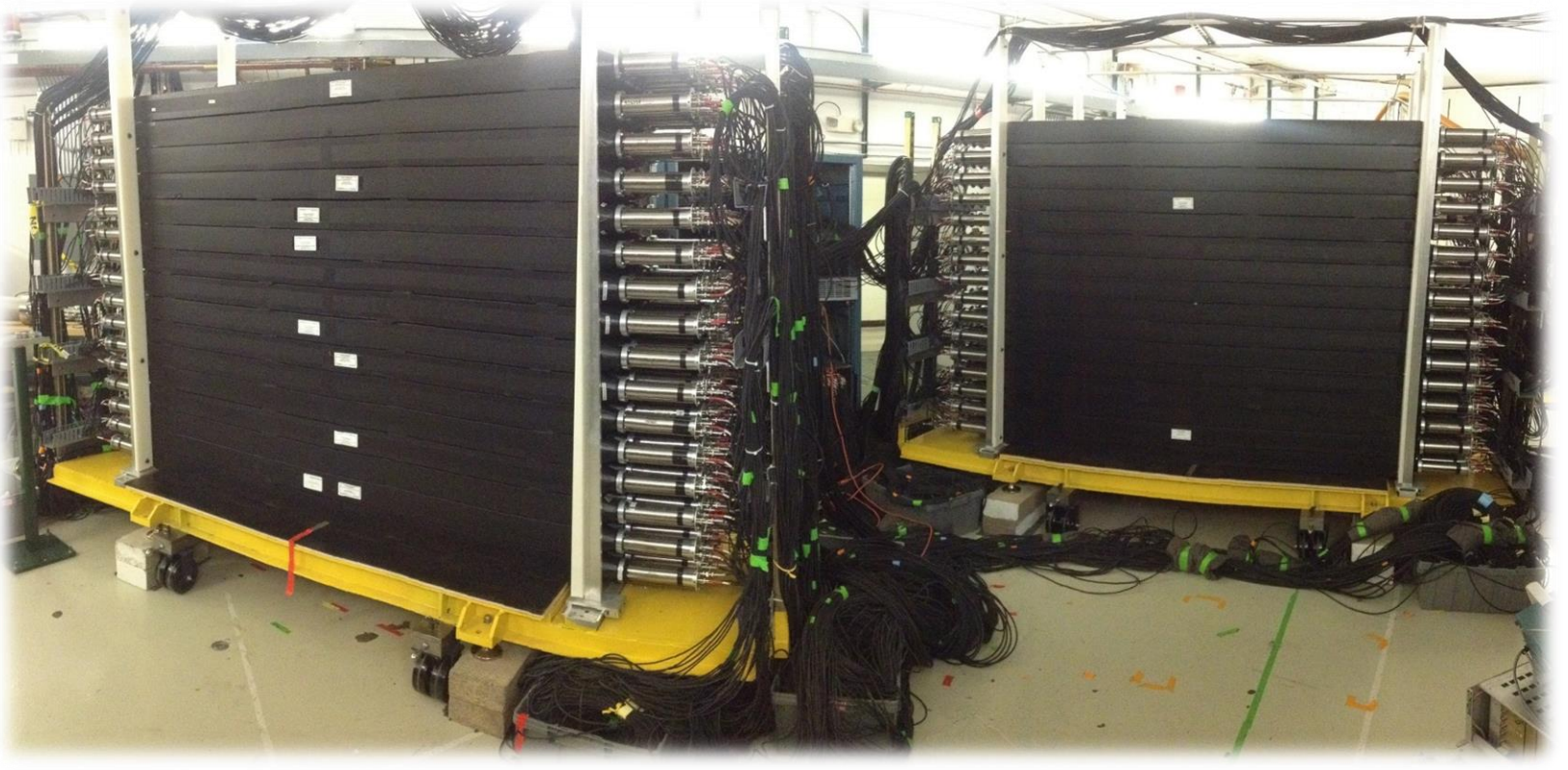
Identification of multiple neutrons (and knockout reactions) with MoNA



Anthony N. Kuchera
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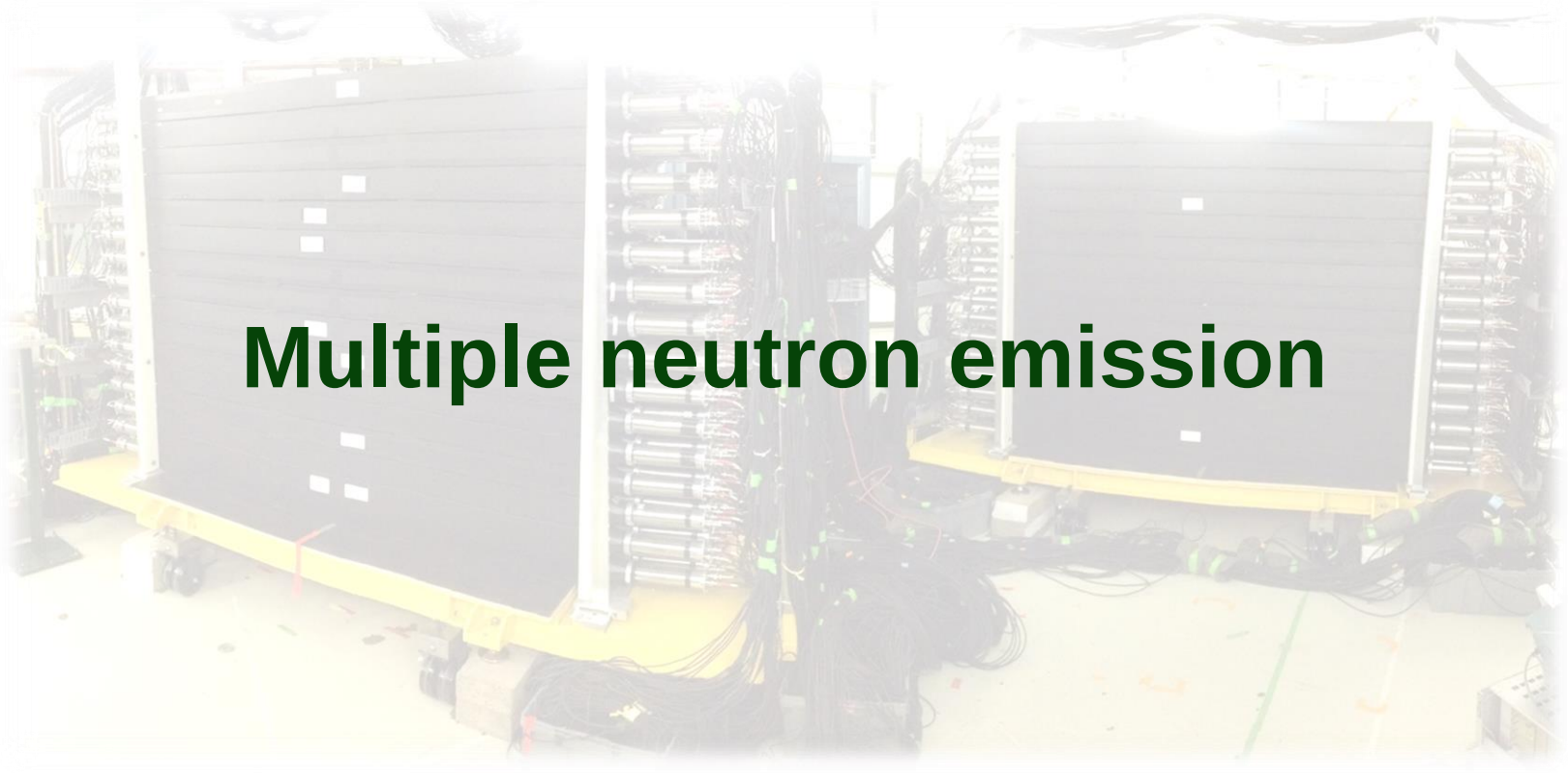
Michigan State University

Outline

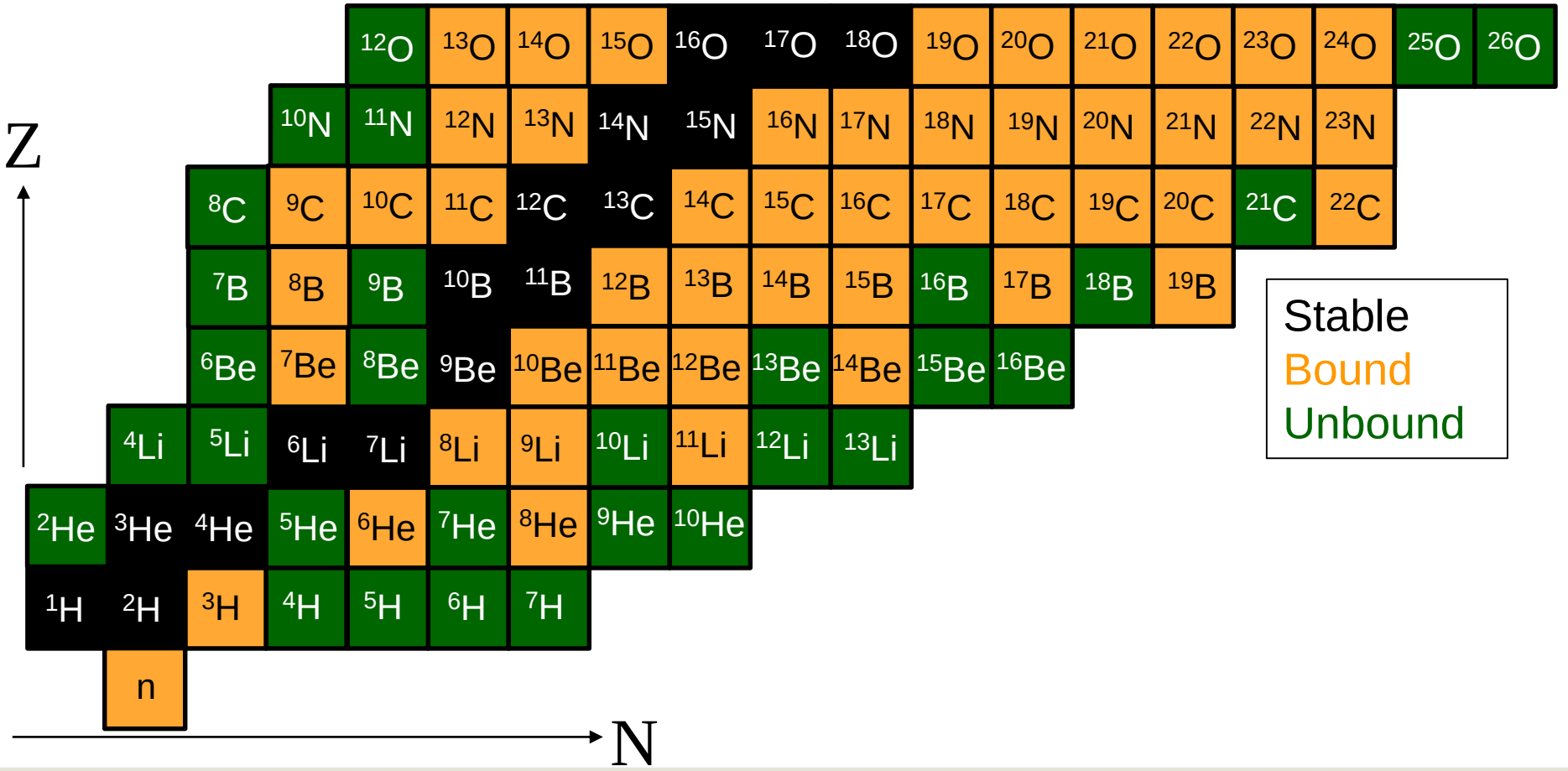
- Multiple neutron emission
  - $^{24}O \rightarrow ^{22}O + 2n$
  - $^{15}Be \rightarrow ^{12}Be + 3n$
  - $^{12}He \rightarrow ^{8}He + 4n$
- Recent Work on Knockout Reactions in *p*-shell nuclei
  - Understanding proton-knockout reaction mechanism
  - Using cross sections to guide structure theory
- New Experiment at NSCL
  - CCF facility and experimental set up
  - Momentum distributions and gamma-ray spectra
  - Preliminary results
  - Future plans



