Study of the 2-neutron decay of ^{13}Li and ^{11}Li via the invariant mass method @RIBF

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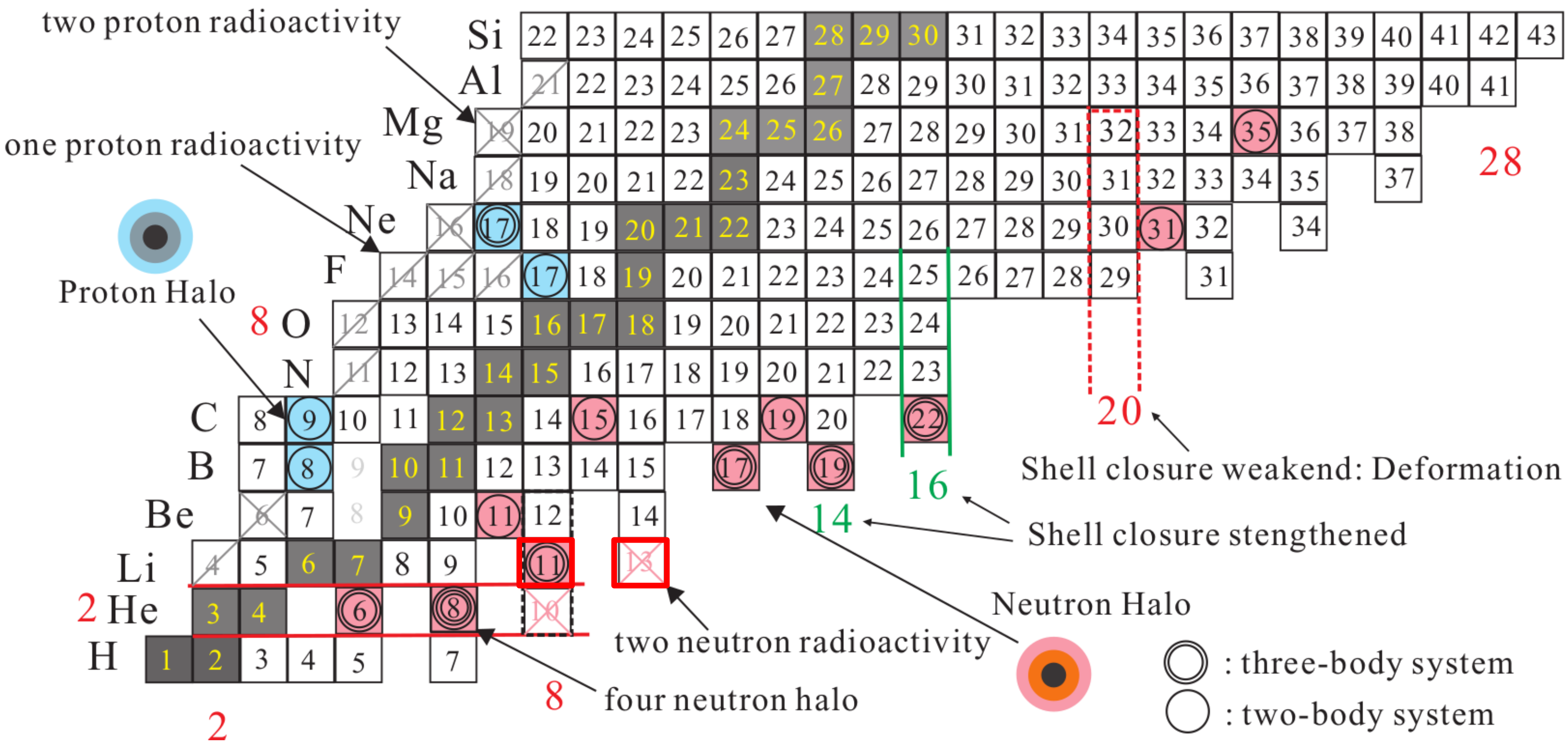
Nuclear Physics at the edge of stability

07/07/2022

Neutron-rich isotopes



→ What are the limits of nuclear existence ?

→ Emergence of exotic structures ? (Halo, dineutron)

Neutron-rich isotopes : testing ground for n-n correlations

Figure : C.-B. Moon *et al.*, AIP Advances **4** (2014)

How to study n-n correlations ?

- Coulomb dissociation

T. Nakamura *et al.*, PRL **96** (2006)

- 2n interferometry

F.M. Marques *et al.*, Phys. Lett. B **476** (2000)

- Neutron transfer reactions

I. Tanihata *et al.*, PRL **100** (2008)

- Fragmentation reactions

H. Simon *et al.*, Nucl. Phys. A **791** (2007)

- Quasi-free scattering reactions

[1] Y. Kubota *et al.*, PRL **125** (2020)

-<u>2n decay</u>

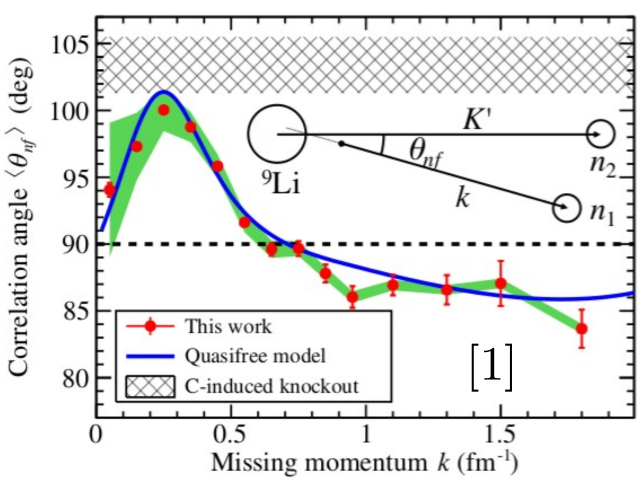
of ^{26}O

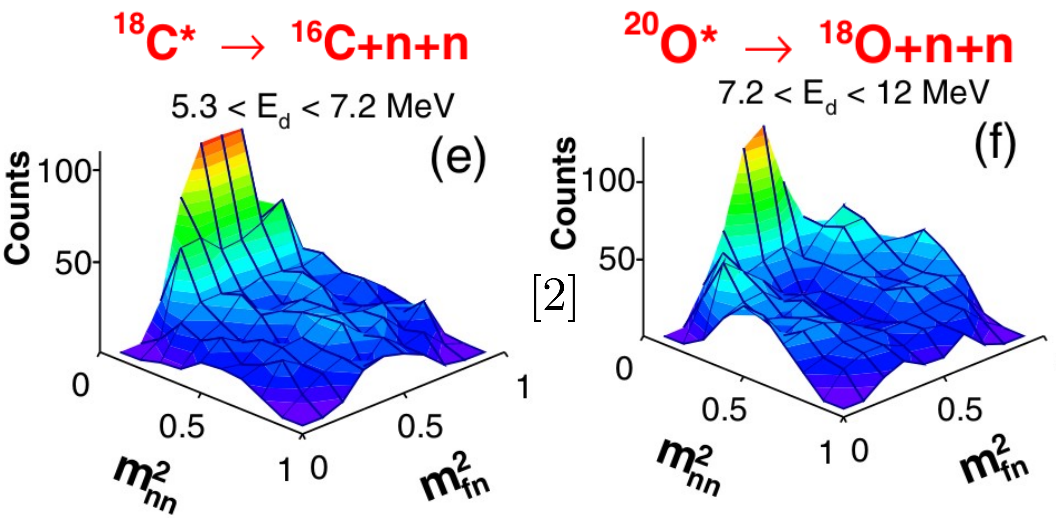
Y. Kondo *et al.*, PRL **116** (2016)

K. Hagino, H. Sagawa, Phys. Rev. C **90** (2016)

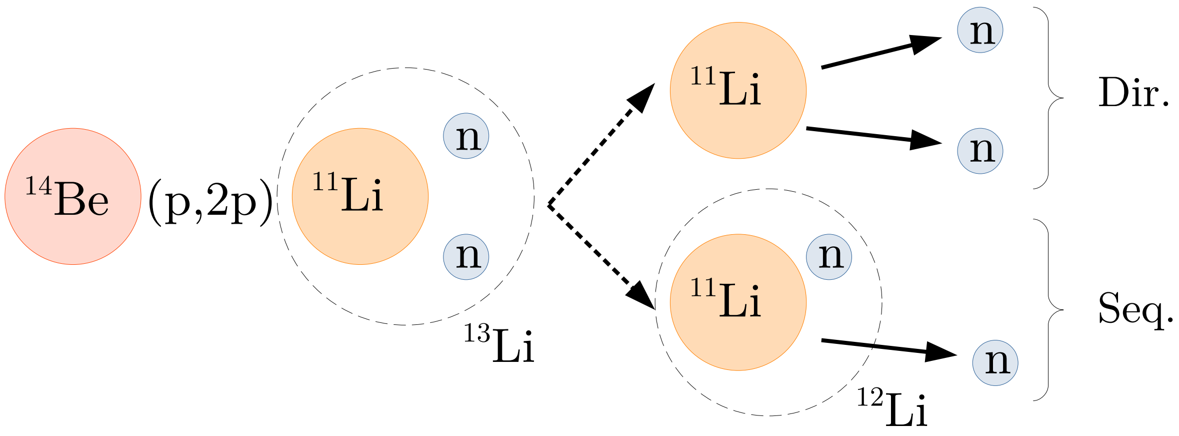
of ^{18}C and ^{20}O

[2]A. Revel *et al.*, PRL **120** (2018)





Decay paths



- Direct decay : Simultaneous emission of neutrons with correlations
- Sequential decay : emission of one neutron after the other

$$C_{nn} = \frac{\mathrm{d}^2 n/\mathrm{d}p_{n_1}\mathrm{d}p_{n_2}}{(\mathrm{d}n/\mathrm{d}p_{n_1})(\mathrm{d}n/\mathrm{d}p_{n_2})} \simeq \int W(\vec{r}, t, r_{nn}, \tau_{nn}) F(\vec{r}, q_{nn}, r_{nn}) \mathrm{d}t\mathrm{d}\vec{r} \quad [1]$$

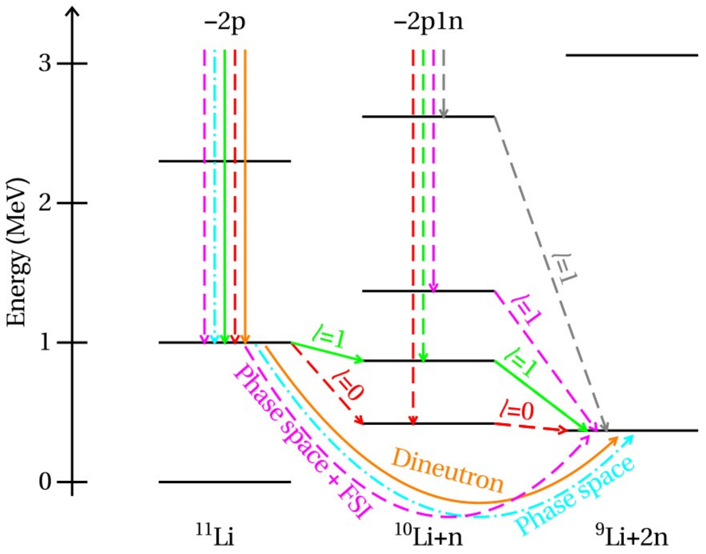
n-n distance

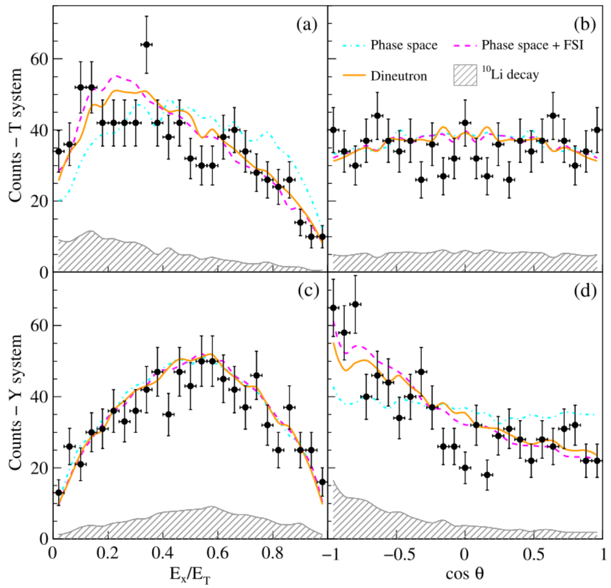
[1] R. Lednicky, V.L. Lyuboshits, Sov. J. Nucl. Phys. **35**(5) (1982)

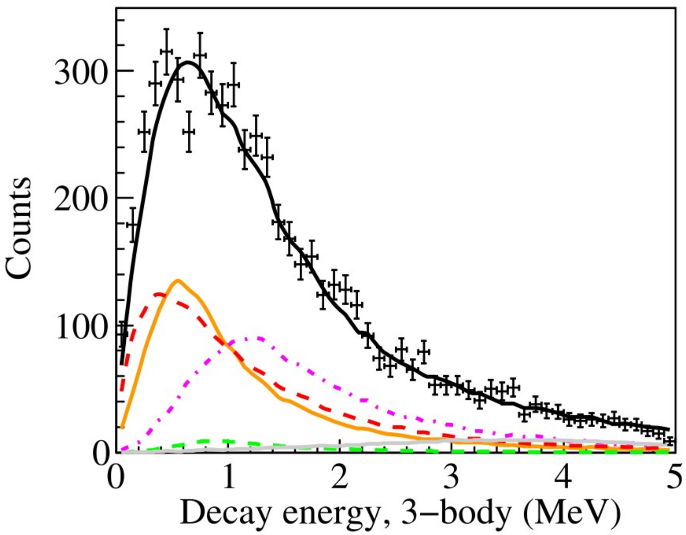
State of the art for ^{11}Li

Decay path as ansatz of the contributions in the fit

3B and 2B decay energy spectra & Jacobi coordinates





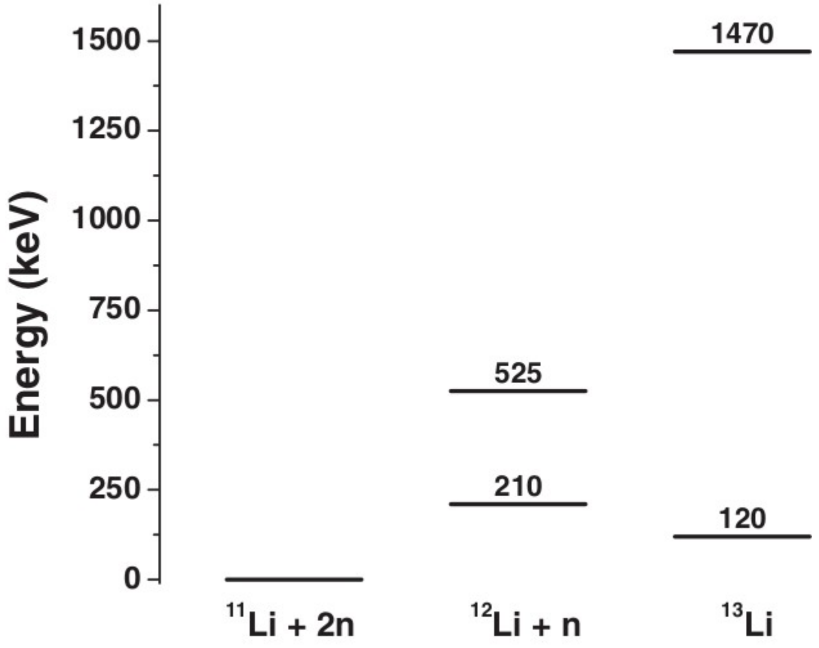


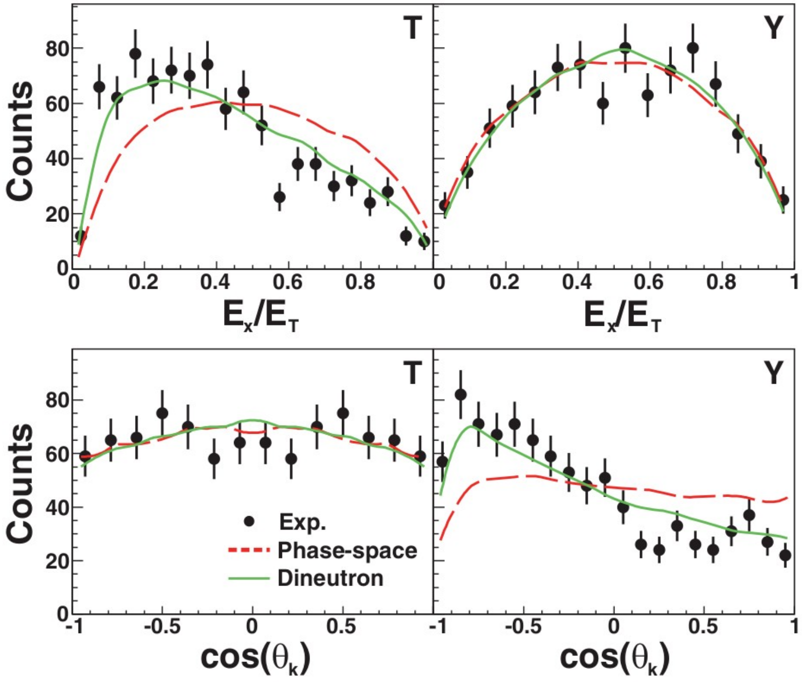
- Measurement of a ~810keV resonant state in ^{11}Li
- Best reproduction of Jacobi coordinates with direct decay

