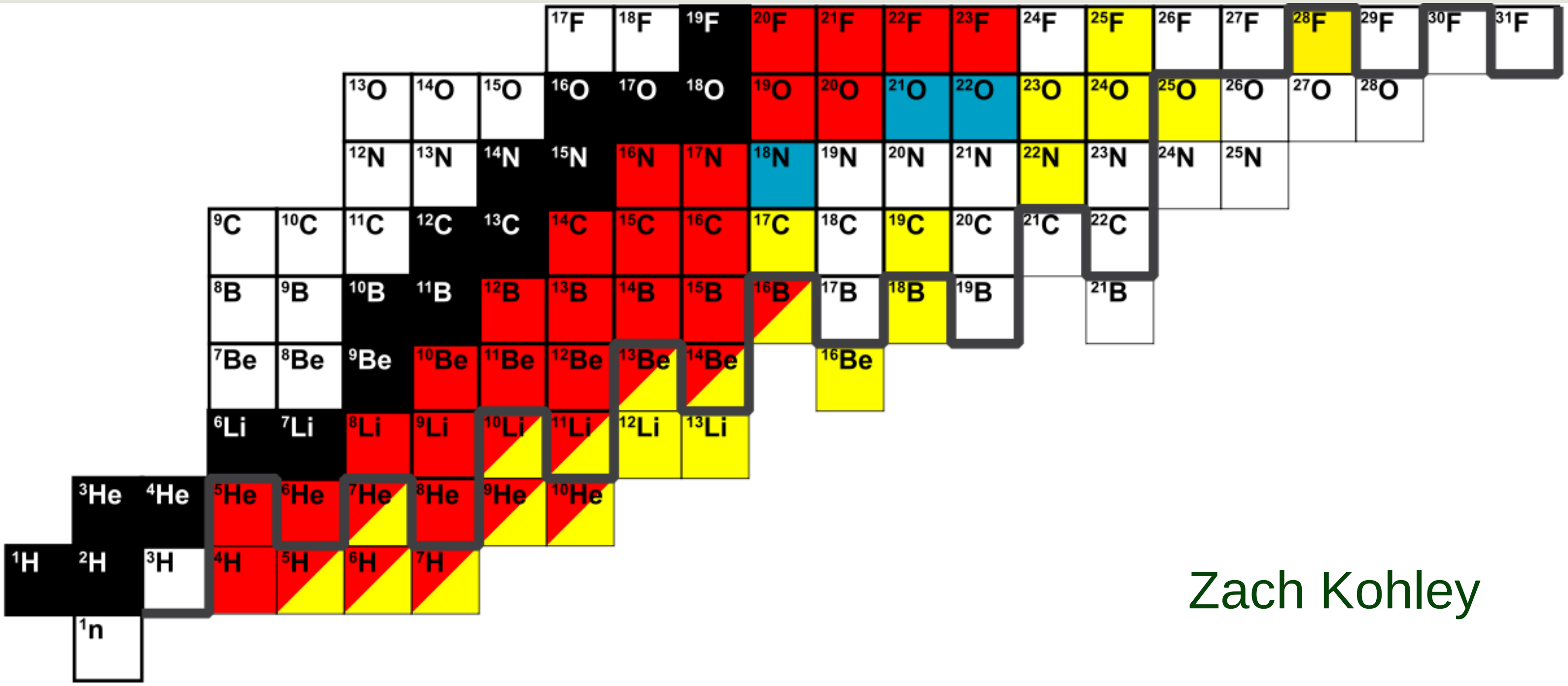
Structure and decay of neutron unbound systems
(a trip along the dripline)

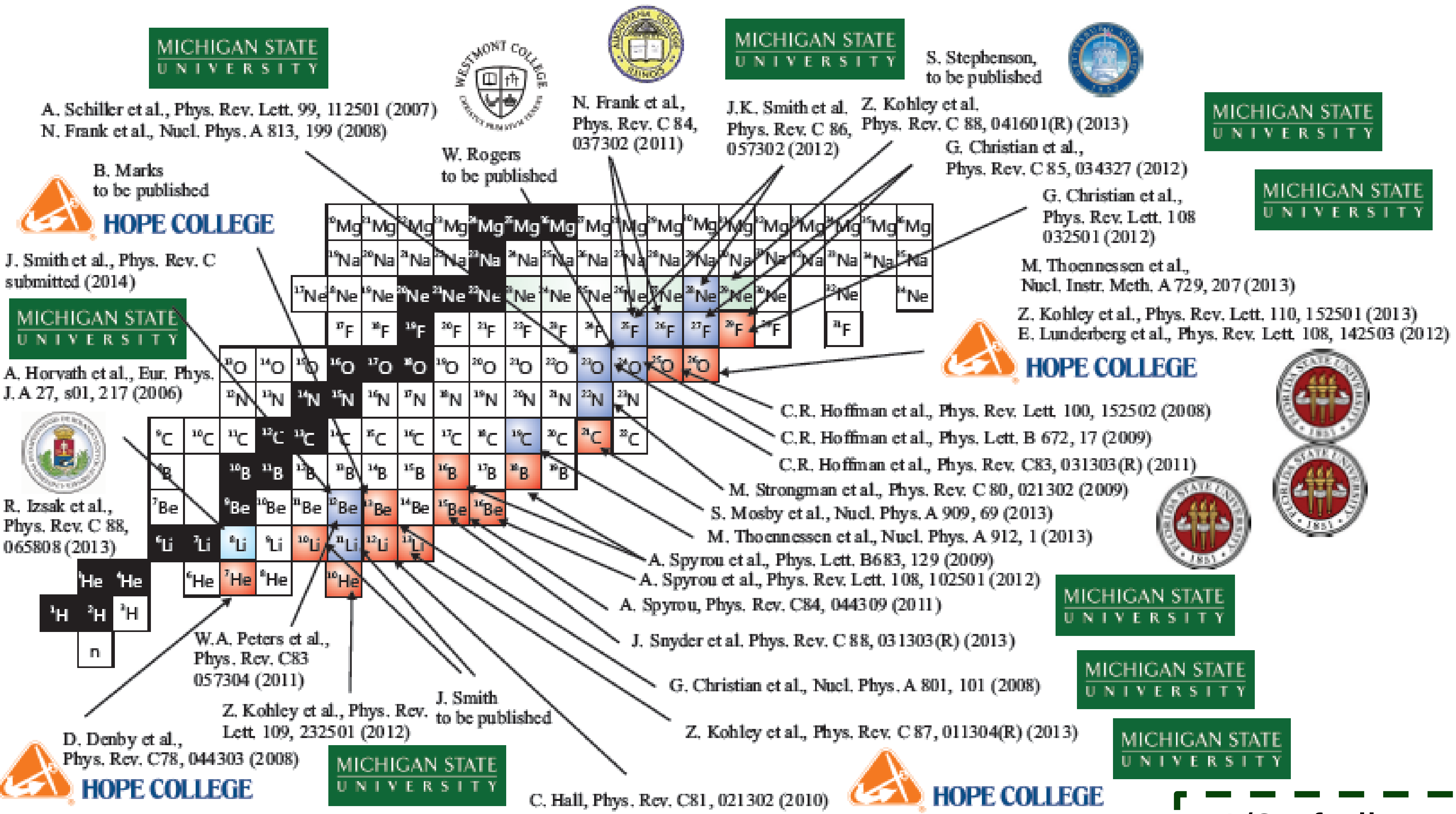


Zach Kohley

MoNA Collaboration
National Superconducting Cyclotron Laboratory
Michigan State University, E. Lansing, MI

International Collaborations in Nuclear Theory:
Theory for open-shell nuclei near the limits of stability
May 19, 2015

10 Years of MoNA

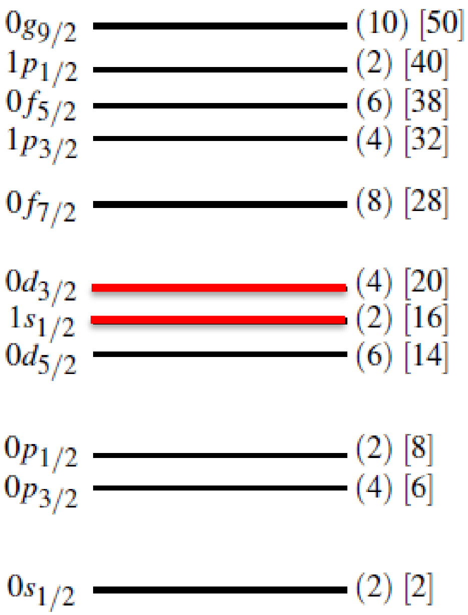


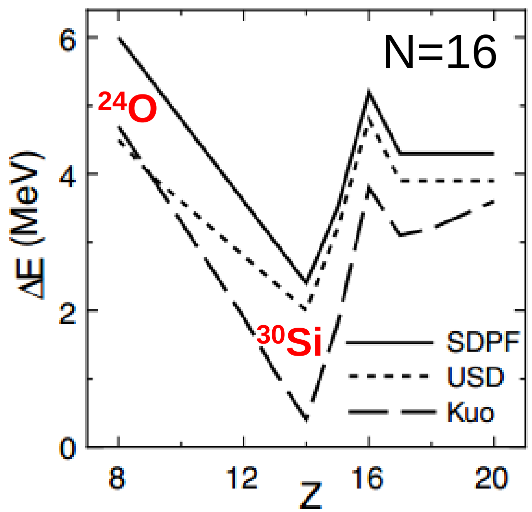
>1/3 of all unbound nuclei discovered by MoNA Collab.

Motivation

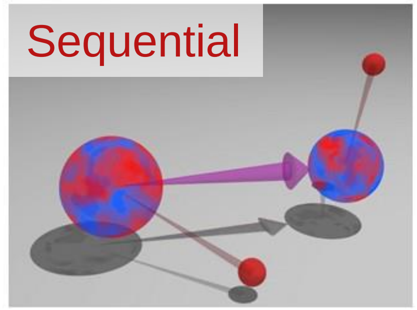
Explore nuclear structure at extreme neutron-to-proton ratios. (Evolution of Shell Model)

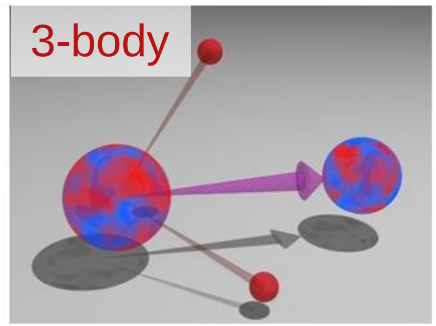
Connecting 3-body decay correlations to nuclear structure

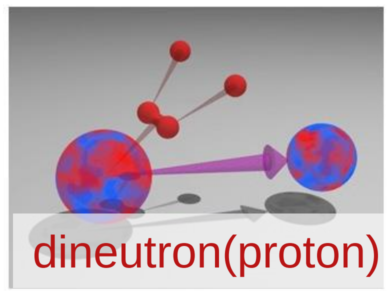




Otsuka *et al.* PRL. **87,** 082502 (2001).

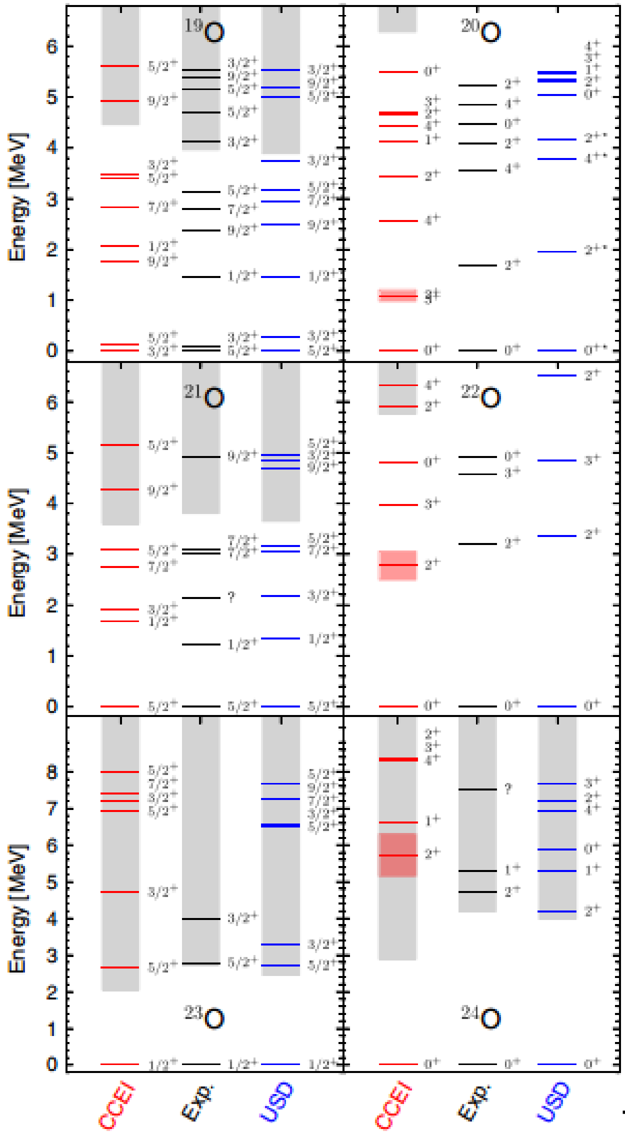






http://www.cenbg.in2p3.fr/desir/Beta-delayed-charged-particle

Motivation



Exciting agreement with experiments!

Calculations for continuum systems strongly desired to help guide us in experiments.

Jansen et al. PRL (2014)

Outline

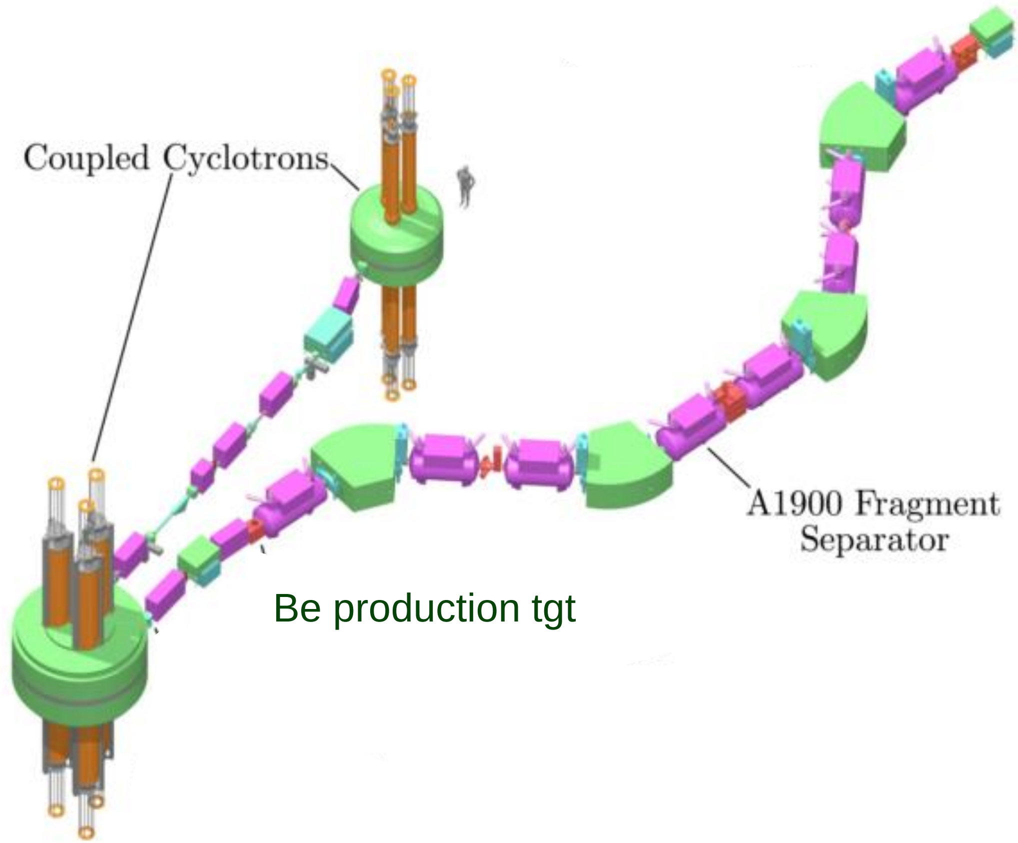
Stuff we really want theorists to calculate accurately

Discussion topics

Questions in pink!

- Confusion in ^{9}He and ^{10}He
- Level str
- zzle
- Evidence for 2n radioactivity (^{26}O)
- 3-body correlations (^{13}Li, ^{16}Be, ^{26}O)
- Nitrogen Request [^{23}N*, ^{24}N(g.s.)]

Experiments @ NSCL



82 MeV/u ^{27}F
15 pps

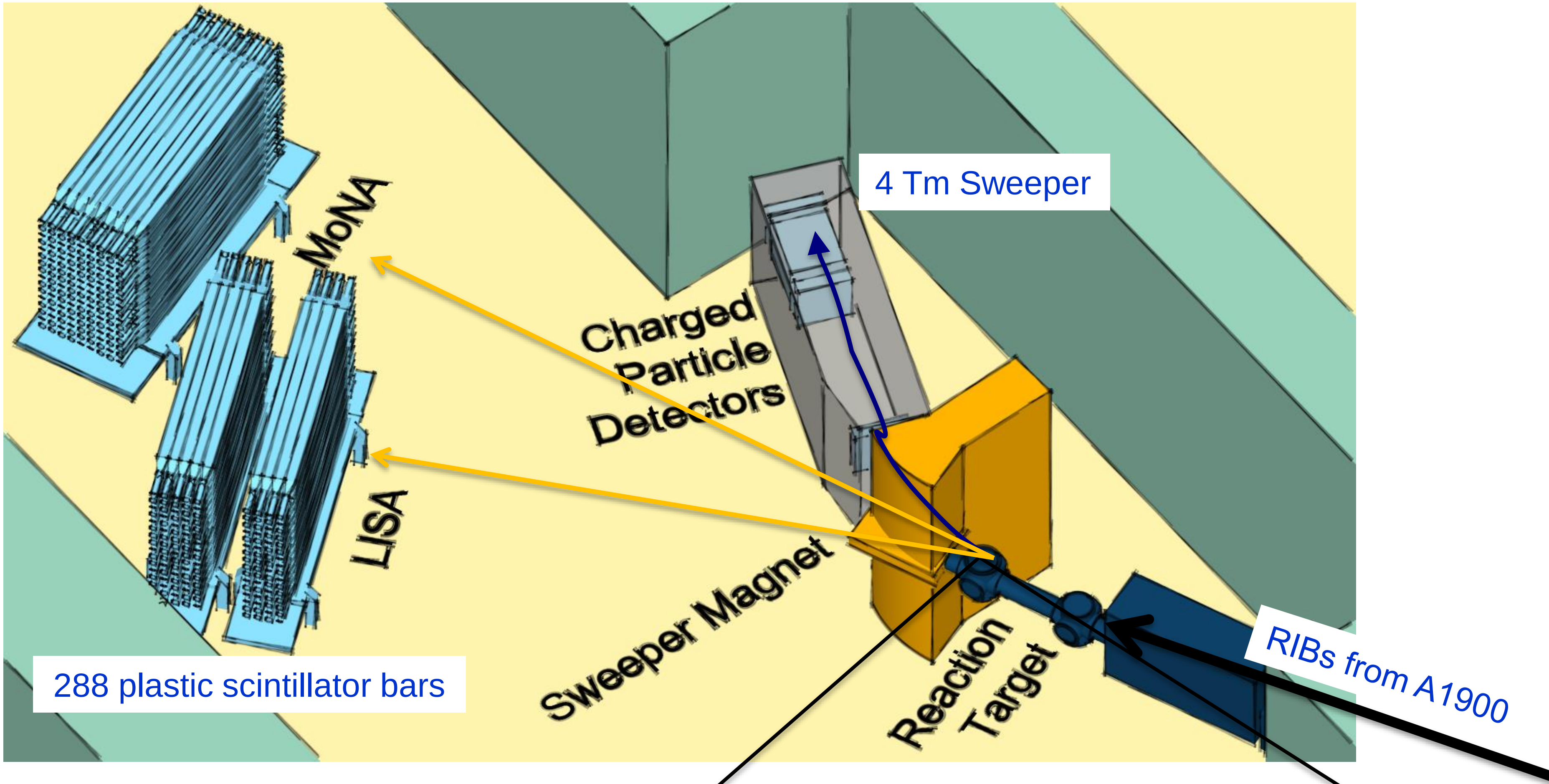
Be production tgt

140 MeV/u ^{48}Ca

	^{26}O	^{16}Be	^{13}Li	^{10}He
Primary Beam	^{48}Ca	^{22}Ne	^{18}O	^{18}O
Secondary Beam	^{27}F	^{17}B	^{14}Be	^{14}Be
Beam Rate (pps)	15	250	500	700

MoNA-LISA-Sweeper

Example: ^{26}O experiment



Reaction:

$^{27}F(-p) \rightarrow {}^{26}O \rightarrow {}^{24}O + n + n$

Measure complete kinematics of reaction
Invariant Mass Spectroscopy

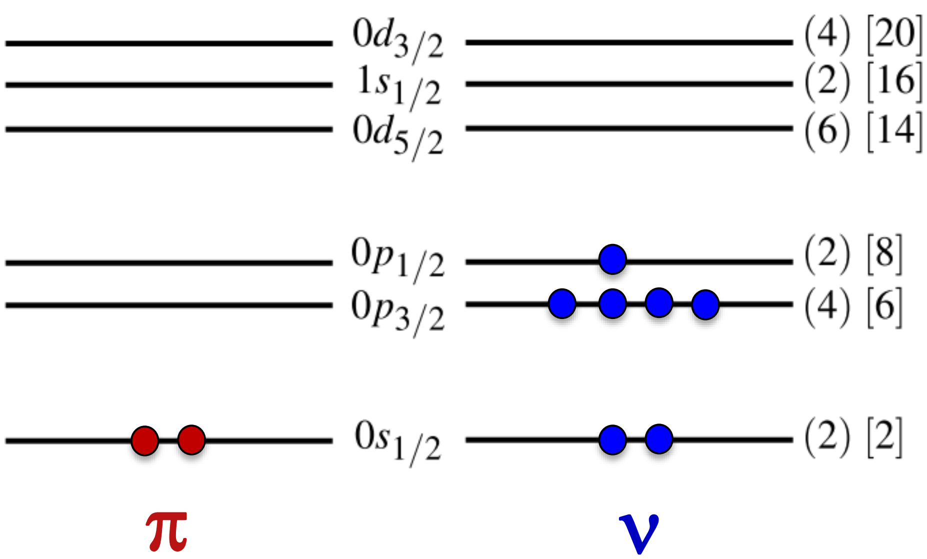
MoNA-LISA-Sweeper

Let's break it down to what you care about.
What can we measure:

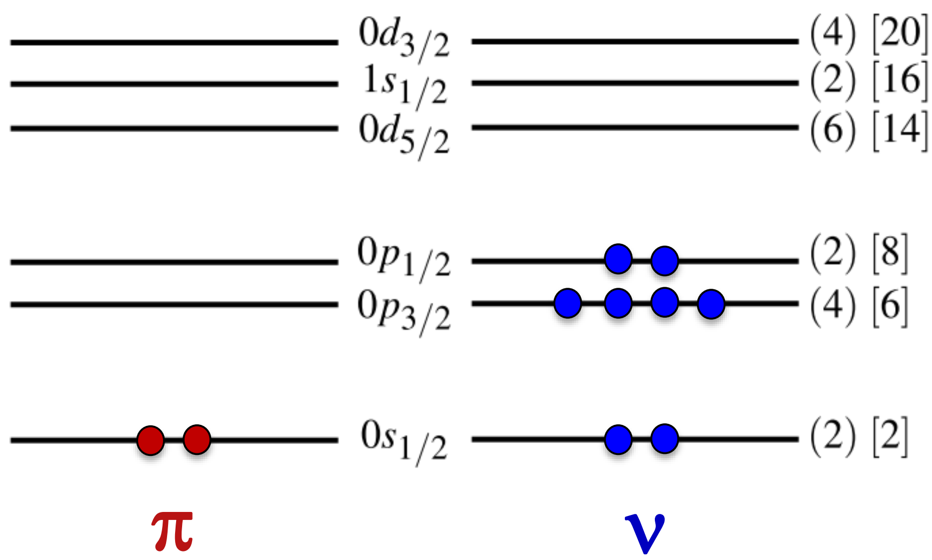
- Resonance energy of unbound states
- Extract the width, Γ, of the resonance (or a limit)
- From 2n decay, we can extract 3-body correlations
- We, generally, cannot provide insight into spin-parity

