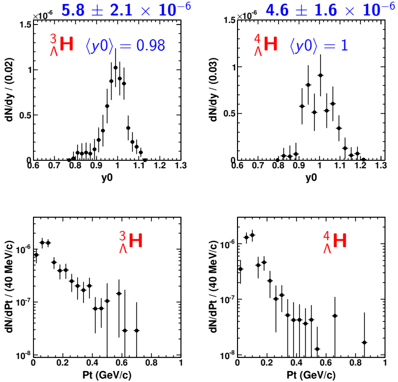




Hypernuclear production cross section in spectator region

Production cross section & multiplicity :

	CS
Λ	1.7 ± 0.8 mb
${}^{3}_{\Lambda}$H	3.9 ± 1.4 μb
${}^{4}_{\Lambda}$H	3.1 ± 1.0 μb
${}^{3}_{\Lambda}$H/${}^{4}_{\Lambda}$H	1.4 ± 0.8
${}^{3}_{\Lambda}$H/Λ	$2.6 \pm 1.4 \times 10^{-3}$
${}^{4}_{\Lambda}$H/Λ	$2.1 \pm 1.1 \times 10^{-3}$
${}^{3}\mathrm{H}/{}^{3}\mathrm{He} \cdot \mathrm{p}/\Lambda$	0.28 ± 0.14
${}^{4}\mathrm{H}/{}^{4}\mathrm{He} \cdot \mathrm{p}/\Lambda$	0.08 ± 0.04

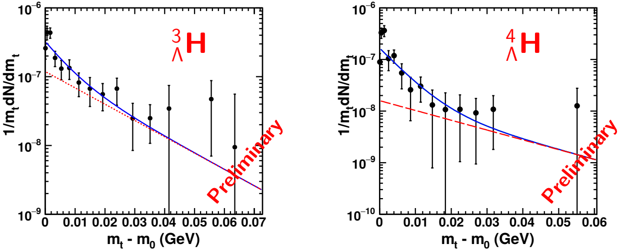


[C. Rappold *et al.*, Phys.Lett. B**747** (2015) 129]

Inverse slope / Temperature

Inverse slope T, m_t spectrum :

$$f(m_t - m_0) = K_1/T_1\ e^{-(m_t - m_0)/T_1} + K_2/T_2\ e^{-(m_t - m_0)/T_2}$$



- for ${}^{3}_{\Lambda}$H : $T_1 \sim 7 \pm 2$ MeV & $T_2 \sim 18 \pm 7$ MeV
- for ${}^{4}_{\Lambda}$H : $T_1 \sim 6 \pm 2$ MeV & $T_2 \sim 13 \pm 6$ MeV
- very similar to multi-fragmentation ALADIN results

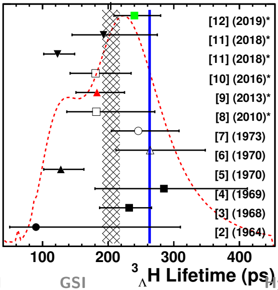
  [T. Odeh et al., Phys. Rev. Lett. 84 (2000) 4557]

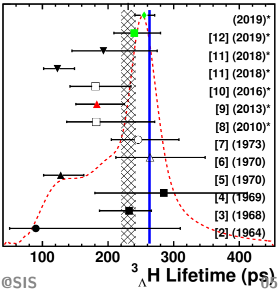
- How Λ low p_t can coalesce with fragment ? $\rightarrow$ probing the reaction dynamics.