J.K. Smith *et al.*, Nucl. Phys. A **955** (2016)

State of the art for ^{13}Li

3B and 2B decay energy spectra & Jacobi coordinates



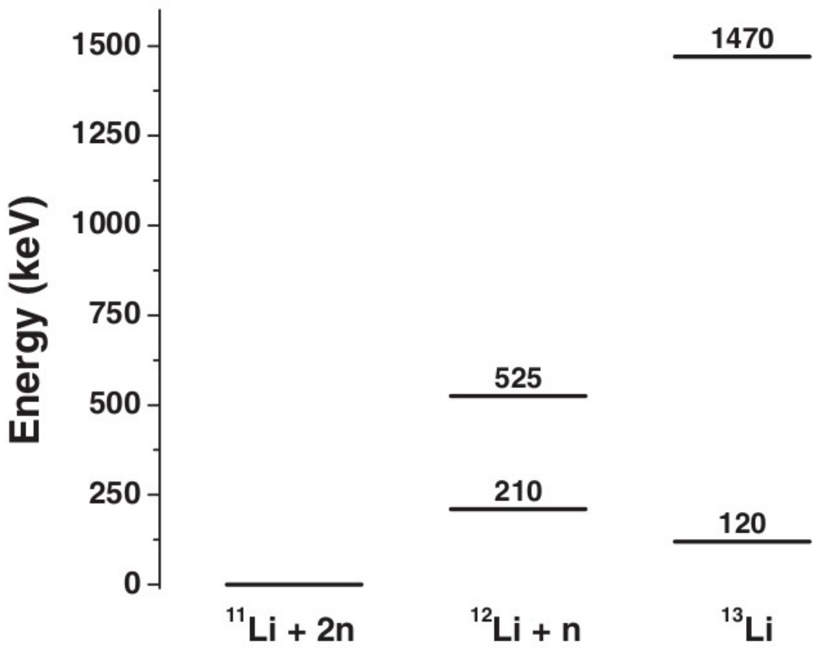


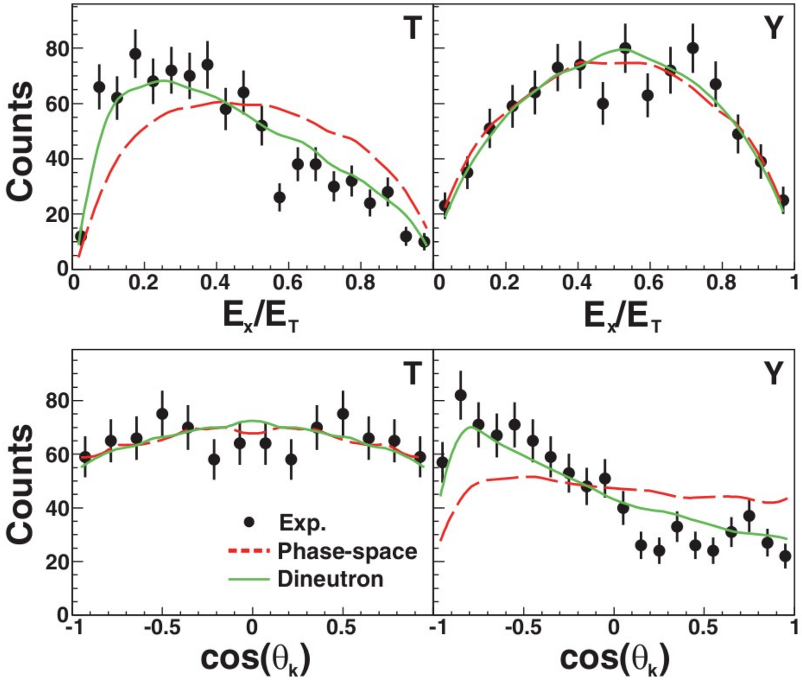
- First measurement of the ground state of ^{13}Li
- First observation of n-n correlations in ^{13}Li

Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

State of the art for ^{13}Li

3B and 2B decay energy spectra & Jacobi coordinates





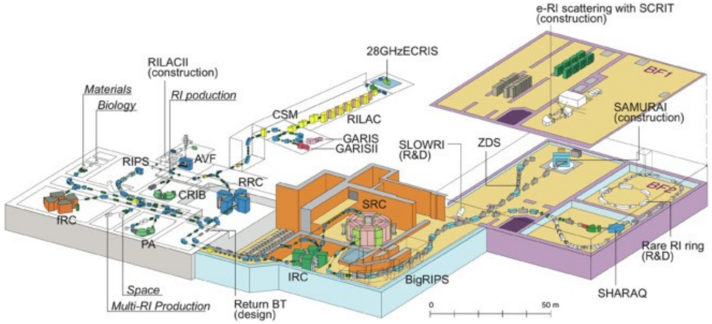
- First measurement of the ground state of ^{13}Li
- First observation of n-n correlations in ^{13}Li

→ Improvement of resolution and statistics in this study

Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

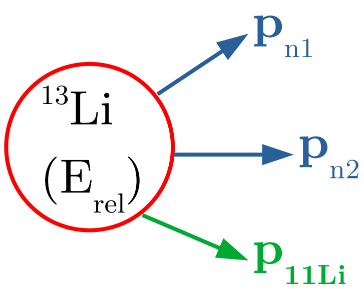
Outline

I – Experimental set-up

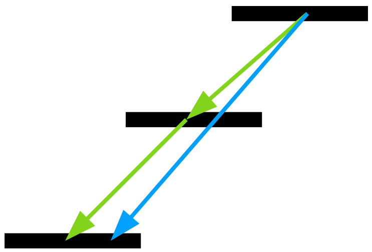


II – Data analysis :

Cross-talk and simulations



III – Results : decay process of ^{13}Li and ^{11}Li



Experimental set-up

RIBF @ Riken Nishina Center

Radioactive **I**sotope **B**eam **F**actory

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RIKEN Nishina Center for Accelerator-Based Science
Introduction to RI Beam Factory and Users' Information

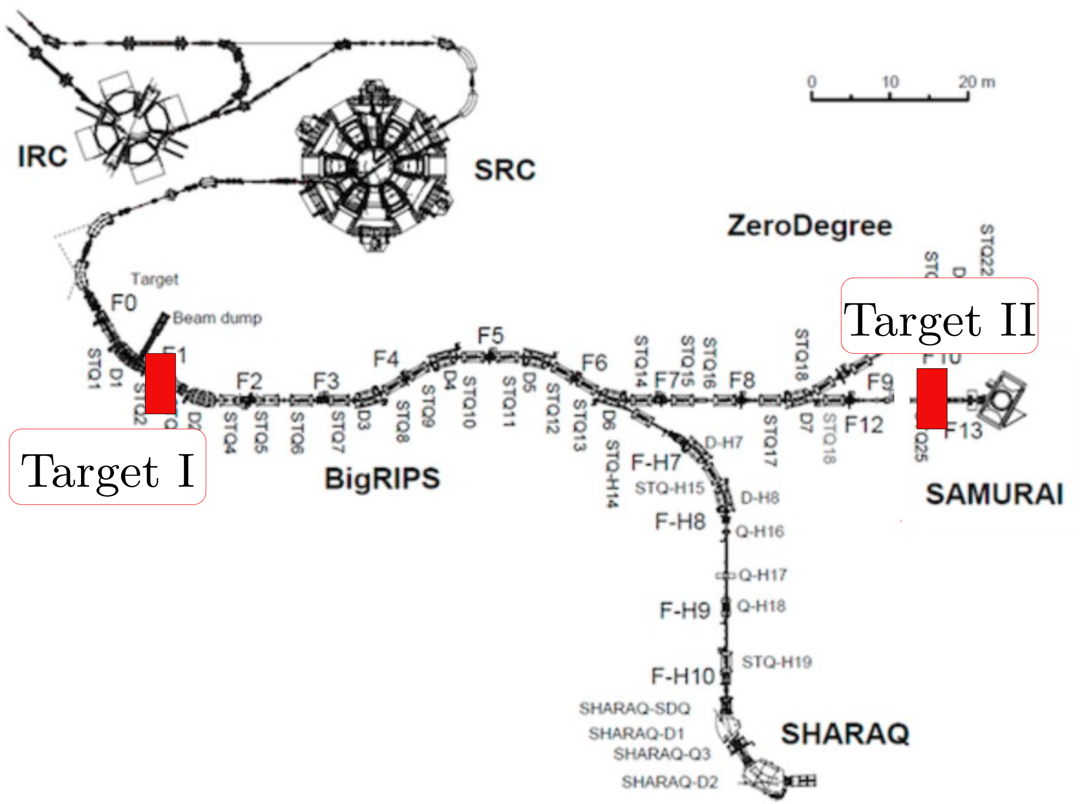

Fig. : https://www.nishina.riken.jp/ribf/SAMURAI/overview.html

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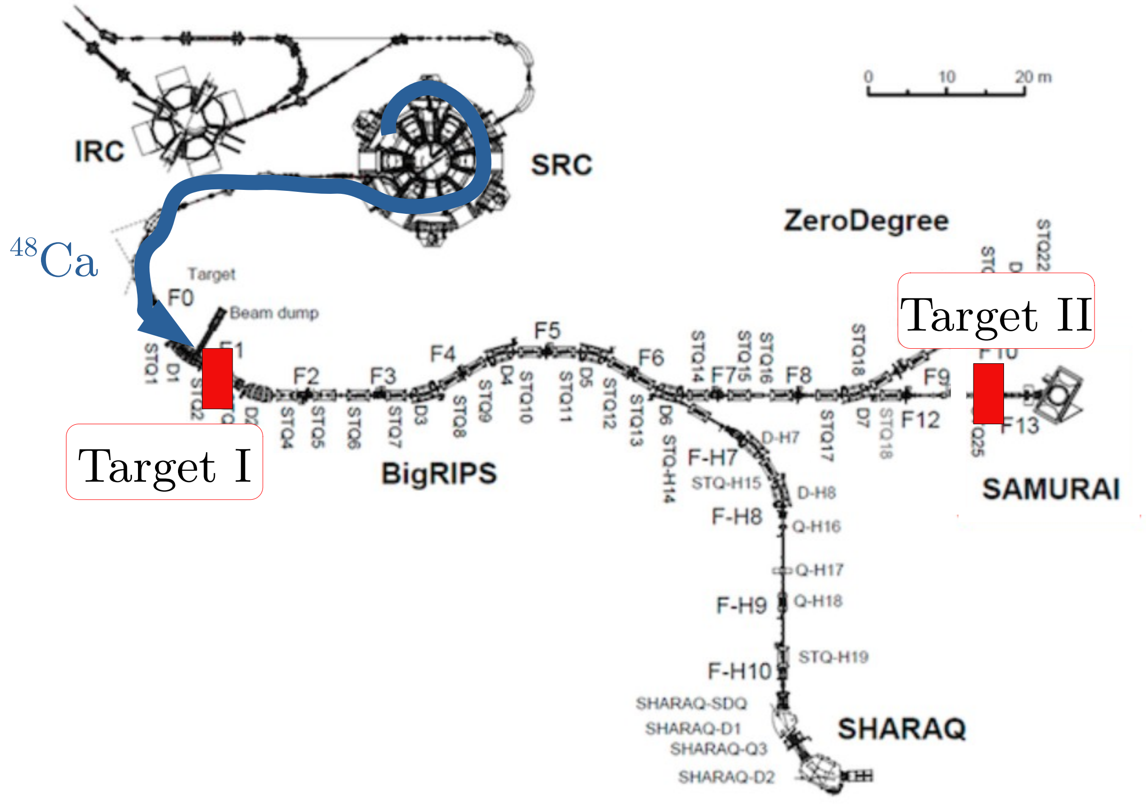

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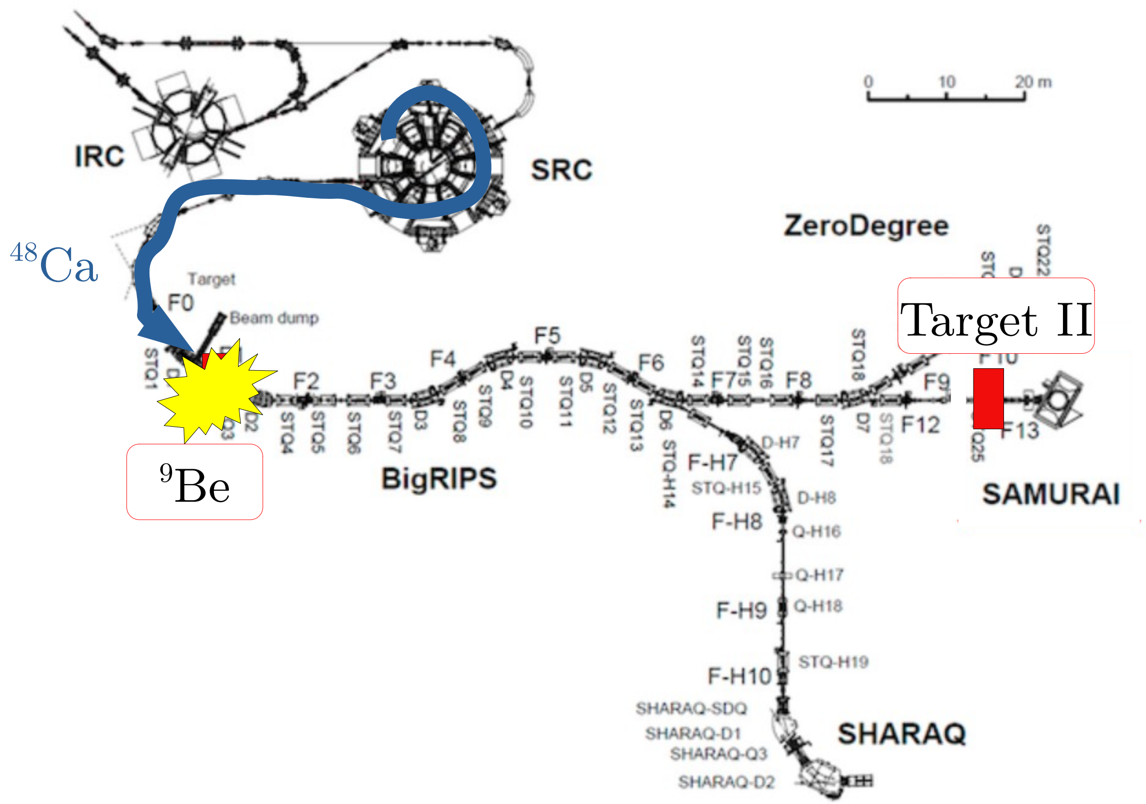

