Probing the exotic structures using one-nucleon transfer reactions

------ Be isotopes as examples

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Outline

- Overarching questions of nuclear physics

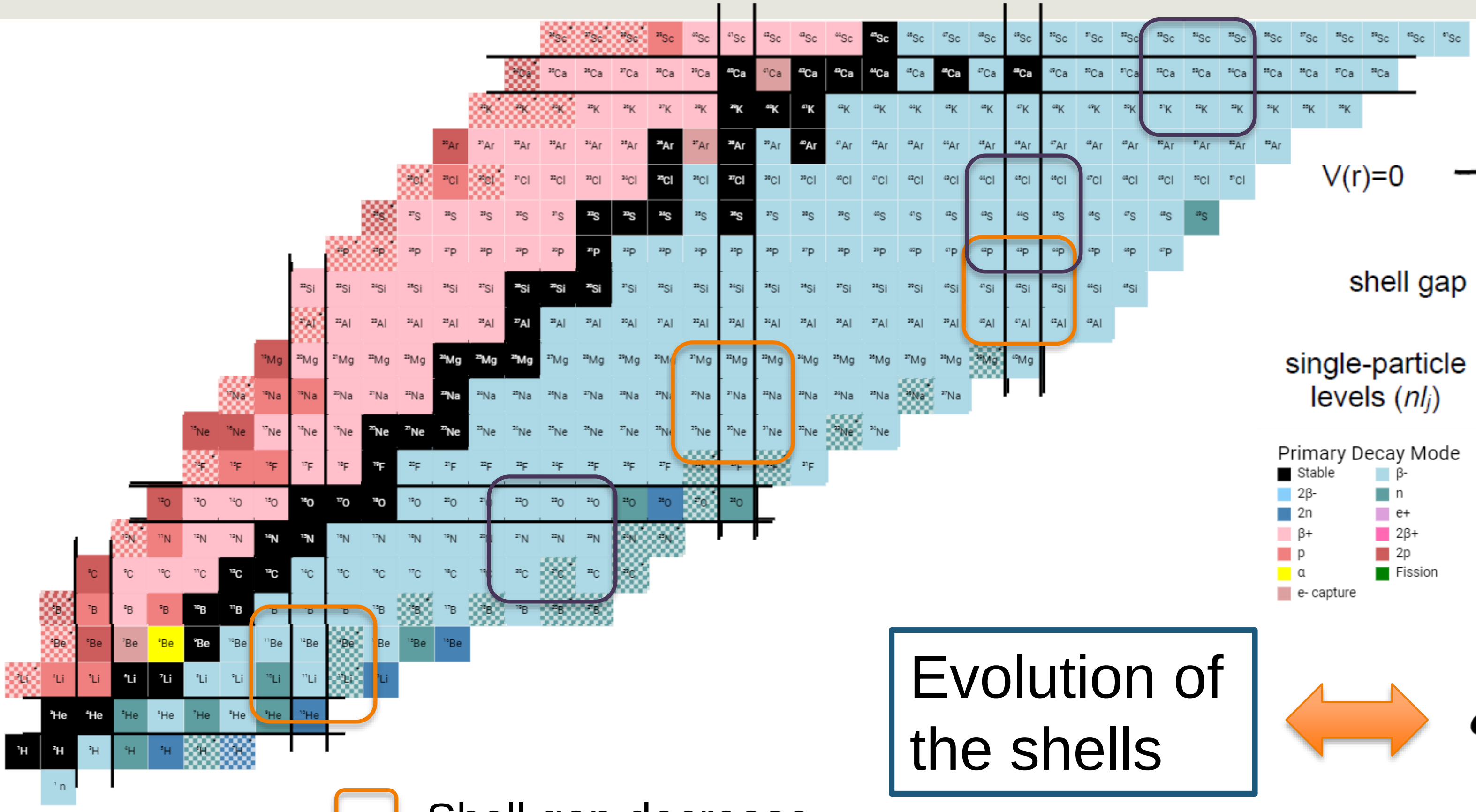
  ----- Migration of Shell Gaps and Magic Numbers

