B(E2) measurements in light radioactive nuclei for guiding *ab-initio* calculations

Samuel L. Henderson

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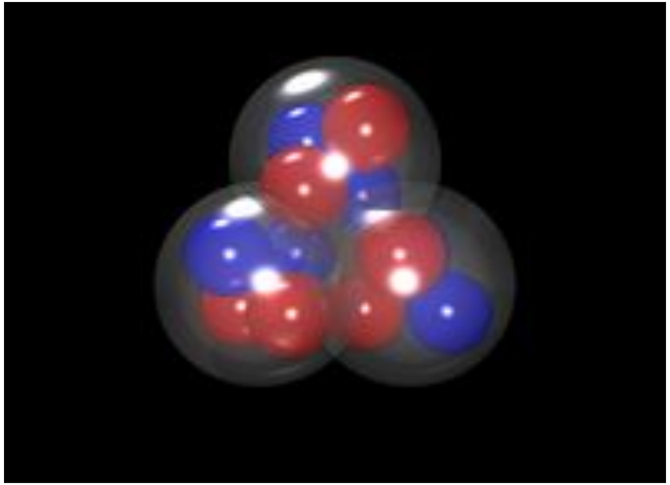
Questions in Nuclear Structure

- We want to understand the structure of nuclei
- What causes clusters and Halo nuclei?
- Want a fundamental theory to explain structures



Martin Freer, Rev. Mod. Phys. 90, 035004 (2018)

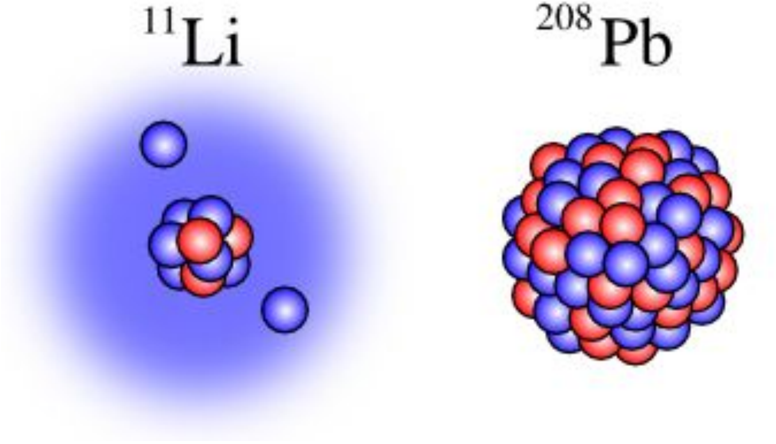


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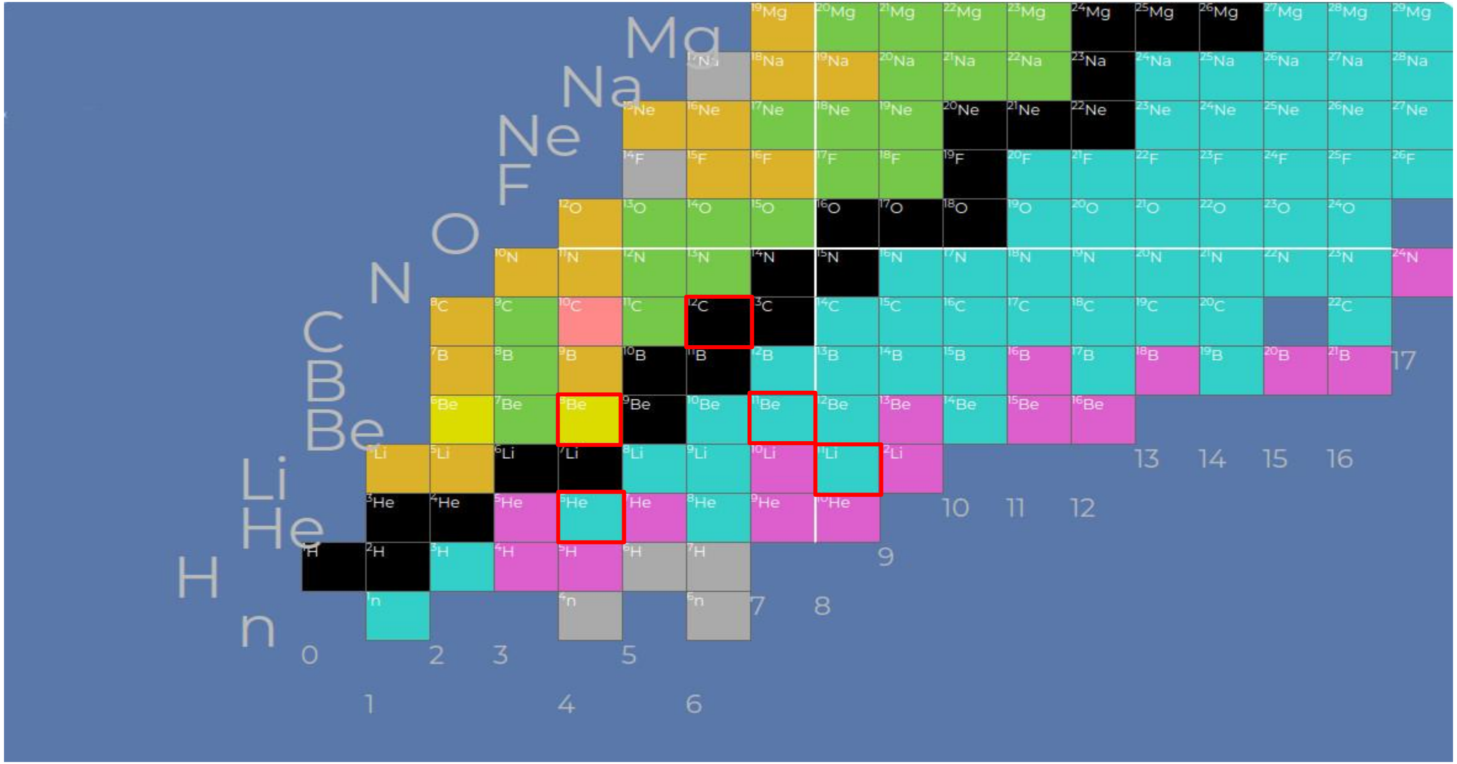
Chart of Nuclides



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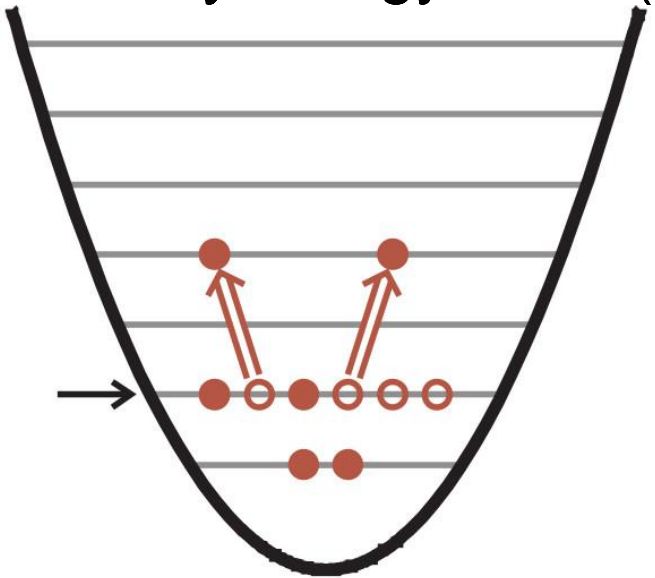
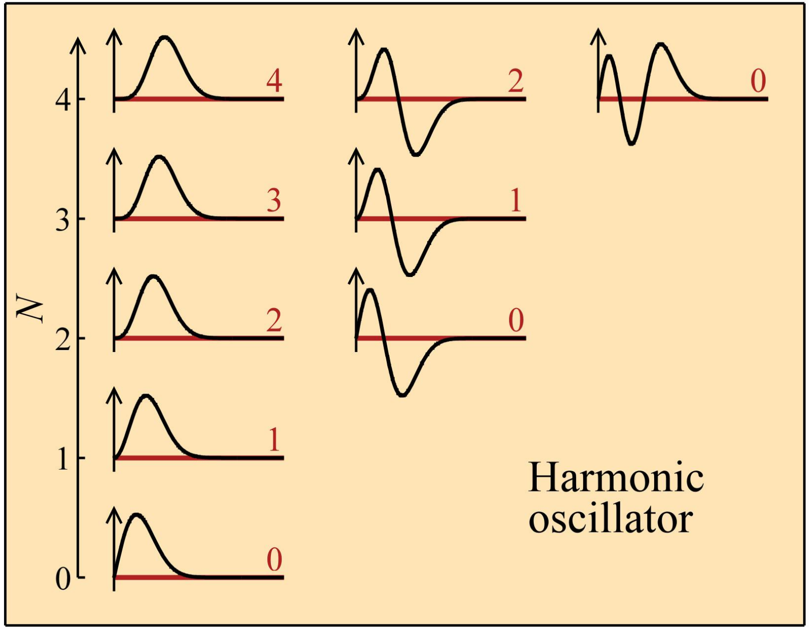
Ab Initio Theory

- From nuclear *first principles*
  - Nucleon-nucleon interactions
  - Input as potential into Shrödinger equation
- Reality is complex
  - Describing the interaction is difficult
  - Solving the Shrödinger equation directly is impractical
  - Multiple approaches

No-Core Shell-Model Approach

- Start from nucleon interactions
- Include more and more basis states (Nmax)
- Vary energy scale (ħΩ)





Courtesy of M. Caprio

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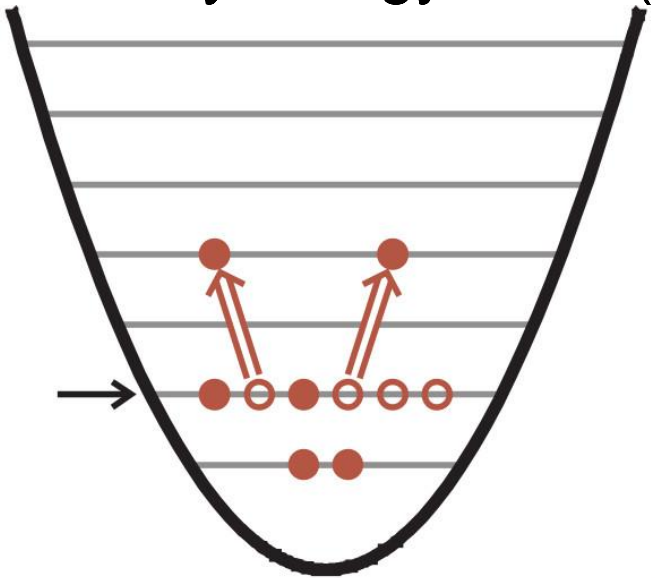

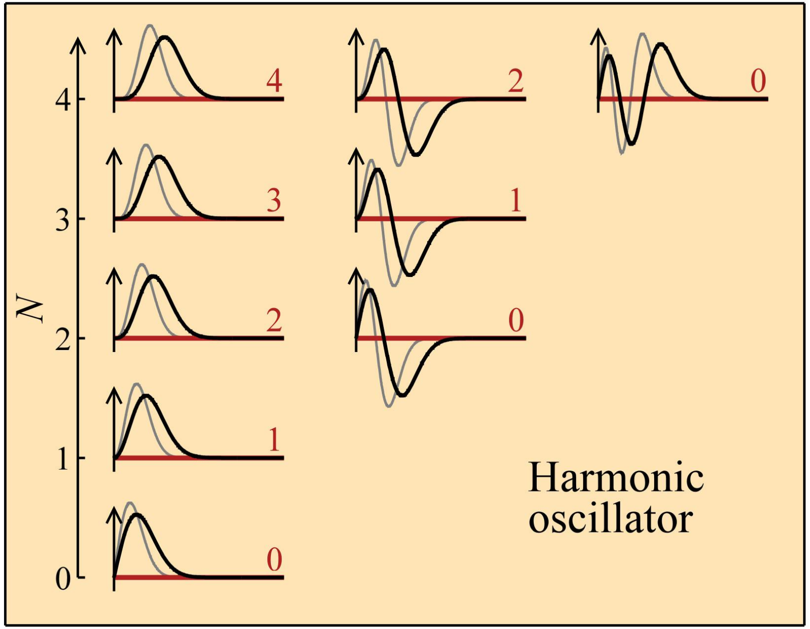

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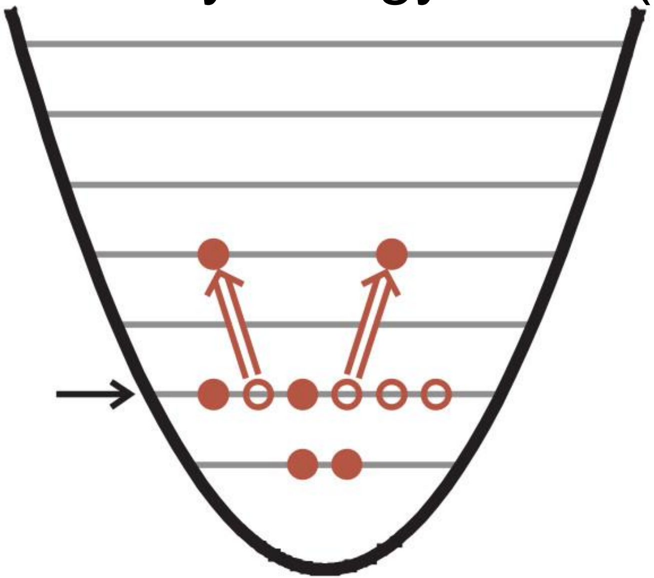
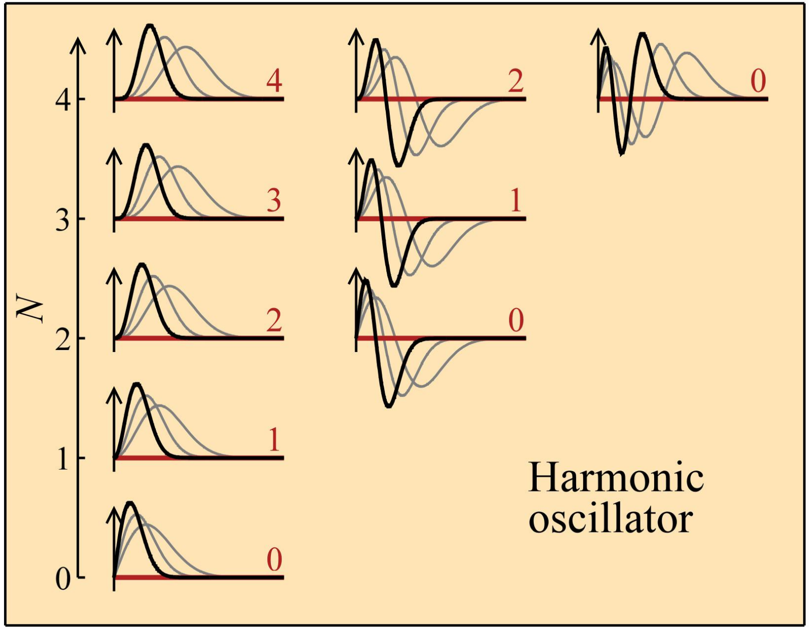
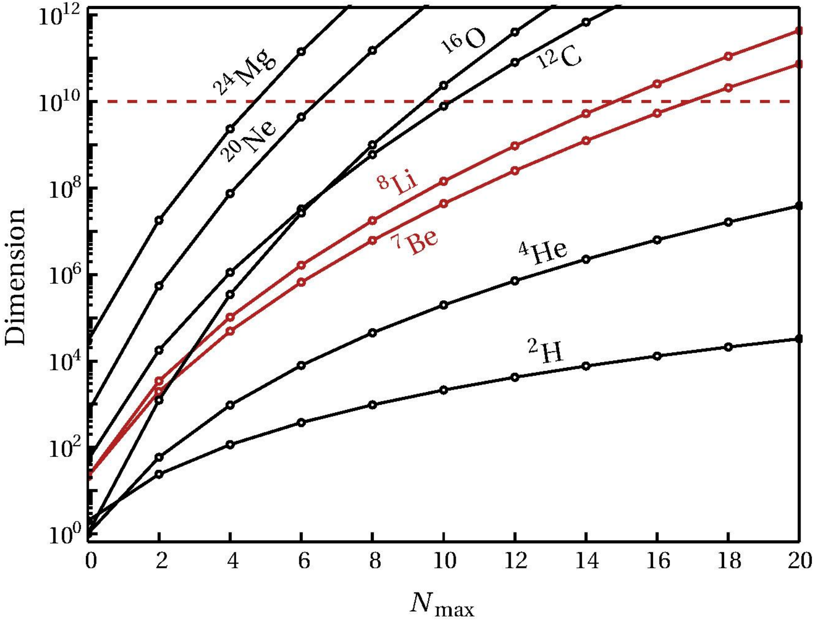


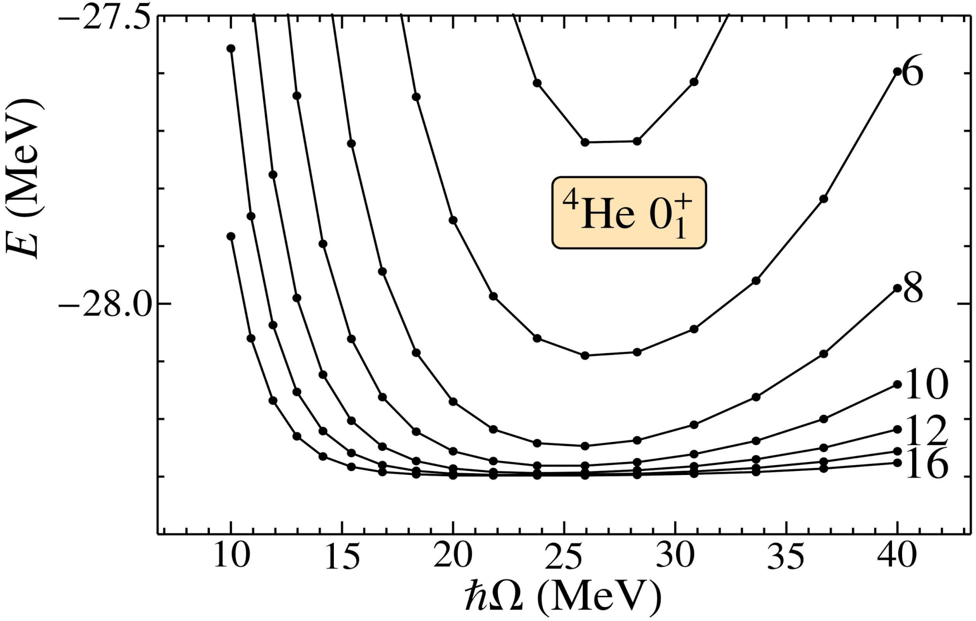


Courtesy of M. Caprio

No-Core Shell Model Cont.

