Optimal design for experimental production of exotic hypernuclei

Fourth MODE Workshop

23-25/09/2024, Valencia (Spain)

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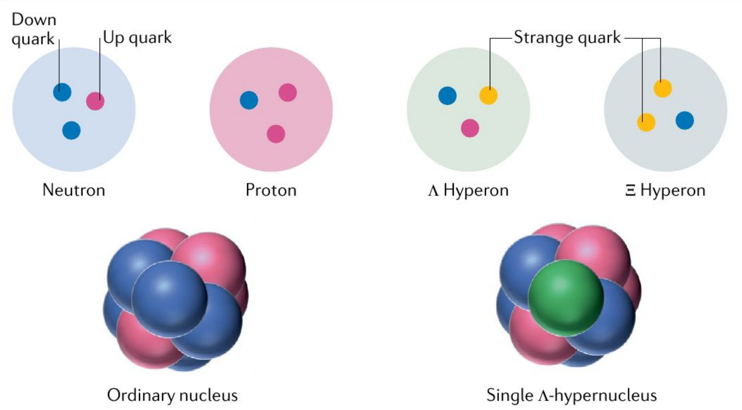
Introduction to hypernuclei

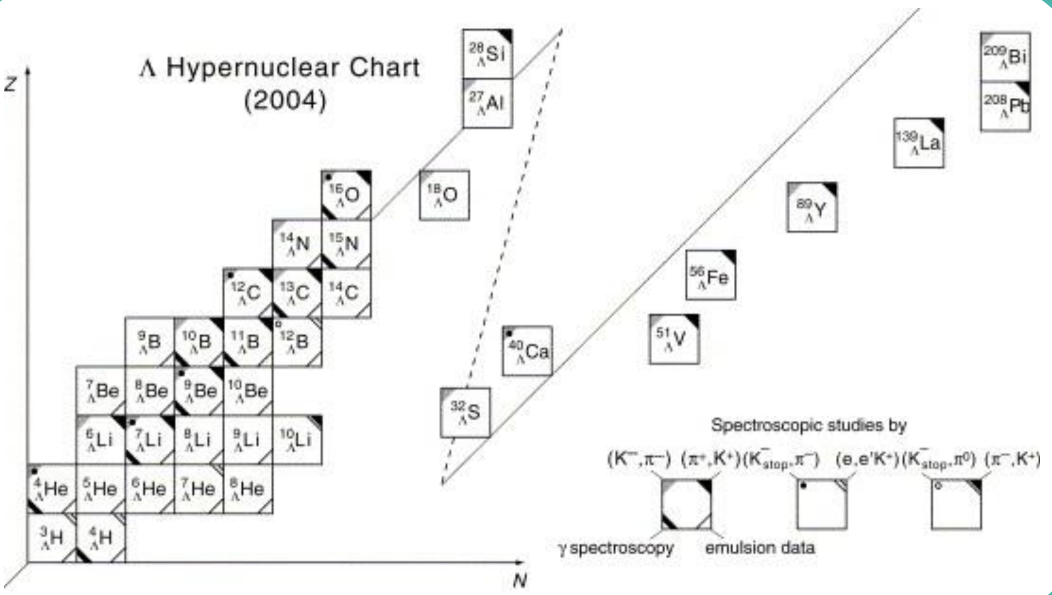


[T.R. Saito *et al.*, Nature Reviews Physics **3** (2021) 803-813]

<u>Study Y-N and Y-Y interaction:</u>

- Difficult to get scattering data
  - Short lifetime
- Analyse Charge Symmetry Breaking (CSB)
  - Difference Y-p and Y-n
- Describe hypernuclei (mass and half-life)
- Modelize high-density environments
  - Neutron stars cores

Introduction to hypernuclei



[O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. **57** (2006) 564]

