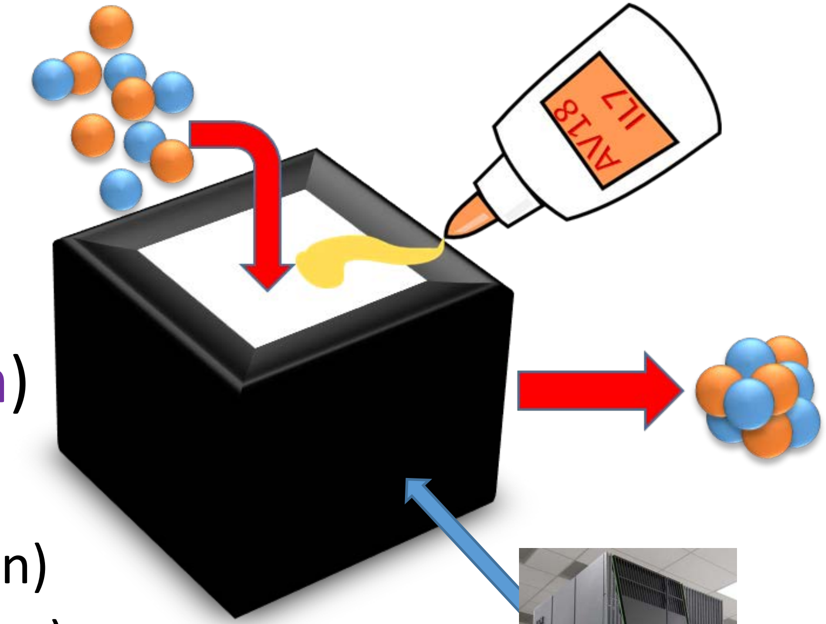
Experimental tests of *ab initio* nuclear structure calculations

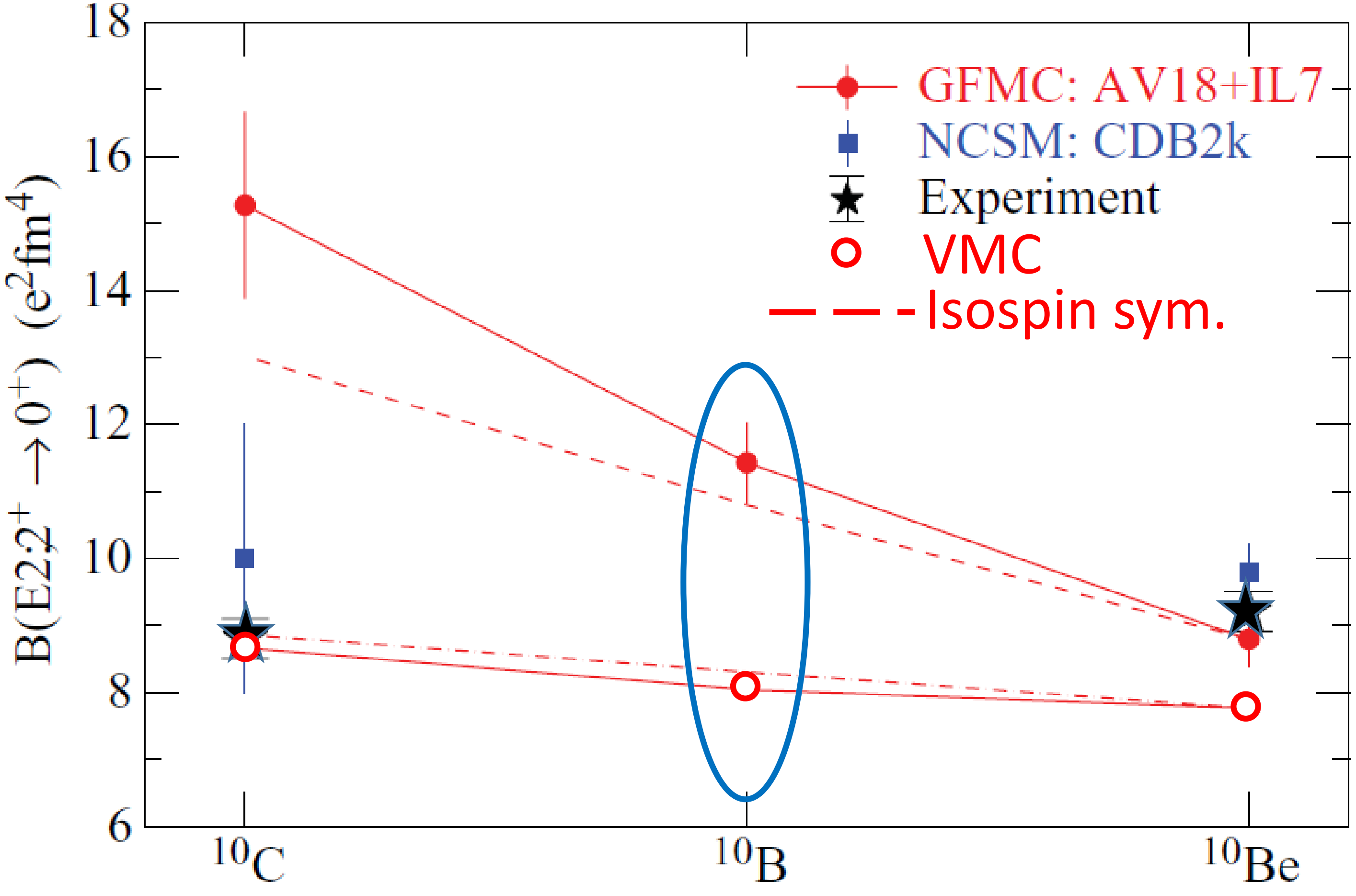


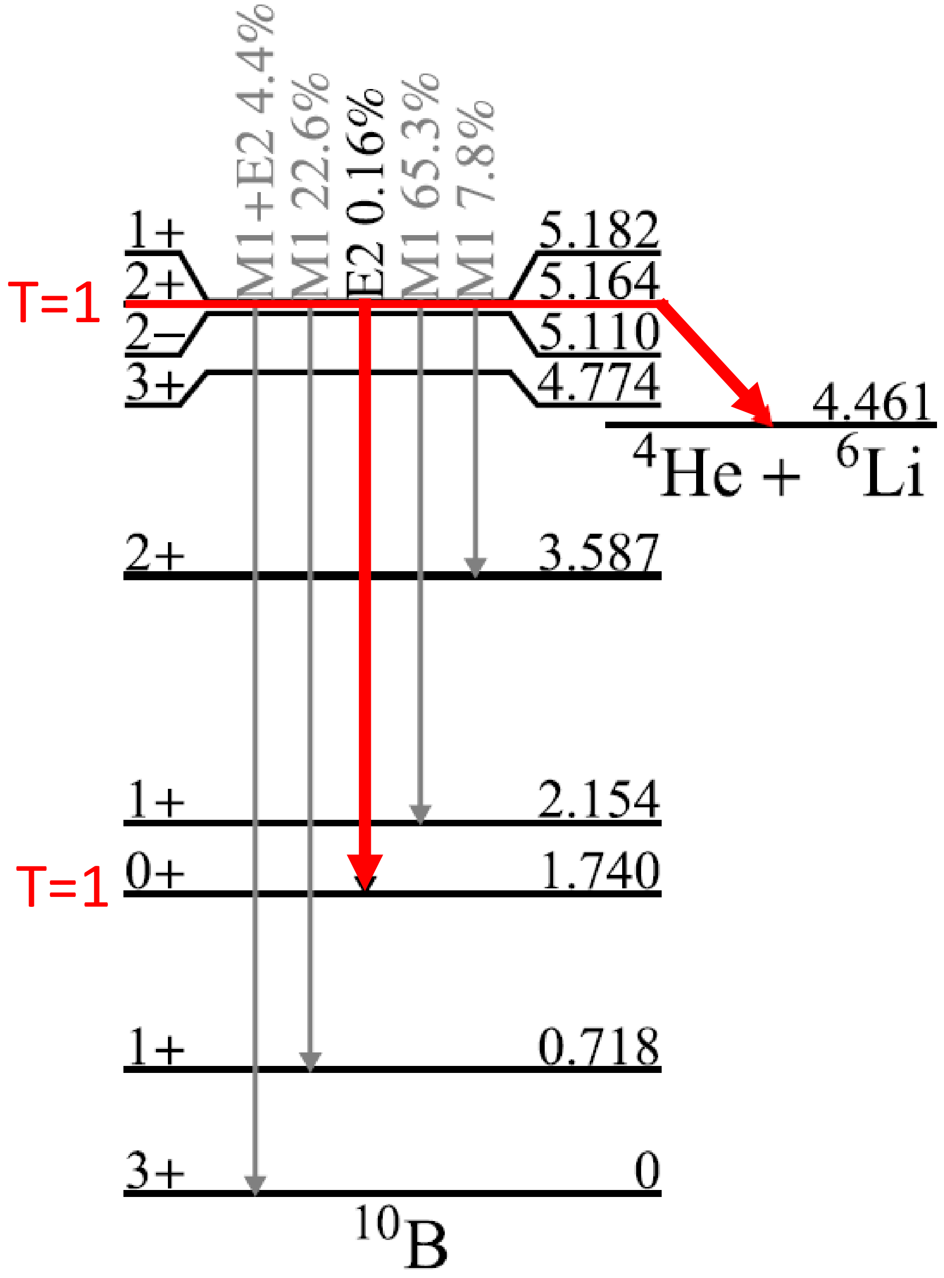
- ***Ab-initio***: start with 2N, 3N forces (e.g. AV18+IL7, CD Bonn)
- **Q**uantum **M**onte **C**arlo – limited to A≤12
  - **V**ariational **M**onte **C**arlo (lowest energy/configuration by variation)
  - **G**reen's **F**unction **M**onte **C**arlo (evolve VMC state in imaginary time)
- **N**o **C**ore **S**hell **M**odel – Harmonic-oscillator basis, converge to large $\hbar\Omega$

- Many Successes
  - Binding and excitation energies
  - Charge and matter radii
  - Spectroscopic overlaps / spectroscopic factors
  - Transition matrix elements
  - Continuum states

Alan Wuosmaa
University of Connecticut
Department of Physics

EM transitions in T=1, A=10 triplet

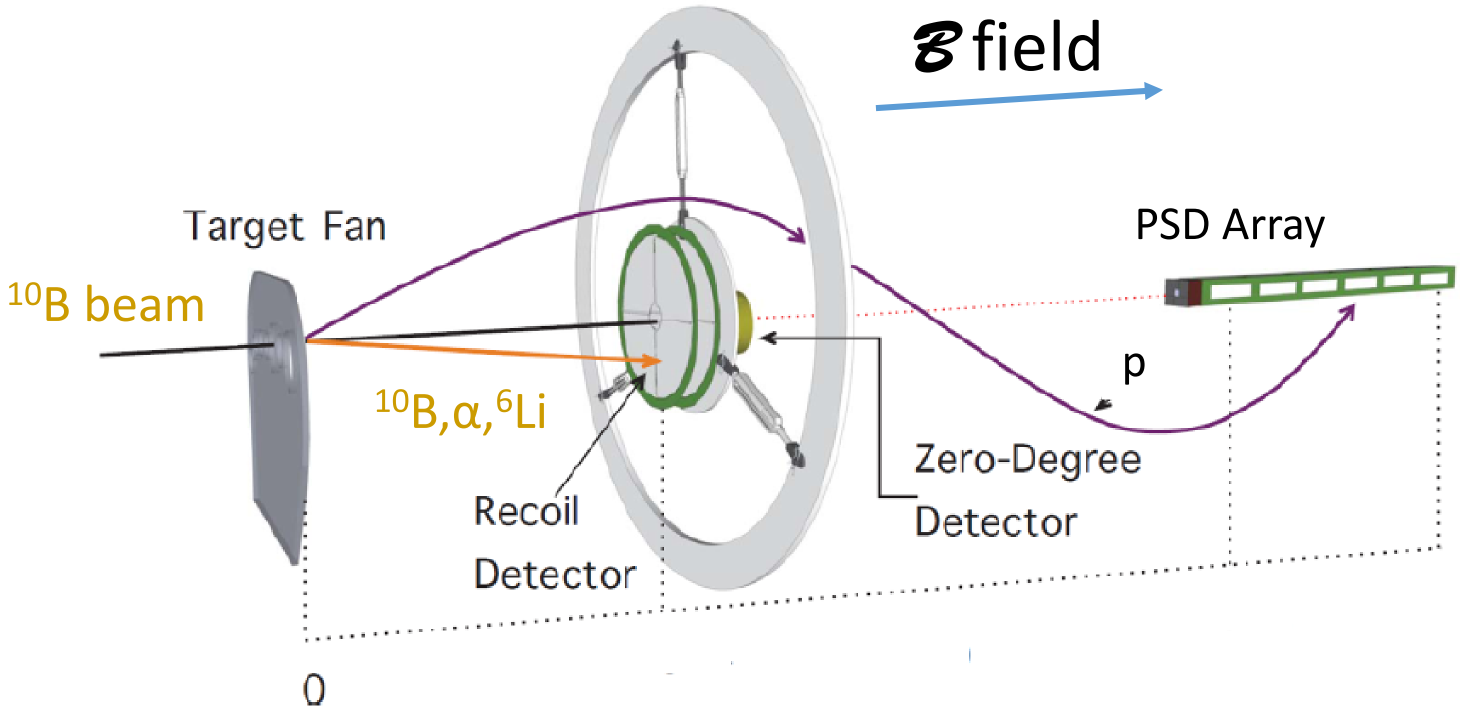




E. A. McCutchen *et al.*, PRL **103**, 192501 (2009) (^{10}Be); PRC **86**, 014312 (2012) (^{10}C); PRC **86**, 057306 (2012) (^{10}B)

$^{10}B(p,p')^{10}B^*$ in HELIOS at ANL

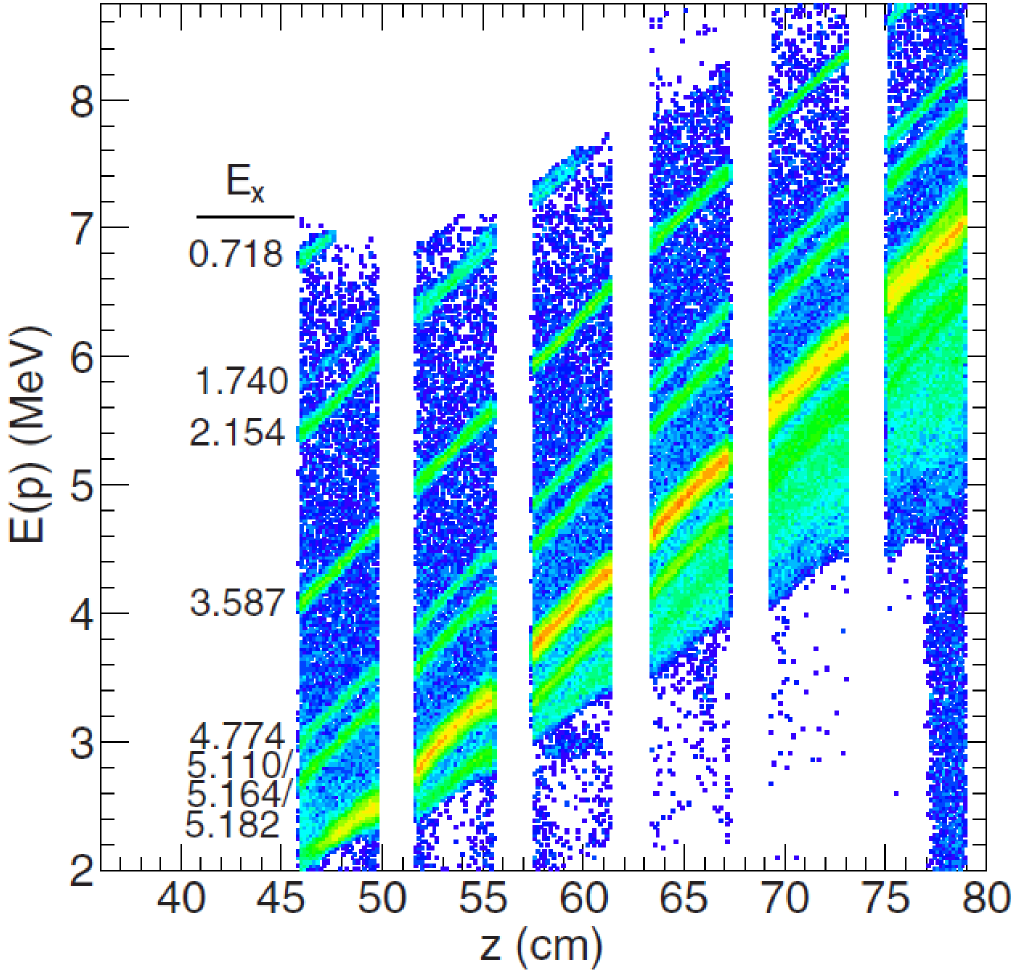
$E(^{10}B)$=100 MeV



Protons follow helical trajectories in uniform magnetic field.