- The QM Many-Body problem is turned a into linear algebra problem



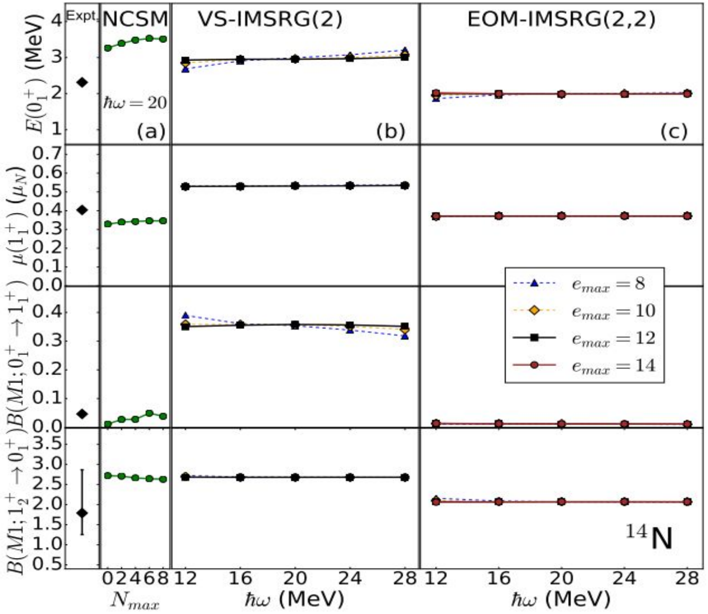


Courtesy of P. Fasano

Courtesy of Ch. Constantinou

Differences in calculations

- NCSM only one approach of many
- Different approaches can yield divergent results
- Which *first principle* calculation do we trust?



N. M. Parzuchowski et al, PRC 96, 034324 (2017)

Differences in calculations

- Interaction choice causes differences as well
- Green's Function Monte Carlo (GFMC) example in ^{10}Be
- Not all interactions performed equivalently

H	AV18	AV18 + UIX	AV18 + IL2	AV18 + IL7	Exp.
$\|E_{gs}(0^+)\|$	50.1(2)	59.5(3)	66.4(4)	64.3(2)	64.98
$E_x(2_1^+)$	2.9(2)	3.5(3)	5.0(4)	3.8(2)	3.37
$E_x(2_2^+)$	2.7(2)	3.8(3)	5.8(4)	5.5(2)	5.96
$B(E2; 2_1^+ \rightarrow 0^+)$	10.5(3)	17.9(5)	8.1(3)	8.8(2)	9.2(3)
$B(E2; 2_2^+ \rightarrow 0^+)$	3.3(2)	0.35(5)	3.3(2)	1.7(1)	0.11(2)
$\Sigma B(E2)$	13.8(4)	18.2(6)	11.4(4)	10.5(3)	9.3(3)

E. A. McCutchan et al PRL103, 192501 (2009)

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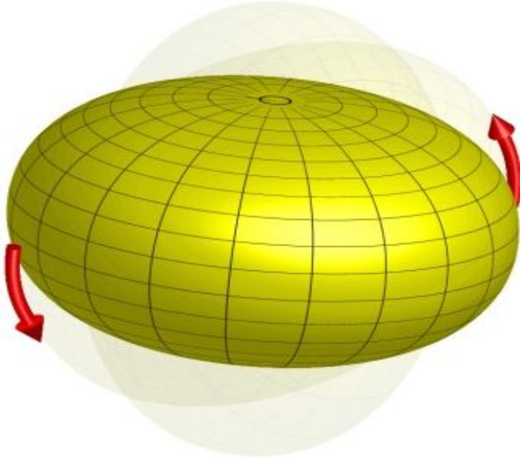
B(E2) values

- B(E2) is a good candidate to benchmark calculations
  - Reduced electric quadrupole transition probability
  - Sensitive value to calculation choices
  - Theory of EM transitions well understood
  - Connects to nuclear shapes



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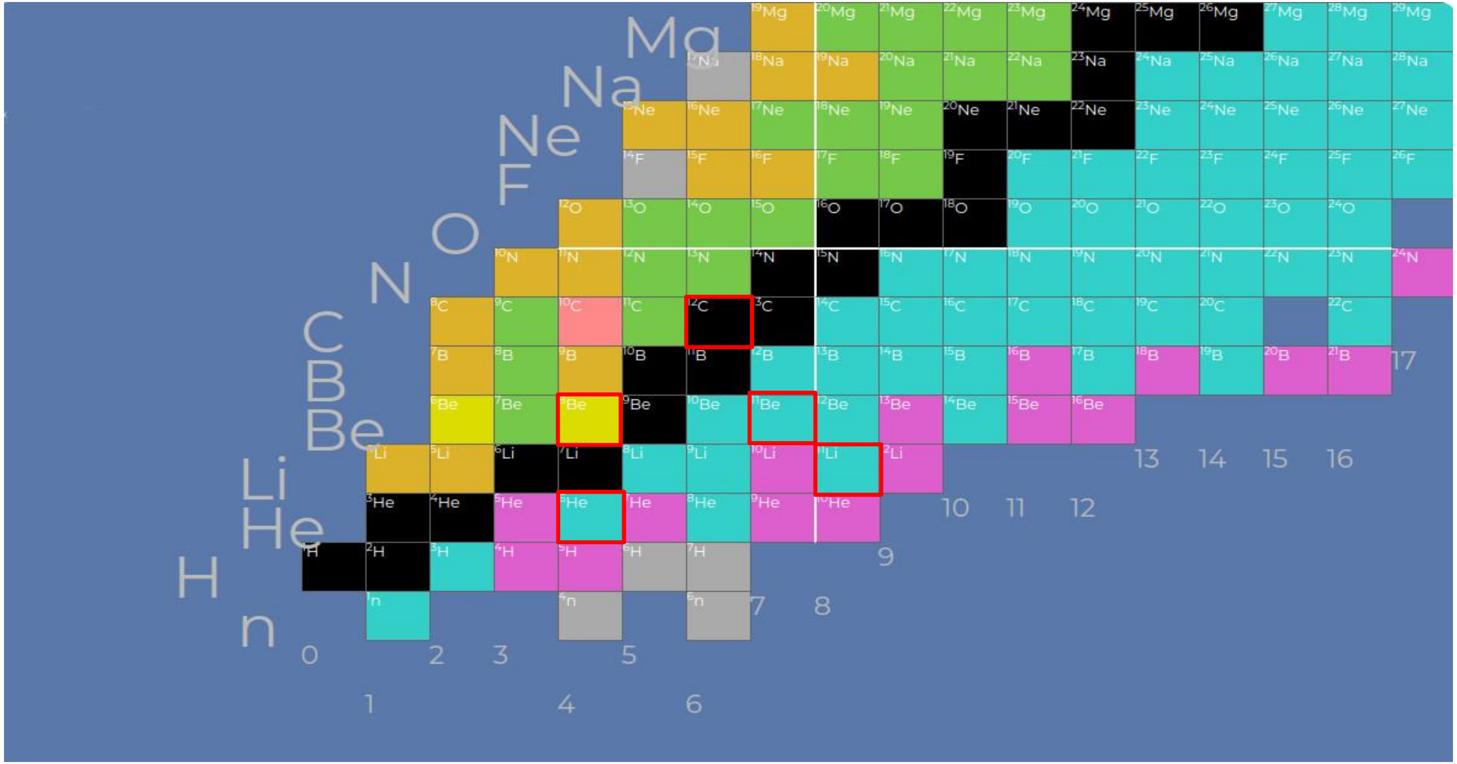
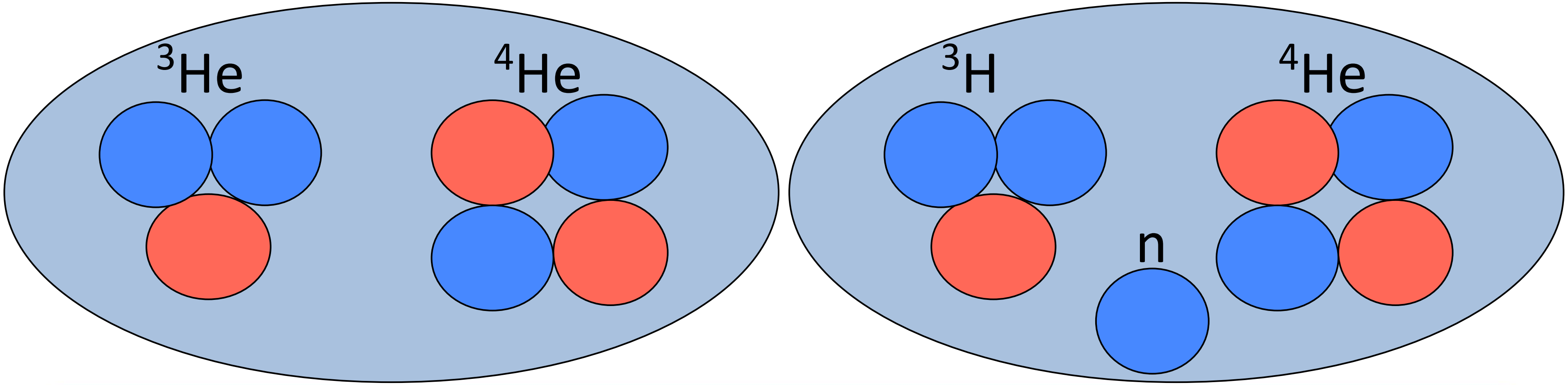


Nuclei to measure

- Measuring ^{7}Be and ^{8}Li
- Light nuclei with potential cluster structures



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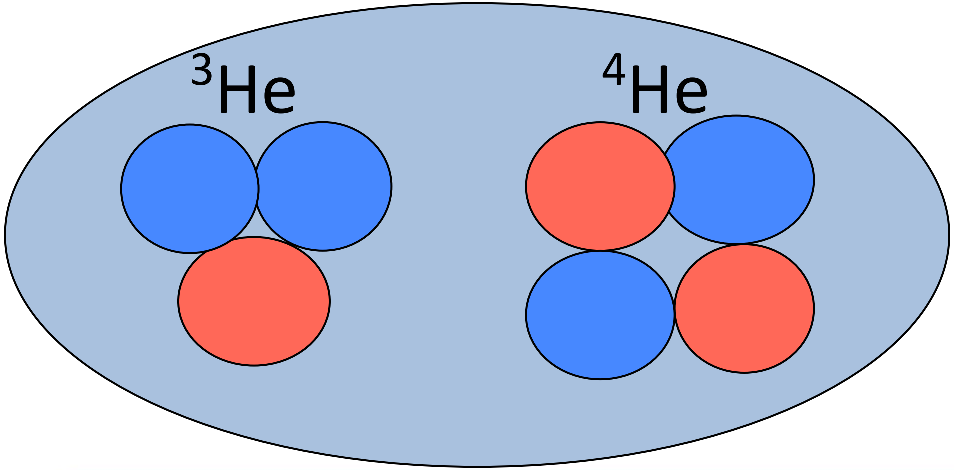
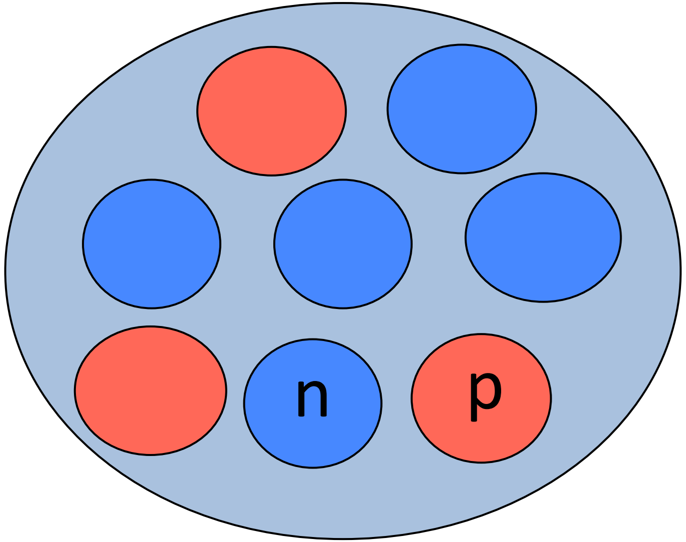
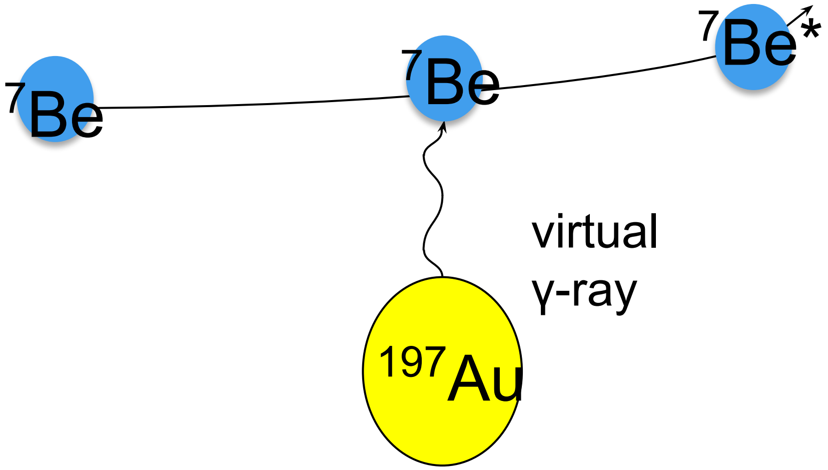
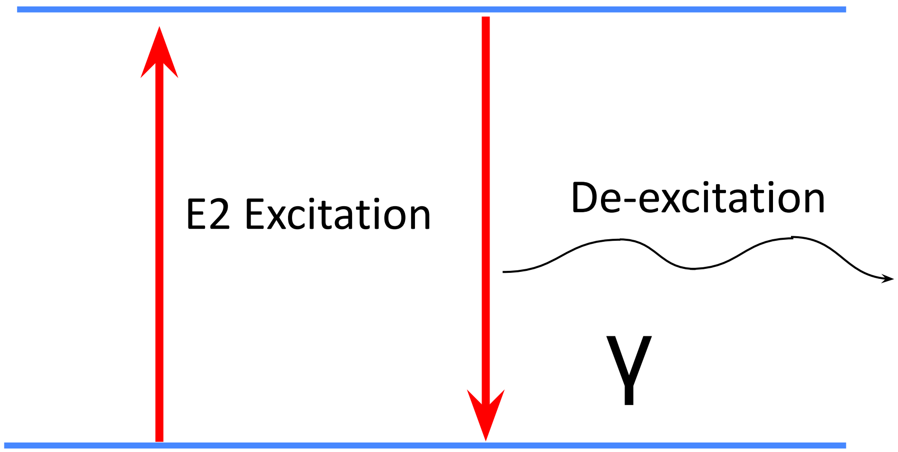




Coulomb excitation schematic

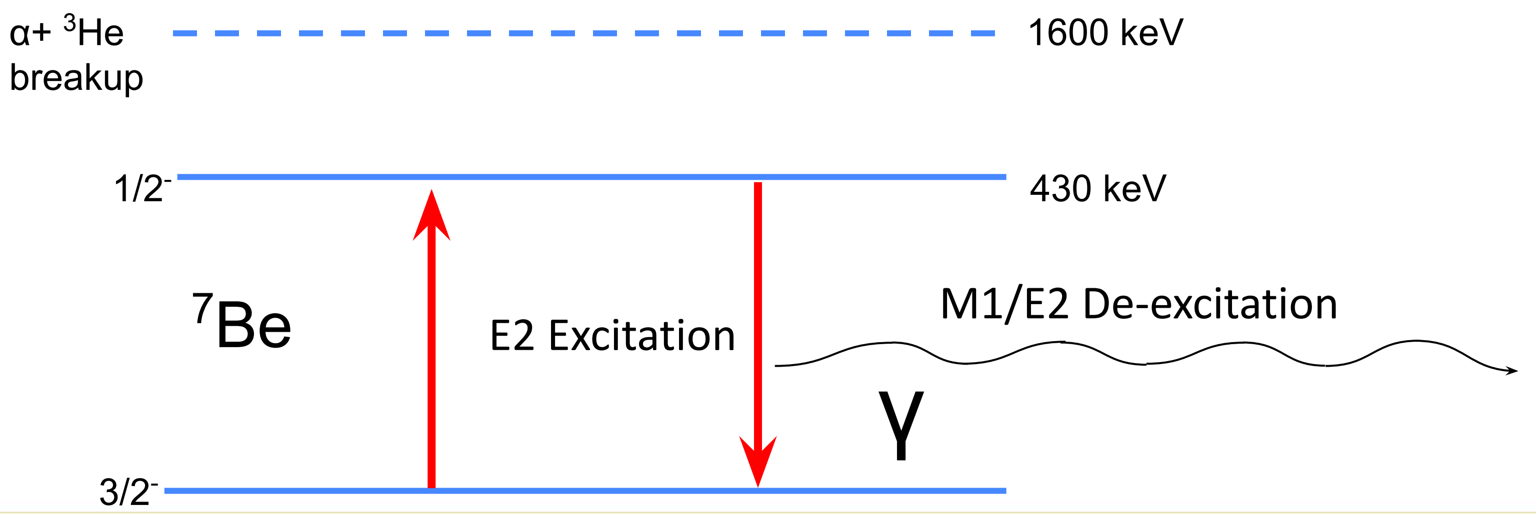
- Goal is to excite purely with EM interaction
- Take advantage of nuclear force short range.





