Probing exotic structure using one-nucleon transfer reactions

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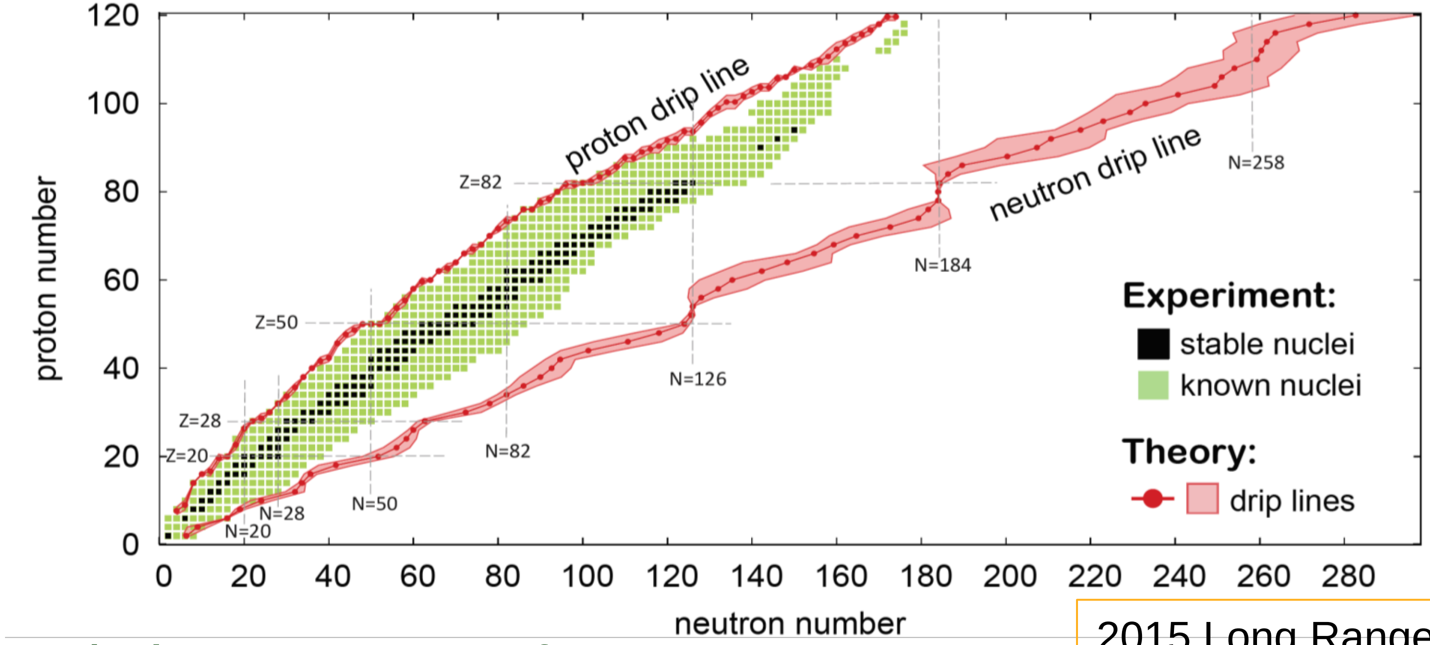
Outline

- Overarching questions of nuclear physics

  ----- Migration of shell gaps and magic numbers

- Understanding of exotic nuclei ----- Examples: Be isotopes
  - ^{11}Be negative parity states
  - ^{12}Be intruder states and single-particle configuration mixing
- Resonances in weakly-bound nuclei and the role of continuum
  - ^{12}Be resonances with intruder configurations
- Instrumentation for transfer reactions
- Approaching the nuclear force : N-N effective interaction ----- Example: ^{22}F $1d_{5/2}$-orbital
- Opportunities with FRIB
  - Commissioning of the AT-TPC and SOLARIS using long-lived beams

Overarching questions of nuclear physics

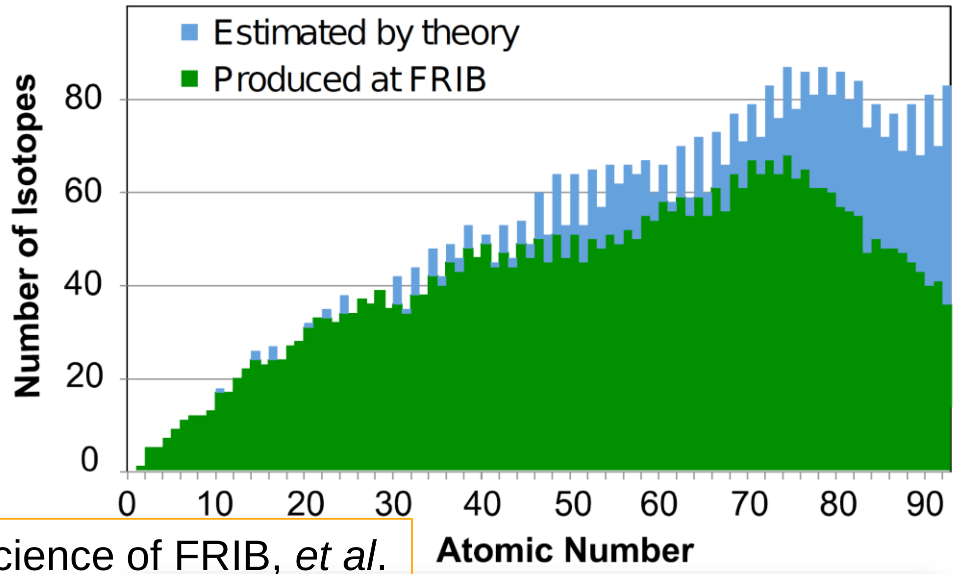


2015 Long Range Plan Reaching for the Horizon https://science.energy.gov/np/nsac/.

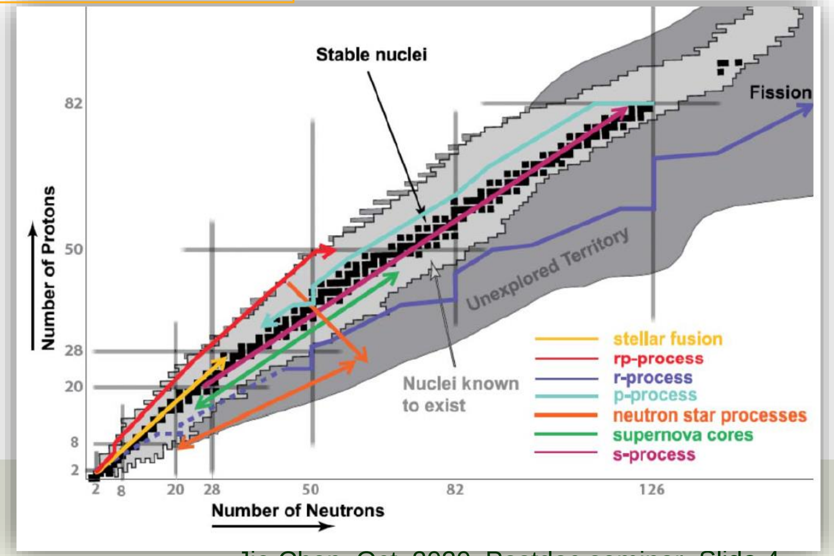
- Where do nuclei and elements come from?
- What combinations of neutrons and protons can form a bound atomic nucleus?
- New experimental insights on rare nuclei to guide theoretical developments.
- Integration low-energy nuclear experiments and theory with knowledge from astrophysics and computational science.

Overarching questions of nuclear physics

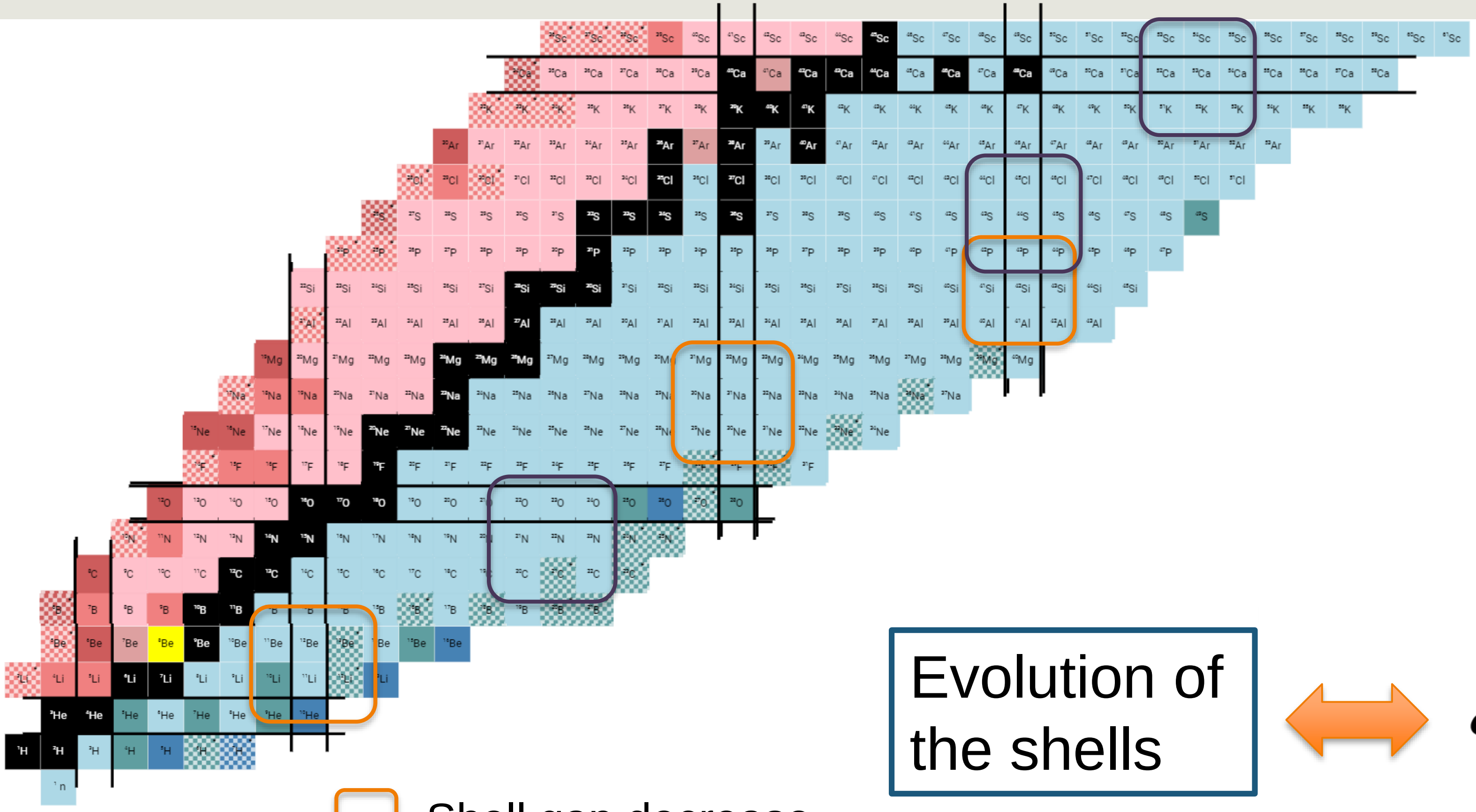
- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- Advanced understanding of the nature of weakly-bound nuclei by measurement of exotic and dripline nuclei
- Determine shell structure and test configuration interaction theories
- Measure resonances in weakly-bound nuclei and test the role of continuum



The Science of FRIB, *et al*.



Migration of Shell Gaps and Magic Numbers

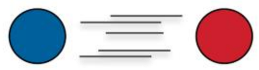


Shell gap decrease

Shell gap increase

Evolution of the shells

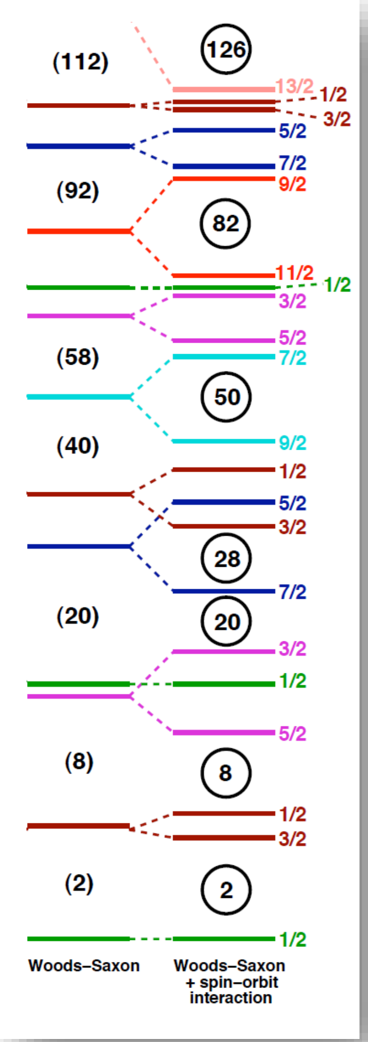
Nucleon-Nucleon interactions



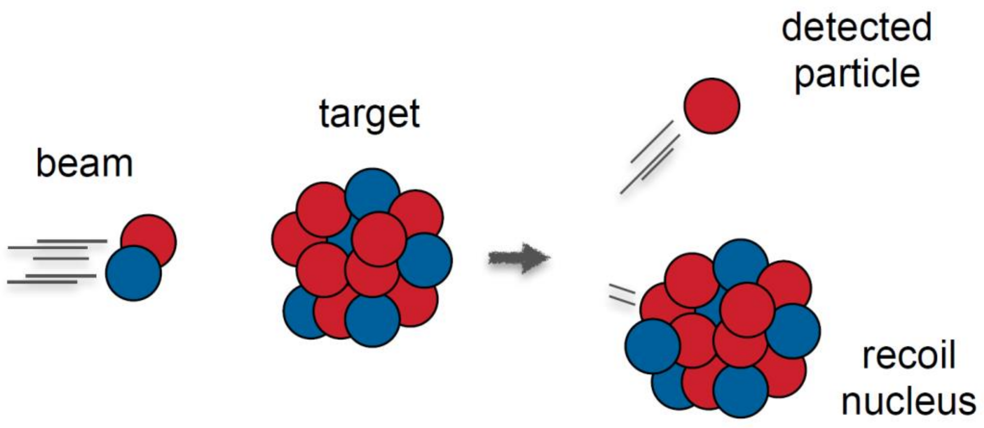
$$\varepsilon_i \; + \; V_{ij}^{JT}$$

Effective Single-particle energy

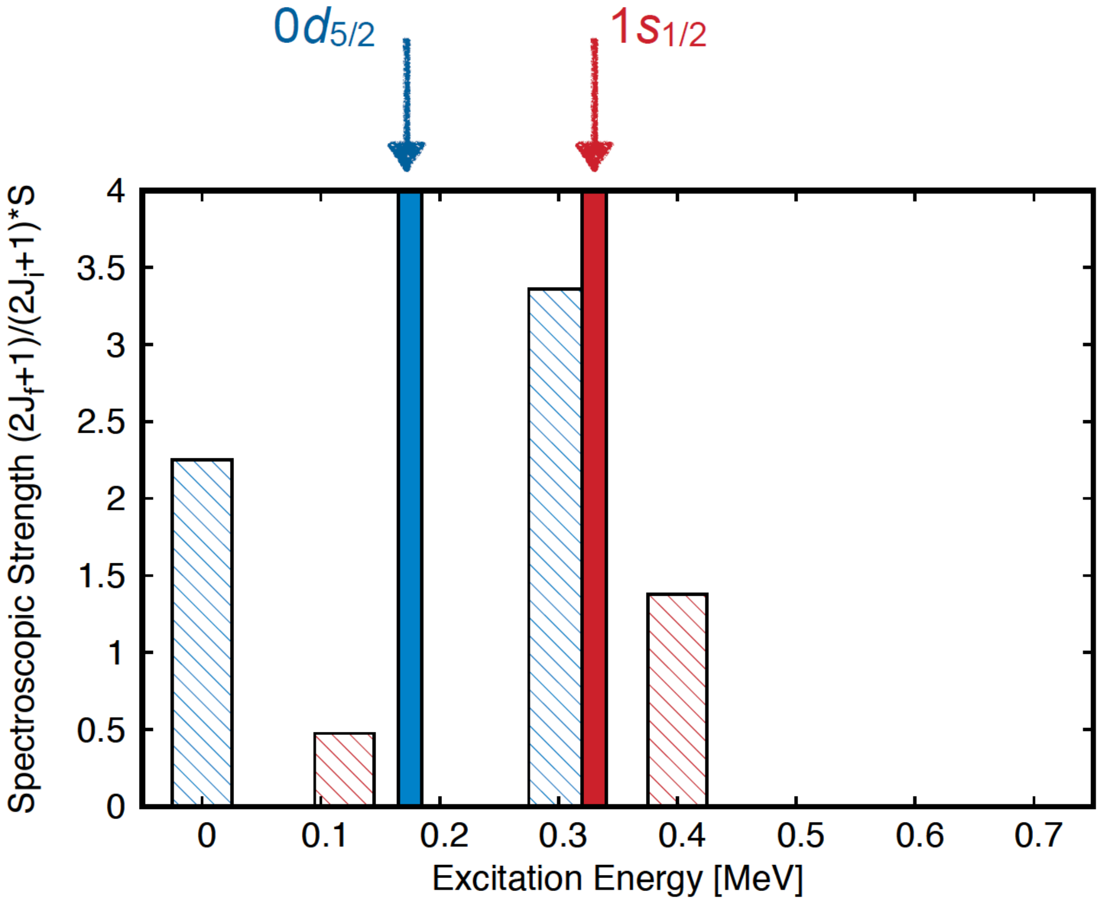
diagonal Terms



Tools to study the evolution of shells / N-N-interaction

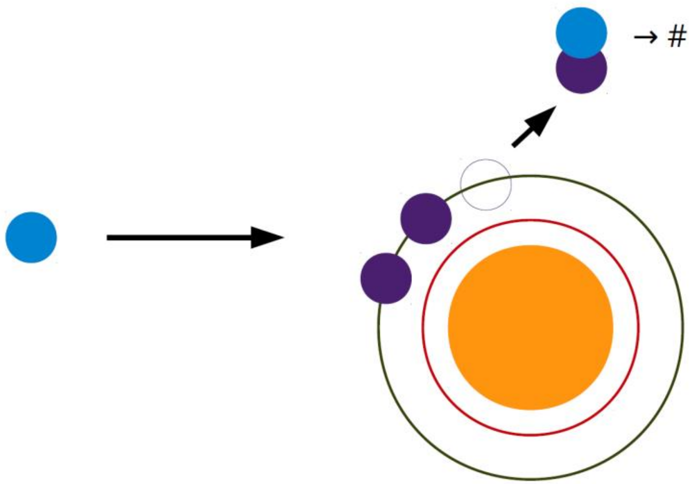


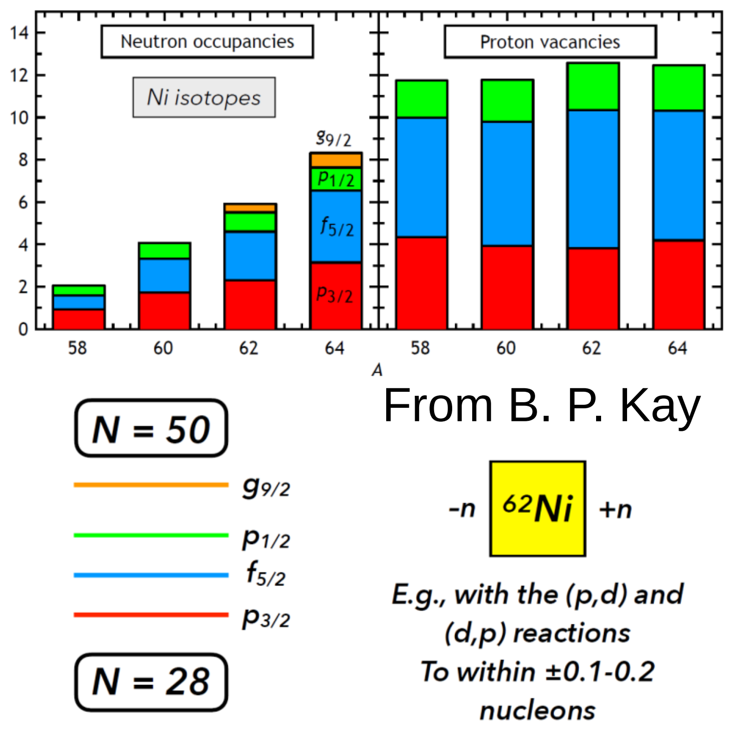
$$E_{centroid} = \frac{\sum (2j_f+1) S_{\ell j} * E_{ex}}{\sum (2j_f+1) S_{\ell j}}$$