To produce hypernuclei far from the stability line

Need of exotic isotope beams

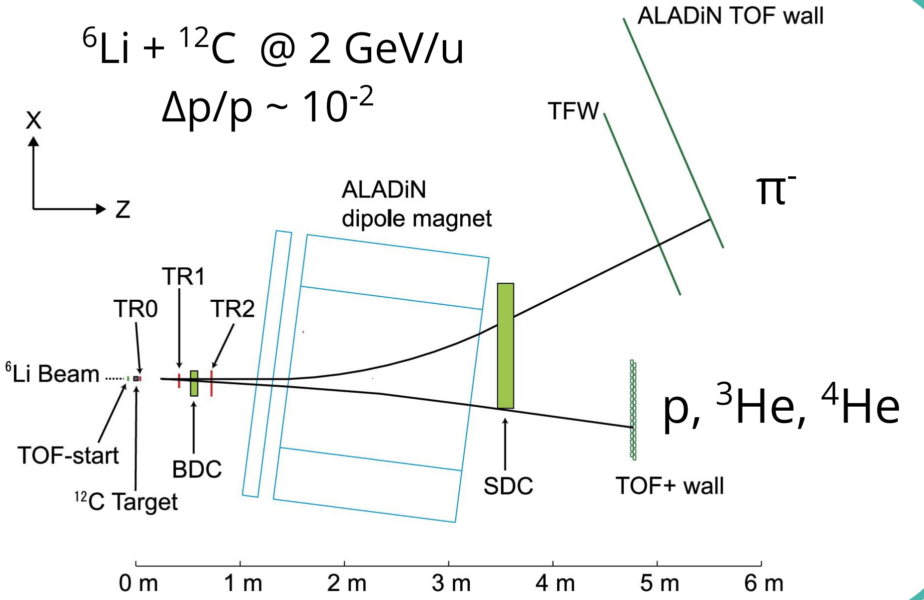
Use of a fragment separator

Experiments without fragment separator

- Phase 0 of HypHI Project in GSI-FAIR (Germany) in 2009

$^{6}Li + ^{12}C$ @ 2 GeV/u

$\Delta p/p \sim 10^{-2}$



[C. Rappold *et al.*, Nucl. Phys. A **913** (2013) 170-184]