Coulomb Excitation

- Measuring 1st excited state transition
- Both nuclei are mixed M1/E2 transition
- Coulomb Excitation links B(E2) to inelastic cross section
- $\sigma_{E2} = (Z_T e/\hbar\nu)^2 a^{-2} B(E2) f_{E2}(\xi)$



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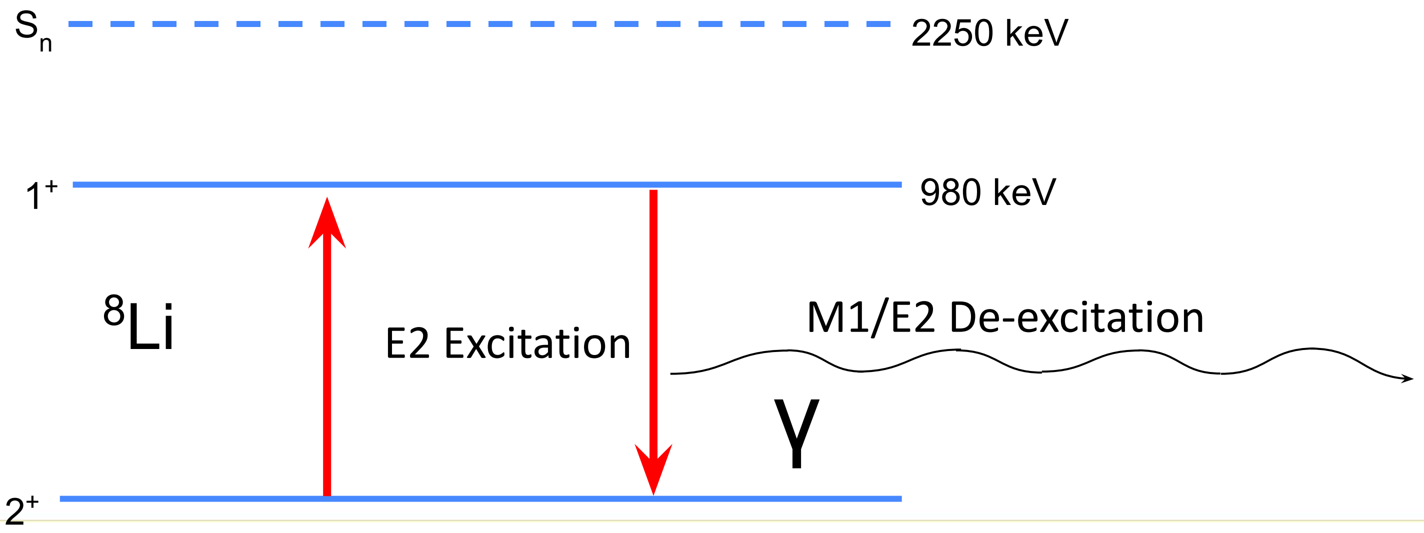

ND Nuclear Science Lab (NSL)

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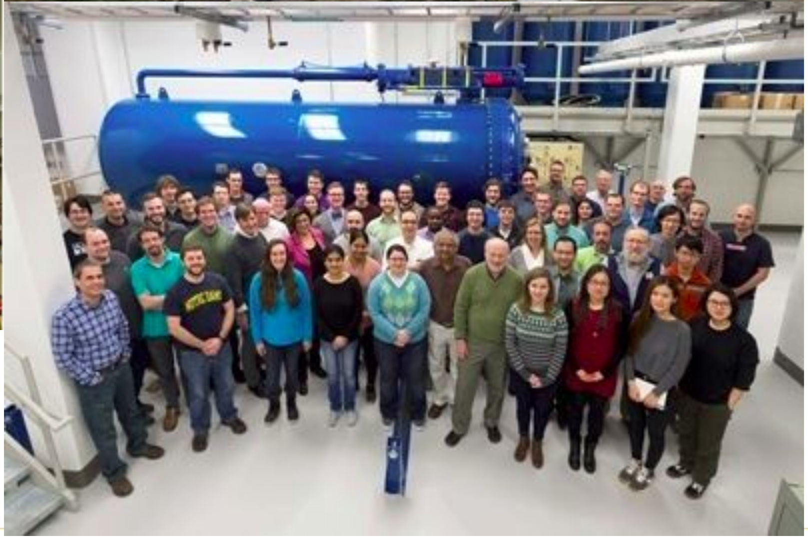
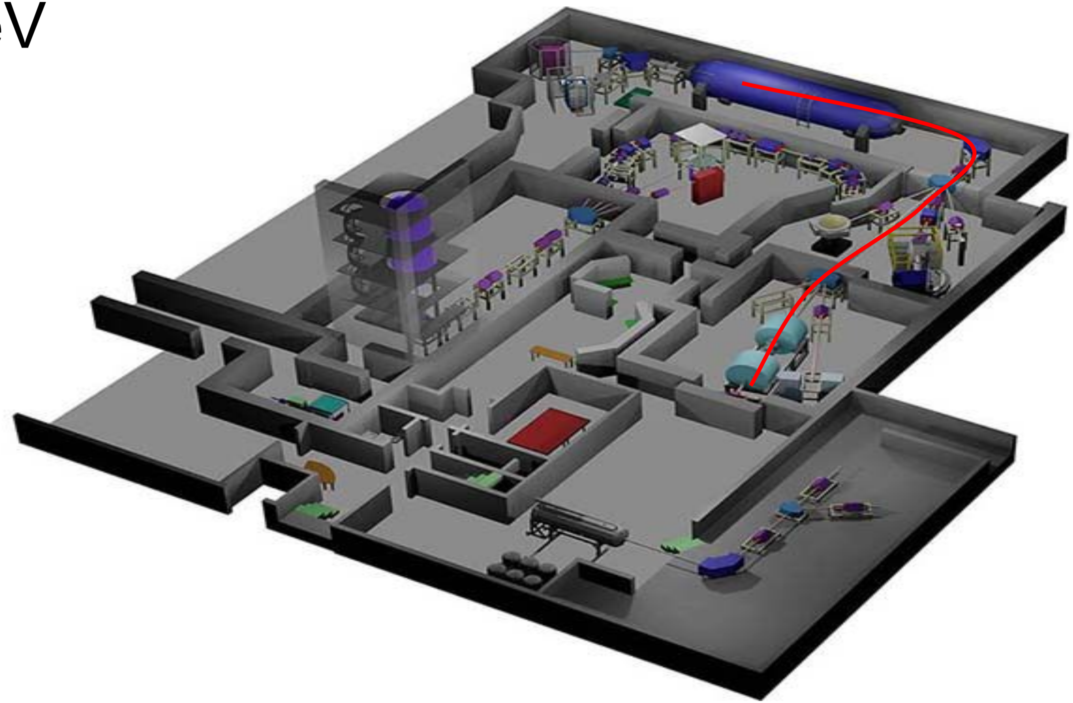


Producing ^{7}Be at NSL

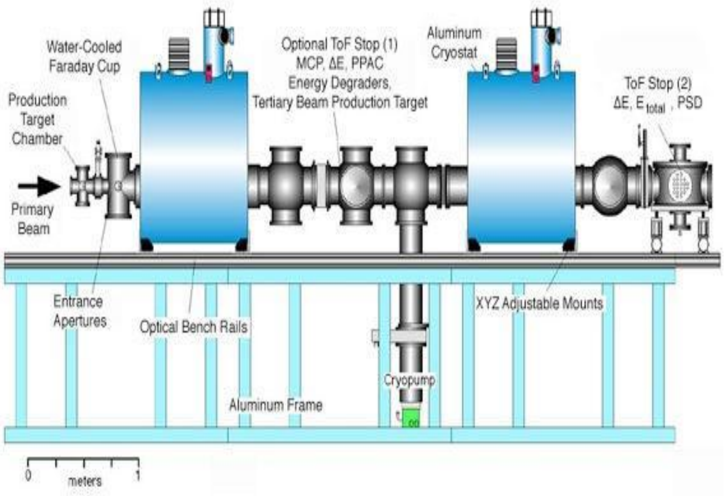
- FN Tandem Van De Graaff accelerator produced ^{6}Li at 34 MeV

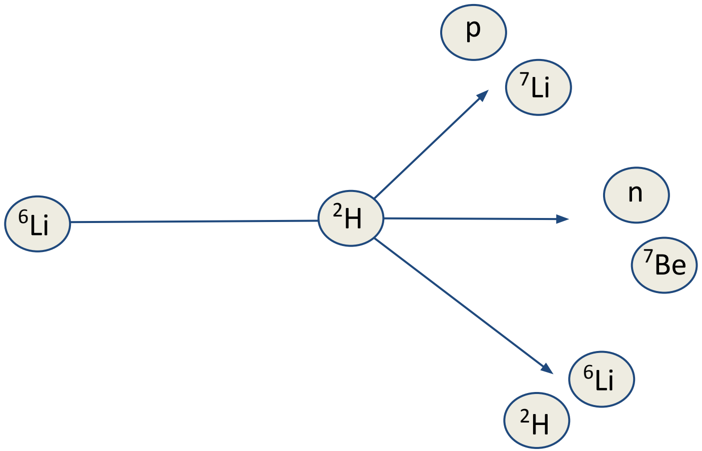


TwinSol at the NSL

Radioactive Beam

- Produced via *TwinSol*
- $^2H(^6Li, ^7Be)n$ produced 10^5 pps of ^7Be over 3.5 days
- ^7Be secondary beam of 30.4 MeV vs. Coulomb barrier of 39.3 MeV





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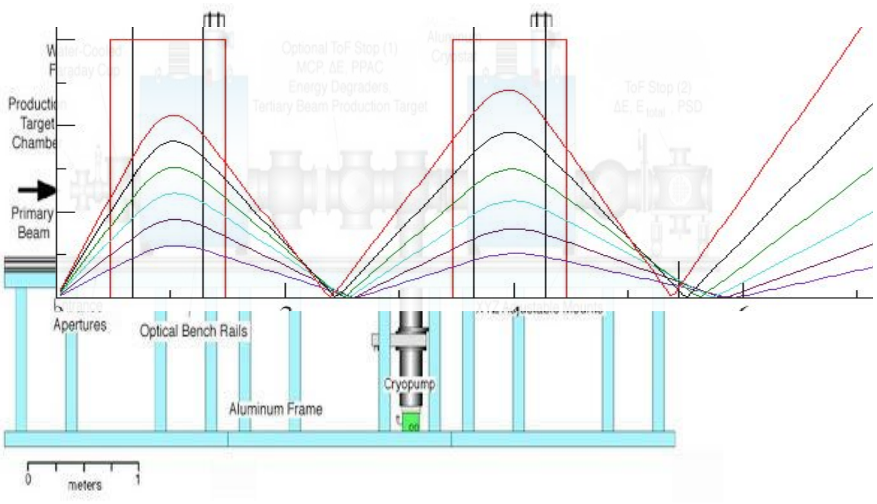
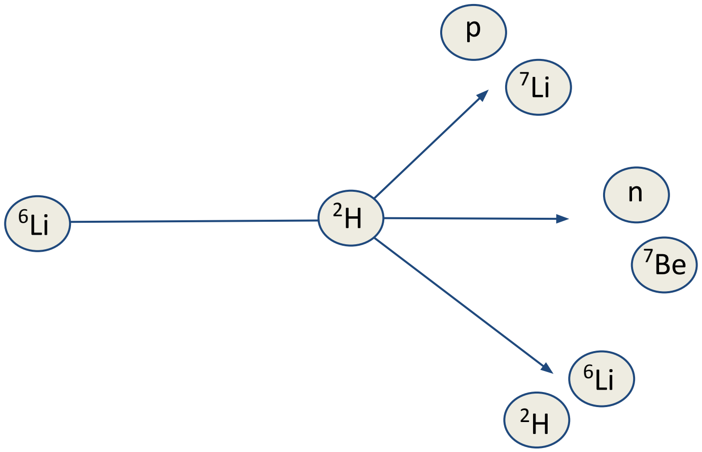
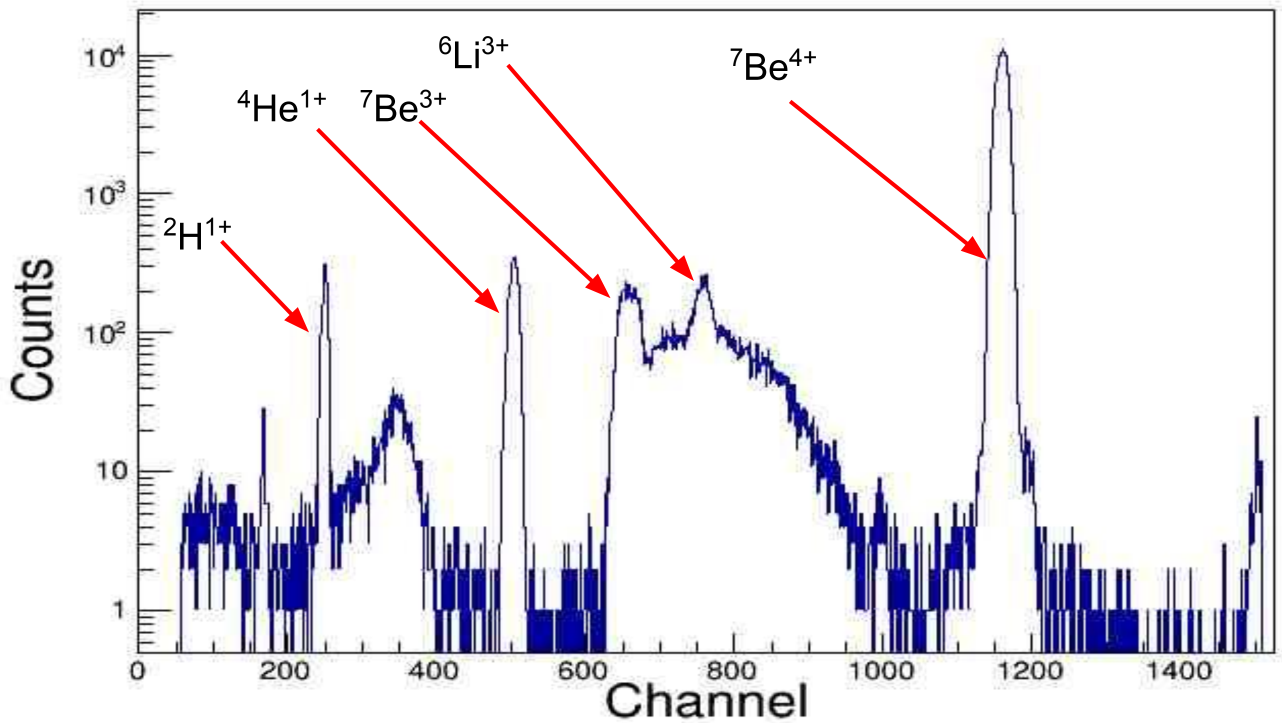