Probing the occupancy and vacancy of the orbitals

- Single-neutron adding probes vacancies (# of holes)
- Single-neutron removal probes occupancies (# of particles)





From B. P. Kay

E.g., with the (p,d) and (d,p) reactions
To within ±0.1-0.2 nucleons

Quenching factor:

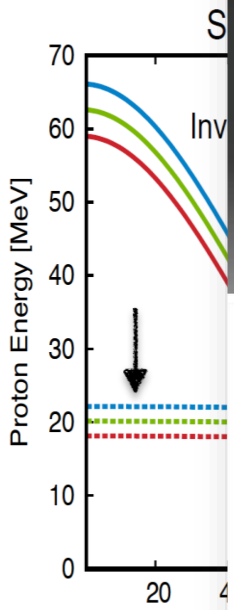
$$F_q \equiv \frac{1}{(2j+1)}\left[\Sigma\left(\frac{\sigma_{\exp}}{\sigma_{\mathrm{DW}}}\right)_j^{\mathrm{add}} + \Sigma\left(\frac{\sigma_{\exp}}{\sigma_{\mathrm{DW}}}\right)_j^{\mathrm{rem}}\right],$$

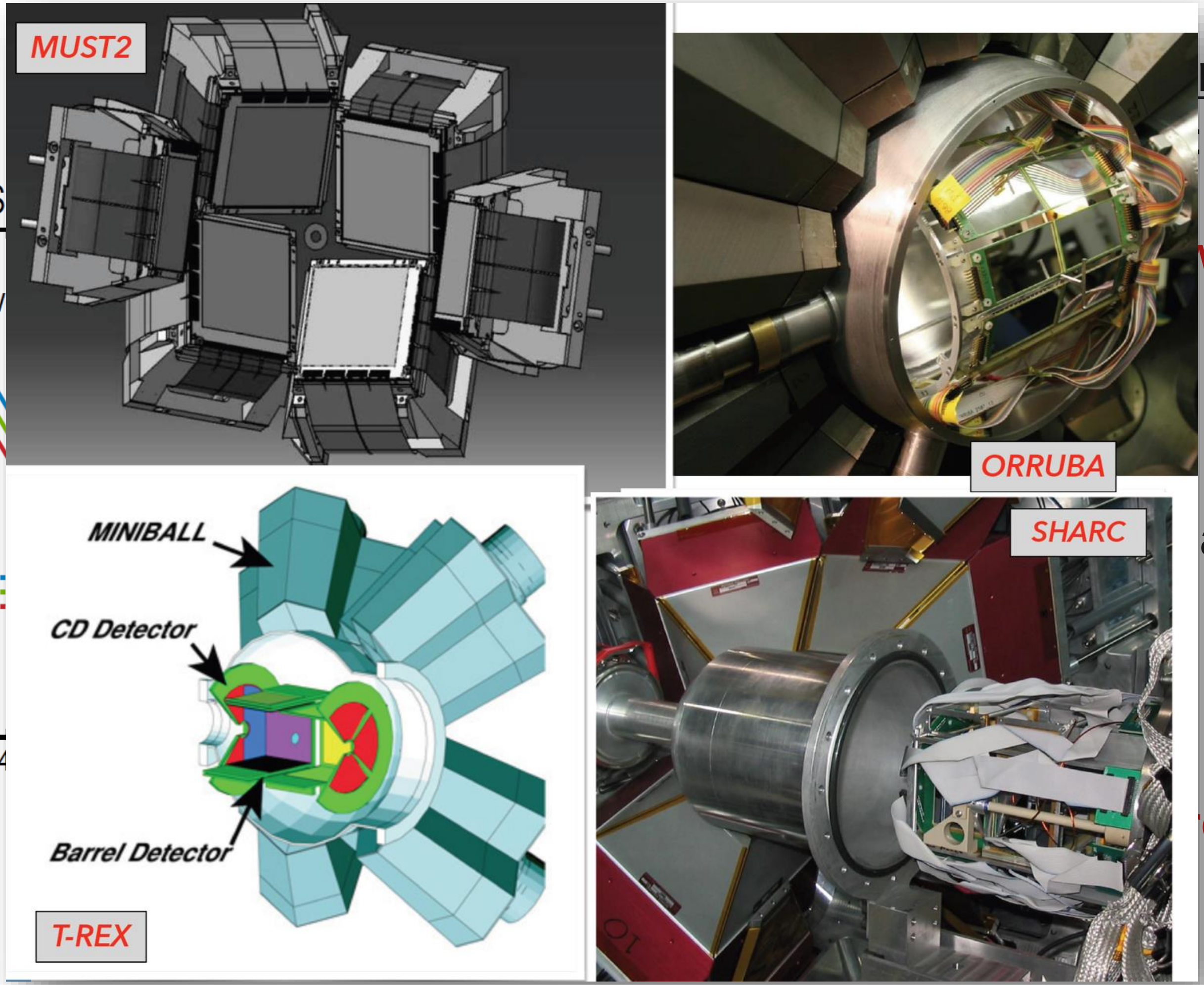
B. P. Kay et. al., PRL 111.042502 (2013)

- Constant value of 0.4~0.7 across all nuclei using consistent optical model parameters
- The Macfarlane-French sum rules can be used to normalize the spectroscopic factors

J. P. Schiffer et. al., PRL 108,022501(2012)

Kinematics: normal vs. inverse





nematics

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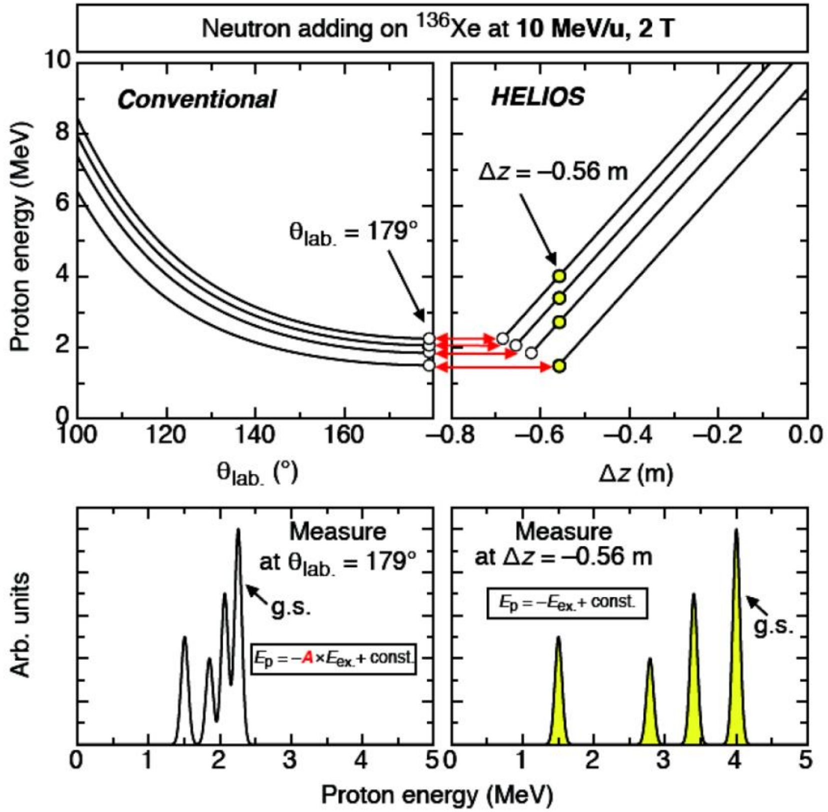
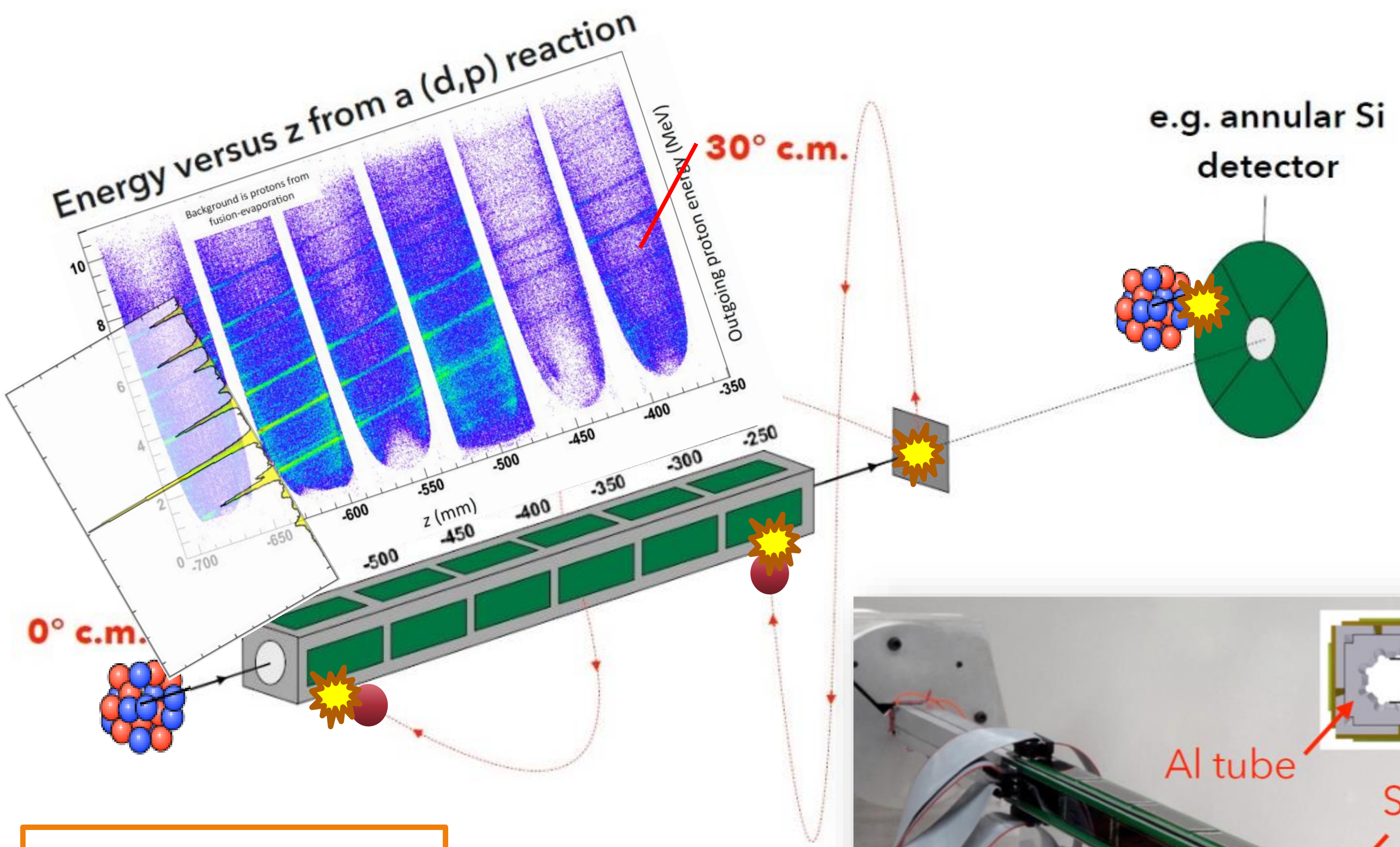
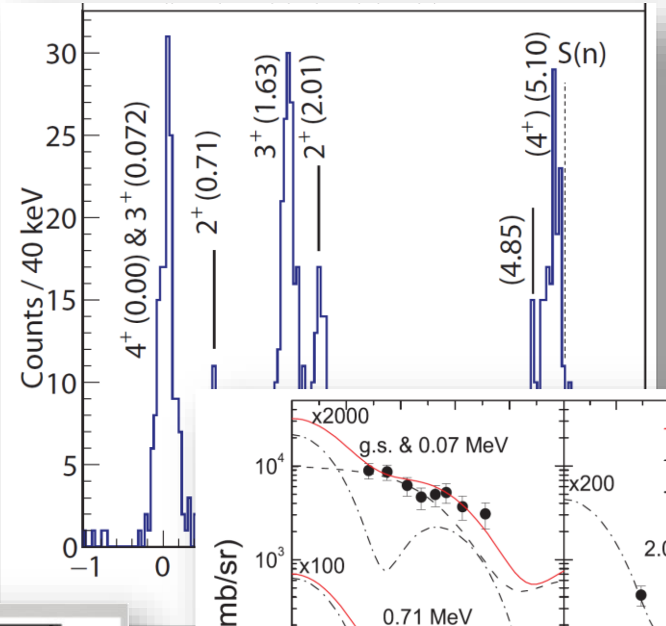
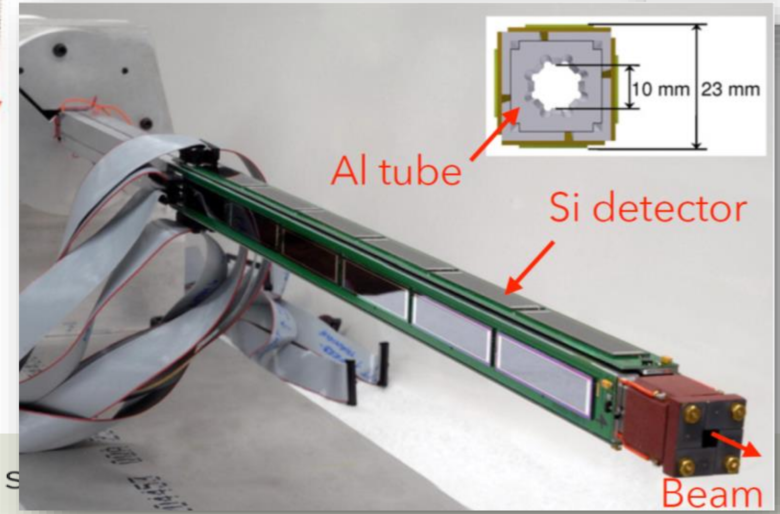
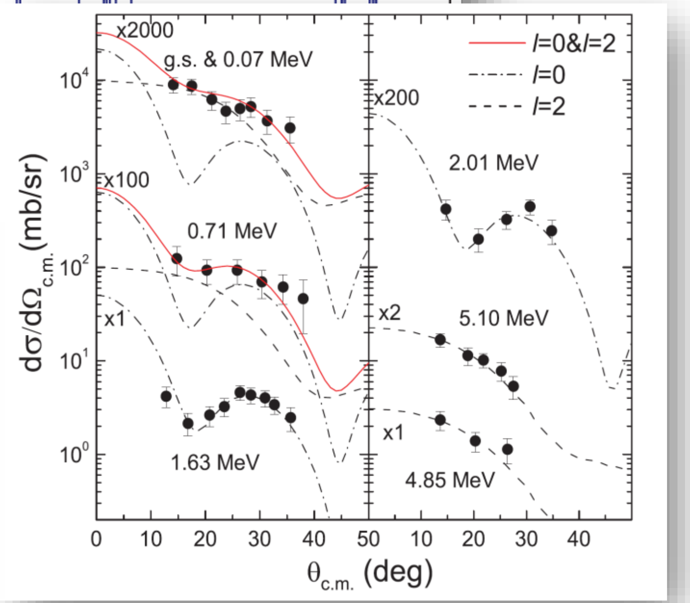


Approaching the nuclear force : N-N effective interaction





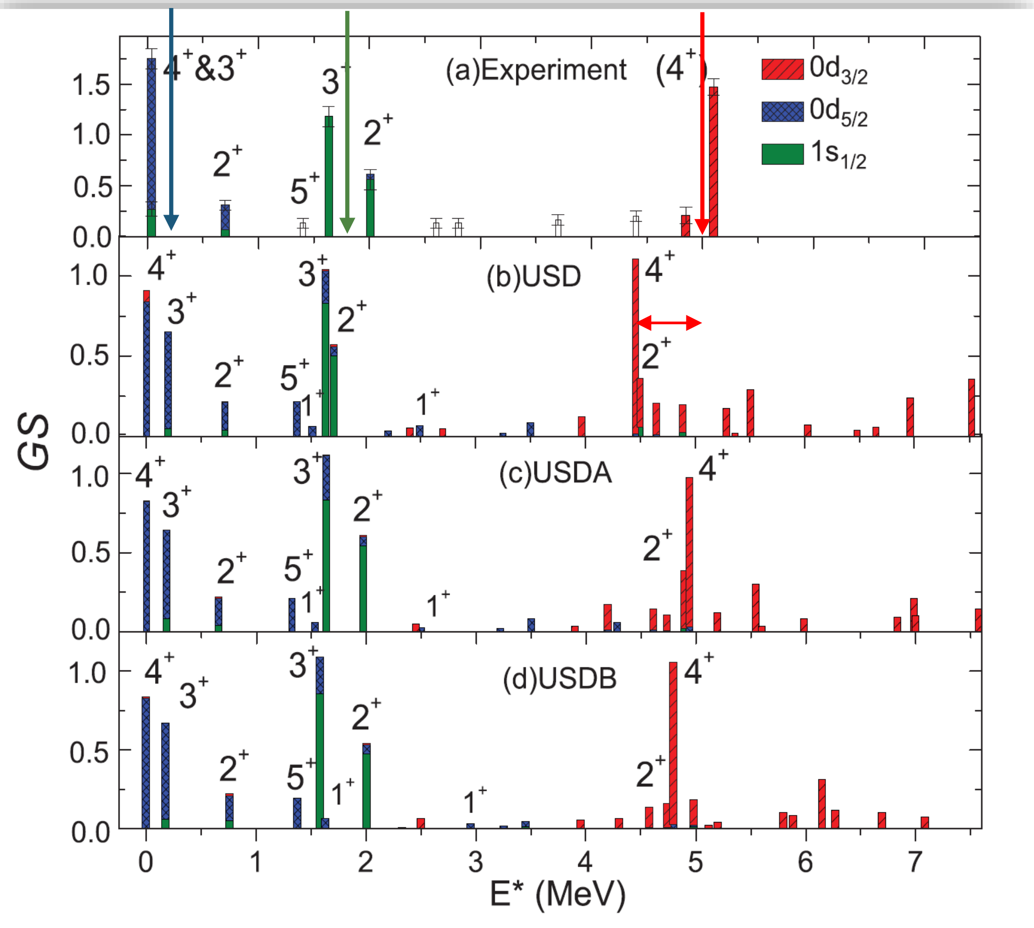




^{21}F 10 *A*MeV

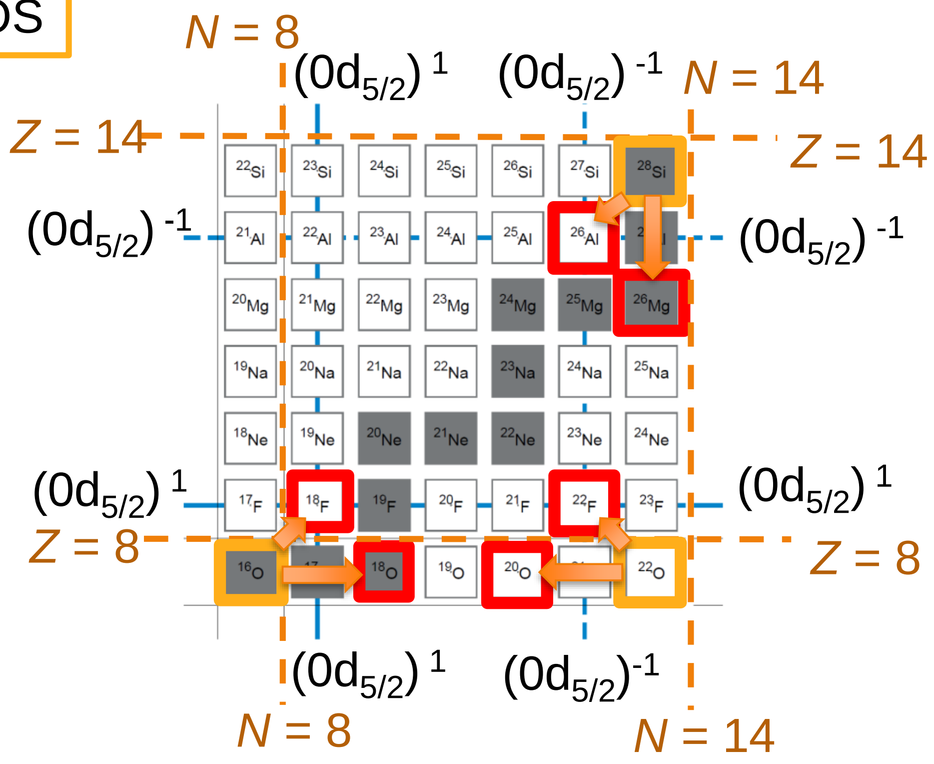
^{21}F(*d*,*p*)^{22}F

Approaching the nuclear force : N-N effective interaction



$^{21}F(d,p)^{22}F$ at 10 MeV/u using HELIOS

Matrix elements in the $1d_{5/2}$ orbital:



N=14 shell gap in ^{22}F : 1.63(6) MeV
Lower limit for *N*=16 shell gap: 3.27(6) MeV

J. Chen *et al*. Phys. Rev. C 98, 014325 (2018)

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National Science Foundation
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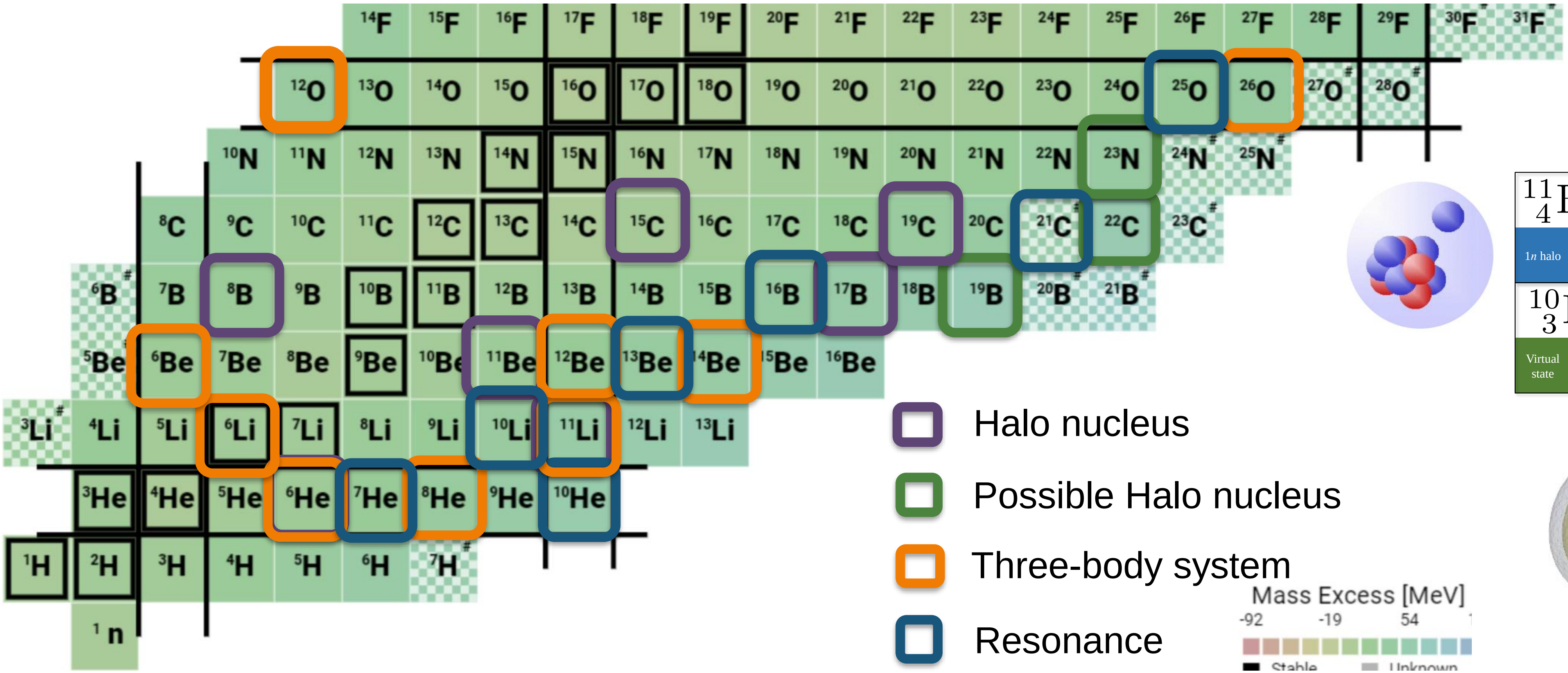
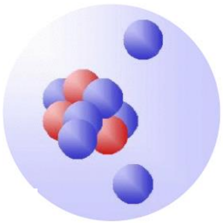
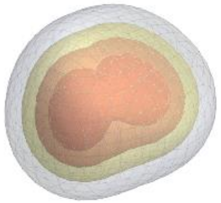
Understanding of exotic nuclei

- Halo, Borromean nuclei, three body system, intruder states
- New experimental insights on rare nuclei to challenge theoretical predictions.

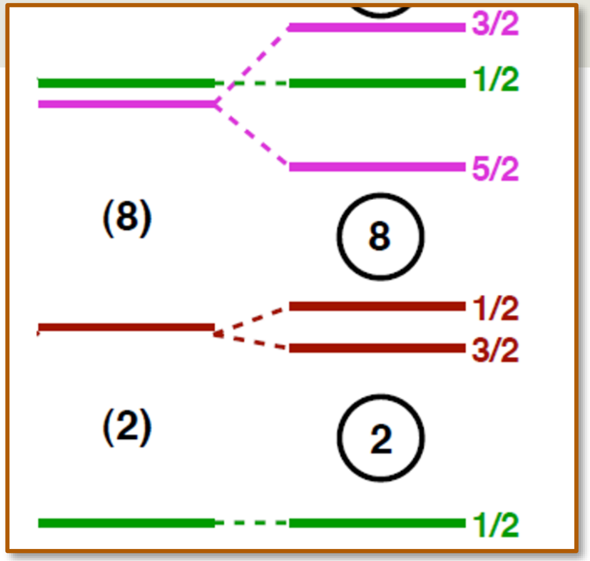


$^{11}_{4}\mathrm{Be}_{7}$		$^{12}_{4}\mathrm{Be}_{8}$
1*n* halo	Parity inversion	Clusterization
$^{10}_{3}\mathrm{Li}_{7}$		$^{11}_{3}\mathrm{Li}_{8}$
Virtual state	Parity inversion	2*n* halo

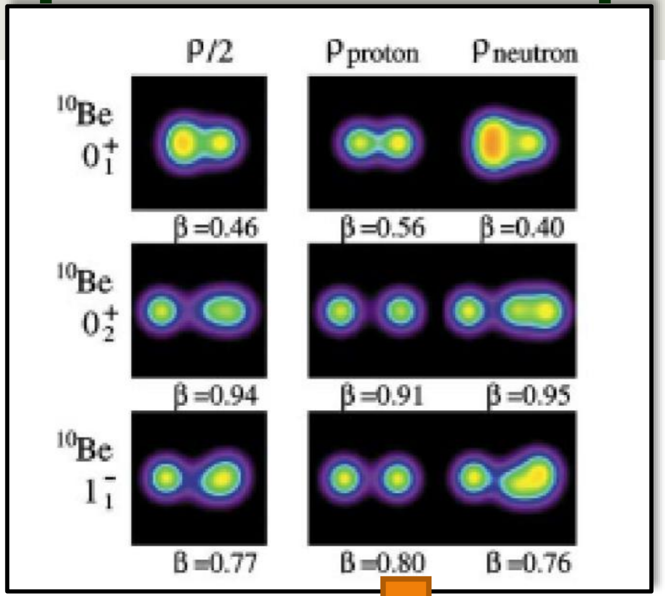




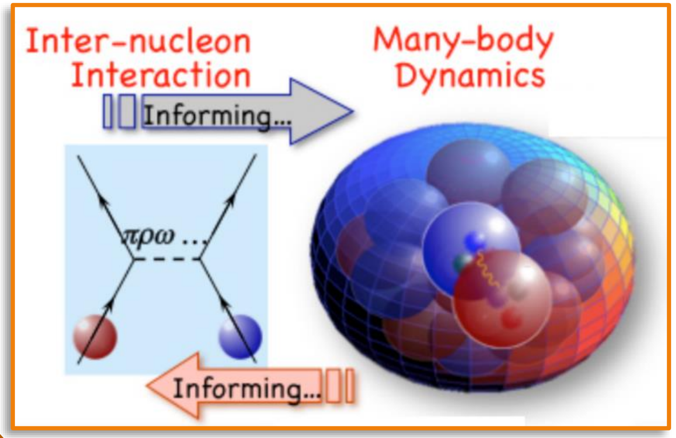
Examples: Be isotopes



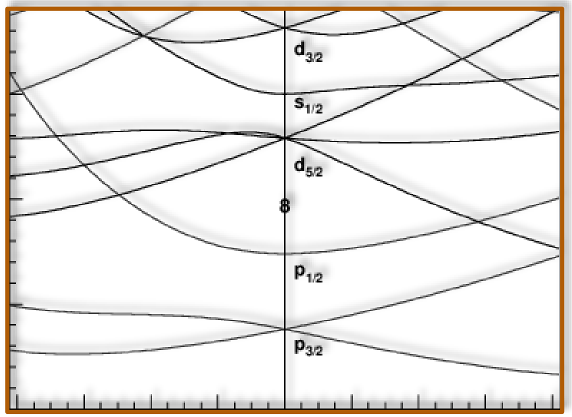
Shell model



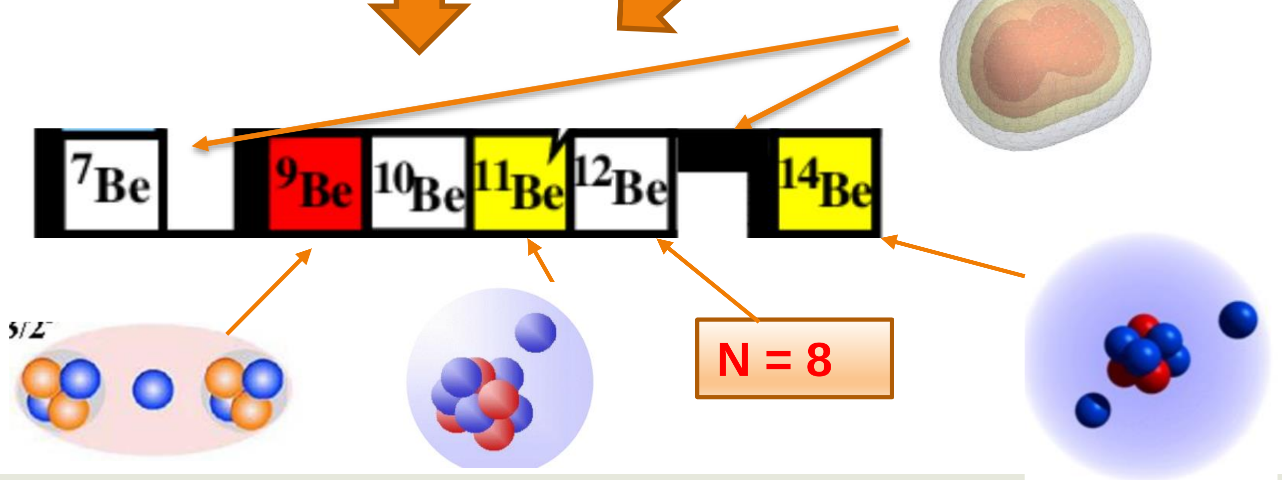
Cluster model



ab-initio method

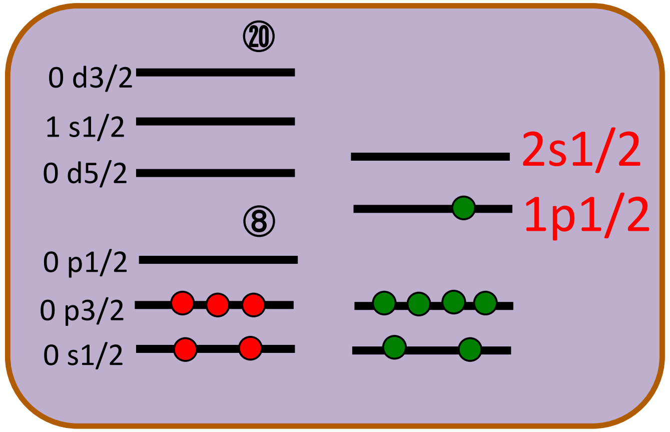


Nilsson model

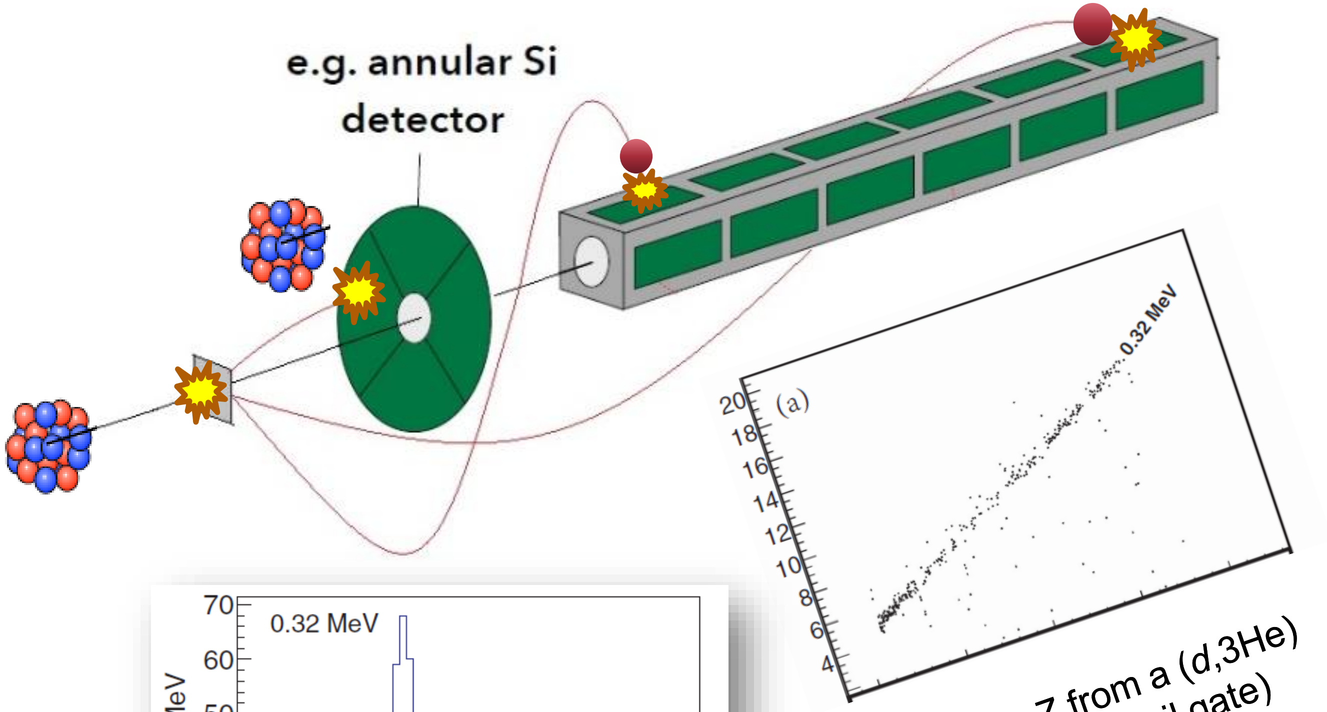


^{11}Be negative parity states

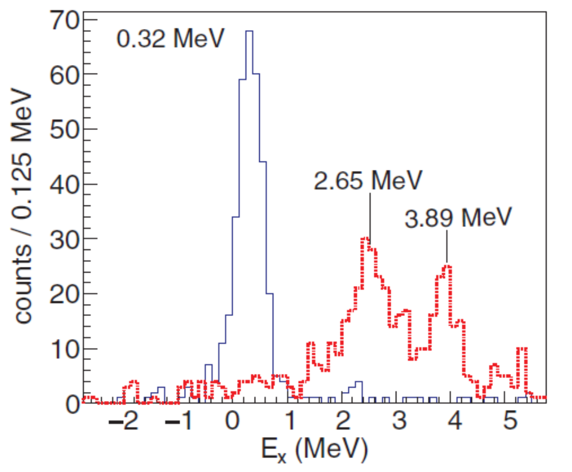
- Neutron loosely bound $S_n = 0.504$ MeV
- Larger radius R = 2.91 fm
- ^{10}Be core + n($2s_{1/2}$)
- g. s. $1/2^+$
- First excited: 1/2-



^{12}B (d, ^{3}He)^{11}Be



Energy vs. Z from a (d,3He) reaction (with recoil gate)

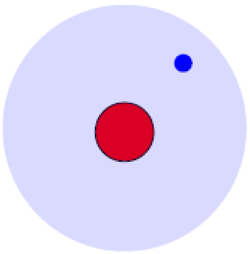


^{11}Be negative parity states

- Neutron loosely bound $S_n = 0.504$ MeV
- Larger radius R = 2.91 fm
- ^{10}Be core + n($2s_{1/2}$)
- g.s. $1/2^+$