Hypernuclear experiment at SIS energy

Important Conclusion

- Demonstration→spectroscopy via ion induced reaction
- Identification of Λ, $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H via invariant mass
- Cross sections, multiplicity in y & pt, yield ratios, S3 & S4.
- Estimation of the lifetime of Λ, $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H
- Combined lifetime analysis excludes all current models of $^{3}_{\Lambda}$H





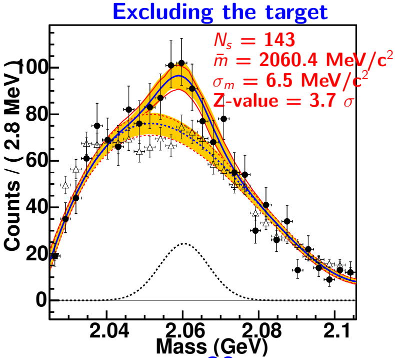
Since Monday

Search for evidence of ${}^{3}_{\Lambda}$n by observing d+π^- and t+π^-

[C. Rappold *et al.*, Phys. Rev. C (Rapid Comm.) **88**, 041001 (2013)]

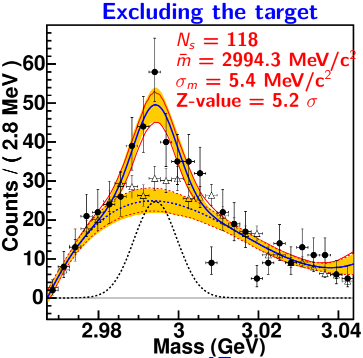
Possible bound state ${}^{3}_{\Lambda}$n (nnΛ) ?

${}^{3}_{\Lambda}\mathbf{n} \rightarrow \mathbf{d}+\pi^-$



$\tau = 181^{+30}_{-24} \pm 25$ps

${}^{3}_{\Lambda}\mathbf{n} \rightarrow \mathbf{t}+\pi^-$



$\tau = 190^{+47}_{-35} \pm 36$ps

Search for evidence of ${}^{3}_{\Lambda}$n by observing d+π^- and t+π^-

[C. Rappold *et al.*, Phys. Rev. C (Rapid Comm.) **88**, 041001 (2013)]

Important Points

- Possible signals in the invariant mass of d+π^- and t+π^-
- the decay attributed to strangeness-changing weak interaction
- A possible interpretation : ${}^{3}_{\Lambda}$n
  - t+π^- : two-body decay via ${}^{3}_{\Lambda}\mathrm{n} \rightarrow \mathrm{t} + \pi^-$
  - d+π^- : three-body decay via ${}^{3}_{\Lambda}\mathrm{n} \rightarrow \mathrm{t}^* + \pi^- \rightarrow \mathrm{d} + \mathrm{n} + \pi^-$

However:

- theoretical studies show ${}^{3}_{\Lambda}$n not bound
  - No explanation within the current understanding of the ΛN interaction (by A. Gal (arxiv :1404.5855), E. Hiyama (PRC 89, 061302) and H. Garcilazo (PRC 89, 057001))
  - Even its lifetime would be longer ! (A. Gal & H. Garcilazo, PLB 791 (2019) 48)

Outline

Prospects in Hypernuclear Physics for FRS/SuperFRS

Future of HypHI project : Exotic hypernuclei / strangeness cluster

Use heavy ion and RI beam to study @ FRS & SuperFRS :

- Hypernuclei toward the proton and neutron drip-lines with Exotic beam $\Rightarrow$ **SuperFRS**
- $\Lambda - \Sigma$ coupling in the nuclear matter $\Rightarrow$ **SuperFRS**
- Lifetime of exotic hypernuclei. $\Rightarrow$ **FRS / SuperFRS**
- Most urgent : Confirmation of ${}^{3}_{\Lambda}$n $\Rightarrow$ **FRS**

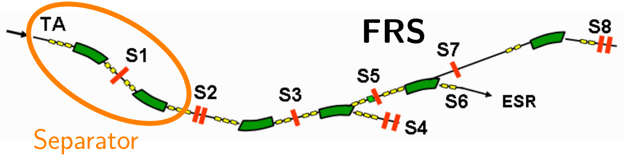
Prospects in Hypernuclear Physics for FRS/SuperFRS