^{9}He and ^{10}He

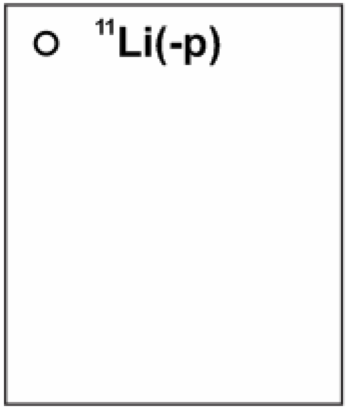
Explore the N=7 chain

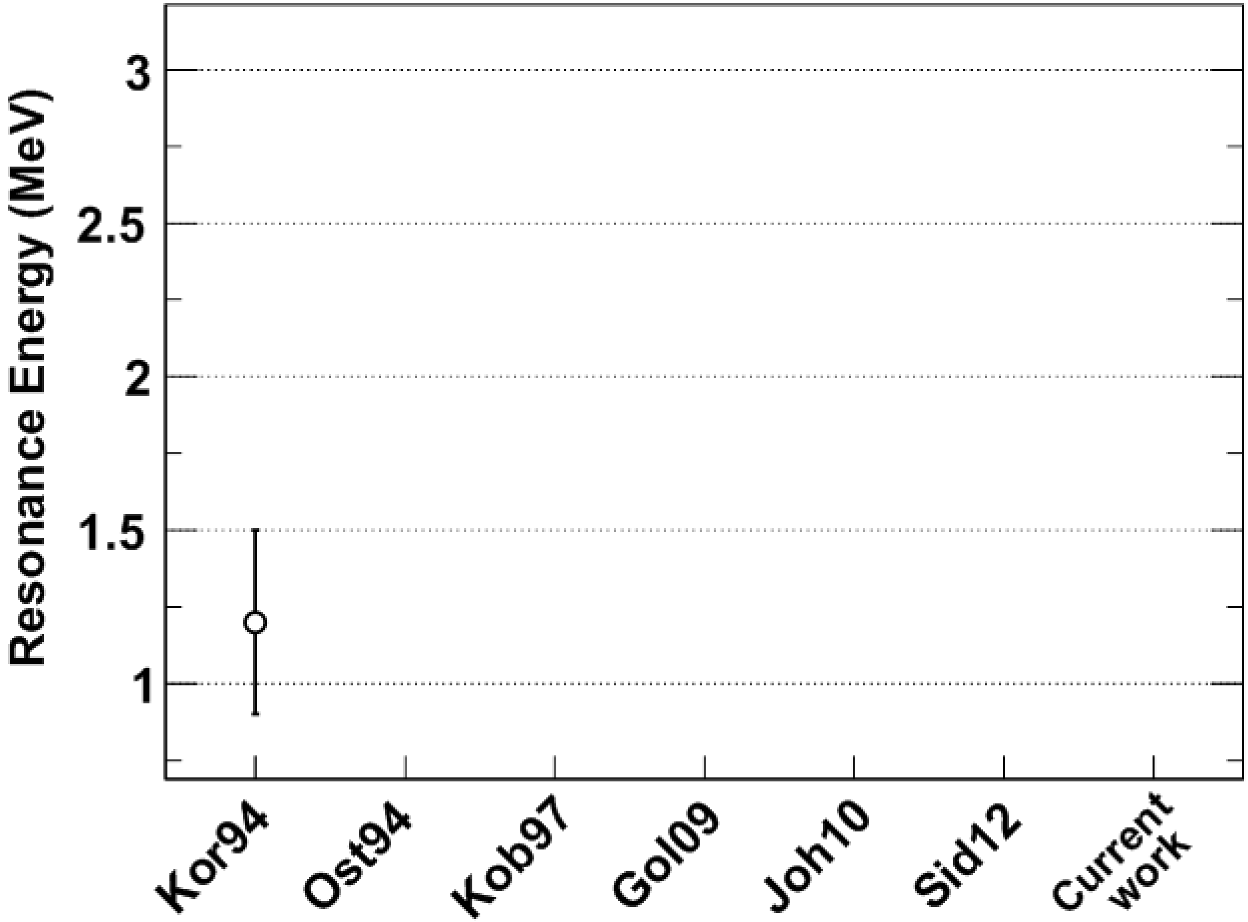


Doubly magic?
Z=2 and N=8

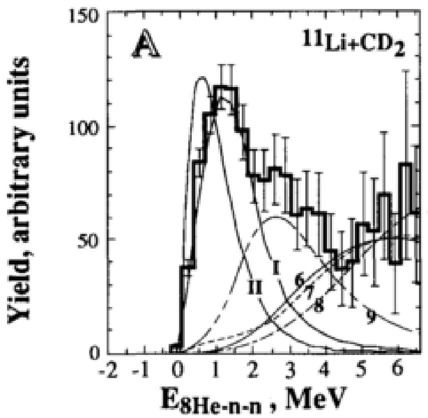


Background Story – ^{10}He



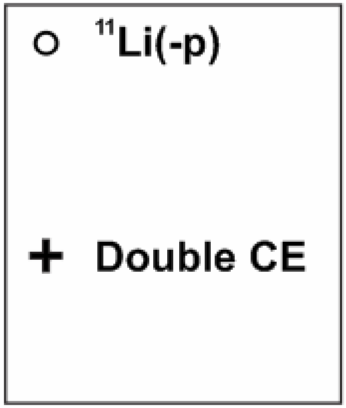


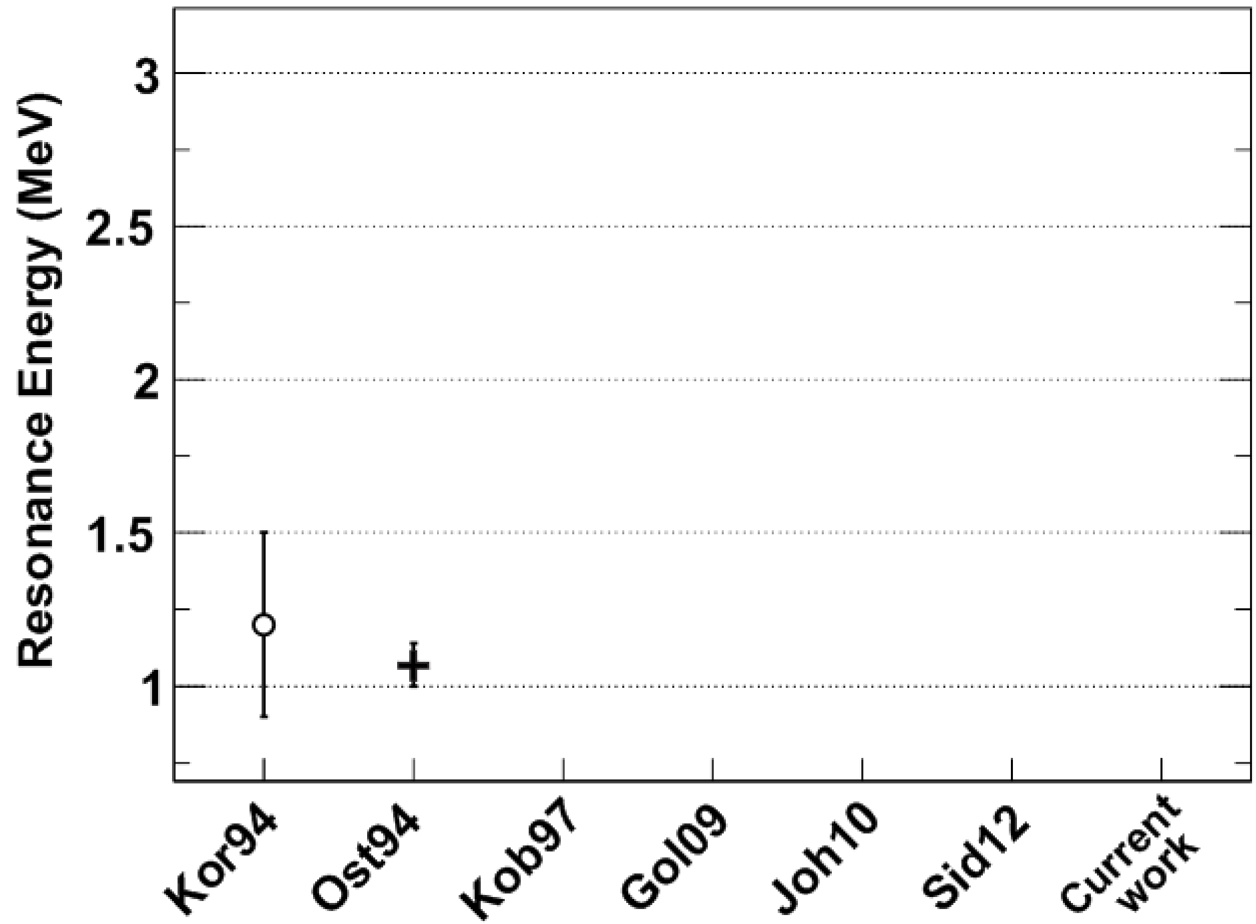
E_r = 1.2(3) MeV



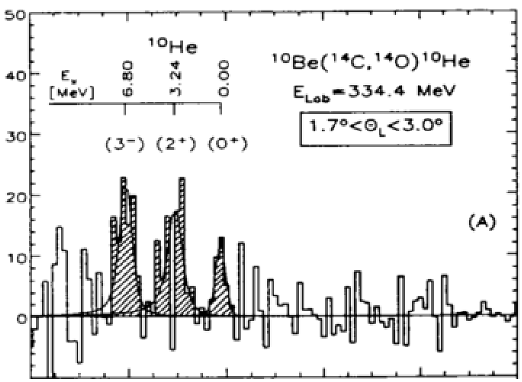
Korsheninnikov et al.,
PLB **326**, 31 (1994)

Background Story – ^{10}He



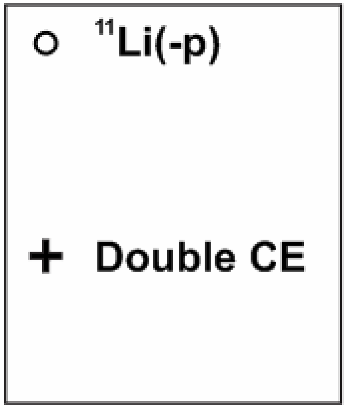


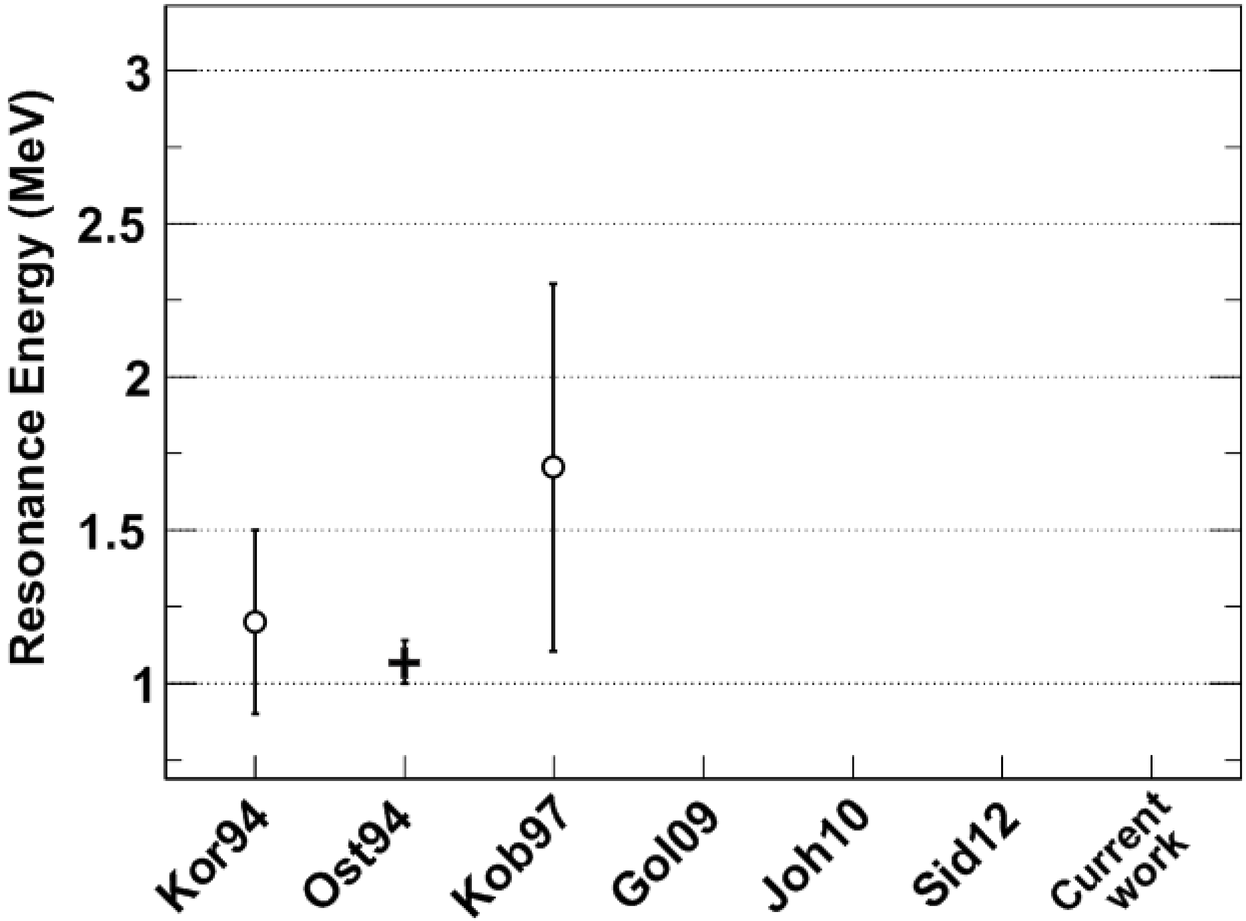
E_r = 1.07(7) MeV



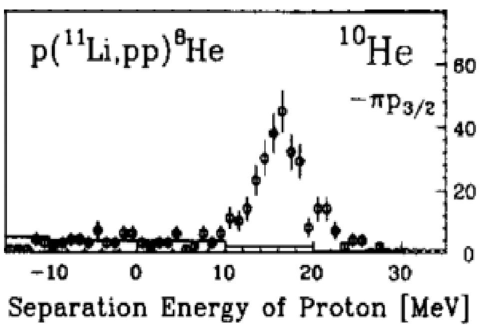
Ostrowski et al.,
PLB **338**, 13 (1994)

Background Story – ^{10}He



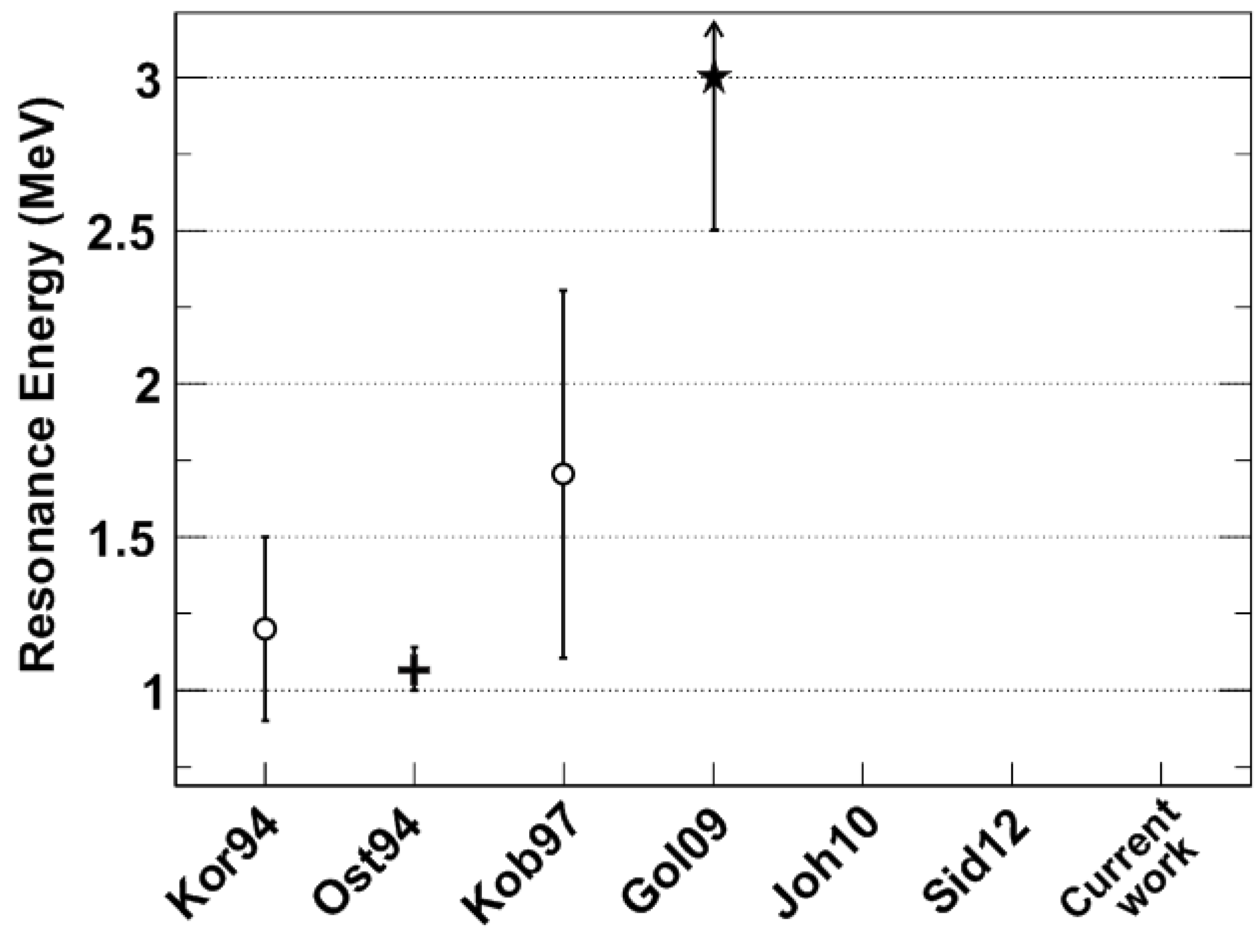


E_r = 1.7(6) MeV



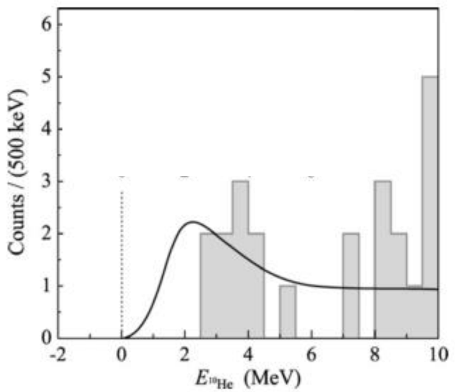
Kobayashi et al.,
NPA **616**, 223c (1997)

Background Story – ^{10}He



E_r = ~3 MeV

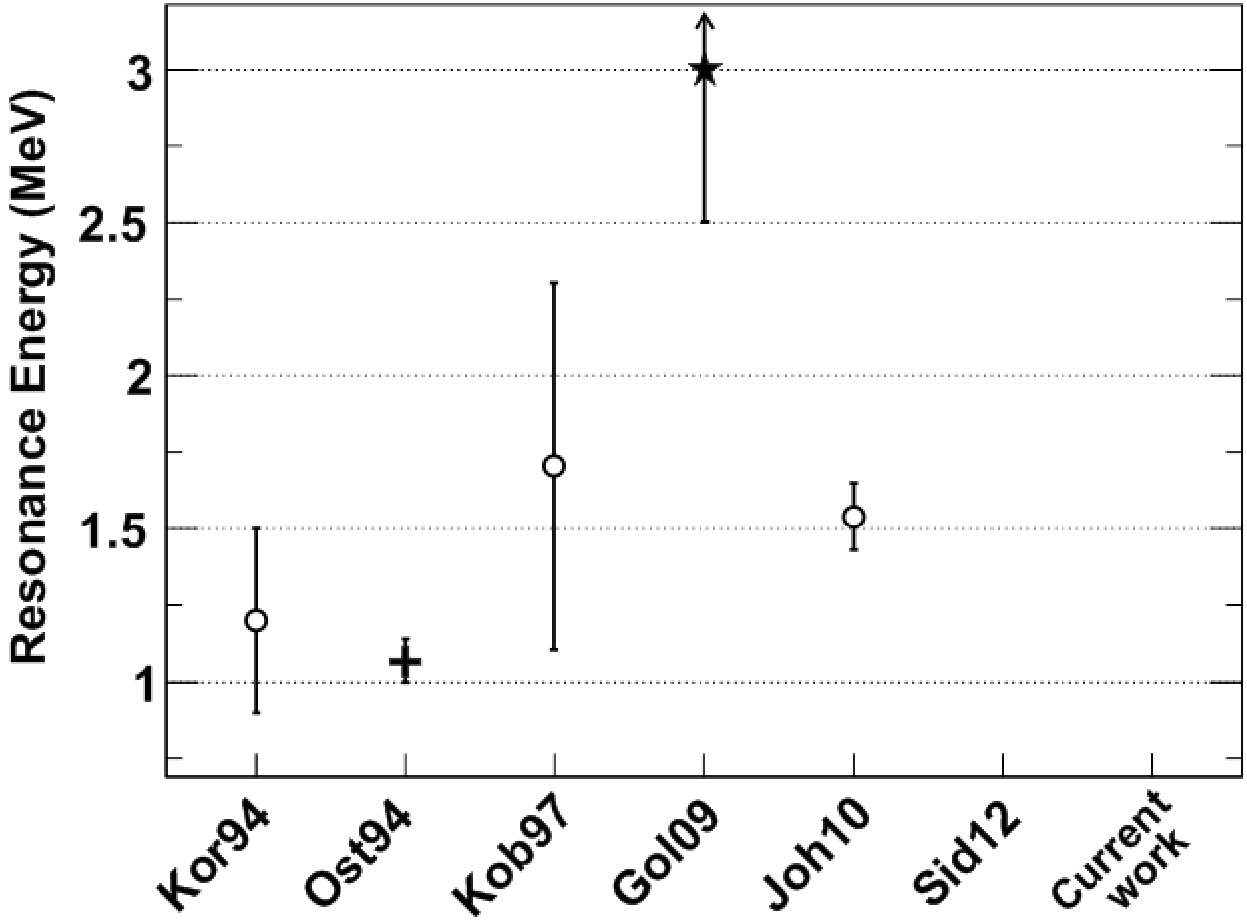
$^{3}H(^{8}He,p)^{10}He$



Golkov, et al. PLB **672,** 22 (2009).