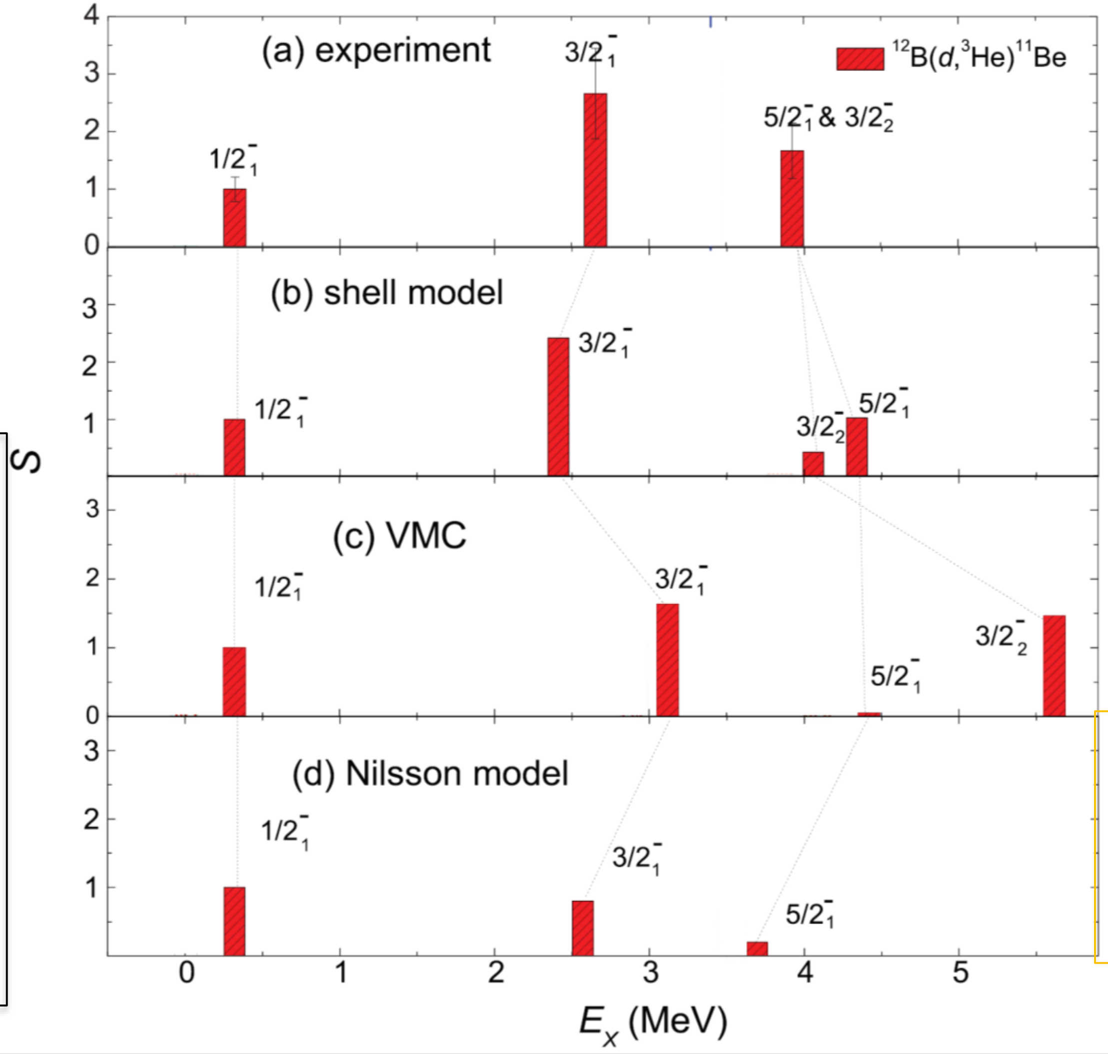
- Testing of various theories

Shell model



Nilsson model

Variational Monte Carlo calculations (VMC)



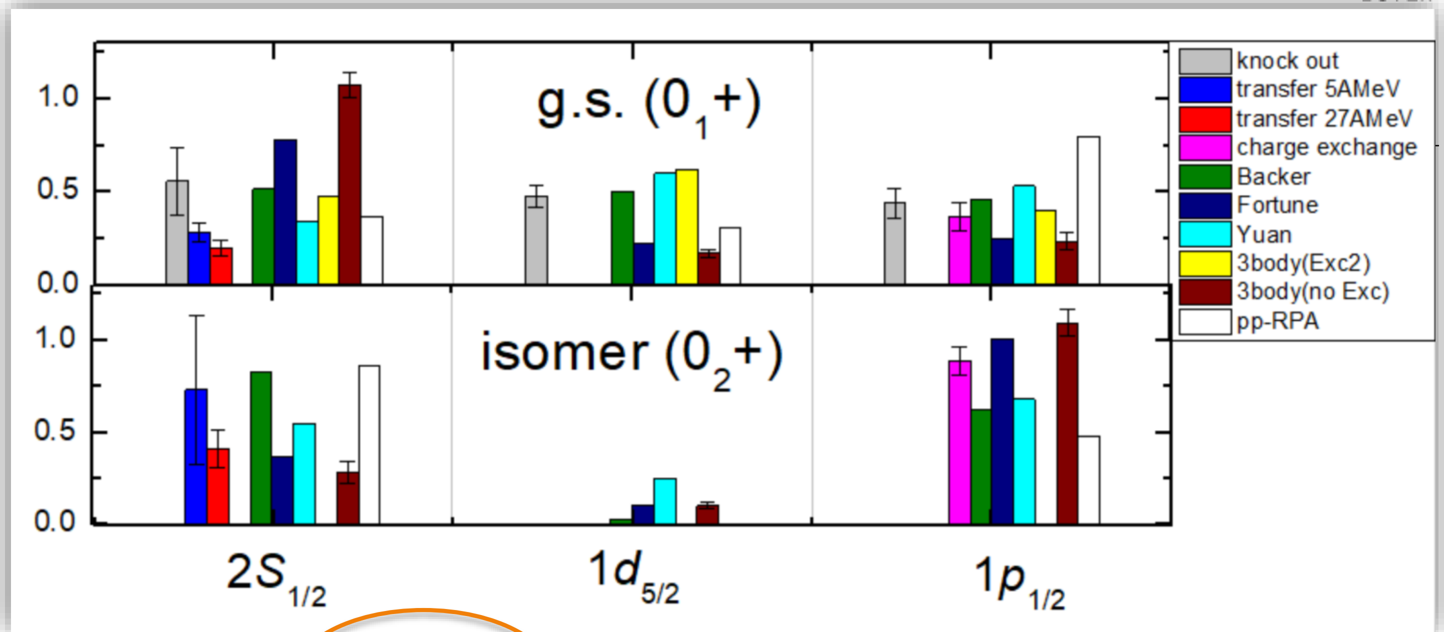
Not a pure strong coupling picture

J. Chen *et al*. Phys. Rev. C 100, 064314 (2019)

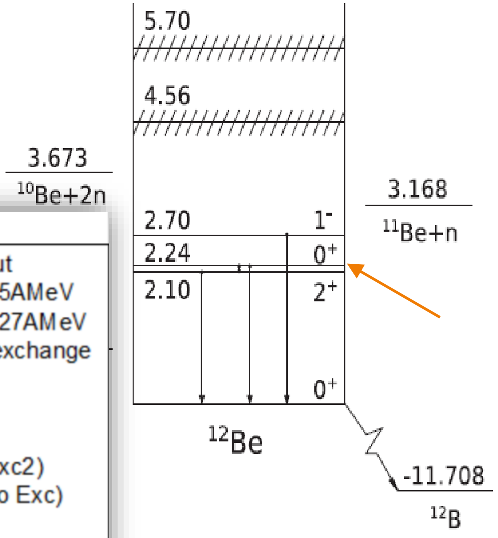
^{12}Be intruder states and single-particle configuration mixing

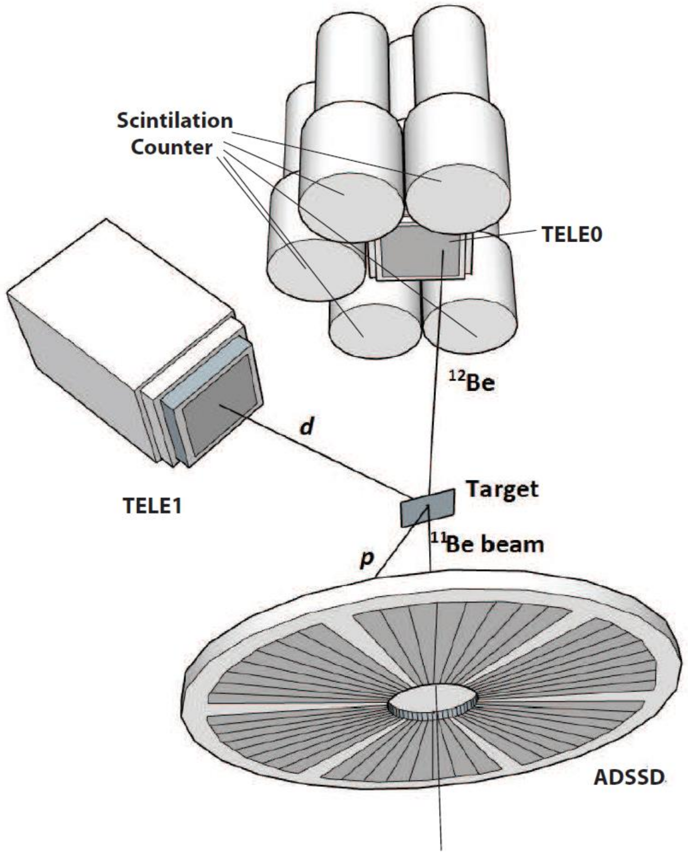
- **Breakdown** of conventional magic number： N=8
- **Isomeric state**： 0_2^+ 331(12) ns

E0 decay: e+e- pair **creation** **511keV γ ~83(2)%**



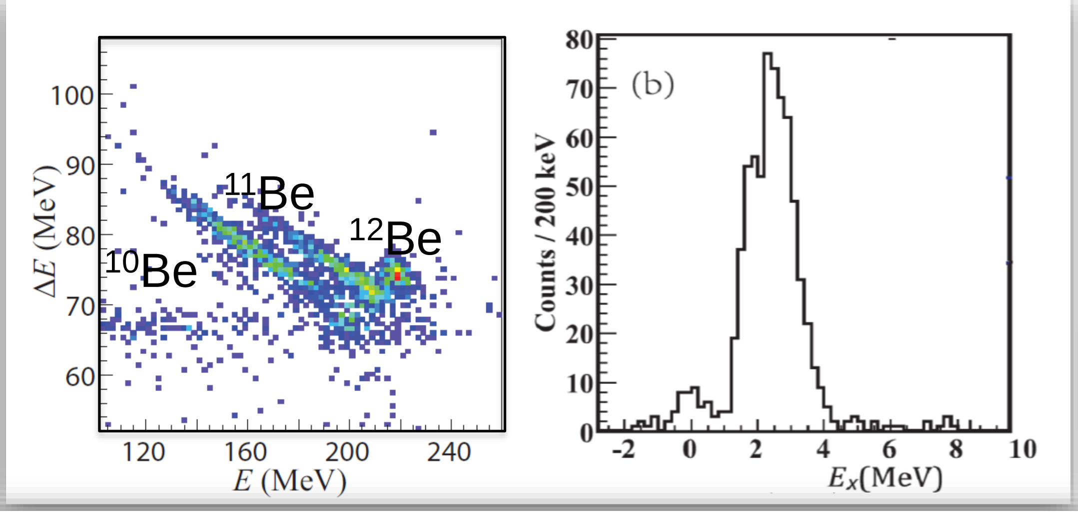
$$|0_i^+\rangle = a_i|1s_{1/2}^2\rangle + b_i|0d_{5/2}^2\rangle + c_i|0p_{1/2}^2\rangle \; (i = 1,2)$$

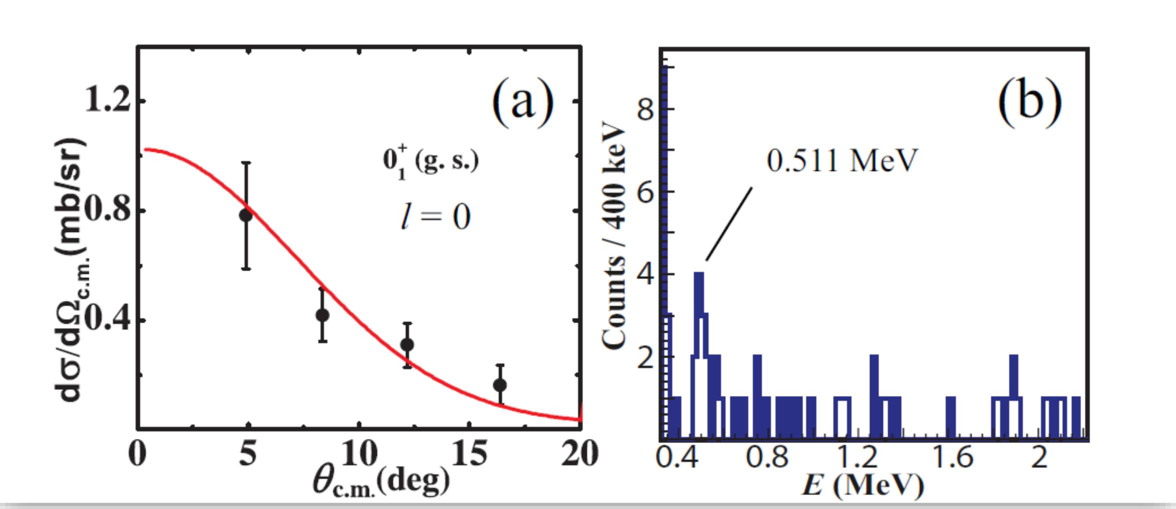




^{11}Be(*d,p*)^{12}Be
J. Chen, J. L. Lou,*et al*. RCNP E407

^{12}Be intruder states and single-particle configuration mixing





ADWA calculation

$$|0_i^+\rangle = a_i|1s^2_{1/2}\rangle + b_i|0d^2_{5/2}\rangle + c_i|0p^2_{1/2}\rangle \ \ (i = 1, 2)$$

$$a_i^2 + b_i^2 + c_i^2 = \alpha_i + \beta_i + \gamma_i = 1$$

$$a_1 * a_2 + b_1 * b_2 + c_1 * c_2 = 0$$

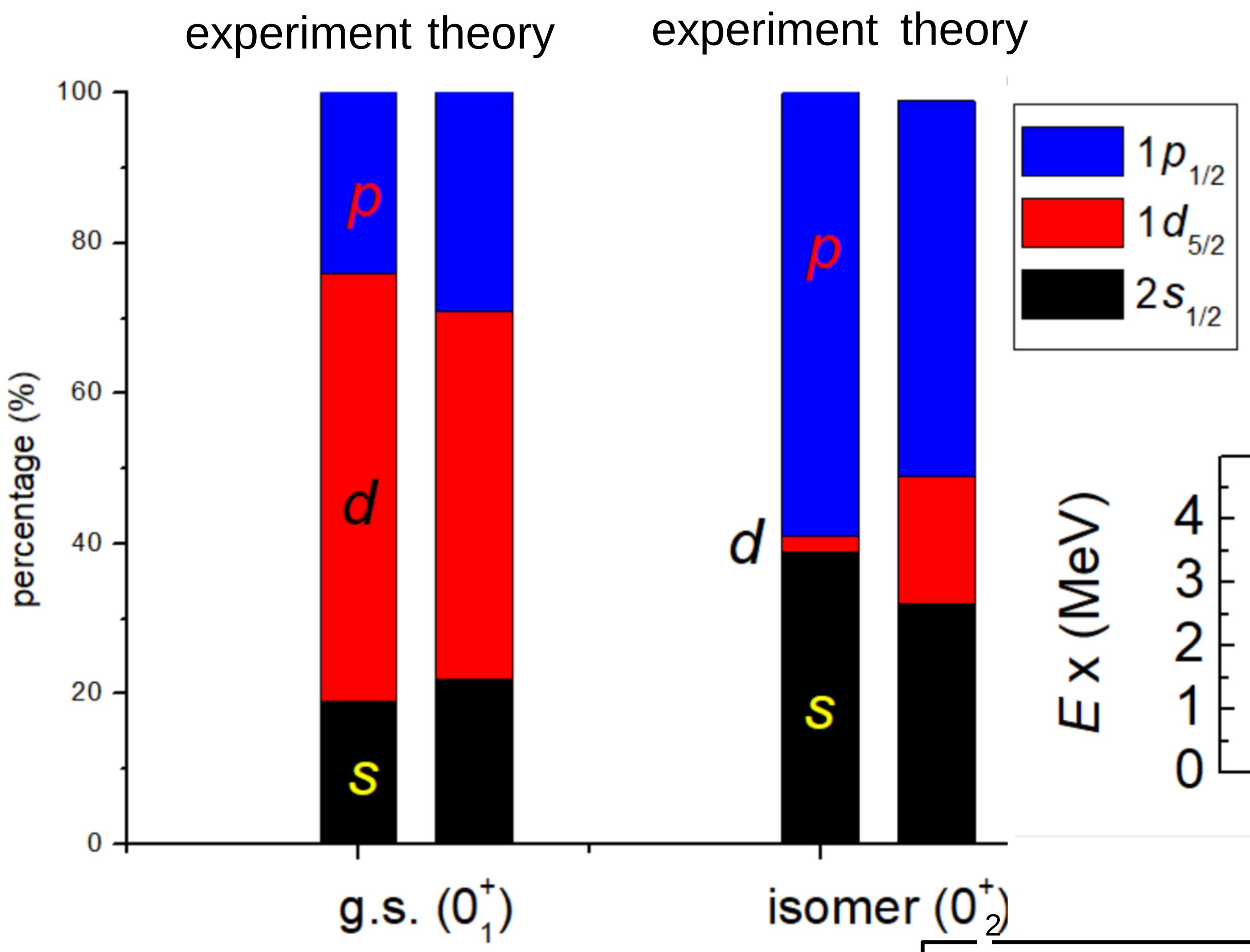
Ratio of $2s_{1/2}$ intensity: $\alpha_1/\alpha_2 = 0.20/0.41 = 0.49^{+0.15}_{-0.16}$

charge-exchange : γ_1= 0.24 and γ_2= 0.59

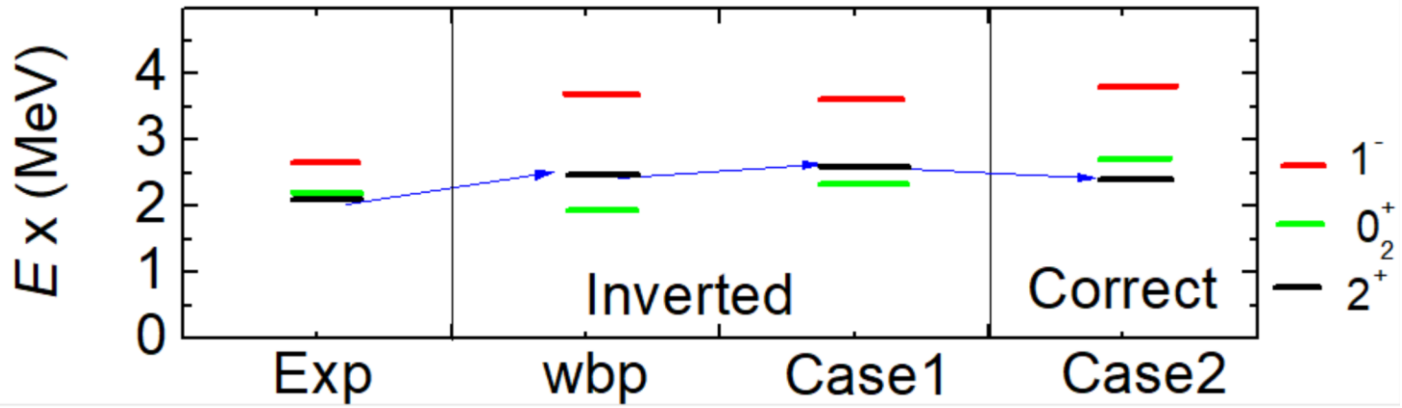
0_1^+			0_2^+		
$\alpha_1(\%)$	$\beta_1(\%)$	$\gamma_1(\%)$	$\alpha_2(\%)$	$\beta_2(\%)$	$\gamma_2(\%)$
($2s_{1/2}$)	($1d_{5/2}$)	($1p_{1/2}$)	($2s_{1/2}$)	($1d_{5/2}$)	($1p_{1/2}$)
19±7	57 ± 7		39 ± 2	2 ± 2	