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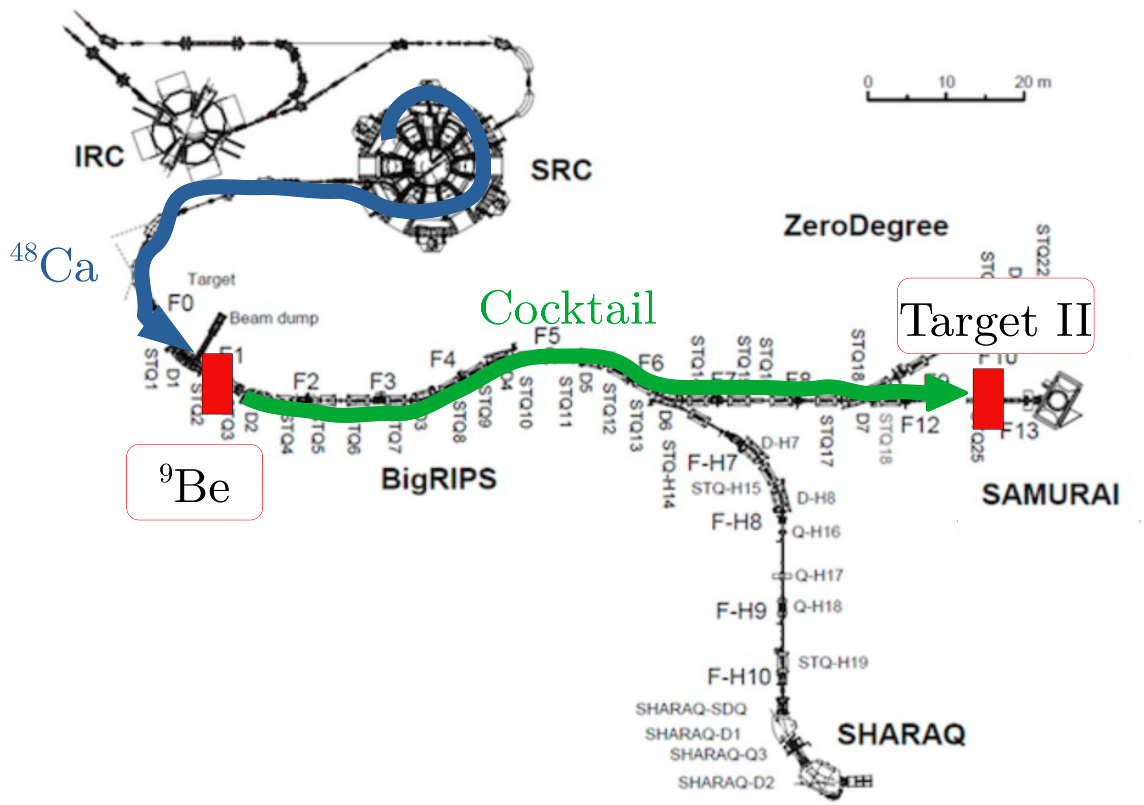

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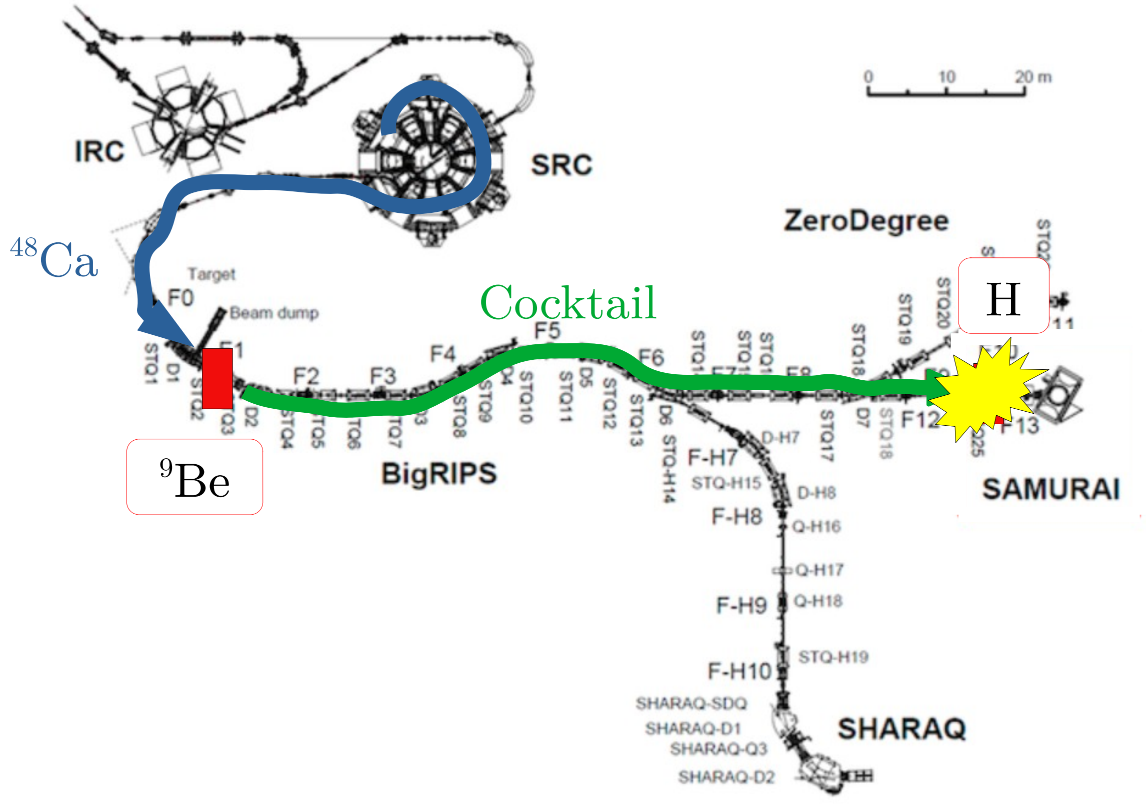

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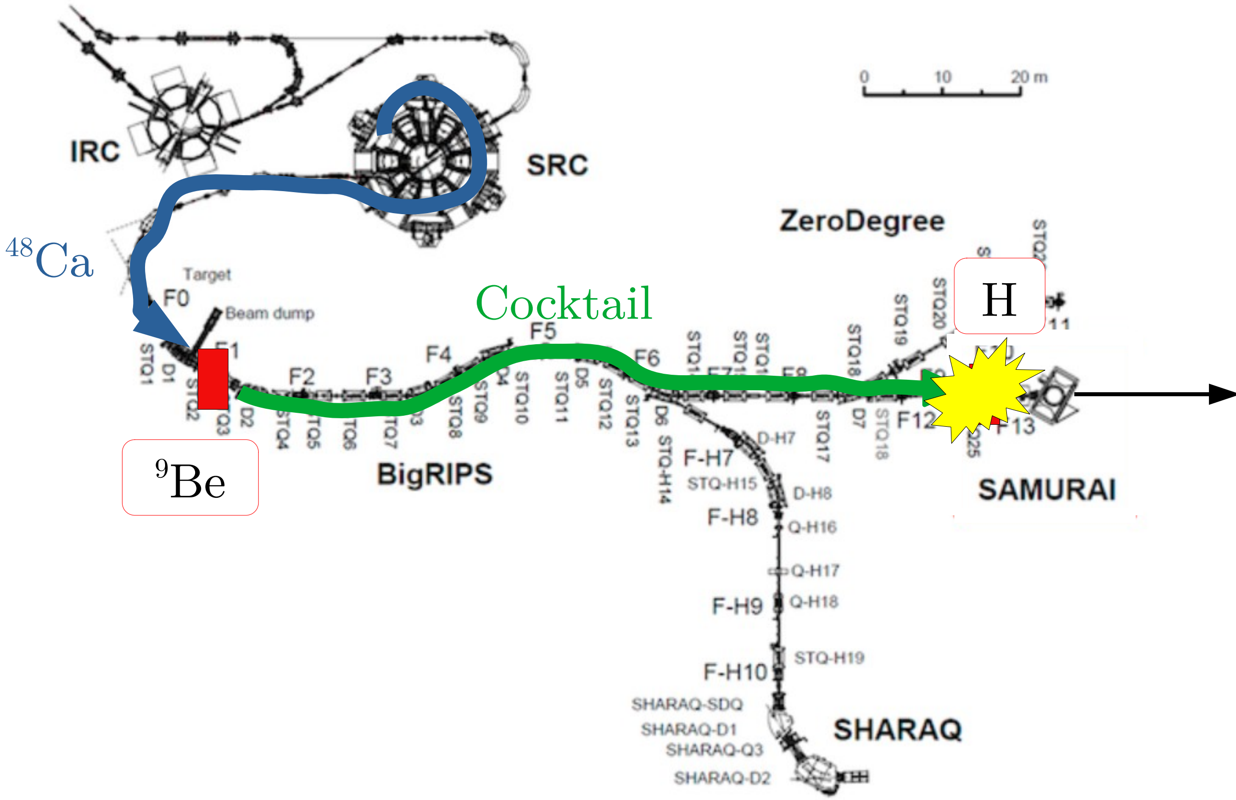


Detection of decay products

In the cocktail beam :

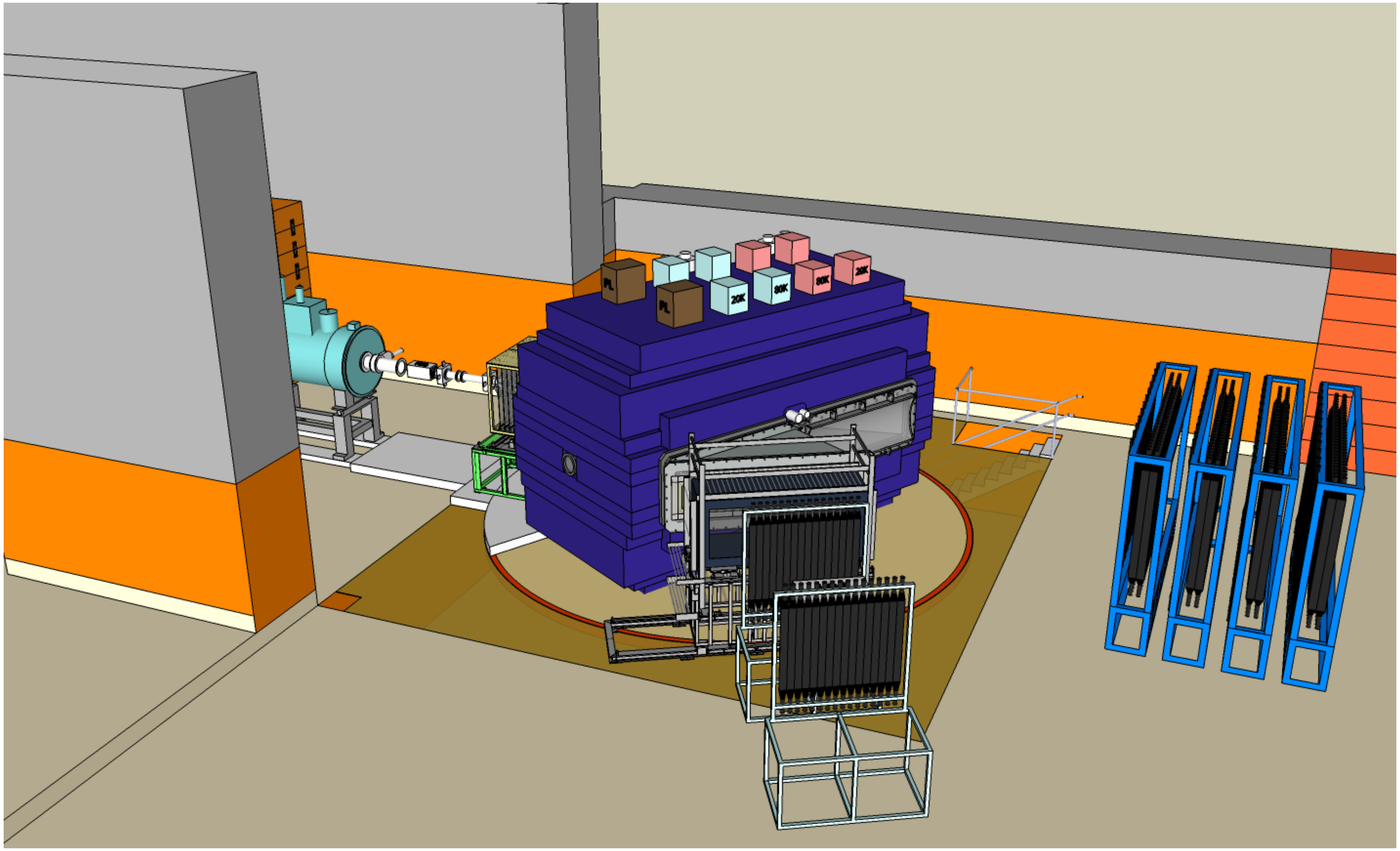
- 80% of ^{11}Li
- 12% of ^{14}Be
- 8% of ^{17}B

Reactions of interest :