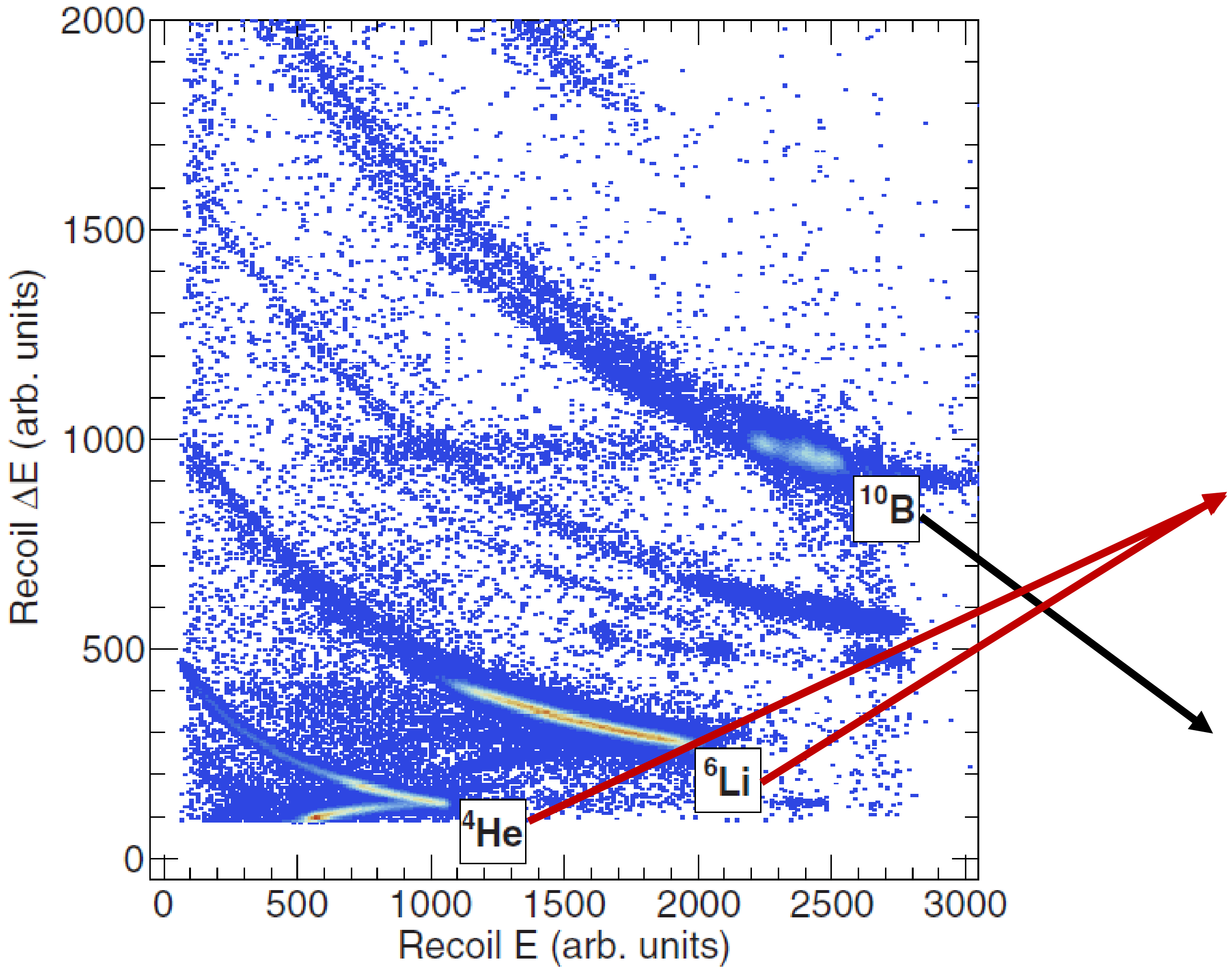
Pure beam + recoil detection = better isolation of reaction and ability to observe weak transitions

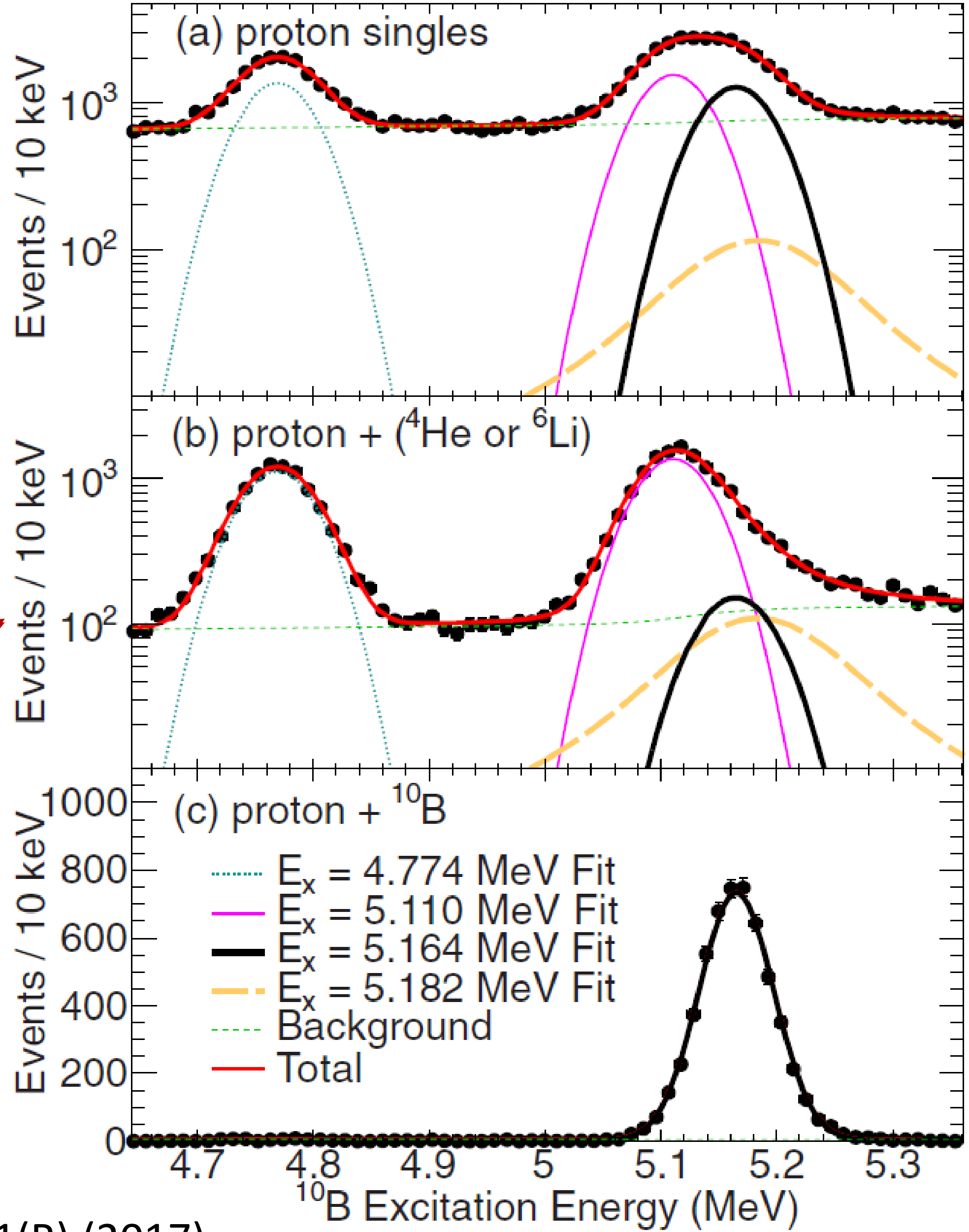
Correlation between proton energy and position



Kuvin et al., PRC **96**, 041301(R) (2017)

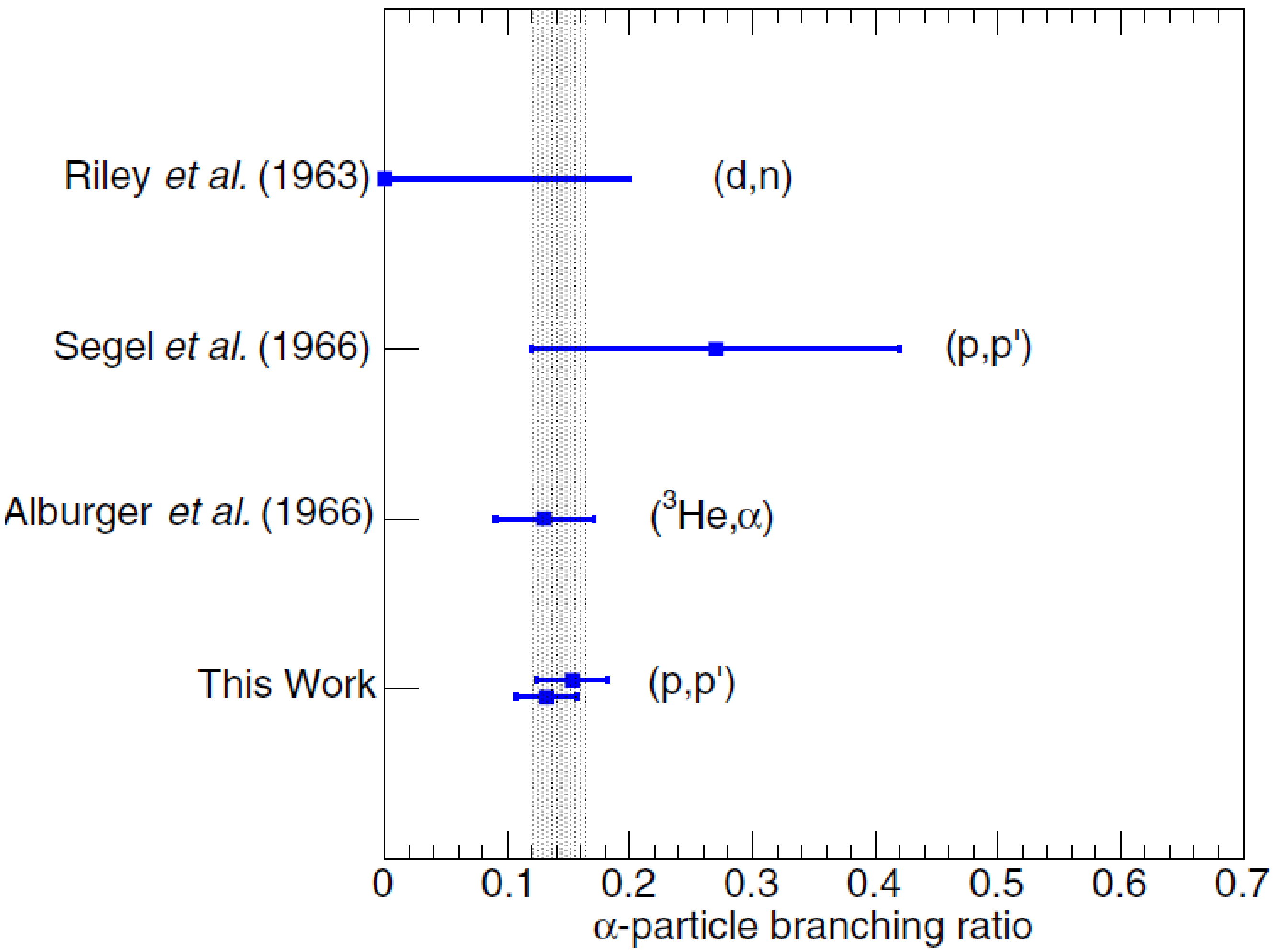
PID and particle branches



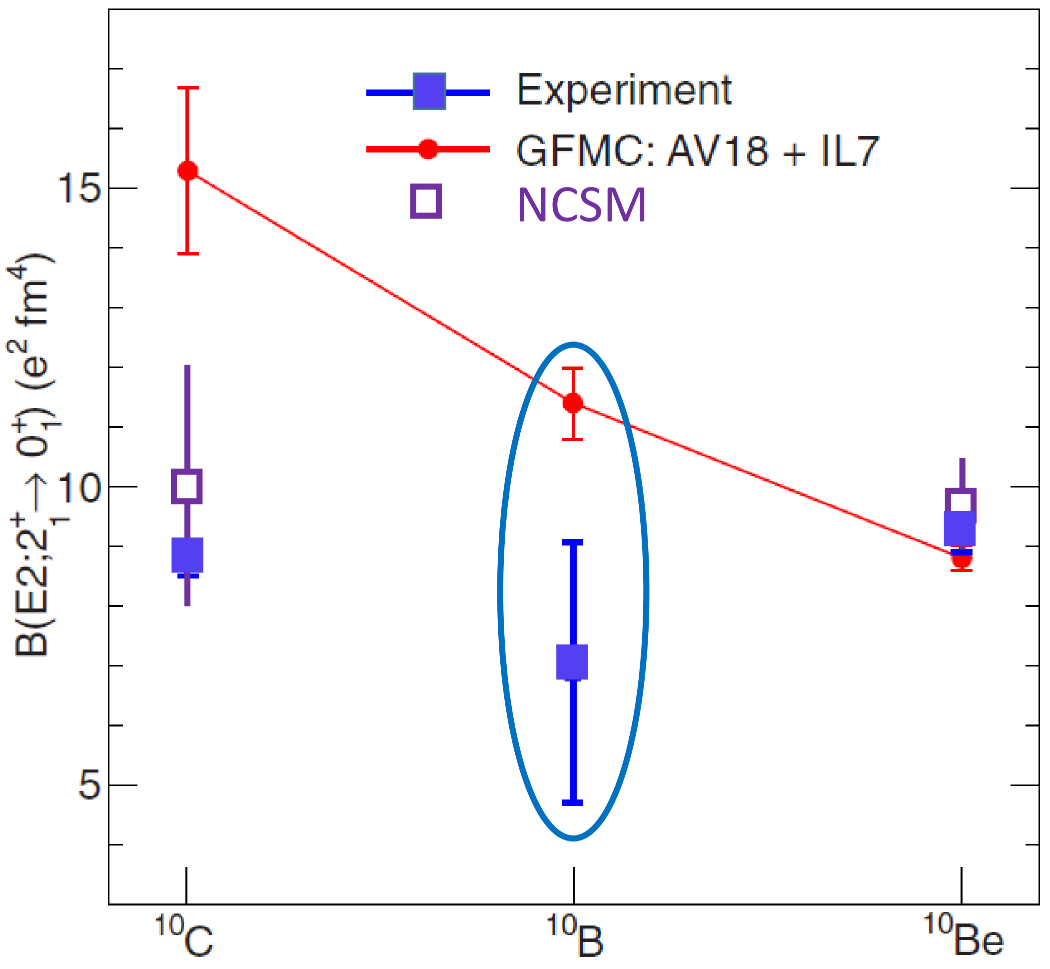


Kuvin et al., PRC **96**, 041301(R) (2017)