- Quenching Factor: $F_q = \frac{SF_{\rm exp}}{I(2j+1)}$ =0.55(10)

^{12}Be intruder states and single-particle configuration mixing



- The g. s. of ^{12}Be is dominated by a *d*-wave intruder configuration
- Dramatic change compared to ^{11}Be
- Possibly due to stronger pairing in $d_{5/2}$-orbital
- Deformation lowered $d_{5/2}$-orbital energy



J. Chen *et al.* Phys. Lett. B 781 (2018) 412 – 416
J. Chen *et al.* Phys. Rev. C 94, 064620 (2016)
J. Chen *et al.* Phys. Rev. C 98, 014616 (2018)
J. Chen *et al.* Phys. Rev. C 93, 034623 (2016)

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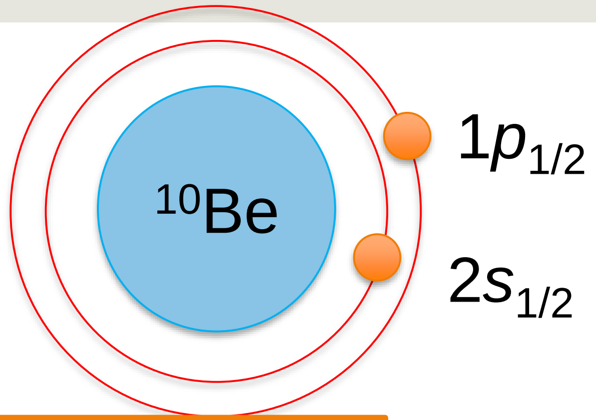
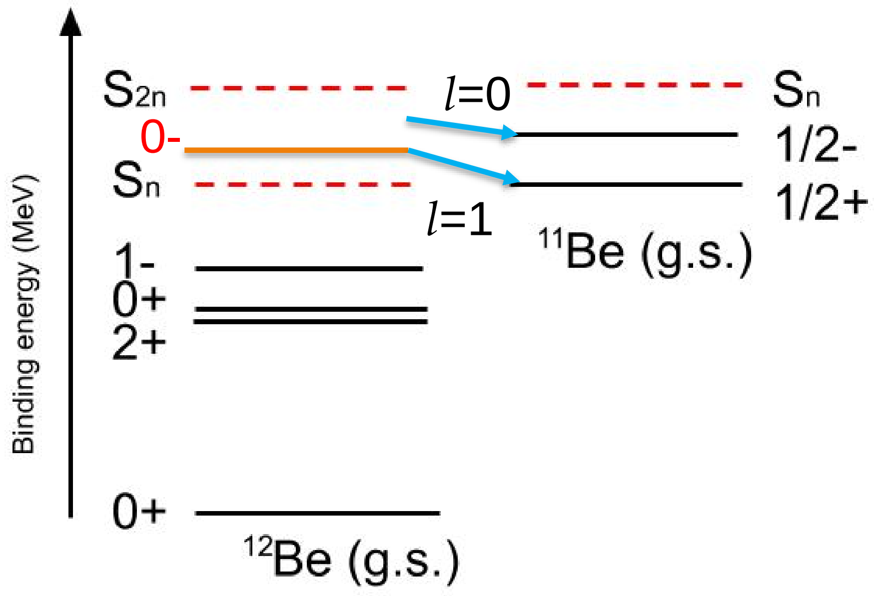
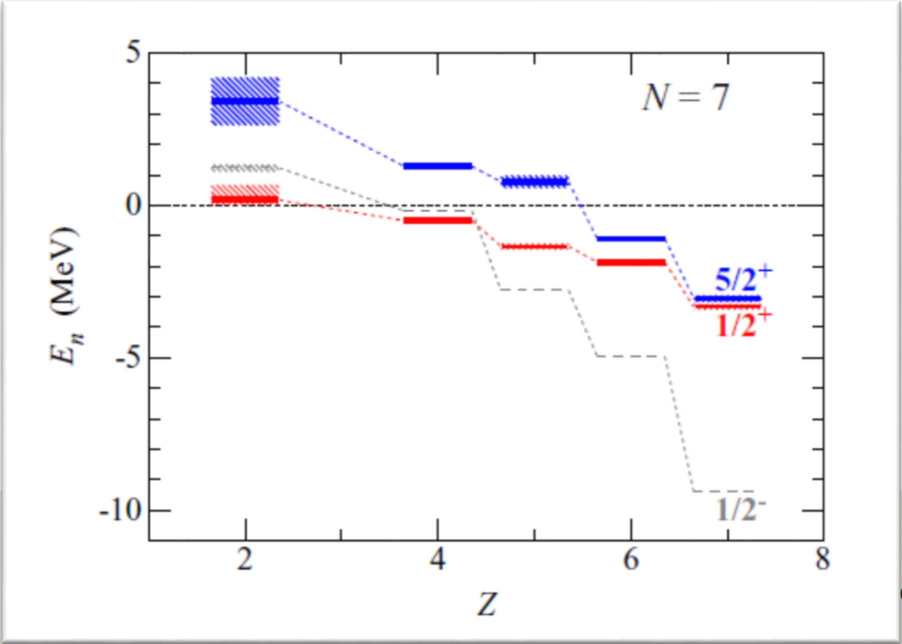
^{12}Be unbound states

- Breakdown of N=8 ⟷ 1p-1h across the N=8
- Neutrons in $2s_{1/2}$ and $1p_{1/2}$ ⟷ 1- and 0- states
- Previous measurements ruled out a bound 0- state

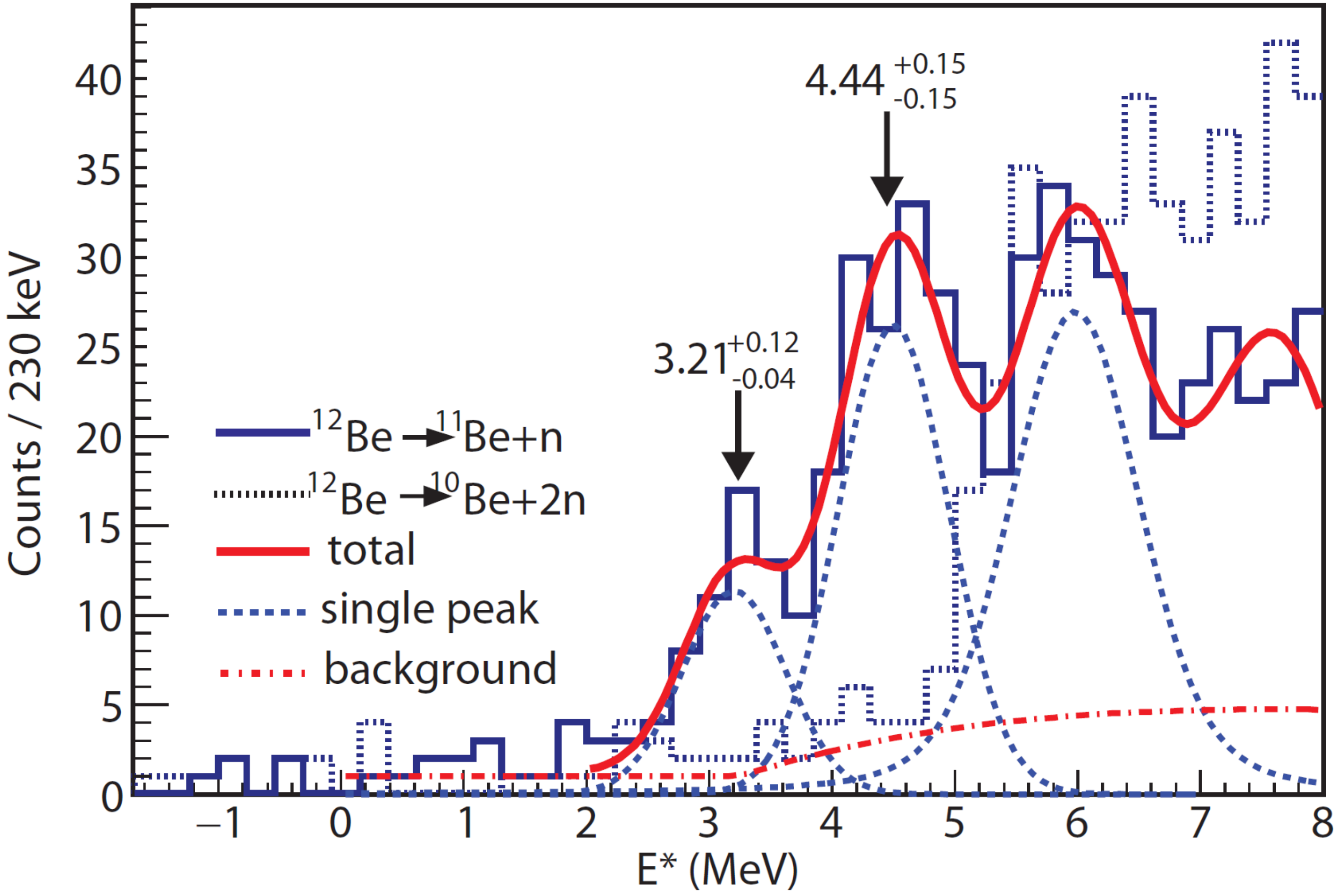




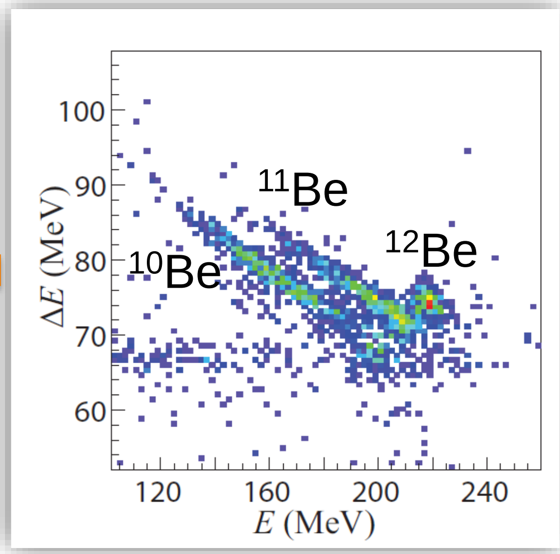
Convenient location of the 0- state



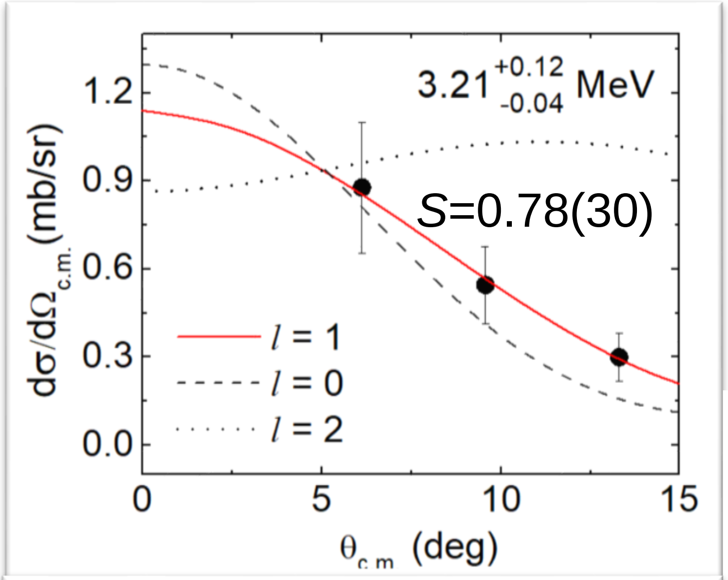
^{12}Be unbound states

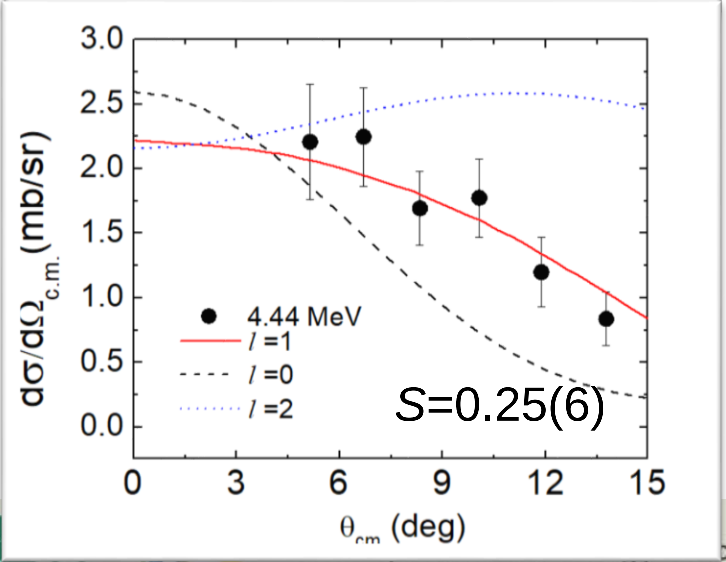


- One state just above the S_n
- One state above the S_{2n}, but has >80% 1n-decay

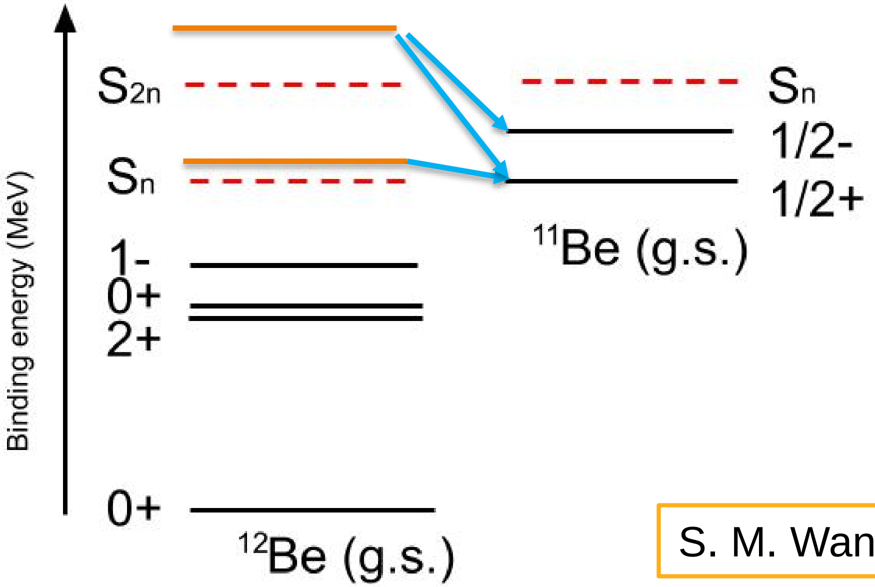


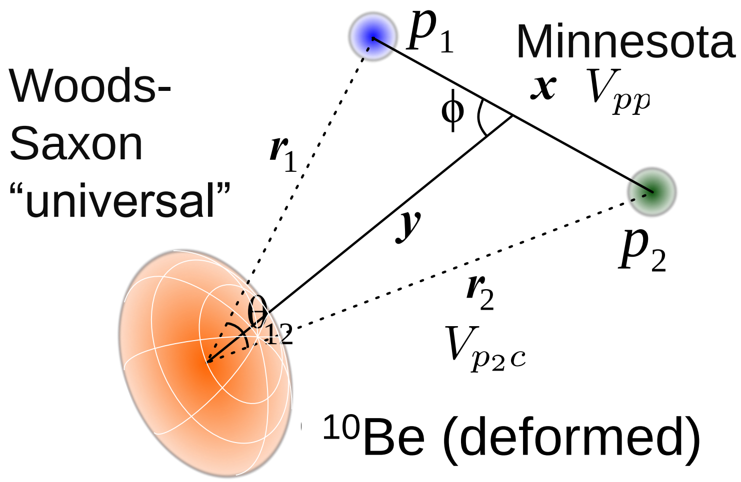
Resonances in ^{12}Be and the role of continuum





- Both are *l* =1, limit the possibility to 0-,1-,2-
- Both have a dominant decay branching ratio to ^{11}Be+n
- Gamow coupled-channel approach