Multiple neutron emission

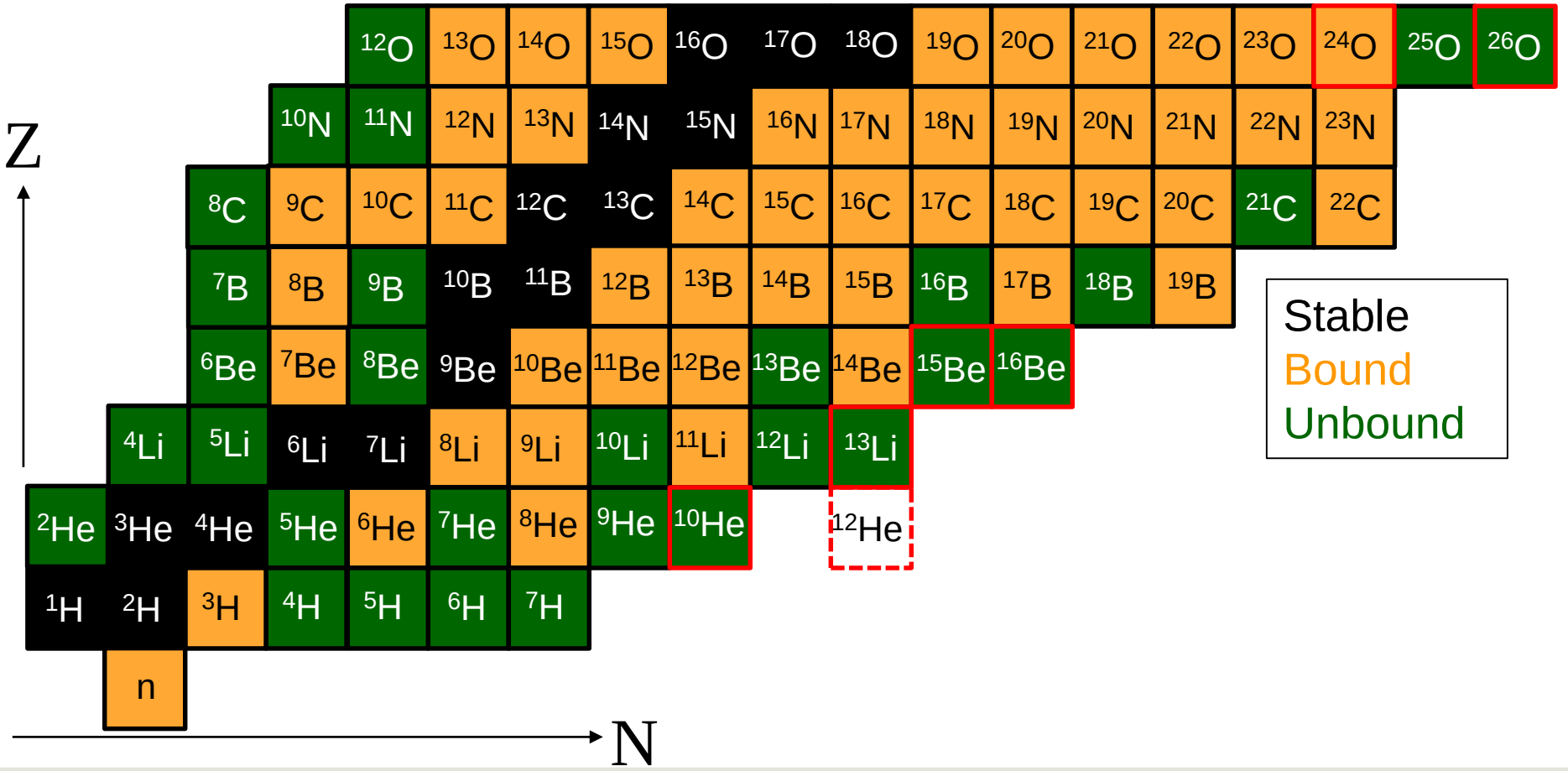
Nuclear structure of light nuclei

Light nuclei are interesting for many reasons including many exotic features and are accessible for several theoretical approaches starting from first principles.



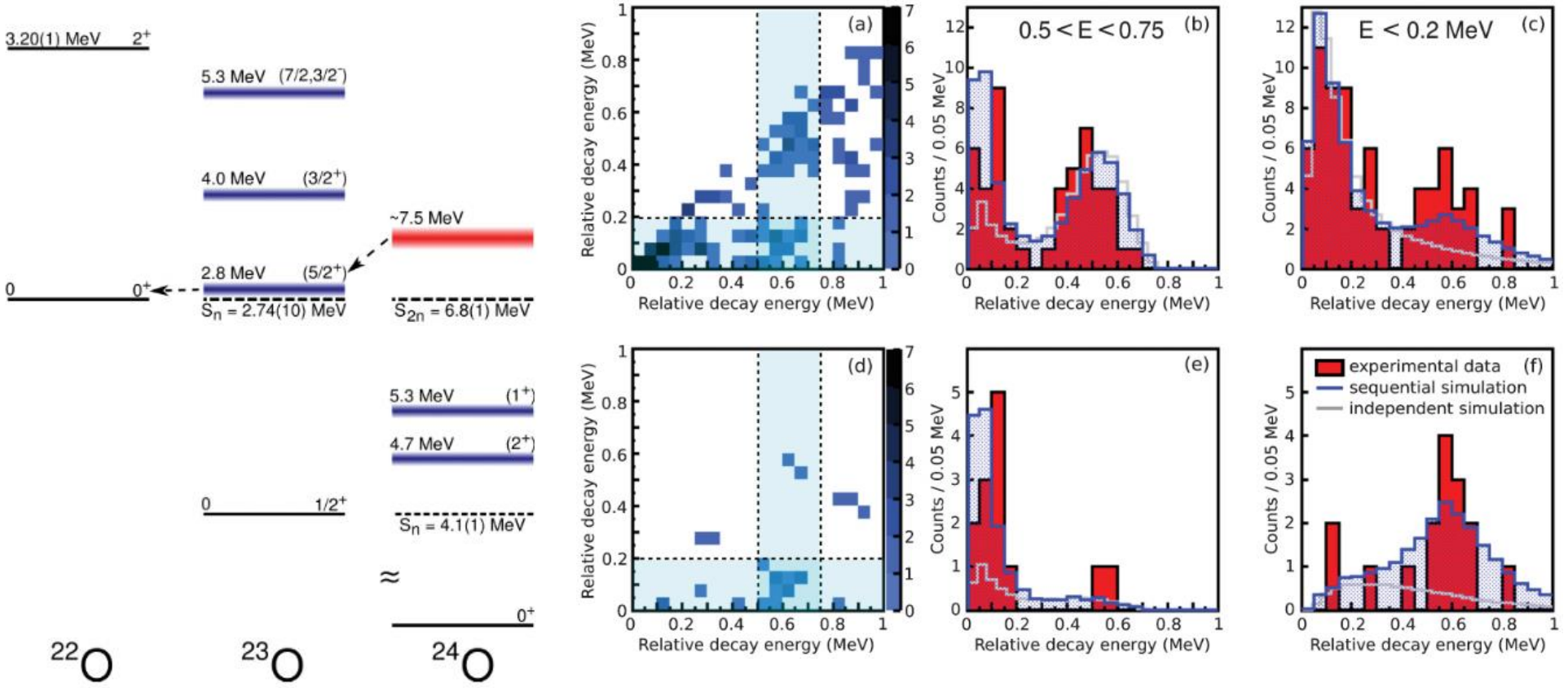
MoNA measurements for multiple neutrons

The red boxed nuclei have seen evidence for or searched for decays by multiple neutrons using MoNA(LISA).



Two neutrons from ^{24}O

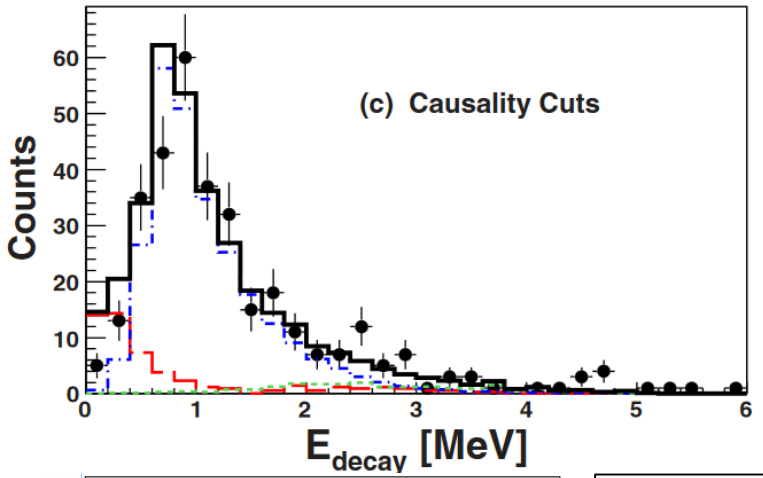
Using two discrete neutron energies in coincidence