Two-body
mesonic weak decay

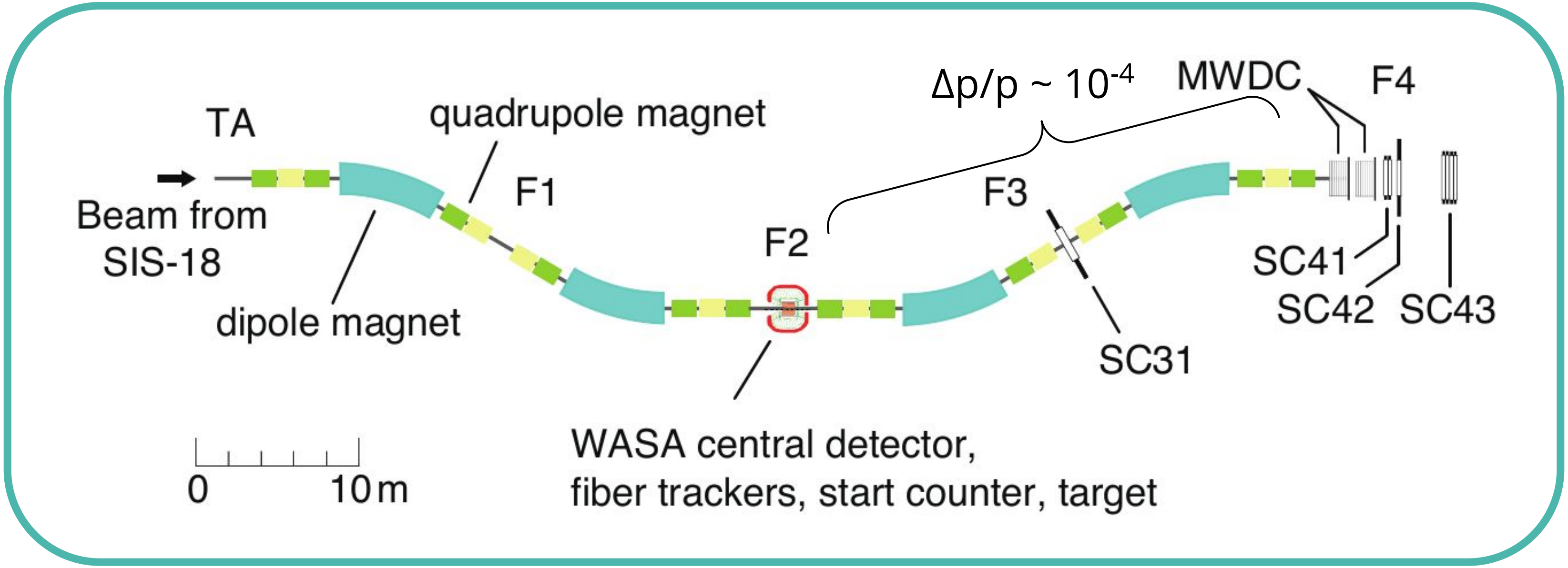
$\Lambda \rightarrow p + \pi^-$

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

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

Experiments with fragment separator

- WASA-FRS Experiment of HypHI Project in GSI-FAIR (Germany) in 2022



Experiments with fragment separator

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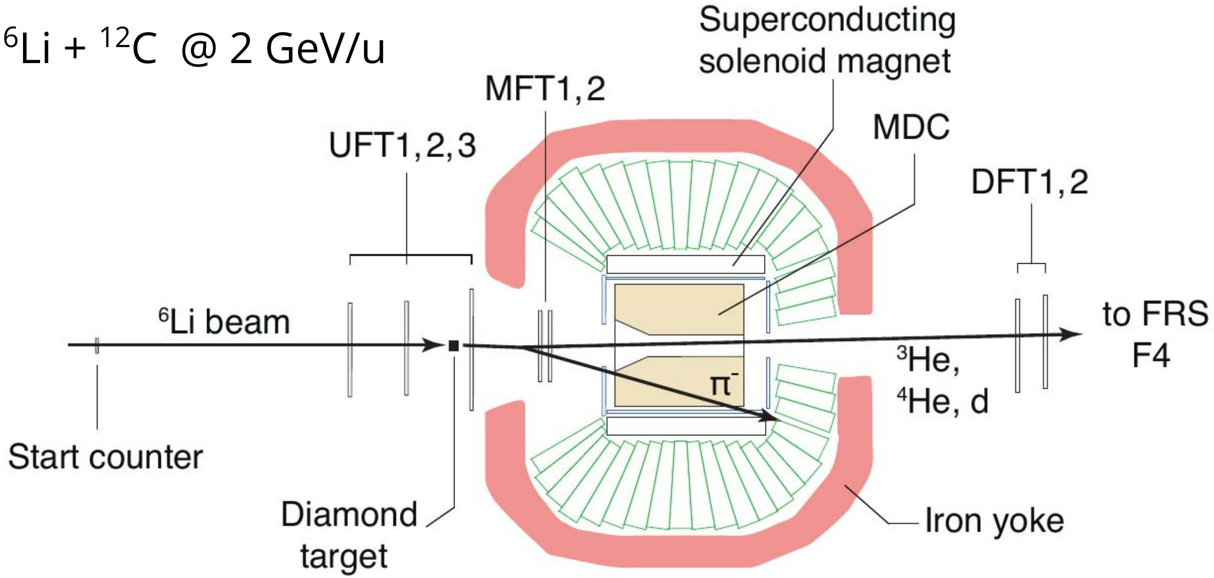
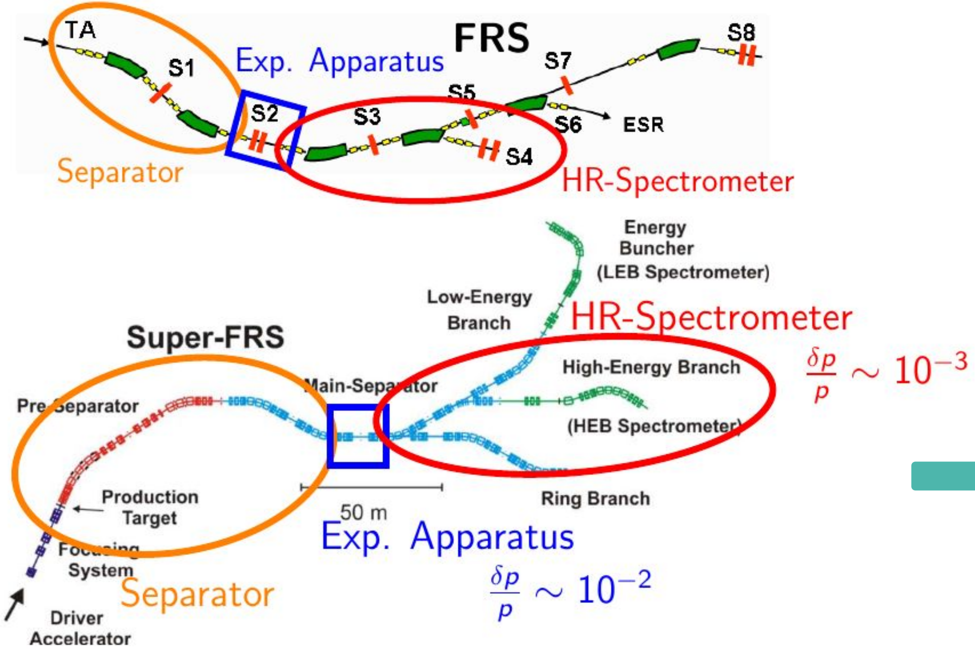


Experiments with fragment separator

- New experiment in SuperFRS of HypHI Project in GSI-FAIR (Germany)

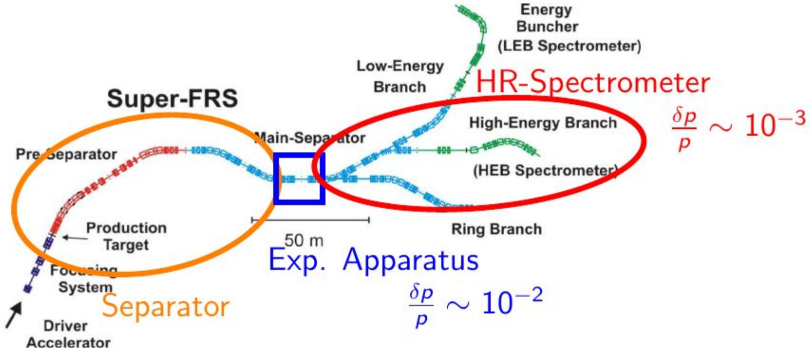


Allow for hypernuclear production via exotic beams

Exp. optimization for hypernuclear production

<u>Goal:</u>

➢ Maximize hypernuclear yield



<u>Many parameters:</u>

➢ Primary beam: isotope, energy

➢ Primary target: isotope, thickness

➢ Separator setup for exotic beam: Bρ, slits, degrader → intensity, energy, contaminants

➢ Secondary target: isotope, thickness

Production of exotic beam

Optimization of:

- ➢ Exotic beam yield
  (all isotopes from H to $_{21}$Sc)