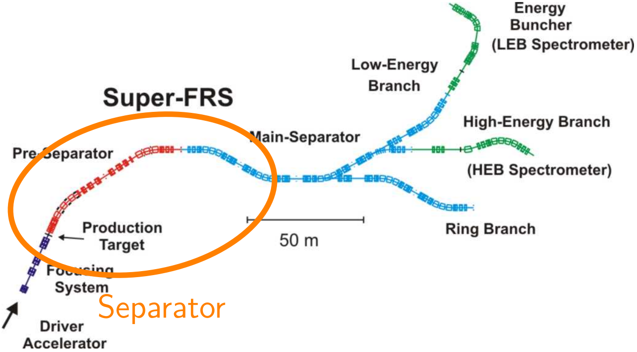
Why at FRS / Super FRS ?

- high momentum resolution for forward fragments : $10^{-4}\delta p/p$ optimal
  - to be compared with previous experimental apparatus : $\sim 10^{-2}\delta p/p$
- Exotic hypernuclei : Need RI beam
  - With high energy ~ 2 AGeV (min 1.6AGeV)
  - With high intensity : small cross section ($\sim \mu$b)
- Optimizing each experiment to one decay / species

$\Rightarrow$ **Only possible at GSI/FAIR and FRS / SuperFRS**

The concept & Layouts: Exclusive experiment





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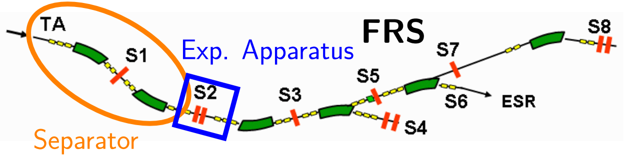

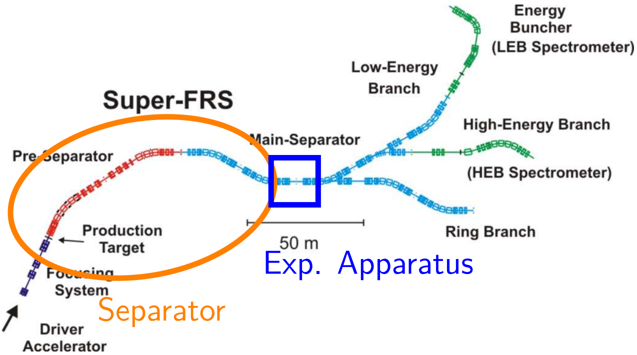

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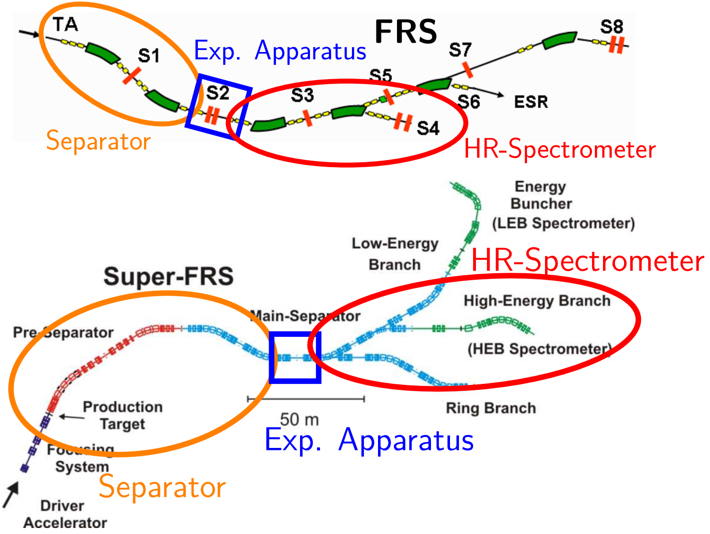