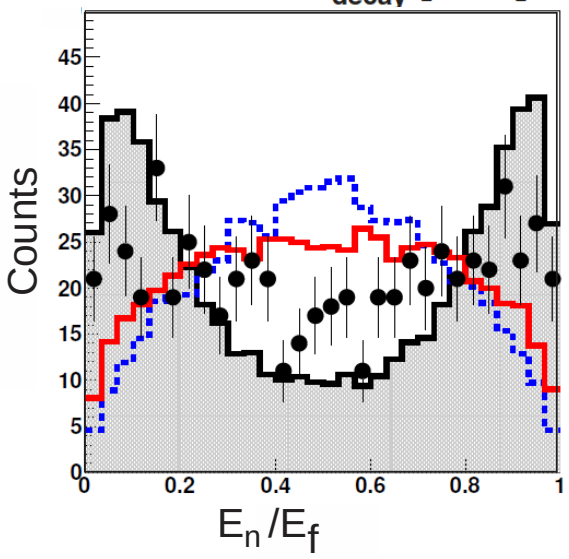


C. R. Hoffman *et al*. Phys. Rev. C 83, 031303(R) (2011)

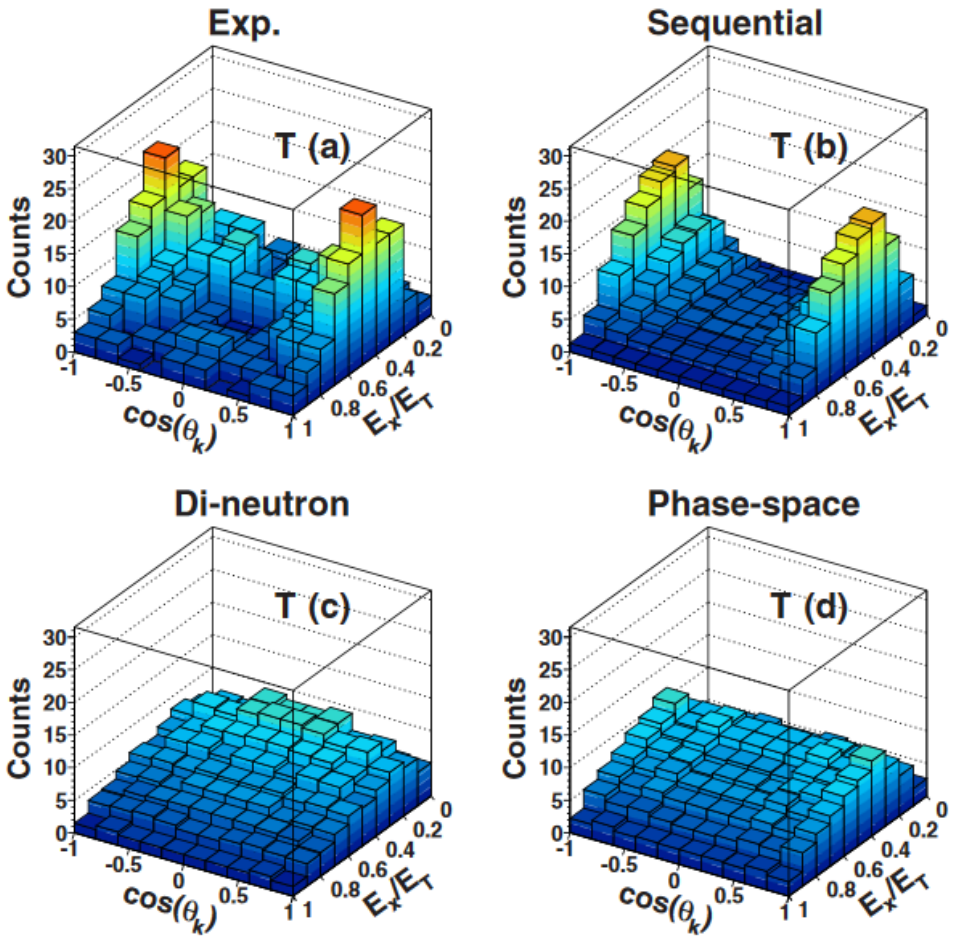
Two neutrons from ^{24}O

Using energy and angular correlations from $^{24}O \rightarrow ^{22}O+2n$





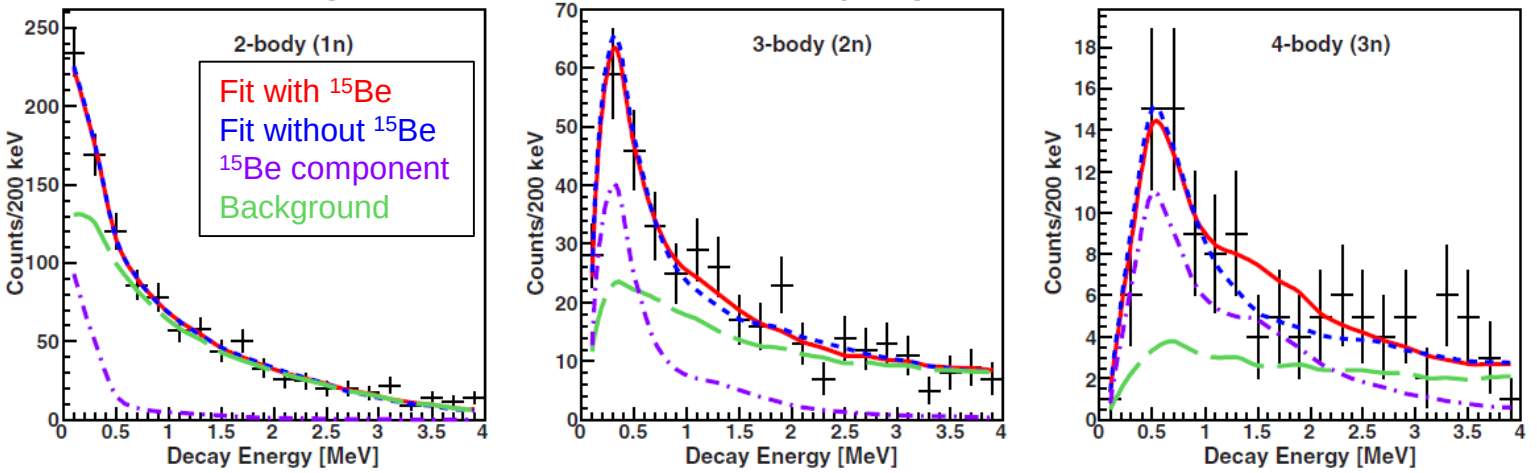
Phase Space
Di-neutron
Sequential



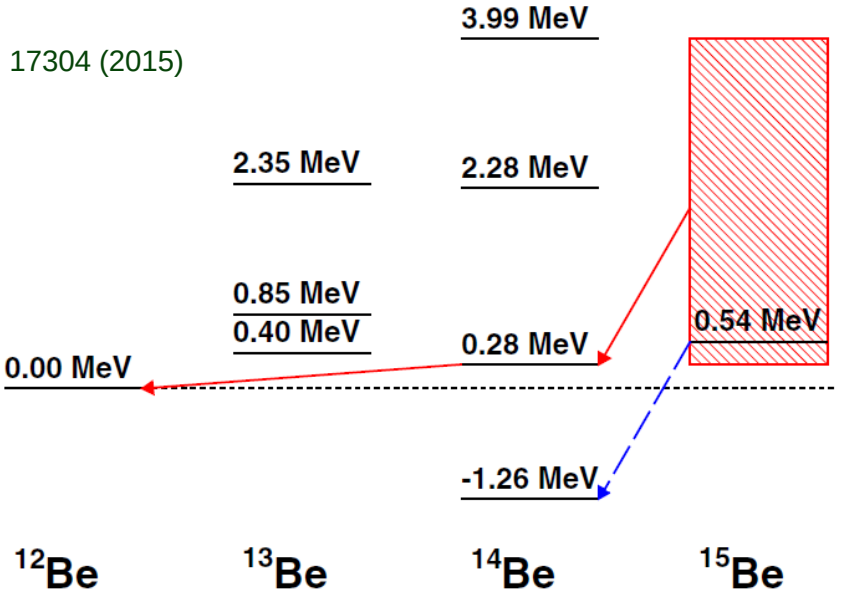
M. D. Jones *et al*. Phys. Rev. C 92, 051306(R) (2015)

Search for three neutrons from ^{15}Be

Simultaneous fitting of 2-, 3-, and 4-body spectra

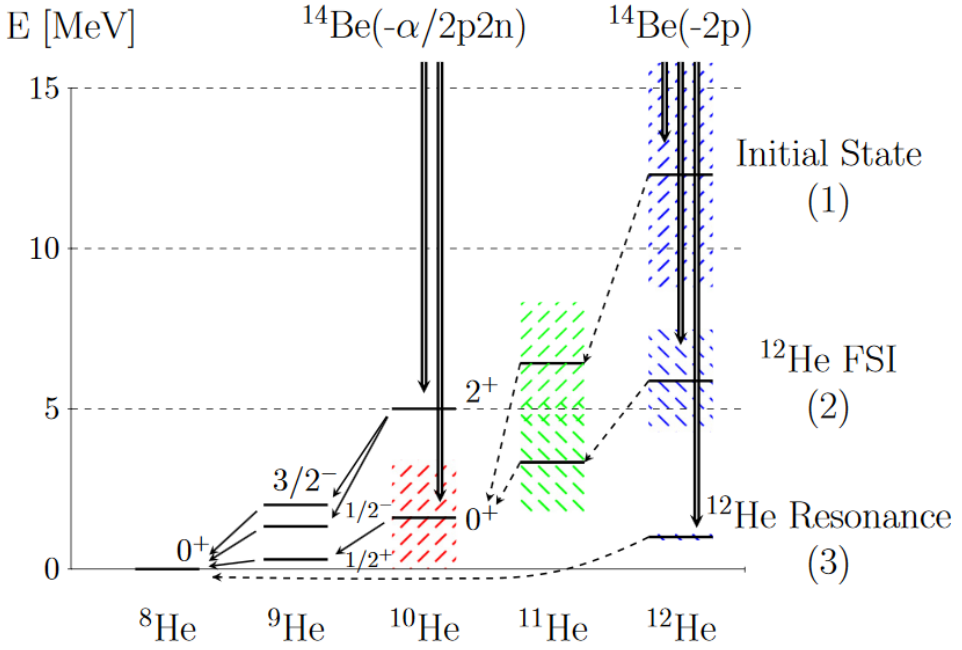


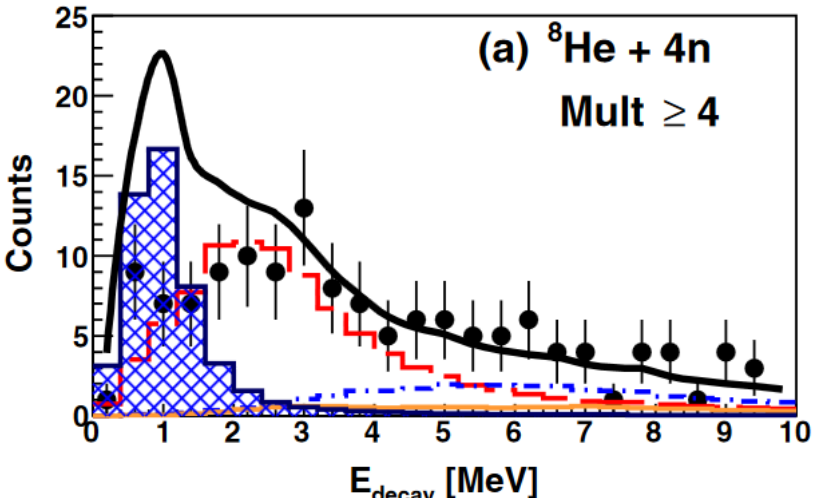
A. N. Kuchera *et al*. Phys. Rev. C 91, 17304 (2015)

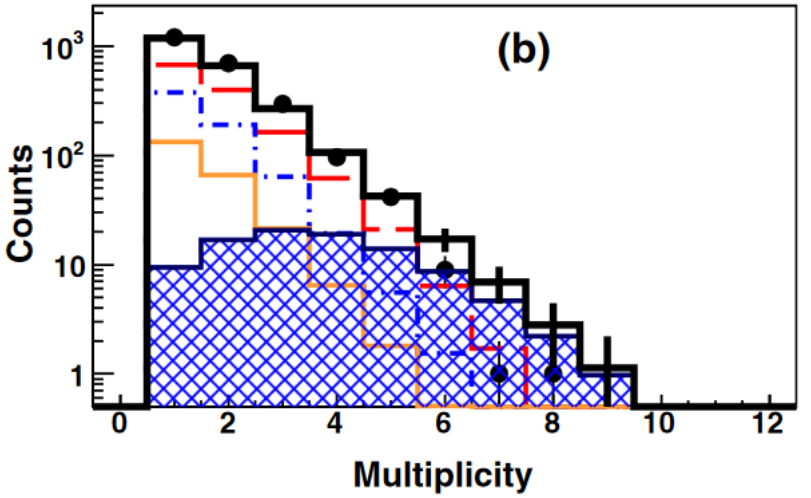


Search for four neutrons from ^{12}He

Construct 5-body spectra and include weakly populated resonance





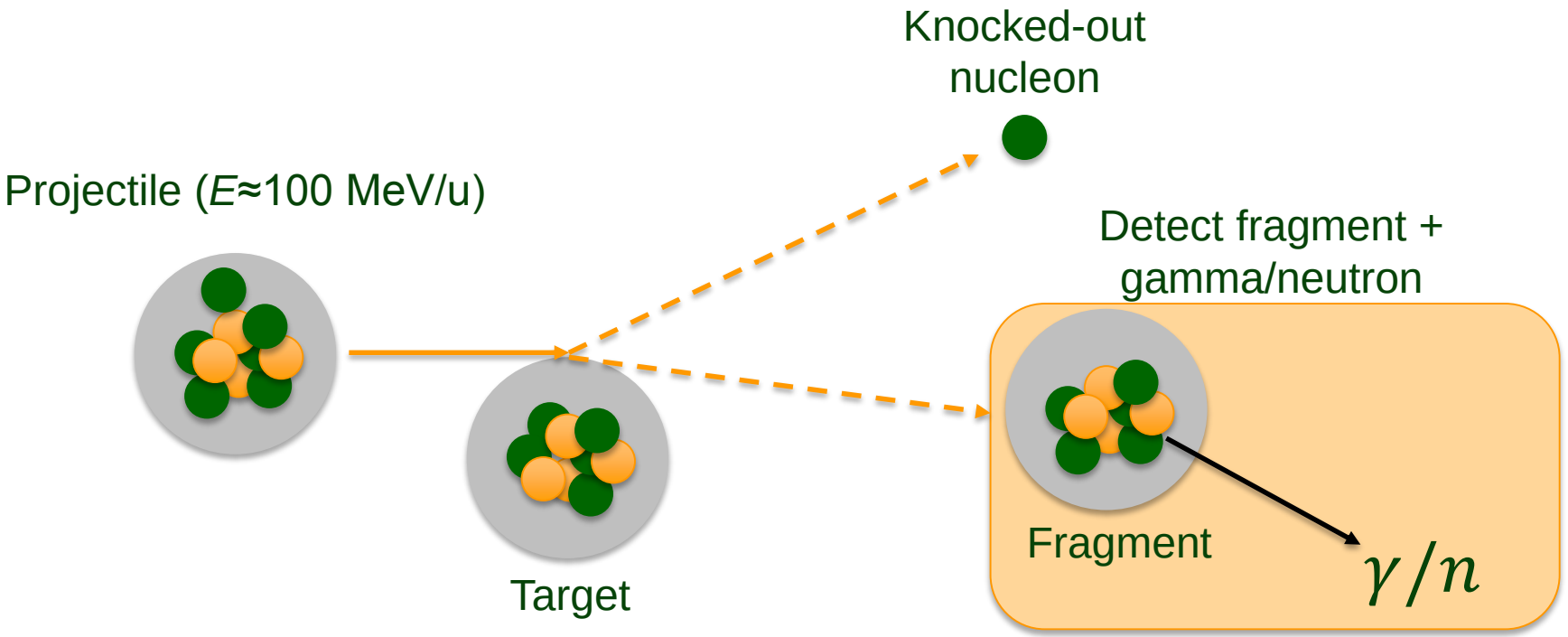


M.D. Jones *et al*. Phys. Rev. C 91, 044312 (2015)

Previous work on knockout reactions in the *p*-shell at NSCL

Nucleon-removal reactions

- Nucleon-removal (knockout) reactions are used at fragmentation facilities, such as NSCL, where secondary beams are produced at *E*≈100 MeV/u.
- Typically one or two nucleons are removed from projectile with a light nuclear target (ex. Be or C).