Variables:

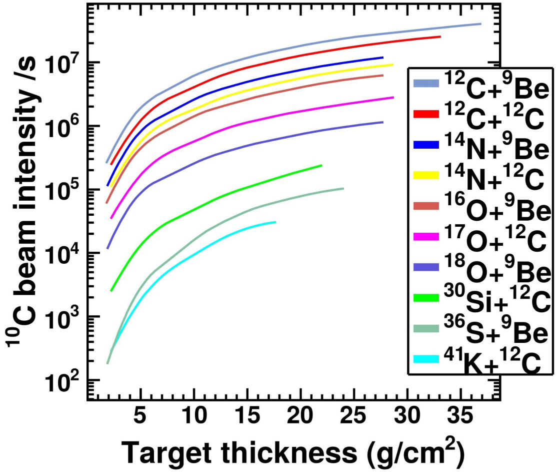
- ➢ Primary beam isotope
- ➢ Primary target isotope
  (all stable up to ^{40}Ca)
- ➢ Primary target thickness

Fix parameter:

- ➢ Primary beam intensity: 5×10^9 ions/s

Universal empirical formula EPAX for fragmentation cross sections

Example for ^{10}C production

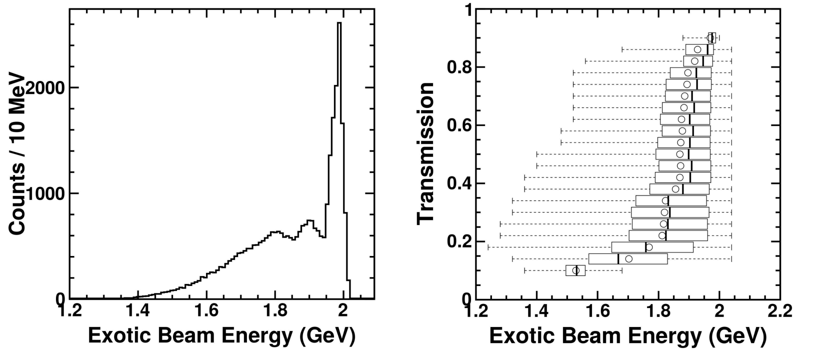


[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

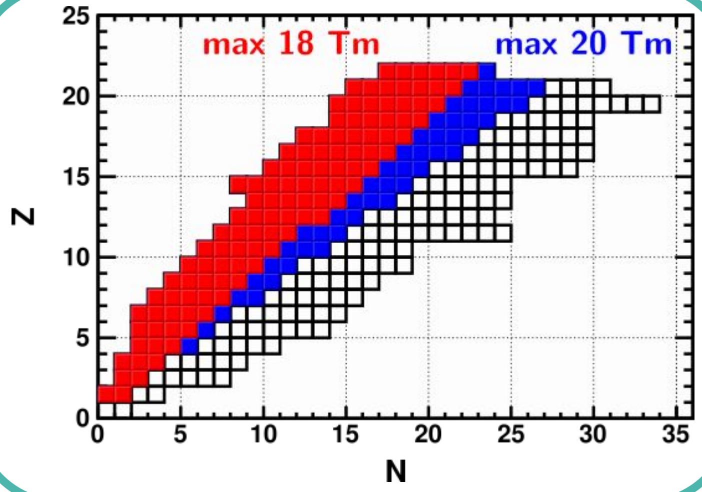
Transmission of exotic beam

MOCADI code for MC simulations of ion-optic transmission

Magnetic rigidity limitation: maximum of 20 Tm



[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]



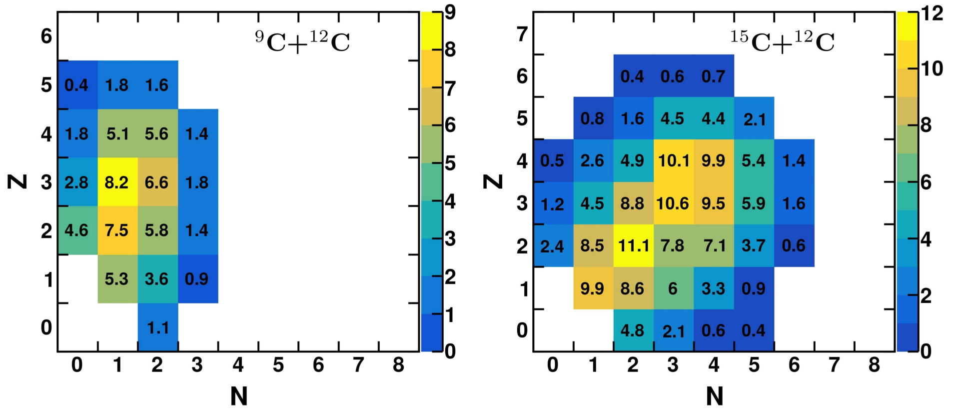
Production of hypernuclei

Theoretical model for collisions hadron-hadron, hadron-N, N-N:
Quark-Gluon String Model (QGSM)

Hypernuclear production cross-section (μb)