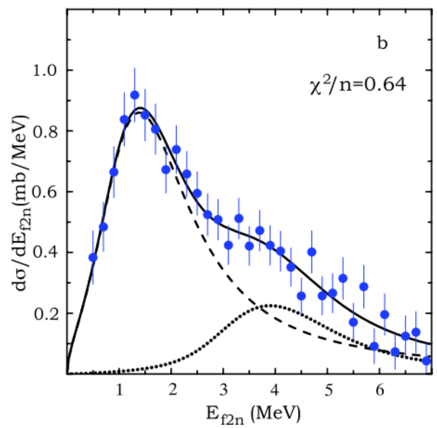
Very low statistics (~6-7 cnts)

Background Story – ^{10}He



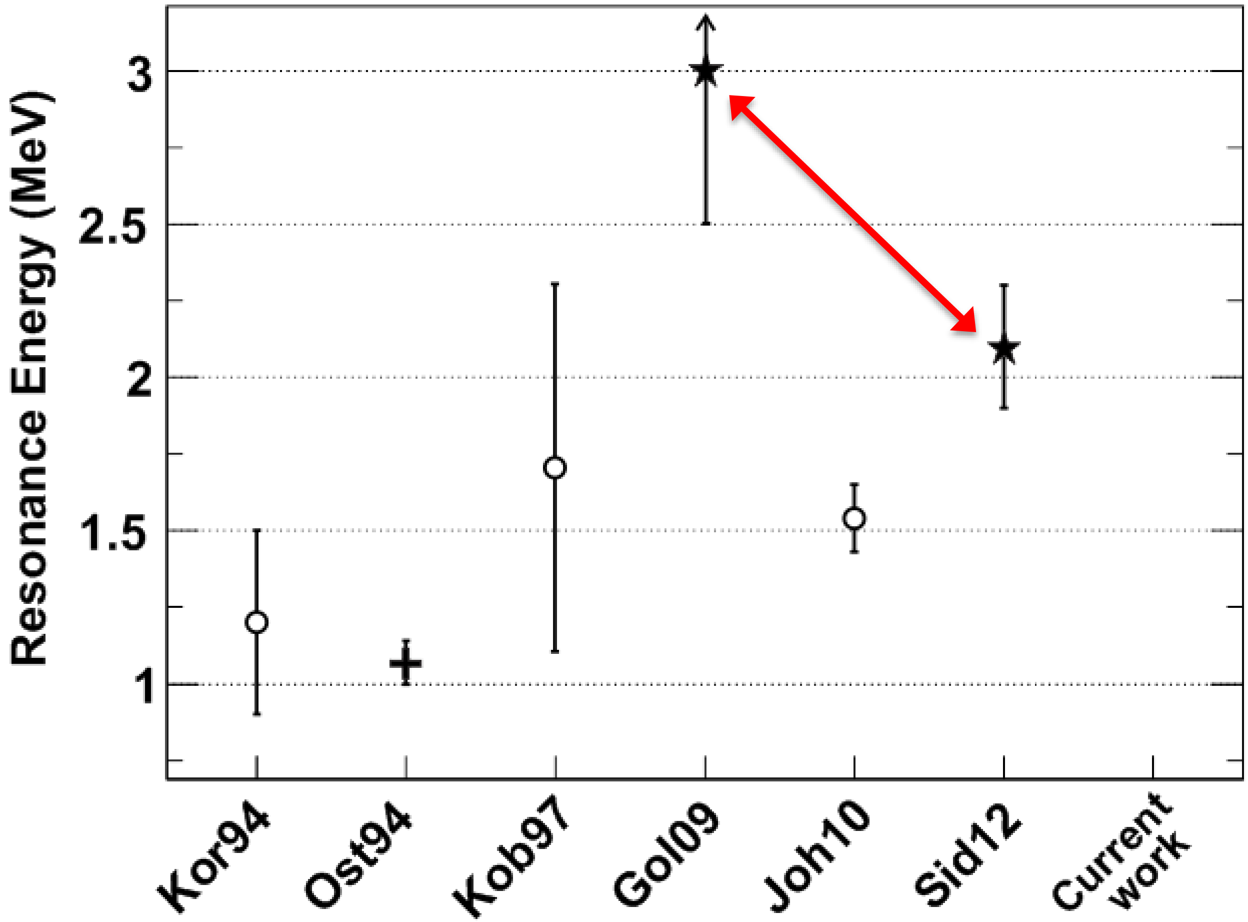
E_r = 1.54(11) MeV

^{11}Li(-p) → ^{10}He

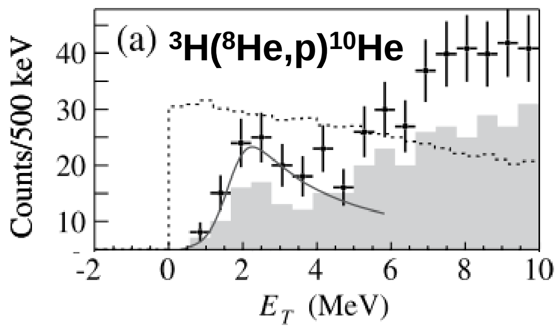


Johansson et al., NPA **842**, 15 (2010)

Background Story – ^{10}He



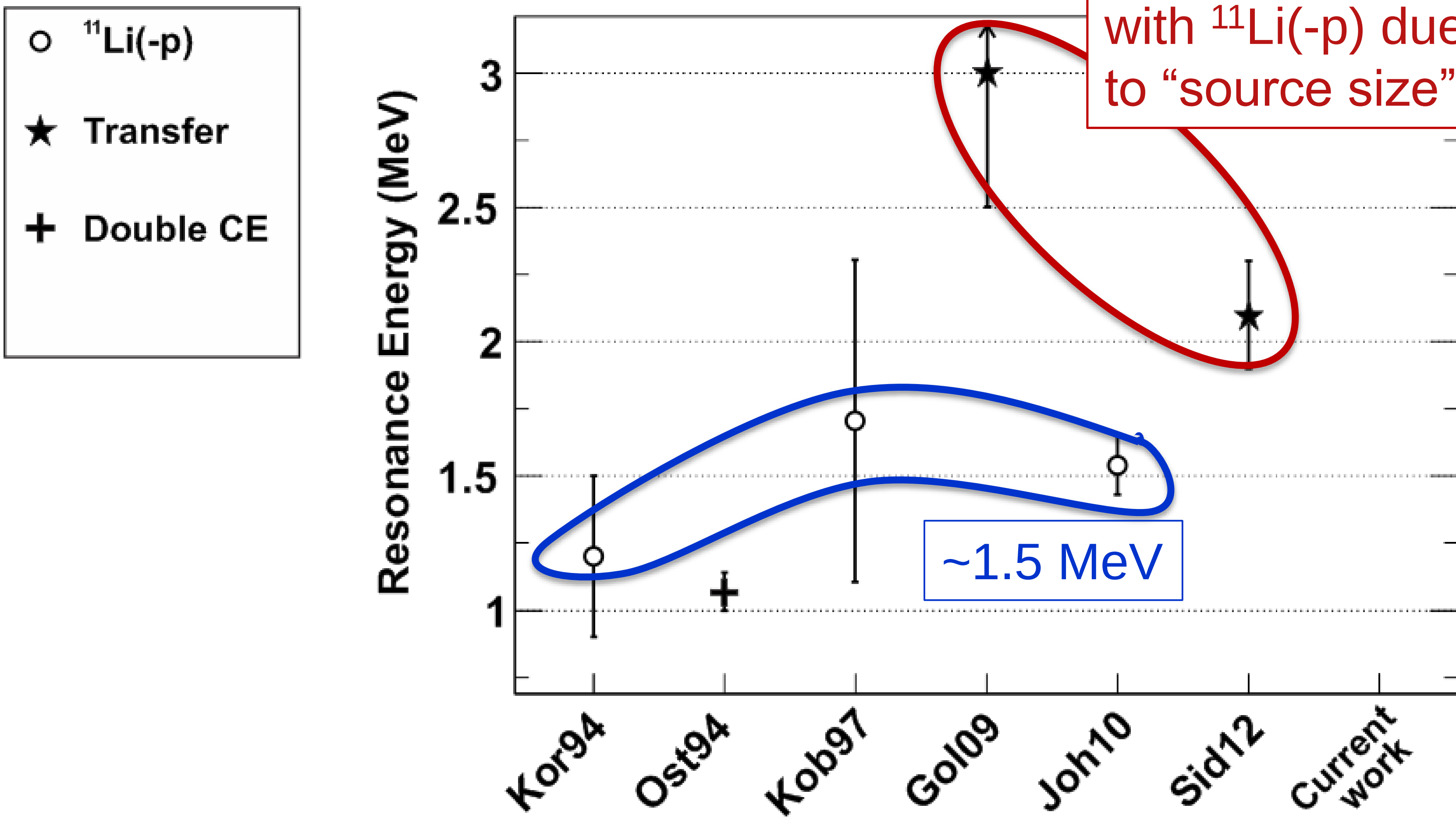
E_r = 2.1(2)MeV



Sidorchuk, et al.
PRL **108,** 202502 (2012).

Repeat of Gol09

Background Story



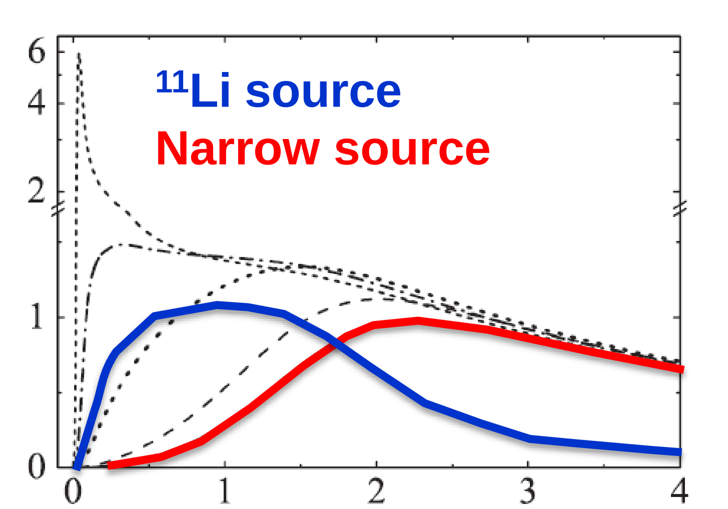
Results agree with ^{11}Li(-p) due to "source size"

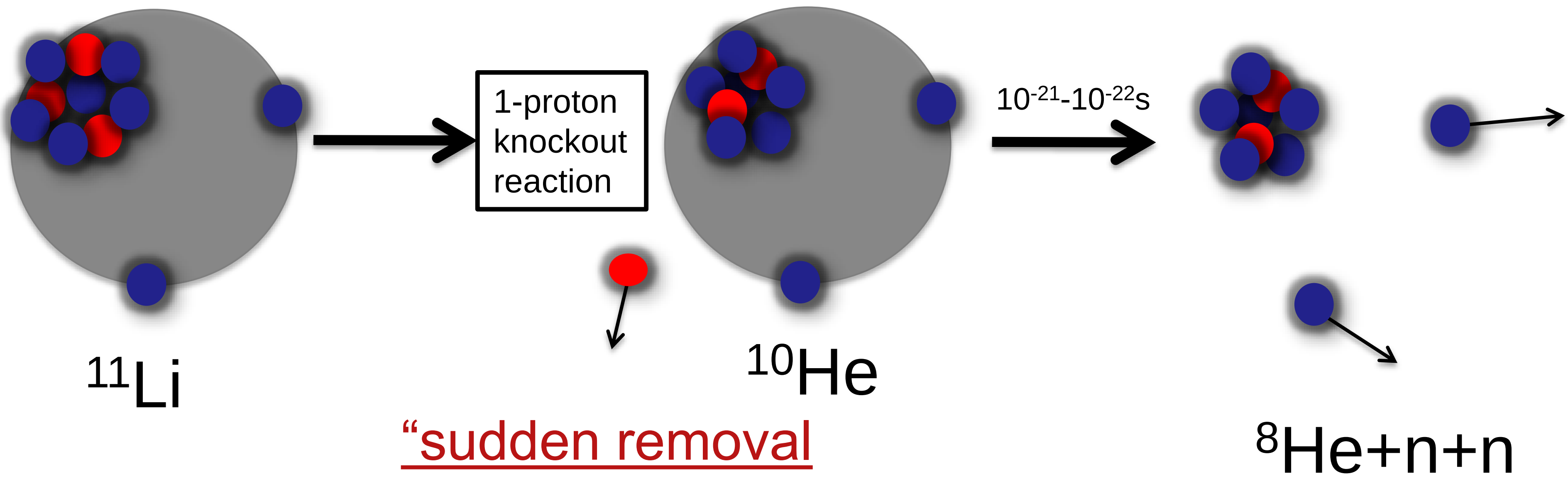
Source size effect

PHYSICAL REVIEW C **77**, 034611 (2008)

Problems with the interpretation of the ^{10}He ground state

L. V. Grigorenko[1,2,3] and M. V. Zhukov[4]
[1]*Flerov Laboratory of Nuclear Reactions, JINR, RU-141980 Dubna, Russia*
[2]*Gesellschaft für Schwerionenforschung mbH, Planckstrasse 1, D-64291, Darmstadt, Germany*
[3]*RRC "The Kurchatov Institute", Kurchatov sq. 1, RU-123182 Moscow, Russia*
[4]*Fundamental Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden*
(Received 28 September 2007; revised manuscript received 1 January 2008; published 27 March 2008)





<u>"sudden removal approximation"</u>

Results

χ^2 minimization

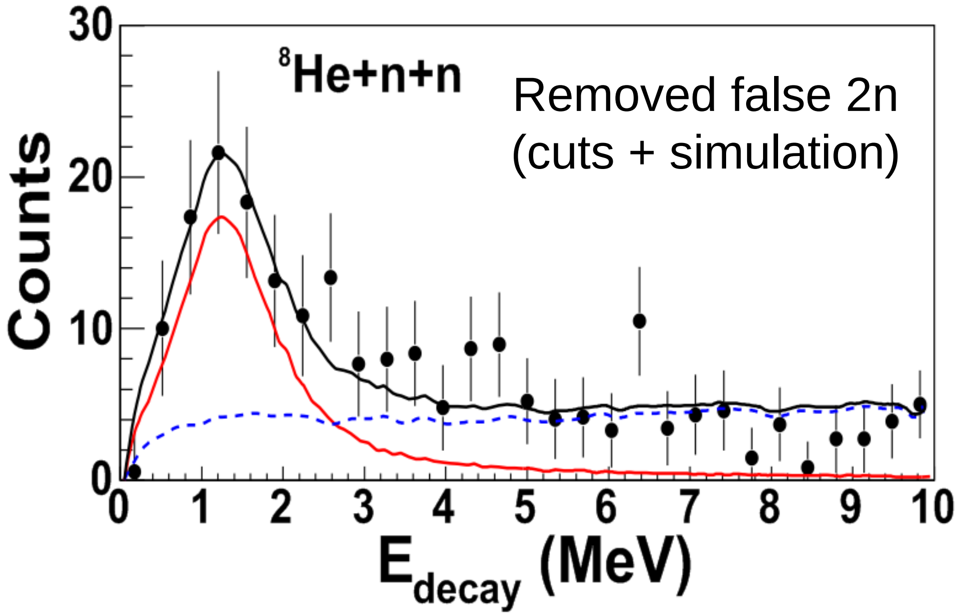
^{10}He ground state resonance
E_r = 1.60(25) MeV
Γ_r = 1.8(4) MeV

T = 4 MeV thermal bckgrd.

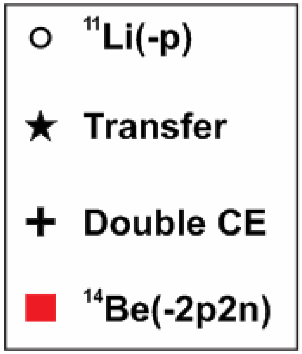
Systematic error estimated from varying background function(s).

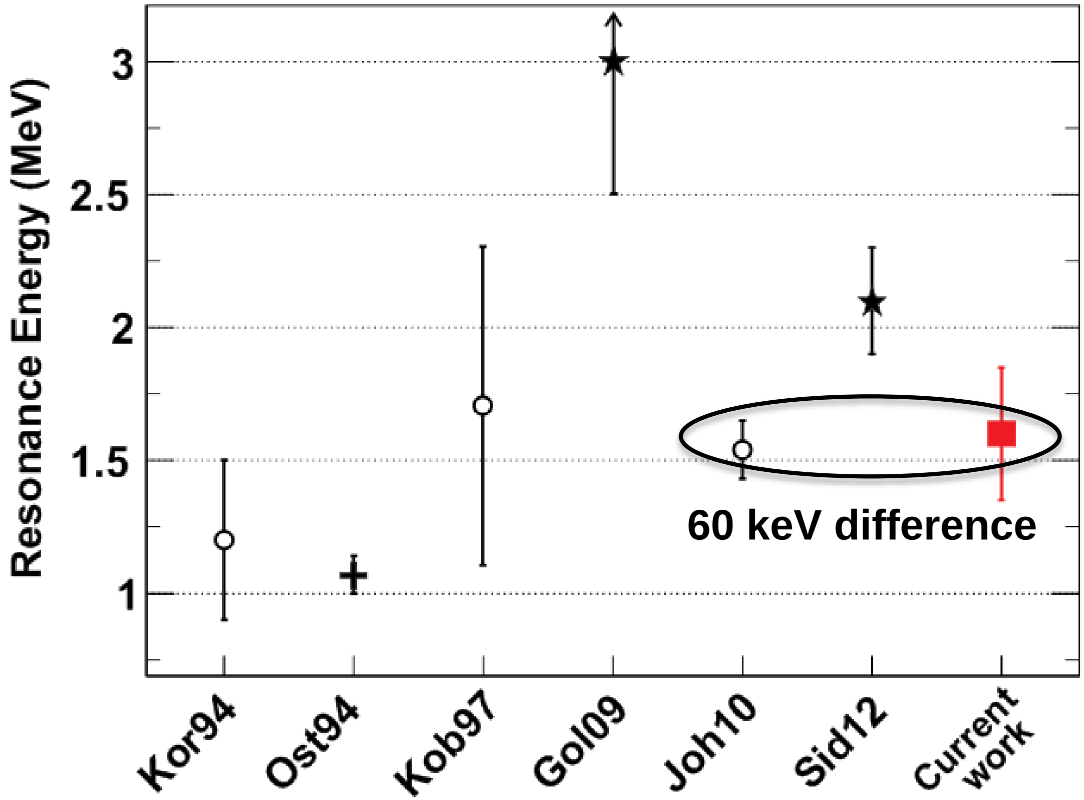
Need to test the "consistency" of the ^{11}Li and transfer reactions.

Use a new reaction mechanism ^{14}Be(-2p2n)



Results





-^{10}He ground state measured at E = 1.60(25) MeV.

-Excellent agreement with GSI ^{11}Li(-p) appears to invalidate the “shift” theory.

- Discrepancy remains with the transfer reaction results.

But…..

Results

Recent calculations indicate that the “shift” may also be expected from the ^{14}Be “source size” in α alpha-knockout rxn.

Crucial to verify or disprove this theory.

Has implications for many studies of neutron unbound systems.

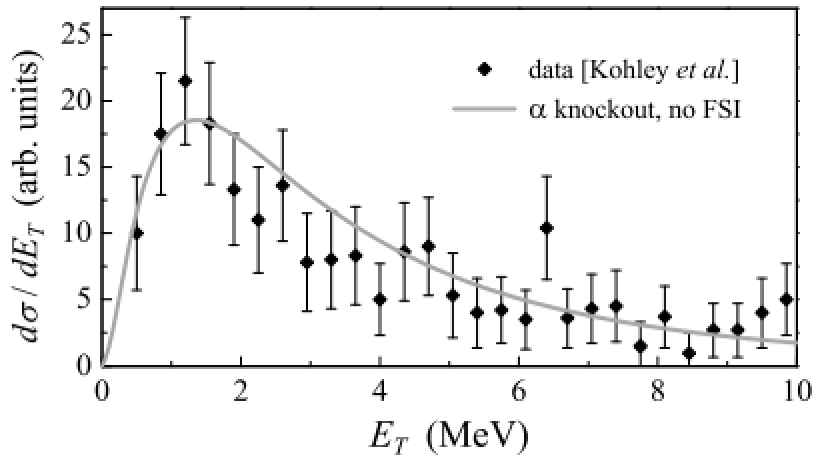


FIG. 13. “No FSI” estimate for the ^{10}He spectrum populated in α knockout from ^{14}Be. The $q = 100$ MeV/c value is selected.

Sharov, Egorova, and Grigorenko. PRC 90, 24610 (2014)

Comparison of theory and experiment from 2p decay “verifies” prediction….

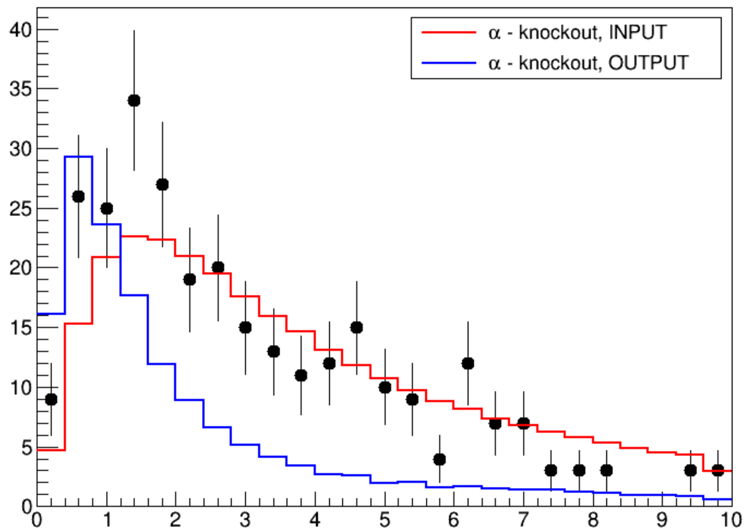
PHYSICAL REVIEW C **86**, 061602(R) (2012)

Sensitivity of three-body decays to the reactions mechanism and the initial structure by example of ^{6}Be

L. V. Grigorenko,[1,2,3] I. A. Egorova,[4] R. J. Charity,[5] and M. V. Zhukov[6]

But there is more….

Sharov *et al.* did not take detector response into account



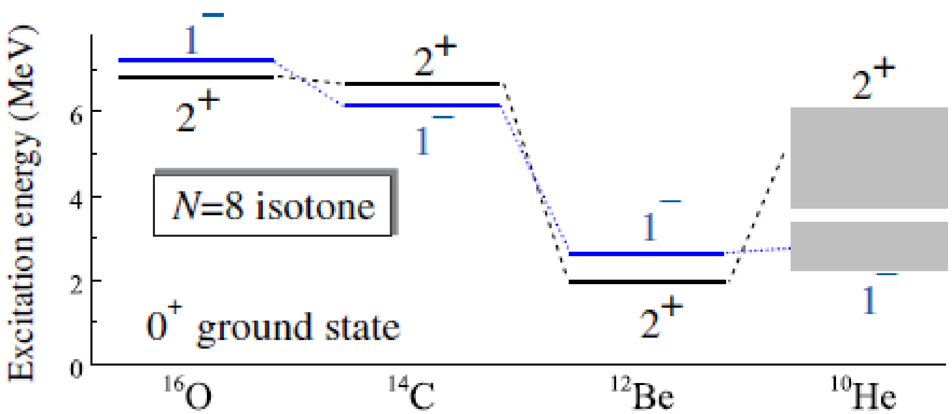
M.D. Jones, PRC 91, 044312 (2015)

- Where is the ground state?
- Can the rxn mechanism effect the observed g.s.?