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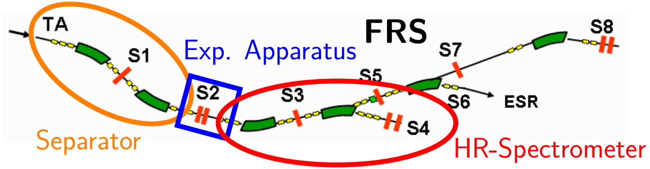
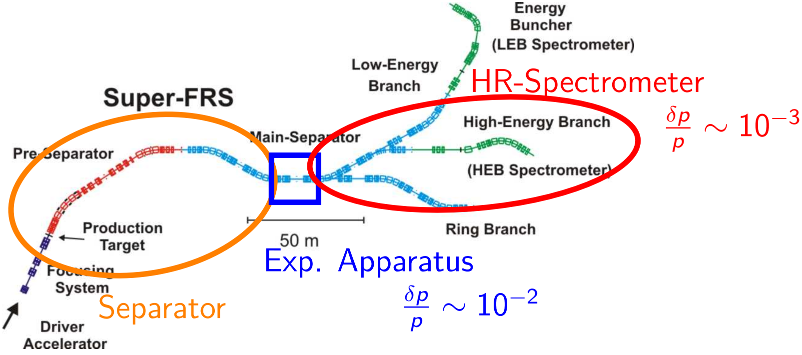
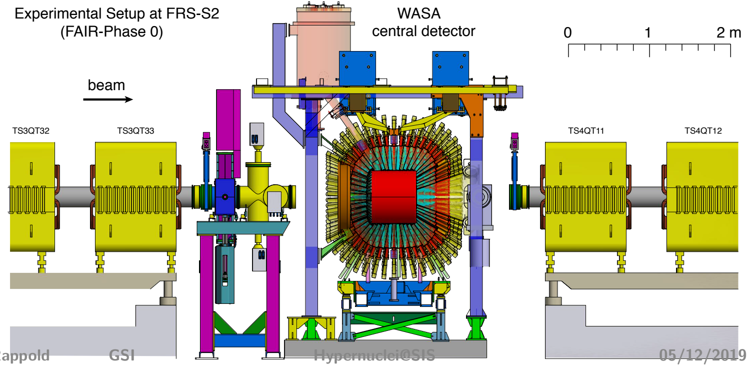




Wasa at S2: Solenoid magnet scenario

- Generic setup that can be used for different experiments:
- Large angular coverage :
  - close to 4π acceptance in mid-rapidity, projectile and/or target rapidity region.
- Good momentum (P_t and $P_{//}$) and vertex resolution.
- High rate & granularity for multiplicity.



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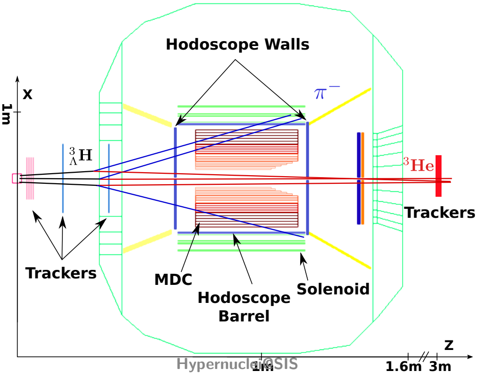
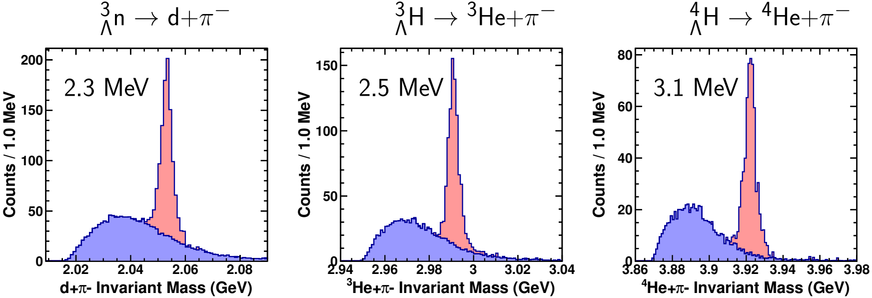