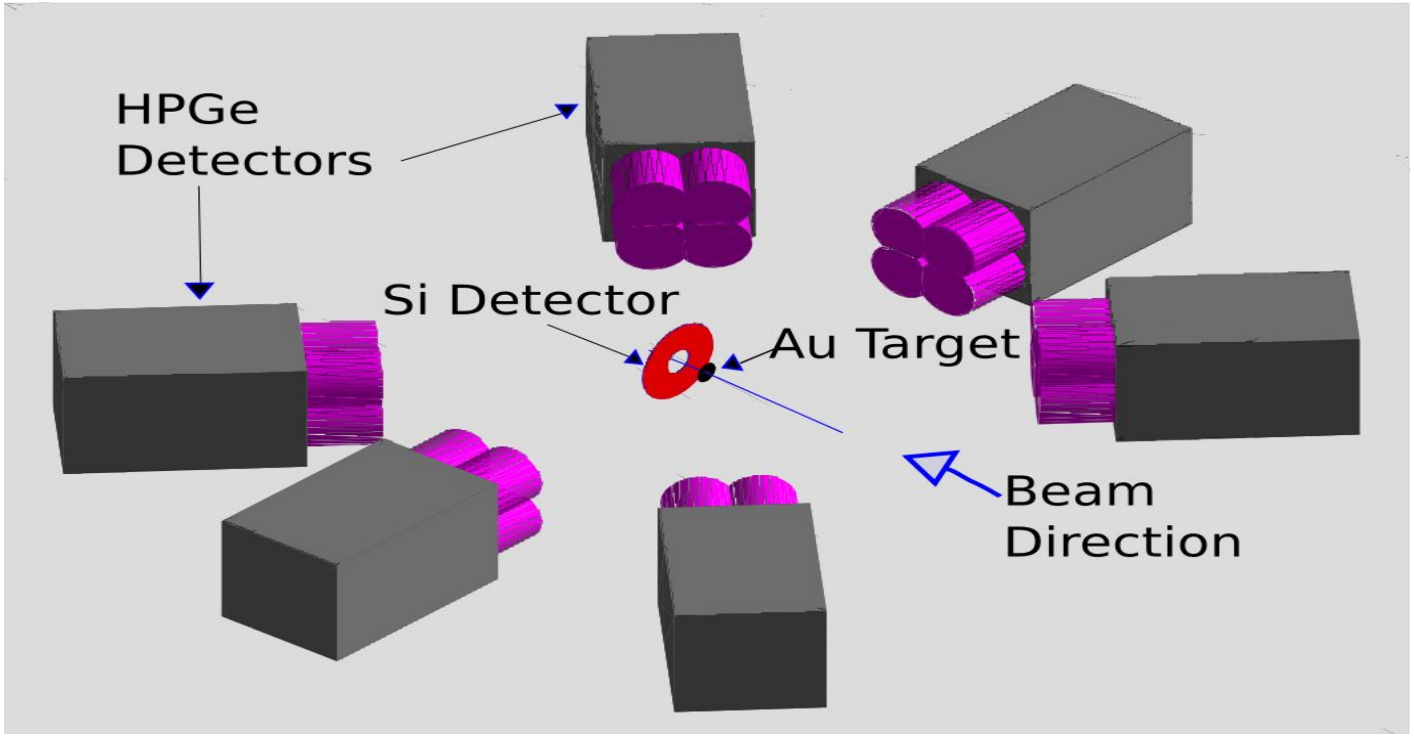


Particle Identification

- Beam was identified as 85% ^{7}Be

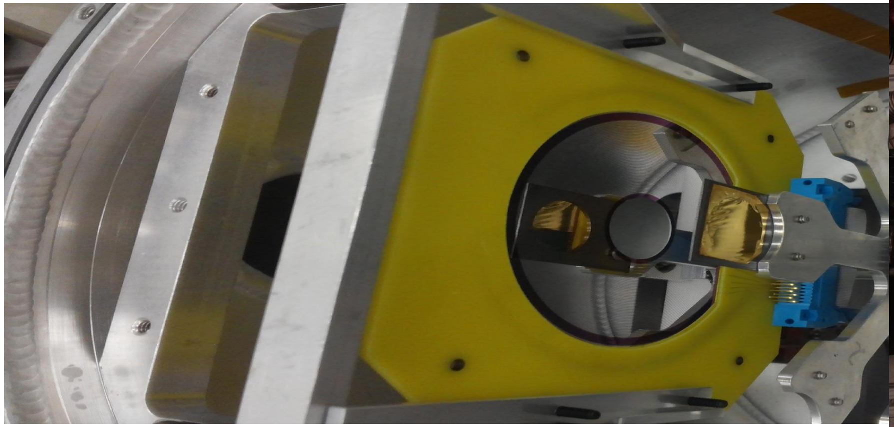


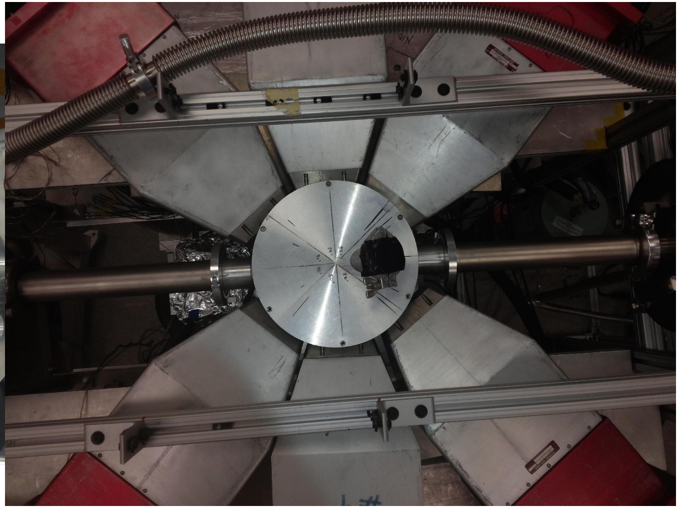
Detector Set-up



Experimental Setup

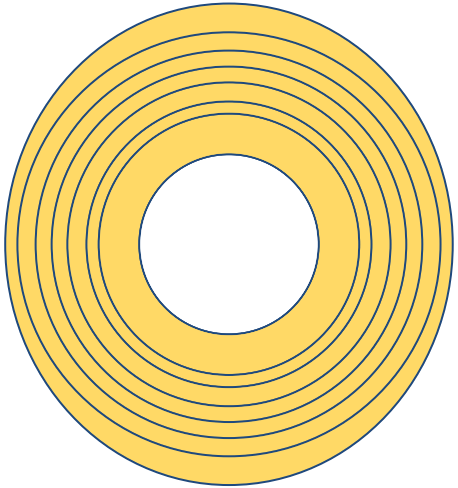
- 1 μm (1.9 mg/cm^2) gold foil
- HPGe clover detectors
- Annular Si detector with 24 ring channels, 8 sectors



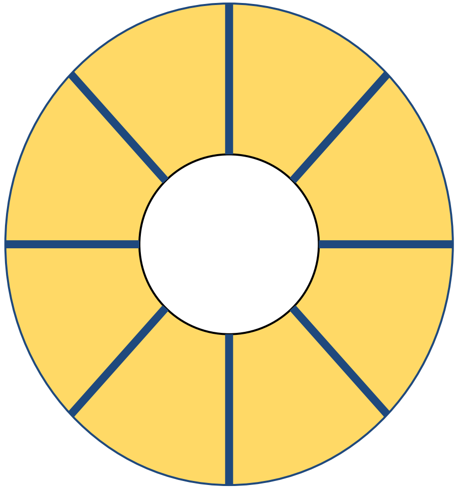


Si Detector Segmentation

- Segmentation give us θ and φ

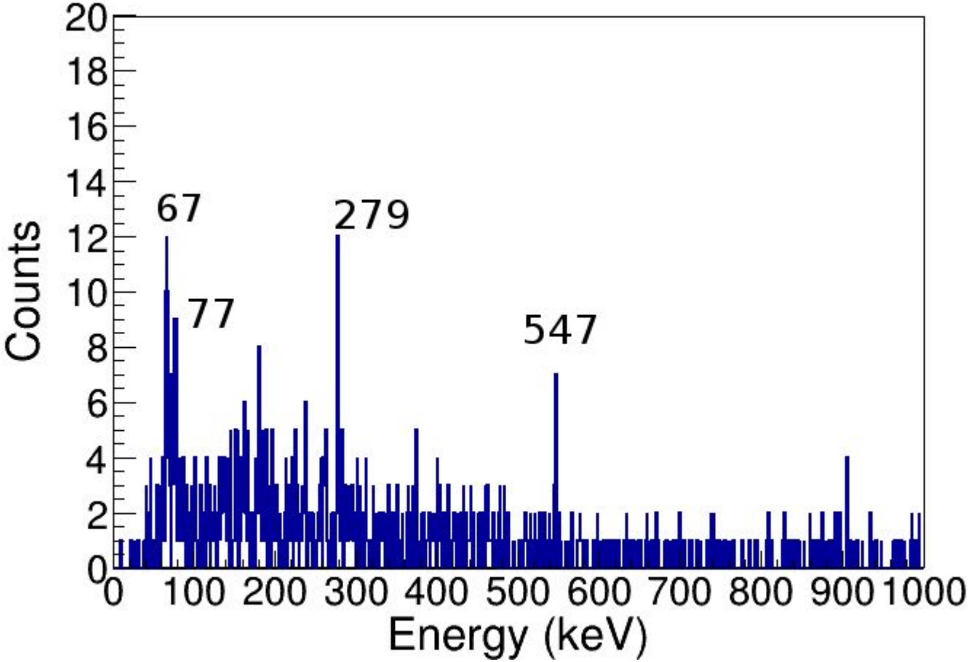


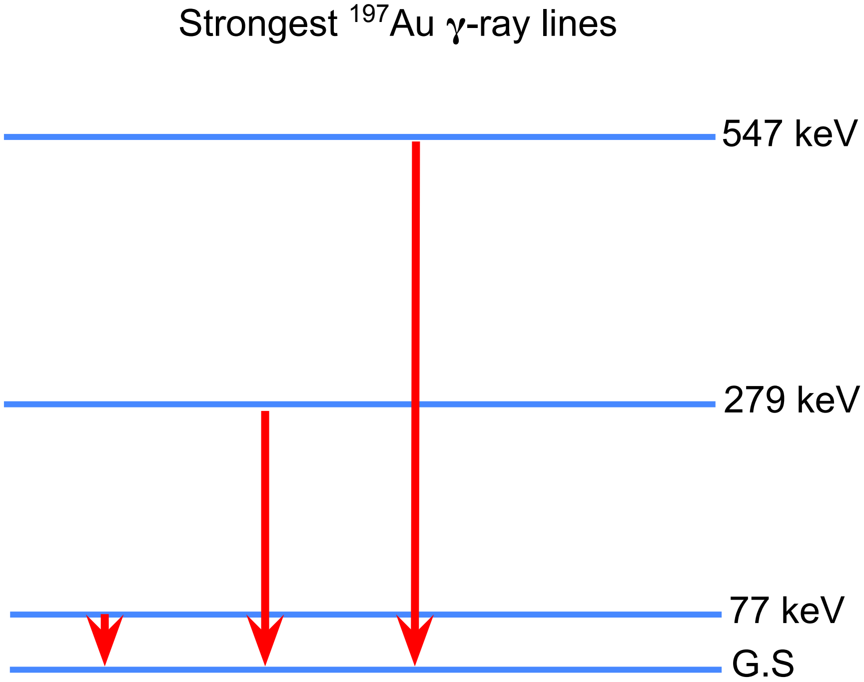
Front



Back

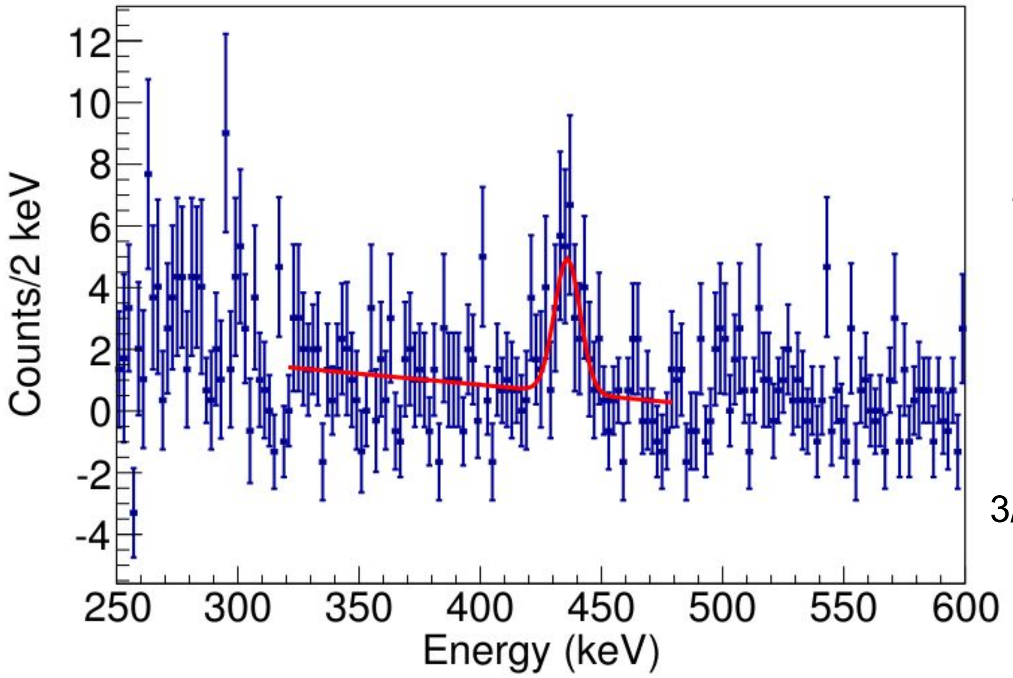
^{197}Au Coulomb Excitation

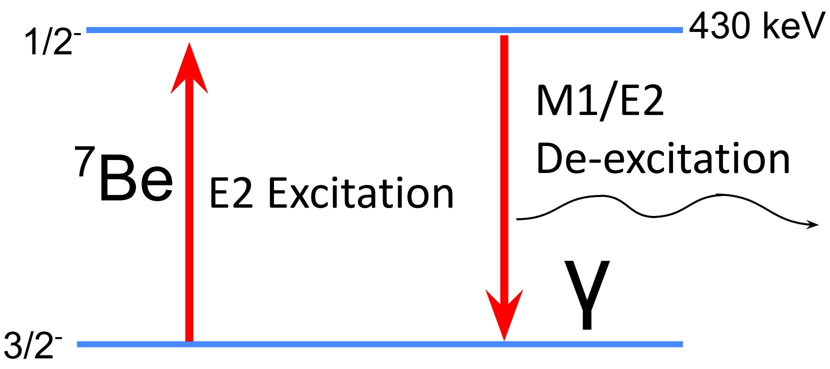




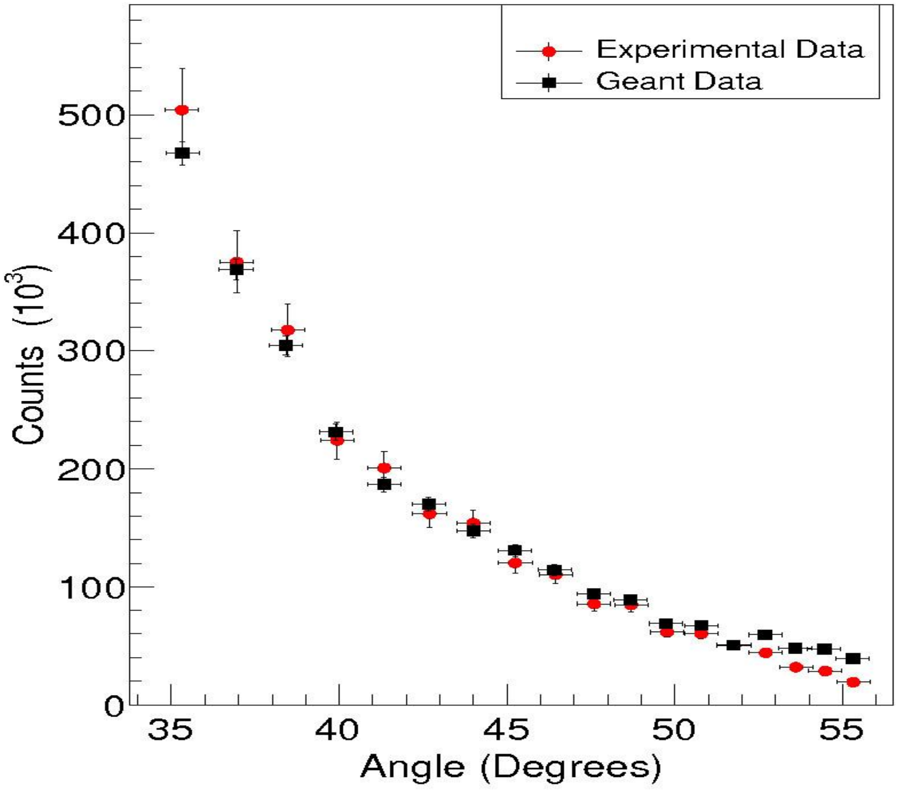
Doppler Corrected Spectrum

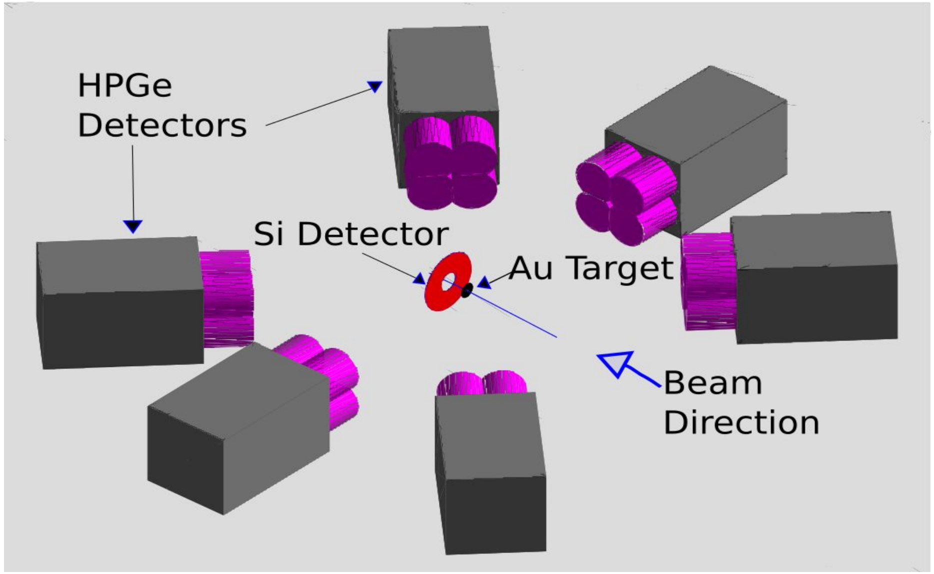
- Final peak with 30(6) counts at 430 keV