2 more questions:

1) Could there be a second low-lying 0+ state? (Fortune PRC 2013)

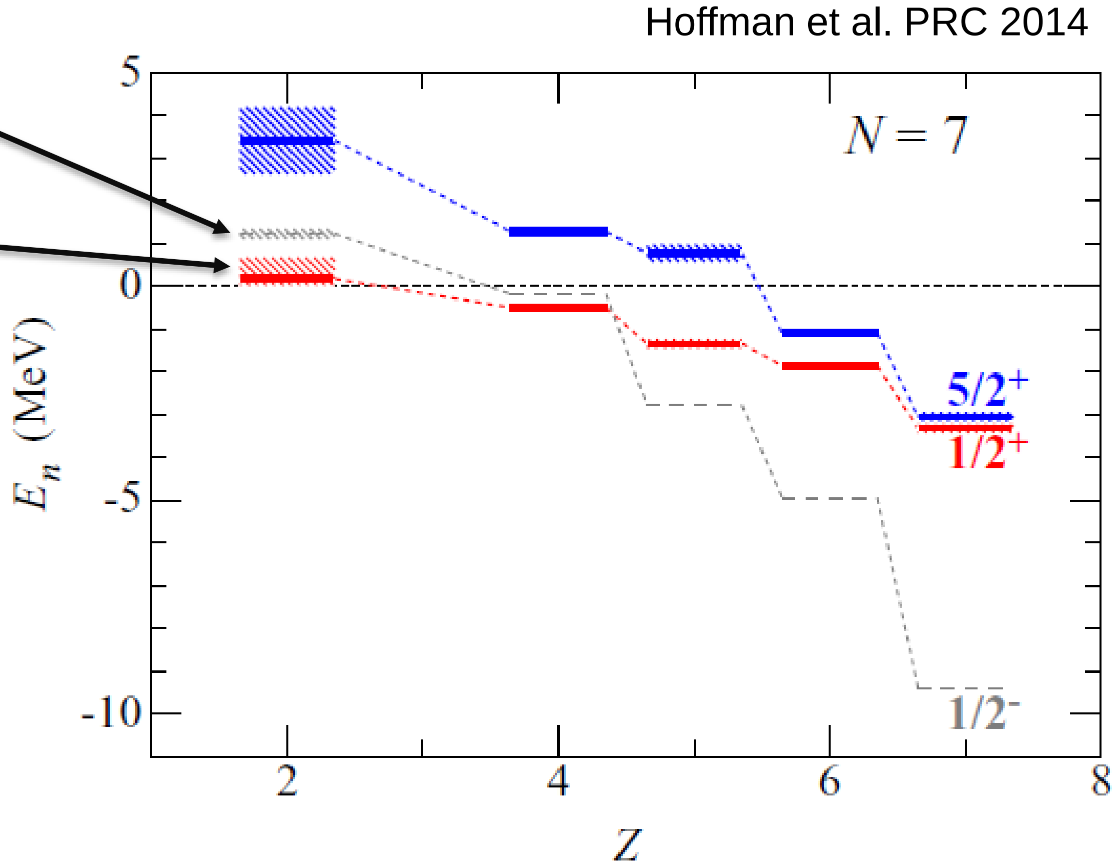
2) First excited state a 1- intruder?



Sidorchuk et al., PRL (2012)

Background Story – ^{9}He

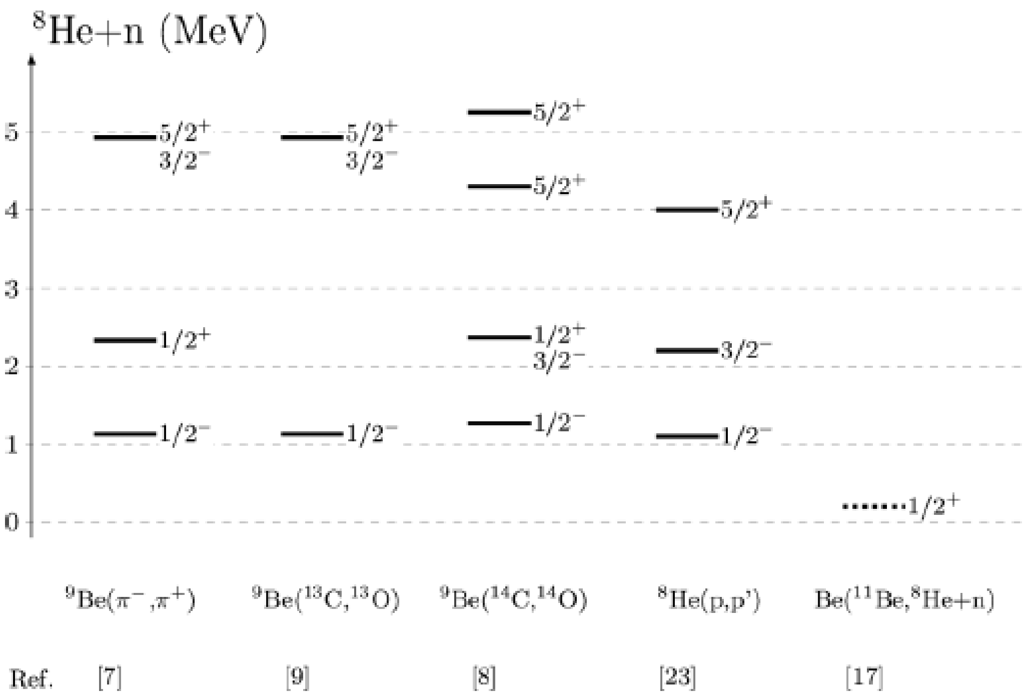
Inverted ½+ ground state?



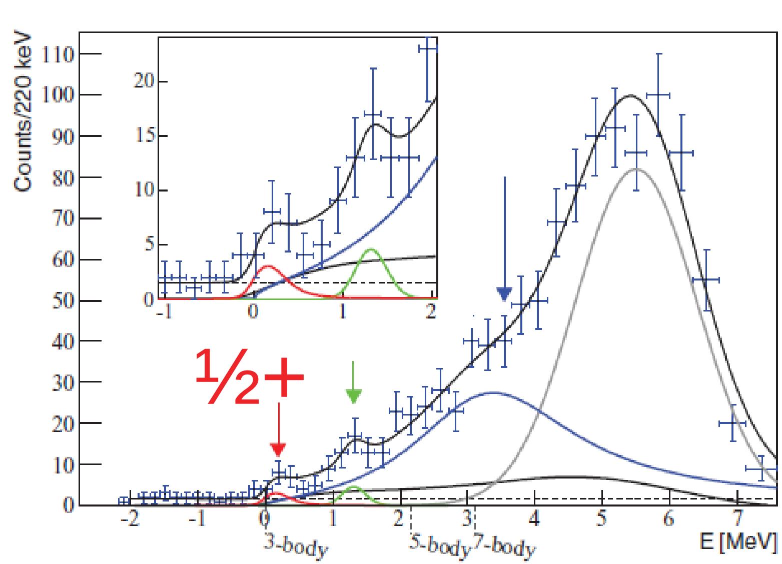
The location or scattering length of ½+ s-state is strongly connected to the structure of ^{10}He.

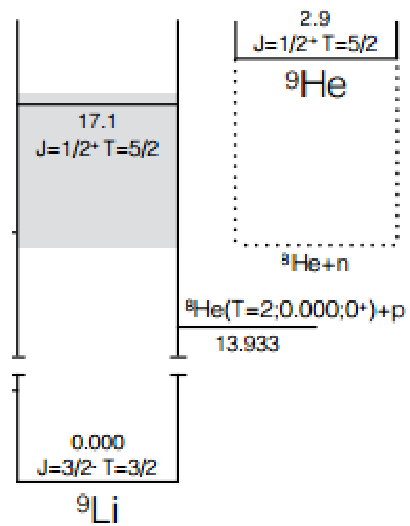
Background Story – ^{9}He

Inverted ½+ ground state?



Kalanee et al. PRC 2013





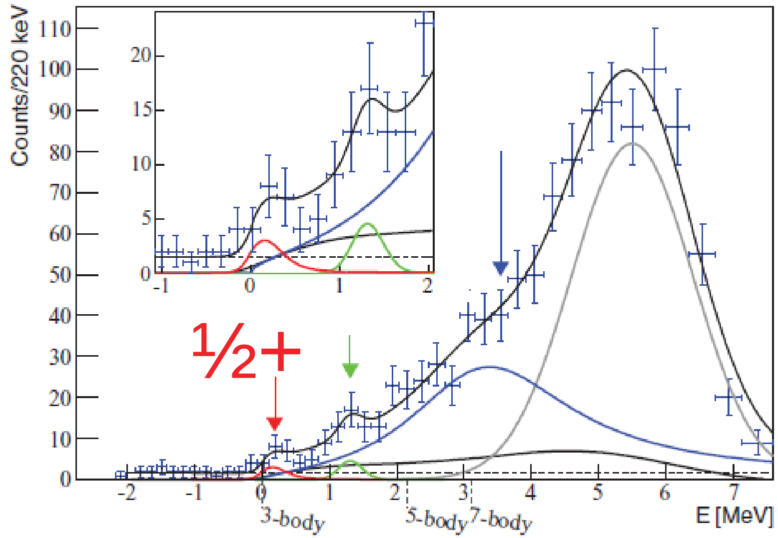
No p-state!

½+ > 2 MeV

Uberseder, Rogachev, et al. ArXiV (2015)

Background Story – ^{9}He

Kalanee et al. PRC 2013

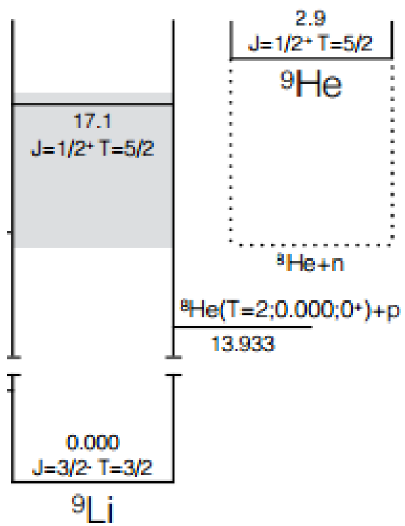


Inverted ½+ ground state?

What is the ground-state and 1st excited state configurations?

What energies are they expected at?

PAC39 proposal to provide more experimental guidance



No p-state!

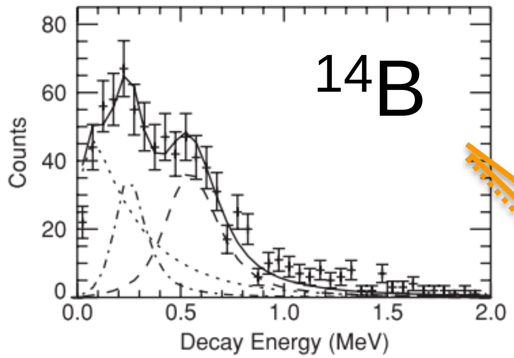
½+ > 2 MeV

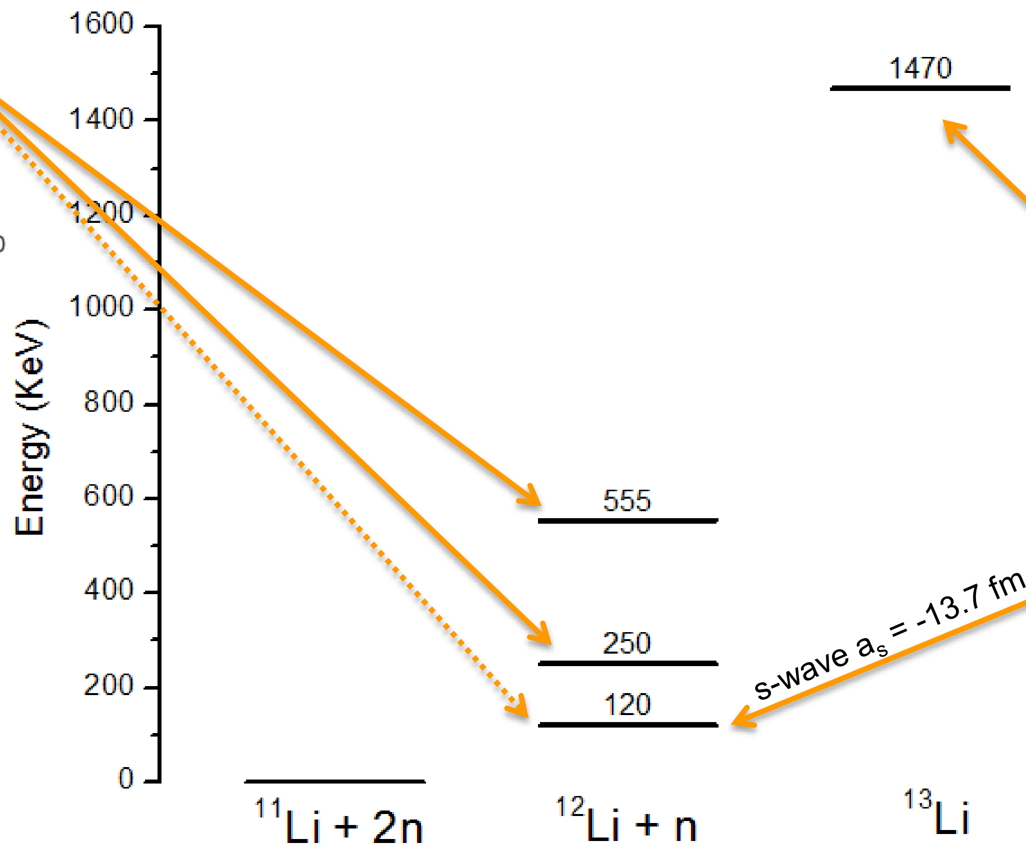
Uberseder, Rogachev, et al. ArXiV (2015)

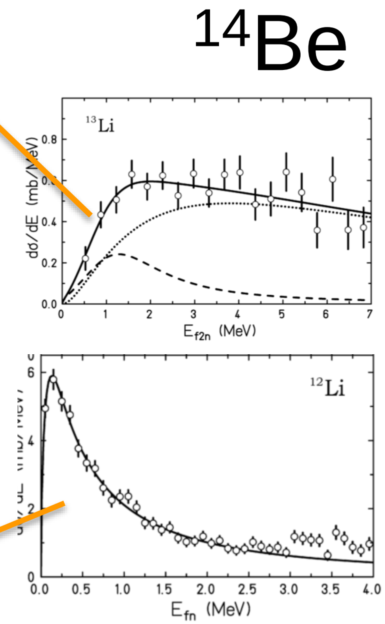
$^{12,13}Li$

Background

MoNA
Hall *et al.*,
PRC 81, 021302(R) (2010).





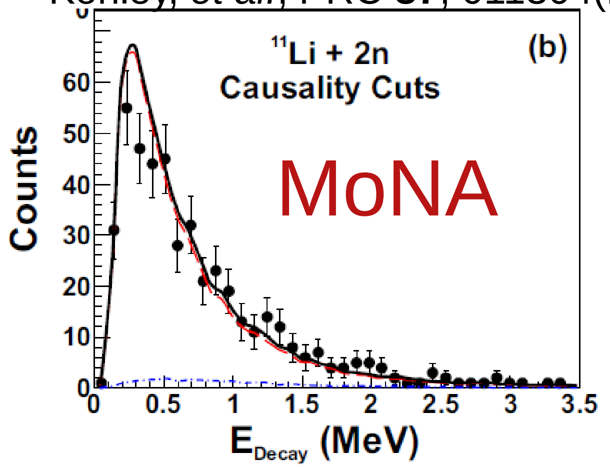


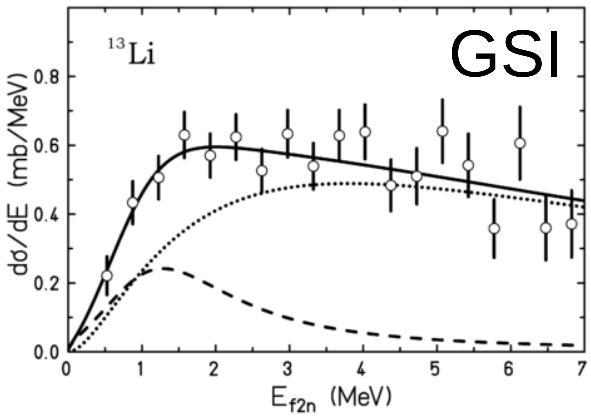
GSI-LAND
Aksyutina *et al.*,
PLB 666, 430 (2008).

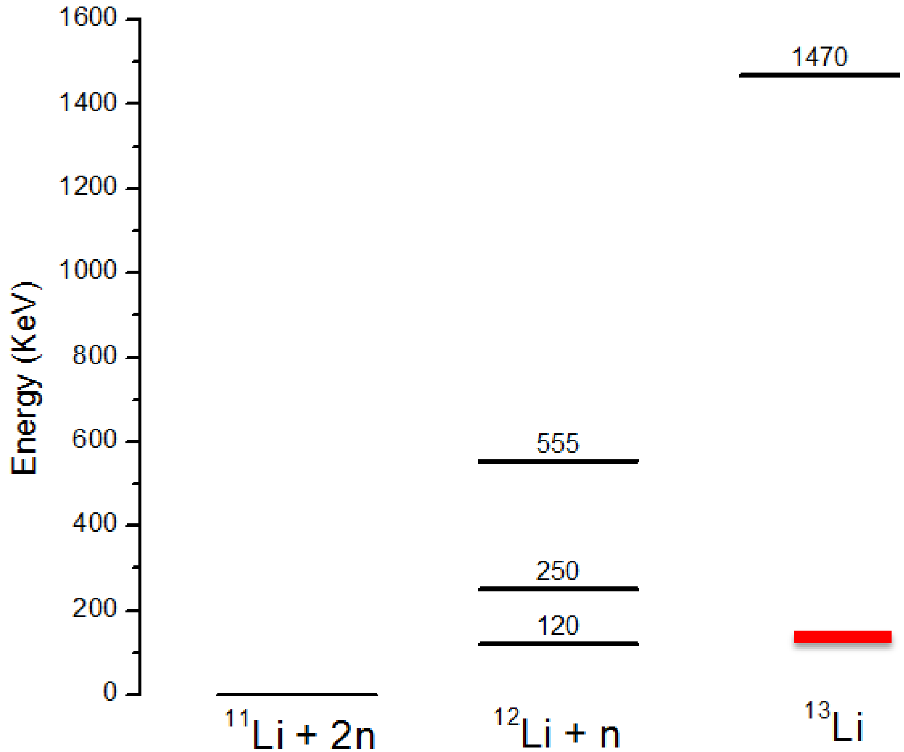
Results

53 MeV/u ^{14}Be beam.
(Same beam as GSI-LAND)

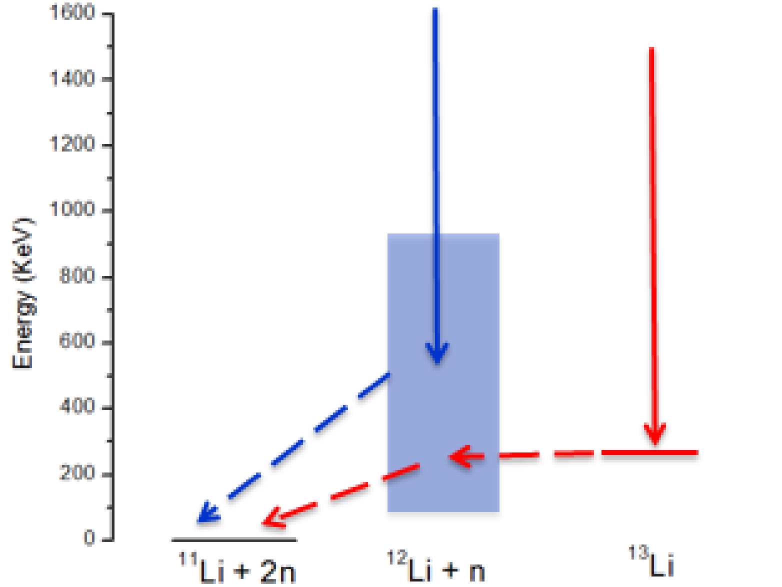
Kohley, *et al.*, PRC **87**, 011304(R)



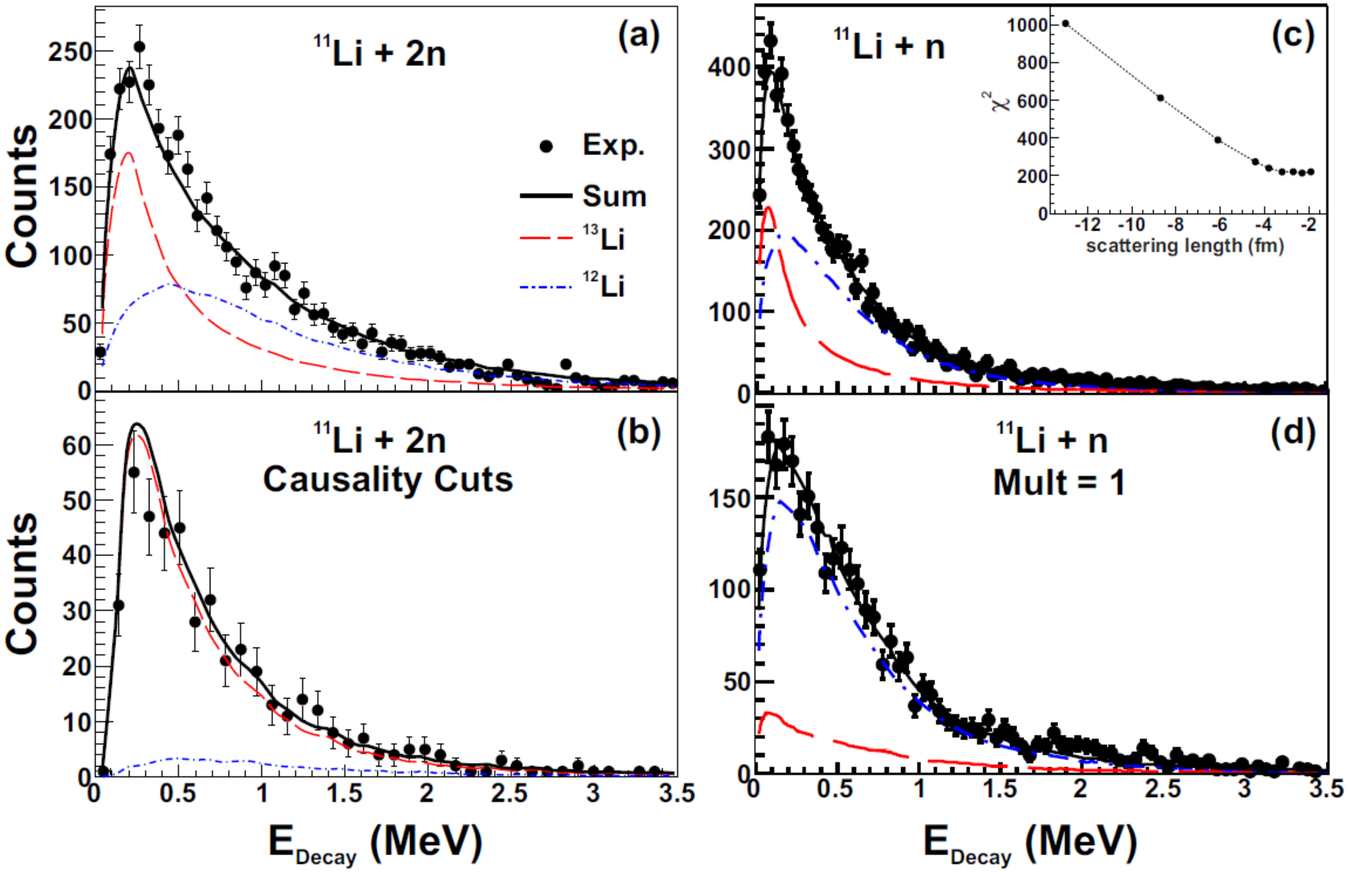




Results



Simultaneous χ^2-minimzation of all relevant ^{13}Li and ^{12}Li components.