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

  ----- Normal and inverse kinematics

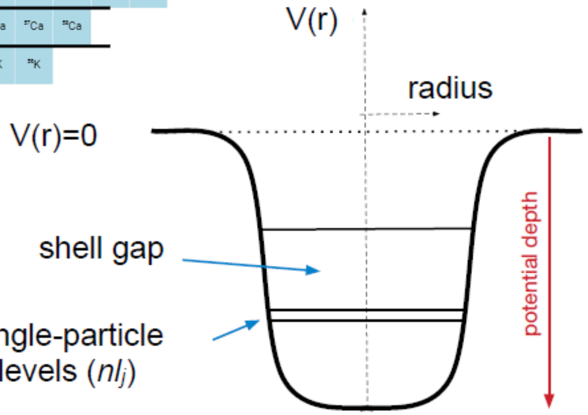
- Approaching the nuclear force : N-N effective interaction ----- Example: ^{22}F 1$d_{5/2}$-orbital
- Understanding of exotic nuclei ----- Examples: Be isotopes
  - ^{11}Be negative parity states
  - ^{12}Be intruder states and single-particle configuration mixing
- Resonances in weakly-bound nuclei and the role of continuum
  - ^{12}Be resonances with intruder configurations
- New science opportunities with ReA coupling to AT-TPC and SOLARIS

Migration of Shell Gaps and Magic Numbers



Shell gap decrease

Shell gap increase

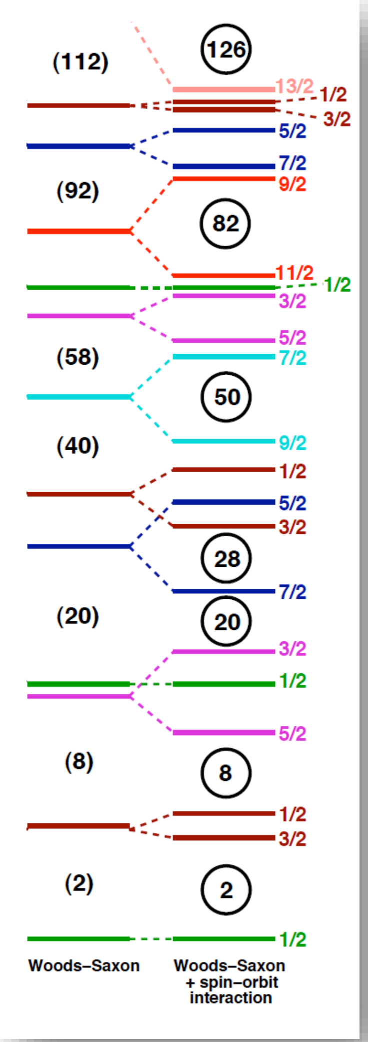


Nucleon-Nucleon interactions

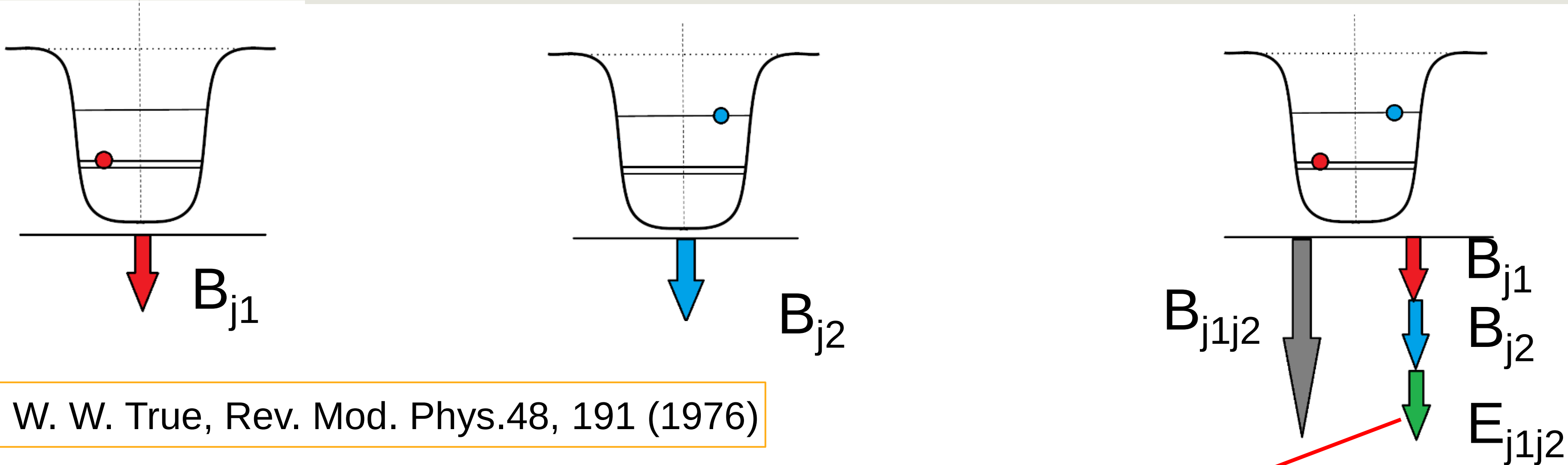
Evolution of the shells ⟷ $\varepsilon_i + V_{ij}^{JT}$