- ^{14}Be(p,2p)^{13}Li
- ^{12}Be(p,2p)^{11}Li

Fig. : https://www.nishina.riken.jp/ribf/SAMURAI/overview.html

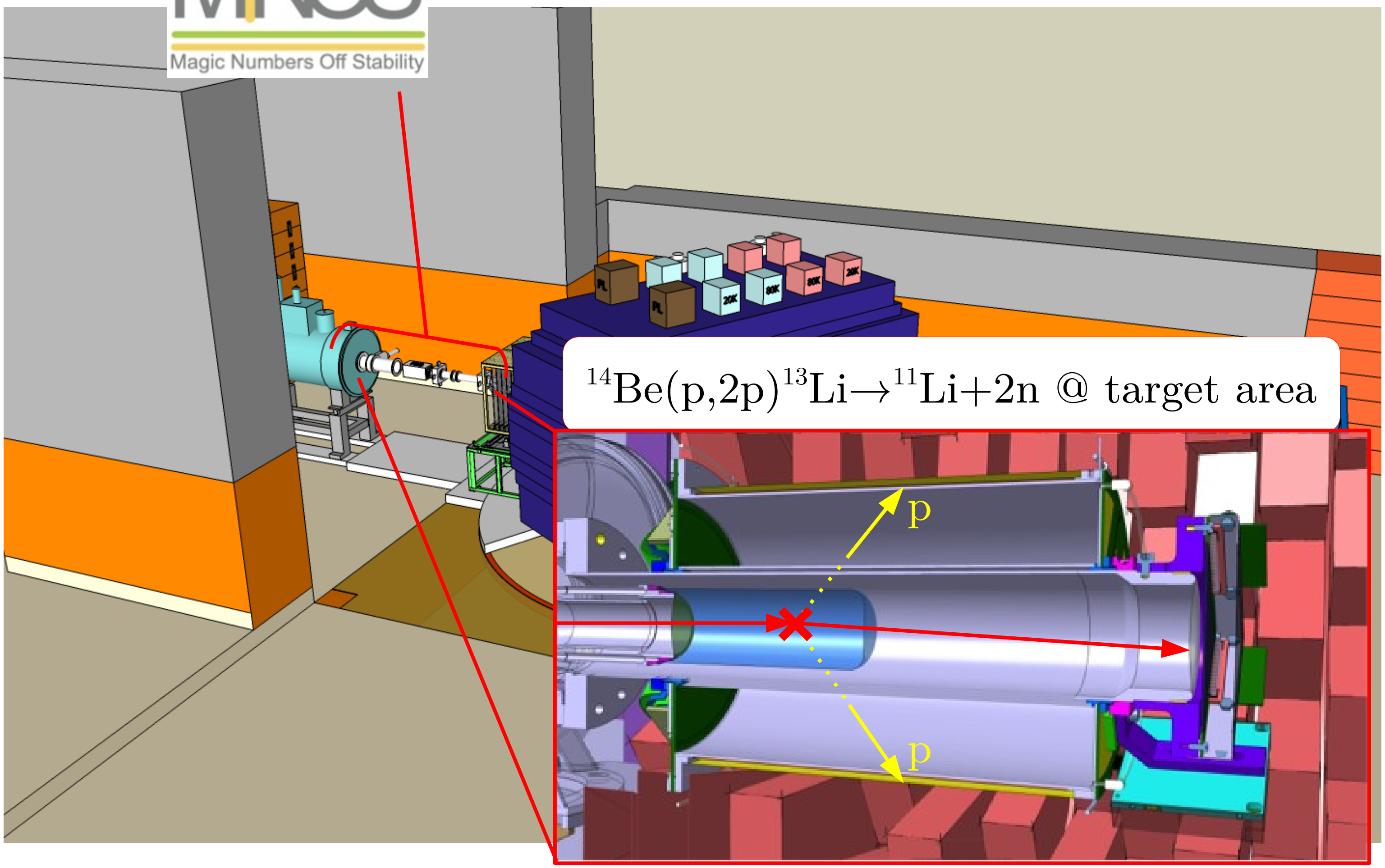
MINOS, NEBULA & SAMURAI



T. Kobayashi *et al.*, Nucl. Instrum. Methods Phys. Res. B **317** (2013)

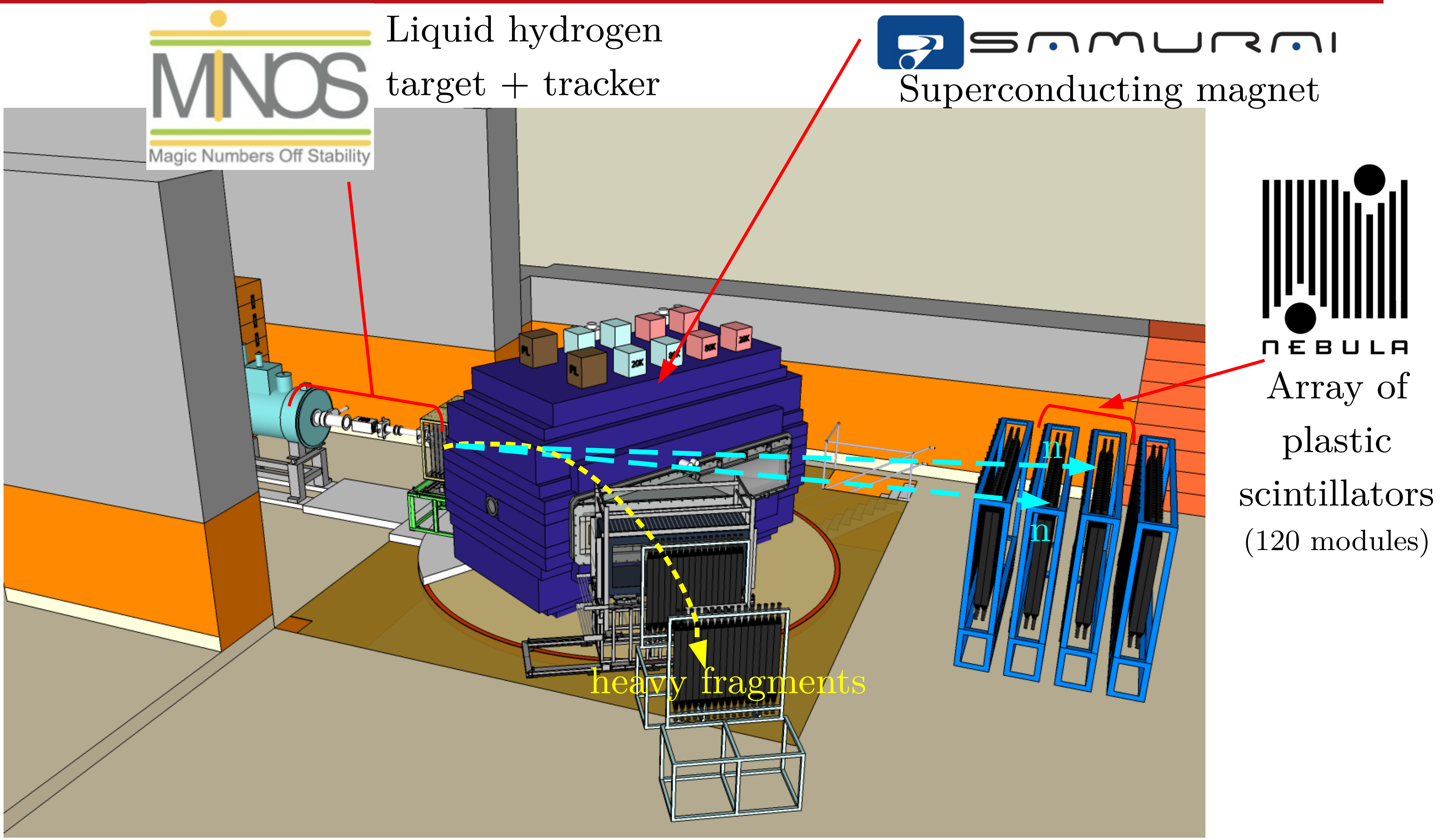
MINOS, NEBULA & SAMURAI

Liquid hydrogen target + tracker



A. Obertelli *et al.*, Eur. Phys. J. A **50** (2014)

MINOS, NEBULA & SAMURAI



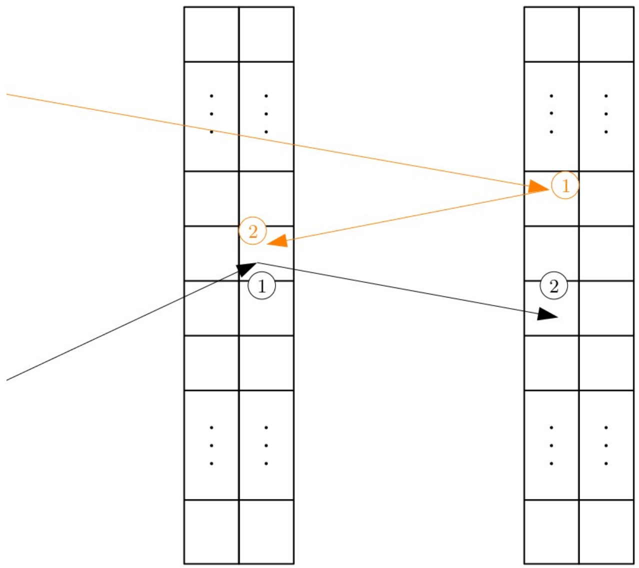
T. Kobayashi *et al.*, Nucl. Instrum. Methods Phys. Res. B **317** (2013)

Data analysis

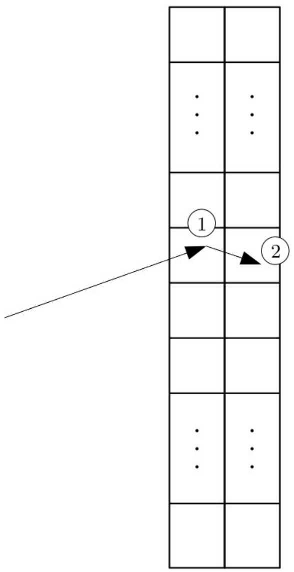
Neutron cross-talk

Removing 1n events that yield 2 signals in NEBULA

Different-wall events :



Same-wall events :



+ γ ray cut : removing all events below 6MeVee

T. Nakamura, Y. Kondo, Nucl. Instrum. Methods Phys. Res. B, **376** (2016)

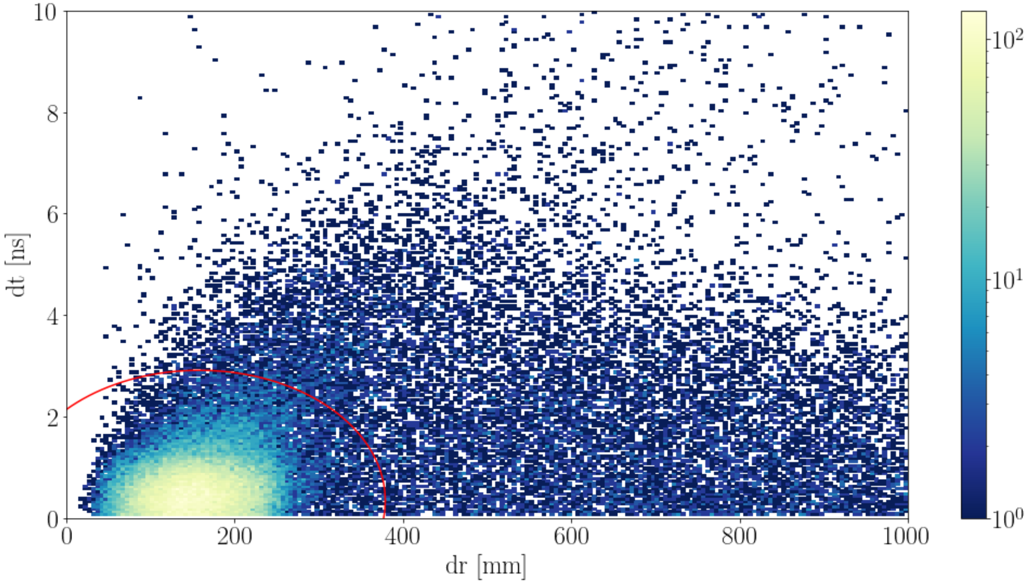
Same-wall events

Removing hits too close to each other : • spatially

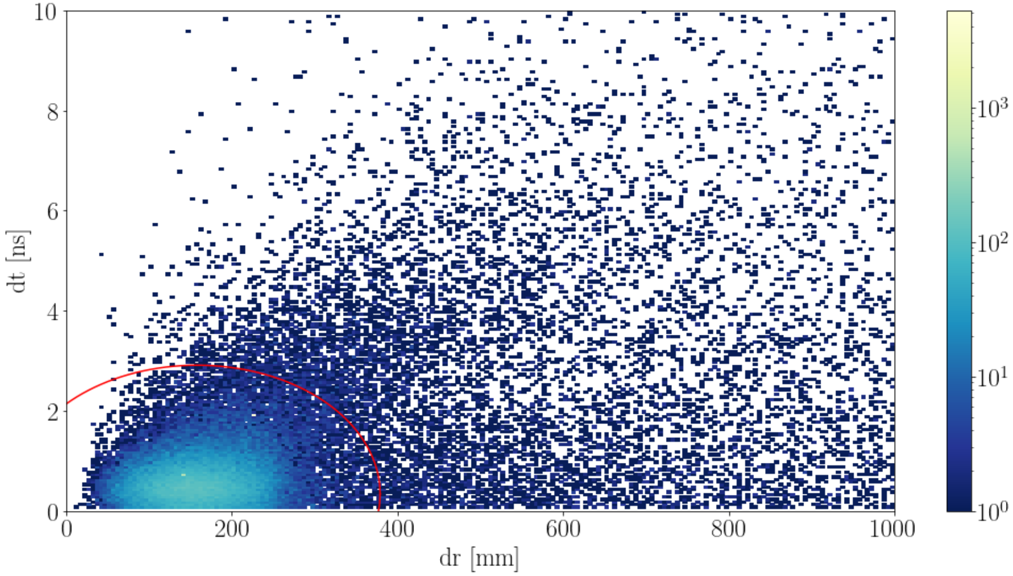
• temporally

$dt = t_2\text{-}t_1$; $dr = |\boldsymbol{r}_2\text{-}\boldsymbol{r}_1|$: $(\boldsymbol{r}_1,t_1)$ & $(\boldsymbol{r}_2,t_2)$ coordinates for both signals

Simulation :



Data :



T. Nakamura, Y. Kondo, Nucl. Instrum. Methods Phys. Res. B, **376** (2016)

Different-wall events : causality cuts

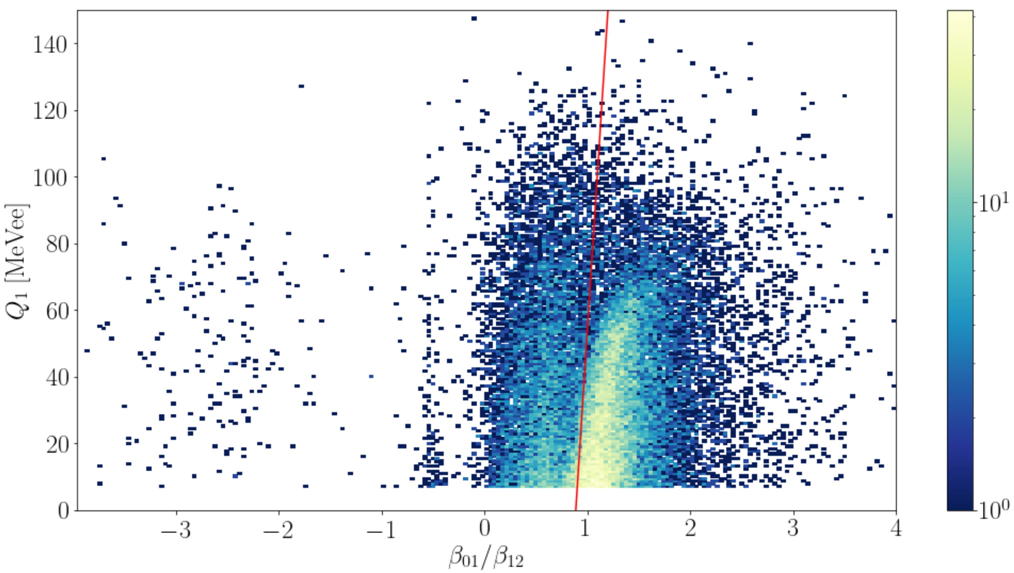
Checking causality between events with using energy loss

β_{01} : velocity between target and 1st hit scintillator

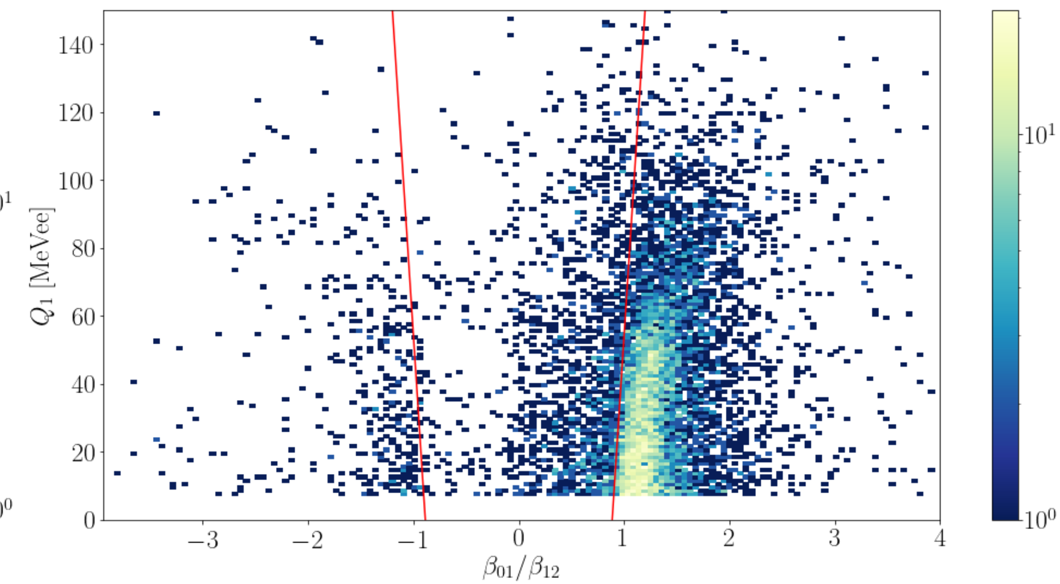
β_{12} : velocity between 1st and 2nd hit scintillator

$\rightarrow$ Removing events with $\beta_{01}/\beta_{12} > 1$

Simulation :



Data :



T. Nakamura, Y. Kondo, Nucl. Instrum. Methods Phys. Res. B, **376** (2016)

Observables

Invariant mass for a 3B system :

$$M_{inv,3B} = \sqrt{E_{tot,3B}^2 - \overrightarrow{P}_{tot,3B}^2}$$

$\Longrightarrow$

<u>Relative energy :</u>

$$E_{rel,3B} = M_{inv,3B} - 2m_n - m_f$$

with $E_{tot,3B} = E_f + E_{n_1} + E_{n_2}$

$\overrightarrow{P}_{tot,3B} = \overrightarrow{P}_f + \overrightarrow{P}_{n_1} + \overrightarrow{P}_{n_2}$

R.J. Charity *et al.*, Phys. Rev. C **84** (2011)

Observables

Invariant mass for a 3B system :

$$M_{inv,3B} = \sqrt{E^2_{tot,3B} - \overrightarrow{P}^2_{tot,3B}}$$

with $E_{tot,3B} = E_f + E_{n_1} + E_{n_2}$

$\overrightarrow{P}_{tot,3B} = \overrightarrow{P}_f + \overrightarrow{P}_{n_1} + \overrightarrow{P}_{n_2}$