The discrepancy remains for GFMC in ^{10}B



New results favor a smaller α branch, reduce combined uncertainty



Uncertainty in B(E2) now dominated by 0.16% gamma-ray branching ratio

Kuvin et al., PRC **96**, 041301(R) (2017)

Possible reasons

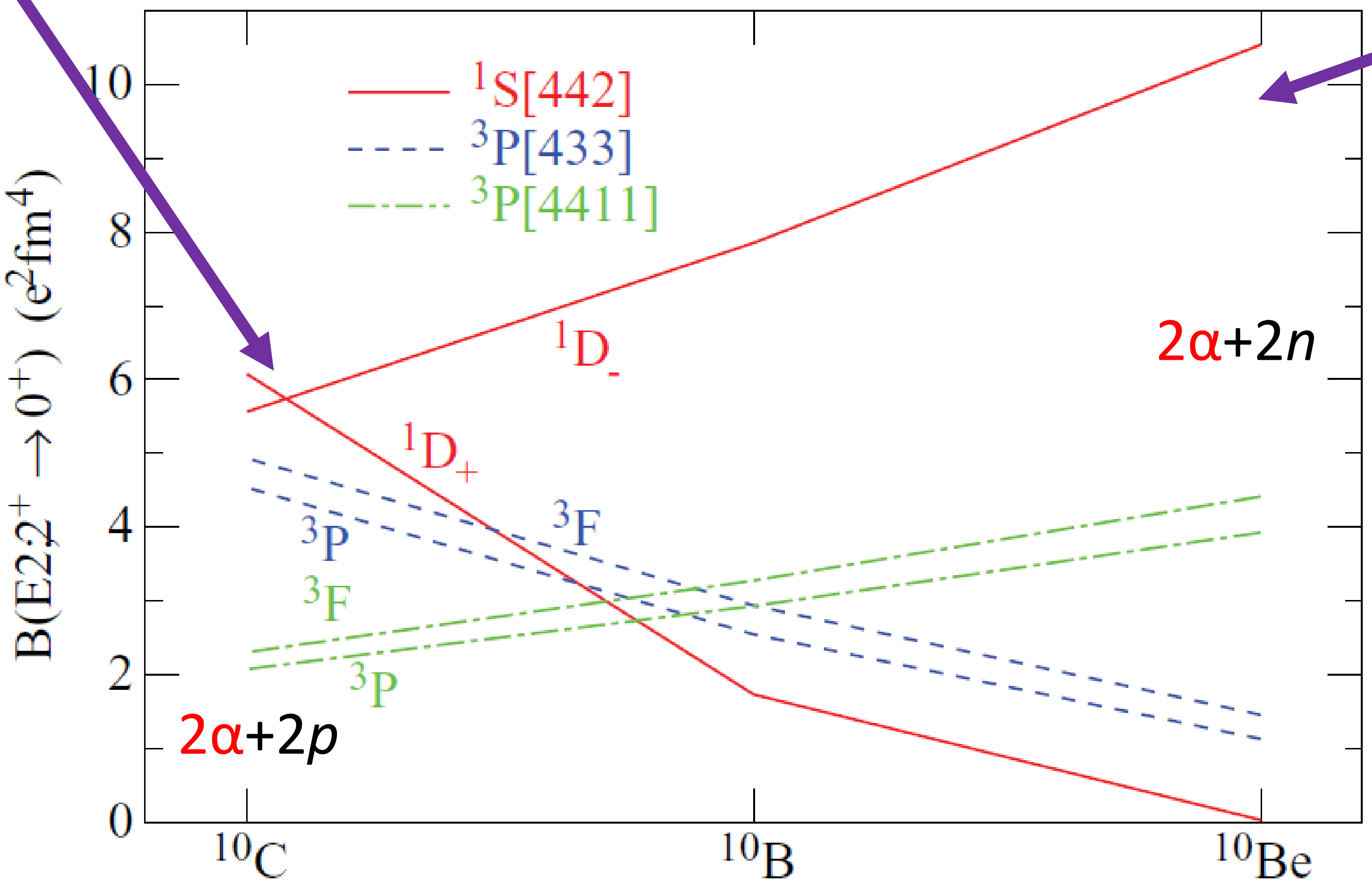
^{10}C: Many spatial symmetry components

^{10}Be: ~One spatial symmetry component

Isovector E2 small

Mixing Enhanced by 3BF in GFMC

Hamiltonian tuned for energy?



E. A. McCutchen et al, PRC **86**, 014312 (2012)

Spatial symmetry components combine to make B(E2)

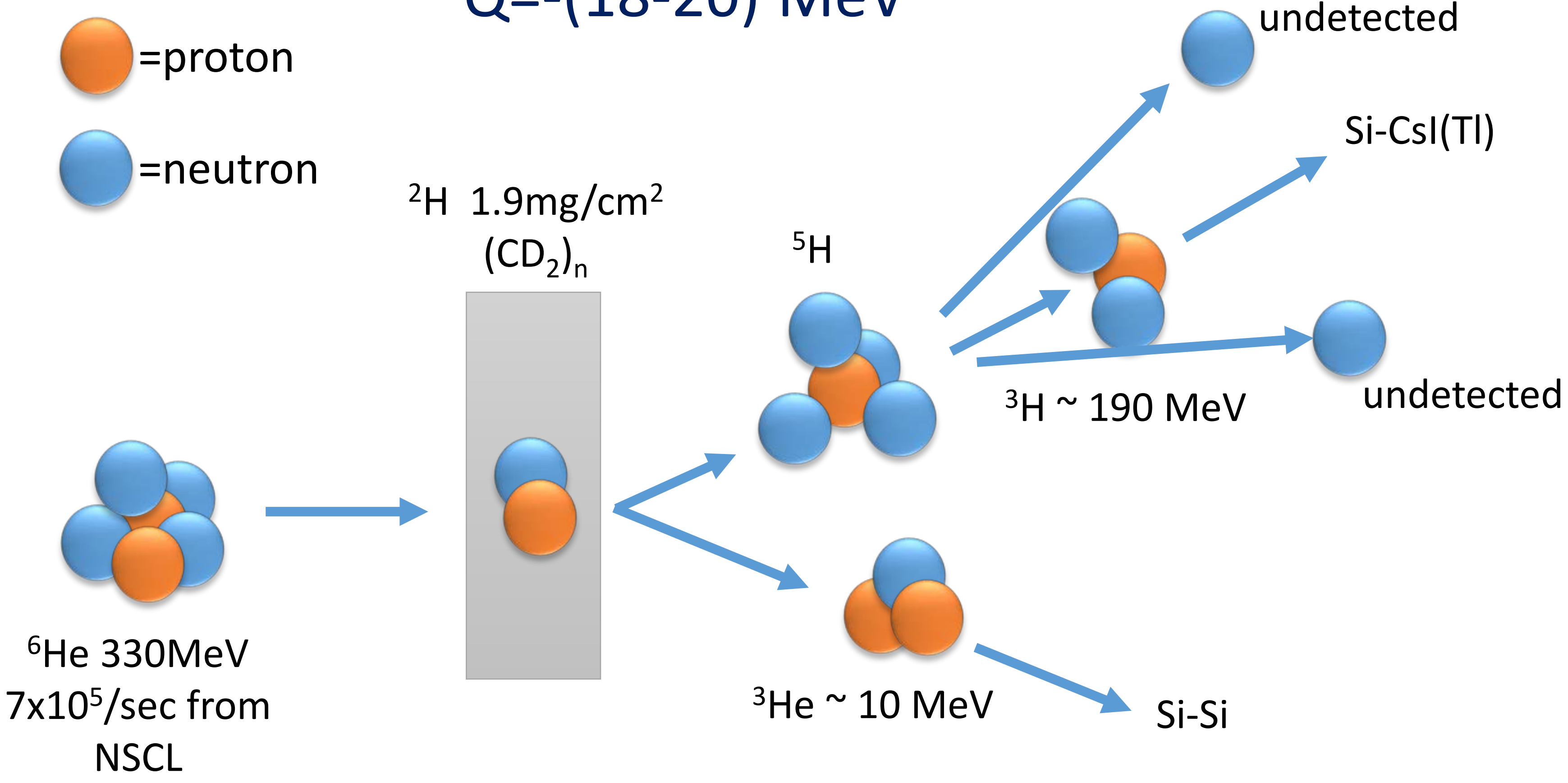
In the continuum: ^{5}H

- Very close to ^4n (the "tetra-neutron")
- Very unbound to ^{3}H+2*n* but potentially observable
- Many data exist, with conflicting values of the resonance energy and width (Typically: E_R~1.8 MeV, Γ~1-2 MeV).
- Properties are very sensitive to *nn* interaction, influence of the continuum: possibility of observing *nn* correlations
- Challenge for *ab-initio* methods
  - NCSMC[1]; QMC[2] for limited cases (2-body clusters)
  - Can overlaps be believed for very unbound systems?

[1]P. Navrátil, Phys. Scr. **91**, 053002 (2016), S. Quaglioni *et al*., PRC **97**, 034332 (2018)
[2]K. Nollett *et al*., PRL **99**, 022502 (2007), J. Carlson *et al*., Rev. Mod. Phys. **87**, 1067 (2015)

Reaction of interest: $^{6}He(d,^{3}He)^{5}H(^{3}H+2n)$

Q=-(18-20) MeV

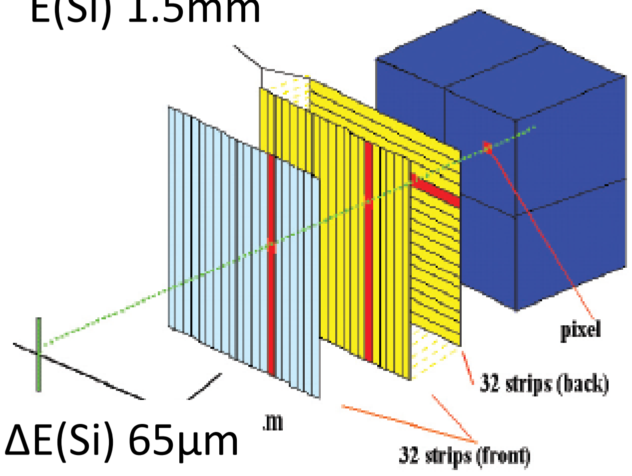


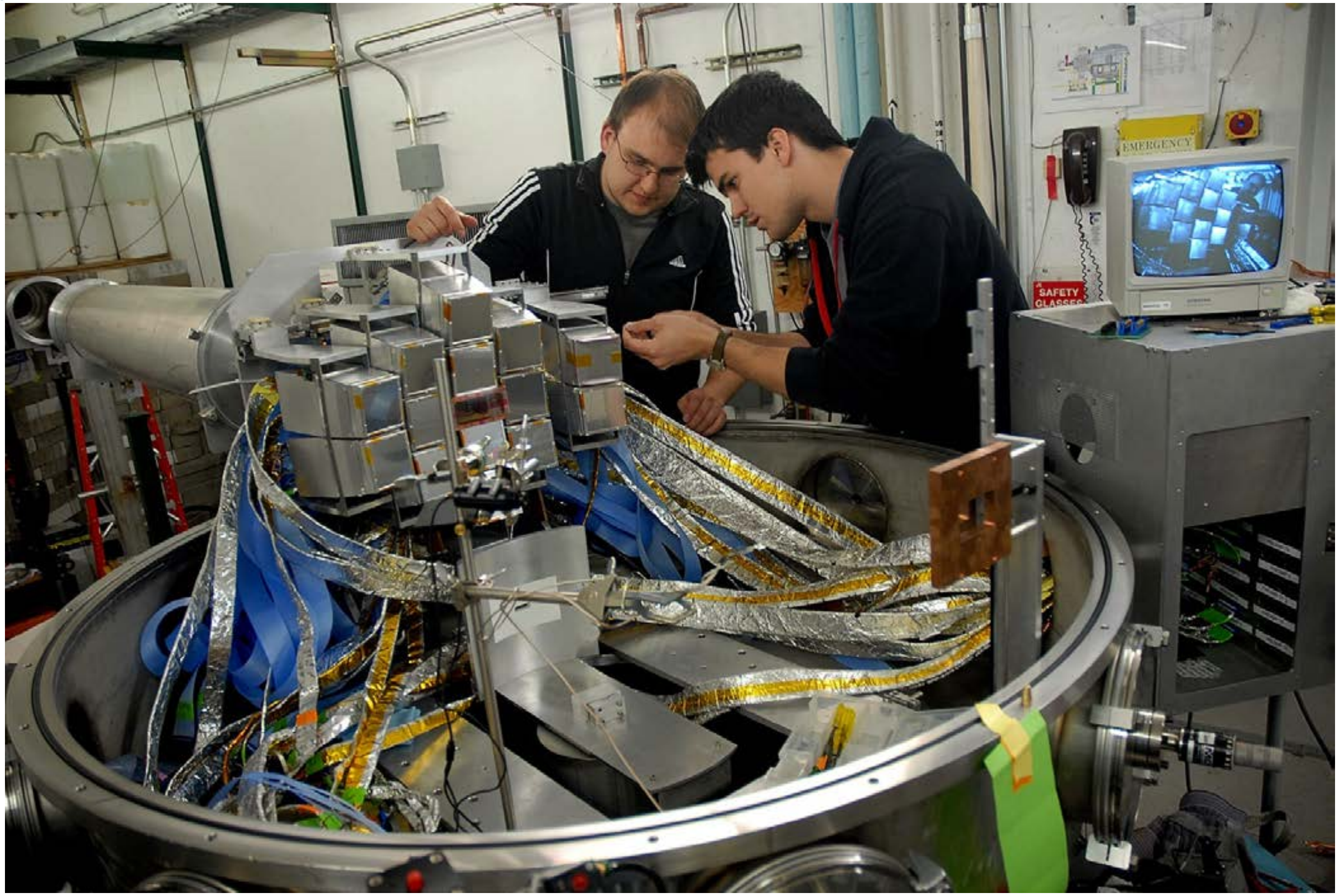
Reaction products have wide dynamic range in energy:
Requires two different types of particle-detector telescope for PID