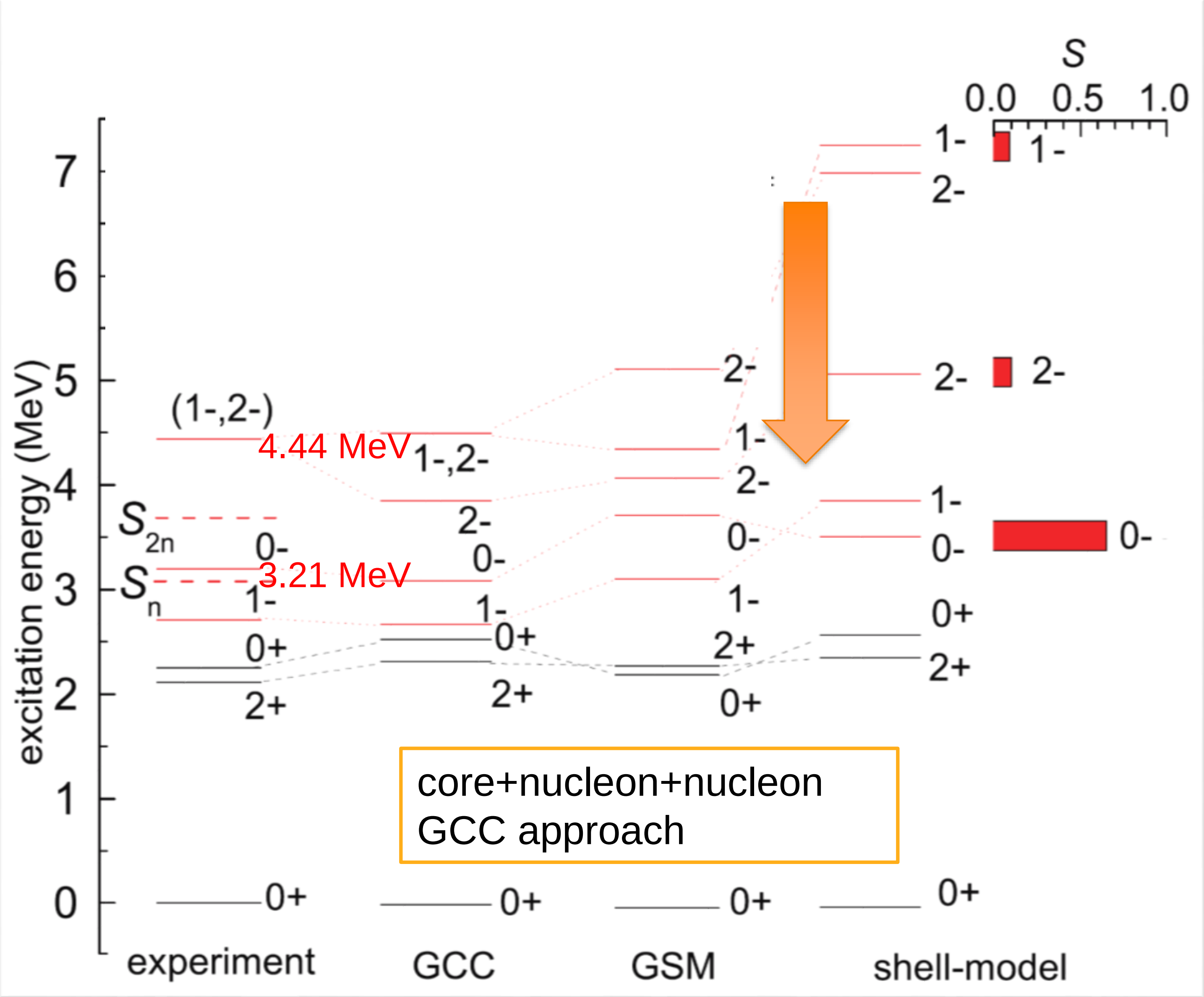


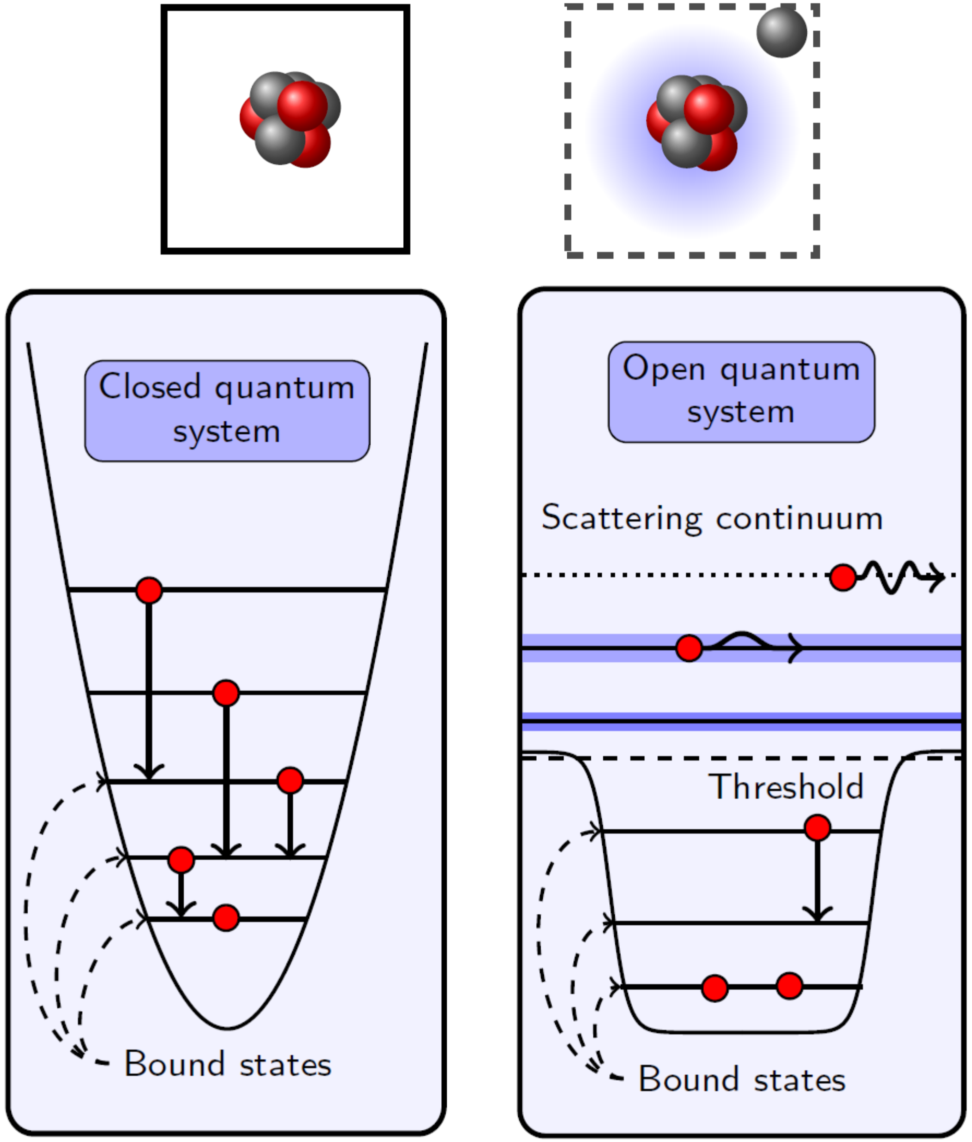


S. M. Wang, *et al*. Phys. Rev. C 99, 054302 (2019)

DWBA calculation by H. T. Fortune
Vincent-Fortune technique

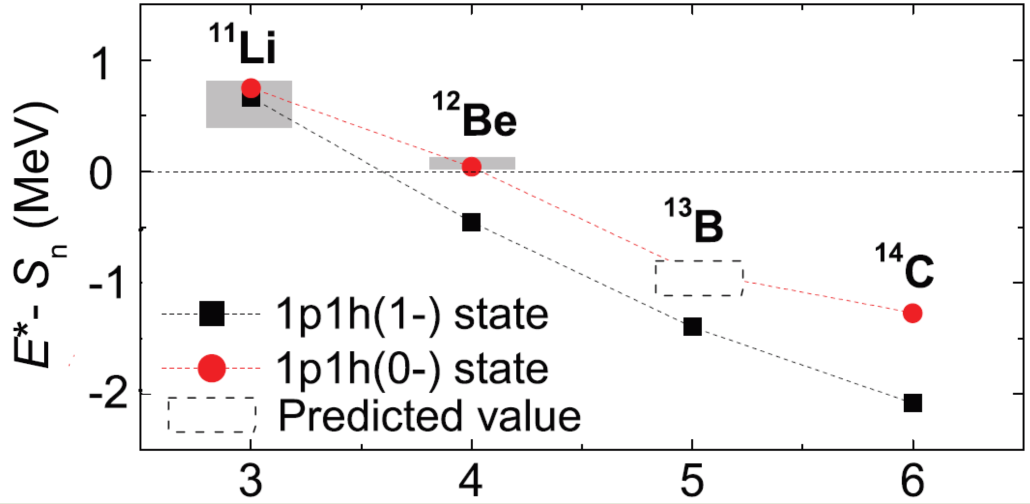
Resonances in ^{12}Be and the role of continuum

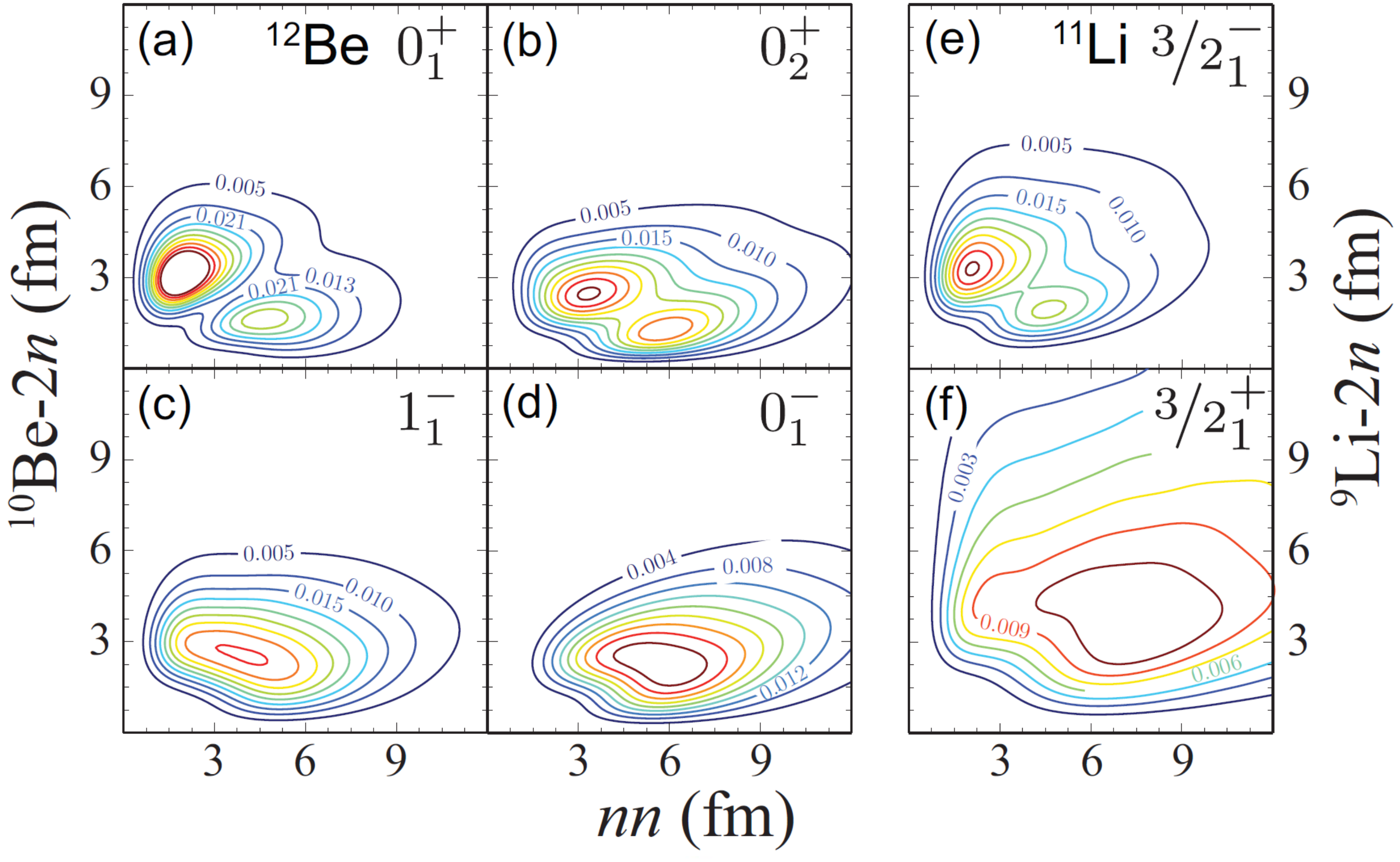




Three-body GCC approach

- Two-nucleon density distributions
- g.s: mixture of a dineutron structure and a cigar-like configuration
- 0_2+ state: halo structure like the ^{11}Li g.s.
- 0- and 1_1- states: two valence neutrons are less correlated





1p-1h resonances in ^{11}Li: experimentally observed dipole resonances

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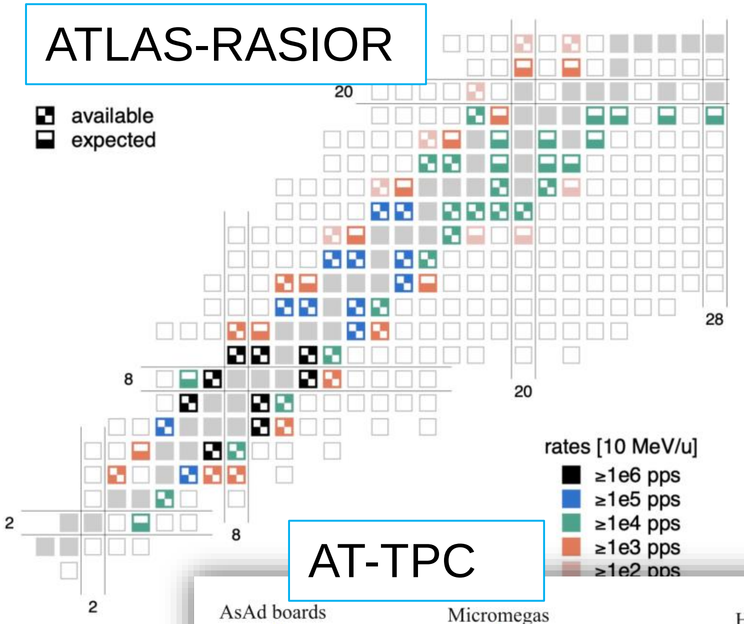
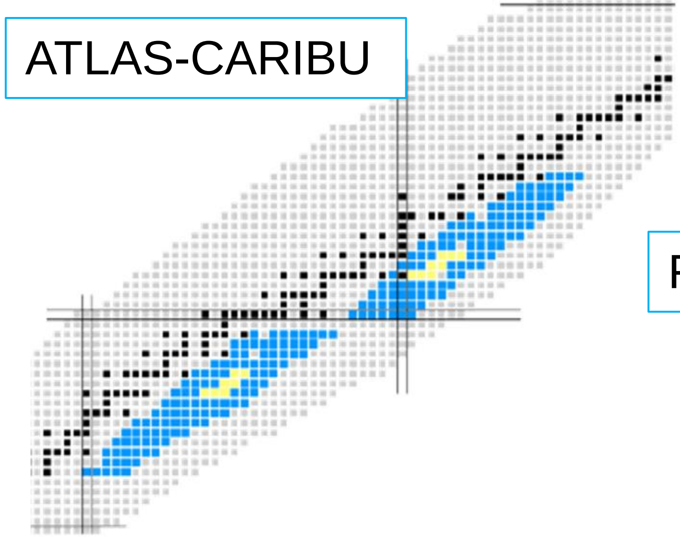
- Approaching the nuclear force : N-N effective interaction ----- Example: ^{22}F $1d_{5/2}$-orbital
- Opportunities with FRIB
  - Commissioning of the AT-TPC and SOLARIS using long-lived beams