Structure and reaction models

Using nuclear reactions to study nuclear structure contains one observable with two model parameters.

$$\sigma^{if} = \sum_{|J_f - J_i| \le j \le J_f + J_i} S_j^{if} \, \sigma_{s.p.}$$

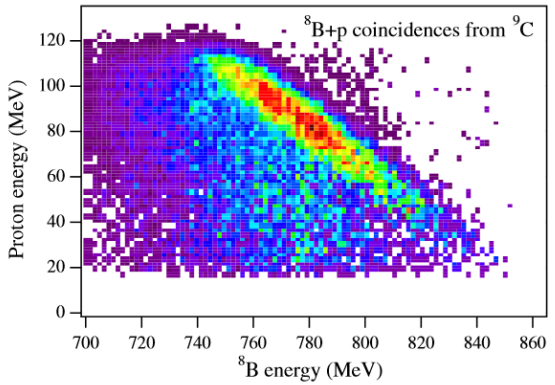
- Observable cross section
- Spectroscopic factor (from structure models, ex. shell model)
- Single particle cross section (from reaction models, ex. eikonal model)

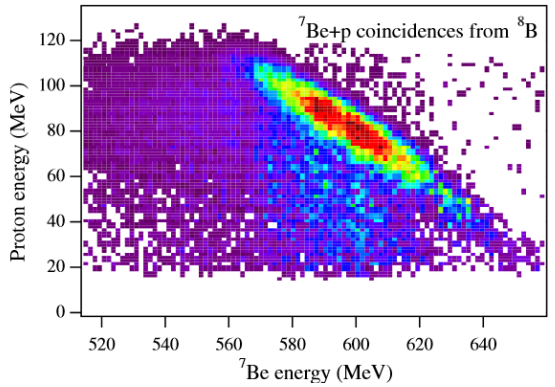
$$\sigma_{s.p.} = \sigma_{str} + \sigma_{dif} + \sigma_C$$

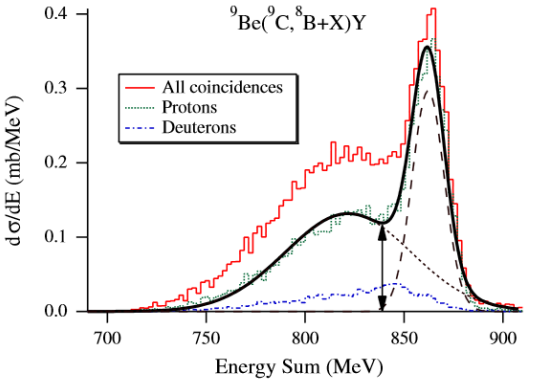
- *Stripping* is inelastic breakup (populated excited states).
- *Diffraction* is elastic breakup.
- The *Coulomb* term is the elastic breakup from the Coulomb interaction.

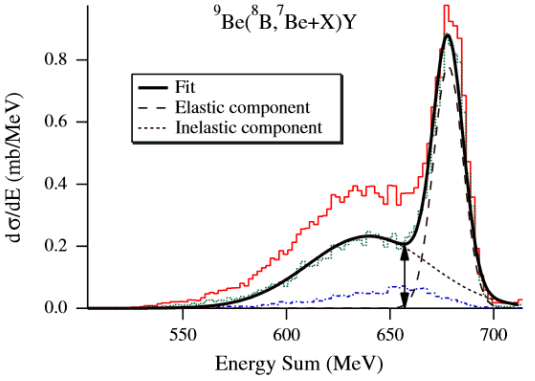
Proton knockout reaction mechanism

- Typically the removed nucleon is not measured in knockout experiments and results rely on reaction model calculations.
- Coincident measurements were made with the knocked-out proton and fragment were to quantify the cross section components.









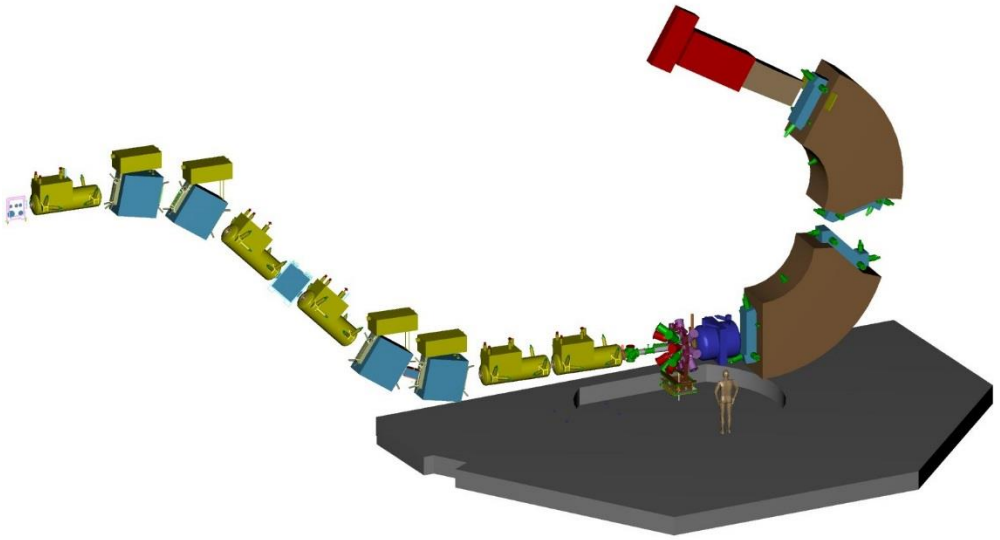
Ratio of elastic cross section to total

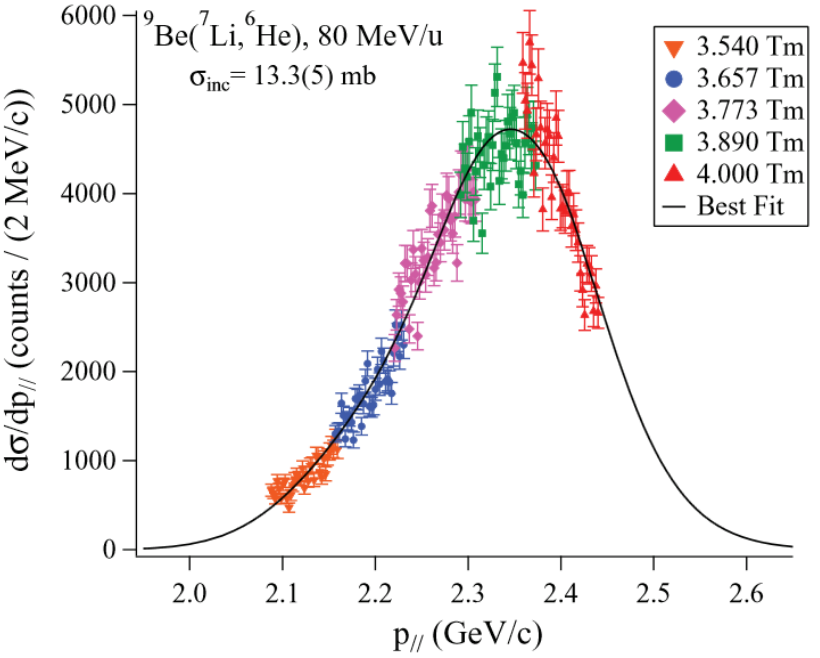
Reaction	Eikonal	Experiment
(^{9}C, ^{8}B)	26.8%	25(2)%
(^{8}B, ^{7}Be)	37.1%	38(3)%

D. Bazin *et al.*, PRL 102, 232501 (2009)

Single nucleon knockout cross sections

- Precise cross sections needed to benchmark and guide theory.
- Seven single-nucleon knockout reactions from *p*-shell nuclei were performed at the NSCL using S800 spectrograph (see below).
- Inclusive cross sections were measured and compared to theory.

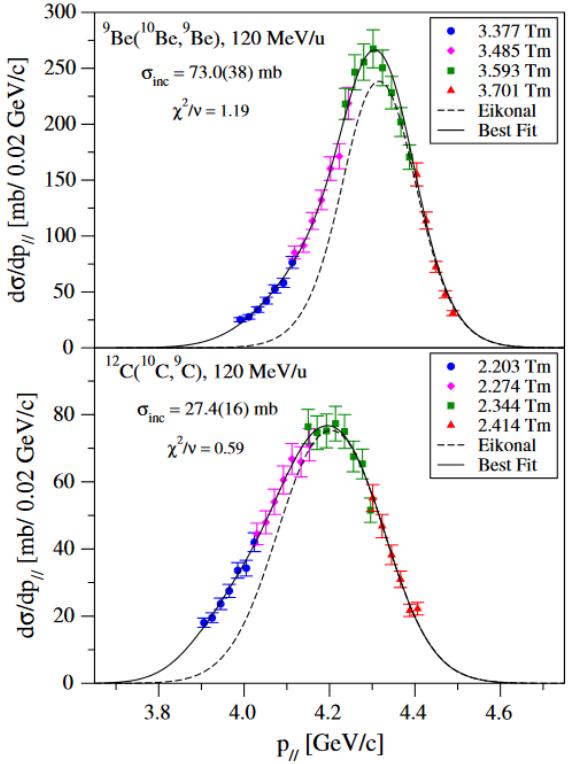




G. F. Grinyer *et al*. PRL 106 162502(2011)
G. F. Grinyer *et al*. PRC 86 24315 (2012)

Examples without bound excited states

- Two of the reactions include fragments that have no bound excited states: (^{10}Be,^{9}Be) and (^{10}C, ^{9}C).
- These offer the most direct comparison to theory because the final state of the nucleus is immediately known.