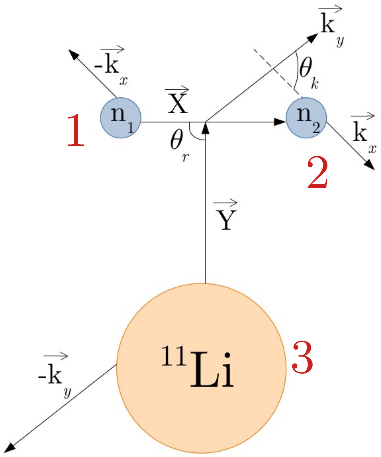
<u>Relative energy :</u>

$$\Longrightarrow \quad E_{rel,3B} = M_{inv,3B} - 2m_n - m_f$$

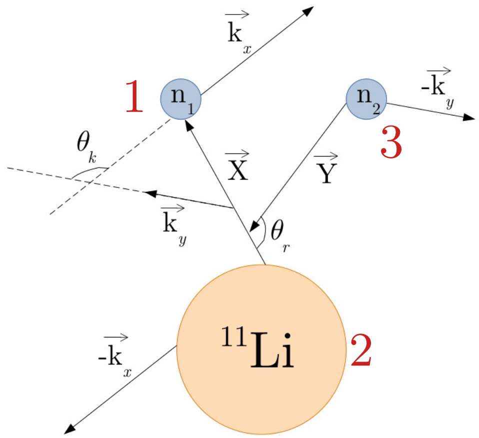
<u>Jacobi coordinates :</u>

$$E_{x,T} = \frac{k^2_{x,T}}{m_n} \qquad E_{x,Y} = \frac{(m_n + m_{^{11}Li})\, k^2_{x,Y}}{2m_n m_{^{11}Li}}$$

$$\cos\theta_k = \frac{\overrightarrow{k}_x \cdot \overrightarrow{k}_y}{k_x k_y}$$



T system



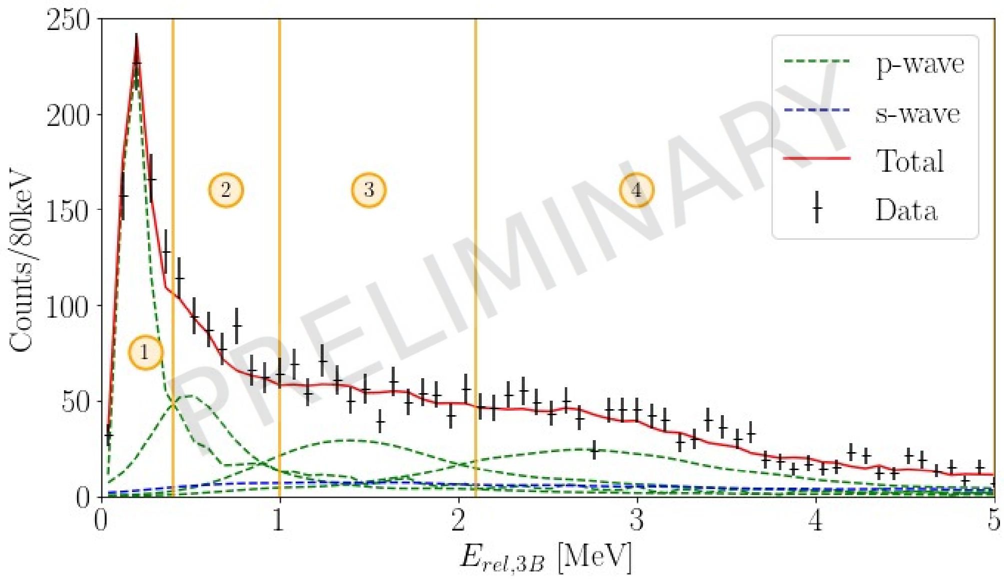
Y system

R.J. Charity *et al.*, Phys. Rev. C **84** (2011)

Results : ^{13}Li

The 3-body spectrum for ^{13}Li

3B relative energy spectrum
(different-wall events)



Gating in the 3B relative energy
→ Fitting the Jacobi coordinates
for each gate

Tentative fit for ^{13}Li

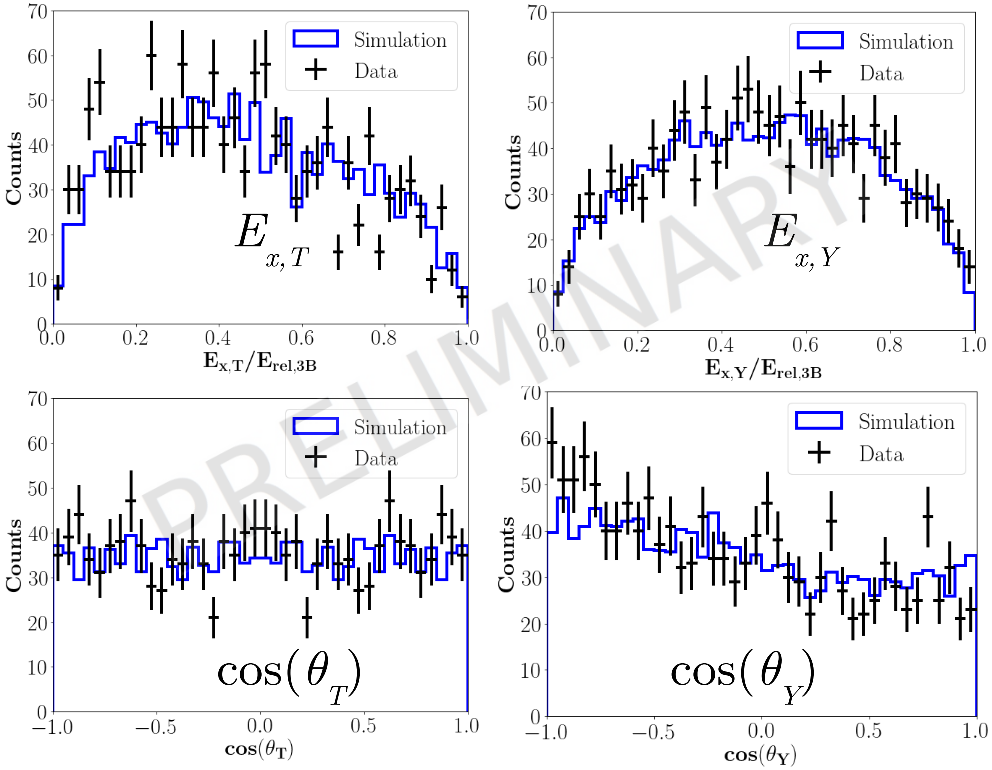
p-wave	E_{res} [MeV]	Γ_{res} [MeV]
1 [1]	0.16	0.12
2	0.45	0.22
3 [2]	1.47	1.70
4	2.82	1.46
s-wave	a_s [fm]	
5	-4	

[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)
[2] Yu. Aksyutina *et al.*, Phys. Lett. B **666** (2008)

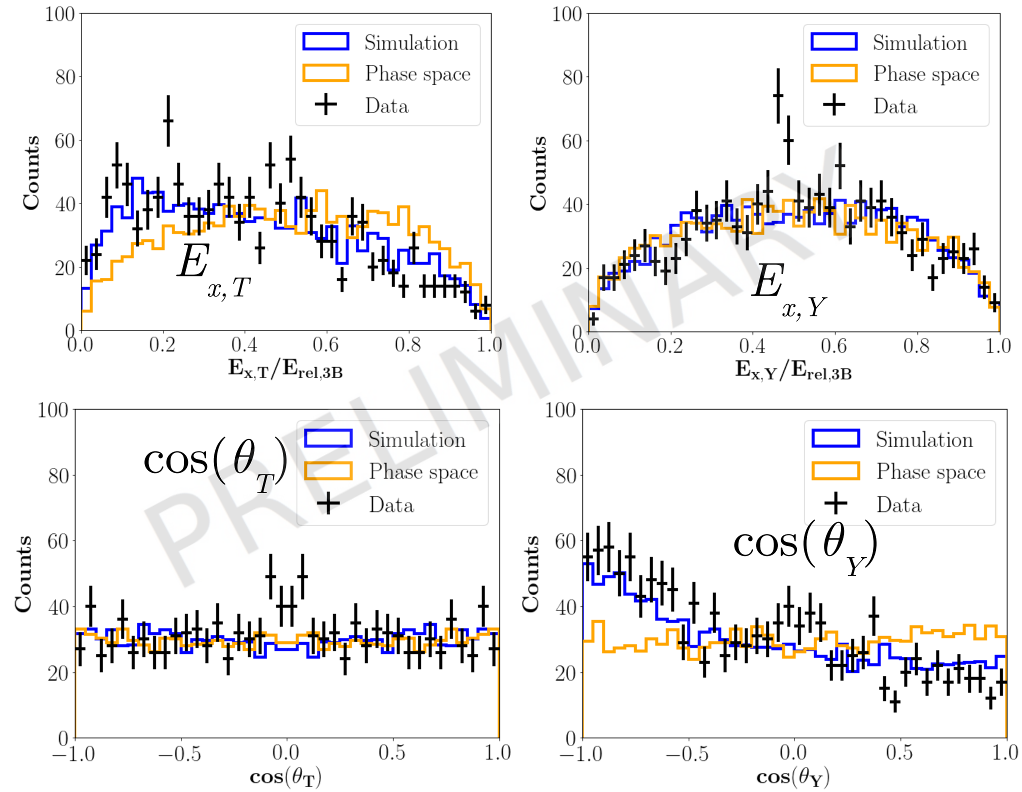
Jacobi coordinates : $0 < E_{rel,3B} < 0.4\text{MeV}$ $0.4 < E_{rel,3B} < 1\text{MeV}$

Data reproduced with direct decay only (r_{nn}=5.2 fm)

$0 < E_{rel,3B} < 0.4\text{MeV}$



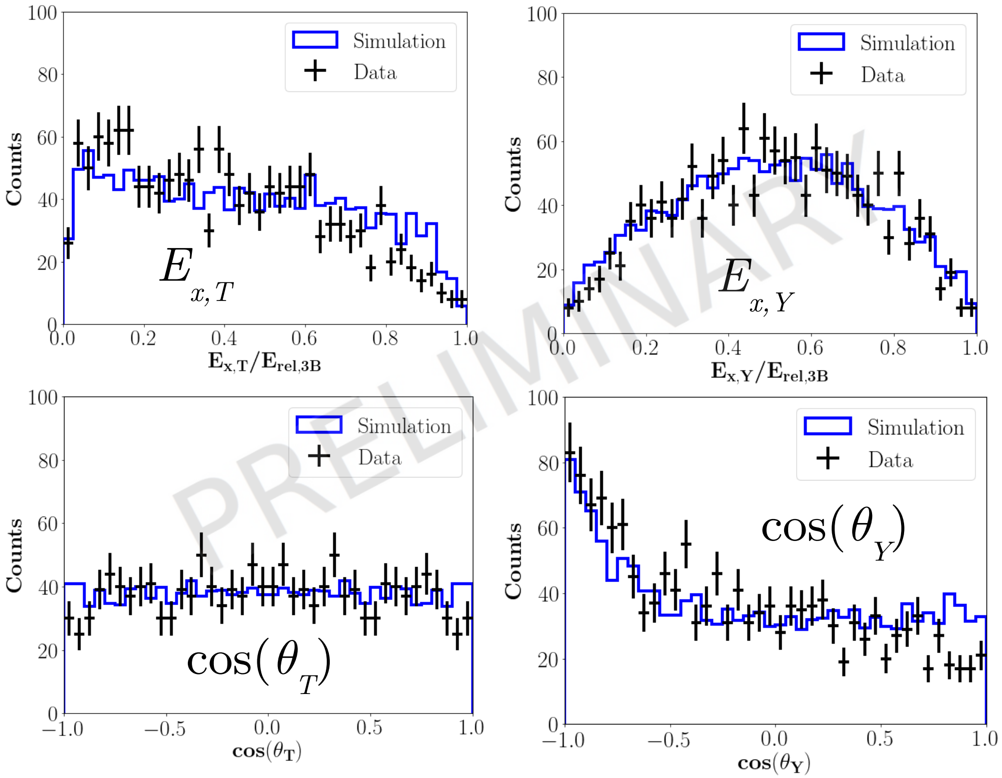
$0.4\text{MeV} < E_{rel,3B} < 1\text{MeV}$



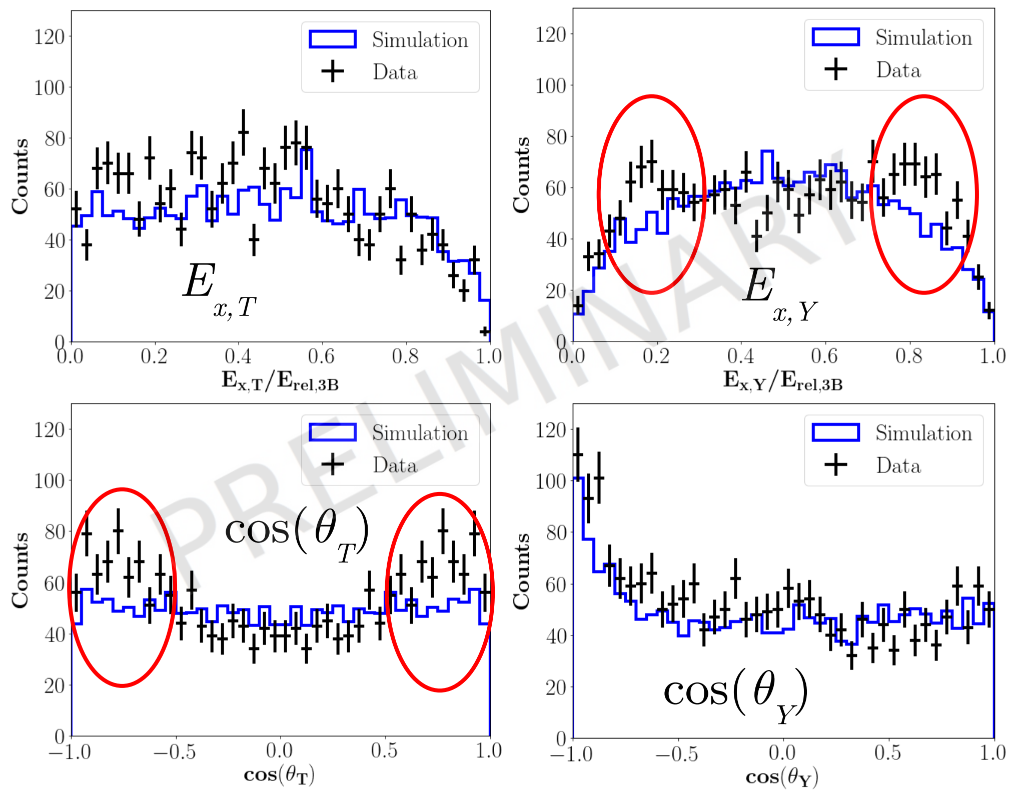
Jacobi coordinates : $1 < E_{rel,3B} < 2.1\,\mathrm{MeV}$ / $2.1 < E_{rel,3B} < 5\,\mathrm{MeV}$

Data reproduced with direct decay only (r_{nn}=5.2 fm)

$1 < E_{rel,3B} < 2.1\,\mathrm{MeV}$



$2.1\,\mathrm{MeV} < E_{rel,3B} < 5\,\mathrm{MeV}$

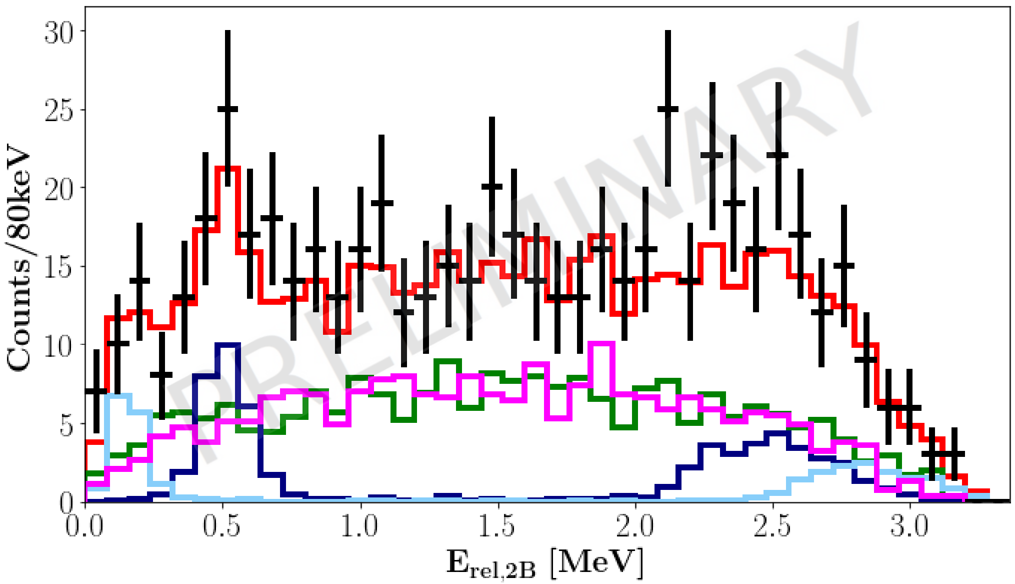


Adding sequential contribution

Data reproduced with direct and sequential contributions (r_{nn}=5.2 fm)