Geant Beam Fit



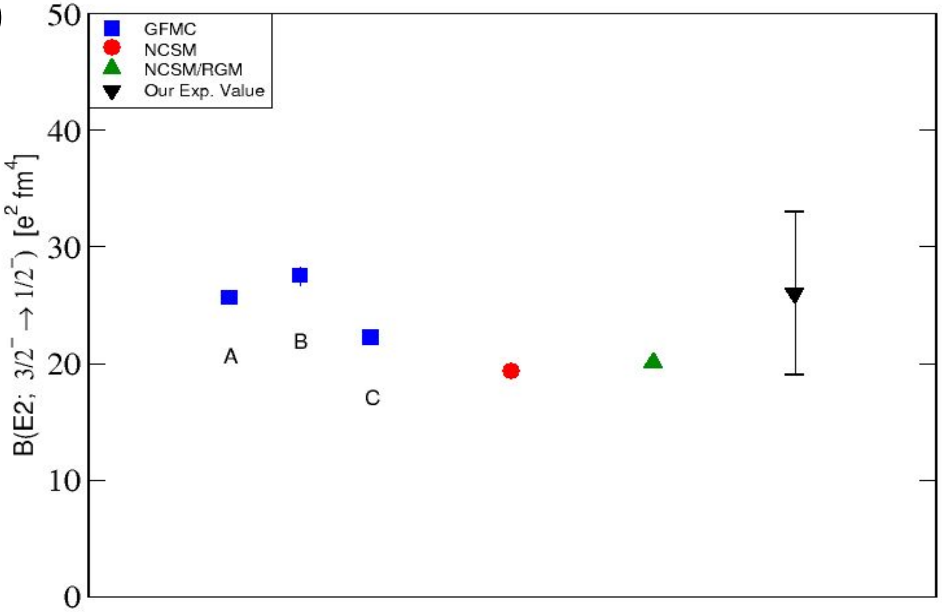


Calculating the B(E2)

- $\sigma_{E2} = (Z_T e/\hbar\nu)^2 a^{-2} B(E2) f_{E2}(\xi)$
- $B(E2;\ 3/2^- \rightarrow 1/2^-)=26(6)(3)\ e^2fm^4$

Results Comparison

- Blue squares = GFMC (A and B: AV18+IL2, C: AV18 +IL7)
- Red circle = NCSM (EM N^3LO)
- Green triangle = NCSM with Continuum (EM N^3LO) formerly NCSM/RGM
- Additional NCSM calculations were unconverged



Henderson et al, Phys. Rev. C 99, 064320 (2019)

Convergence Question

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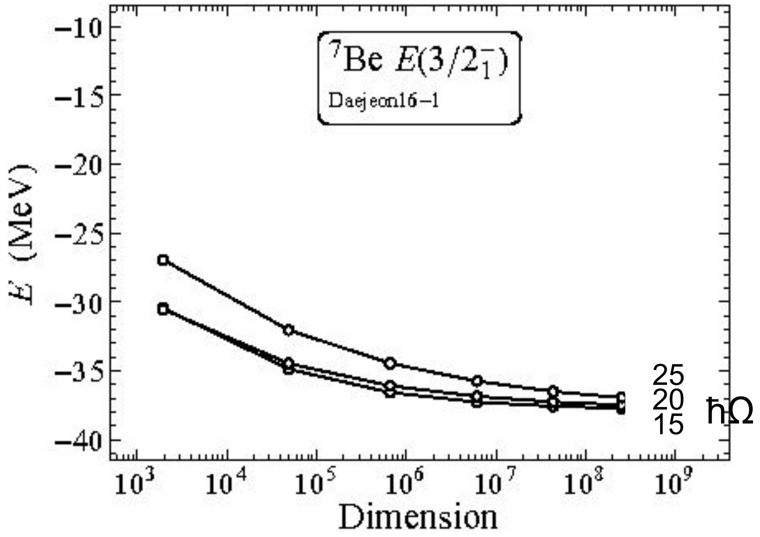

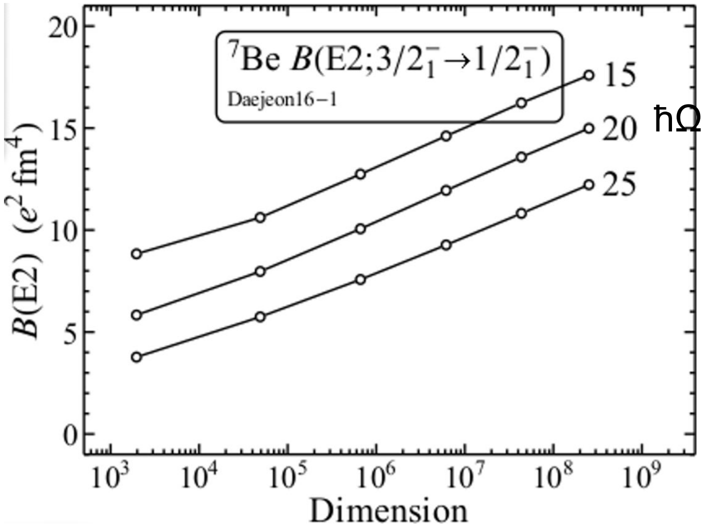

Courtesy of P. Fasano *et al.* 2018
Midwest Theory Get-Together

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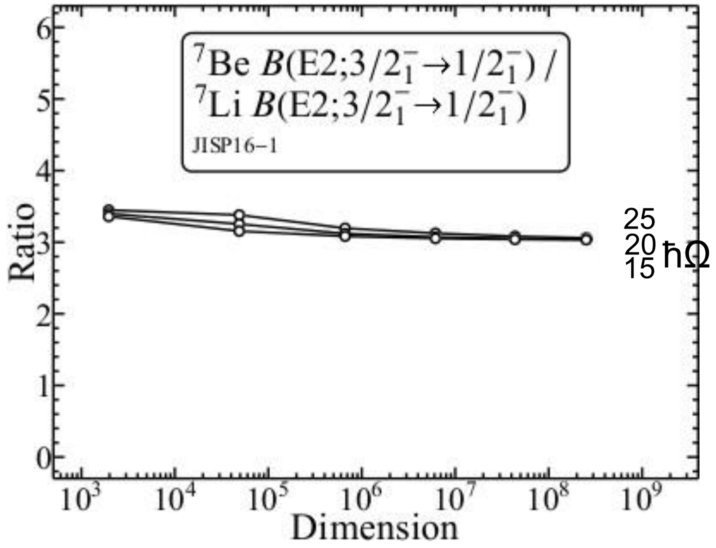
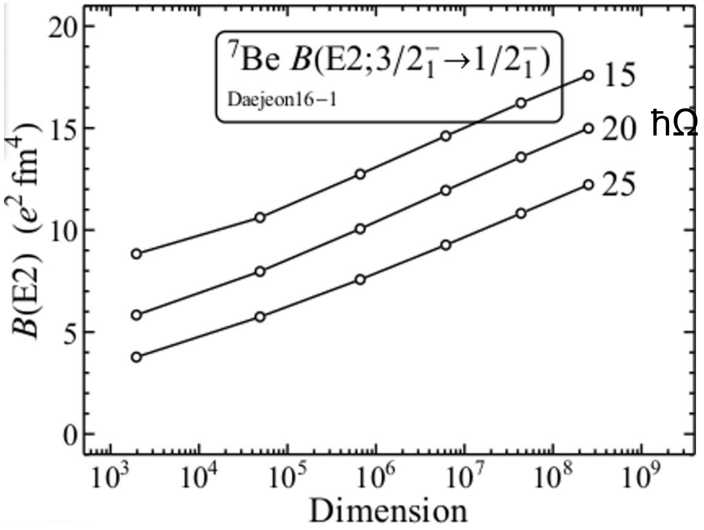
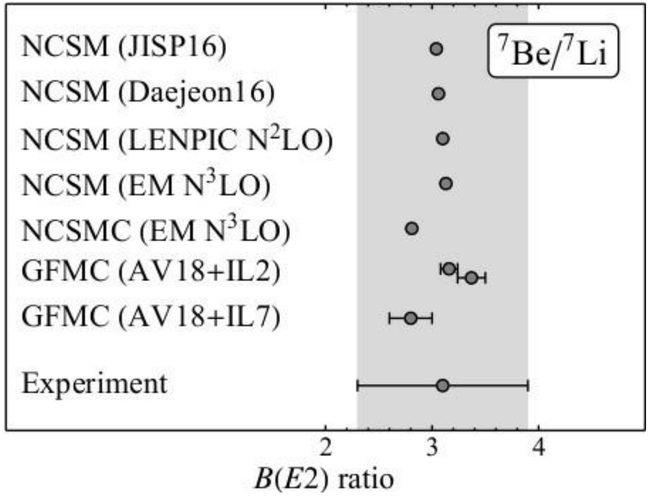


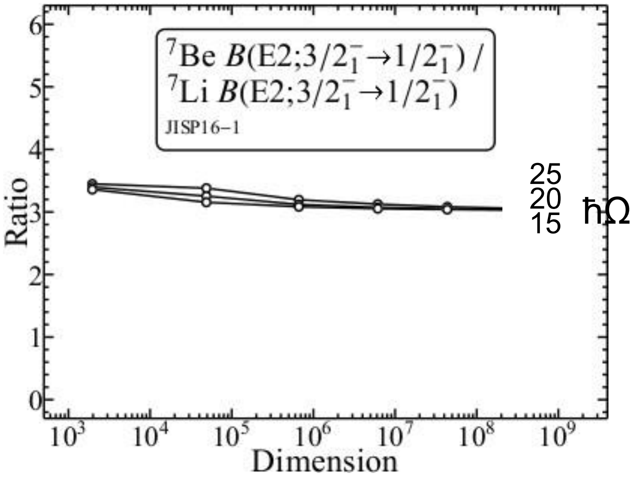


Courtesy of P. Fasano *et al.* 2018
Midwest Theory Get-Together

Ratio Comparison

- Ratios agree well with each other and experiment
- Using a literature ^{7}Li B(E2) value of 8.3(5)



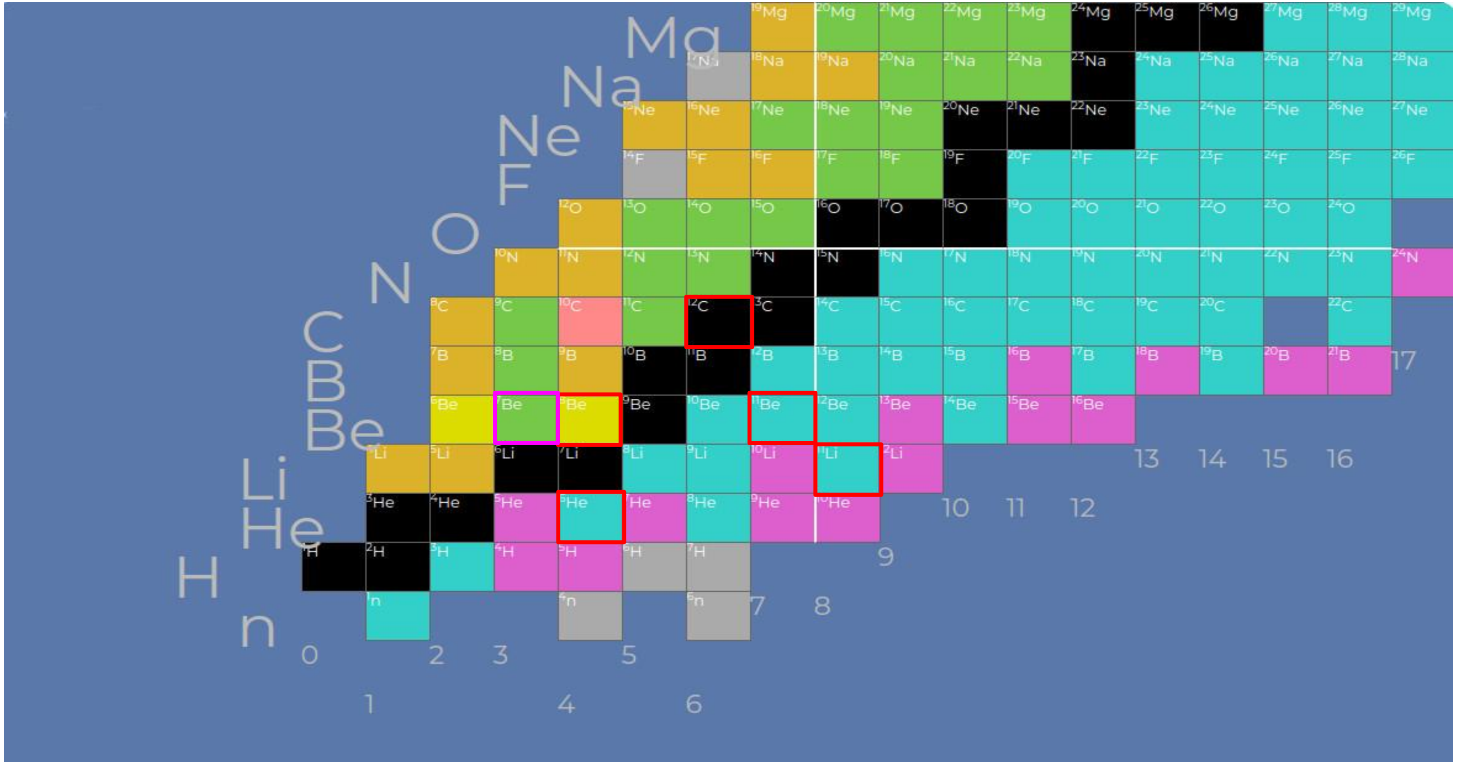


Comparison graph from Henderson et al Phys. Rev. C 99, 064320 (2019)

^{7}Be takeaways

- First measurement of ^{7}Be was made
- *Ab initio* calculations in very good agreement with experiment for ratios
- Want to test ratios with additional measurements to see if these results extend to other nuclei

Chart of Nuclides



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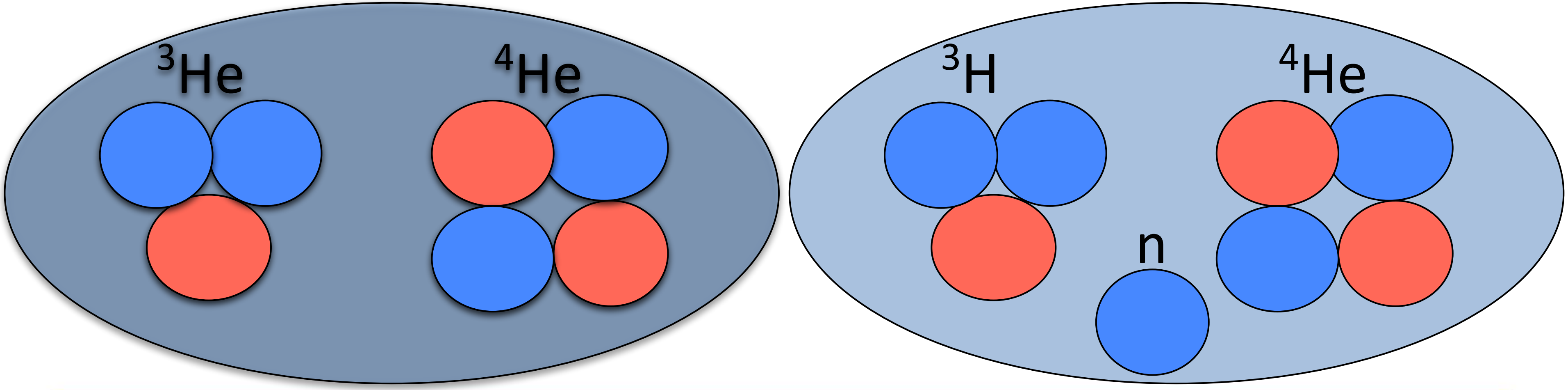
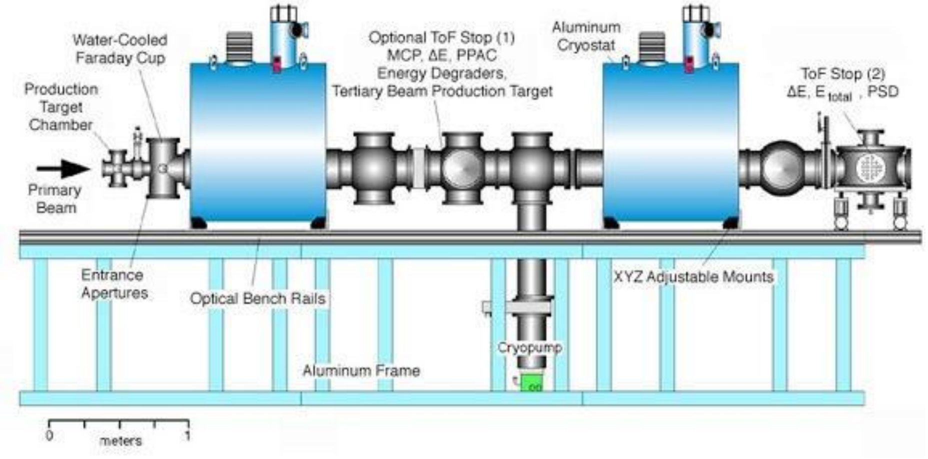
Nuclei to measure

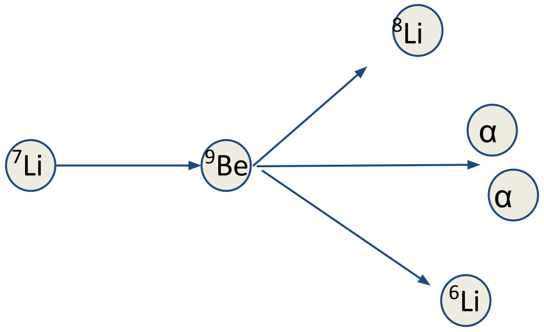
- Measured ^{8}Li next
- How does a neutron affect the situation?