Instrumentation for transfer reactions

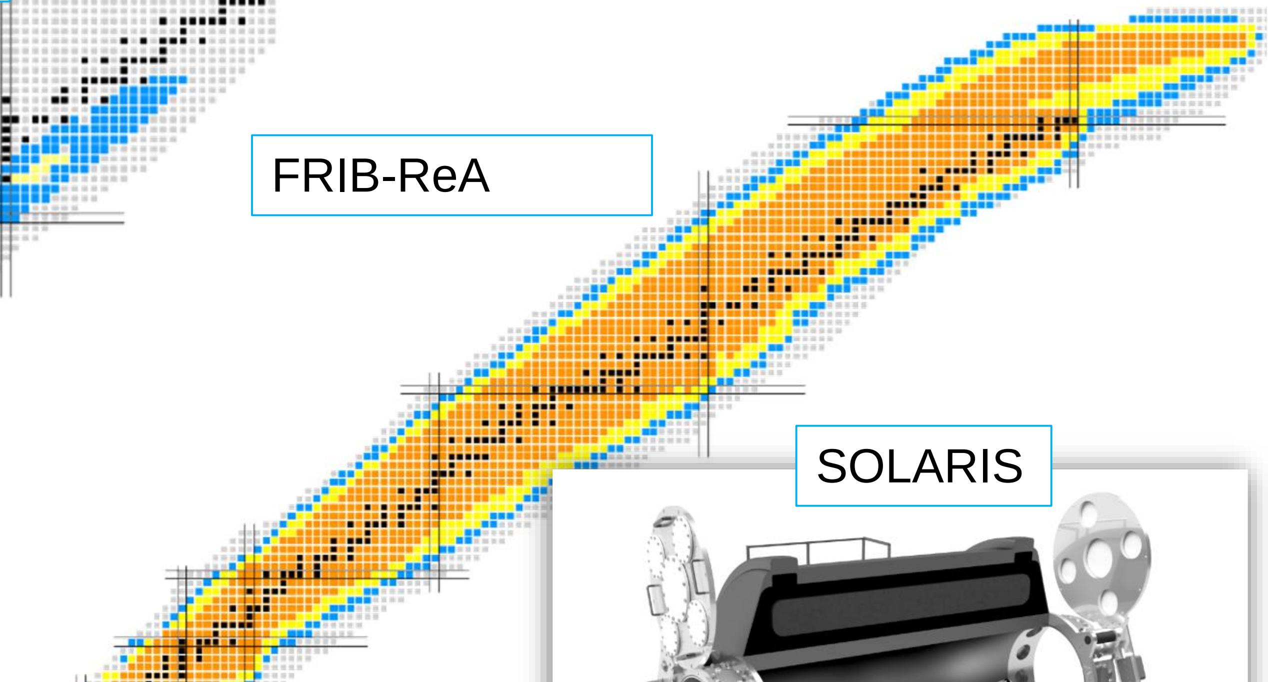
ATLAS-RASIOR



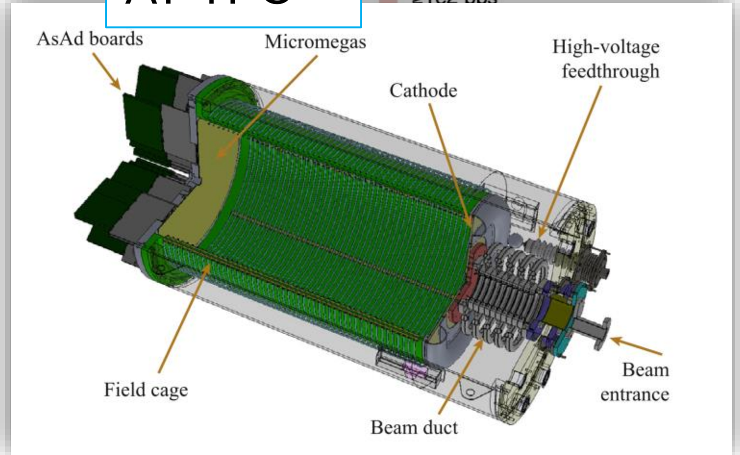
ATLAS-CARIBU



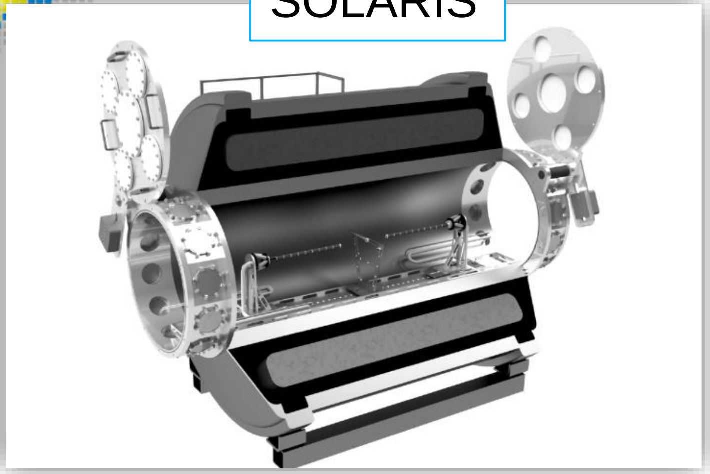
FRIB-ReA



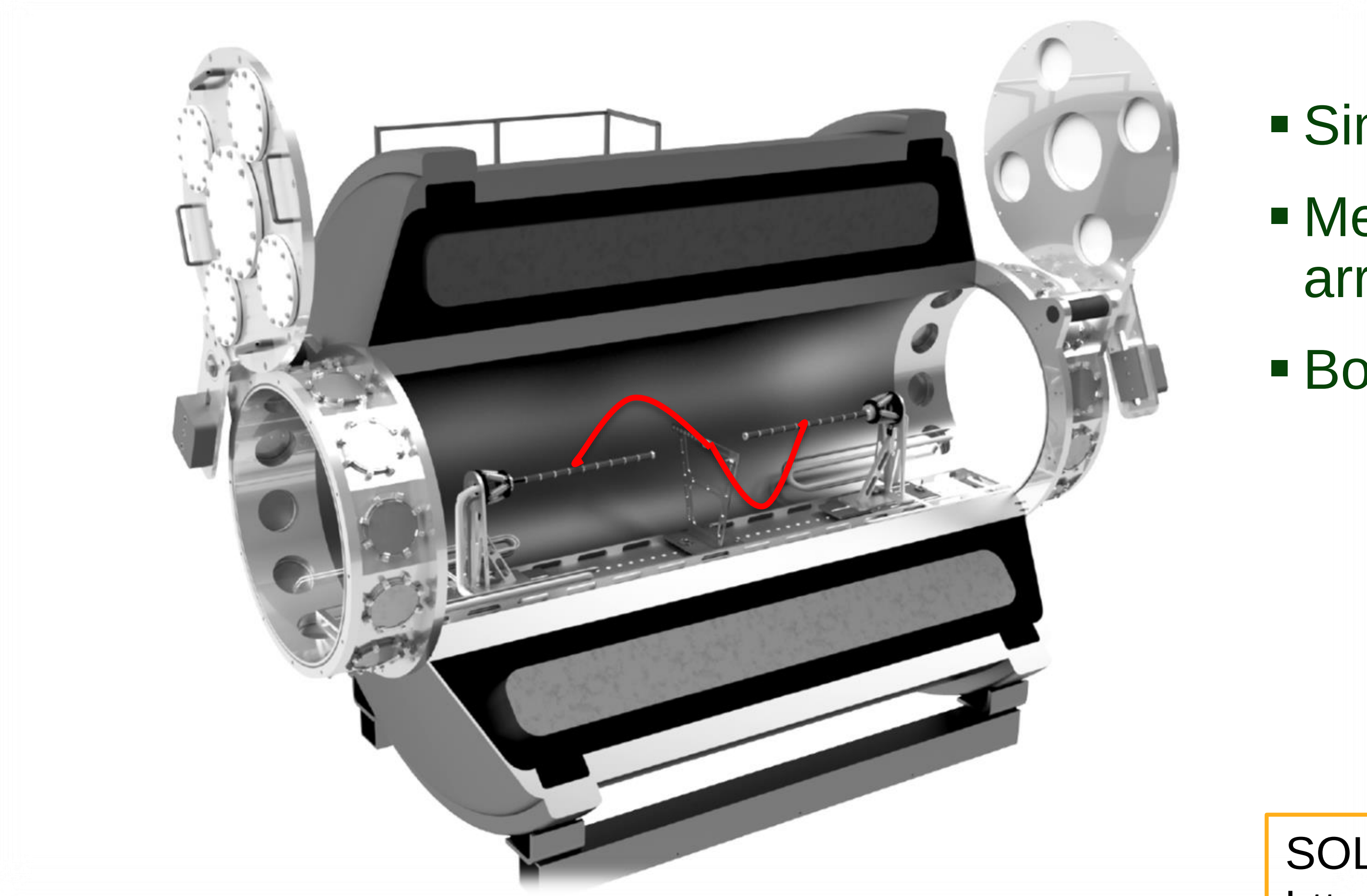
AT-TPC



SOLARIS



Instrumentation for transfer reactions

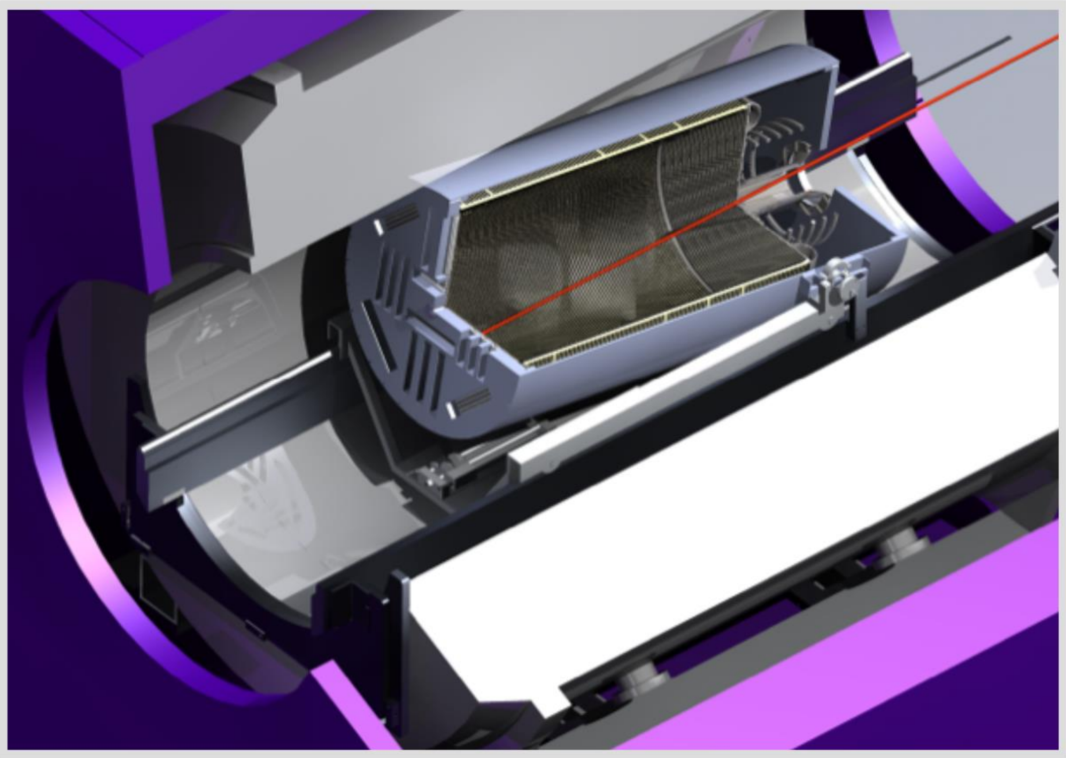


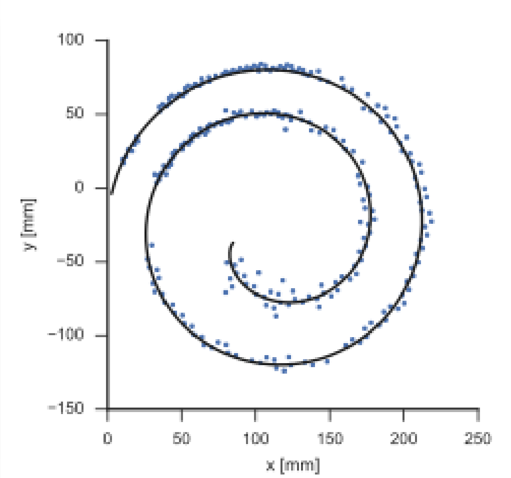
- Similar to Helios
- Measure the reaction with both silicon array upstream and downstream
- Both in AT-TPC and Si-Array modes

SOLARIS White Paper, https://www.anl.gov/phy/solaris.

Instrumentation for transfer reactions

- large-volume gas-filled detector ⟷ target isotopes as well as the tracking medium
- a large effective luminosity ⟷ beams as low as hundreds of pps
- There has been some resonance scattering measurement with the AT-TPC



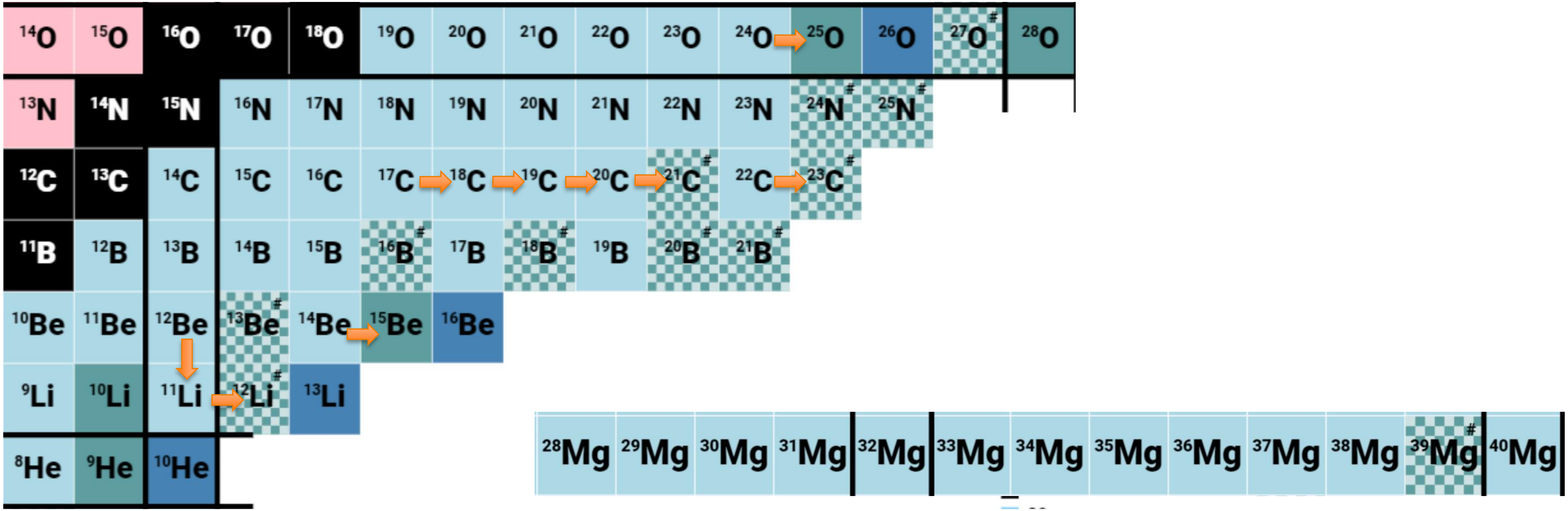


J. Bradt et al., Nucl. Instrum. and Methods in Phys. Res. A 875, 65 (2017)

longer trajectories can be recorded

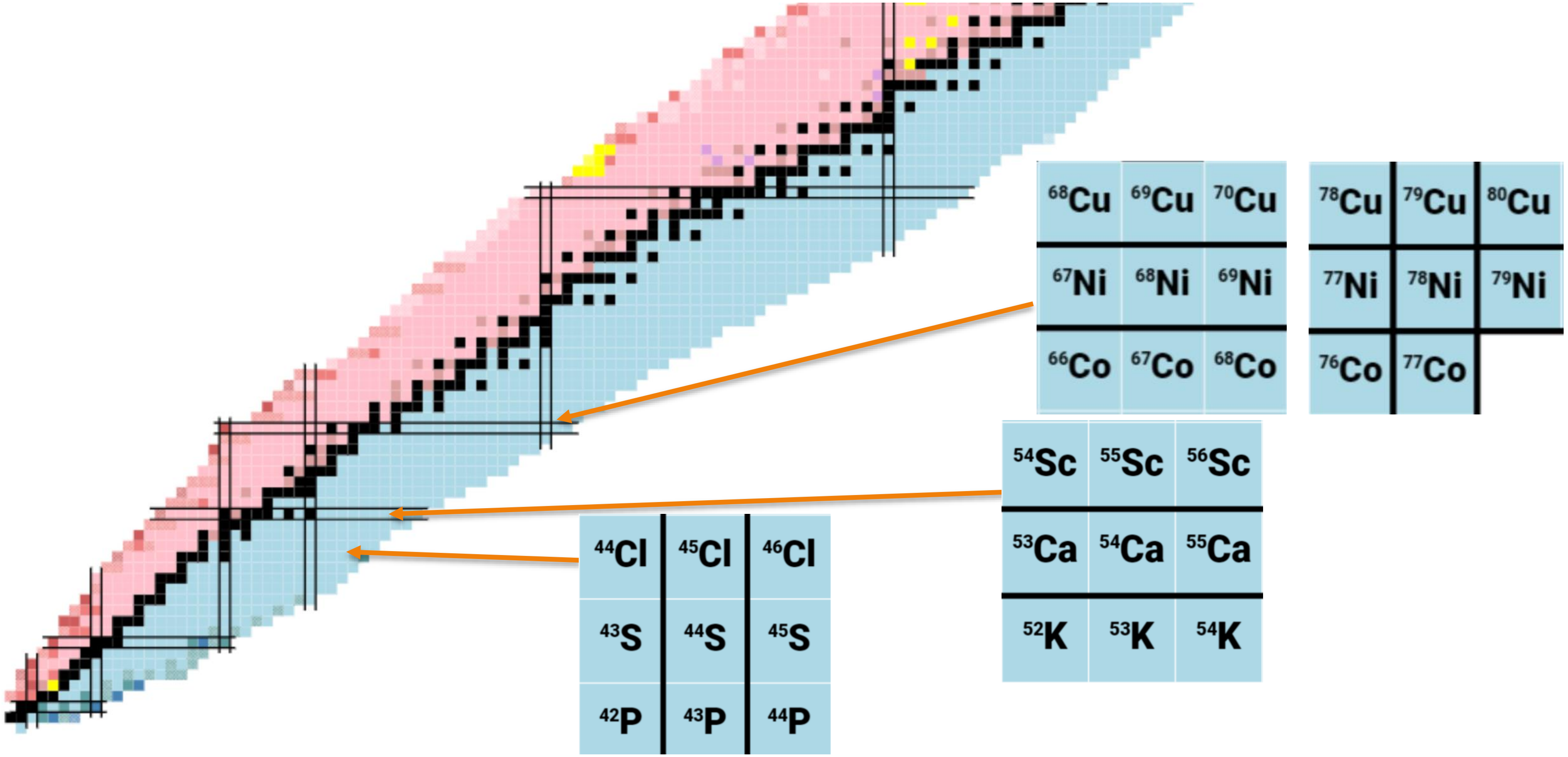
AT-TPC also opens a possible way of the (^{3}He,*d*) and (α,t) reaction.

Opportunities with FRIB



- C isotopes—*psd*-shell single-particle structure, *N* =14 and 16 shell decrease
- Mg isotopes—*psdfp*-shell singe-particle structure, *N* = 20 shell decrease

Opportunities with FRIB



- Ni isotopes—*pf*-shell singe-particle structure, above *N* = 40, 50
- Ca isotopes—*pf*-shell single-particle structure, *N* = 34 shell increase

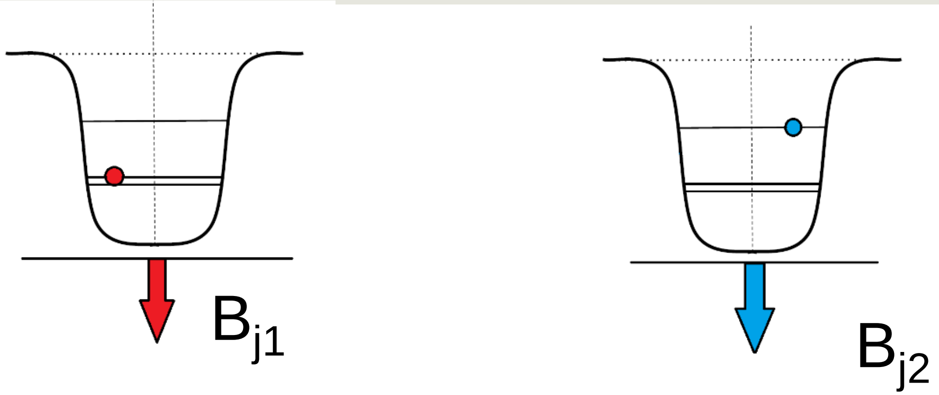
Outline

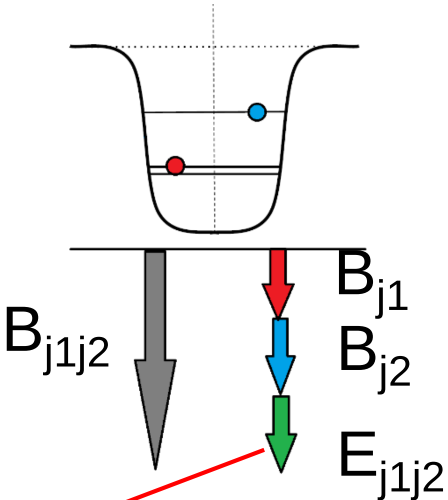
- Overarching questions of nuclear physics

  ----- Migration of Shell Gaps and Magic Numbers

- Understanding of exotic nuclei ----- Examples: Be isotopes
  - ^{11}Be negative parity states
  - ^{12}Be intruder states and single-particle configuration mixing
- Resonances in weakly-bound nuclei and the role of continuum
  - ^{12}Be resonance with intruder configurations
- Instrumentation for transfer reactions
- Approaching the nuclear force : N-N effective interaction ----- Example: ^{22}F $1d_{5/2}$-orbital
- Opportunities with FRIB
  - Commissioning of the AT-TPC and SOLARIS using long-lived beams

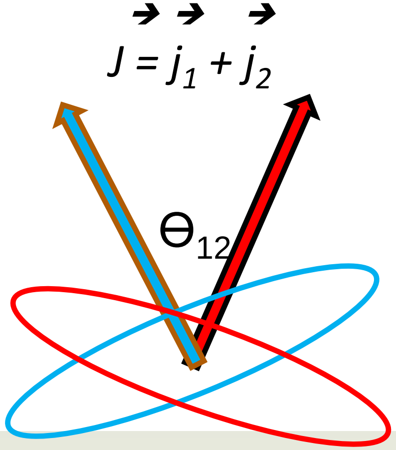
Approaching the nuclear force : N-N effective interaction

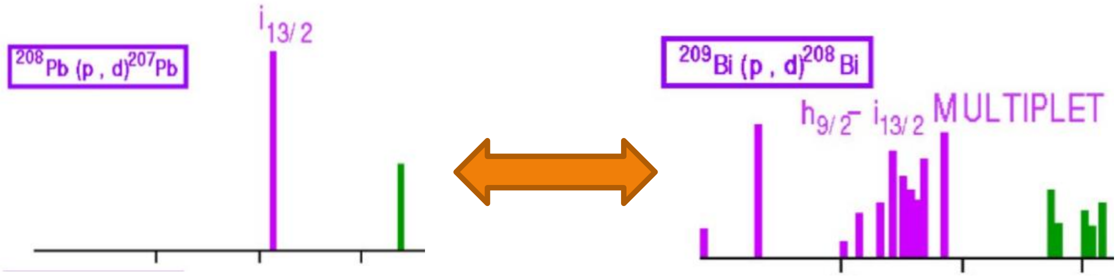




J. P. Schiffer and W. W. True, Rev. Mod. Phys.48, 191 (1976)

Diagonal two-body matrix elements: $E_{j1j2} = B_{j1j2} - B_{j1} - B_{j2}$



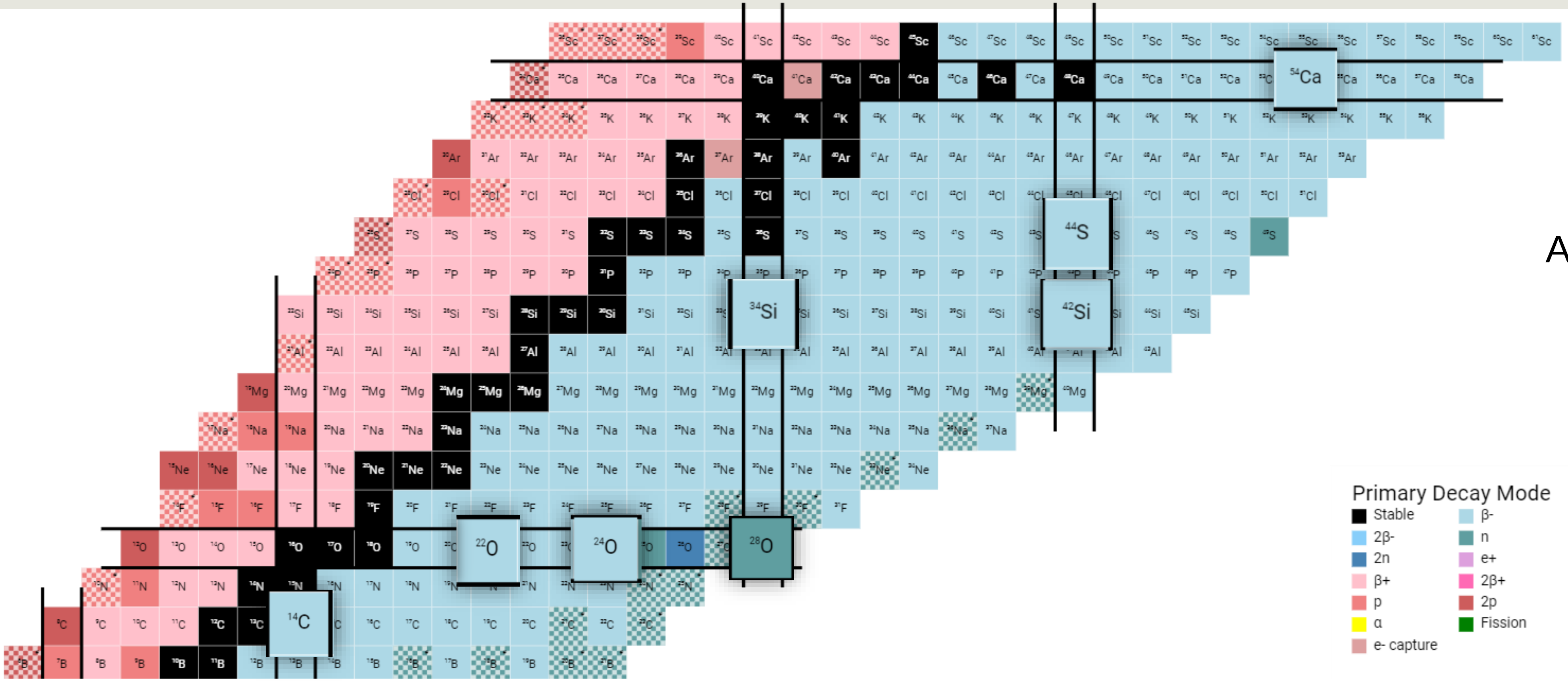


example: $j_1 = 5/2$, $j_2 = 5/2$, $J = 0 - 5$ multiplets

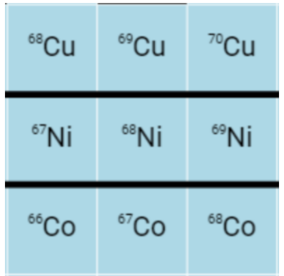
Average of the multiplets → monopole interaction