Bombarding energy is 2.5 times higher than previous measurements

Detection with the High-Resolution Array (HiRA[1]) at MSU/NSCL

- 2 Si layers
- 4 CsI(Tl) crystals





- ΔE(Si): SSD 32 strips
- E(Si): DSSD 32x32 strips ($\Delta\theta_{lab}$=0.13°/pixel)
- 14 Telescopes, covers $\theta_{c.m.}$=~1-10°

[1]M. S. Wallace et al., Nucl. Instrum. and Meth. A 583, 302 (2007)

Final Results

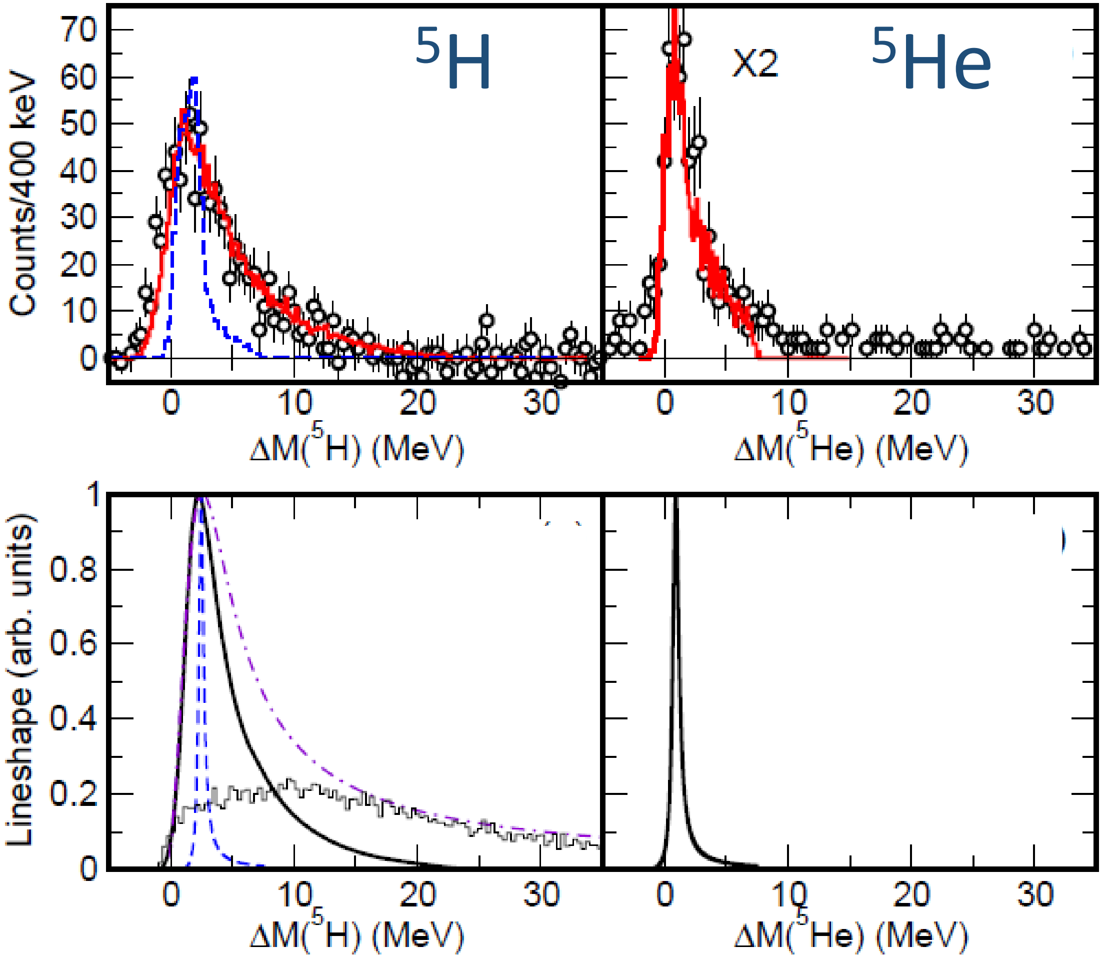
$^{5}H_{g.s.}$ is broad

E_R= 2.4±0.3MeV
Γ(lab)= 4.8±0.4MeV

Can either *ab-initio* approach contend with such a short-lived system?

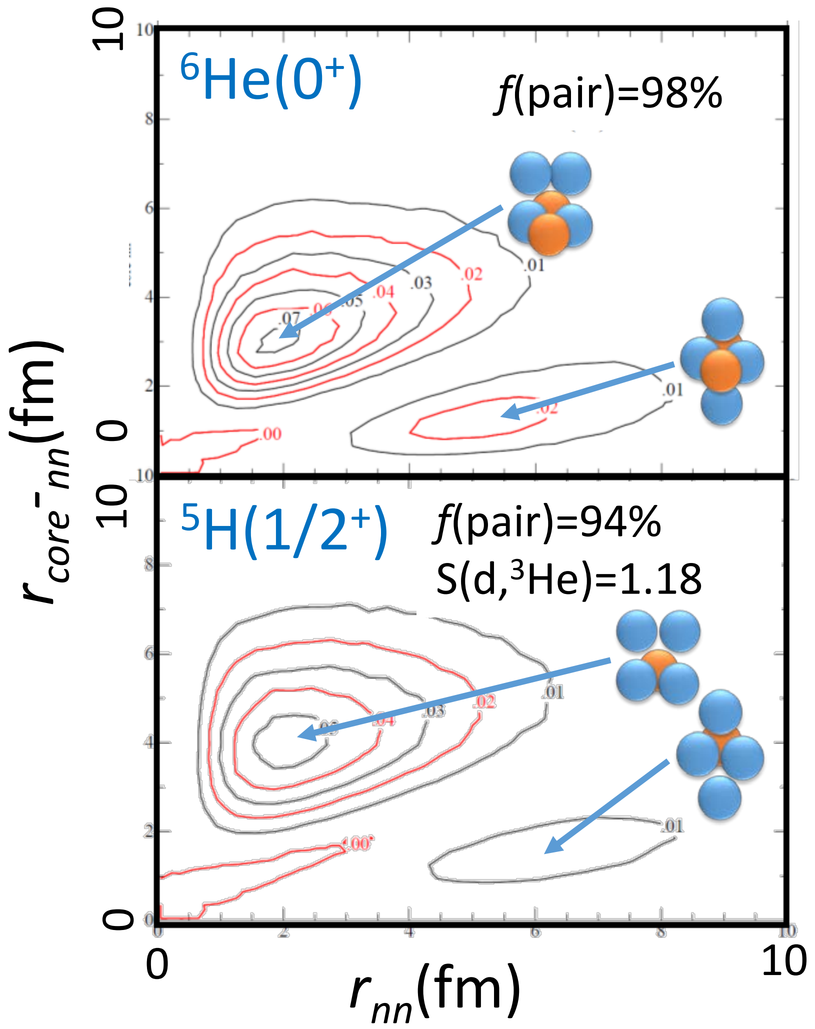
PRC **95**, 014310 (2017)

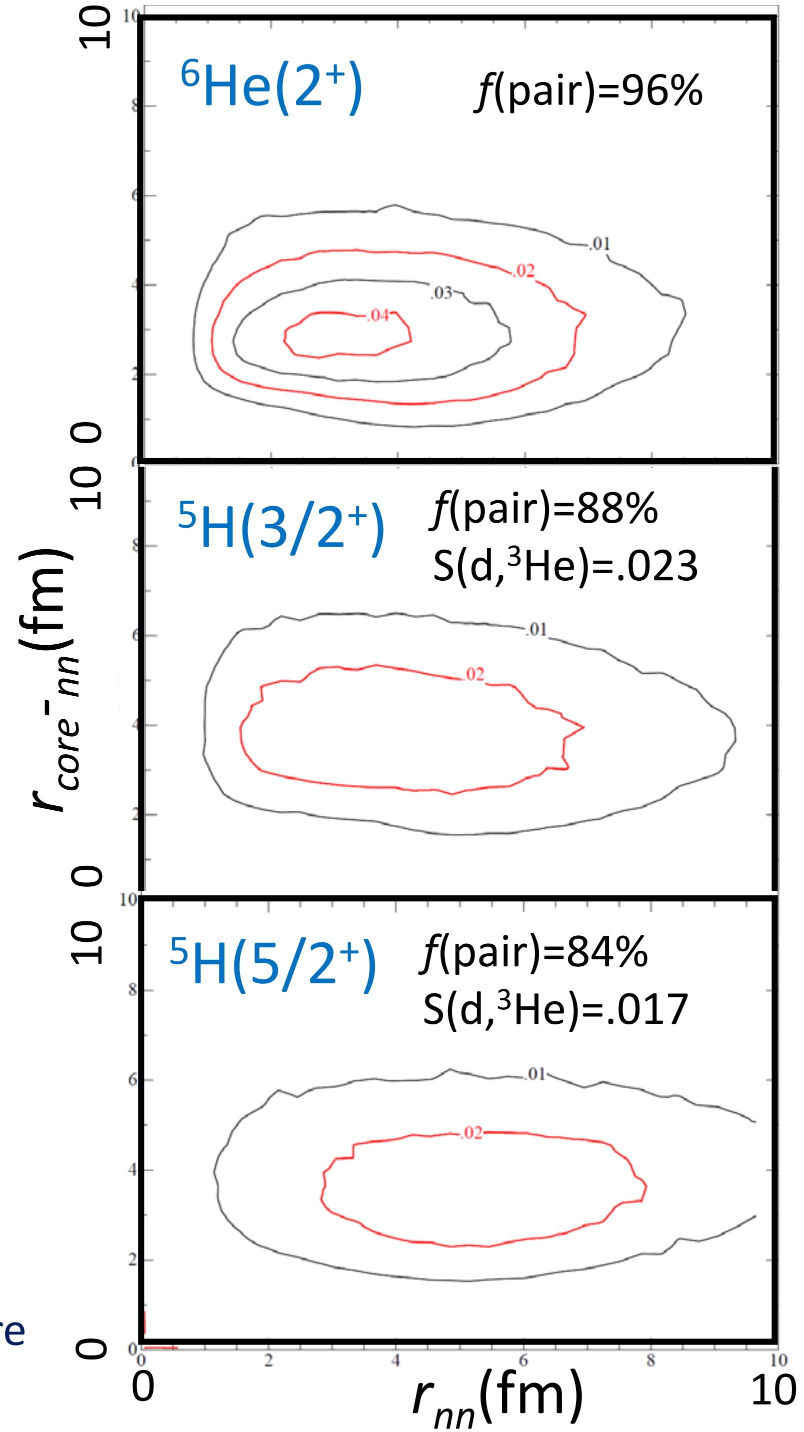
Missing-mass spectra



Line shapes. Thick curve: best fit; dashed-blue illustrates ^{5}H resolution; Histogram: efficiency

GFMC overlaps and two-neutron densities





All Contours start at 0.01; intervals are 0.01.

Quantum Monte Carlo
R. B. Wiringa, ANL

Ab Initio with NCSMC

PHYSICAL REVIEW C **97**, 034332 (2018)

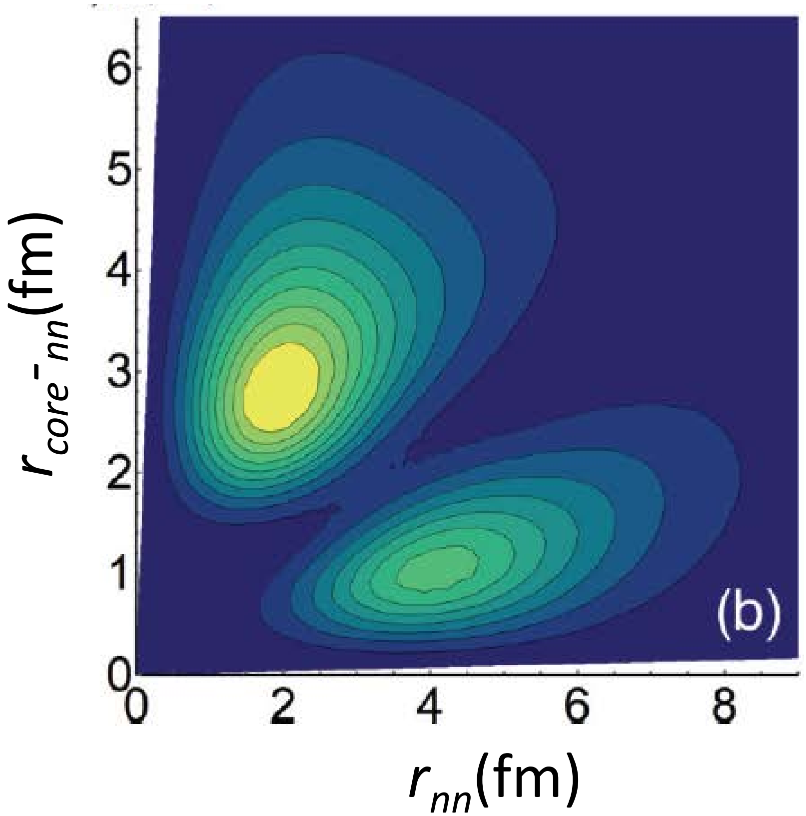
Three-cluster dynamics within the *ab initio* no-core shell model with continuum: How many-body correlations and α clustering shape ^{6}He

Sofia Quaglioni,[1,*] Carolina Romero-Redondo,[1,†] Petr Navrátil,[2,‡] and Guillaume Hupin[3,§]

No-Core Shell Model and QMC 2-neutron densities are very similar

(This is $^{6}He_{g.s.}$, but the neutron configurations in $^{5}H_{g.s.}$ and $^{6}He_{g.s.}$ should be similar)

Ab initio calculations support strong di-neutron correlations



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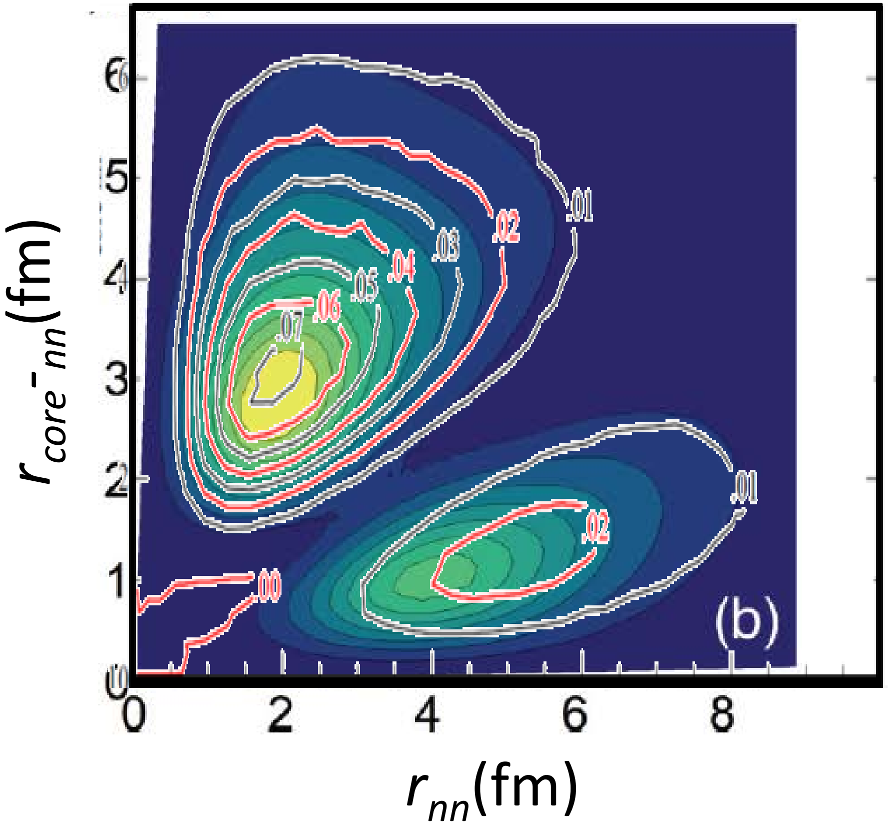