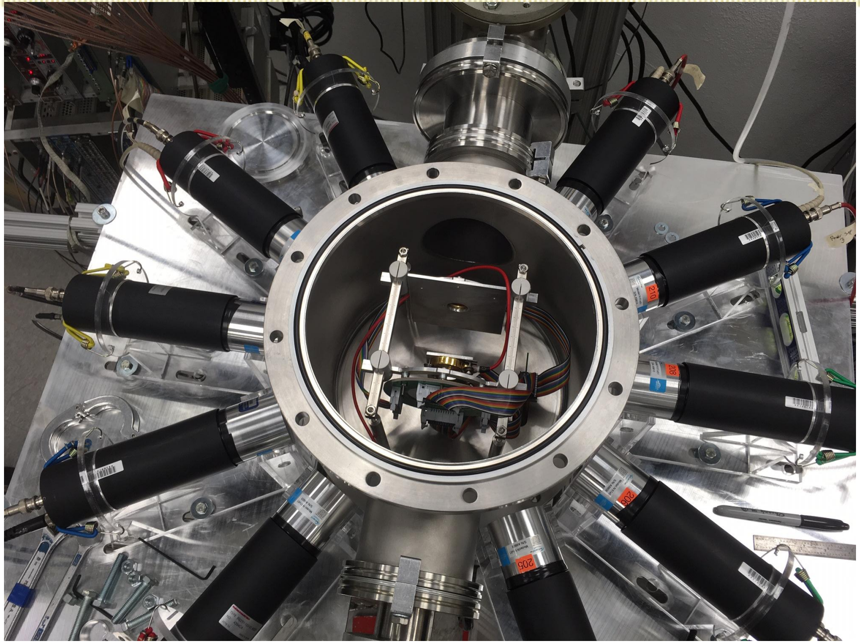
Radioactive Beam

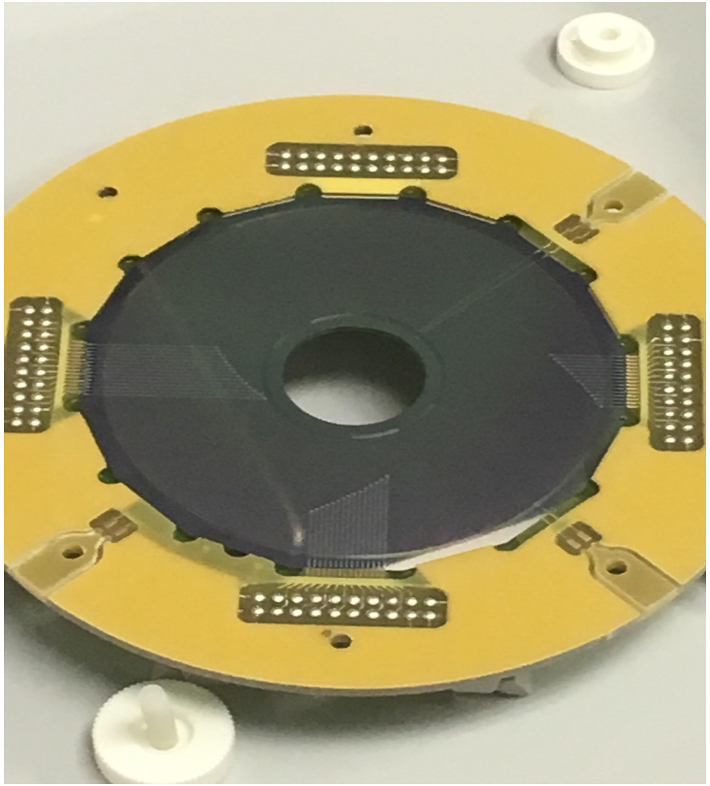
- Primary beam of ^{7}Li at 26 MeV
- ^{7}Li(^{9}Be,^{8}Be)^{8}Li produced 4x10^{5} particles/s over 5 days
- ^{8}Li secondary beam of 23(1) MeV vs Coulomb barrier of 36.4 MeV





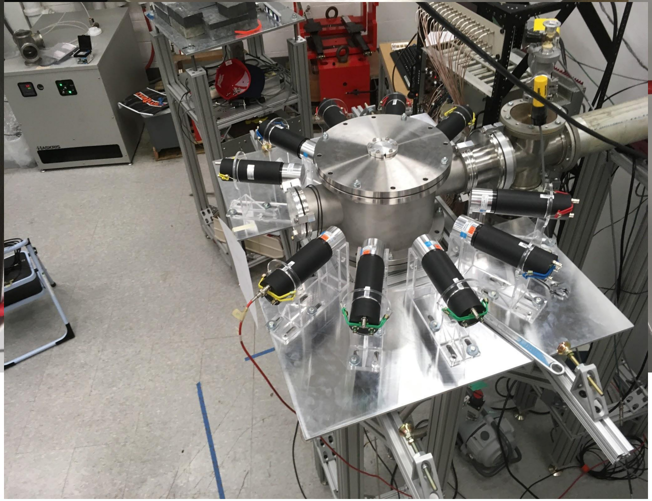
Si and $LaBr_3$ detectors

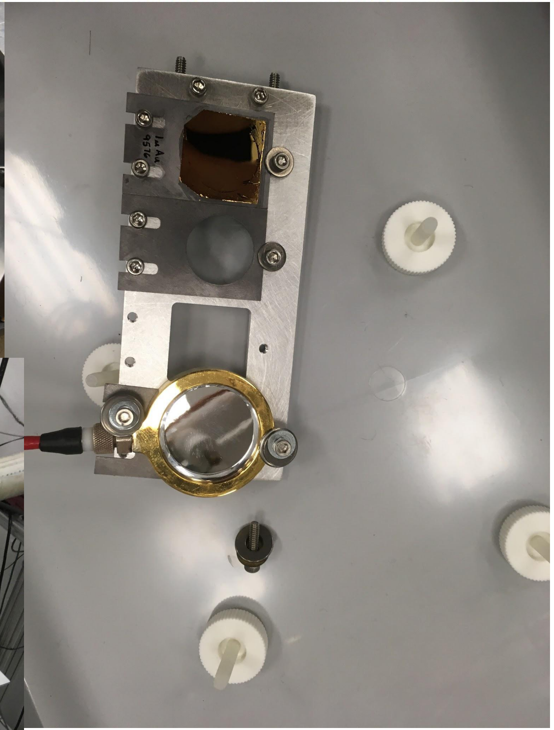




1. K. Smith *et al.*, Nucl Instruments and Methods in Physics Research Section B 414, 190-194 (2018)

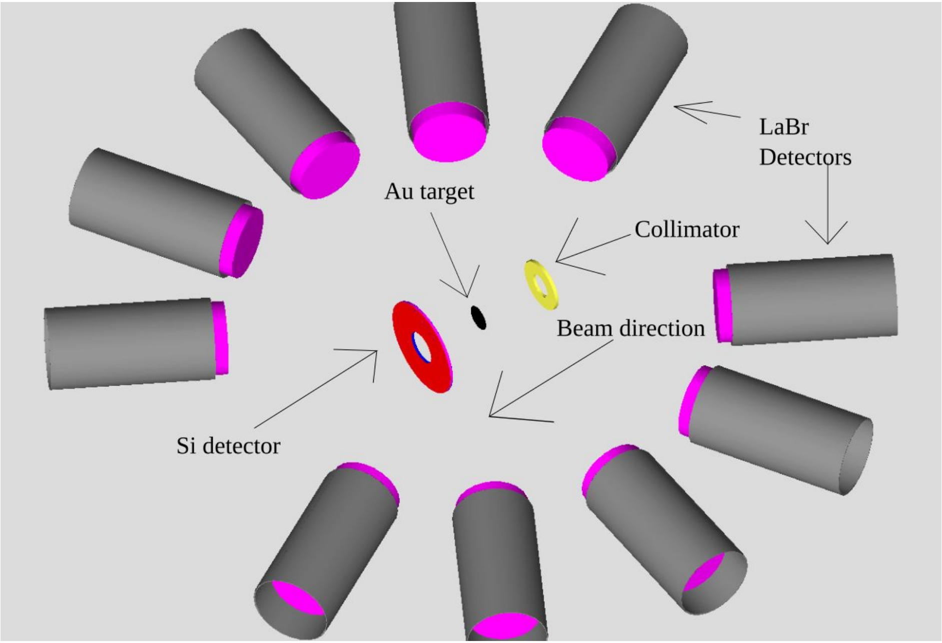
New Experimental Pieces





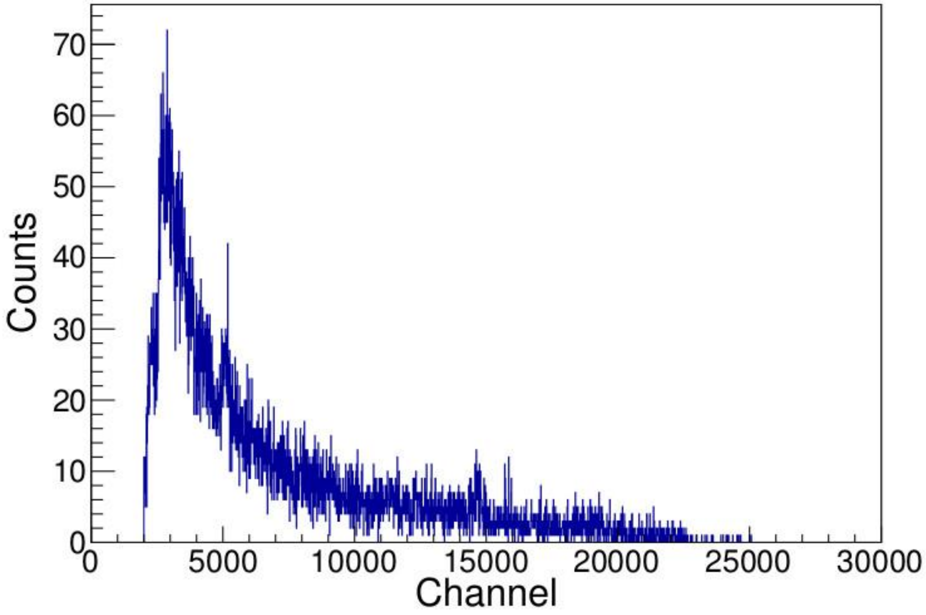
Experiment Setup

- Annular Si detector
- 22 rings, 16 sectors
- 10 $LaBr_3$ detectors from HAGRiD[1] array



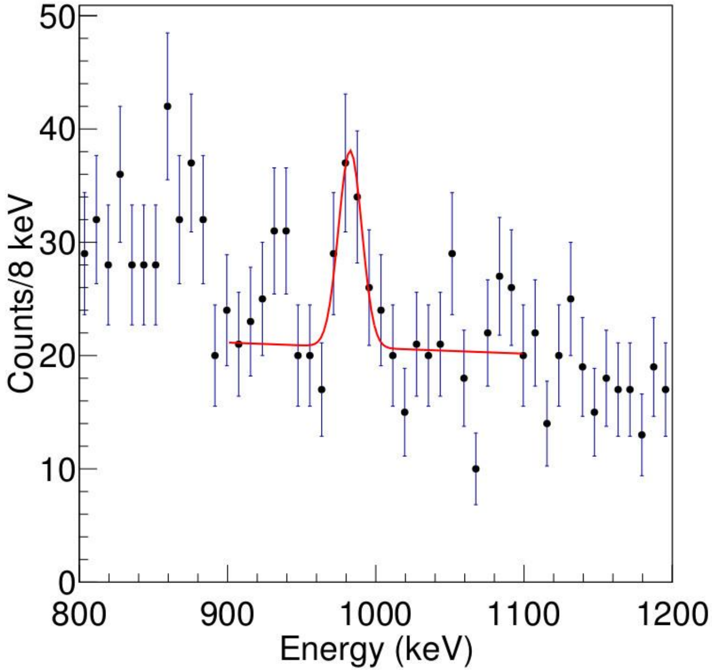
Example ^{8}Li spectra

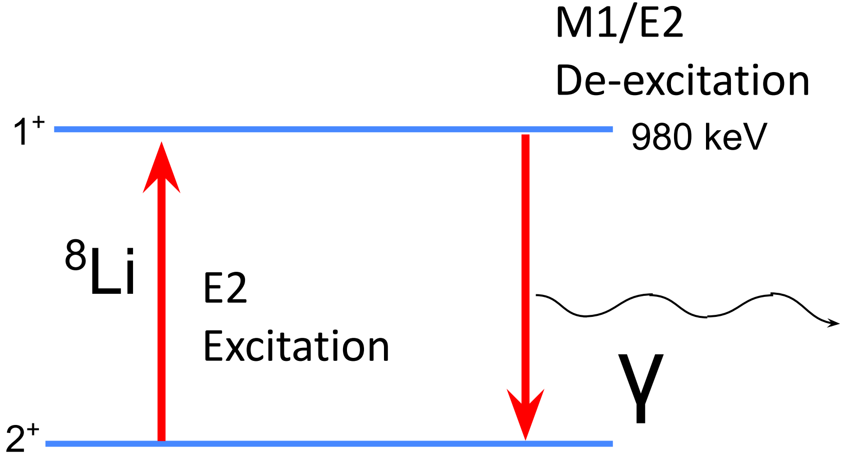
- Absolute γ efficiency was higher for this experiment
- More background counts as well



Final Peak

- 43(14) counts at 983(3) keV





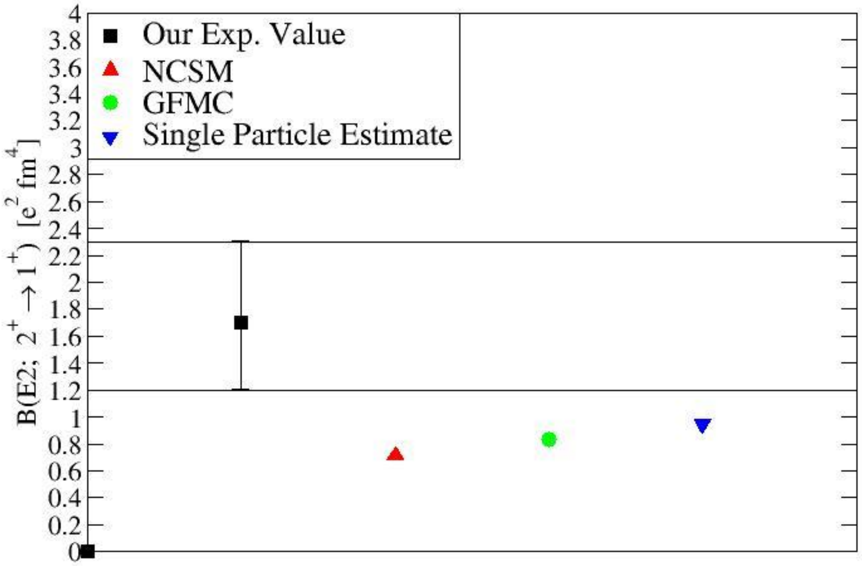
B(E2; $2^+ \rightarrow 1^+$) comparison

- Our value: 1.7(5) e^2fm^4
- Disagrees with previous measurement[1] of 55(15) e^2fm^4
- Older experiment with just particle detectors

1. J. A. Brown *et al.*, Phys. Rev. Letters 66, 19 (1991)

B(E2; $2^+ \rightarrow 1^+$) comparison

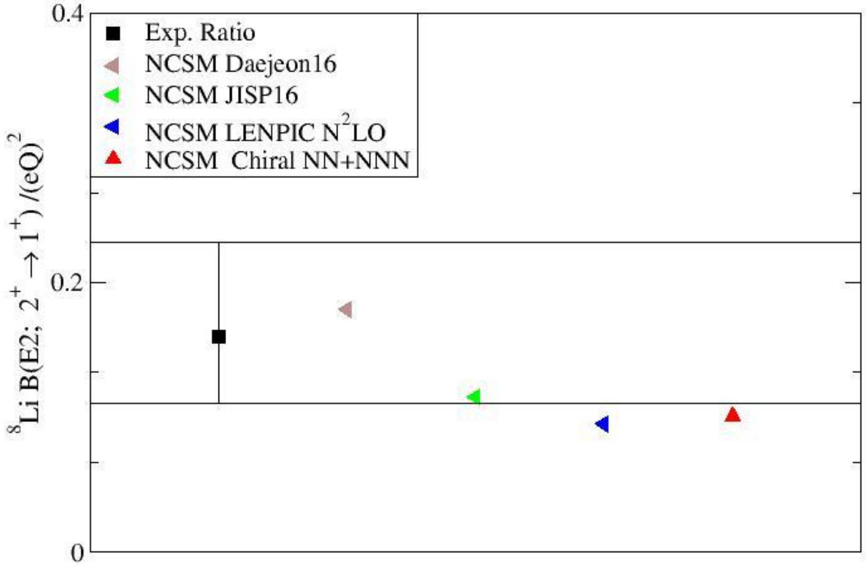
- Our value: 1.7(5) e^2fm^4
- Previous measurement of 55(15) e^2fm^4 is not shown[1]