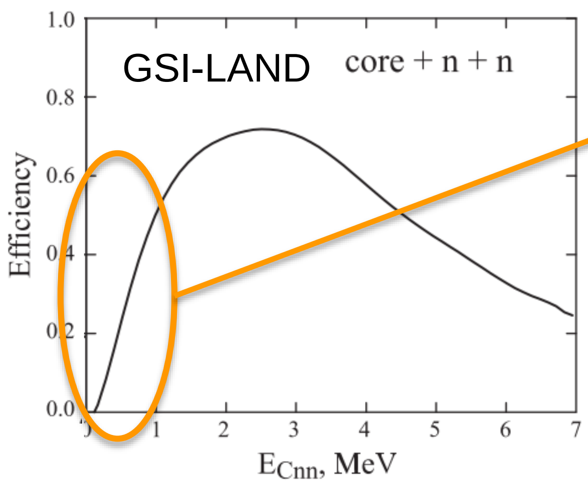
^{13}Li g.s. = 120(50) keV

^{12}Li s-wave $a_s > -4$ fm

Results

Inconsistent with the GSI-LAND results:

	MoNA	GSI-LAND
^{13}Li g.s.	130 keV	1470 keV
^{12}Li s-wave	-3.8 fm	-13.7 fm

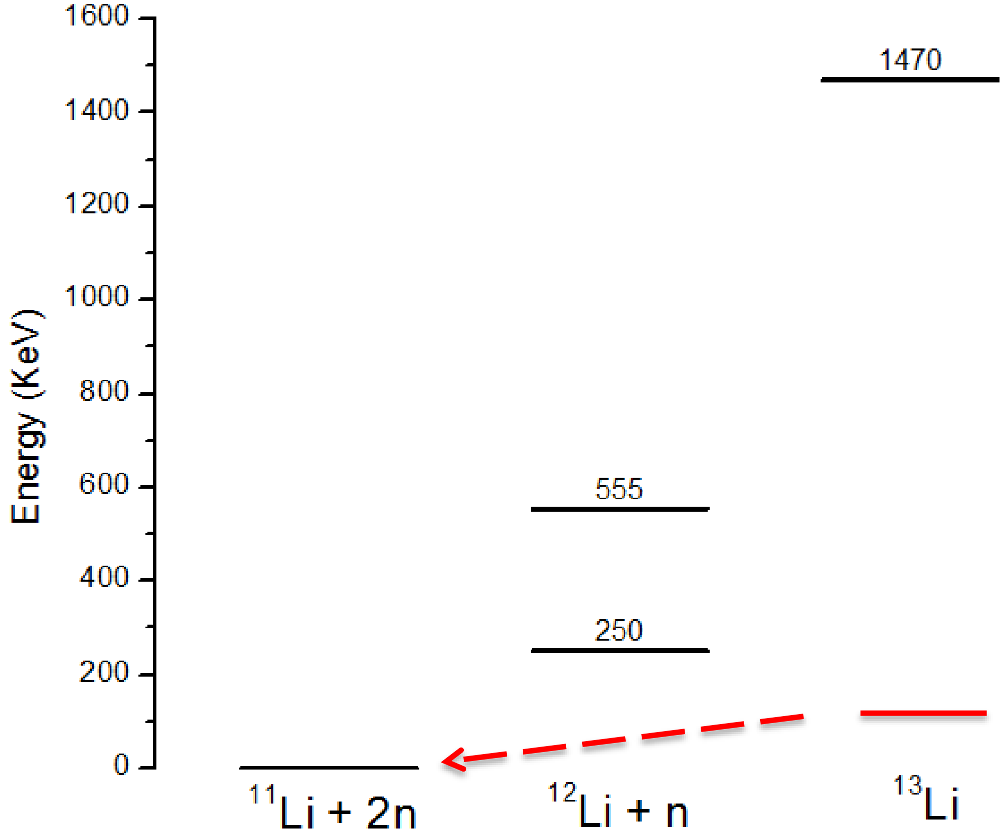


Below 200 keV = zero effic.

Unidentified ^{13}Li peak included into ^{12}Li spectra?

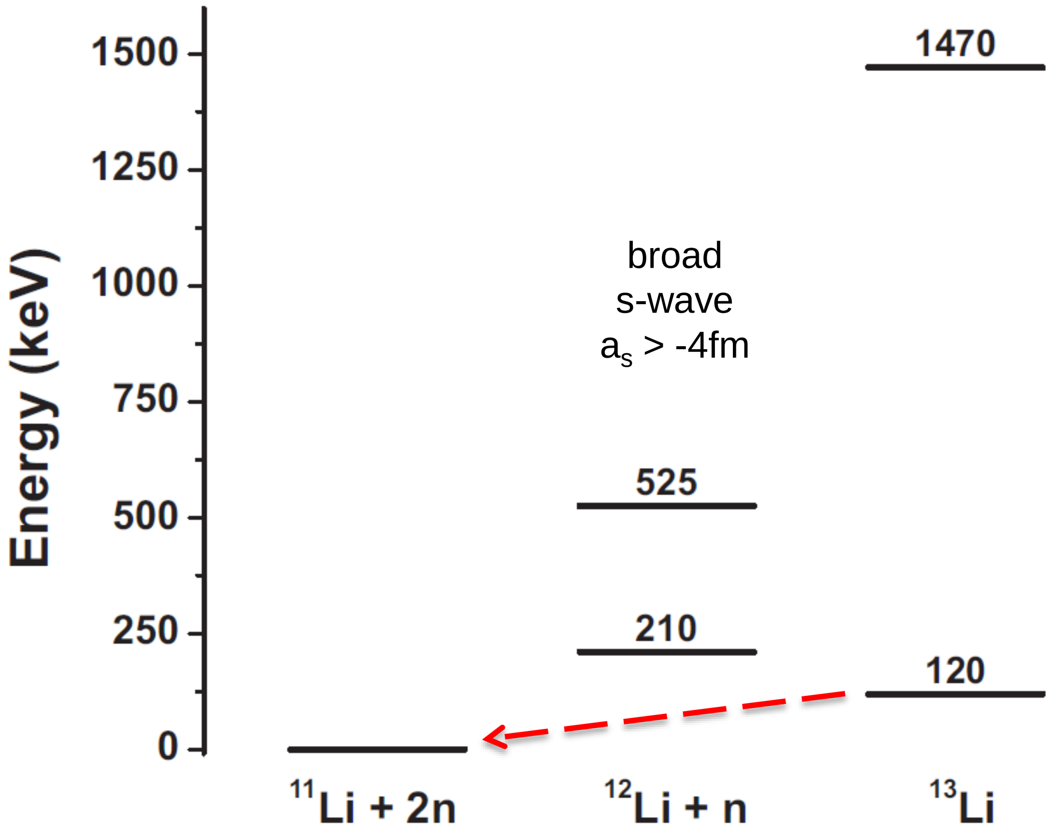
Aksyutina *et al.*, PLB 666, 430 (2008).
Aksyutina. PhD Thesis 2009

Results



Energy (KeV)
1600
1400
1200
1000
800
600
400
200
0
1470
555
250
^{11}Li + 2n
^{12}Li + n
^{13}Li

Results



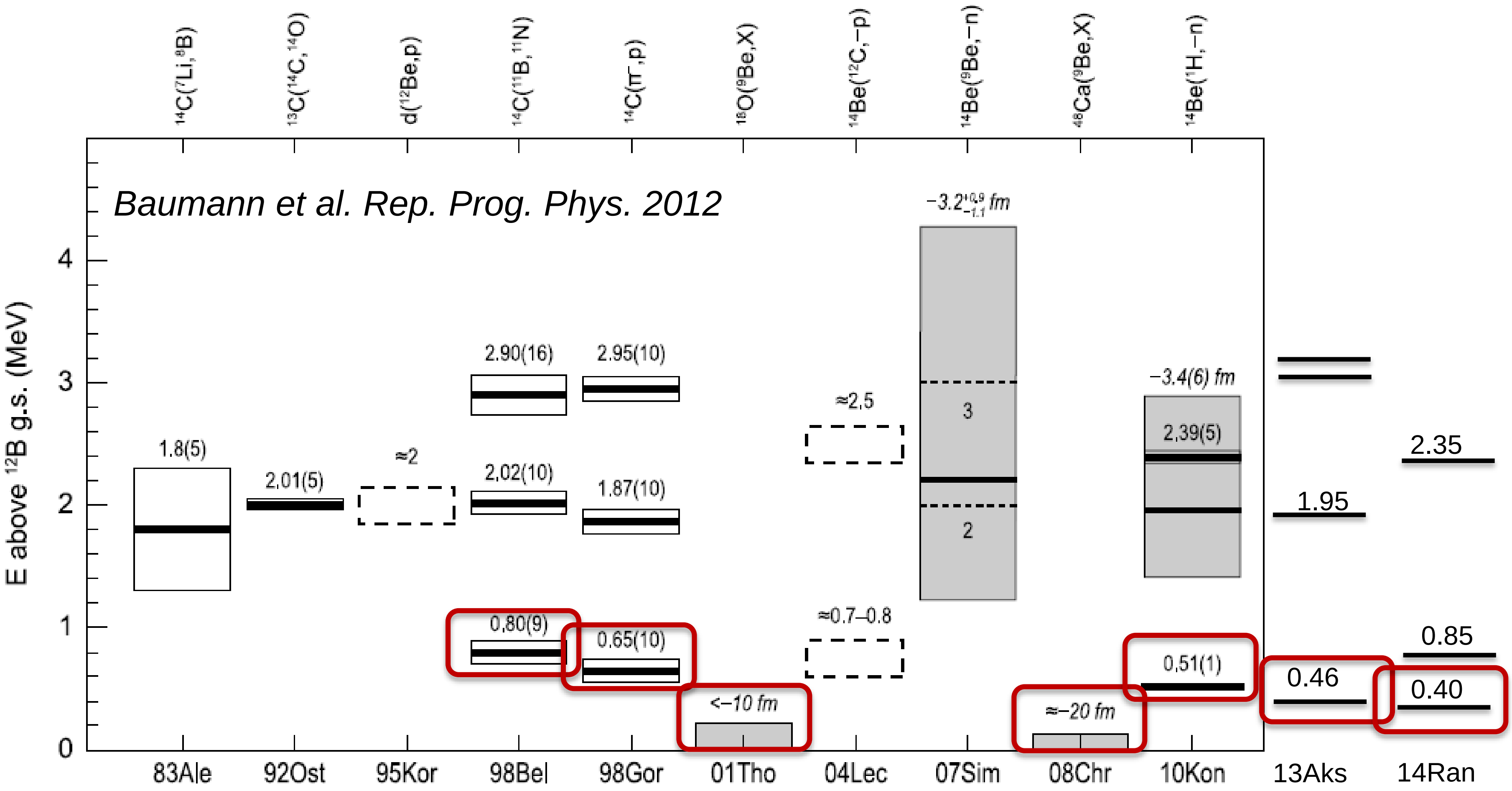
Can theory provide support to these conclusions (ground-state of ^{12}Li)?

Energy of ^{13}Li g.s.?

How does the ^{11}Li halo structure effect the ^{12,13}Li?

^{13}Be puzzle

Background – Here we go again….

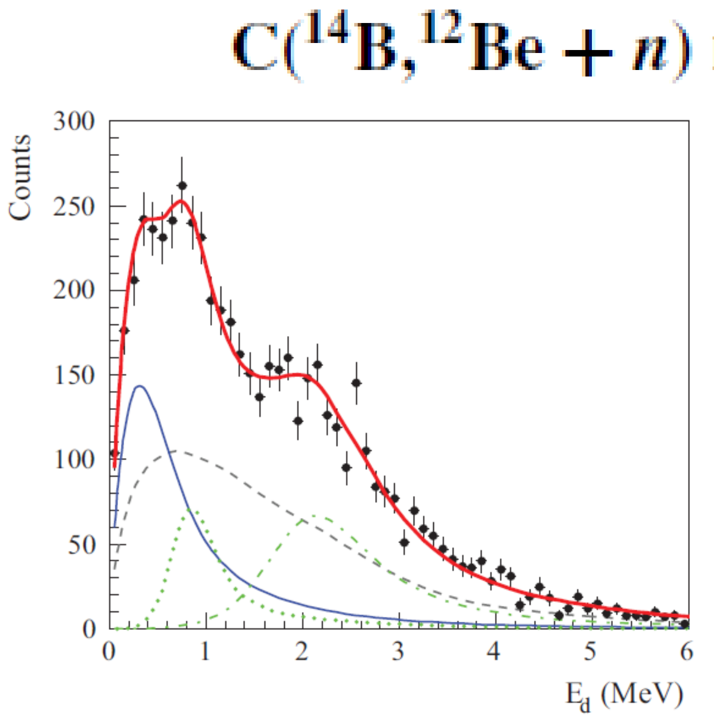


Randisi et al. PRC 2014

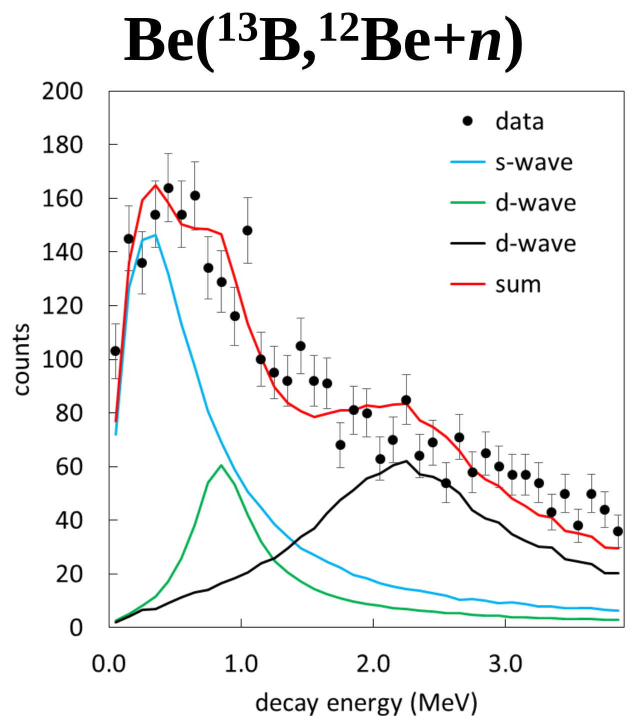
Low-lying ½+ ground state?

Background – Here we go again….

New MoNA data can be described with resonance parameters from Randisi et al.

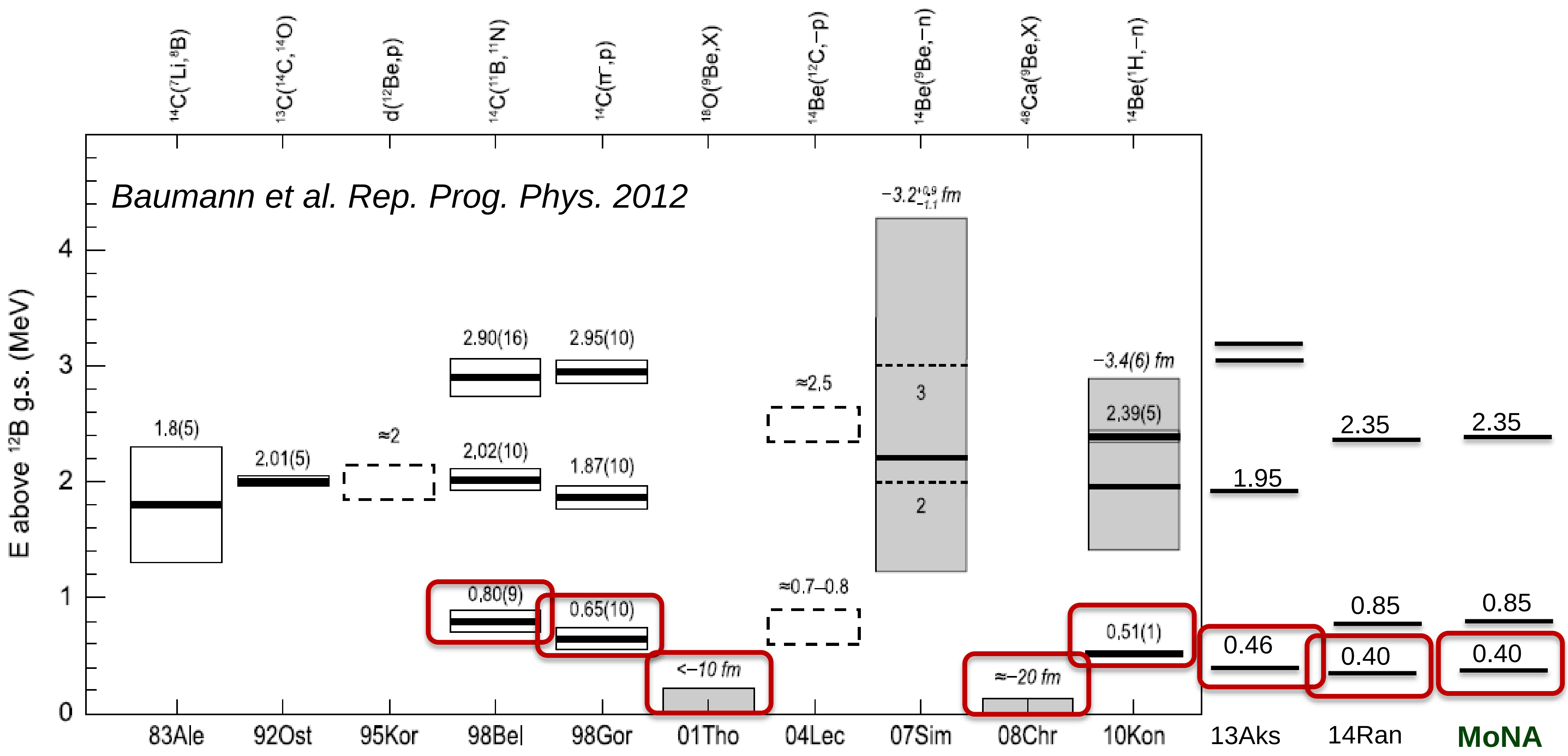


G. Randisi *et al.,* Phys. Rev. C 89 (2014) 034320



B. Marks *et al.,* in preparation

Background – Here we go again….



Does theory agree? ½+ ground state? What energy?

Guidance from theory….

The ^{9,10}He, ^{12,13}Li, and ^{13}Be demonstrate the intense need for guidance from theory.

Difficulty in experiments leads to difficulties in consistently interpreting:

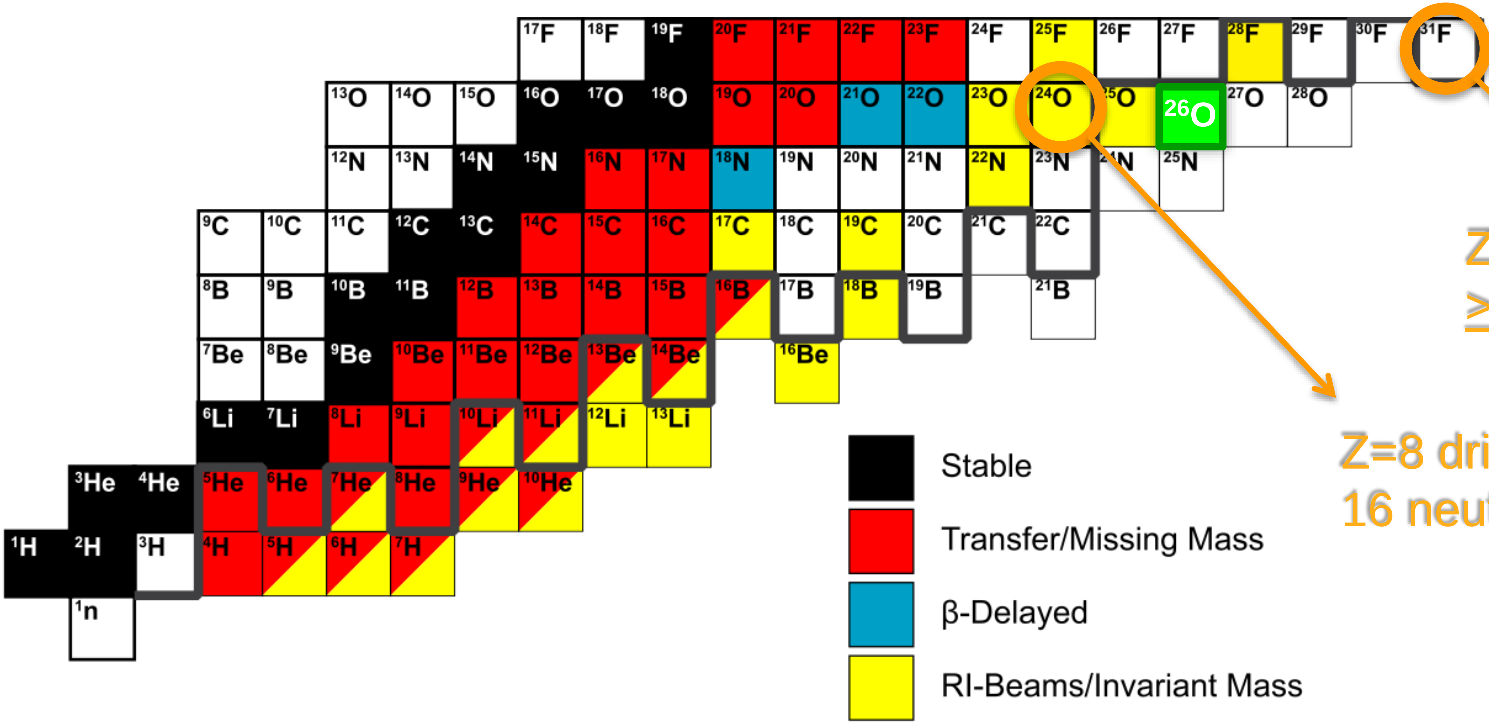
- ground states configurations
- level ordering
- number of low-lying levels.

Evidence for 2n radioactivity

$^{27}F(-p) \rightarrow {}^{26}O \rightarrow {}^{24}O + n + n$

Motivation

Understanding drastic change in neutron dripline between Z=8 and Z=9

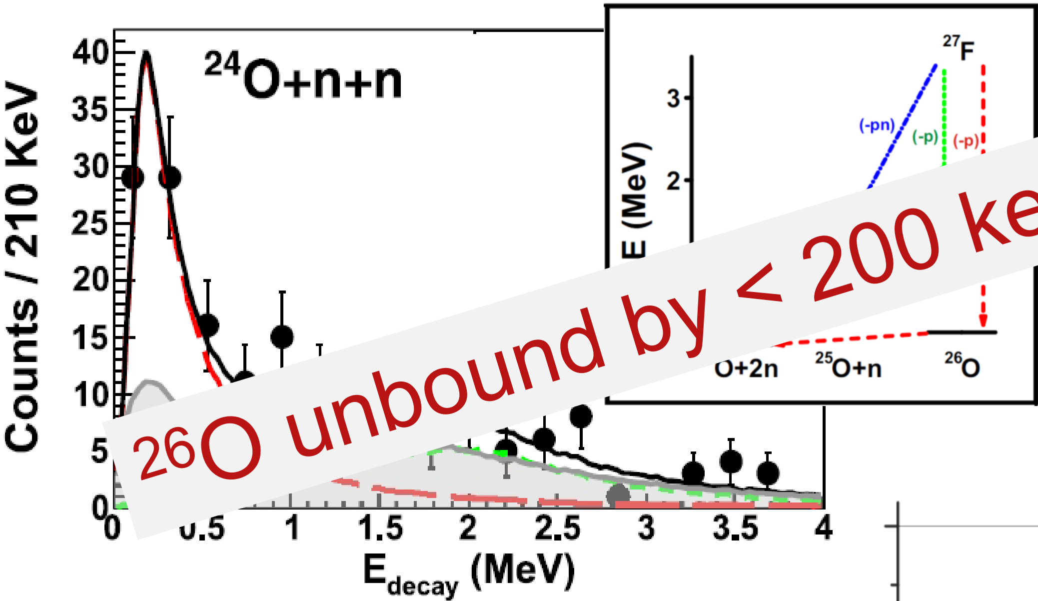


Z=9 dripline ≥ ^{31}F
≥ 22 neutrons bound

Z=8 dripline: ^{24}O
16 neutrons bound

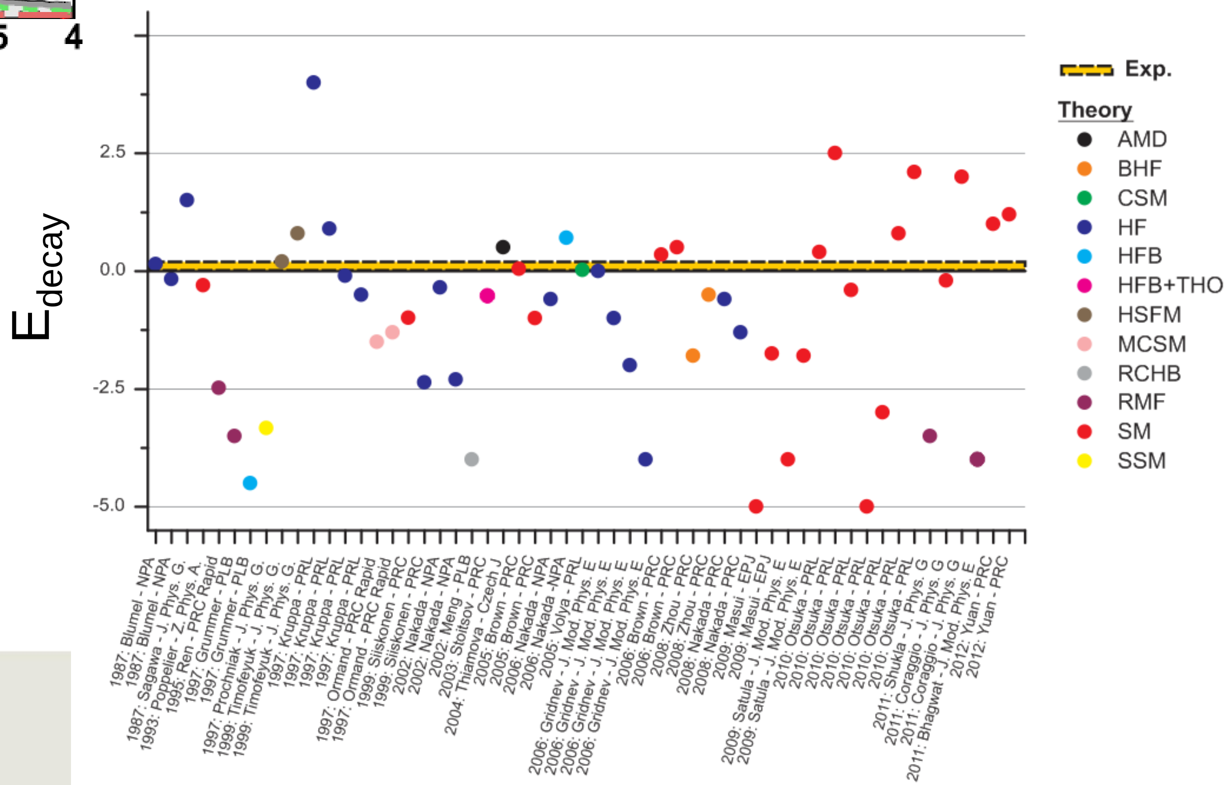
Baumann *et al.* Rep. Prog. Phys. **75,** 036301 (2012).