Fixed parameter:
collision at 2 GeV/u

Hypernucleus



[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

Production of hypernuclei

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Hypernuclear production cross-section (μb)

Fixed parameter:
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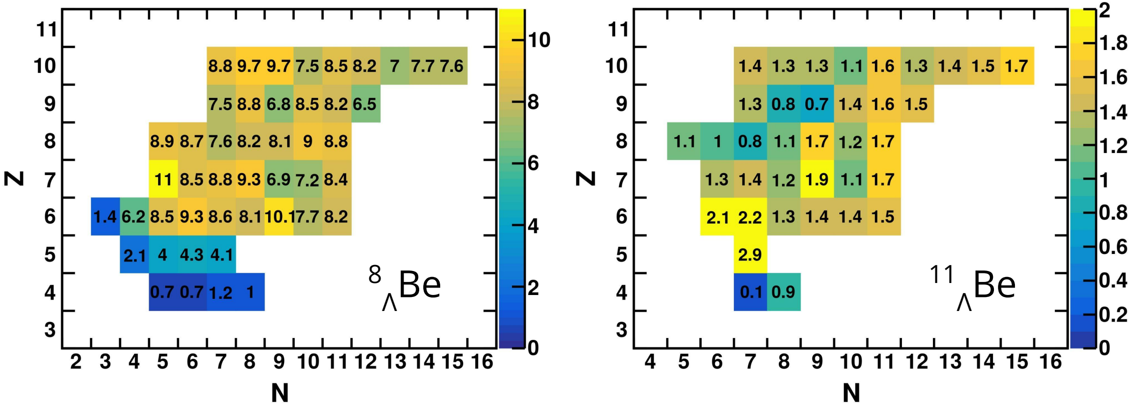
^{12}C target

Exotic beam isotope



[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

Multivariate analysis

Cost function:

$F_{\alpha,\beta}(C, E, T, I) = \alpha C + \beta E - \gamma T + \delta I$

$\alpha^2 + \beta^2 + \gamma^2 + \delta^2 = 1$

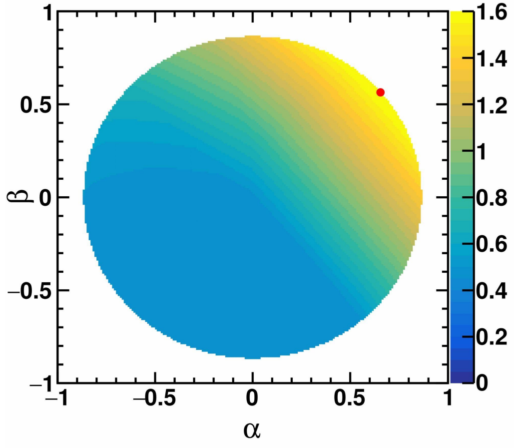
$\alpha, \beta, \gamma, \delta \in [-1, 1]$

$\delta = 0.5$ (for numerical stability)

Maximize cost function:

$$\underset{C,E,T,I}{\text{argmax}}\{F_{\alpha,\beta}(C, E, T, I)\}$$

Calculation for ${}^{8}_{\Lambda}$Be



[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

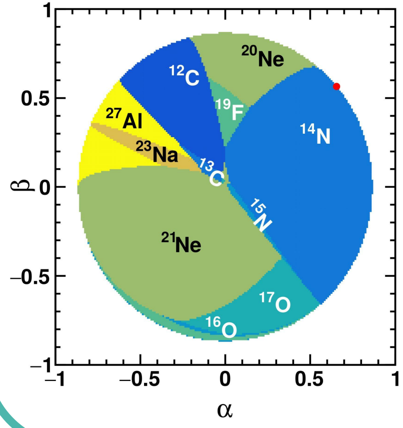
Multivariate analysis

Maximax criterion:

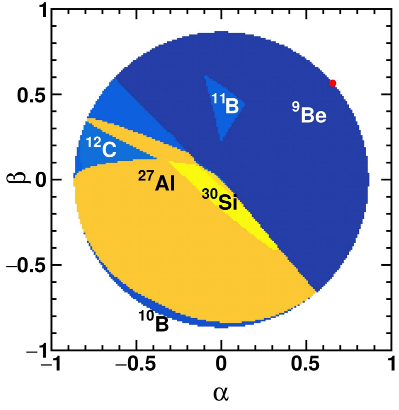
$$\underset{\alpha,\beta}{\text{argmax}} \max_{C,E,T,I} \{F_{\alpha,\beta}(C,E,T,I)\}$$

Calculation for $^{8}_{\Lambda}$Be

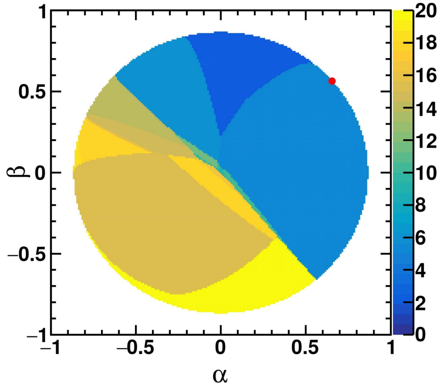
Primary beam isotope



Primary target isotope



Primary target thickness (g/cm^2)