Ab initio calculations support strong di-neutron correlations

Inspiration for further experiments and calculations

- EM transitions: Re-measure 0.16% E2 gamma-ray branching ratio for ^{10}B (current limit on uncertainty for measured B(E2)) – Planned experiment using GAMMASPHERE
- Energy and width of $^{5}H_{g.s.}$ (NCSMC calculation; ^{5}He is not bad)
- ^{5}H (and unbound ^{6}He): Compare *n*-*n* correlations following $^{6}He(d,^{3}He)^{5}H$ and ^{6}He breakup
- Other reactions to study continuum states in ^{6}He: Two-neutron transfer with $^{4}He(t,p)^{6}He$ (Previously studied only twice in the 70's at low energies)

Many thanks to:

^{10}B:

S. A. Kuvin,[1] C. J. Lister,[2] M. L. Avila,[3] C. R. Hoffman,[3] B. P. Kay,[3] D. G. McNeel,[1] C. Morse,[2] E. A. McCutchan,[4] D. Santiago-Gonzalez,[5,3] and J. R. Winkelbauer[6]

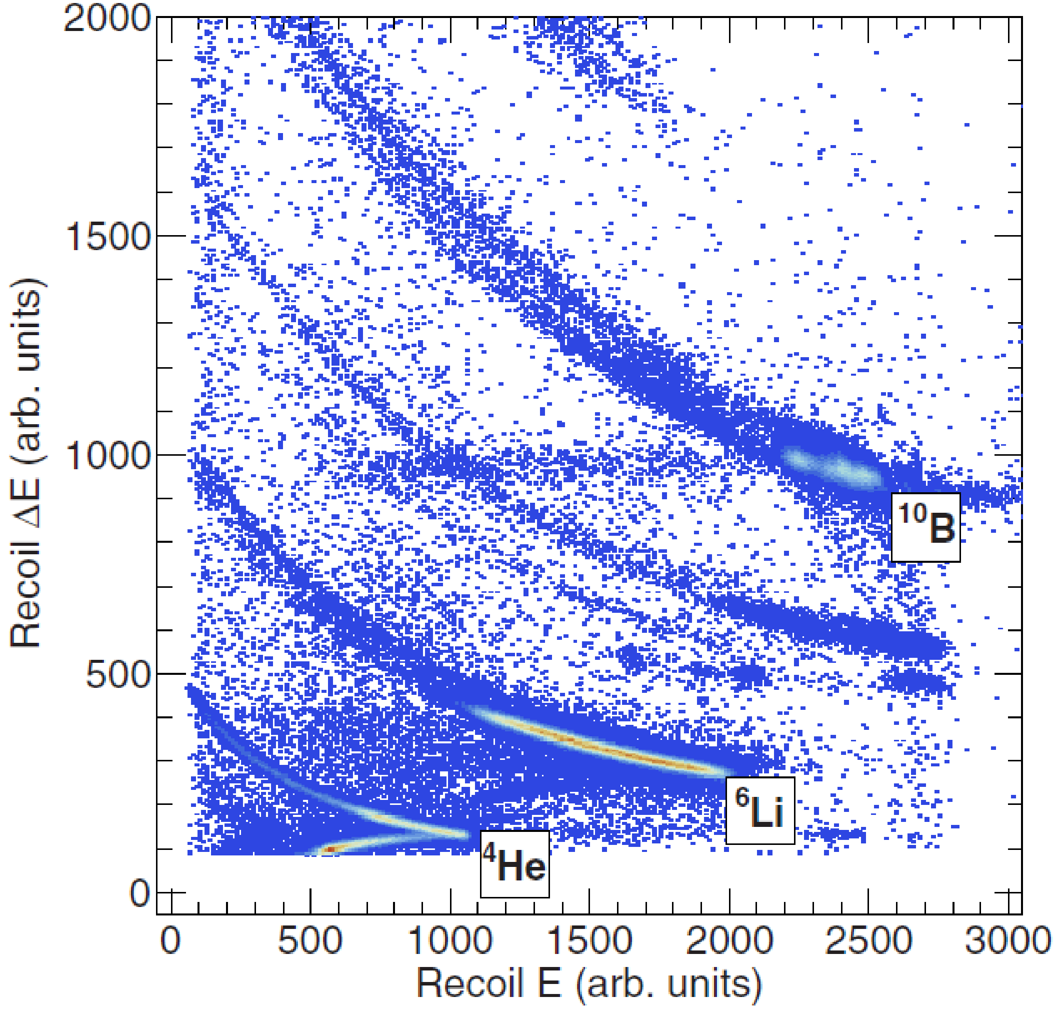
[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*
[2]*Department of Physics and Applied Physics, University of Massachusetts, Lowell, Massachusetts 01854, USA*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York 11973, USA*
[5]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[6]*Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

^{5}H:

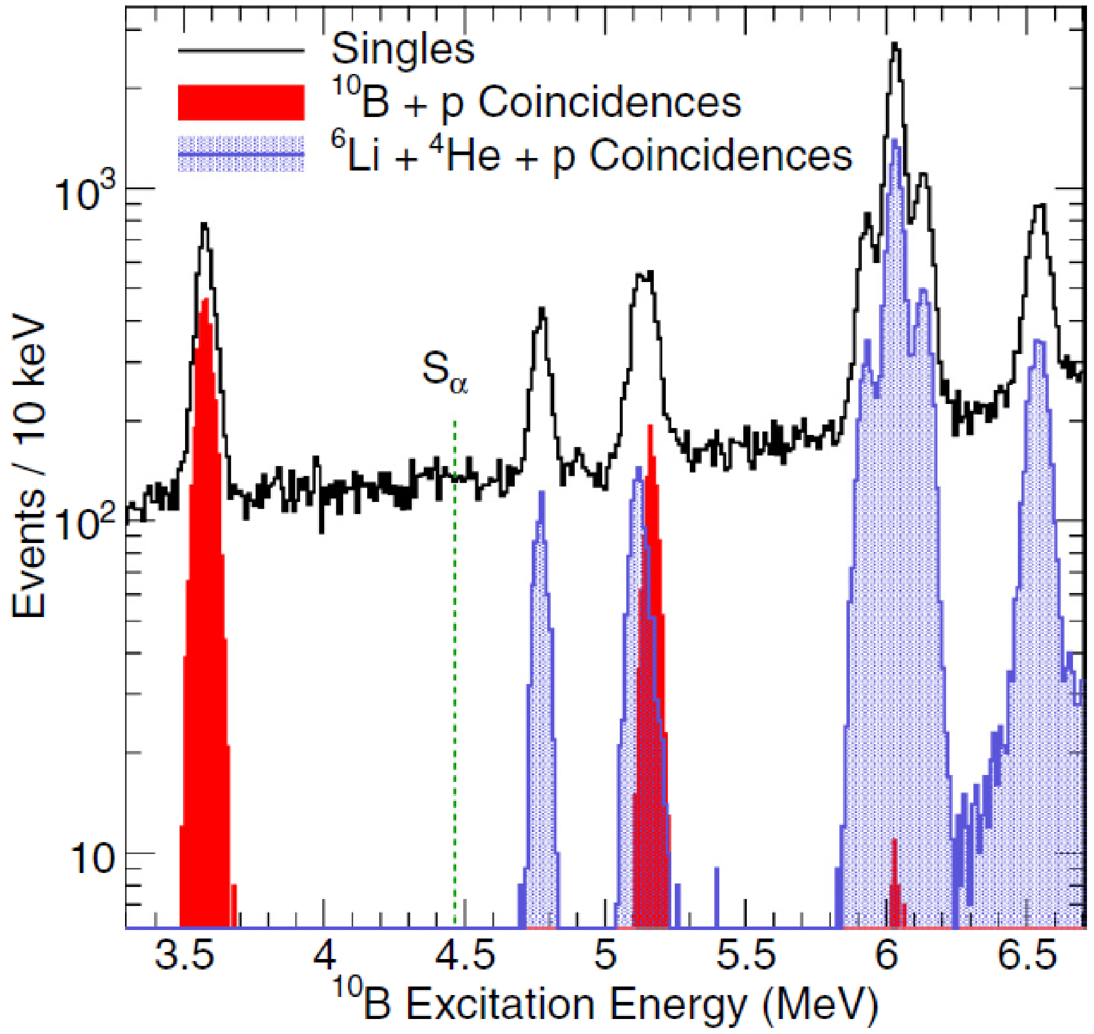
S. Bedoor,[1,2,†] **K. W. Brown**,[3,‡] W. W. Buhro,[4] **Z. Chajecki**,[4] **R. J. Charity**,[3] W. G. Lynch,[4] J. Manfredi,[4] S. T. Marley,[5,§] **D. G. McNeel**,[1,2] A. S. Newton,[2] D. V. Shetty,[6] R. H. Showalter,[4] **L. G. Sobotka**,[3] M. B. Tsang,[4] **J. R. Winkelbauer**,[4,||] and **R. B. Wiringa**[7]

[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06268-3046, USA*
[2]*Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008-5252, USA*
[3]*Departments of Chemistry and Physics, Washington University at St. Louis, St. Louis, Missouri 63130, USA*
[4]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics and Astronomy, University of Notre Dame, South Bend, Indiana 46558, USA*
[6]*Department of Physics, Grand Valley State University, Allendale, Michigan 49401, USA*
[7]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

U. S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Numbers DE-FG02- 04ER41320, DE-SC0014552, DE-FG02-87ER40316, and DE-AC02-06CH11357, and:
The U. S. National Science Foundation under Grant Numbers and PHY-1068192 and PHY-1102511

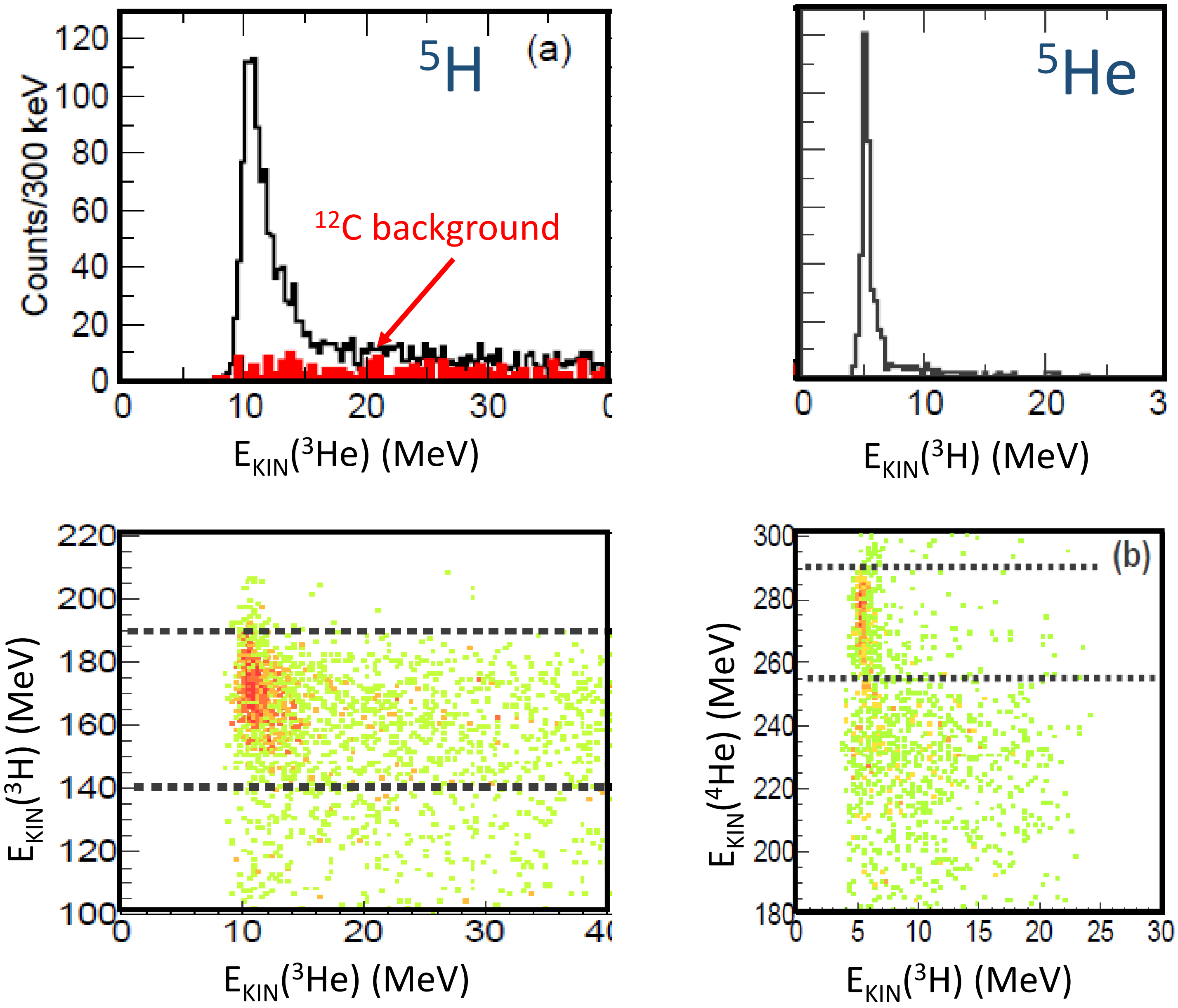


Recoil ΔE (arb. units)
Recoil E (arb. units)
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
10B
6Li
4He