Results: Decay Energy



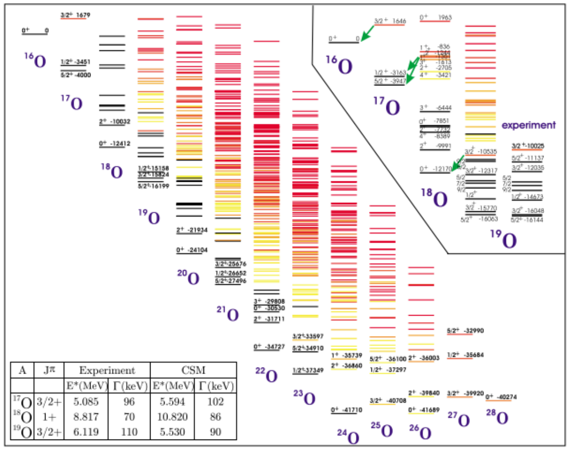
^{26}O unbound by < 200 keV

Lunderberg, *et al.*, PRL **108,** 102501 (2012).

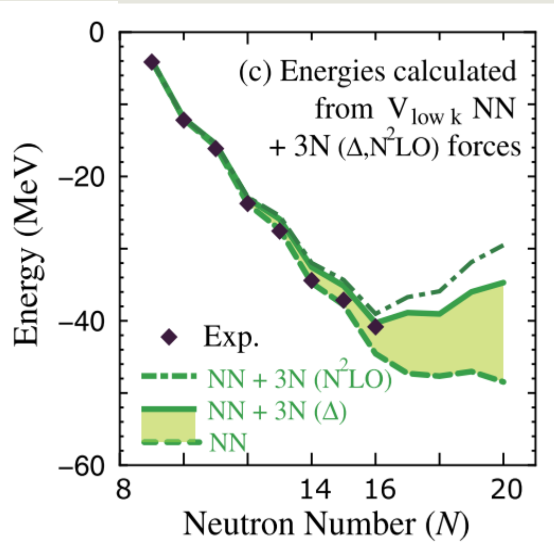


Test of theory

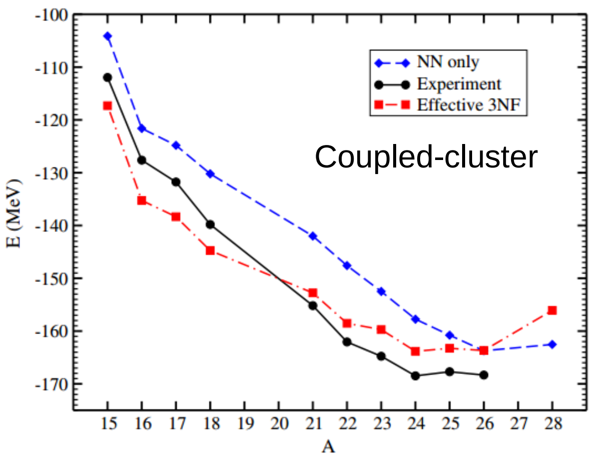
3-body forces



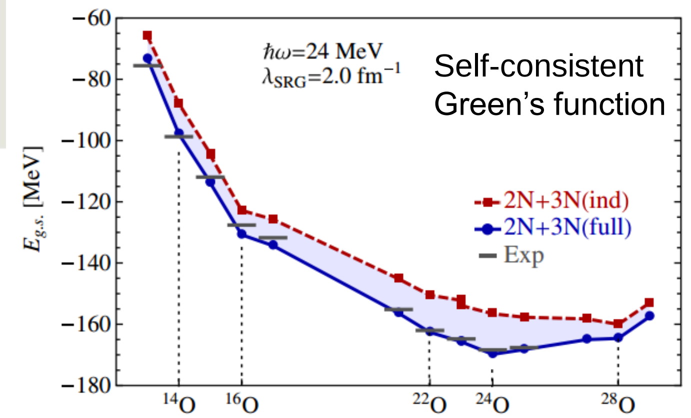
Volya and Zelevisnky
PRL. **94,** 052501 (2005).



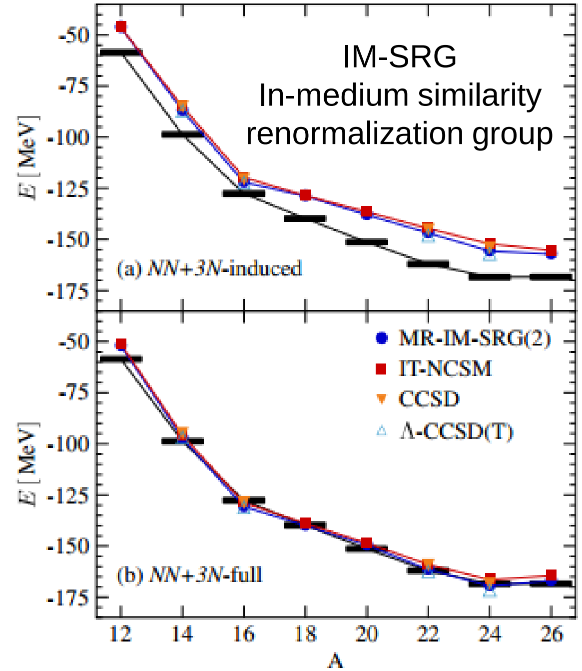
Otsuka *et al.* PRL. **105,** 032501 (2010).



Hagen *et al.* PRL **108,** 242501 (2012).

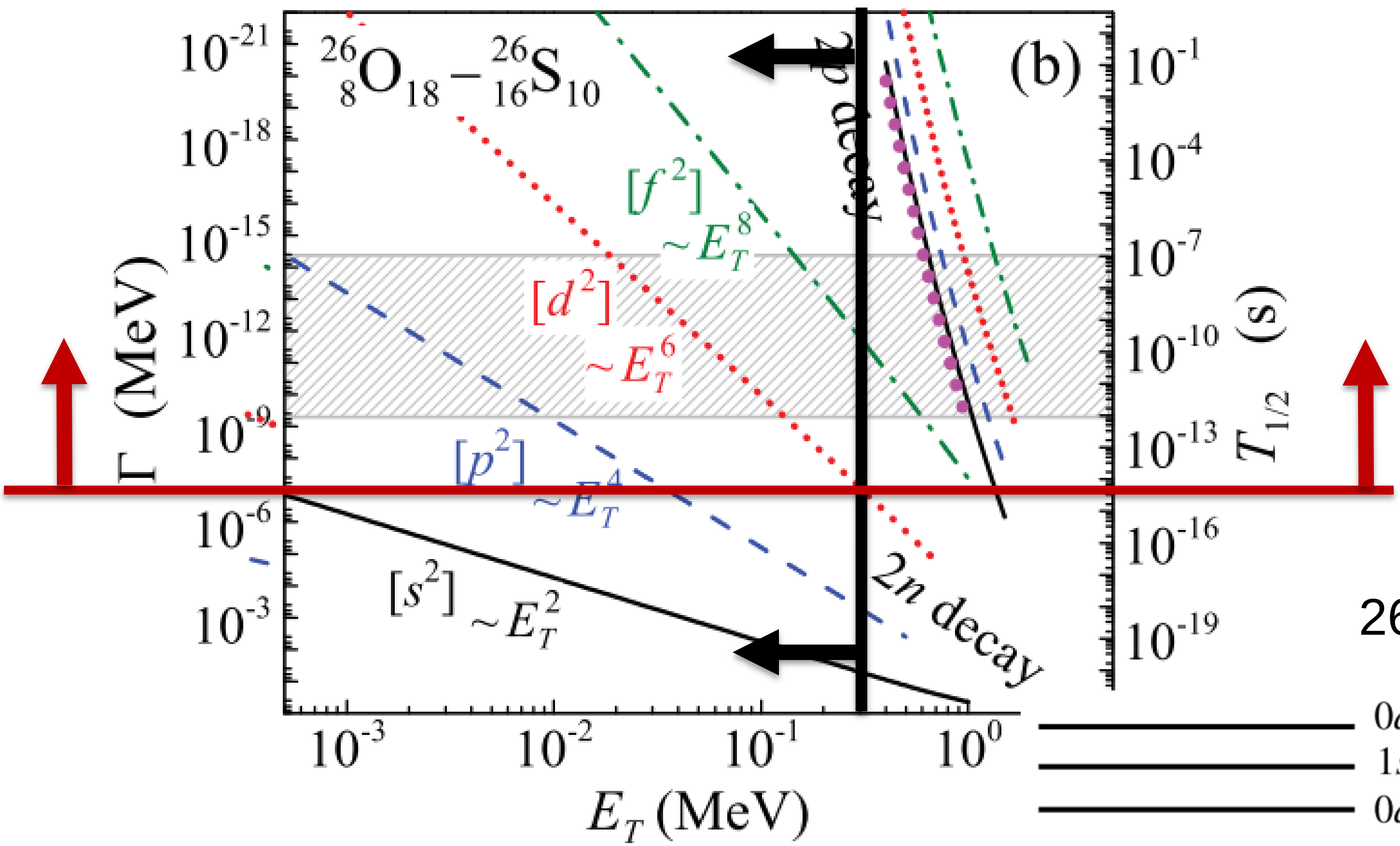


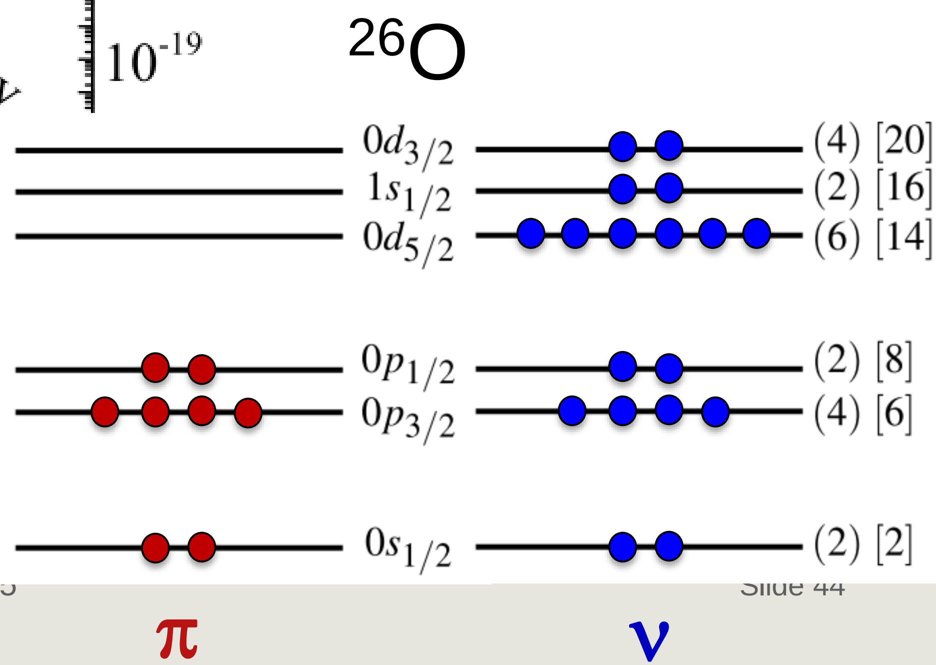
Cipollone *et al.* PRL **111,** 062501 (2013).



Hergert *et al.* PRL **110,** 242501 (2013).

Prediction





Grigorenko et al. PRC **84,** 021303(R) (2011)

Radioactivity

Pfutzner et al. (2012): $T_{1/2} > 10^{-14}$ s (10 fs)

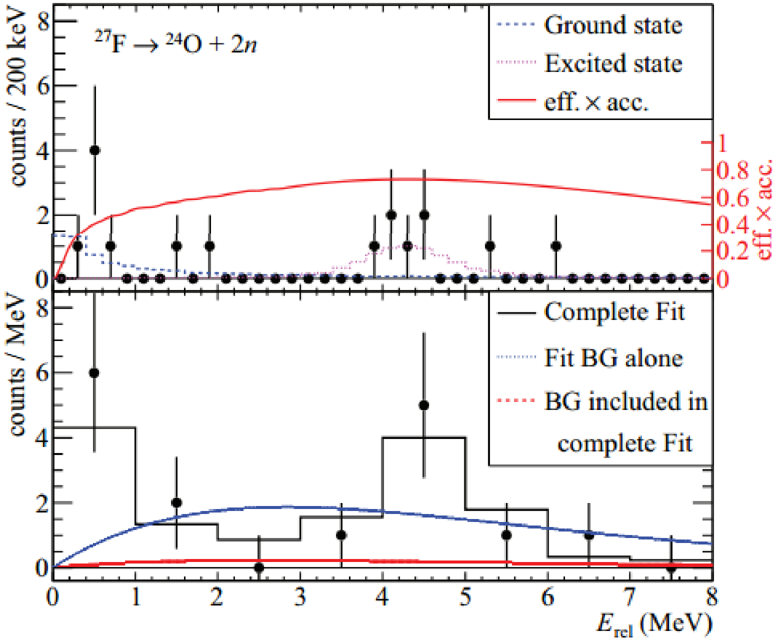
- K-shell vacancy half-life of carbon atom 2 x 10^{-14} s
- Width (Γ) is 0.03 eV, which is about room temp

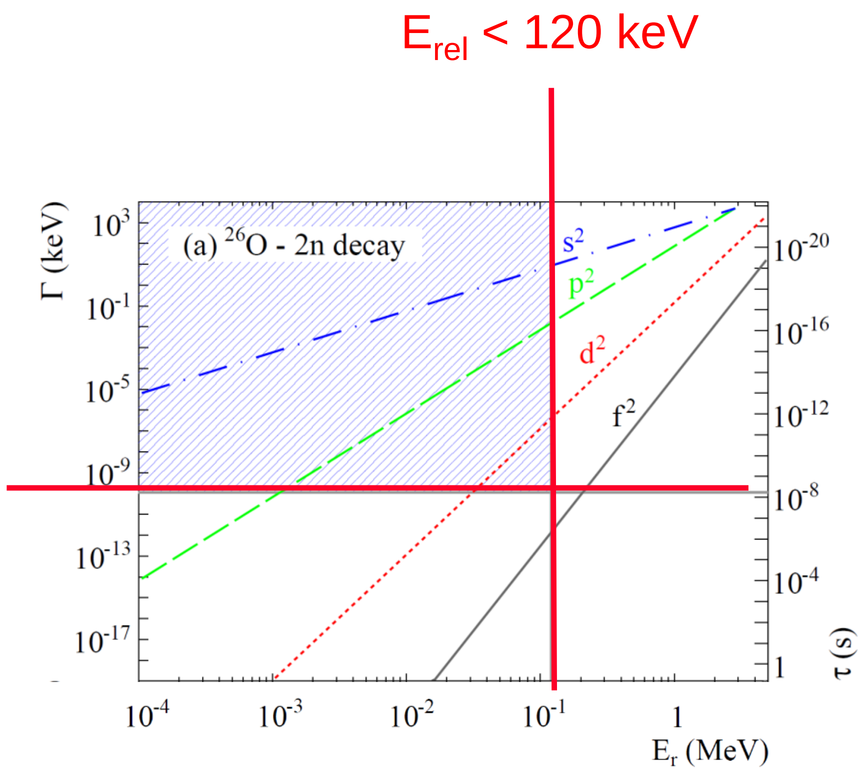
Cerny & Hardy (1977): $T_{1/2} > 10^{-12}$ s (1ps)

IUPAC, discovery of element: $T_{1/2} > 10^{-14}$s (10 fs)

- Around the time for nucleus to acquire outer electrons

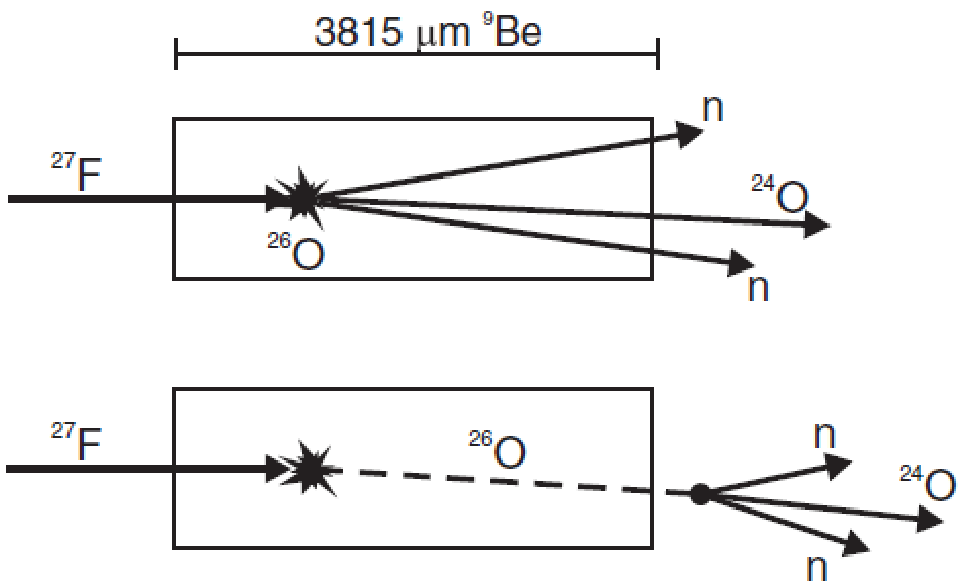
R^3B-LAND results

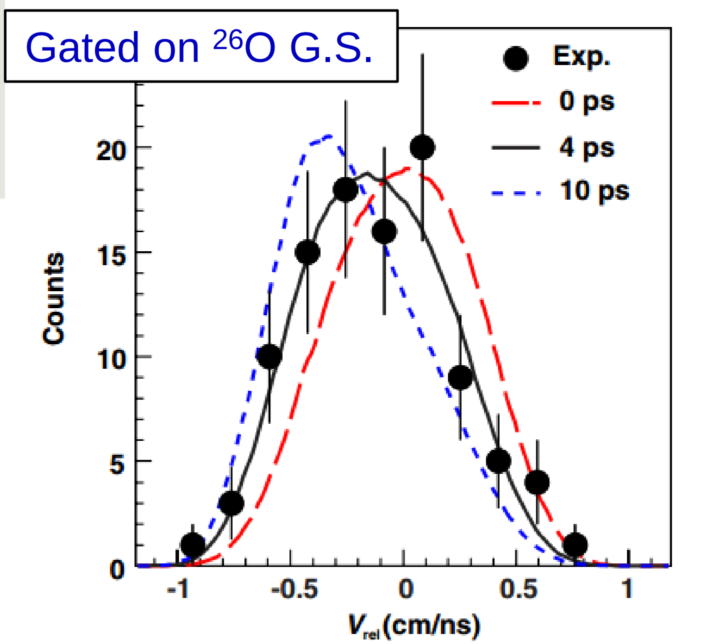




C. Caesar & *R3B Collaboration*, Phys. Rev. C **88**, 034313 (2013)
L.V. Grigorenko et al., Phys. Rev. C 84 (2011) 021303

Half-life measurement

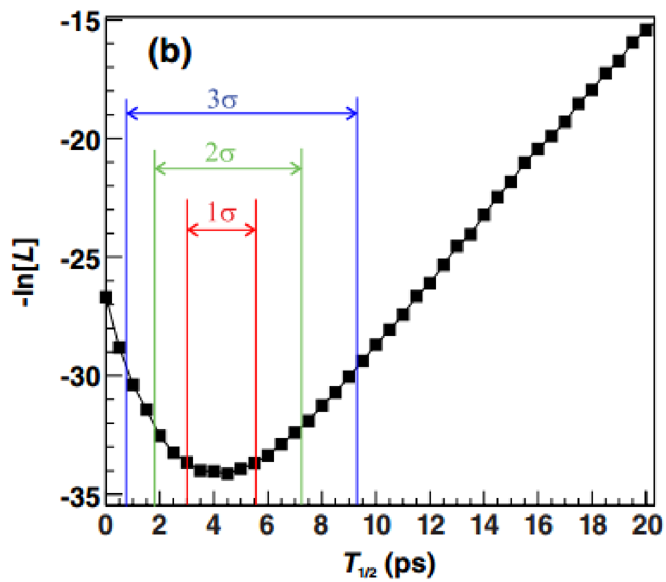




increased lifetime = reduced velocity neutrons

$$V_{rel} = V_n - V_{frag}$$

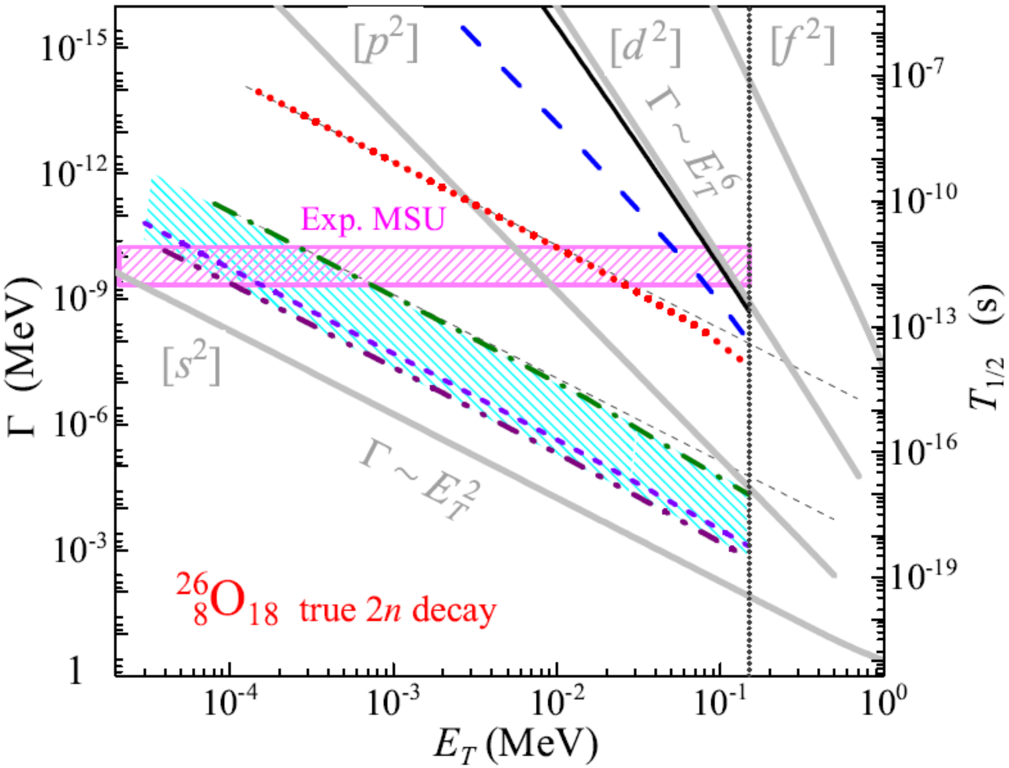
Lifetime: $T_{1/2} = 4.5^{+1.1}_{-1.5}$ ps (1σ)



Unbinned maximum likelihood technique

New Lifetime calculations

L.V. Grigorenko, I.G. Mukha, and M.V. Zhukov, PRL (2013)



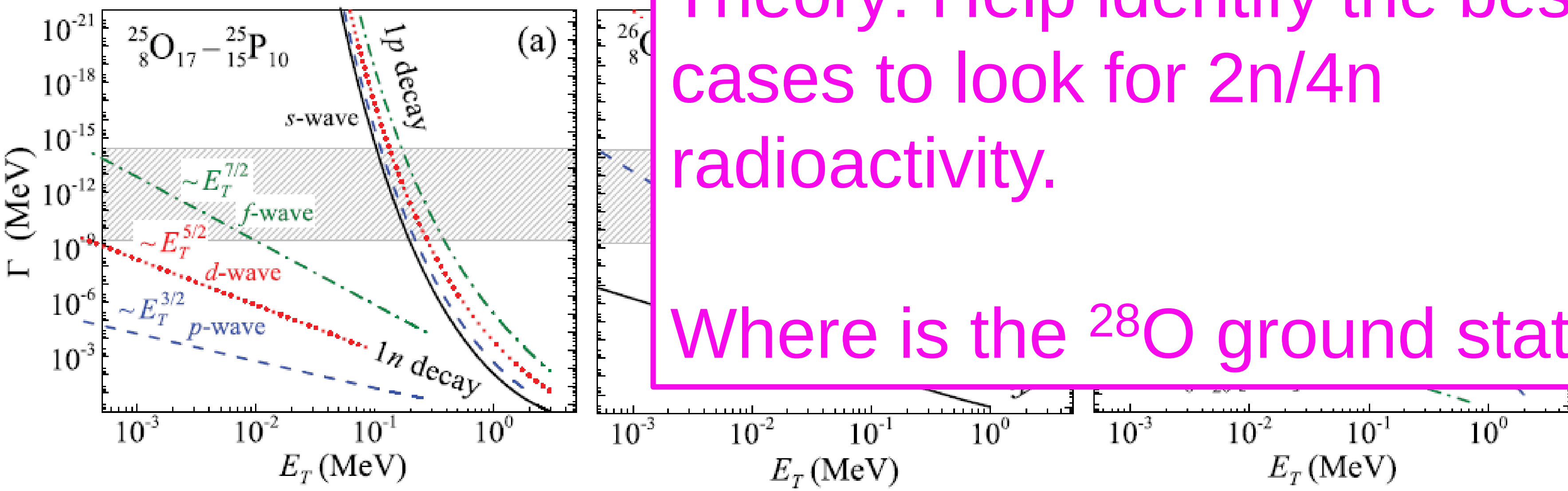
"realistic theoretical limits"

$E_T < 1$ keV

Improve Edecay constraints

Predictions of the width, s/d configuration, energy of the ^{26}O ground state?