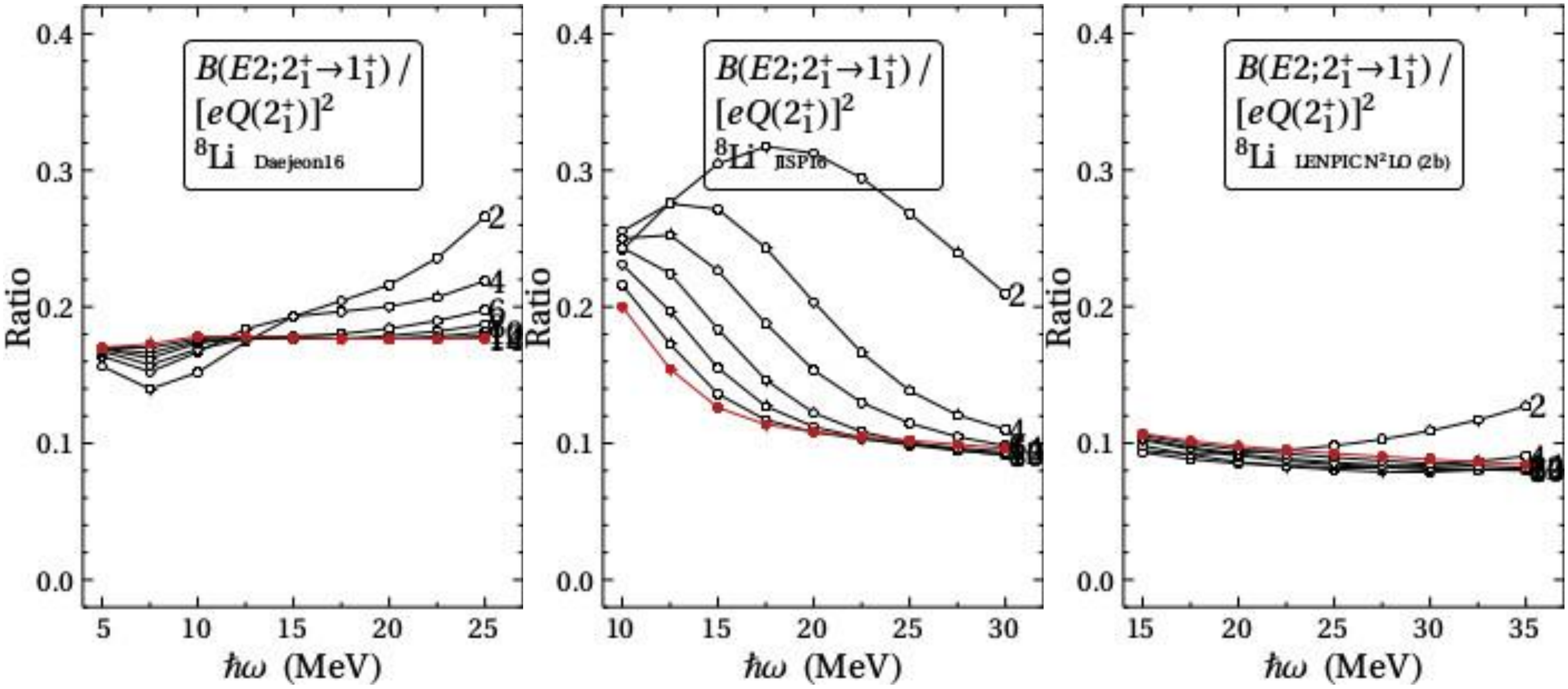
1. J. A. Brown *et al.*, Phys. Rev. Letters 66, 19 (1991)
2. NCSM result: P. Maris *et al.* Phys. Review C 87, 014327 (2013)
3. GFMC result: S. Pastore *et al.,* Phys. Rev. C 87, 035503 (2018)

B(E2)/(eQ)^2 Ratios

- Different ratio, using available data
- Factor of 2 in calcs.
- Ratios appear more successful
- Not all calculations agree within 1 σ



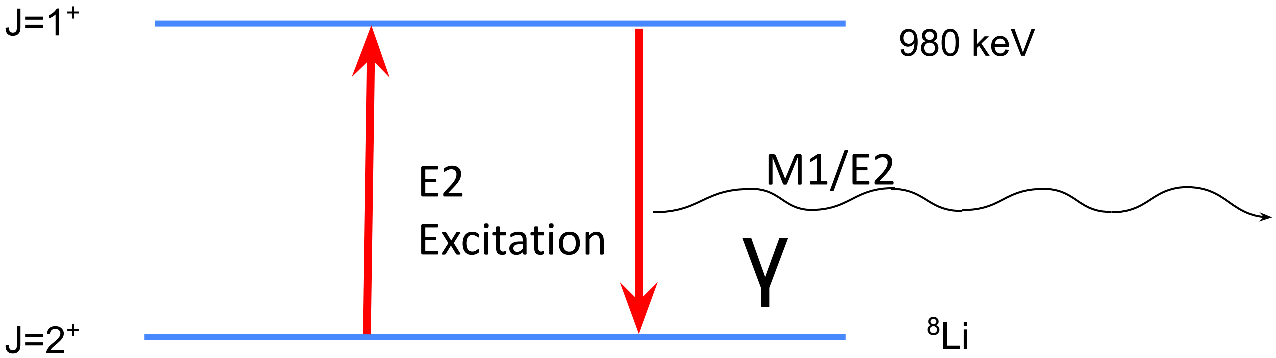
Li-8 Convergence Behavior



Courtesy of M. Caprio et al (private communication)

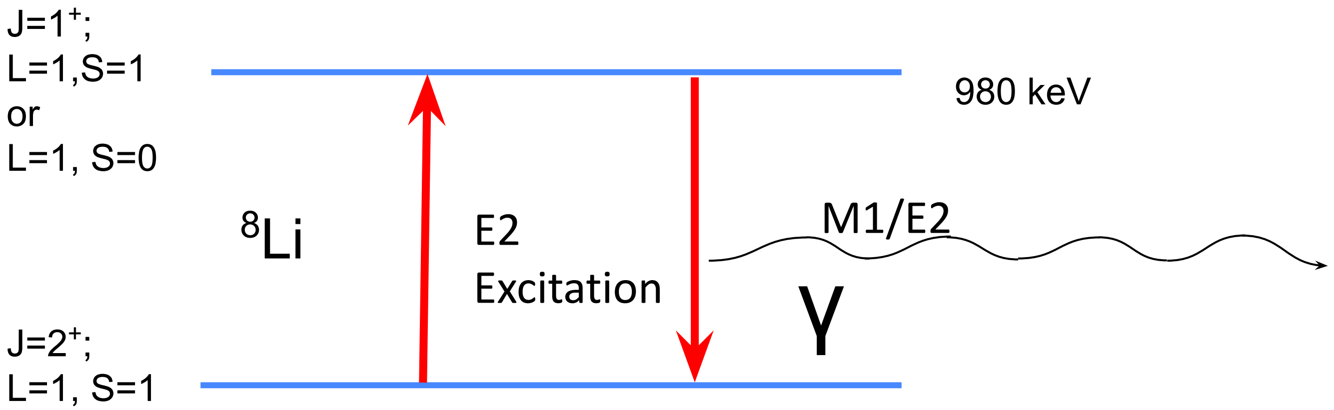
L-S Mixing

- In this odd-odd nucleus, multiple ways to create J of a state.



L-S Mixing Continued

- *Ab initio* decompositions predict roughly 50/50 split of different L-S mixing
- Two state mixing of higher 1^+ state can reduce expected B(E2)



^{8}Li Conclusions

- Ratios improve convergence but ^{8}Li calculations still are interaction dependent
- ^{8}Li is sensitive to L-S treatment of interaction, ^{7}Li and ^{7}Be appear more indifferent
- Same L-S dependence also seen when comparing to ^{9}Be B(E2; $3/2^{-} \rightarrow 7/2^{-}$)
- This heavily mixed 1+ state makes for a challenging calculation

Future Work

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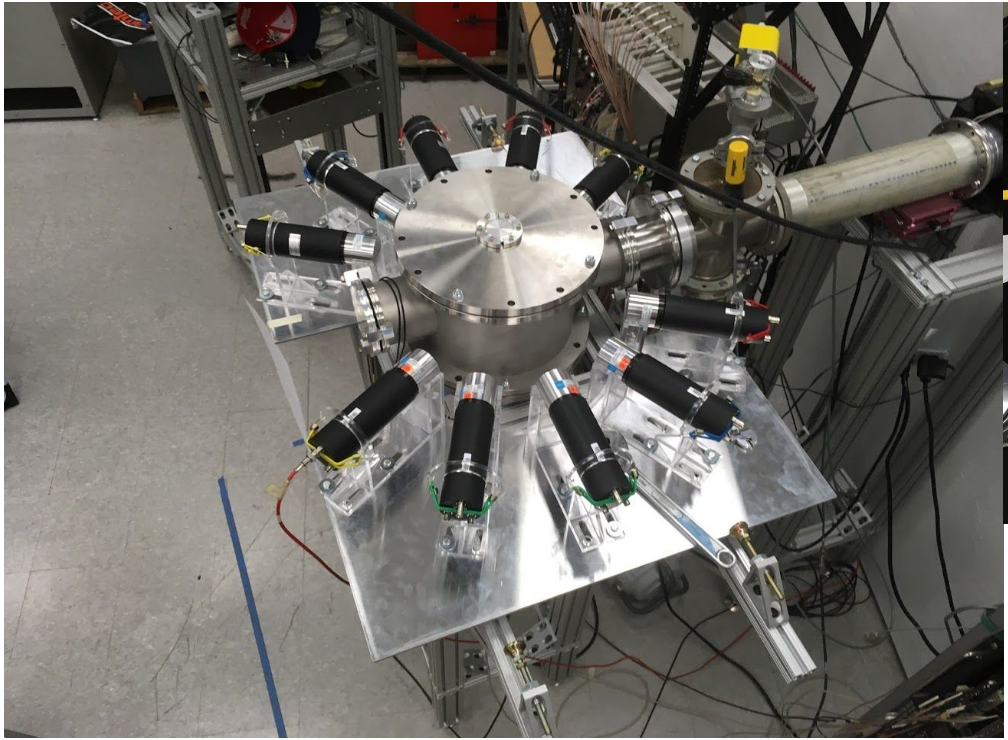
- *Ab initio* calculations have highlighted structural differences between ^{7}Be and ^{8}Li
- *Ab initio* results have already improved, hope to provide further assistance
- Could potentially measure ^{12}B, also odd-odd

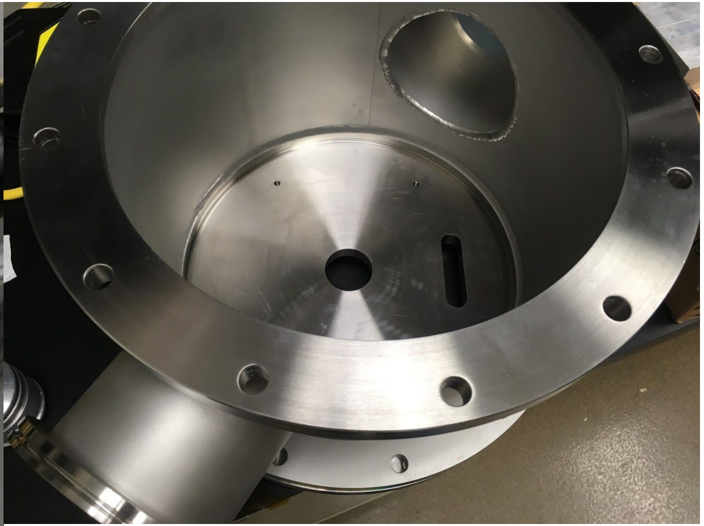
Acknowledgements

- ND People
  - Experimental collaborators - Tan Ahn, Patrick O'Malley, Anna Simon, Craig Reingold, Alexander Dombos, Sebastian Aguilar, Drew Blankstein, J.J. Kolata, Luis Caves, Shilun Jin
  - Theory collaborators - Mark Caprio, Patrick Fasano, Anna McCoy
- Outside Experimental Collaborators
  - CloverShare Collaboration
  - Kate Jones - HAGRiD
- Funding Sources
  - Experimental Funding - NSF PHY 17-13857, PHY 14-01343, and PHY 14-30152
  - Theory Funding - DOE DE-FG02-95ER-40934, DE-FG02-00ER41132 and NRC of Canada
  - Computational Resources - NERSC DE-AC02-05CH11231

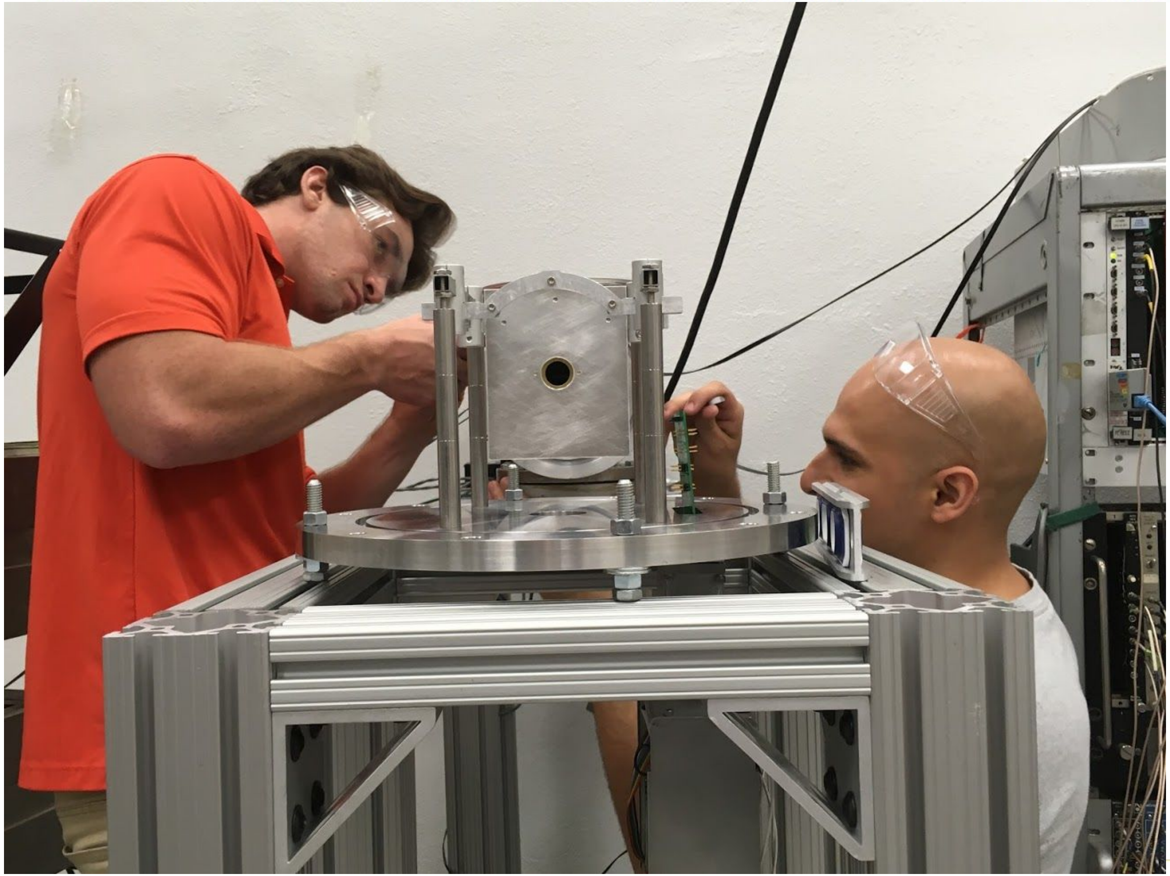
Backup slides

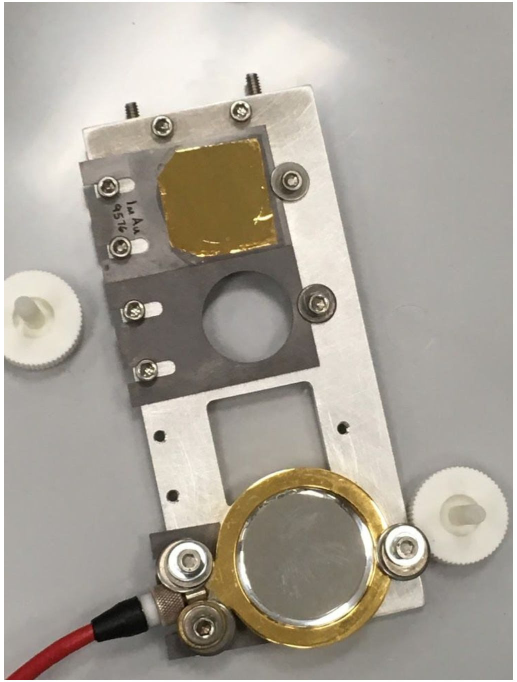
Extra experimental pictures





Additional Experimental Pictures





Ratio Comparison - 2nd int

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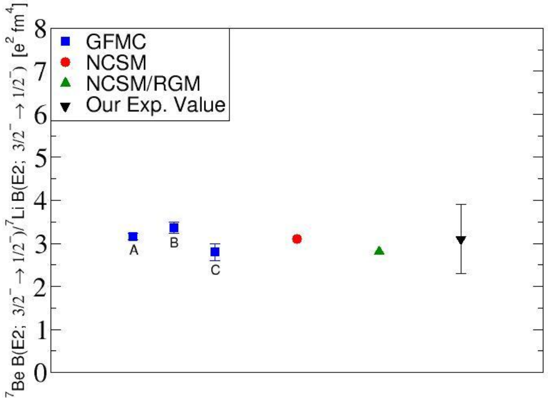
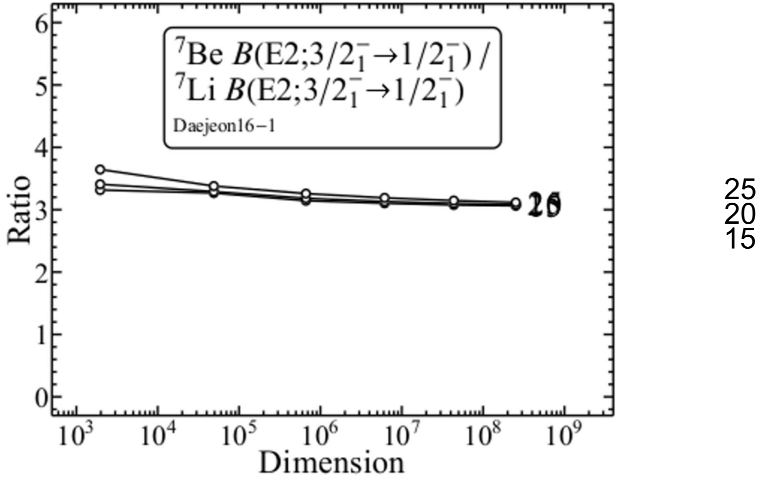
– Using a literature ^{7}Li value of 8.3(5)[1]





1. H.-G. Voelk and D. Fick, Nucl. Phys. A 530, 475 (1991)

Ratio Comparison - 3rd int.