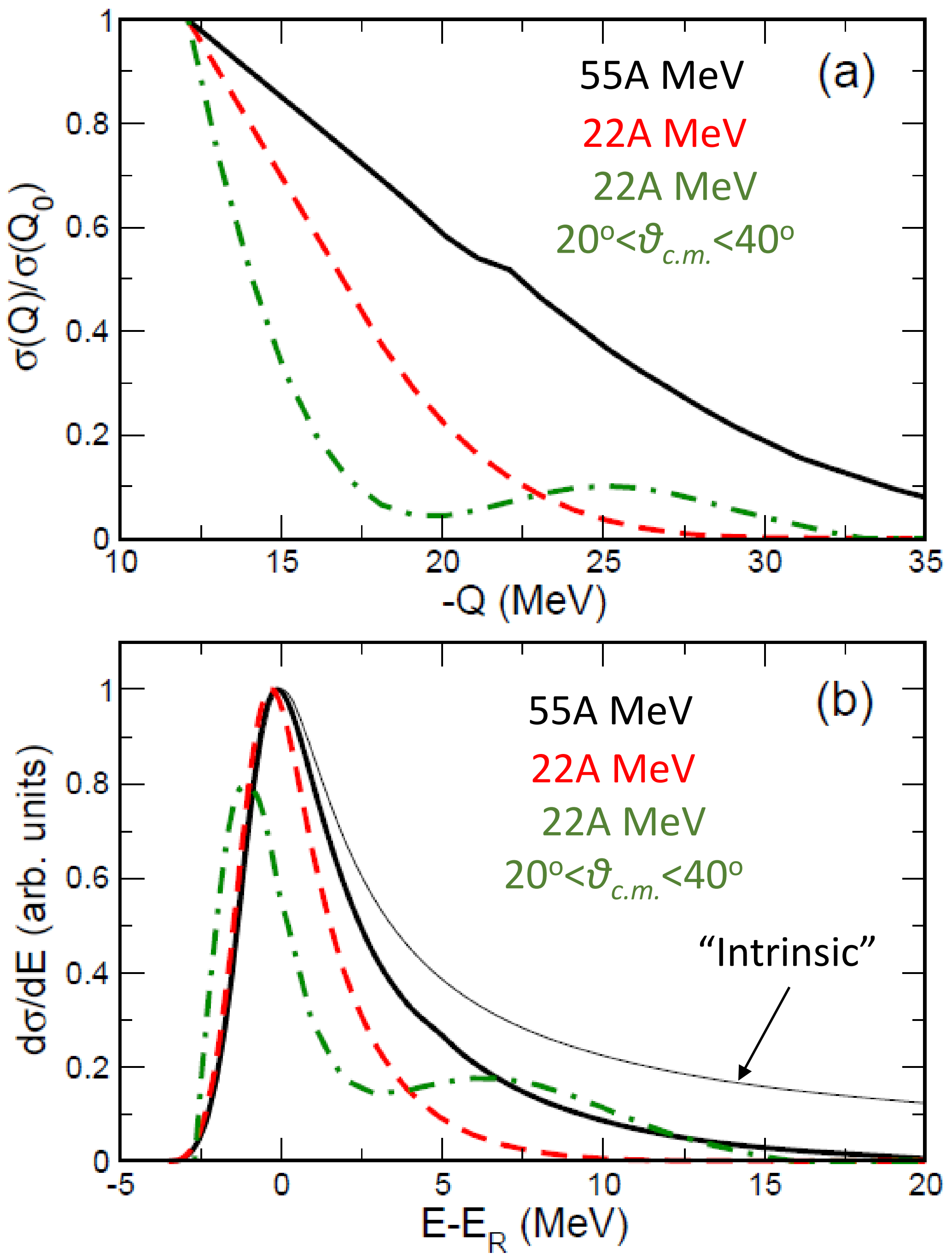
Singles
10B + p Coincidences
6Li + 4He + p Coincidences
Events / 10 keV
10B Excitation Energy (MeV)
Sα
10^3
10^2
10
3.5
4
4.5
5
5.5
6
6.5

Experimental Signatures



σ(E) Q-value dependence

- Cross section decreases with excitation energy, distorting the line-shape (energy conservation and momentum matching)
- Observed profile is narrower and may shift compared to "intrinsic" shape
- Must correct before going any further using reaction theory (DWBA)



Ab Initio comparisons

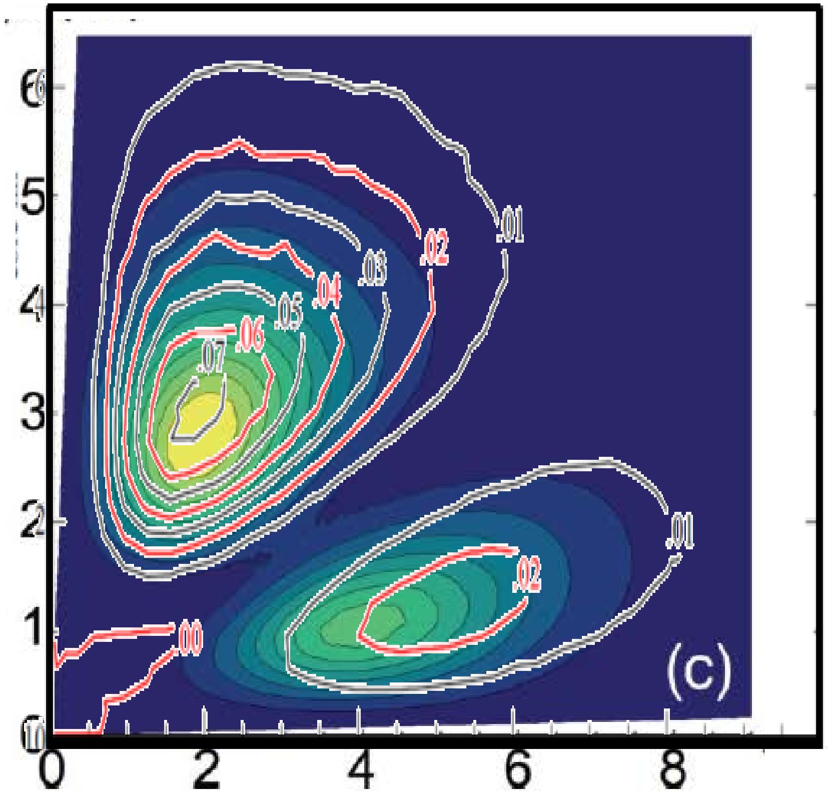
PHYSICAL REVIEW C **97**, 034332 (2018)

Three-cluster dynamics within the *ab initio* no-core shell model with continuum: How many-body correlations and α clustering shape ^{6}He

Sofia Quaglioni,[1,*] Carolina Romero-Redondo,[1,†] Petr Navrátil,[2,‡] and Guillaume Hupin[3,§]

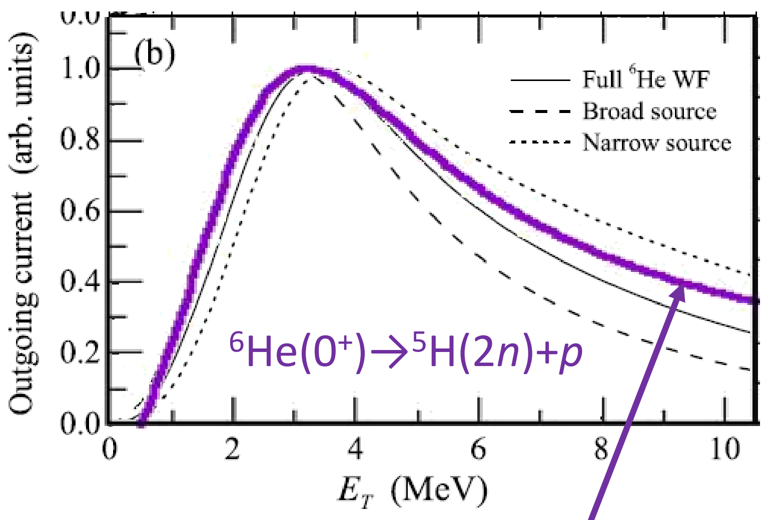
No-Core Shell Model and QMC 2-neutron densities are very similar

(This is ^{6}He, but the neutron configurations in ^{5}H and ^{6}He should be similar)

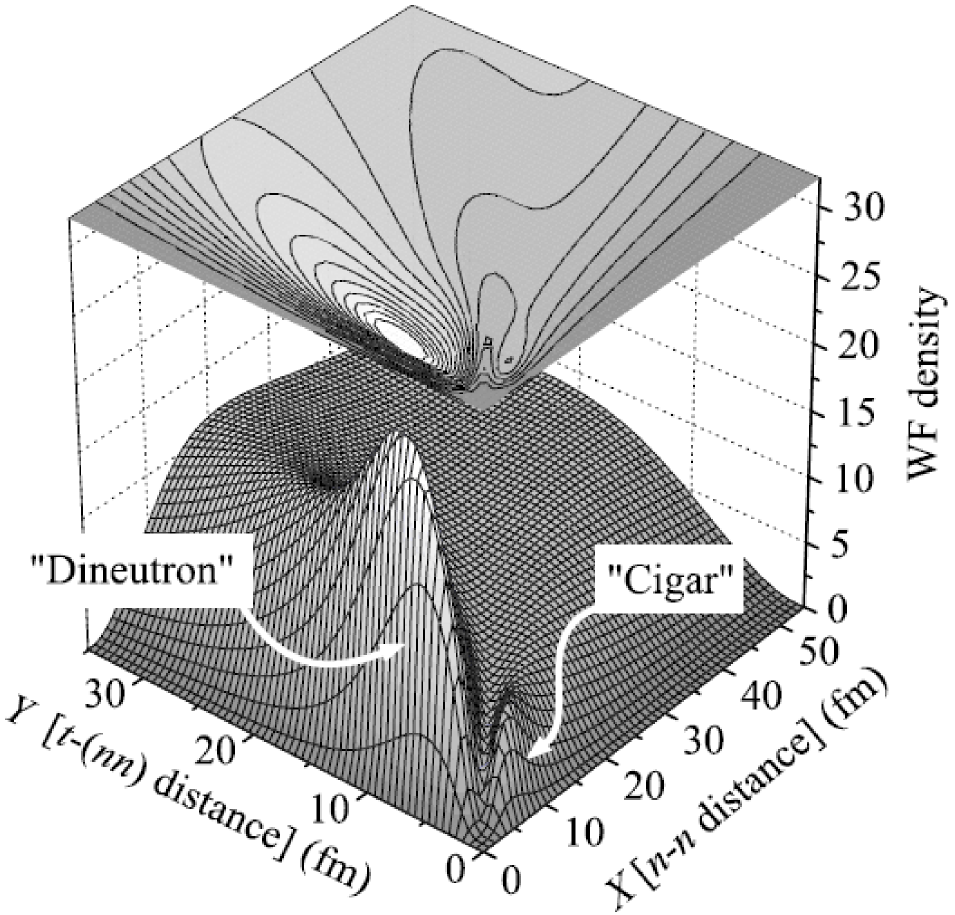


Ab initio calculations support strong di-neutron correlations

A very different theory



Present empirical
“intrinsic” shape



Properties depend on formation mechanism, *e.g*. proton removal from $^6He(0^+)$.

The nucleus does *not* forget:
“Model with source”

Broad states beyond the neutron drip line

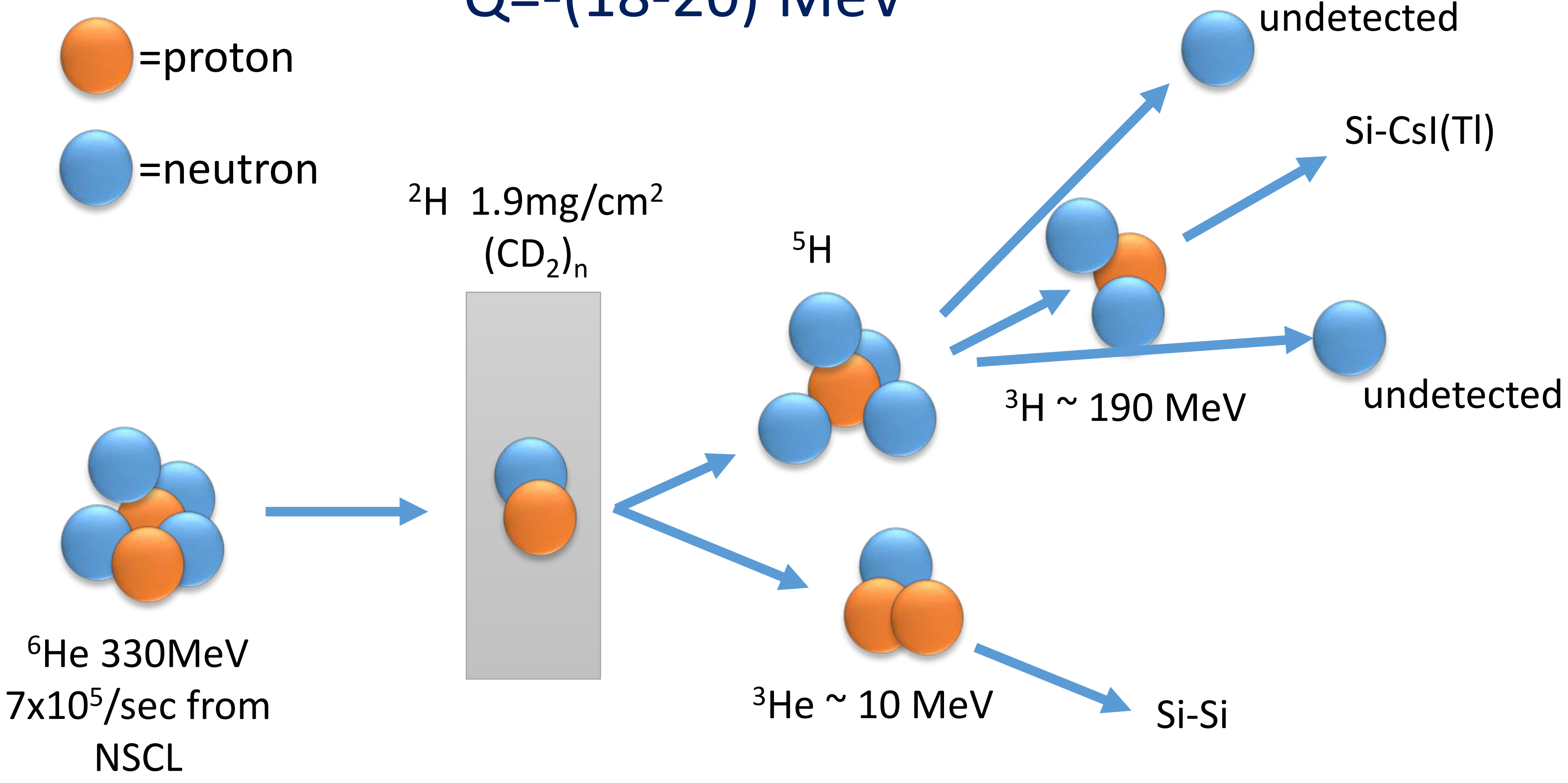
Examples of ^5H and ^4n

L.V. Grigorenko[1,2,a], N.K. Timofeyuk[3], and M.V. Zhukov[4]

Eur. Phys. J. A 19, 187–201 (2004)