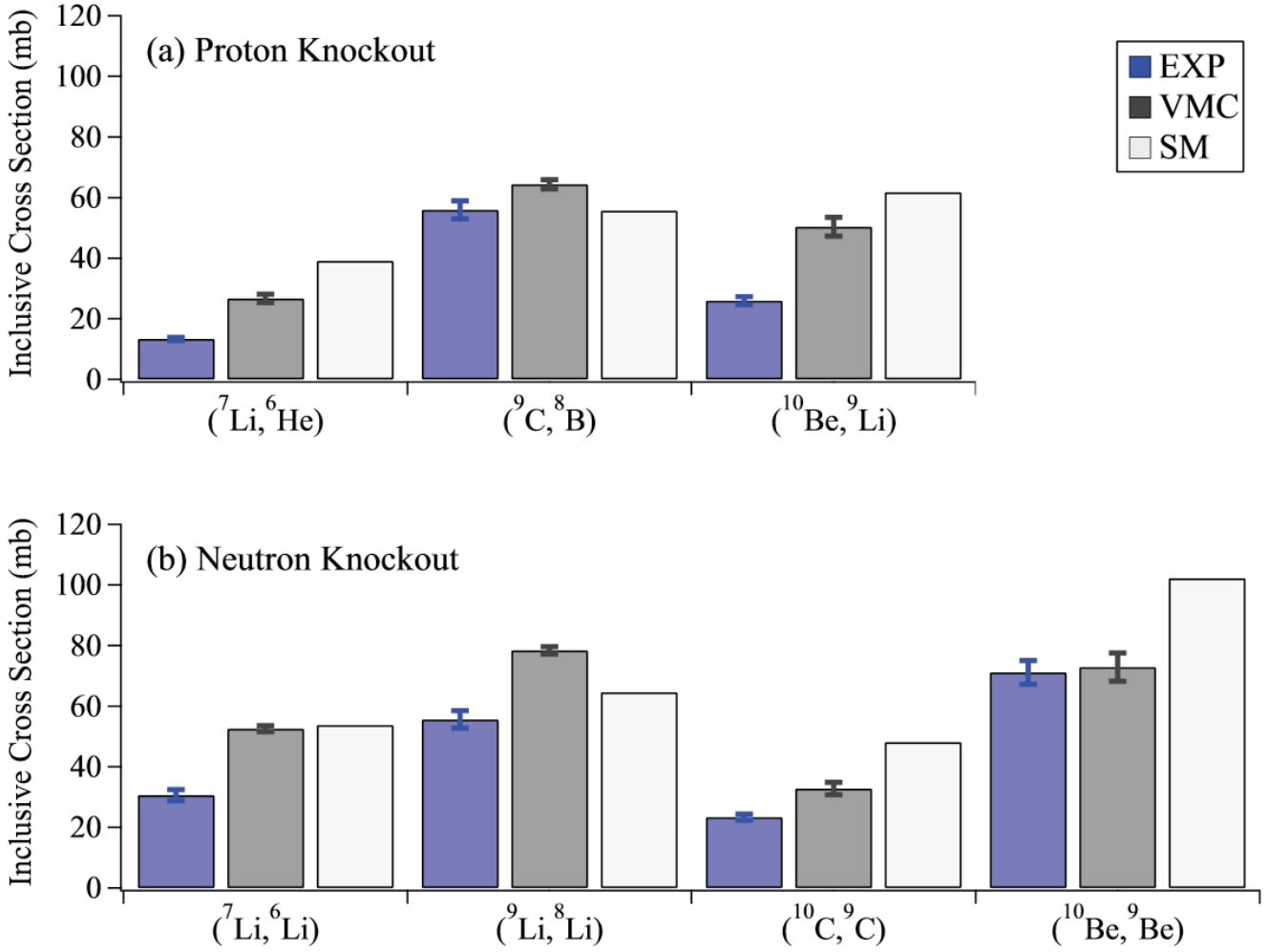


G. F. Grinyer *et al*. PRL 106 162502(2011)

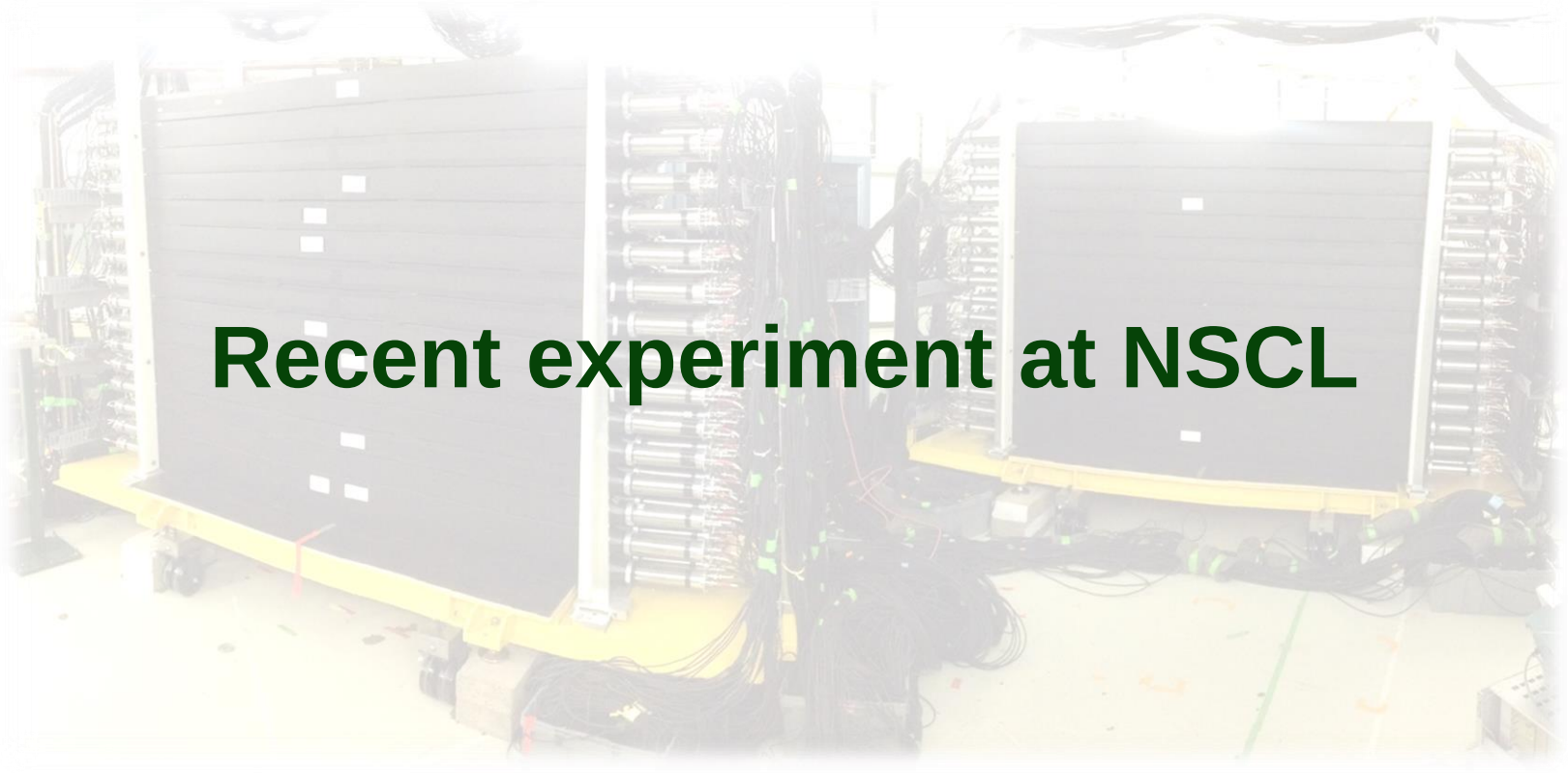
Reaction	σ_{SM} [mb]	σ_{NCSM} [mb]	σ_{VMC} [mb]	σ_{exp} [mb]
(^{10}Be,^{9}Be)	96.6	86.9(16)	72.8(13)	73(4)
(^{10}C,^{9}C)	48.0	43.4(9)	30.8(6)	23.2(10)

Inclusive cross section summary

More work is needed to better guide theory (exclusive cross sections).

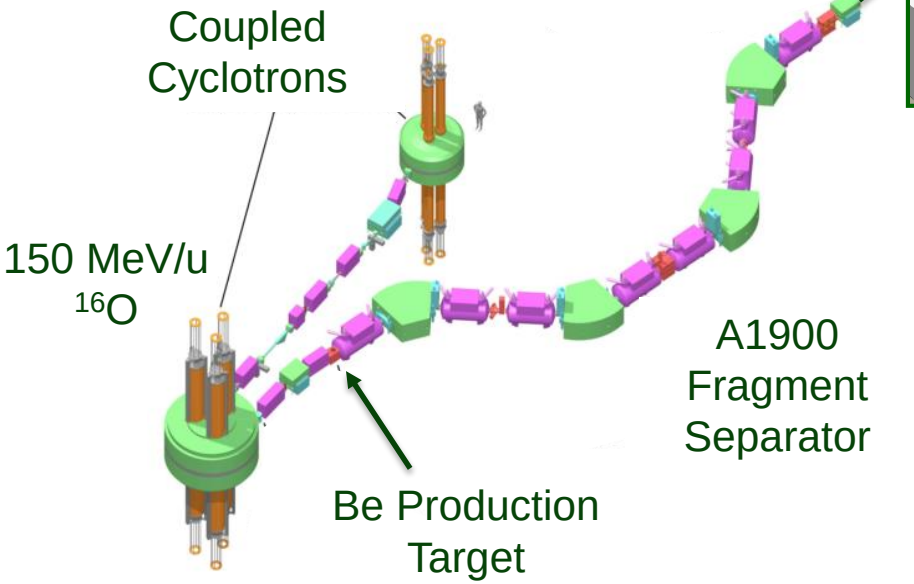


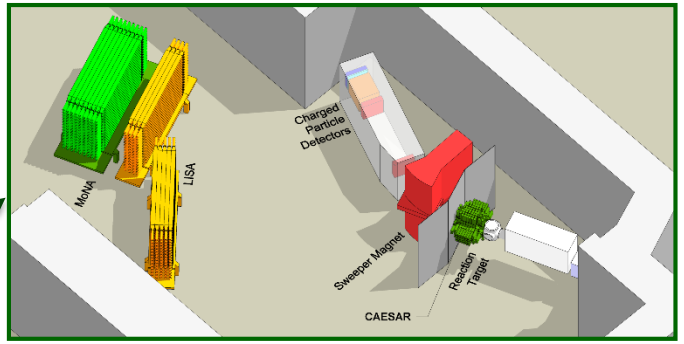
G. F. Grinyer *et al*. PRC 86 24315 (2012)



Recent experiment at NSCL

Coupled Cyclotron Facility - NSCL

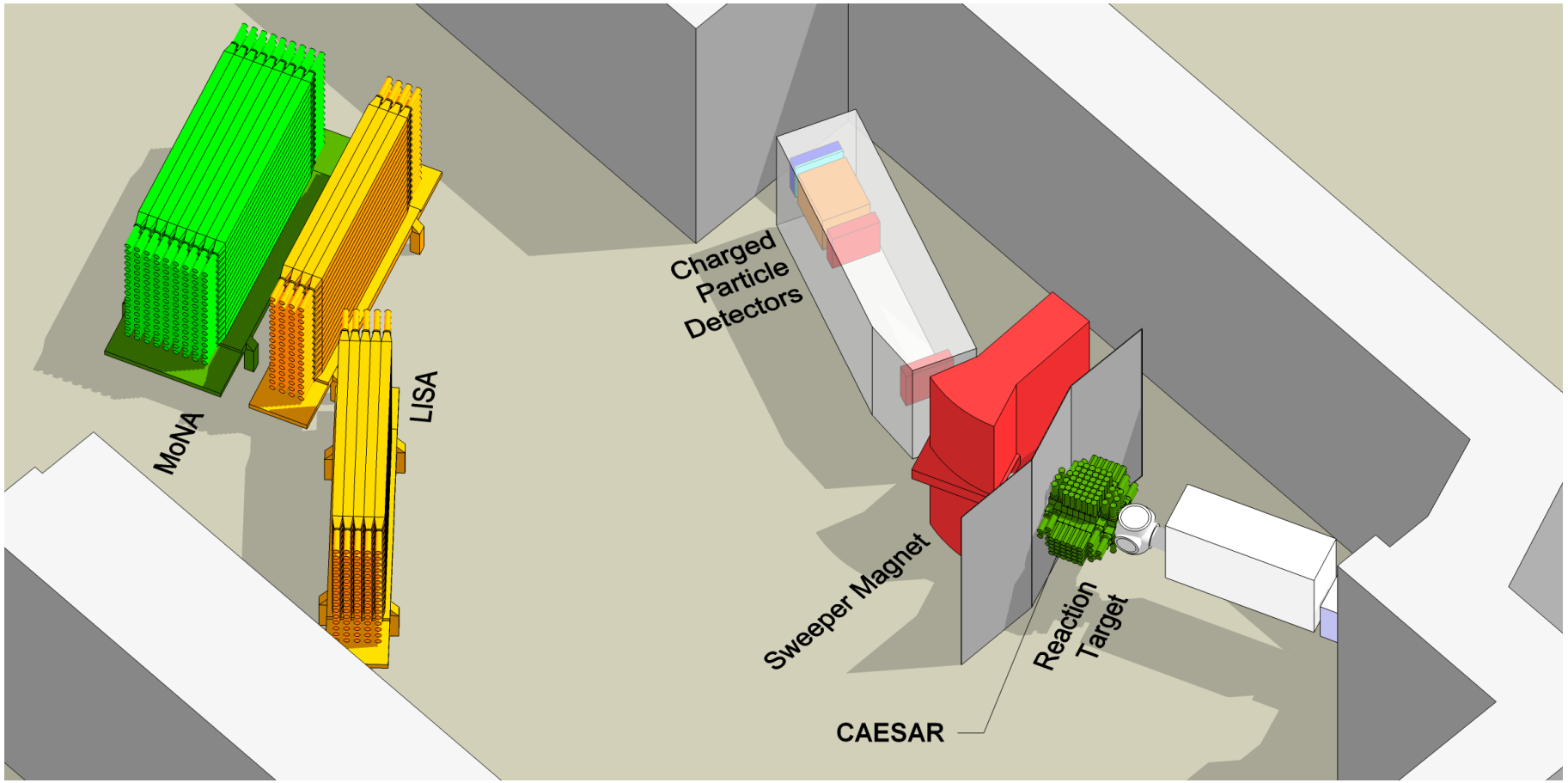




Experimental Vault

Secondary Beam	Energy [MeV/u]
^{7}Li	80
^{9}Li	80
^{10}Be	80
^{11}B	100
^{11}C	120
^{12}C	120