Future possible cases…



Theory: Help identify the best cases to look for 2n/4n radioactivity.

Where is the ^{28}O ground state?

- Finite lifetimes for single neutron emitters are still unlikely
- Other two-neutron emitters could be possible in the 100 keV range
- How about four-neutron emitters?

L.V. Grigorenko et al., Phys. Rev. C 84 (2011) 021303

Correlations in the 3-body decay

$^{16}Be \rightarrow {}^{14}Be + n + n$

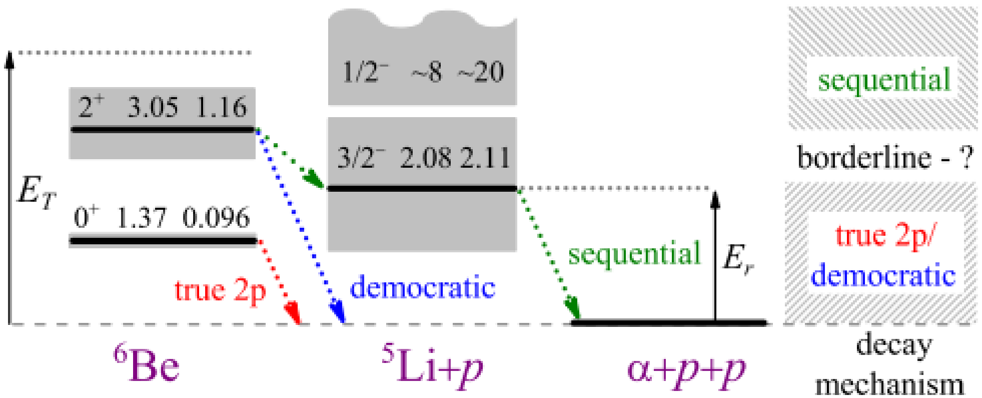
$^{13}Li \rightarrow {}^{11}Li + n + n$

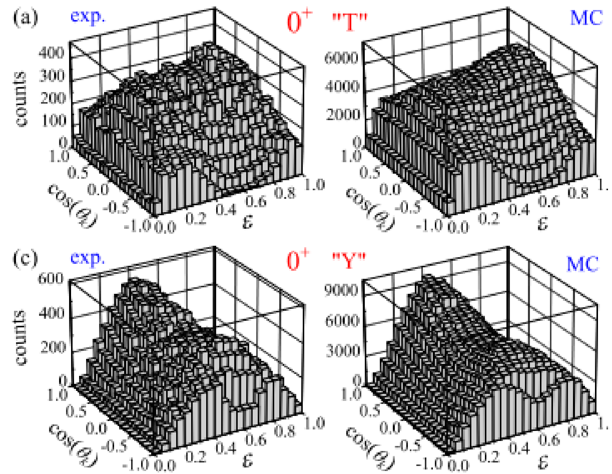
$^{26}O \rightarrow {}^{24}O + n + n$

Spyrou, *et al.*, PRL **108,** 102501 (2012).
Kohley, *et al.*, PRC **87**, 011304(R)
Kohley et al. PRC **91,** 034323 (2015).

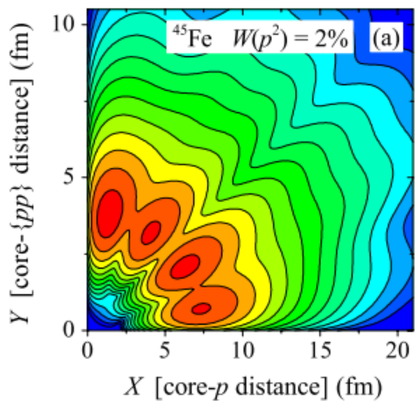
Motivation

Push theory to describe and predict the correlations from 2n decays
(Significant progress has been made in 2p decays)

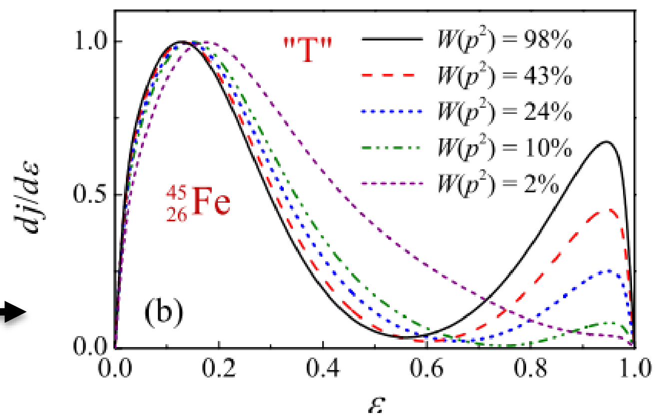




Egorova, Charity, Grigorenko, *et al.* PRL. **109,** 202502 (2012).

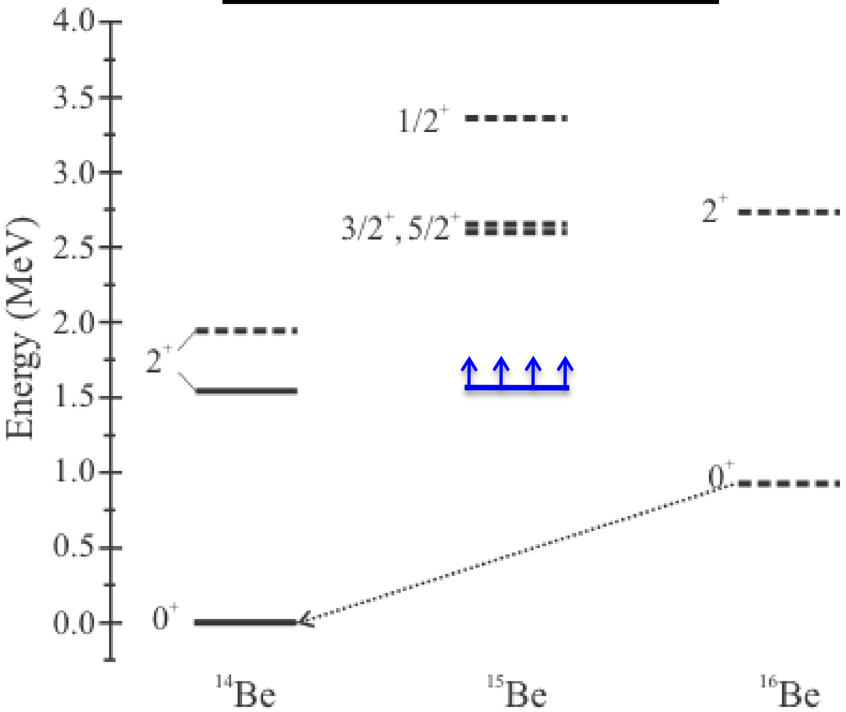


Accessing WFs through correlations



Pfutzner, Karny, Grigorenko, Riisager, RMD. **84,** 567 (2012).

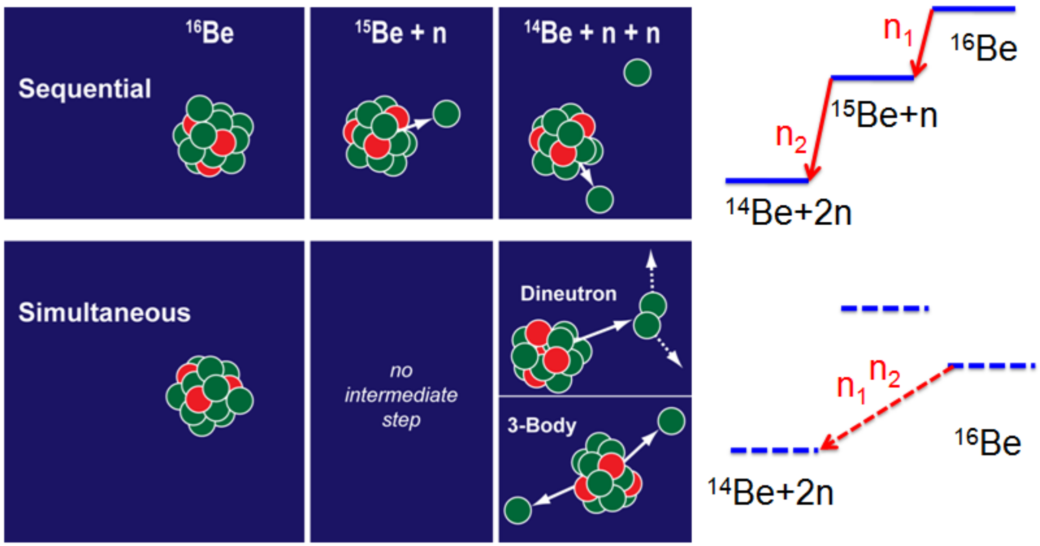
Motivation: ^{16}Be



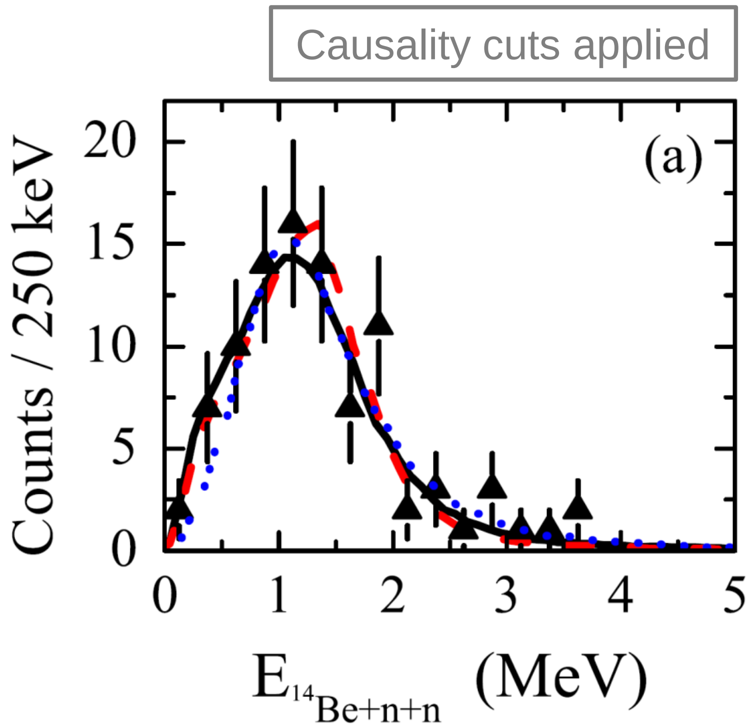
A. Spyrou, J.K. Smith *et al*,
Phys Rev C84(2011)044309

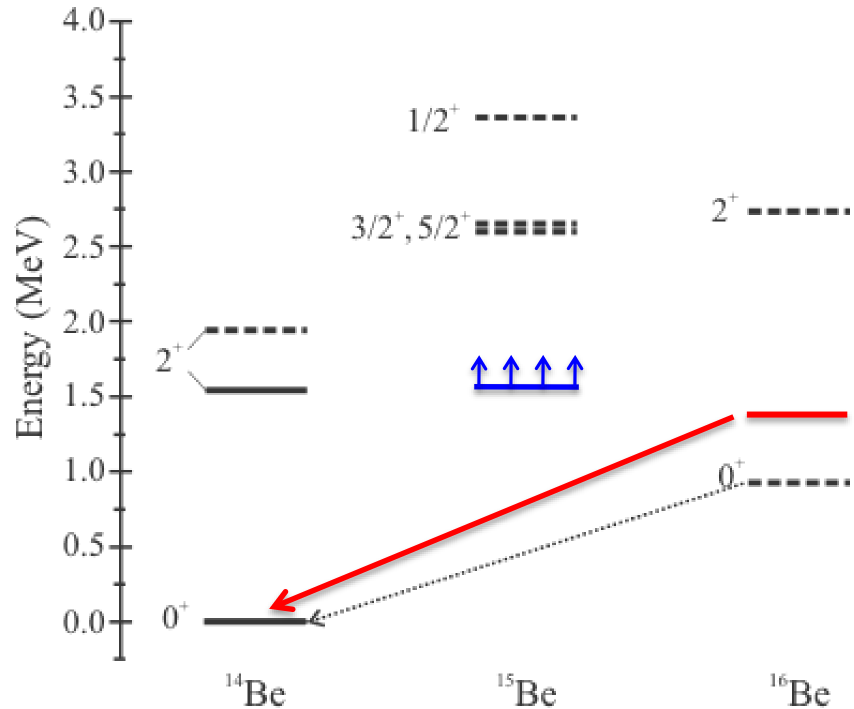
^{16}Be predicted to be:
- unbound with respect to 2n decay
- bound with respect to 1n decay