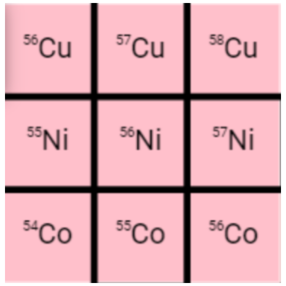
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Probing nuclear forces in weak-binding system



Available with CARIBU





- FRIB: ^{22}O, ^{24}O, ^{56}Ni, ^{68}Ni
- ^{21}O, ^{22}O and beams around ^{132}Sn will be available using RAISOR and CARIBU

Outline

- Overarching questions of nuclear physics

    ----- Migration of Shell Gaps and Magic Numbers

- Approaching the nuclear force : N-N effective interaction ----- Example: ^{22}F $1d_{5/2}$-orbital
- Understanding of exotic nuclei ----- Examples: Be isotopes
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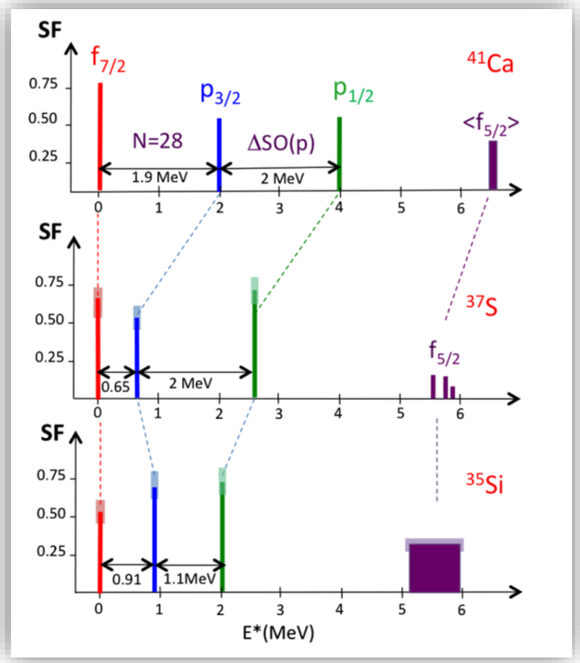
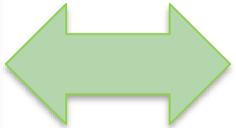
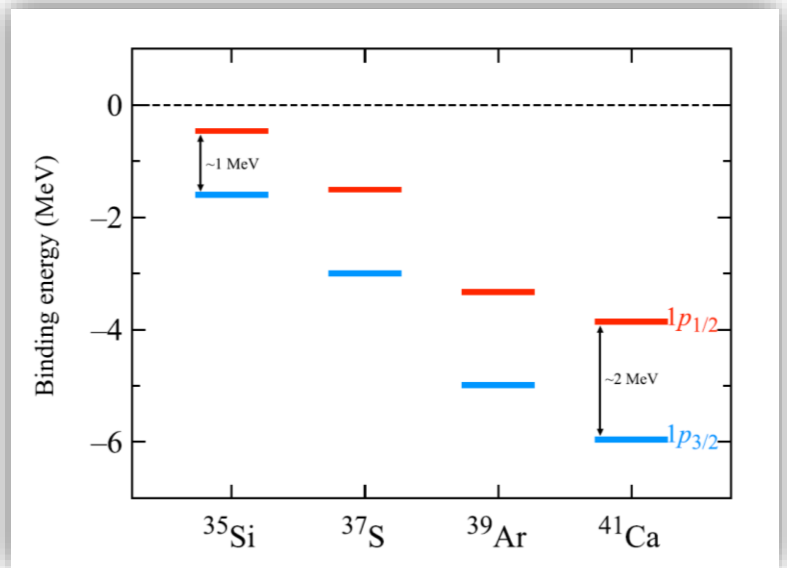
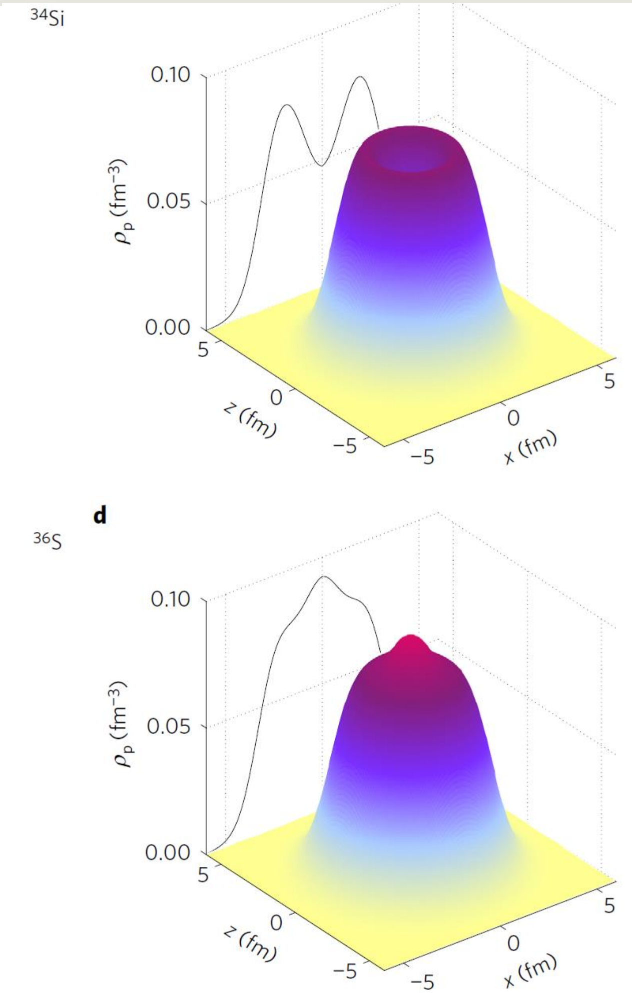
- Opportunities with FRIB
  - Commissioning of the AT-TPC and SOLARIS using long-lived beams

Commissioning of the AT-TPC and SOLARIS using long-lived beams









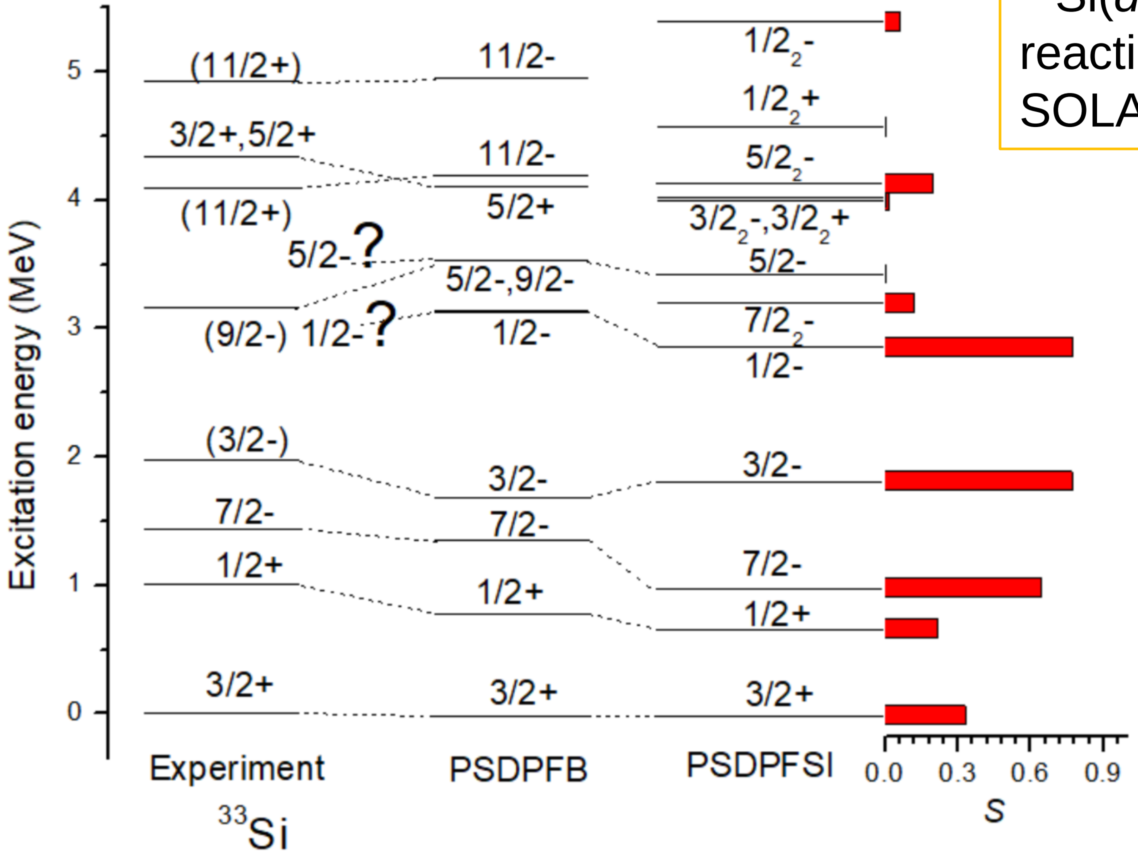
- A similar case can be established by isotonic chain ^{33}Si, ^{35}S, ^{37}Ar
  - What is the trend for the SO-splitting in this case?
  - What is single-particle energies of the orbitals determining the N=20 and N=28 shell gap?
  - Enrich our understanding of the mechanics driving behind
  - Bridge to the nuclei in the island of inversion

A. Mutschler, et al, Nature Physics13, 155 (2016)

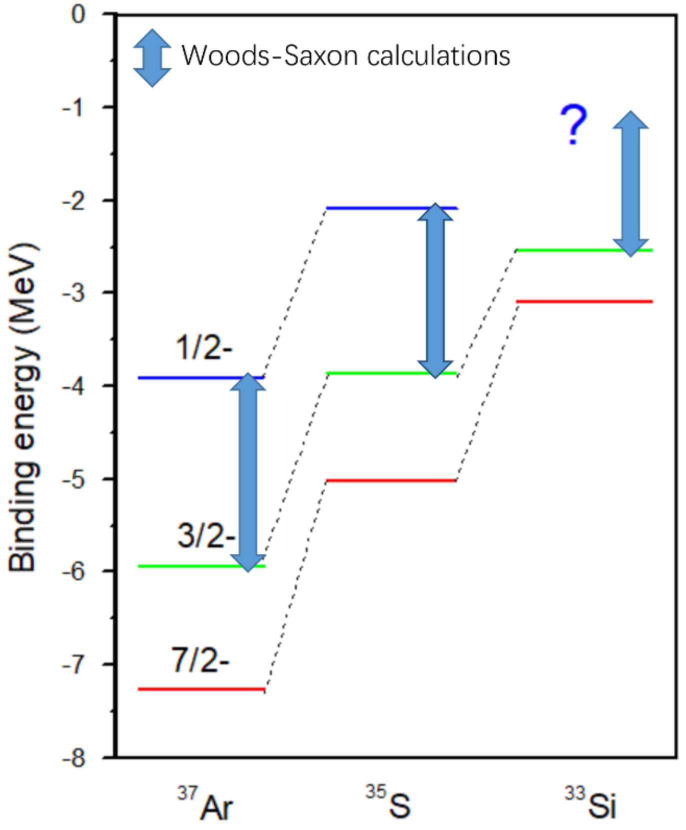
G. Burgunder, et al, Phy. Rev. Lett. 112, 042502 (2014).

B. P. Kay, et al, Phy. Rev. Lett. 119, 182502 (2017).

Commissioning of the AT-TPC and SOLARIS using long-lived beams



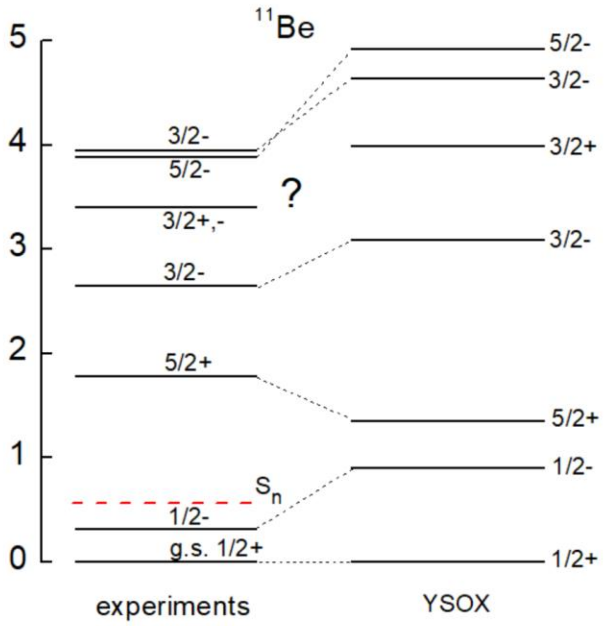
$^{32}Si(d,p)^{33}Si$ reaction with SOLARIS

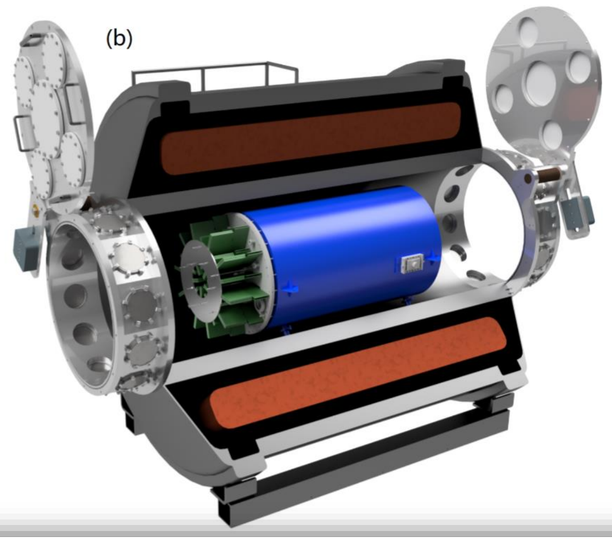


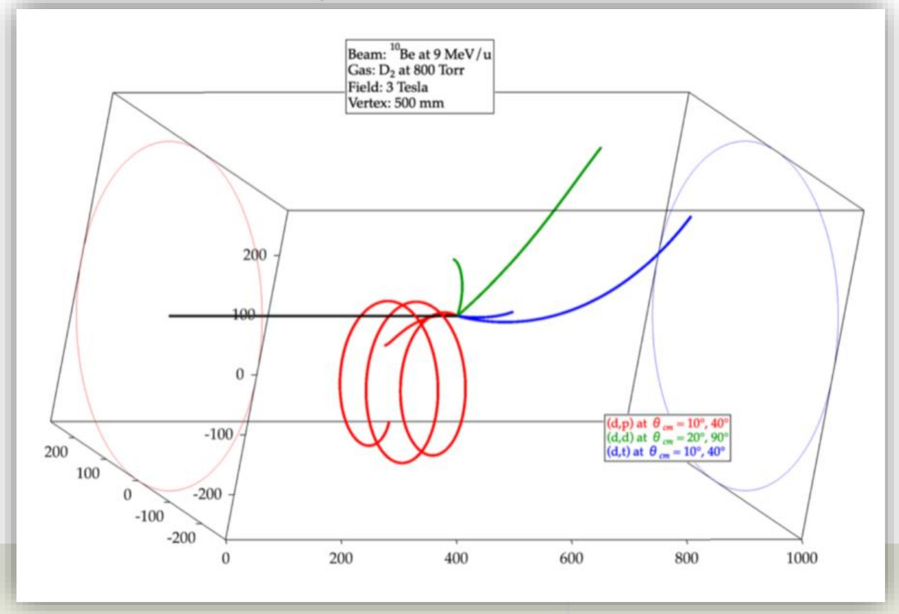
- Approved by NSCL PAC

Commissioning of the AT-TPC and SOLARIS using long-lived beams

- First transfer reaction measurement using the AT-TPC
  - Confirm parity of the 3.41-MeV state
- Unify the structure and reaction.
  - Compare to the calculation within the framework of renormalized nuclear field theory
  - Test capability and resolution of AT-TPC for transfer reaction
  - Approved by NSCL PAC







F. Barranco, G. Potel, R. A. Broglia, and E. Vigezzi, Phys. Rev. Lett, 119, 082501 (2017)

Summary for the present work

- Overarching questions of nuclear physics:
  - ➢nature of the nuclear force
  - ➢origin of simple patterns

- Testing various theories using ^{11}Be negative parity states
  - ➢*ab-initio* approach (VMC), shell model, Nilsson model

New experimental insights on rare nuclei to guide theoretical developments.

- Determining the cross shell configuration mixing of the two low-lying 0+ states in ^{12}Be using ^{11}Be(*d*,*p*)^{12}Be reaction.
  - ➢Lowering of *d*-orbital associated with pairing and deformation

Enhance understanding of the nature of weakly-bound nuclei by measurement of exotic and dripline nuclei

- Testing the role of continuum by measuring unbound state of ^{12}Be.
  - ➢Continuum coupling is essential in ^{12}Be.

Measure resonances in weakly-bound nuclei and test the role of continuum

Summary for the future research plan

- Determine the effective N-N interaction of the $0d_{5/2}$ orbital using ^{21}F(d,p)^{22}F reaction
  - ➢Probing nuclear forces in weak-binding system

Determine shell structure and test configuration interaction theories

- Commissioning of the AT-TPC and SOLARIS at ReA using the (d,p) reactions on ^{10}Be and ^{32}Si
  - ➢Reduction of the spin-orbital splitting and “bubble nucleus”

- ReA combined with SOLARIS and AT-TPC
  - ➢allows detailed spectroscopic information on key nuclei in the islands of inversion and in isotopic chains of C, Mg, Ca, Ni, and Sn isotopes

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