[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

Multivariate analysis

Maximax criterion:

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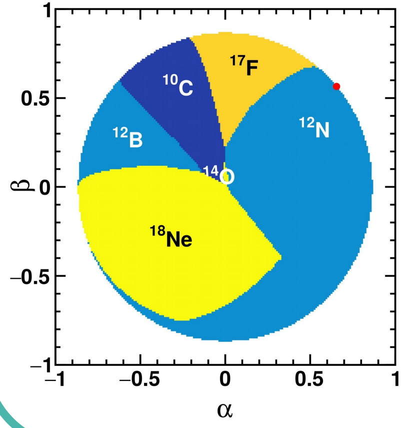
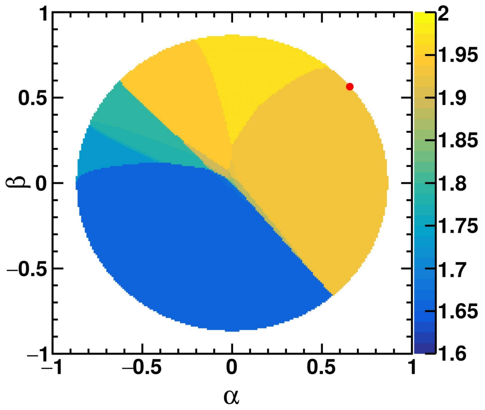
Calculation for $^{8}_{\Lambda}$Be

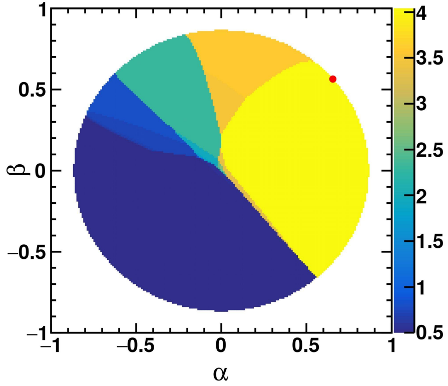
Exotic beam isotope



Exotic beam energy (GeV/u)



Hypernuclear yield (s^{-1})



[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

Multivariate analysis results

	Reaction	Target (cm)	2^{nd} beam	E_k (AGeV)	I (10^6/s)	Yield (/s)
$^{8}_{\Lambda}$C	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.2
$^{9}_{\Lambda}$C	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.8
$^{10}_{\Lambda}$C	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	1.5
$^{11}_{\Lambda}$C	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.9
$^{7}_{\Lambda}$B	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.7
$^{8}_{\Lambda}$B	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	2.7
$^{9}_{\Lambda}$B	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	3.5
$^{10}_{\Lambda}$B	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	2.5
$^{11}_{\Lambda}$B	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	1.2
$^{5}_{\Lambda}$Be	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	0.6
$^{6}_{\Lambda}$Be	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	1.9
$^{7}_{\Lambda}$Be	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	3.9
$^{8}_{\Lambda}$Be	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	4.0
$^{9}_{\Lambda}$Be	stable beam		^{16}O	2.	10.	4.4
$^{10}_{\Lambda}$Be	stable beam		^{14}N	2.	10	3.1
$^{11}_{\Lambda}$Be	^{23}Na+^{11}B	15.5	^{12}B	1.79	1.2	0.6
$^{4}_{\Lambda}$Li	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	1.1
$^{5}_{\Lambda}$Li	^{12}C+^{9}Be	6	^{10}C	1.94	5.1	2.5
$^{6}_{\Lambda}$Li	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	4.3
$^{7}_{\Lambda}$Li	stable beam		^{14}N	2.	10.	5.2