Scenario for "true" 2n emission



^{16}Be Decay Energy





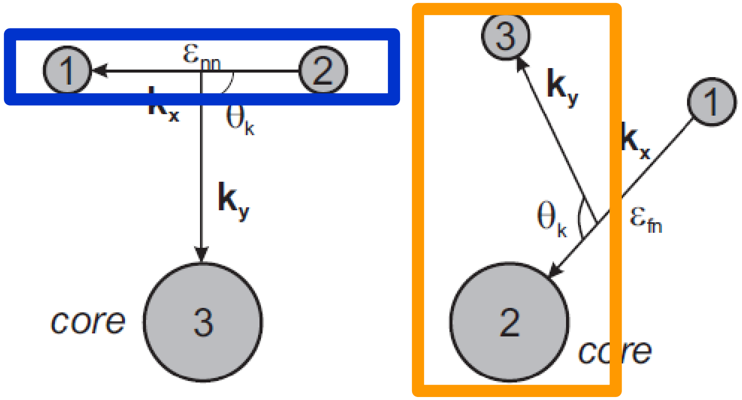
^{16}Be g.s. resonance = 1.35(10) MeV

^{16}Be Correlations

Strong nn correlation observed

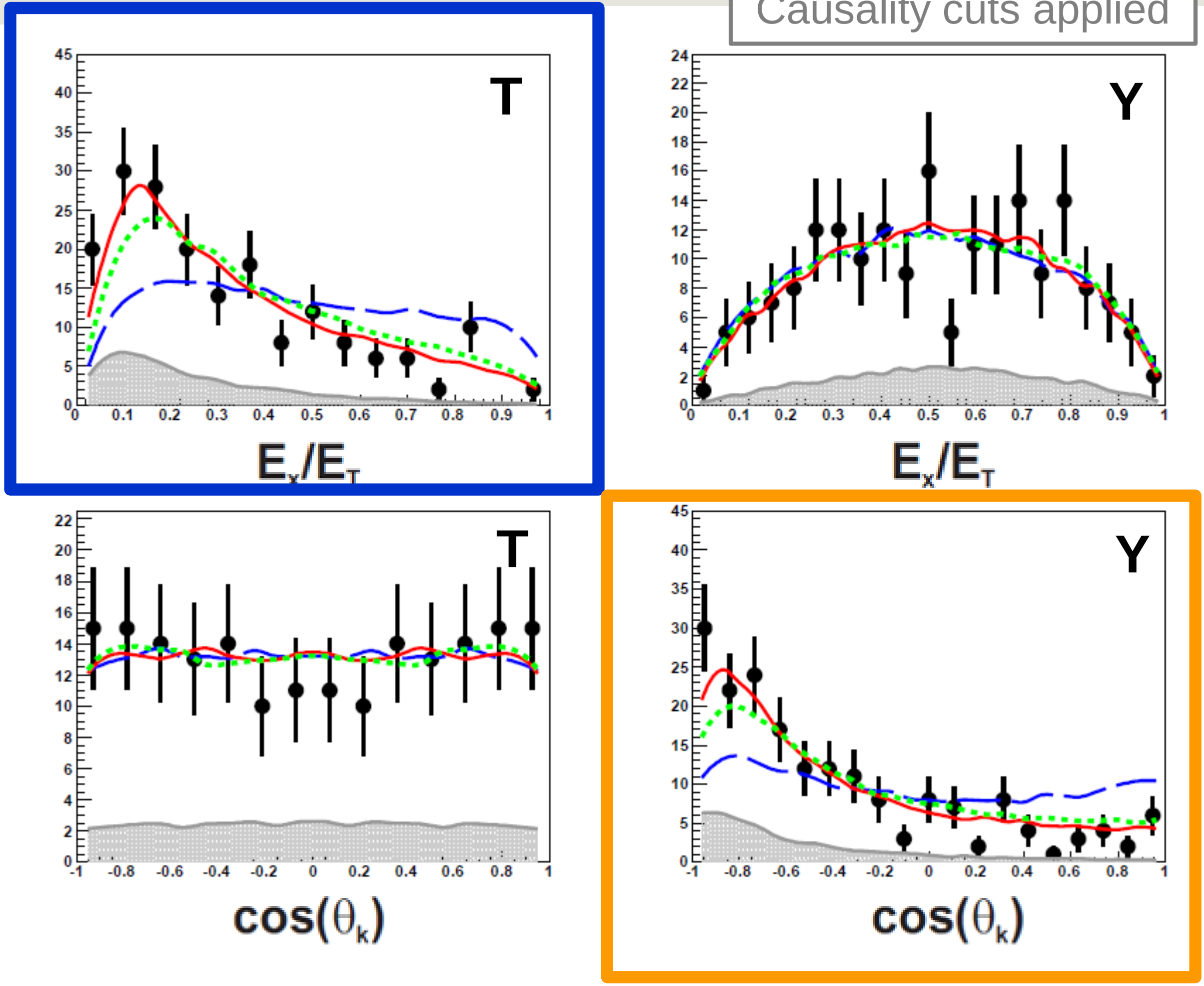
Causality cuts applied

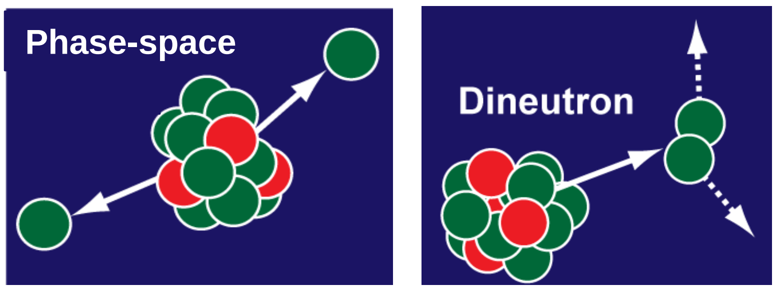
Jacobi systems



T system

Y system



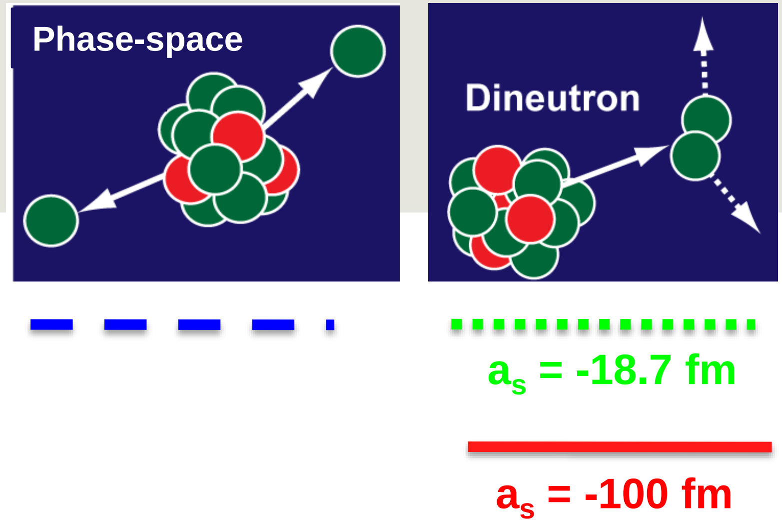


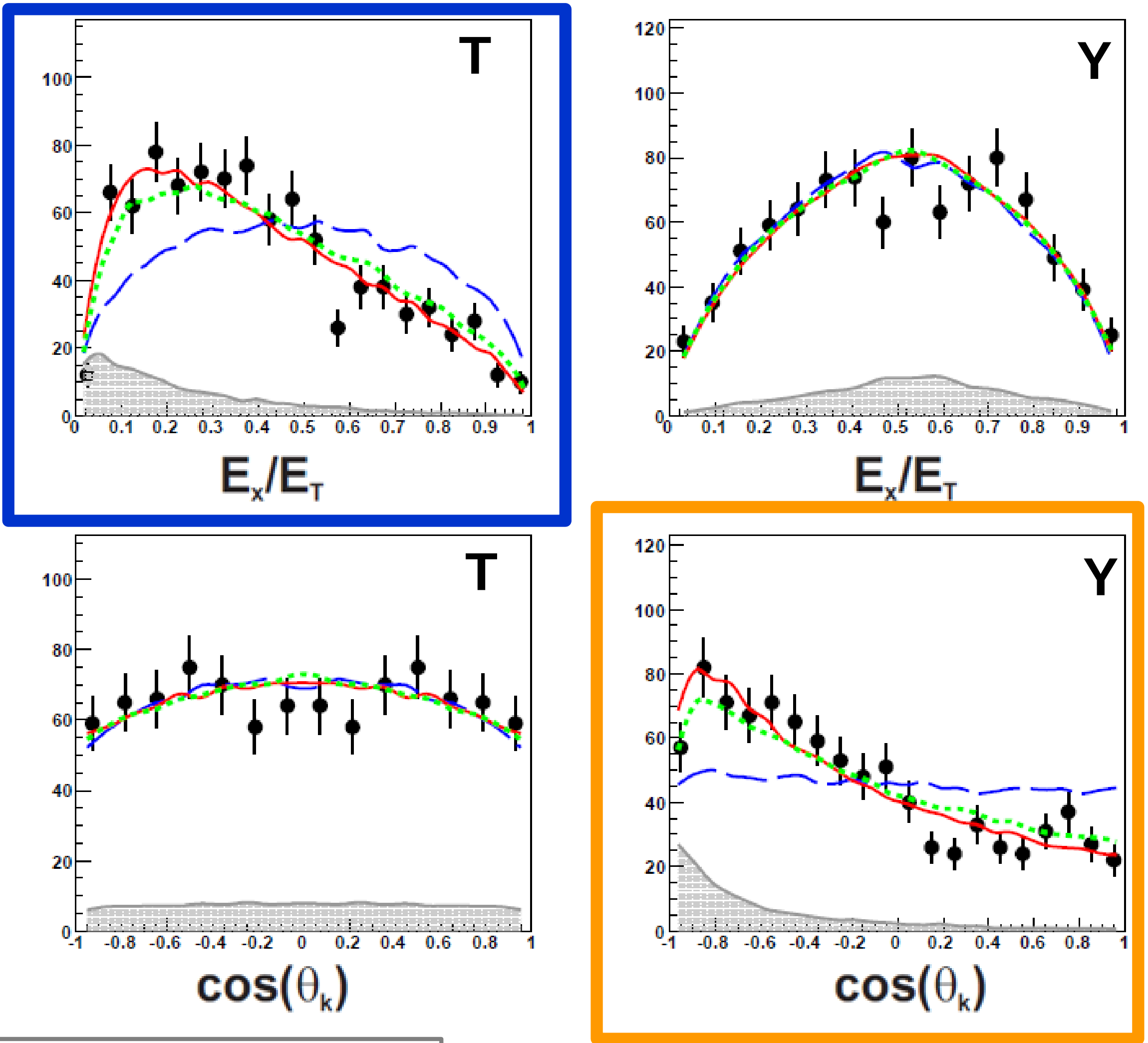
a_s = -18.7 fm

a_s = -100 fm

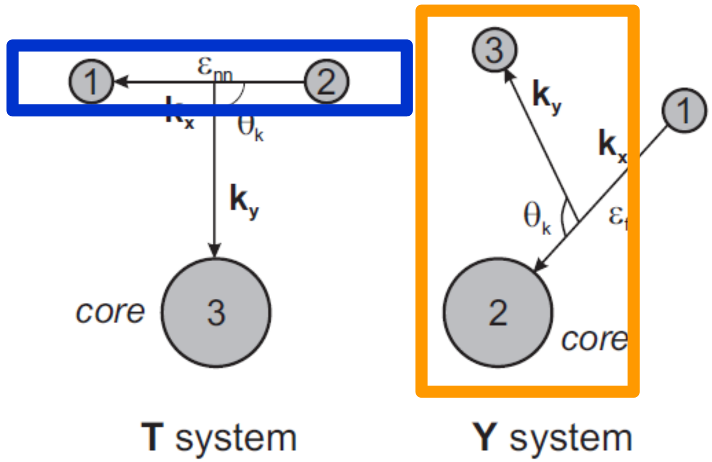
Dineutron model – A. Volya (FSU)
EPJ Web of Conf. **38,** 03003 (2012).

^{13}Li Correlations



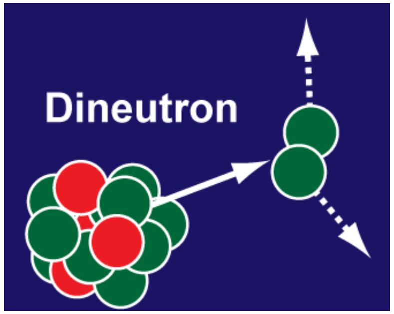


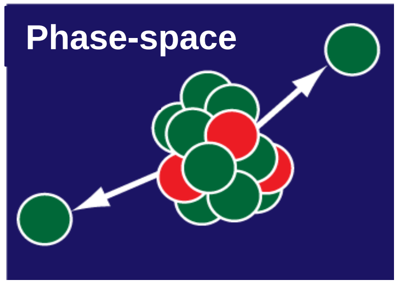
Strong nn correlations in the "dineutron region" *again*…

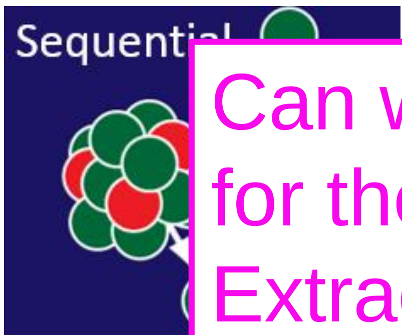


Causality cuts applied

What we learned from the correlations:

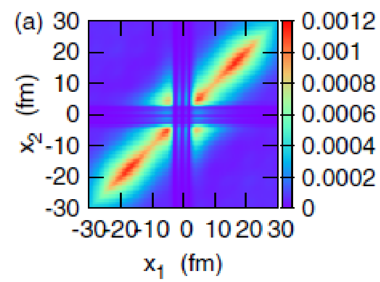






- Simple descriptions provide basic picture of the correlations.
- Strong nn correlations observed
- Need full 3-body calculations to describe the evolution of the system and **connect the measured correlations with initial state or wavefunction of the system.**

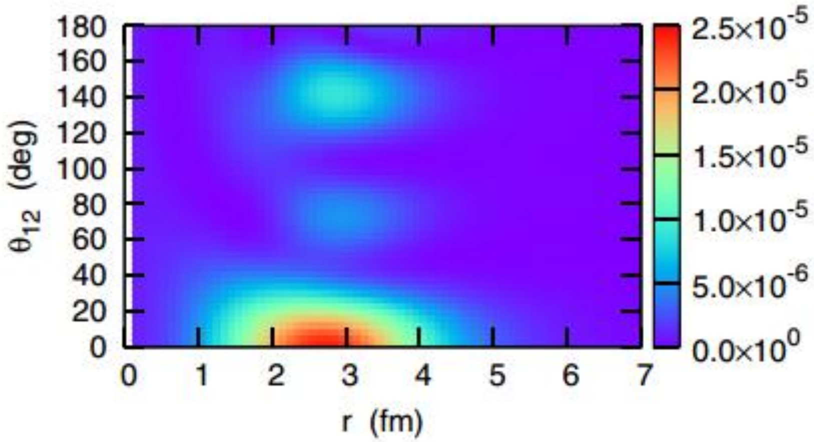
Can we improve the predictions for the decay correlations?
Extract additional information?



Hagino, Vitturi, Perez-Bernal, and Sagawa. JPG 38, 015105 (2011).

^{26}O Correlations

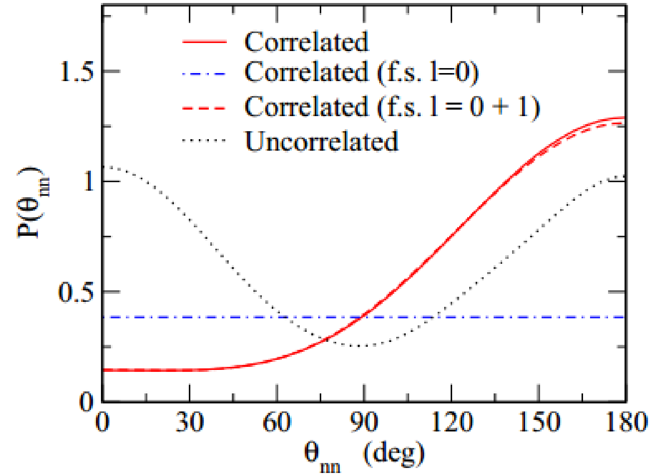
^{26}O g.s. wavefunction (dineutron configuration)



Hagino and Sagawa. PRC 2014

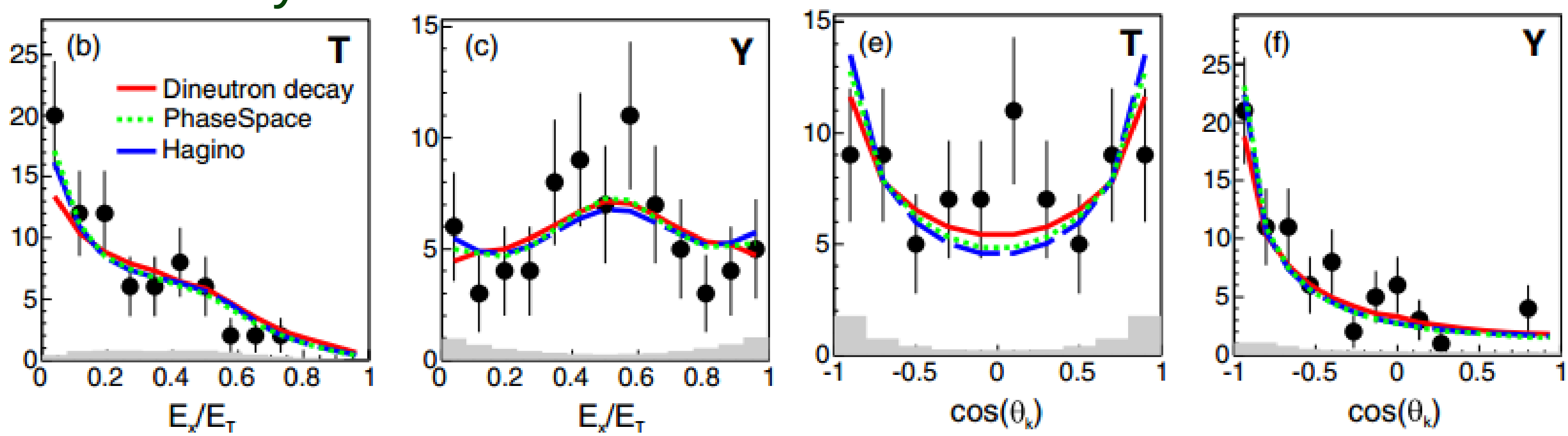
2n decay

manifested as emission of 2n “back to back”



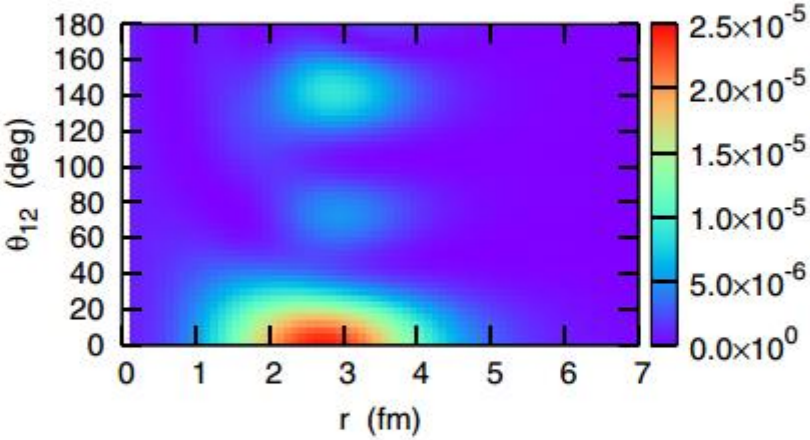
Experimentally measured correlation not sensitive to decay mode.

Kohlev et al. PRC **91**, 034323 (2015).

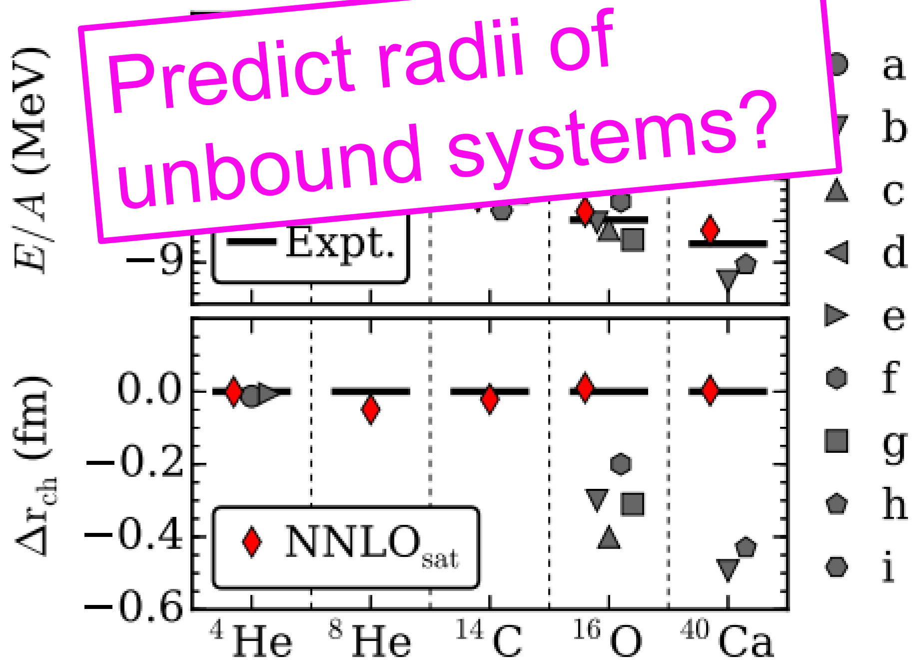


26O – radius?

^{26}O g.s. wavefunction
(dineutron configuration)



Hagino and Sagawa. PRC 2014



Predict radii of unbound systems?

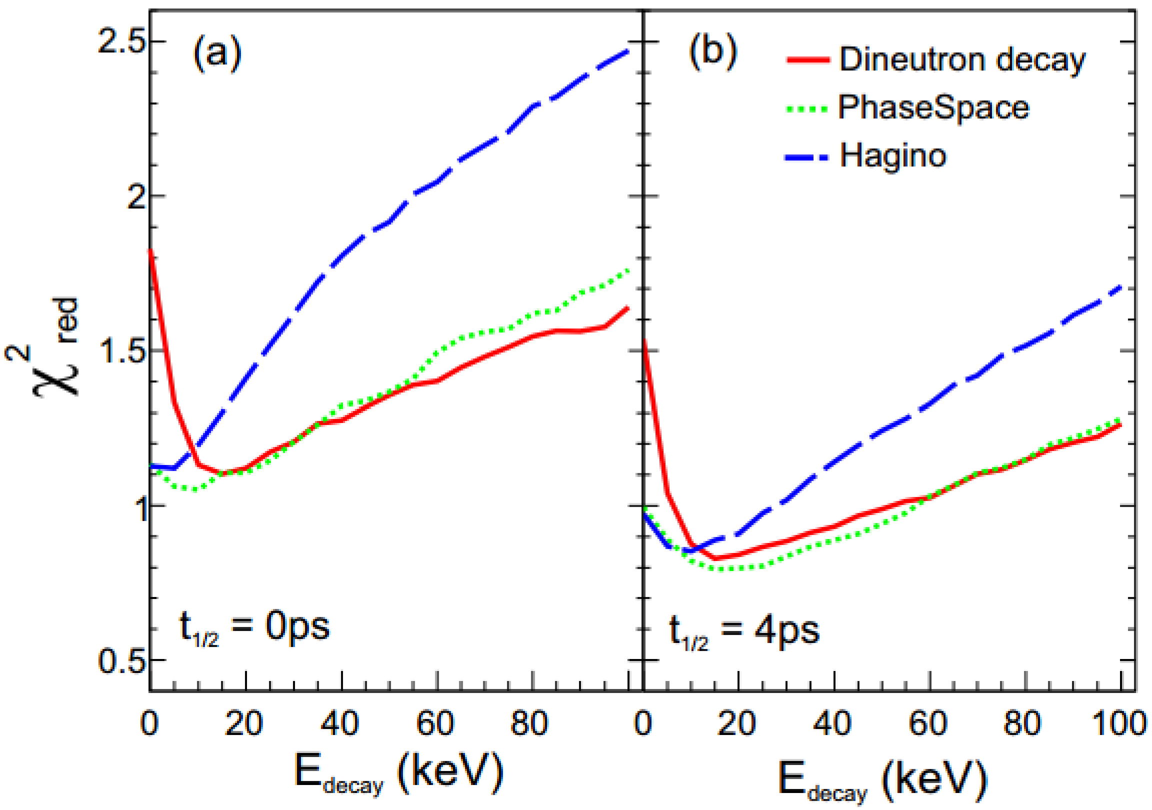
Ekstrom et al. PRC(R) (2015)

Grigorenko et al. PRL (2013)

Formally, the radius of the decaying system (negative separation energy) is infinite. Practically, for systems with radioactive lifetimes, the radial characteristics are reliably saturated for integration in the subbarrier region and we can investigate long-lived ^{26}O in terms of halo structure. In our calculations we have found values around 5.7 fm for the "valence" neutron rms radius in ^{26}O. Such values are typical for ^{11}Li which possesses the most extreme $2n$ halo known so far. The huge halo of ^{11}Li is

^{26}O Correlations

However, the correlations do provide a sensitivity to the decay energy of the ground-state.



NEW LIMIT:

^{26}O ground-state

E_{decay} < 53 keV

Using correlations of Hagino

E_{decay} < 15 keV

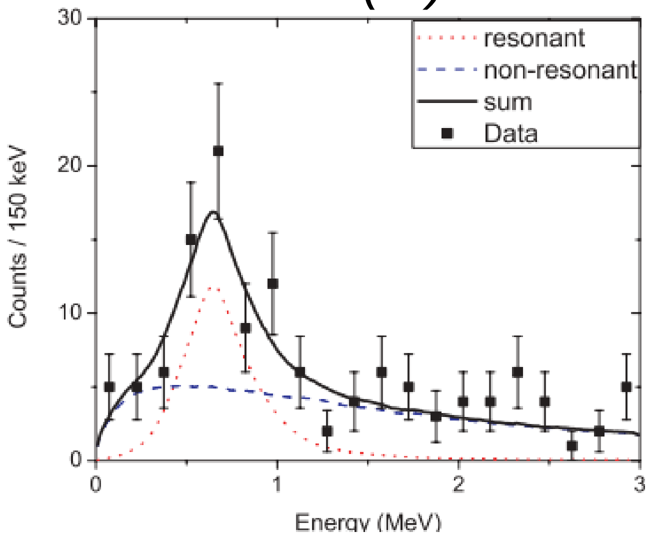
Kohley et al. PRC **91,** 034323 (2015).

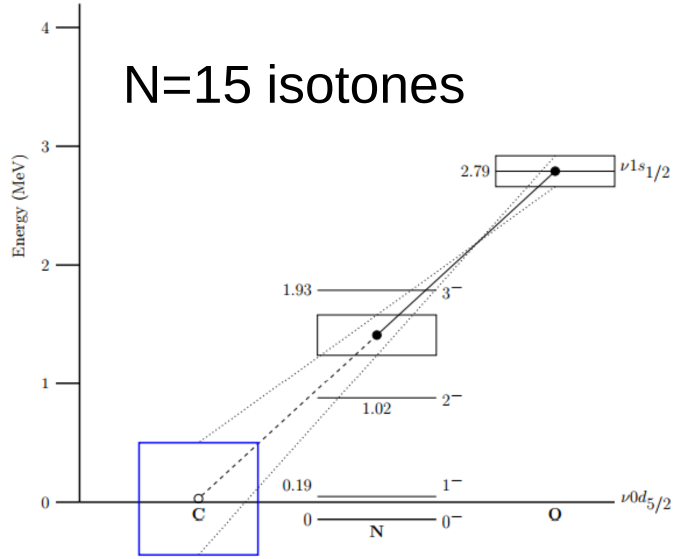
^{23,24}N request

What is known about unbound N states/nuclei?

M.J. Strongman (MoNA). PRC(R) 2009

unbound state (3-) in ^{22}N





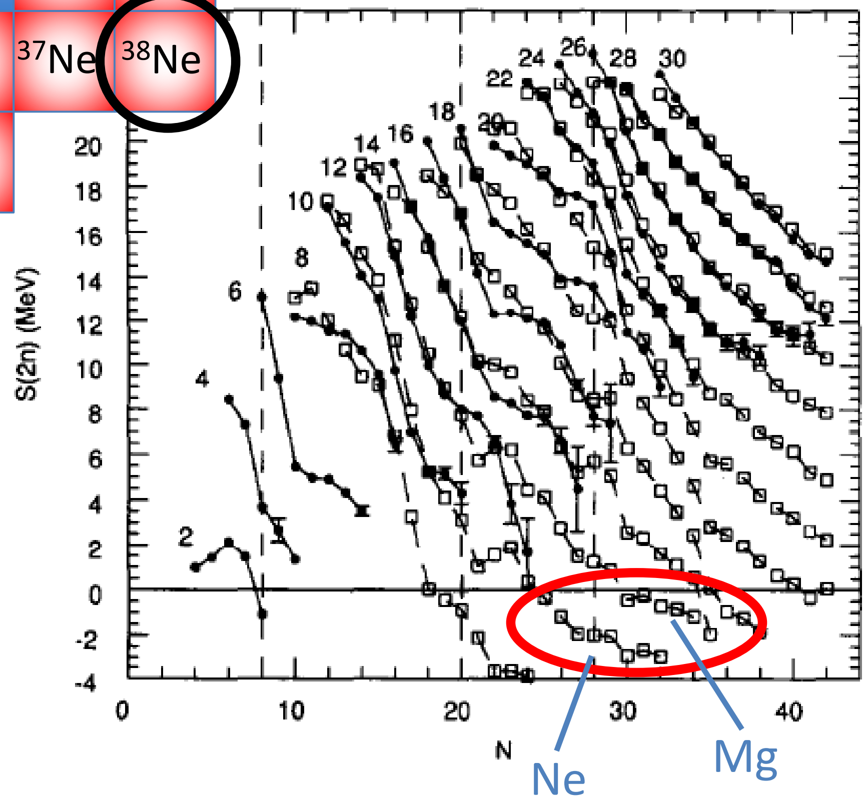
MoNA student has data with unbound states in ^{23}N* (N=16)

MoNA experimental proposal to measure ground-state and excited states ^{24}N (N=17)

Future: Beyond the dripline in the *pf*-shell

^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al	^{37}Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al	^{42}Al
^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg	^{36}Mg	^{37}Mg	^{38}Mg	^{39}Mg	^{40}Mg	^{41}Mg
^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na	^{35}Na	^{36}Na	^{37}Na	^{38}Na	^{39}Na	
^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne	^{33}Ne	^{34}Ne	^{35}Ne	^{36}Ne	^{37}Ne	^{38}Ne	
^{26}F	^{27}F	^{28}F	^{29}F	^{30}F	^{31}F	^{32}F	^{33}F	^{34}F	^{35}F			

- The single particle energies within the $f_{7/2}$ orbit change very little with increasing neutron number
- The separation energies stay almost constant
- Potential for several neutron unbound isotopes with low decay energy



B.A. Brown, Prog. Part. Nucl. Phys. 47 (2001) 517

Summary

Discussion topics

- Confusion in ^{9}He and ^{10}He
- Level structure of ^{12,13}Li
- ^{13}Be puzzle
- Evidence for 2n radioactivity (^{26}O)
- 3-body correlations (^{13}Li, ^{16}Be, ^{26}O)
- Nitrogen Request [^{23}N*, ^{24}N(g.s.)]

Many open questions for these open shell nuclei.

Theoretical guidance would be appreciated and used.

Information such as
- g.s. to g.s. energies
- level spacing
- spin-parity assignments
- decay widths

Acknowledgments

Thomas Baumann
Daniel Bazin
Greg Christian
Mike Jones
Shea Mosby
Michelle Mosby
Jenna Smith
Jesse Snyder
Artemis Spyrou
Anthony Kuchera
Michael Thoennessen

Hope College:
E. Lunderberg
P. A. DeYoung

Theory
Alex Brown
Jeff Tostevin
Alexander Volya
Leonid Grigorenko