Invariant masses and yield estimation



2 - 5 times better resolution

10 - 40 times more stats

Channel of Interest	FRS rigidity (Tm)	Estimated signal Int.
$d+\pi^{-}$	16.675	4.0×10^{3} (8 days)
$^{3}_{\Lambda}H$	12.623	1.5×10^{3} (3 days)
$^{4}_{\Lambda}H$	16.675	5.0×10^{3} (8 days)

Experiment approved by G-PAC to run (2021): 45 shifts (27 main)

Outline

Transport optimization: Final step of optimal search

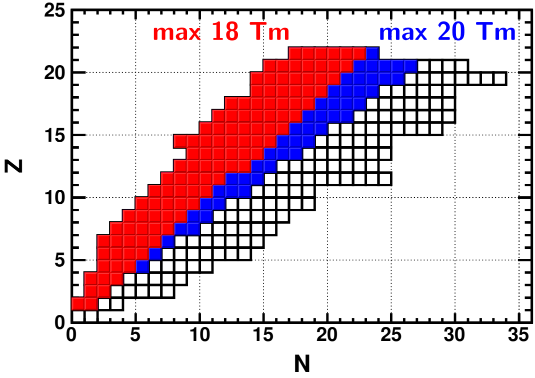
- MOCADI sim. for exotic beam transport within separator part
- Variables: Beam energy, transmission, survival rate, target thickness, contamination
- + EPAX and QGSM: RI beam & hypernuclear cross section
  - QGSM model compared to ^{6}Li+^{12}C results is ×4 smaller
- Multivariate dataset → optimization to find the optimum

	Reaction	Target (cm)	2^{nd} beam	E_k (AGeV)	I (10^6/s)	Yield (/s)
$^{9}_{\Lambda}$C	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.3
$^{11}_{\Lambda}$B	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	0.4
$^{9}_{\Lambda}$Be	stable beam		^{16}O	2.	10.	1.5
$^{5}_{\Lambda}$Li	^{12}C+^{9}Be	6	^{10}C	1.94	5.1	0.8
$^{6}_{\Lambda}$Li	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	1.4
$^{9}_{\Lambda}$Li	^{16}O+^{9}Be	5.5	^{14}O	1.93	5.5	0.7
$^{7}_{\Lambda}$He	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	0.9

[C. Rappold and J. López-Fidalgo PRC 94 (2016) 044616]

Fragmentation and secondary beam

→ Find which exotic beam to used for production of an hypernucleus

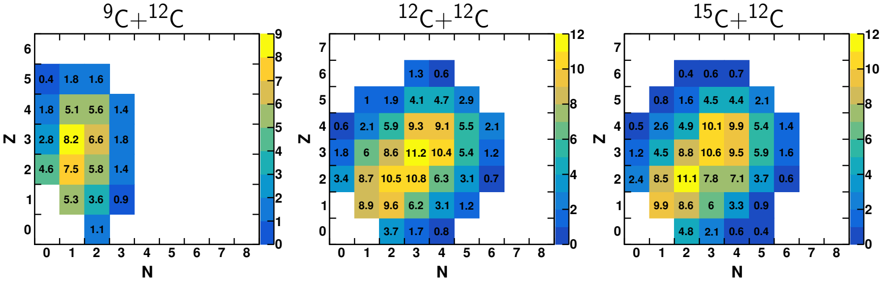


- EPAX model : fragmentation cross sections
- from [H ... Ca] stable beam + [Li, Be, B, C, Al] targets
- All fragments that can be an exotic beam

[C. Rappold and J. López-Fidalgo PRC 94 (2016) 044616]

Hypernuclear production: Effects of beam isotopes

- Hypernuclear production (in μb) from QMD theoretical model: QGSM (Quark Gluon String Model), [A. Botvina *et al.* Phys. Rev. C. **86** (2012) 011601]
- Dynamics of the reaction: hadronisation of the participant region + coalescence model (+ Fermi breakup)