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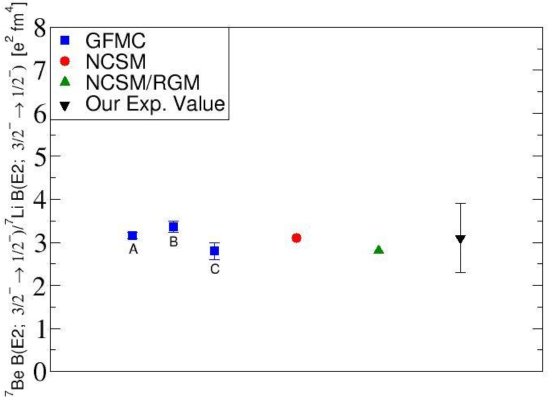
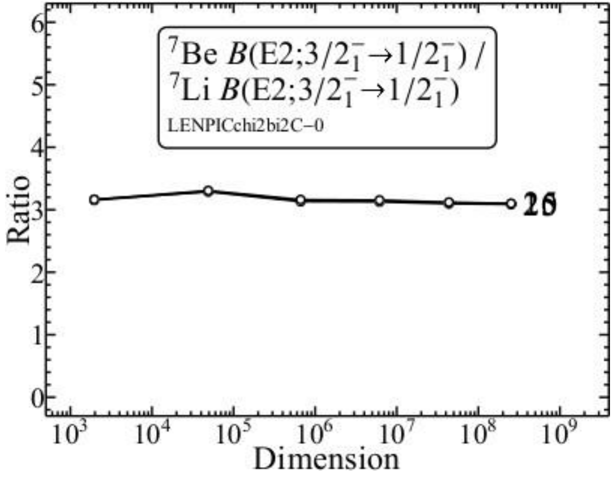
– Using a literature ^{7}Li value of 8.3(5)[1]

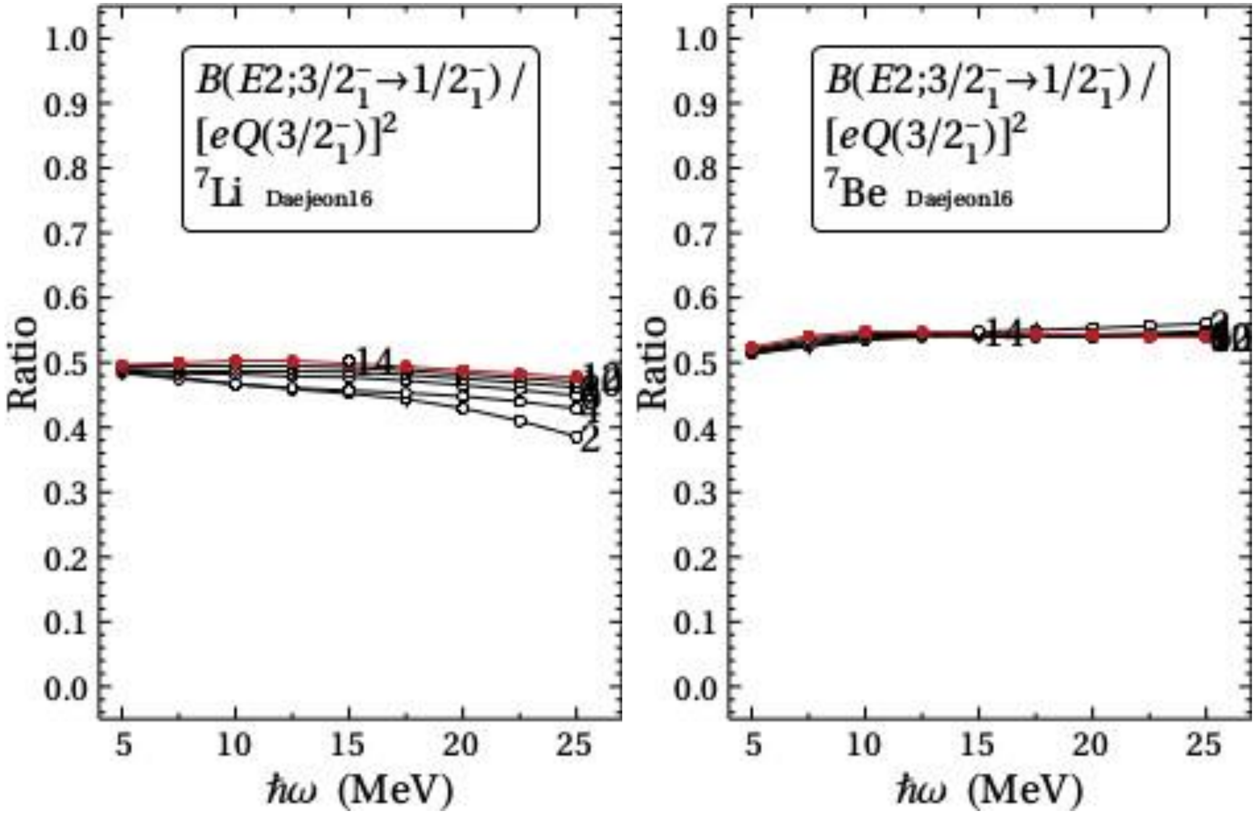




25
20
15

1. H.-G. Voelk and D. Fick, Nucl. Phys. A 530, 475 (1991)

7Li and 7Be B(E2)/(eQ)^2 conv.



9Be 1st and 2nd B(E2)/eQ conv.

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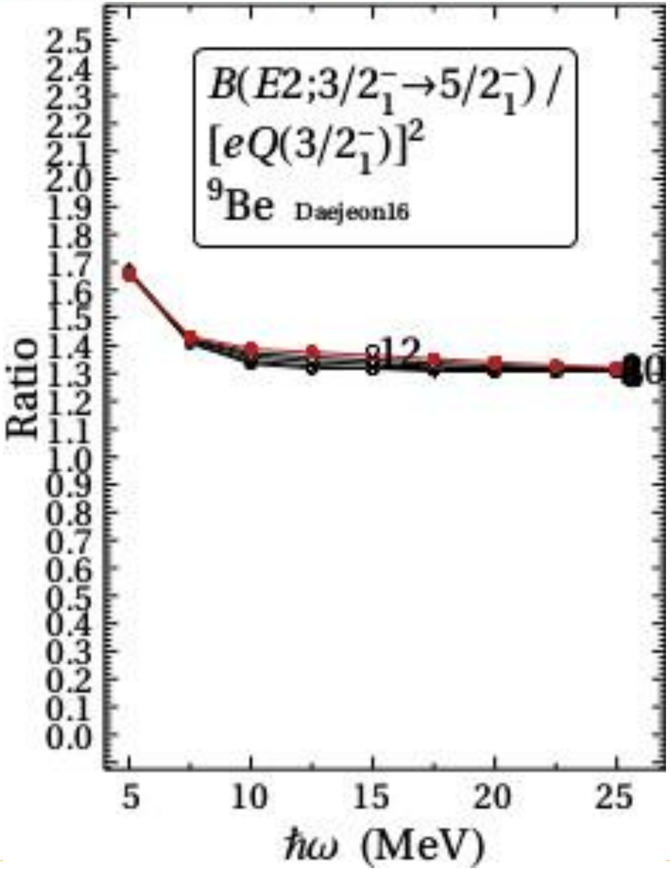
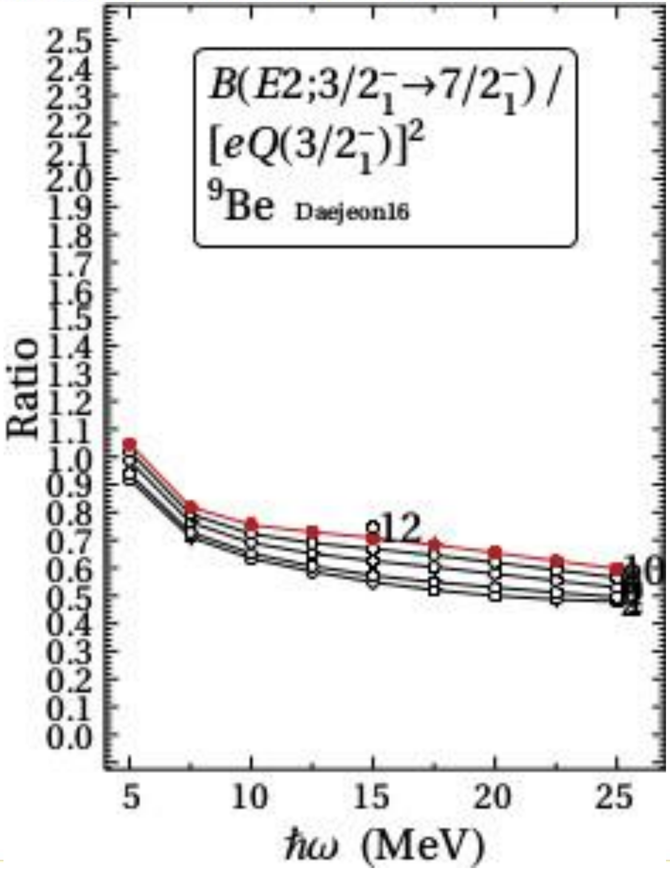
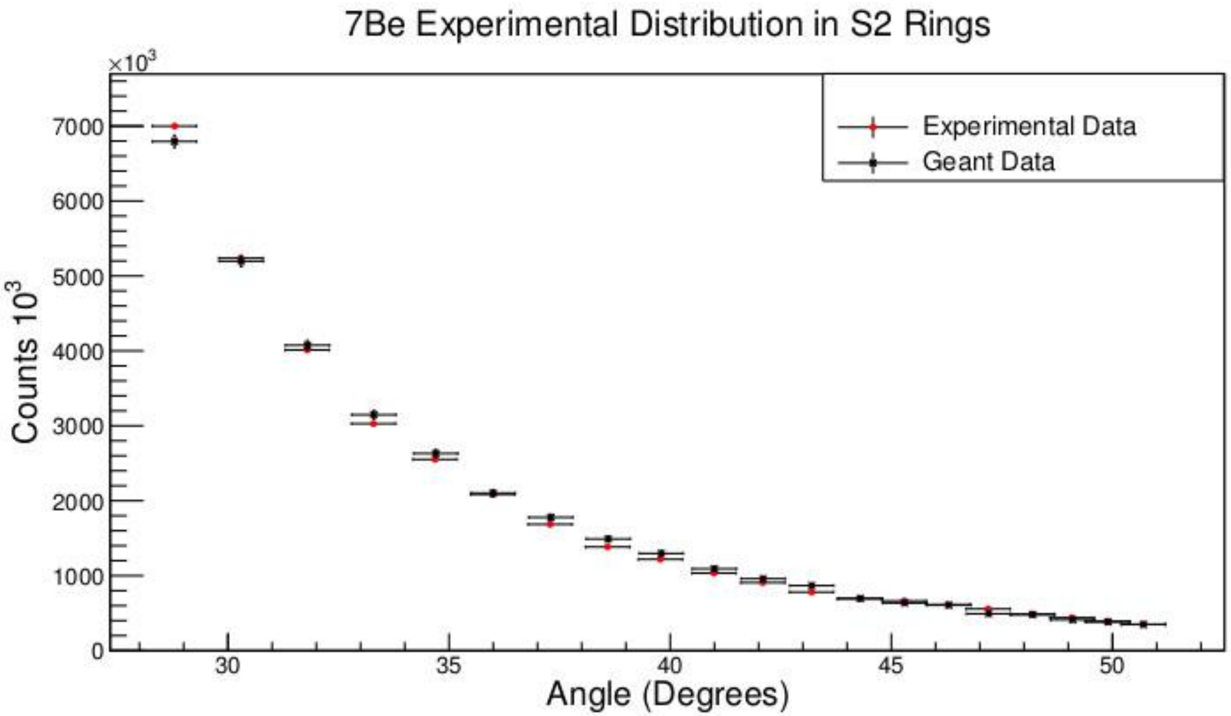




^{8}Li Geant4 beam reproduction



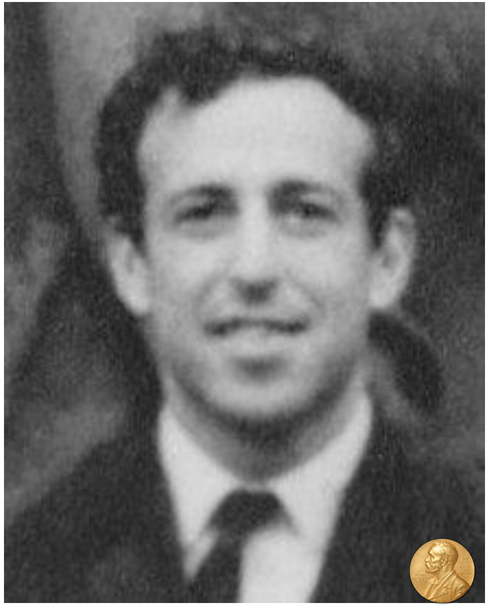
History Note

- Winther & de Boer developed coupled channel code
- Necessary for more complicated excitations
-

History Note

- Bohr and Mottelson laid theoretical groundwork - 1950s
- E2 transitions first link to collective motion

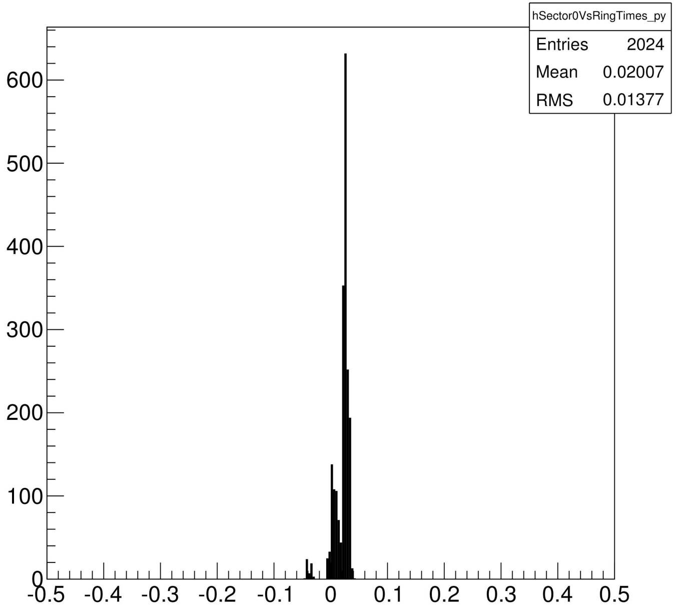
Aage Bohr

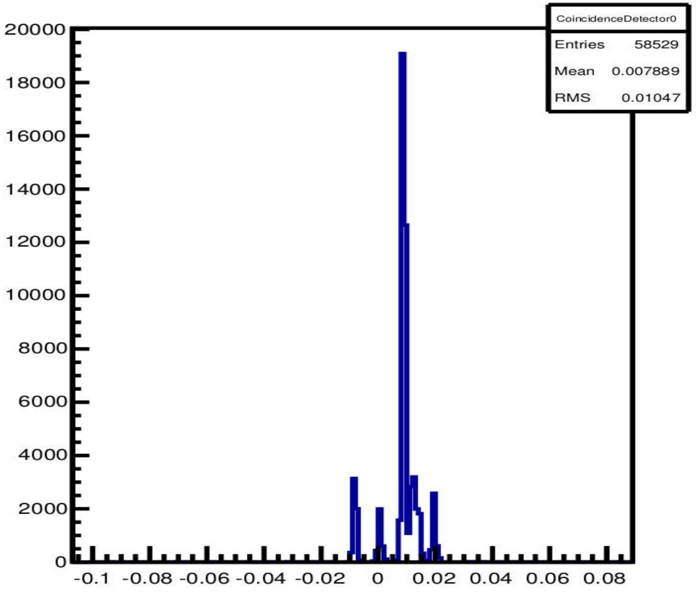


Ben Mottleson

Timing Gates

- Took advantage of Si and $LaBr_3$ detector time resolution





^{7}Li (and ^{197}Au) Coulex