Fit proportions of each decay process (constrained by 3B spectrum integral)

2B relative energy spectrum

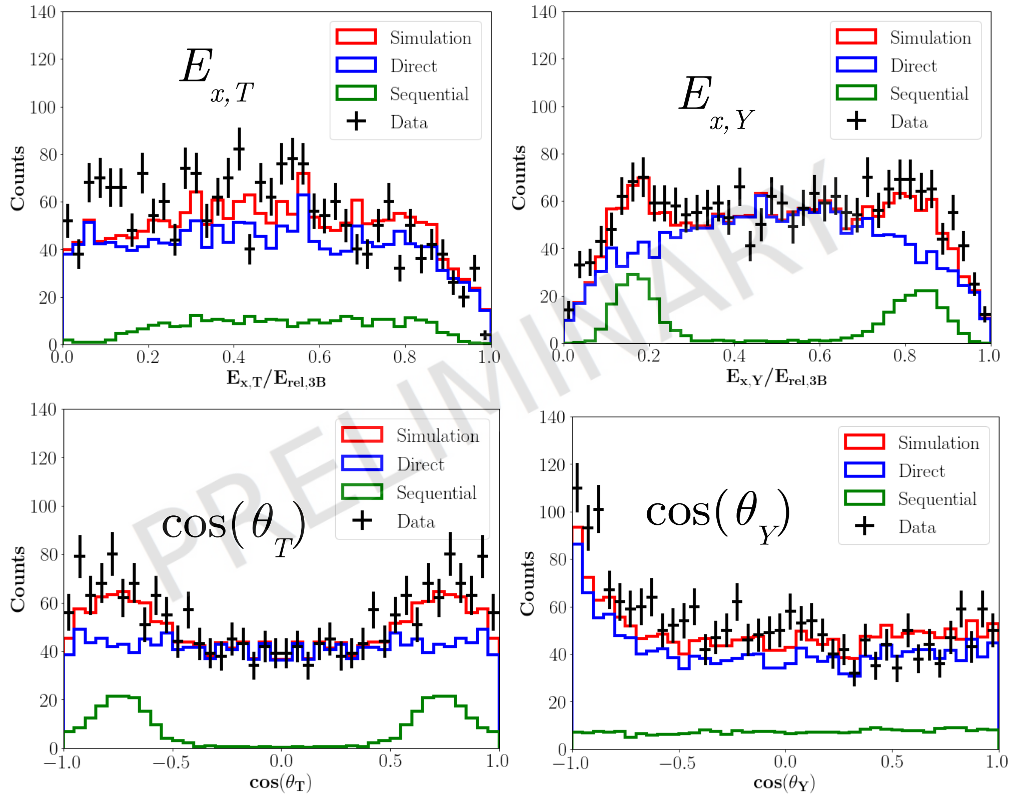


2 resonances in ^{12}Li

Direct decay of high energy resonance in ^{13}Li

Direct decay of other states in ^{13}Li

2.1MeV<$E_{rel,3B}$<5MeV

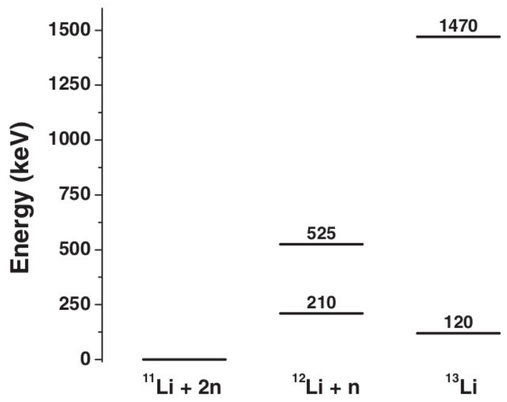


[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

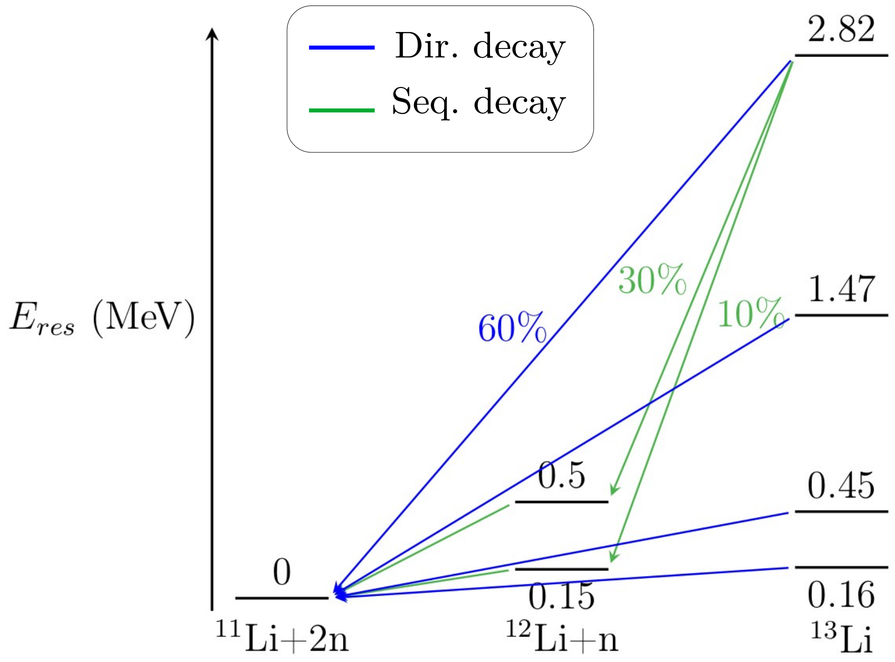
[2] C.C. Hall *et al.*, Phys. Rev. C **81** (2010)

Summary for ^{13}Li

Z. Kohley *et al.* [1] :



This study :



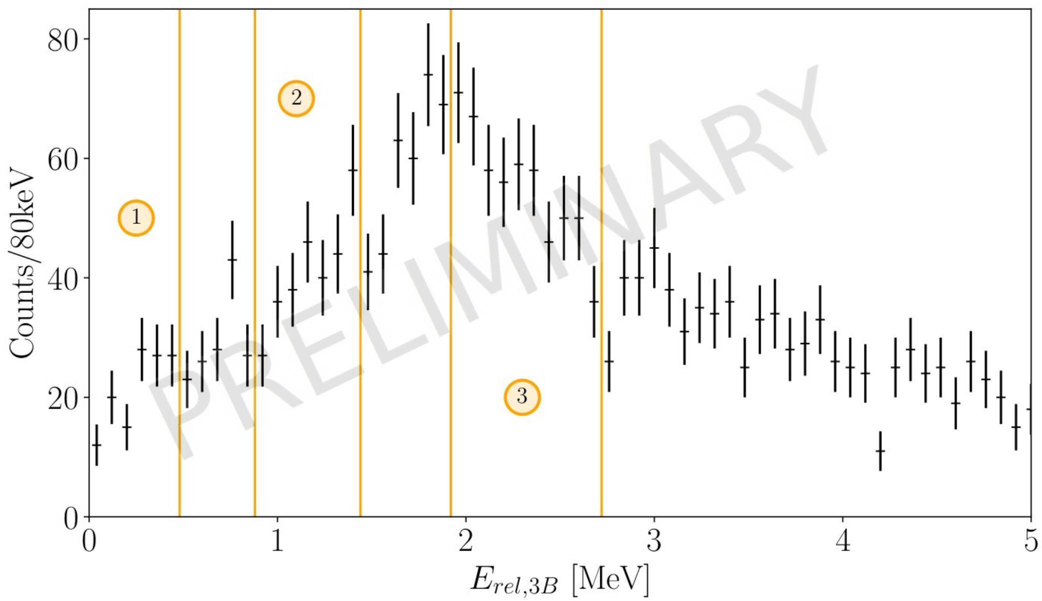
- **First observation of sequential decay at high relative energy**
- Reduced of sensitivity on n-n correlation parameter r_{nn}

[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

Results : ^{11}Li

The 3-body spectrum for ^{11}Li

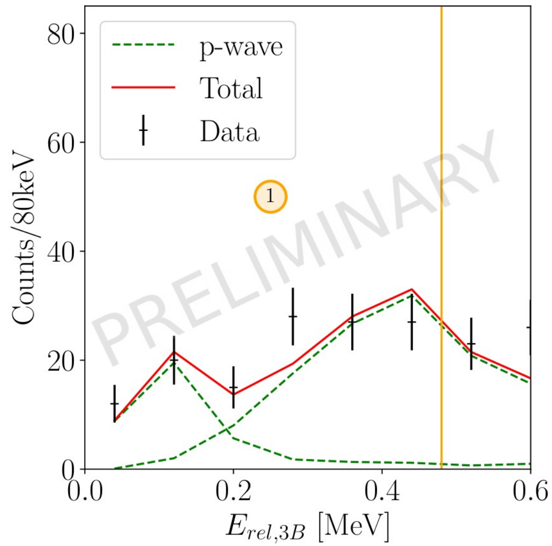
3B relative energy spectrum
(different-wall events)



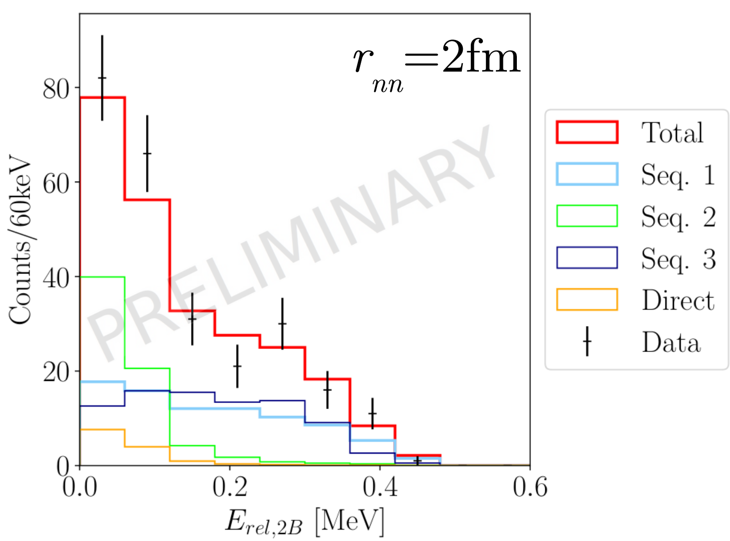
Gating in the 3B relative energy
→ Fitting the Jacobi coordinates for each gate
→ Fitting the 2B relative energy spectrum

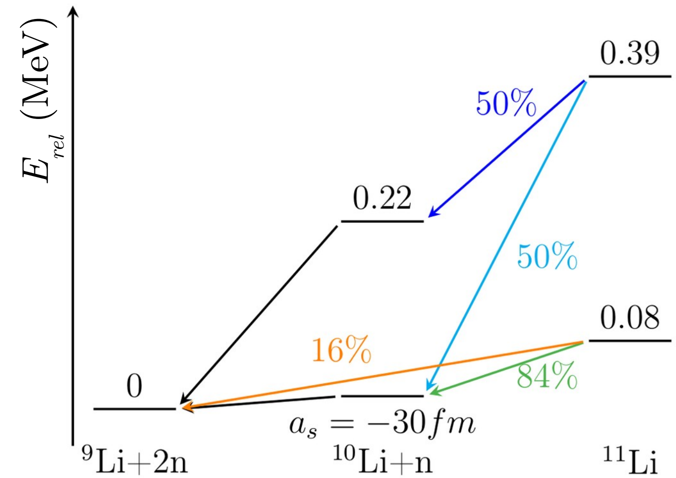
The 3-body spectrum for ^{11}Li : $0 < E_{rel,3B} < 0.48$MeV

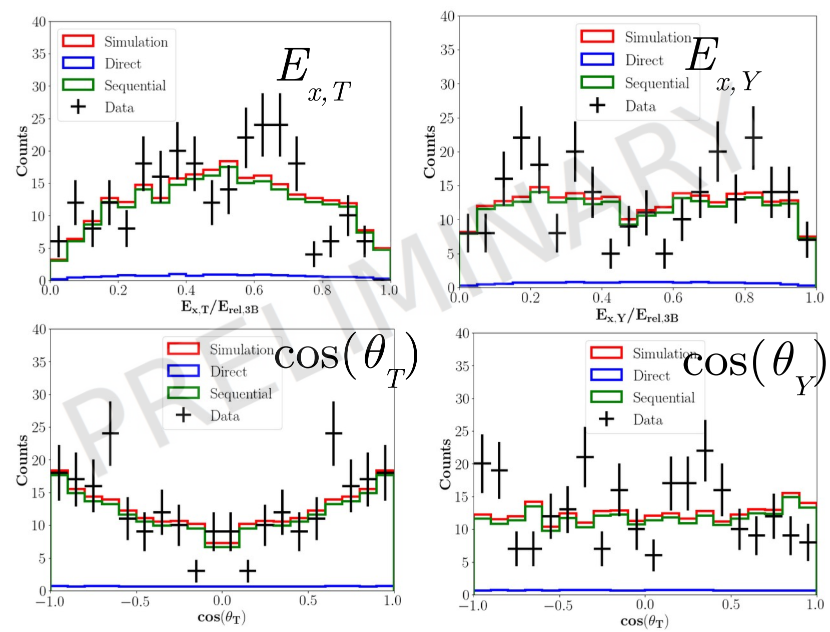
3B relative energy :



2B relative energy :





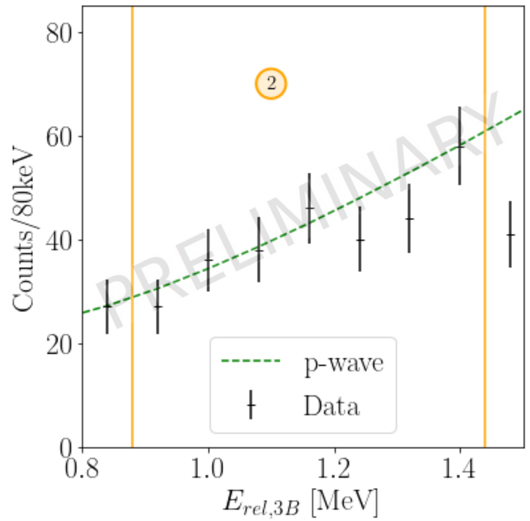


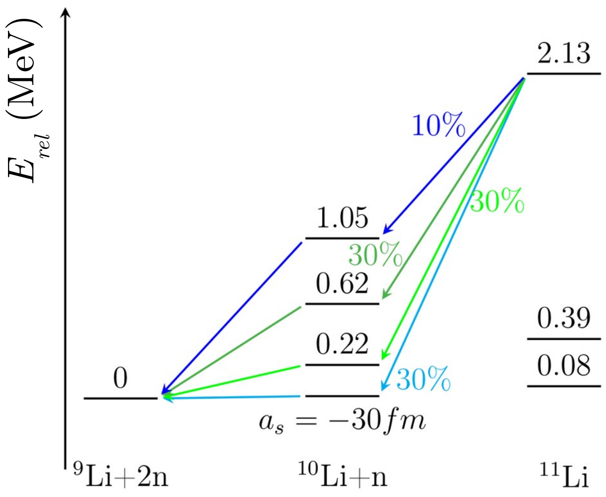
[1] M. Zinser *et al.*, Nucl. Phys. A **619** (1997)

[2] T. Nakamura *et al.*, PRL **96** (2006) [3] H. Simon *et al.*, Nucl. Phys. A **791** (2007)