	Reaction	Target (cm)	2^{nd} beam	E_k (AGeV)	I (10^6/s)	Yield (/s)
$^{8}_{\Lambda}$Li	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	3.7
$^{9}_{\Lambda}$Li	^{16}O+^{9}Be	5.5	^{14}O	1.93	5.5	2.2
$^{10}_{\Lambda}$Li	^{23}Na+^{11}B	15.5	^{12}B	1.79	11.5	1.1
$^{11}_{\Lambda}$Li	^{23}Na+^{11}B	15.5	^{12}B	1.79	11.5	0.12
$^{3}_{\Lambda}$He	^{14}N+^{9}Be	5.5	^{12}N	1.94	5.1	1.8
$^{4}_{\Lambda}$He	stable beam		^{14}N	2.	10.	4.1
$^{5}_{\Lambda}$He	stable beam		^{20}Ne	2.0	10.	5.2
$^{6}_{\Lambda}$He	stable beam		^{12}C	2.	10.	4.8
$^{7}_{\Lambda}$He	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	2.9
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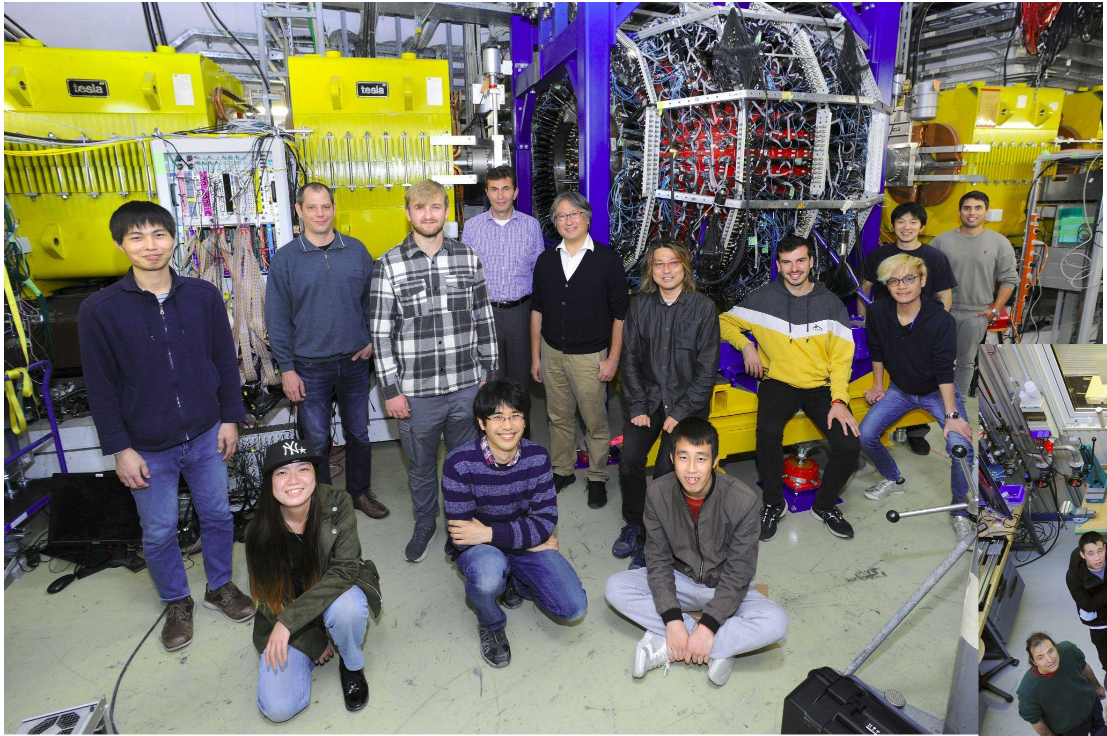
$^{8}_{\Lambda}$H	^{23}Ne+^{9}Be	15.5	^{12}B	1.79	11.5	0.3
$^{3}_{\Lambda}$n	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	2.1
$^{4}_{\Lambda}$n	^{20}Ne+^{9}Be	2	^{17}F	1.97	5.7	1.0

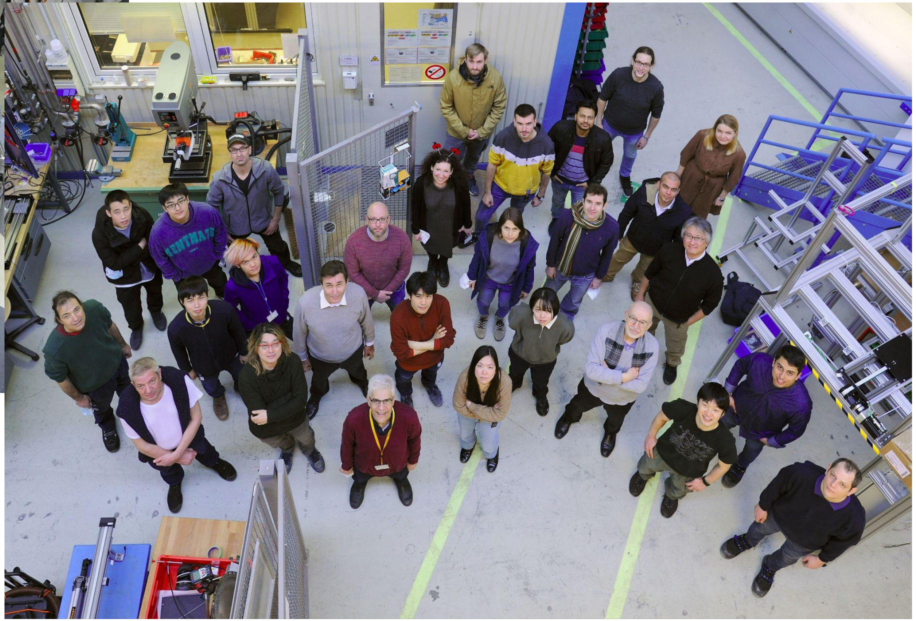
[C. Rappold and J. López-Fidalgo, Phys. Rev. C **94** (2016) 044616]

Conclusion

<u>Optimization of experimental study of exotic hypernuclei</u>

- More precise hypernuclear spectroscopy, targeting sub-MeV
- Use of FRS and SuperFRS
  - Separator to provide exotic beams
  - High resolution spectrometer for decayed fragment
  - Exclusive measurements
- Future at SuperFRS
  - Possibility to study neutron-deficient and neutron-rich hypernuclei
  - Example for $^{8}_{\Lambda}Be$:
    - Primary beam ^{14}N to a 5.5-cm primary target of ^{9}Be, separating ^{12}N to bombard a 4-cm ^{12}C secondary target, in order to produce 4 $^{8}_{\Lambda}Be$ per second