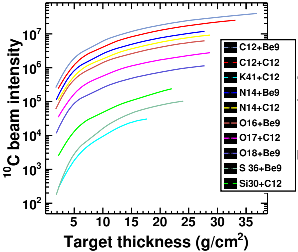


[C. Rappold and J. López-Fidalgo PRC 94 (2016) 044616]

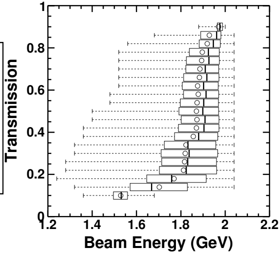
Transport optimization: Final step of optimal search

- MOCADI sim. for exotic beam transport within separator part
- Variables: Beam energy, transmission, survival rate, target thickness, contamination
- + EPAX and QGSM: RI beam & hypernuclear cross section
- Multivariate dataset → optimization to find the optimum
  - ($\sim 2\ 10^5$ MOCADI runs + $\sim 3\ 10^9$ QGSM events)

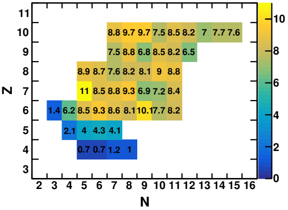
^{10}C prod. vs Thickness



All Frag. E_k vs trans.



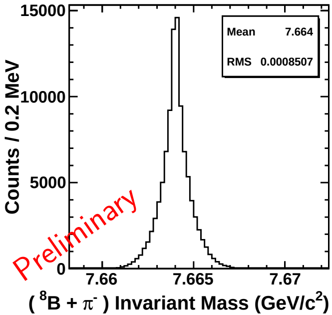
${}^{8}_{\Lambda}$Be : from ^{A}Z exotic+^{12}C



[C. Rappold and J. López-Fidalgo PRC 94 (2016) 044616]

Next at SuperFRS : proton-rich hypernuclei

- Light proton-rich hypernuclei can be produced and studied (ex: ${}^{8}_{\Lambda}$Be).
- at 20 Tm : proton-rich secondary beam can also have higher beam energy :
  - ^{9}C beam at the rigidity of 20 Tm : 3.2 AGeV.
- allows the further study of other hypernuclei species (Σ, Ξ).
- within the SuperFRS, exclusive experiment performing precise spectroscopy.



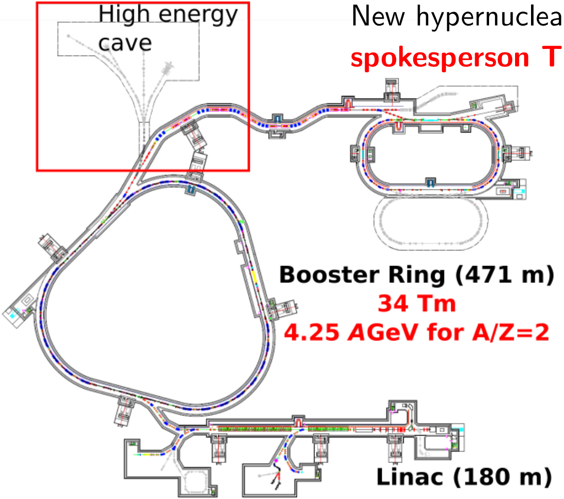
- Mass resolution 0.850 MeV (FWHM 0.79 MeV)
  - with 1% dp/p for π^{-} and 0.1% dp/p for ^{8}B

HIAF in Huizhou - China

High Intensity Heavy Ion Accelerator Facility :