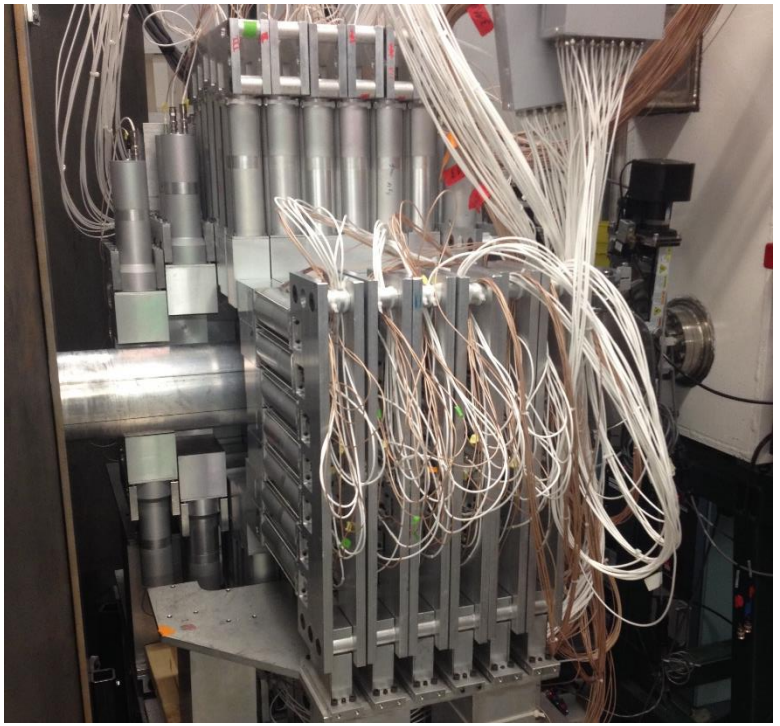
Experimental setup



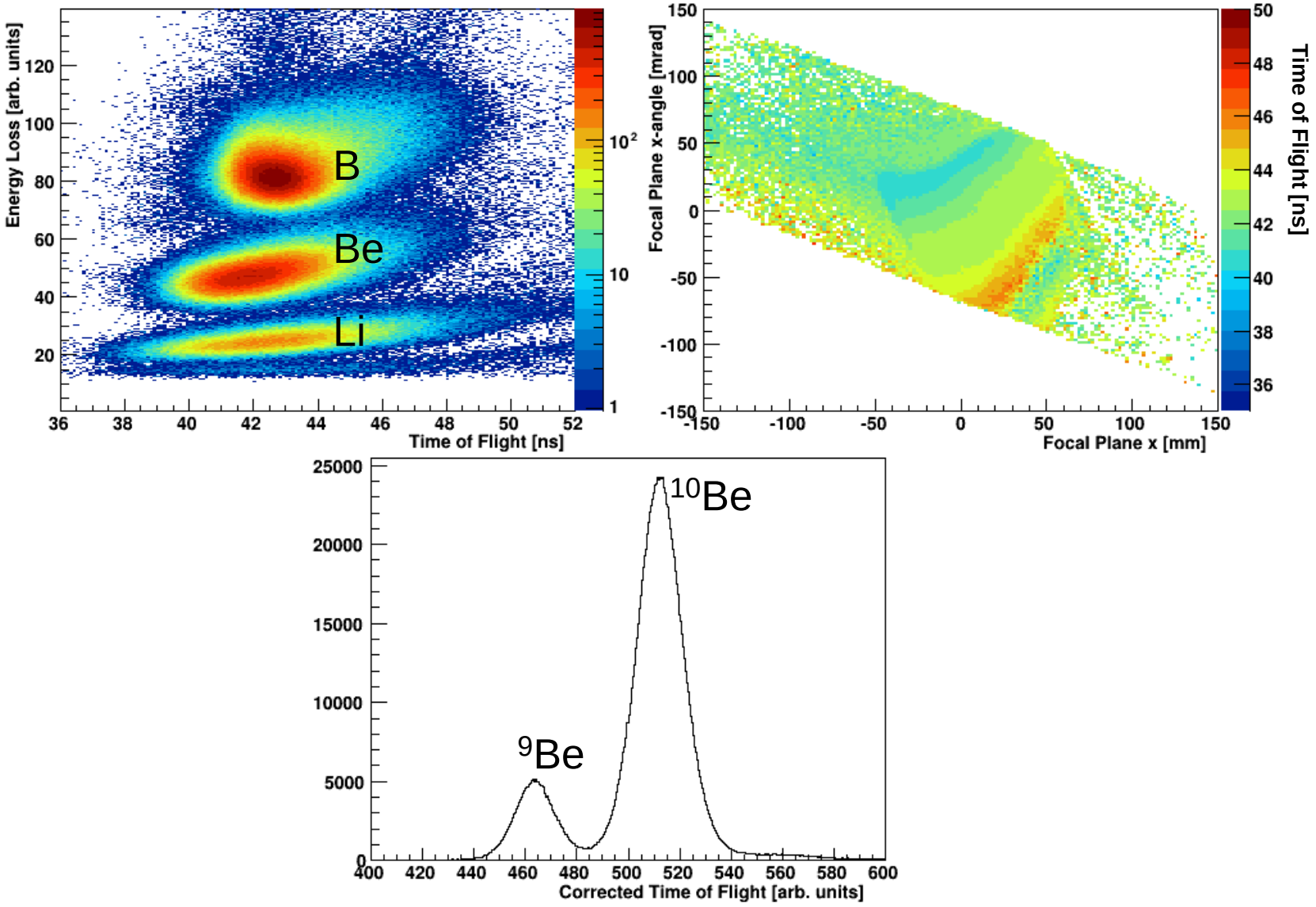
Reactions

- Six secondary beams, eight reaction settings, four days!
- Gamma-ray detector, CAESAR, surrounded the reaction target allows exclusive cross section measurements.

Reaction	Final States
(^{7}Li,^{6}He)	0^{+}(g.s.)
(^{7}Li,^{6}Li)	1^{+}(g.s.), 0^{+}(3.5 MeV)
(^{9}Li,^{8}Li)	2^{+}(g.s.), 1^{+}(1.0 MeV)
(^{10}Be,^{9}Li)	$3/2^{-}$(g.s.), $1/2^{-}$(2.6 MeV)
(^{11}B,^{10}Be)	0^{+}(g.s.), 2^{+}(3.4 MeV)
(^{11}C,^{10}C)	0^{+}(g.s.), 2^{+}(3.3 MeV)
(^{12}C, ^{11}B)	$3/2^{-}$(g.s.), $1/2^{-}$(2.1 MeV)
(^{12}C, ^{11}C)	$3/2^{-}$(g.s.), $1/2^{-}$(2.0 MeV)

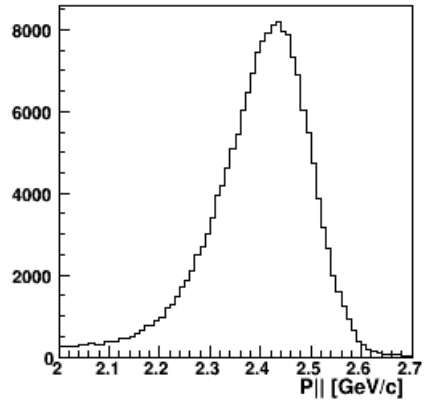


Example of particle ID: (^{11}B,^{10}Be)

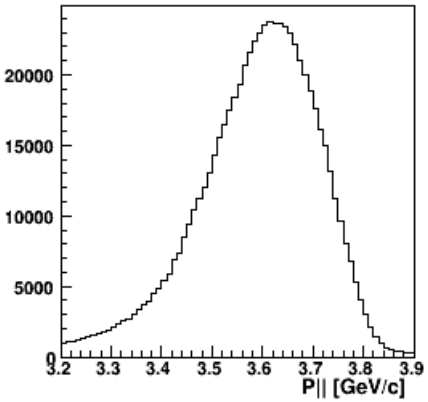


Parallel momentum distributions

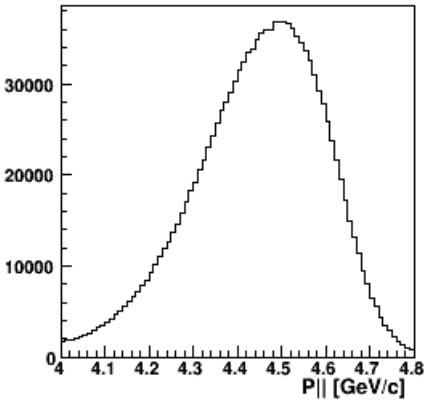
(^{7}Li,^{6}He)



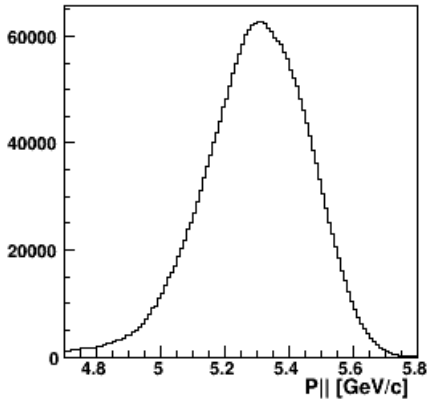
(^{10}Be,^{9}Li)



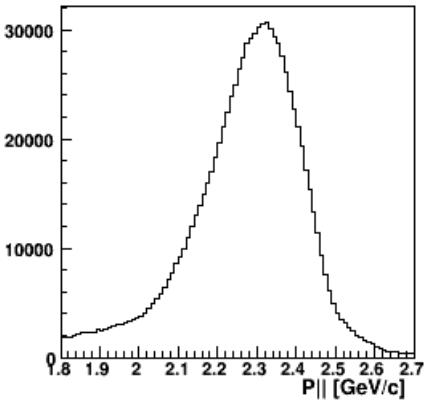
(^{11}B,^{10}Be)



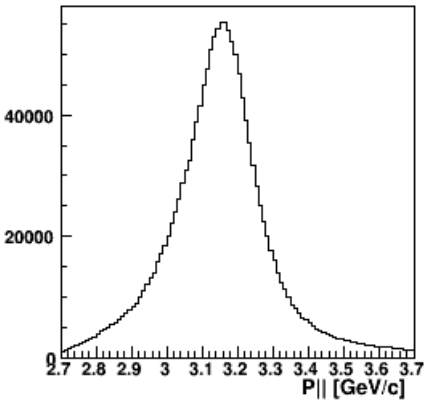
(^{12}C, ^{11}B)



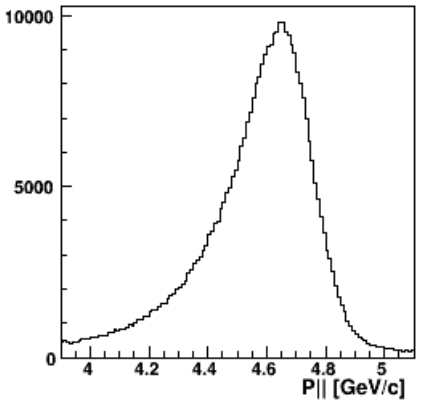
(^{7}Li,^{6}Li)