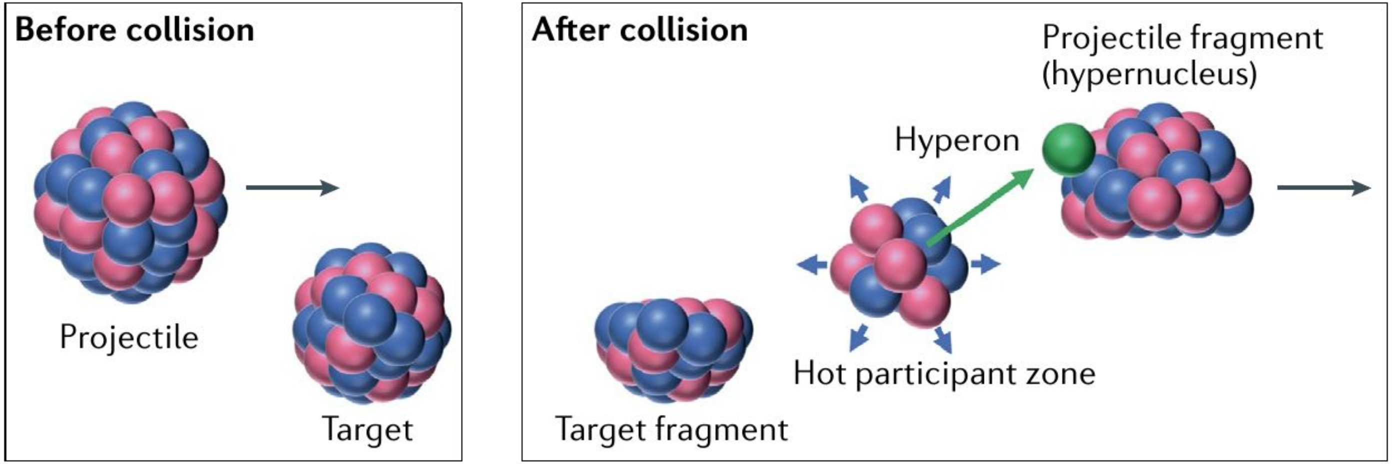
Thank you for your attention!

Back up

Experiments without fragment separator

- Phase 0 of HypHI Project in GSI-FAIR (Germany) in 2009

Coalescence of Λ in spectator fragment
Reaction energy threshold ~1.6 GeV for NN → ΛNN



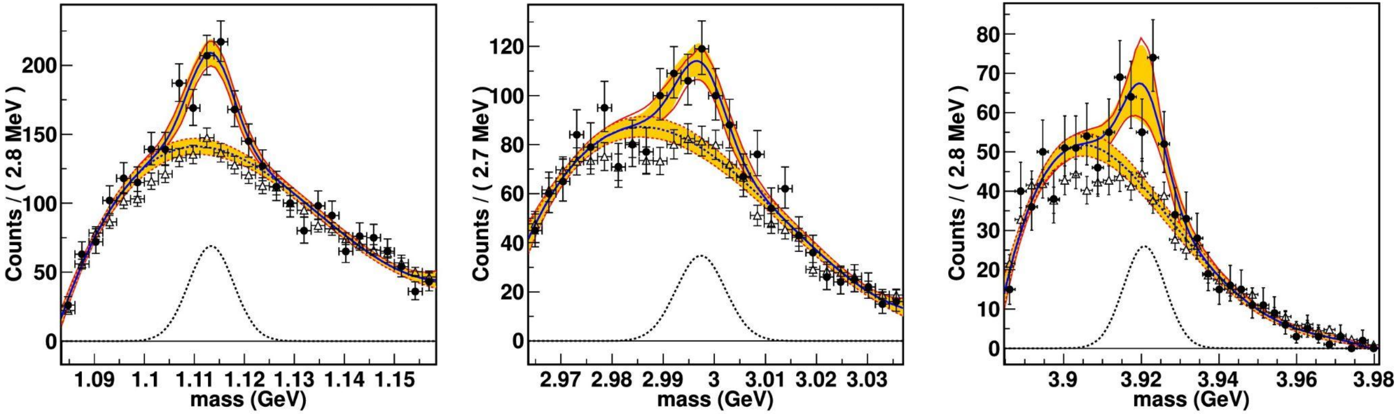
[T.R. Saito *et al.*, Nature Reviews Physics **3** (2021) 803-813]

Experiments without fragment separator

- Phase 0 of HypHI Project in GSI-FAIR (Germany) in 2009

Invariant Mass: $M_{hyp} = \sqrt{\left(\sum E_{decay}\right)^2 - \left\|\sum \vec{p}_{decay}\right\|^2}$

$\Lambda \rightarrow p + \pi^-$ | ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$ | ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$



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