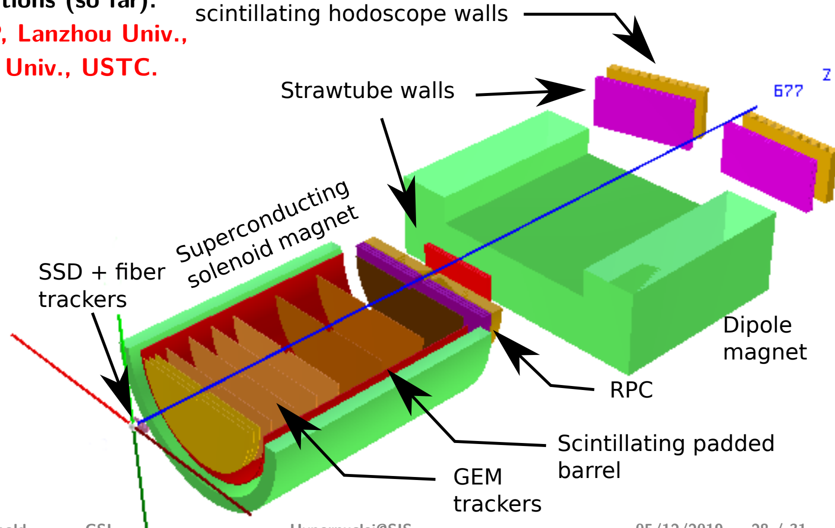
New hypernuclear project:

spokesperson T. Saito



Current setup consideration for HIAF

Collaborations (so far):
GSI, IMP, Lanzhou Univ., Tsinghua Univ., USTC.



Production of double Λ hypernuclei

- Available beam energy : **4.25 *A*GeV**
  $\rightarrow$ Above the Ξ^- production threshold (3.747 GeV)
- In similar fashion within HypHI experiment :
  - Coalescence mechanism between Ξ and spectator fragments.
- The Ξ^- nuclear absorption procudes 2 Λ (Ξ^-p$\rightarrow \Lambda\Lambda$)
  - ^{4}He+$\Xi^- \rightarrow ^5_{\Lambda\Lambda}$H / ^{7}Li+$\Xi^- \rightarrow ^8_{\Lambda\Lambda}$He / ^{9}Be+$\Xi^- \rightarrow ^{10}_{\Lambda\Lambda}$Li

Expected reconstruction rate :

- In case of a ^{20}Ne + ^{12}C @ 4.25 *A*GeV and 10^7/s :

	Single-Λ hypernuclei	Double-Λ hypernuclei
per day	$8 \cdot 10^5$	90
per week	$6 \cdot 10^6$	600
per month	$2 \cdot 10^7$	3000

Outline

Summary

At present :

- Hypernuclear physics: meeting point between particle physics and nuclear physics.
- The Phase 0 of the project was completed in October 2009 $\Rightarrow$ Milestone of the phase 0.
  - Demonstrated the feasibility of HypHI by observing the MWD of Λ, ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H
  - Evidence of ${}^{3}_{\Lambda}$n possible existence
  - Shorten lifetime of ${}^{3}_{\Lambda}$H: More theoretical study needed.
  - Cross sections and yield ratios will constrain hyper-matter production models.

Summary

In near Future :

- hypernuclear study @ FRS and SuperFRS as high resolution forward spectrometer
  - More precise hypernuclear spectroscopy, Sub MeV
  - Exclusive measurements : hypernuclear structure only.
- in near future at FRS (FAIR Phase 0):
  - $\Rightarrow$ Possibility to confirm or not the existence of $^{3}_{\Lambda}$n via d+π^{-}
  - Improve $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H mass resolution + Lifetime
- in future at SuperFRS:
  - Study proton and neutron-rich hypernuclei possible
    Unknown: $^{8}_{\Lambda}$Be, $^{16}_{\Lambda}$C, $^{9}_{\Lambda}$Li, $^{11}_{\Lambda}$Be, $^{13}_{\Lambda}$B
- Unique opportunity with HIAF - China for exotic hypernuclei & multi-hypernuclear object