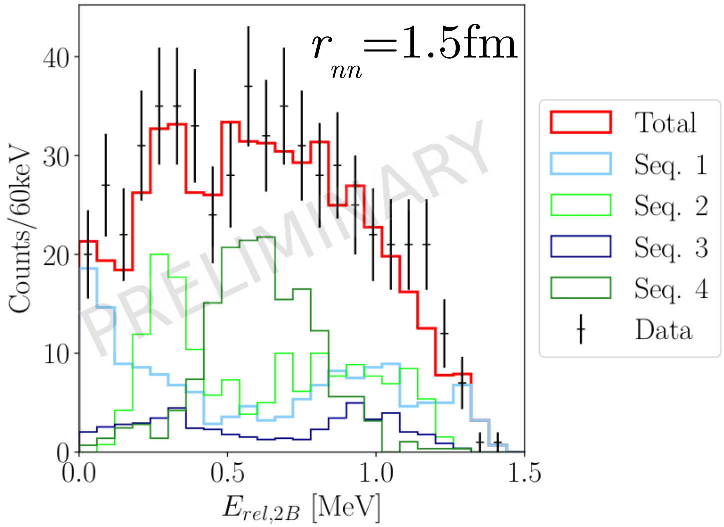
The 3-body spectrum for ^{11}Li : $0.88 < E_{rel,3B} < 1.44$MeV

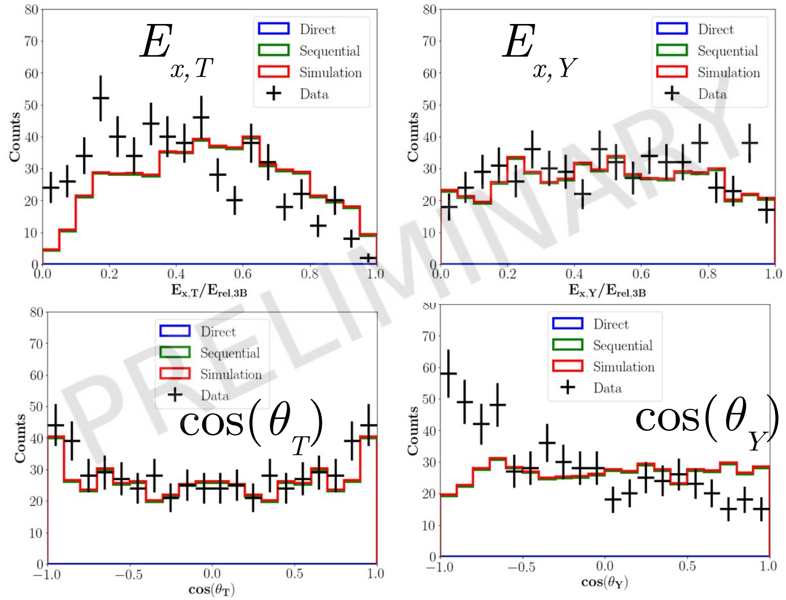
3B relative energy :





2B relative energy :



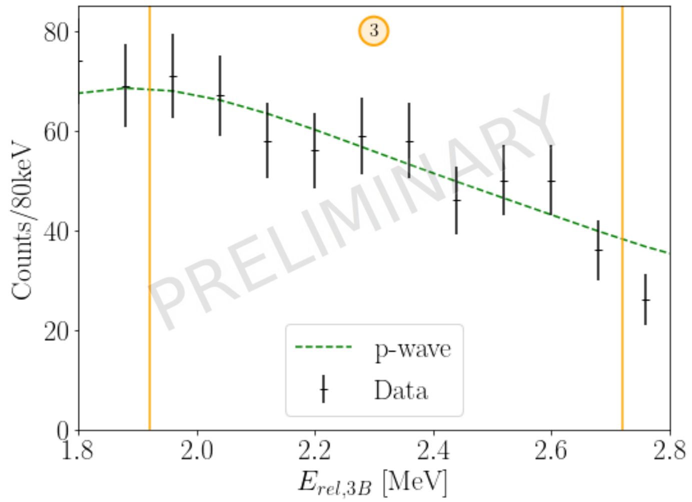


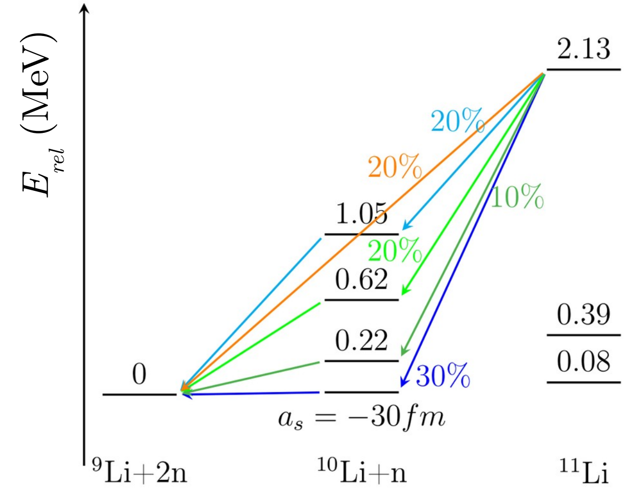
[1] M. Zinser *et al.*, Nucl. Phys. A **619** (1997)

[2] J.K. Smith *et al.*, Nucl. Phys. A **940** (2015)

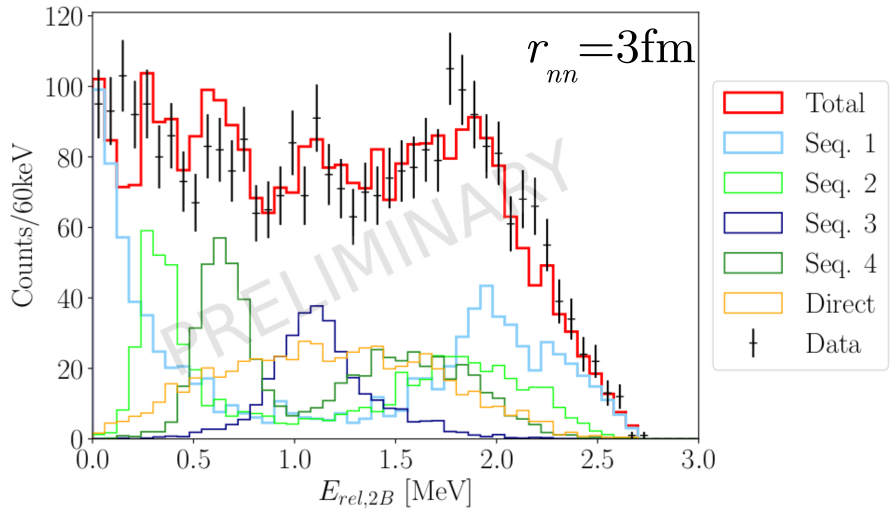
The 3-body spectrum for ^{11}Li : $1.92 < E_{rel,3B} < 2.72$MeV

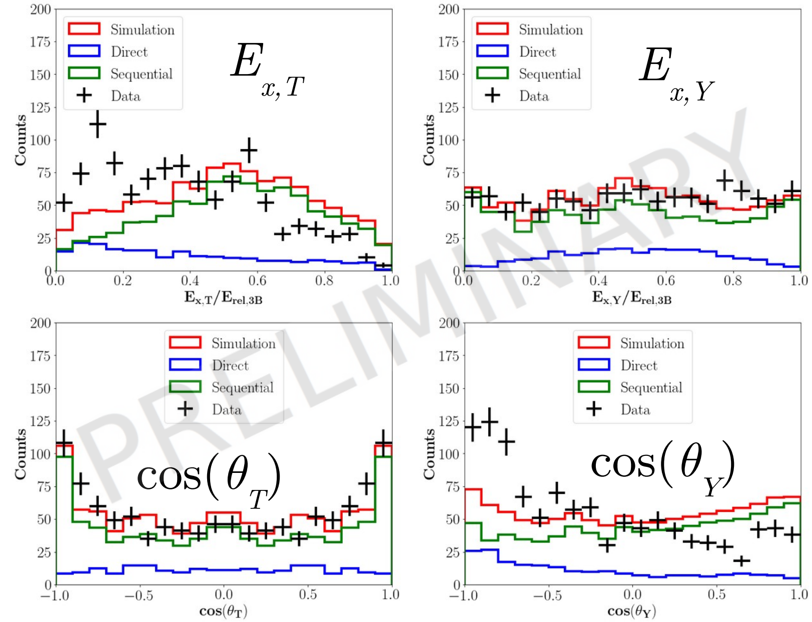
3B relative energy :





2B relative energy :

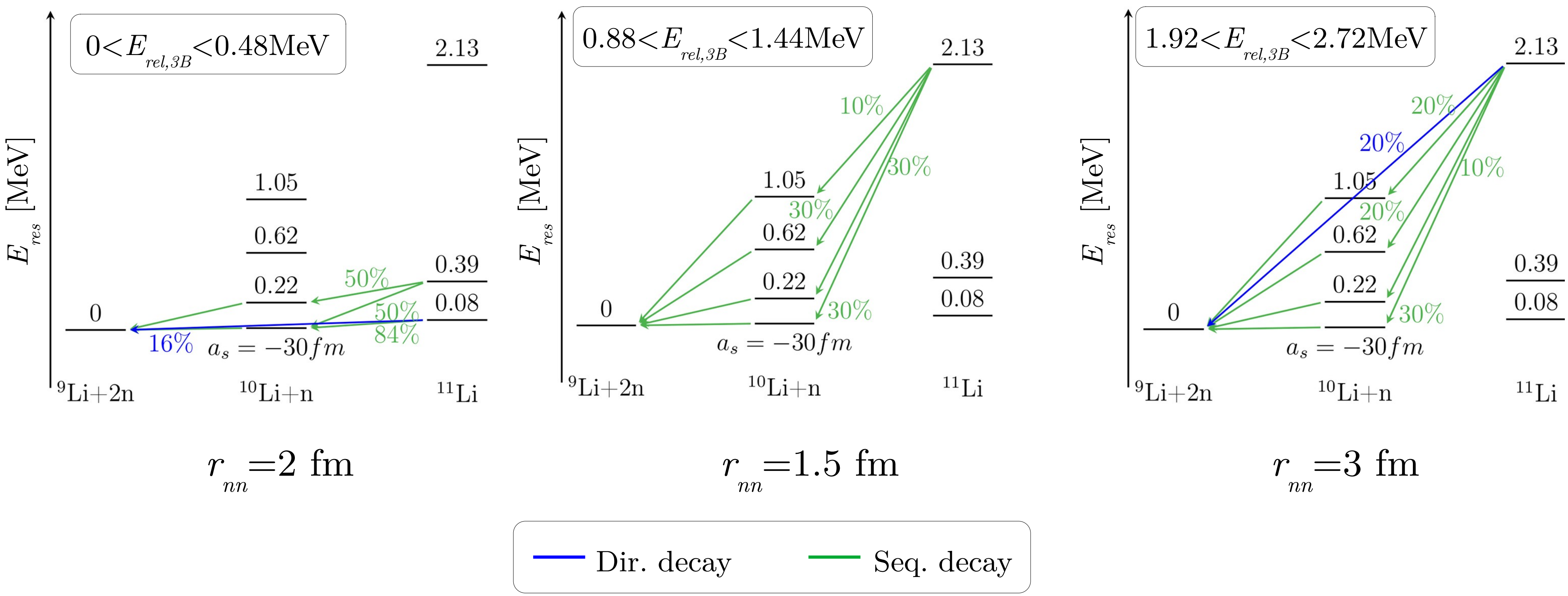




[1] M. Zinser *et al.*, Nucl. Phys. A **619** (1997)

[2] J.K. Smith *et al.*, Nucl. Phys. A **940** (2015)

Summary for ^{11}Li



- Observation of sequential decay with 2B spectrum built with events from the 2n decay
- Small r_{nn}, strong correlations

(r_{nn}=1.67(16) fm for ^{18}C, and r_{nn}=1.75(24) fm for ^{20}O [1])

[1] A. Revel *et al.*, PRL **120** (2018)

Outlook

- Analysis of the core excitation for ^{11}Li

- Ab initio calculations for the mass and structure of ^{11}Li and ^{13}Li (K. Fossez):
  - Already done for excited states until ^{10}Li, masses until ^{11}Li [1]
  - Yields energies and spin assignment of ground state and excited states
  - Computationally expensive calculations

- Comparison with reaction theory (J. Casal, M. Gómez-Ramos [2]) :
  - Comparing Jacobi coordinates and reduced relative energies
  - Compare results for direct, sequential decay and structure of the isotopes

[1] X. Mao *et al.*, Phys. Rev. C **102** (2020)

[2] J. Casal, M. Gómez-Ramos, Phys. Rev. C **104** (2021)

Thank you for your attention !

Supervision :


Anna Corsi

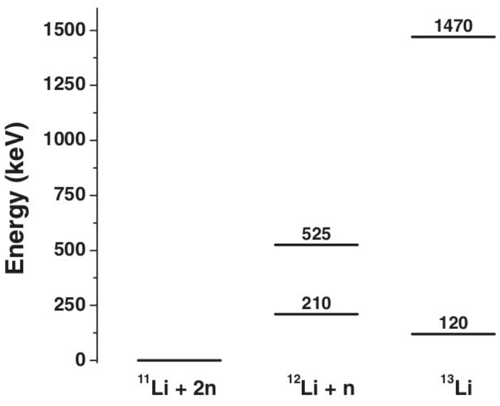

Aldric Revel

Acknowledgements :

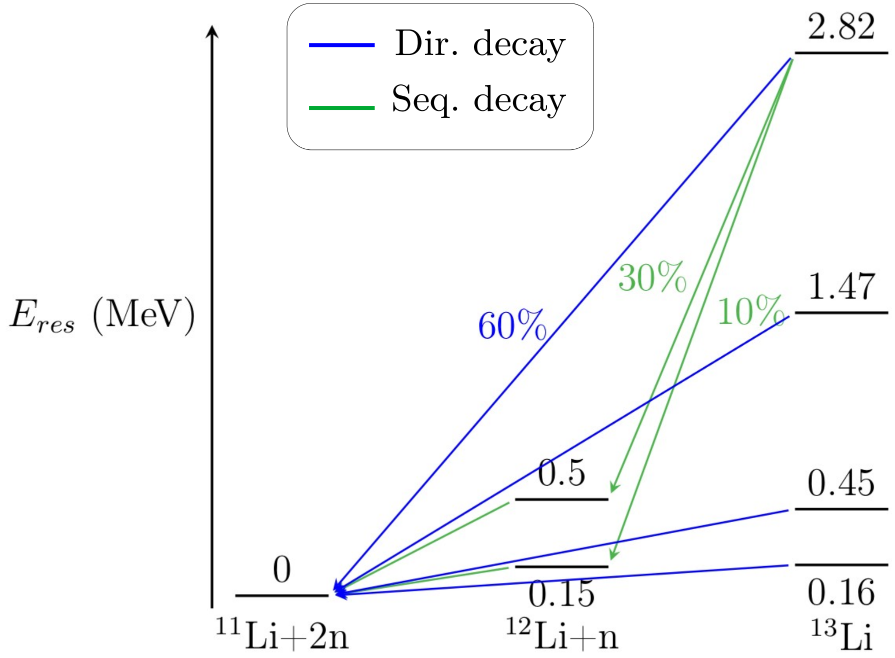
SAMURAI Collaboration

MINOS Collaboration

Z. Kohley *et al.* [1] :



This study :



- **First observation of sequential decay at high relative energy**
- Reduced of sensitivity on n-n correlation parameter r_{nn}