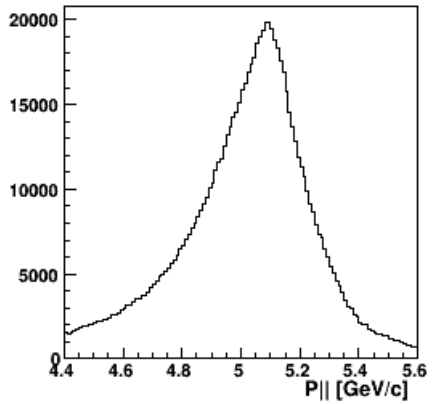
(^{9}Li,^{8}Li)



(^{11}C,^{10}C)

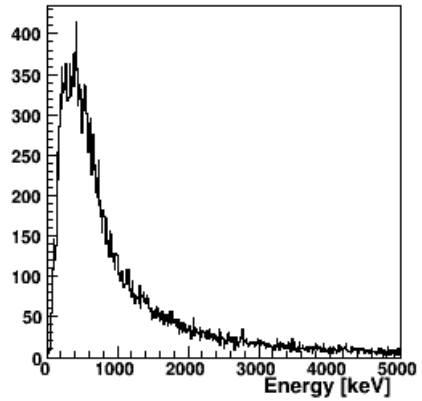


(^{12}C, ^{11}C)

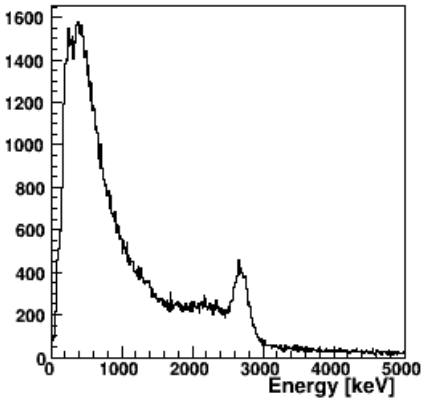


Gamma-ray spectra

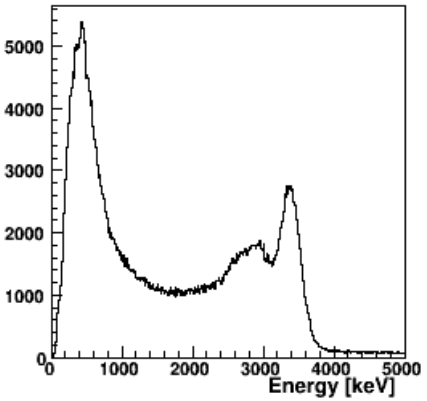
(^{7}Li,^{6}He)



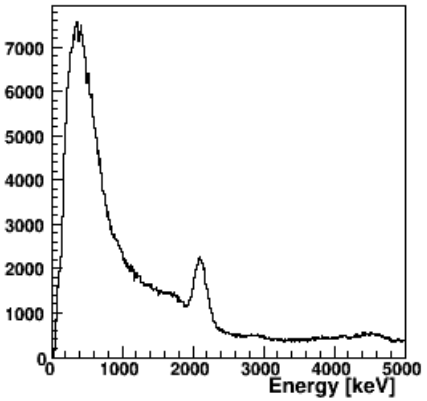
(^{10}Be,^{9}Li)



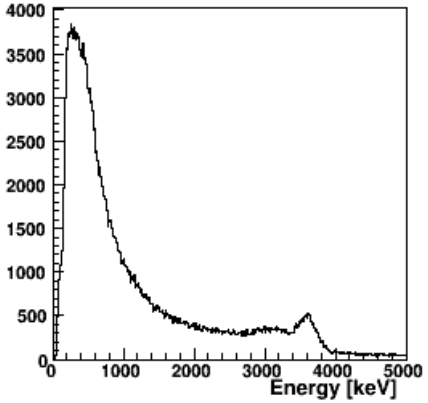
(^{11}B,^{10}Be)



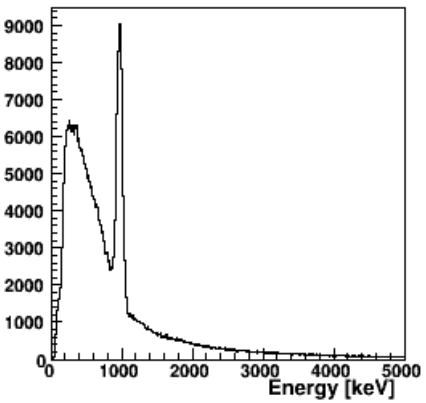
(^{12}C, ^{11}B)



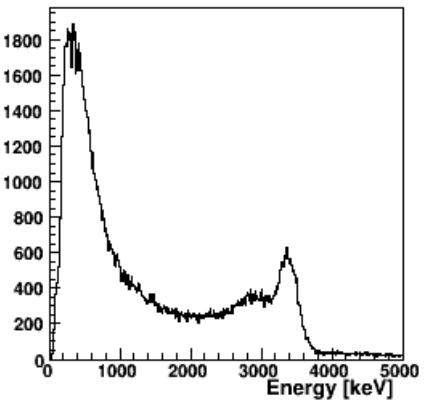
(^{7}Li,^{6}Li)



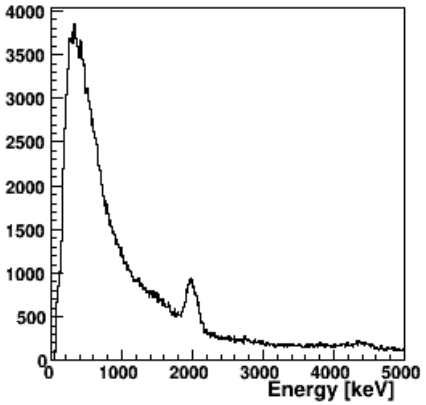
(^{9}Li,^{8}Li)



(^{11}C,^{10}C)



(^{12}C, ^{11}C)



Spectra are Doppler corrected and include neighboring crystal energy add-back.

Preliminary results

- Absolute cross sections are still being finalized.
- Relative cross sections of excited to ground states have been obtained.

Reaction	Final State	σ_{th}^{SM} [mb]	σ_{th}^{VMC} [mb]	σ_{exp} [mb]
(^{10}Be,^{9}Li)	3/2$^-$	54.2	36.3(30)	18.5(9)
	1/2$^-$	7.6	14.0(9)	7.5(4)
	Inclusive	61.8	50.3(31)	26.0(13)

- A similar discrepancy in cross section was observed in the (^{10}C,^{9}C) reaction and was attributed to the accuracy of the eikonal model when dealing with deeply bound nucleons.
  - ^{9}C+n: 21.3 MeV
  - ^{9}Li+p: 19.6 MeV

All theoretical and experimental inclusive cross sections are taken from G. F. Grinyer *et al*. PRC 86 024315 (2012).

Preliminary results

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	1/2$^-$	7.6	14.0(9)	7.5(4)
	Inclusive	61.8	50.3(31)	26.0(13)
(^{9}Li,^{8}Li)	2$^+$	47.3	56.3(11)	20.1(10)
	1$^+$	17.3	22.1(6)	35.0(17)
	Inclusive	64.6	78.4(13)	55.6(29)

- Unclear why the branching for the (^{9}Li,^{8}Li) states is so different from theory. Further analysis required to understand this result.

All theoretical and experimental inclusive cross sections are taken from G. F. Grinyer *et al*. PRC 86 024315 (2012).

Future plans

- Finalize absolute cross section measurements.
- Compare exclusive cross sections to shell model and *ab initio* calculations such as VMC and NSCM.
- Use neutron data from MoNA-LISA to check the validity of neutron-removal reaction models by extracting elastic and inelastic components of cross section.

Conclusions

- The use of direct reactions, especially nucleon-removal reactions, have been successful in the investigations of nuclear structure.
- Multiple-neutron decay experiments are pushing the frontier of nuclear structure.
- A recent experiment at NSCL has been performed to provide more detail into the structure of *p*-shell nuclei for the guidance of *ab initio* approaches to nuclear theory.
- New results to come with exclusive cross sections from particle-gamma coincidences.

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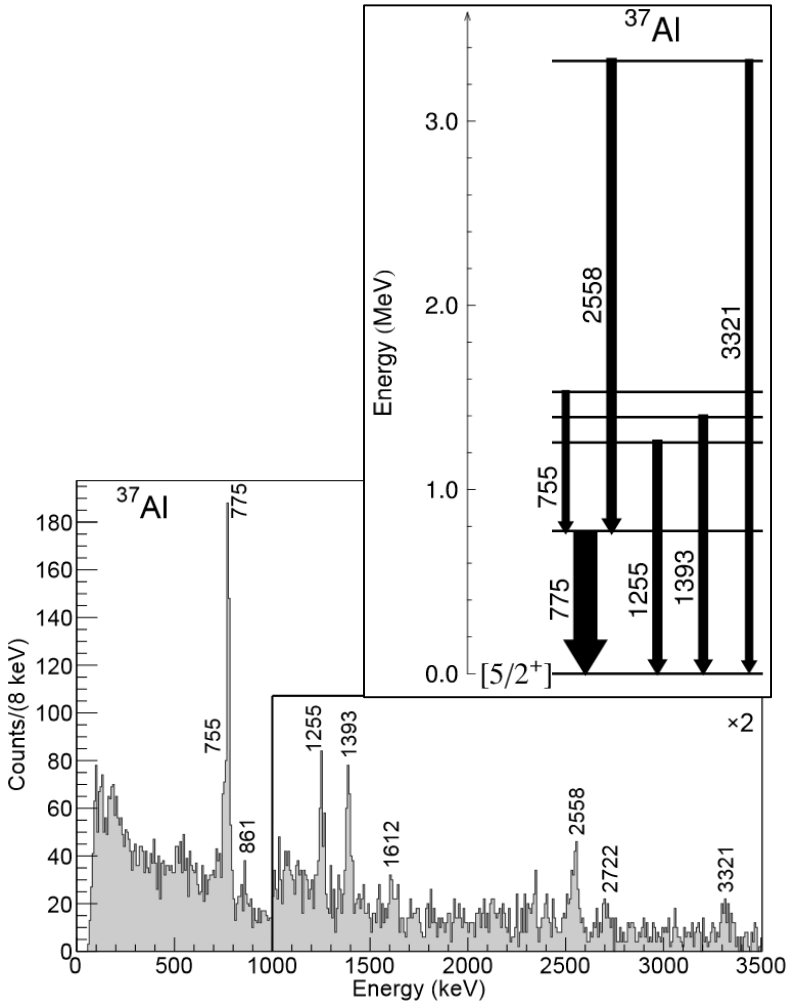
Michigan State University

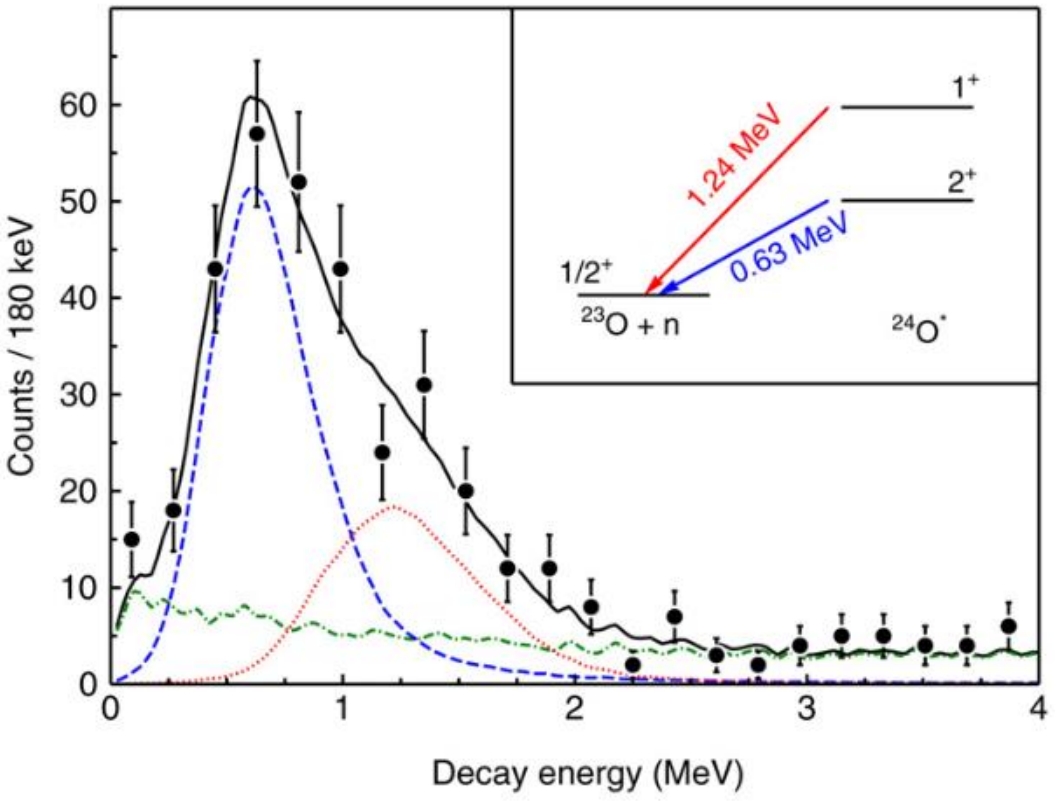
Spectroscopy of bound and unbound states