Reaction of interest: $^{6}He(d,^{3}He)^{5}H(^{3}H+2n)$

Q=-(18-20) MeV

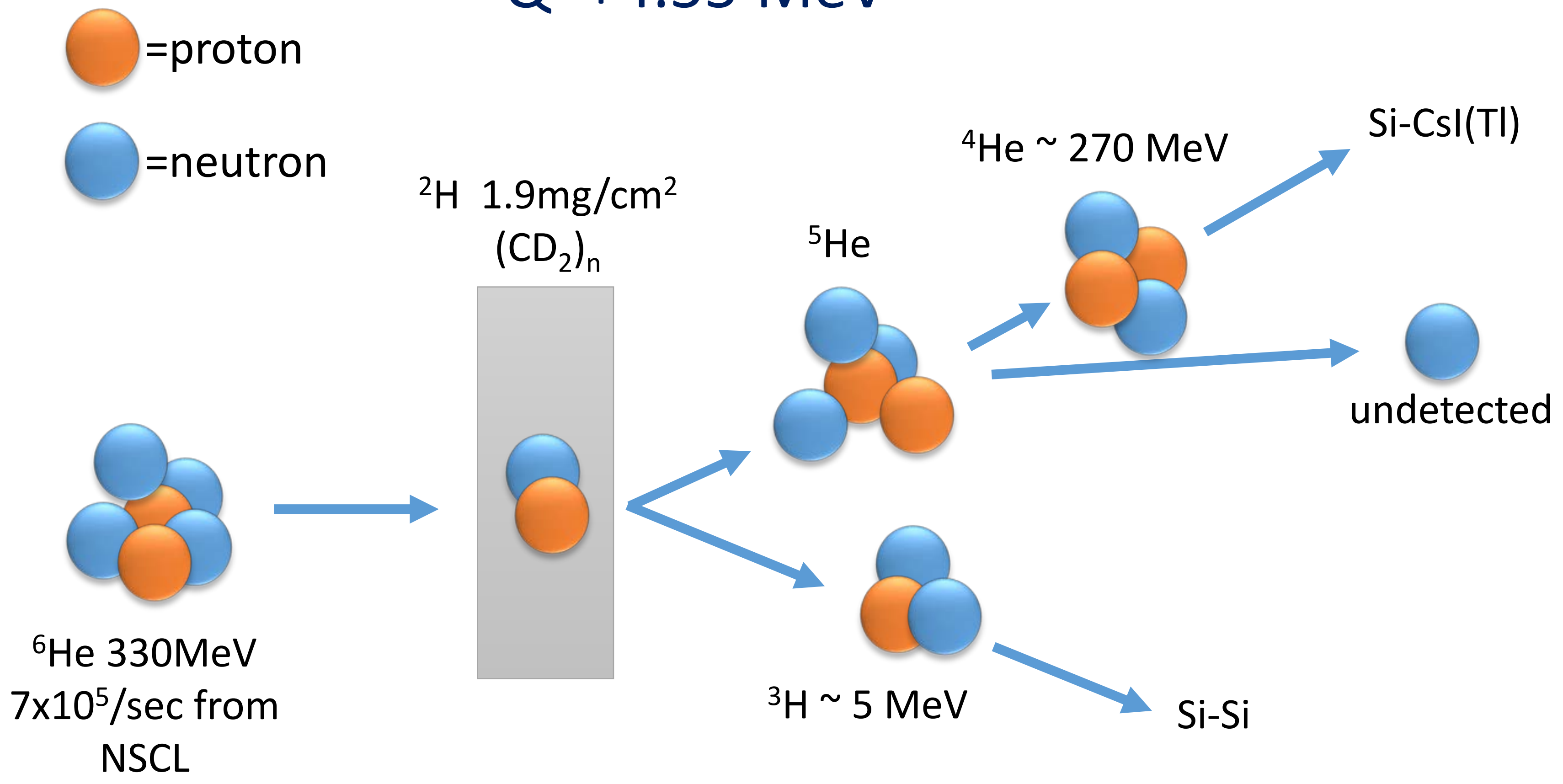


Reaction products have wide dynamic range in energy:
Requires two different types of particle-detector telescope for PID

Bombarding energy is 2.5 times higher than previous measurements

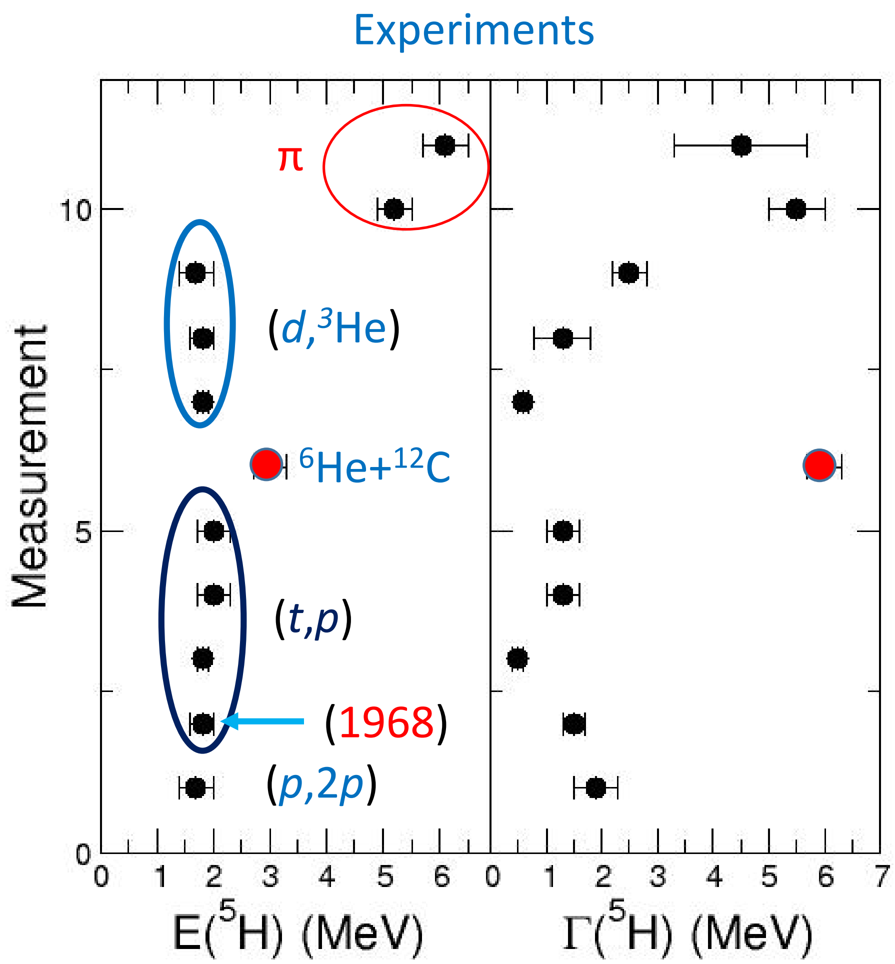
Calibration reaction: $^{6}He(d,t)^{5}He(^{4}He+n)$

Q=+4.55 MeV

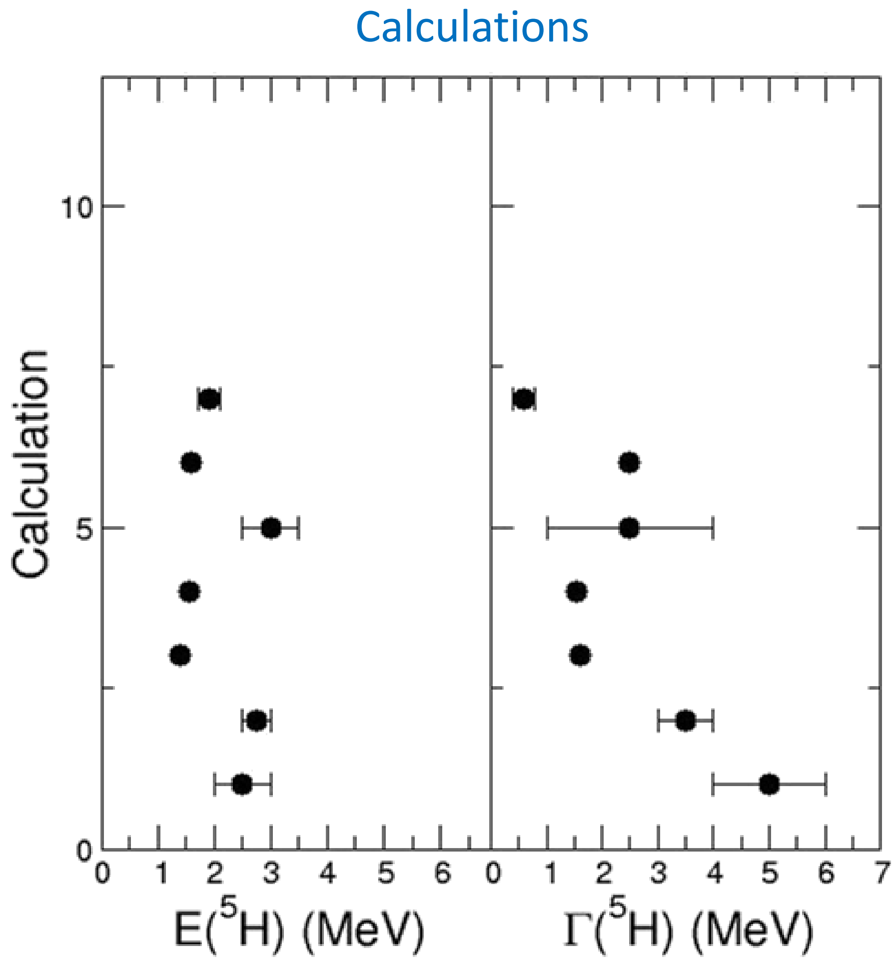


Reaction products have wide dynamic range in energy:
Requires two different types of particle-detector telescope for PID
Properties of $^{5}He_{g.s.}$ are well known.

^{5}H as a resonance: Data and Theory



More variation in measured width than energy

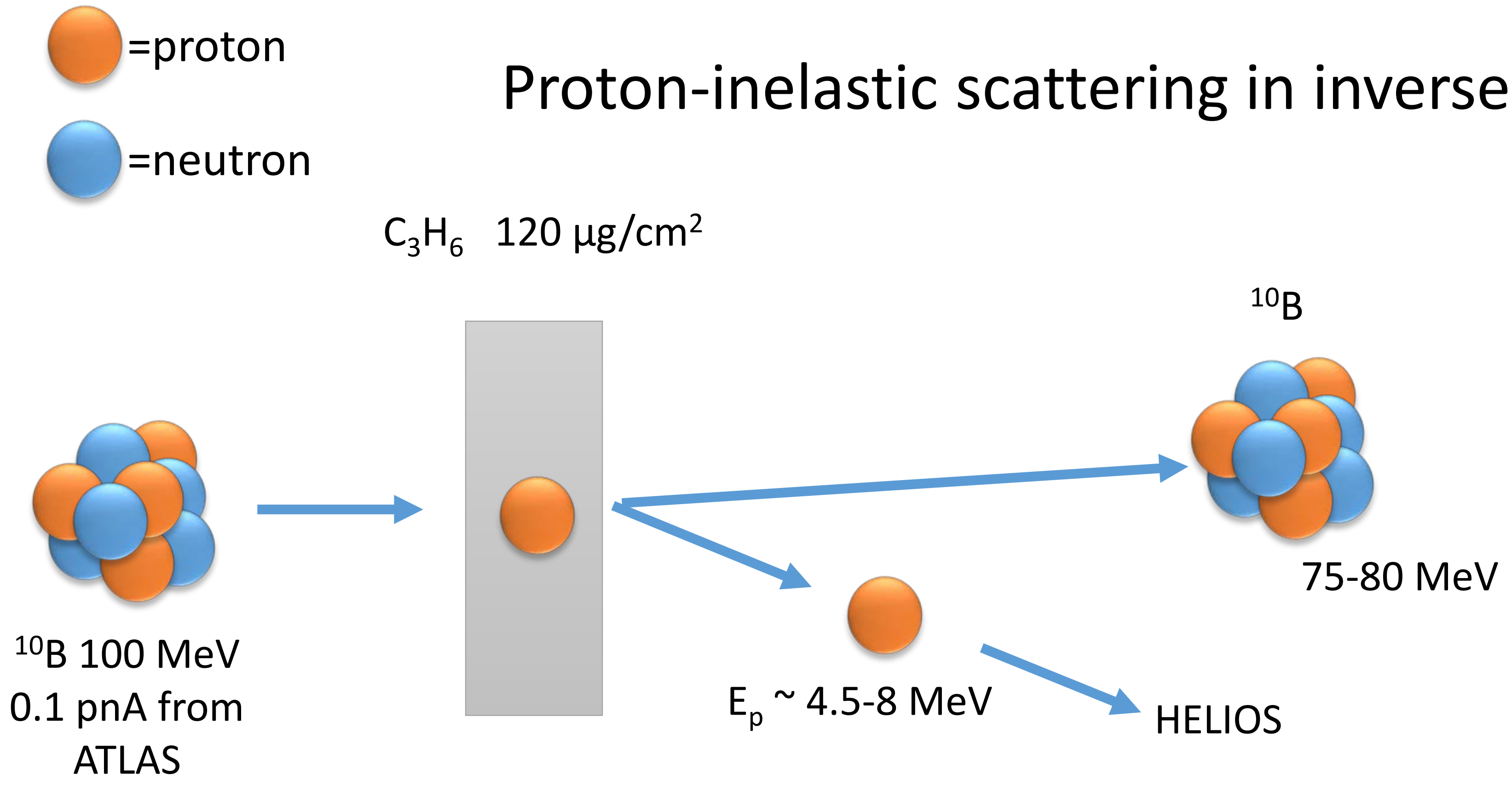


More variation in theory than data (?)

With apologies – too many references to cite

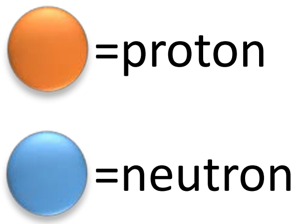
Reaction of interest: $^{10}B(p,p')^{10}B(\gamma)$

Proton-inelastic scattering in inverse kinematics

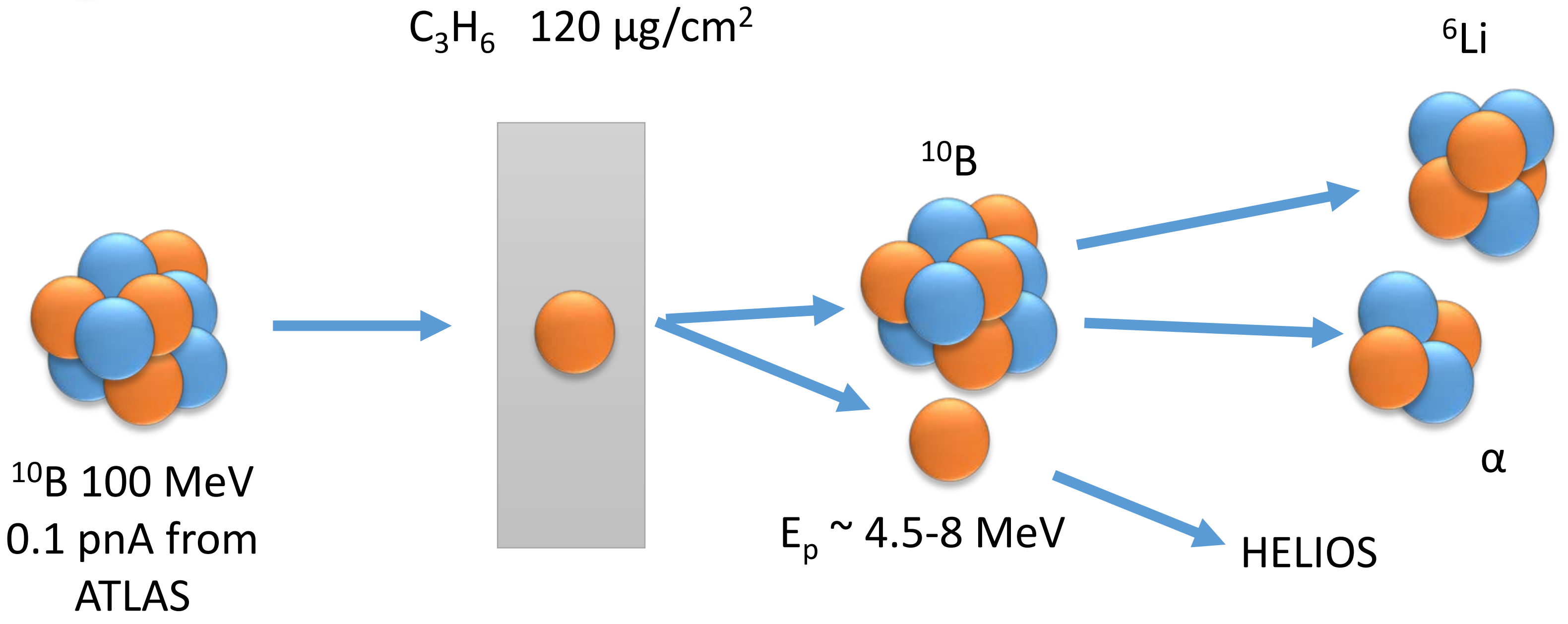


Protons detected in HELIOS; other reaction products identified in Si-Si telescopes