[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

Back Up

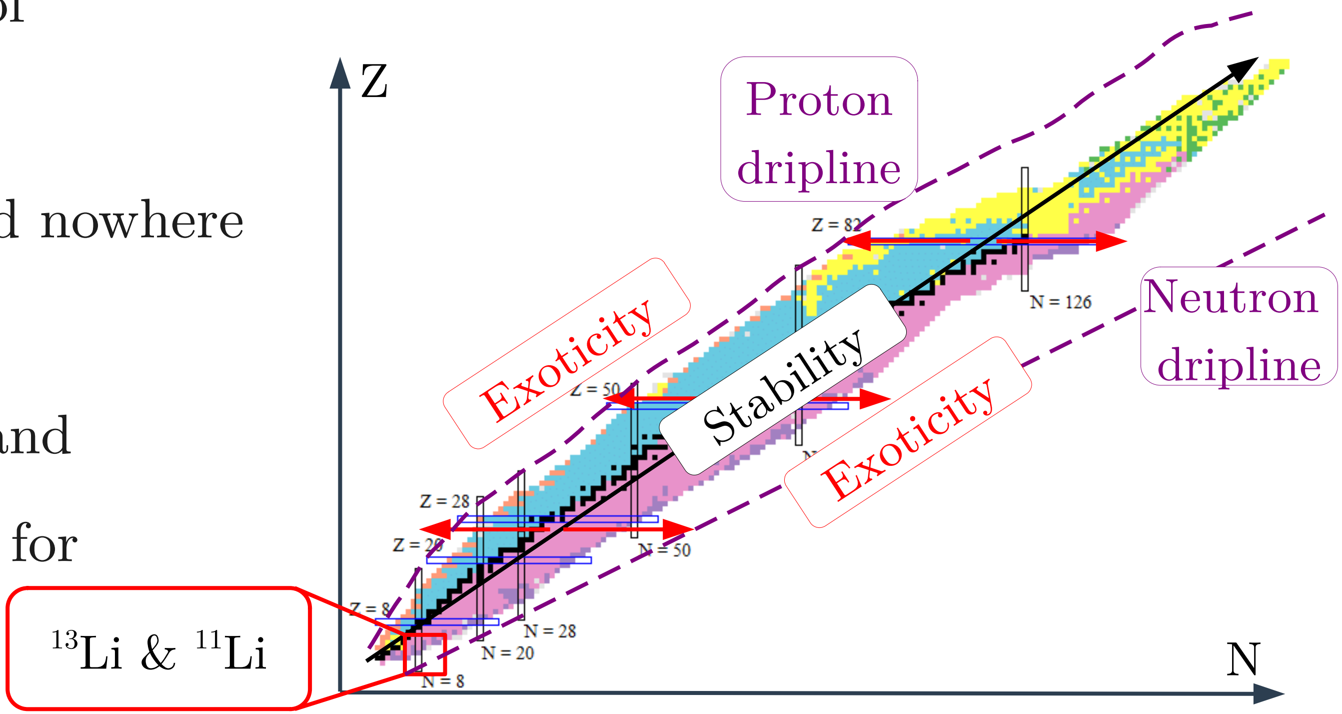
Studying exotic nuclei in inverse kinematics

- Study of nuclei far from stability → short-lived systems
- Inverse kinematics technique : exotic nuclei in beam on target
- Interest of studying exotic nuclei :

  - Testing our knowledge of nuclear interaction

  - Special structures, found nowhere else in the nuclide chart

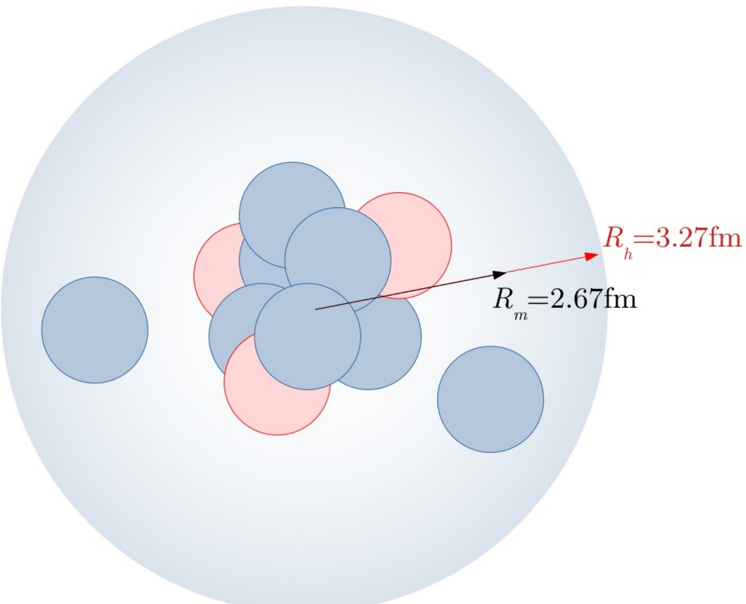
  → Finding fundamental and universal properties valid for the whole chart

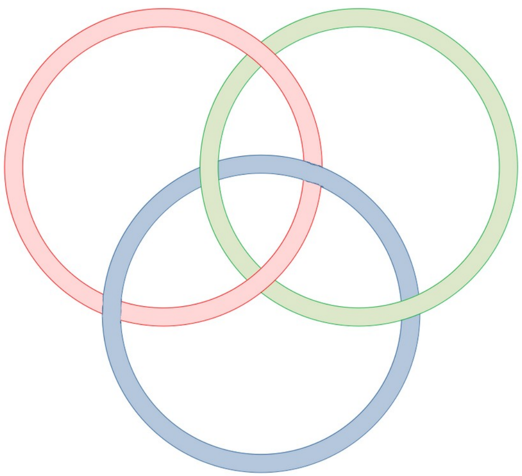


Halo and Borromean nuclei

Special structure of ^{11}Li : halo nuclei[1][2] and Borromean[3]

→ Effective radius > $R_m = r_0 \cdot A^{1/3}$ & ^{11}Li bound while ^{10}Li unbound





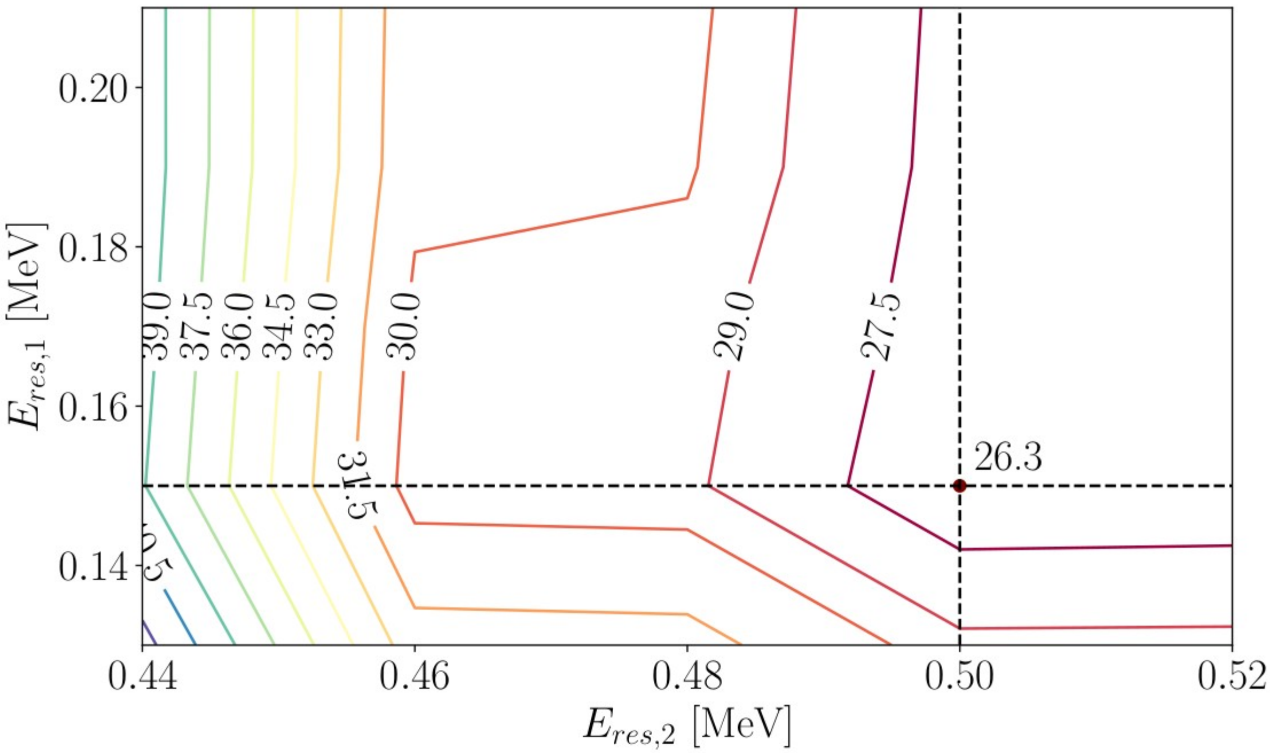
→ Good testing ground for n-n correlations

[1] I. Tanihata *et al.*, PRL **55** (1985) [2] P.G. Hansen, B. Jonson, Europhys. Lett. **4** (1987)
[3] M.V. Zhukov et al., Phys. Rep. **231** (1993)

Constraint of the resonances in ^{12}Li

χ^2 surface with $E_{res,1}$ and $E_{res,2}$ as free parameters

$\Gamma_{res,1}$ and $\Gamma_{res,2}$ fitted for a given resonance energy

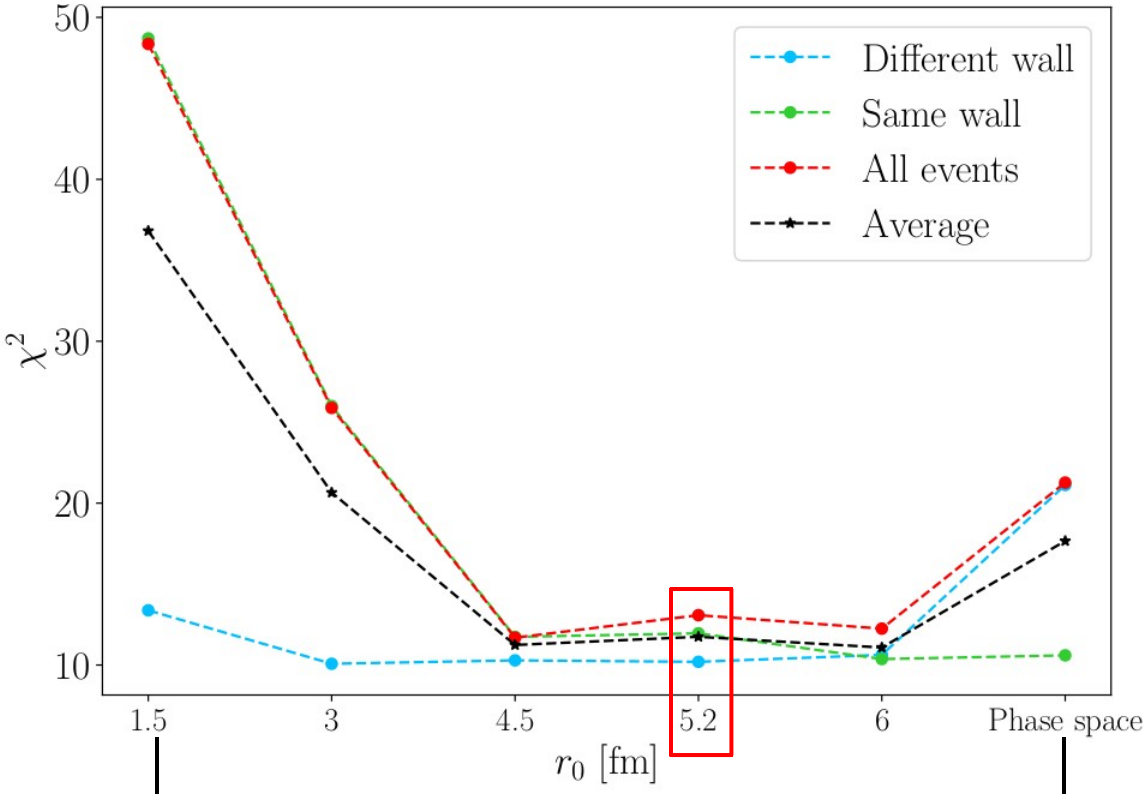


[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

[2] C.C. Hall *et al.*, Phys. Rev. C **81** (2010)

Constraint of r_0 in ^{13}Li

χ^2 plot for fits on Jacobi coordinates with r_0 as free parameters



Minimum value

$r_0 \rightarrow \infty$

Performances of cross-talk cuts

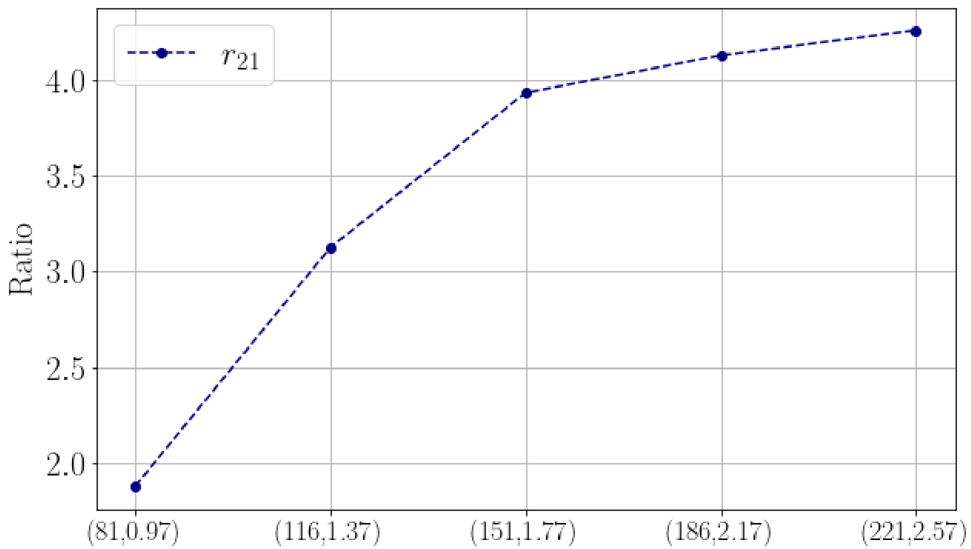
$$r = \frac{N(M > 1, \text{After CT rejection})}{N(M > 1, \text{Before CT rejection})}$$

r_1 on 1n decay channel : ^{11}Li(p,pn)^{10}Li→^{9}Li+n

r_2 on 2n decay channel : ^{14}Be(p,2p)^{13}Li→^{11}Li+2n

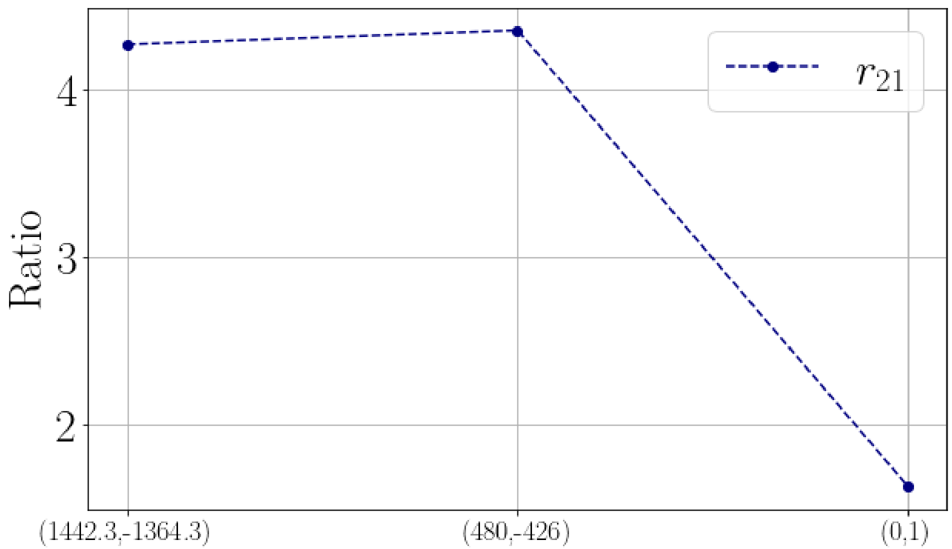
$\rightarrow r_{21} = r_2/r_1$

Same-wall cut



x-axis : semi-axis of ellipse

Different-wall cut



x-axis : parameters for the straight line

Survival rate for 1n channel : 2.32% ; Survival rate for 2n channel : 10.1%

T. Nakamura, Y. Kondo, Nucl. Instrum. Methods Phys. Res. B, **376** (2016)

$0.88 < E_{rel,3B} < 1.44$MeV

$1.92 < E_{rel,3B} < 2.72$MeV

Minimization on the Jacobi coordinates

$0.88 < E_{rel,3B} < 1.44$MeV — 40% Seq. 60% Dir.

$1.92\text{MeV} < E_{rel,3B} < 2.72$MeV — 30% Seq. 70% Dir.