Gamma Spectroscopy: Bound states



S. R. Stroberg *et al*. Phys. Rev. C 90 034301 (2014)

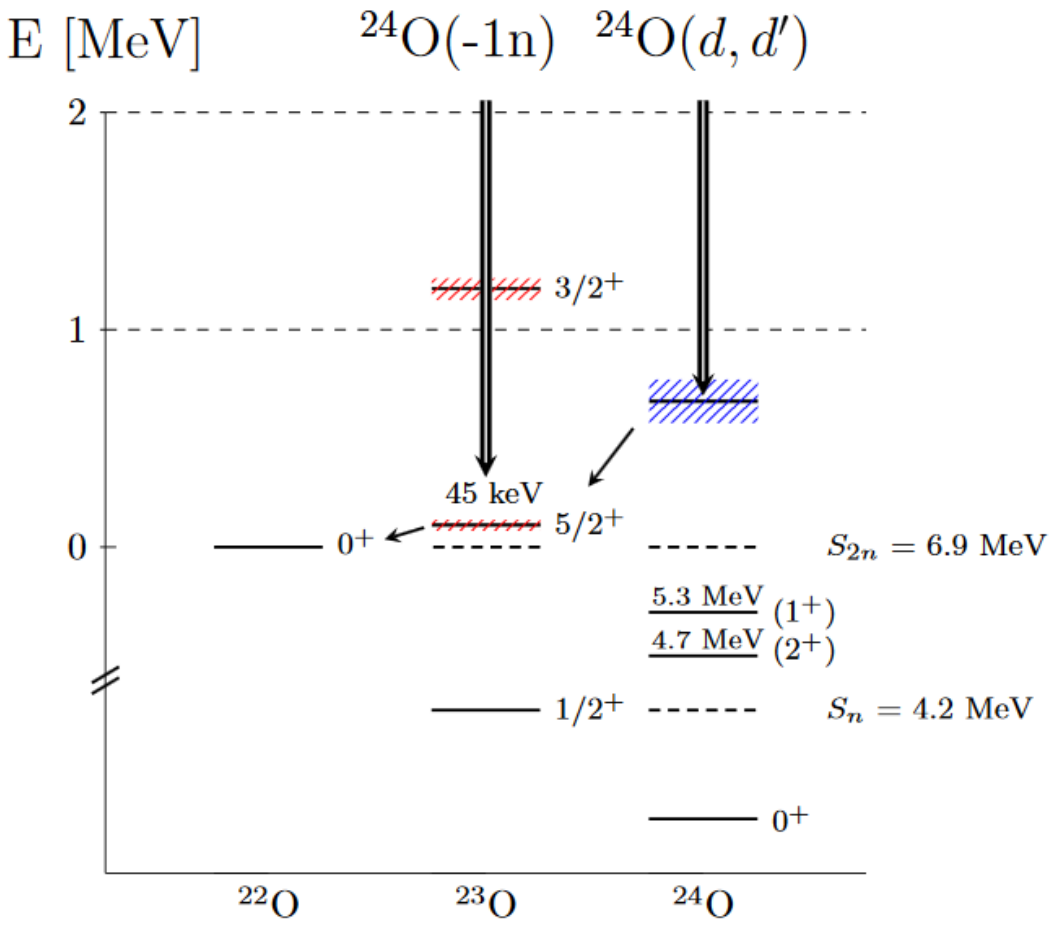
Invariant Mass Spectroscopy: Neutron-unbound states



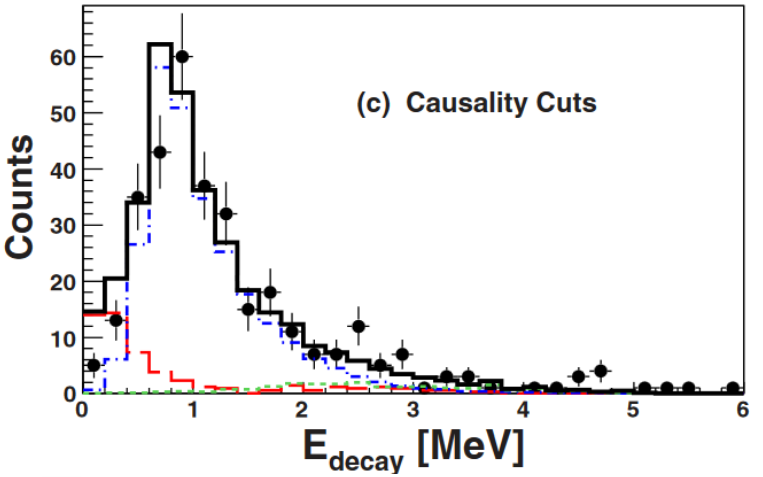
C. R. Hoffman *et al*. Phys. Lett. B 672 (2009)

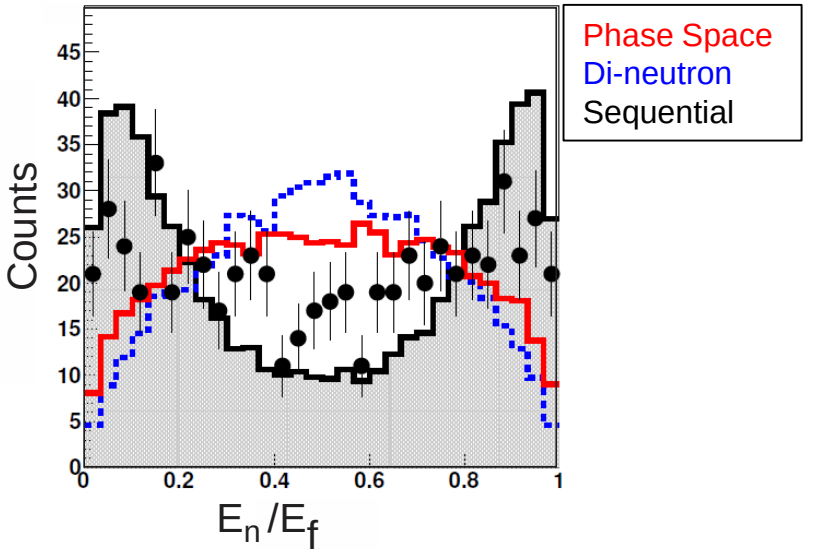
Two neutrons from ^{24}O

Using energy and angular correlations from $^{24}O \rightarrow ^{22}O + 2n$



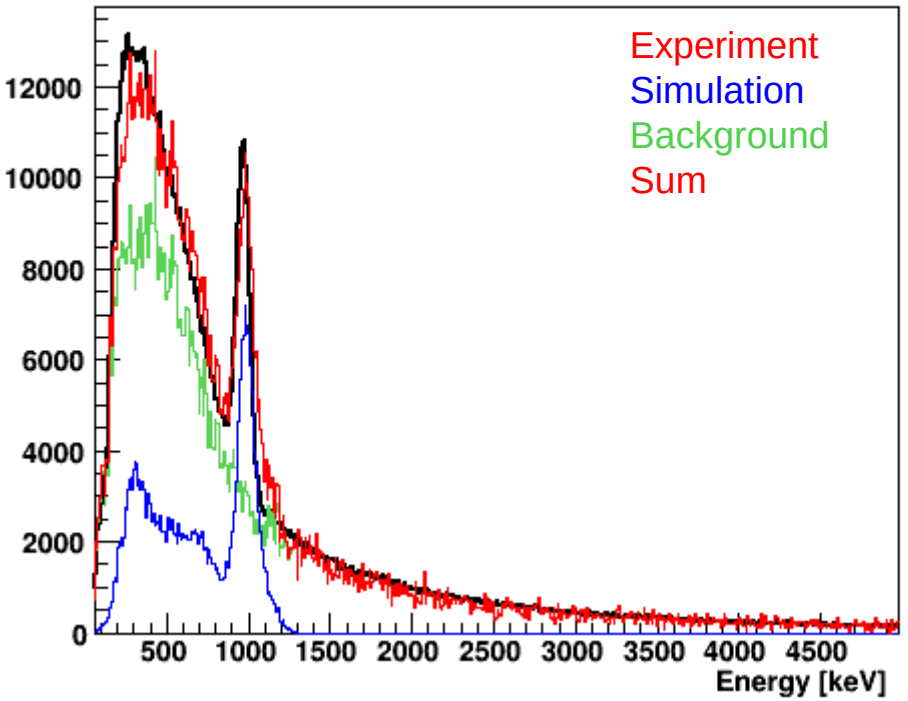
M. D. Jones *et al*. Phys. Rev. C 92, 051306(R) (2015)





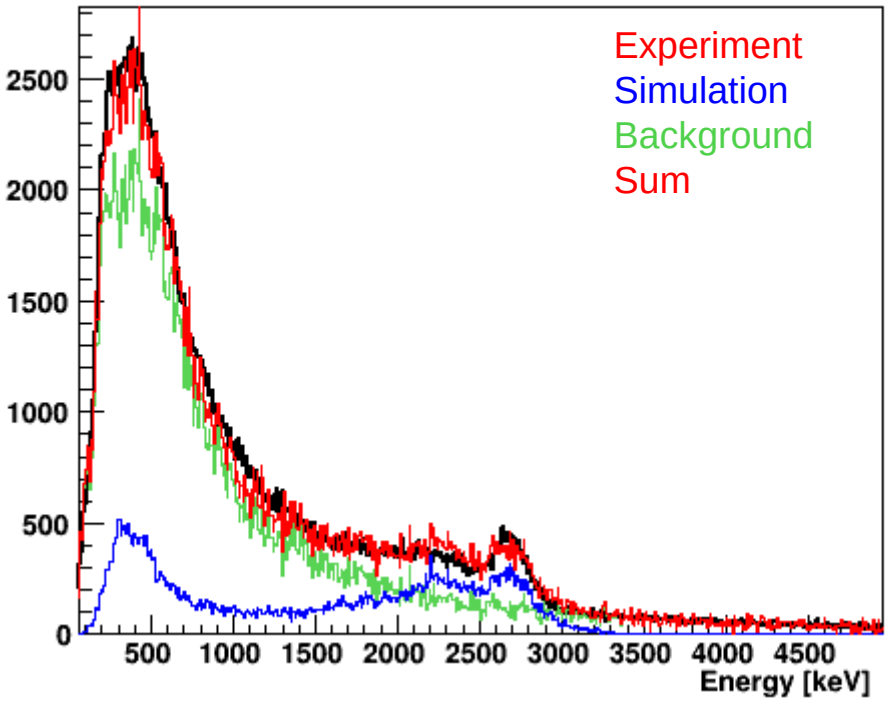
(^{10}Be,^{9}Li*) fitting

Relative strength to excited state determined from GEANT4 simulation of CAESAR combined with background of (^{7}Li,^{6}He).



(^{9}Li,^{8}Li*)

Relative strength to excited state determined from GEANT4 simulation of CAESAR combined with background of (^{7}Li,^{6}He).



Experimental setup