Reaction of interest: $^{10}B(p,p')^{10}B(\alpha+^{6}Li)$



Proton-inelastic scattering in inverse kinematics



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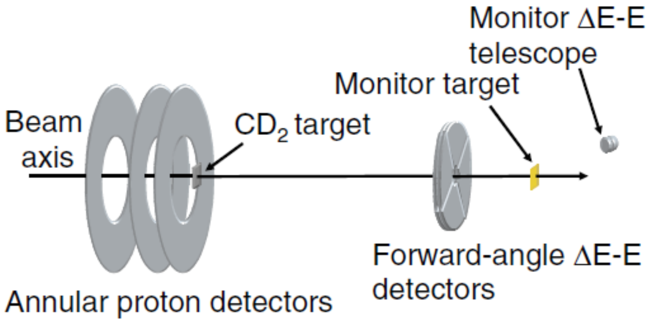
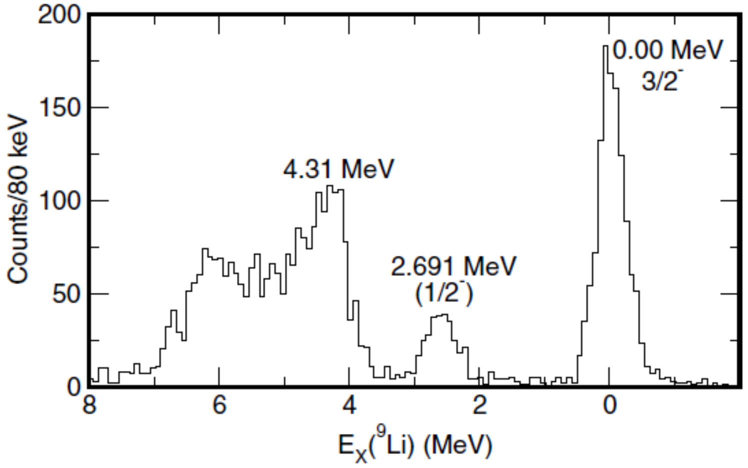
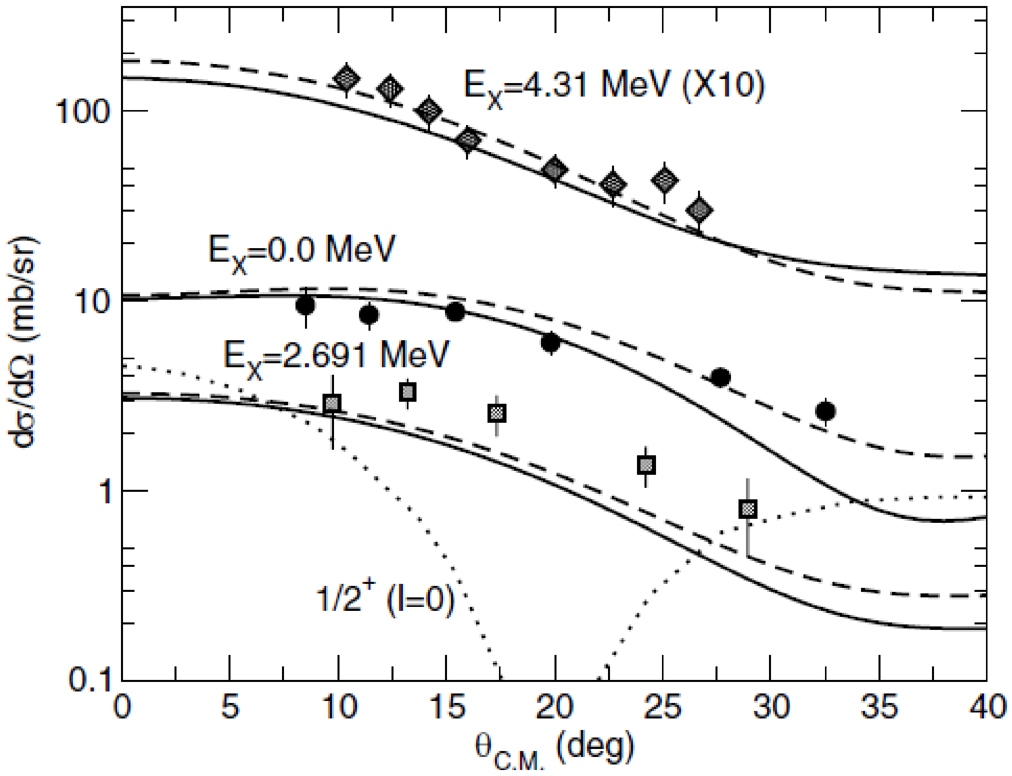
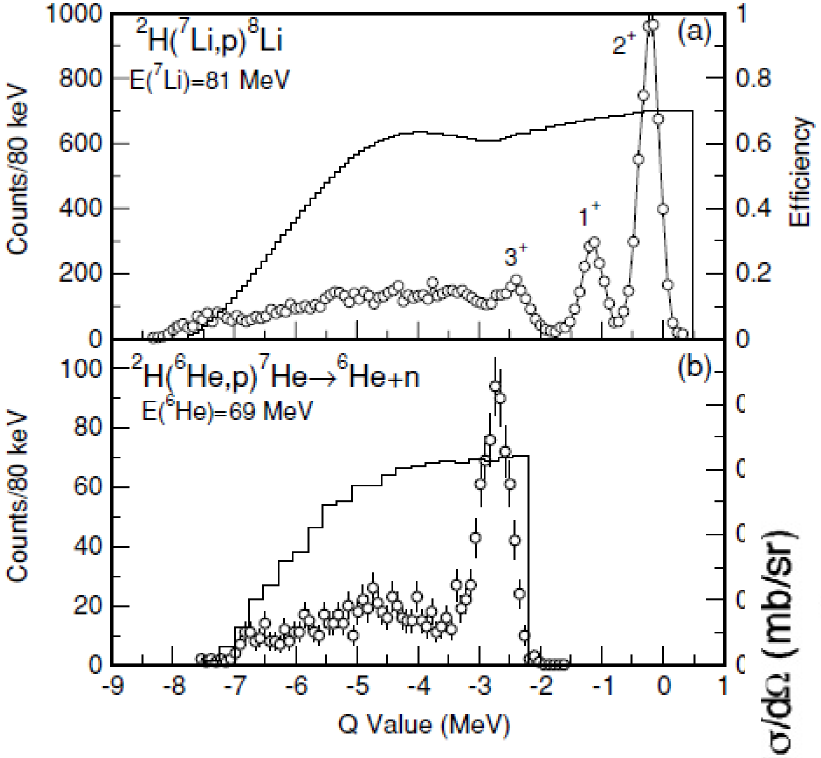
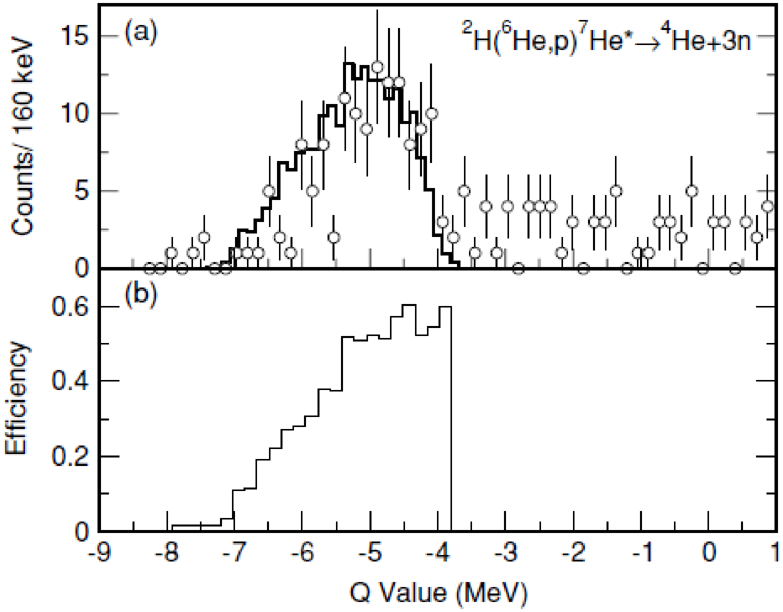

Monitor ΔE-E
telescope
Monitor target
Beam
axis
CD2 target
Forward-angle ΔE-E
detectors
Annular proton detectors


0.00 MeV
3/2-
4.31 MeV
2.691 MeV
(1/2-)
Counts/80 keV
EX(9Li) (MeV)

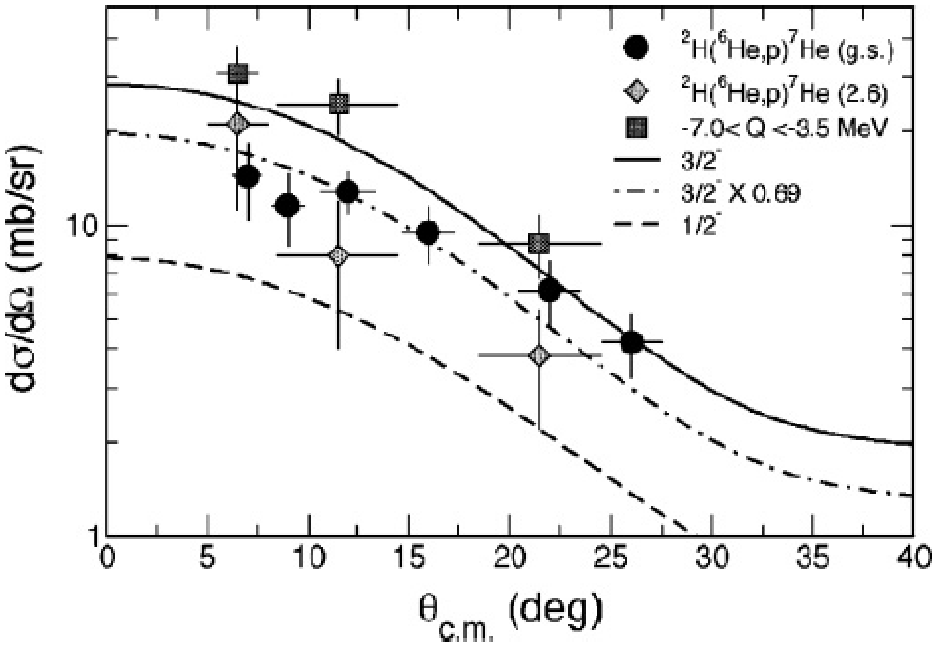

EX=4.31 MeV (X10)
EX=0.0 MeV
EX=2.691 MeV
1/2+ (l=0)
dσ/dΩ (mb/sr)
θC.M. (deg)



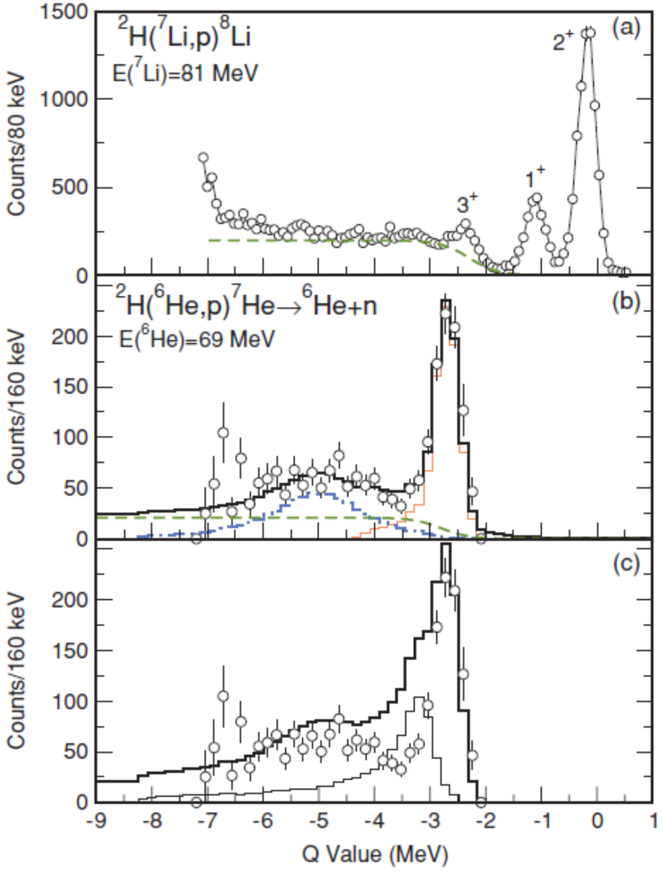
$^2H(^7Li,p)^8Li$
$E(^7Li)$=81 MeV
(a)
2^+
1^+
3^+
Counts/80 keV
Efficiency
$^2H(^6He,p)^7He \rightarrow ^6He+n$
$E(^6He)$=69 MeV
(b)
Q Value (MeV)



(a)
$^2H(^6He,p)^7He^* \rightarrow ^4He+3n$
Counts/ 160 keV
(b)
Efficiency
Q Value (MeV)



$^2H(^6He,p)^7He$ (g.s.)
$^2H(^6He,p)^7He$ (2.6)
-7.0< Q <-3.5 MeV
$3/2^-$
$3/2^-$ X 0.69
$1/2^-$
dσ/dΩ (mb/sr)
$\theta_{c.m.}$ (deg)



$^2H(^7Li,p)^8Li$
$E(^7Li)$=81 MeV
(a)
2^+
1^+
3^+
Counts/80 keV
$^2H(^6He,p)^7He \rightarrow ^6He+n$
$E(^6He)$=69 MeV
(b)
Counts/160 keV
(c)
Counts/160 keV
Q Value (MeV)

Where there are challenges

- T_Z dependence of EM transition matrix elements; Focus on $2^+ \rightarrow 0^+$ transitions in the T=1, A=10 triplet
  - What works, and what doesn't?
  - What aspects are most important? (3BF and different symmetry components)
  - ^{10}B
- The continuum (unbound systems, scattering states)
  - What can we learn about or from (very) unbound systems?
  - What are the limitations and (how) can they be surpassed?
  - How can we learn more?
  - $^{6}He/^{5}H$