Effective Single-particle energy

diagonal Terms

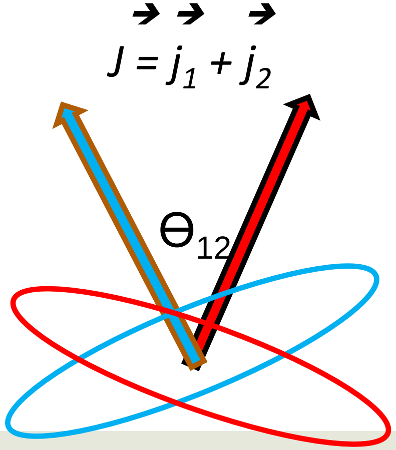


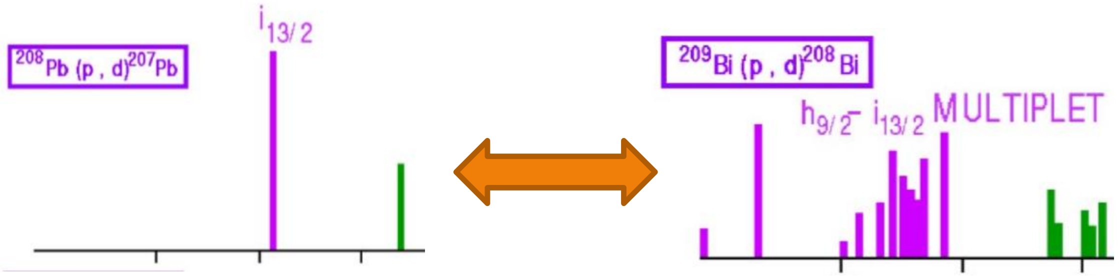
Approaching the nuclear force : N-N effective interaction



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

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

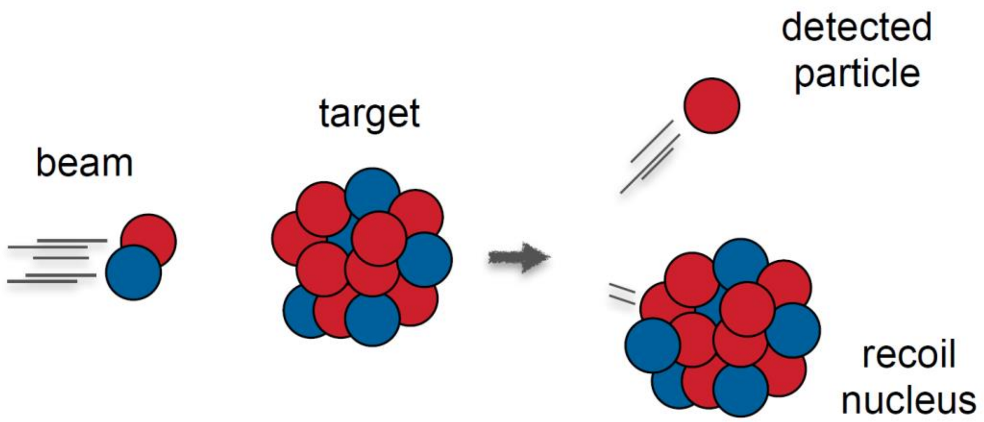




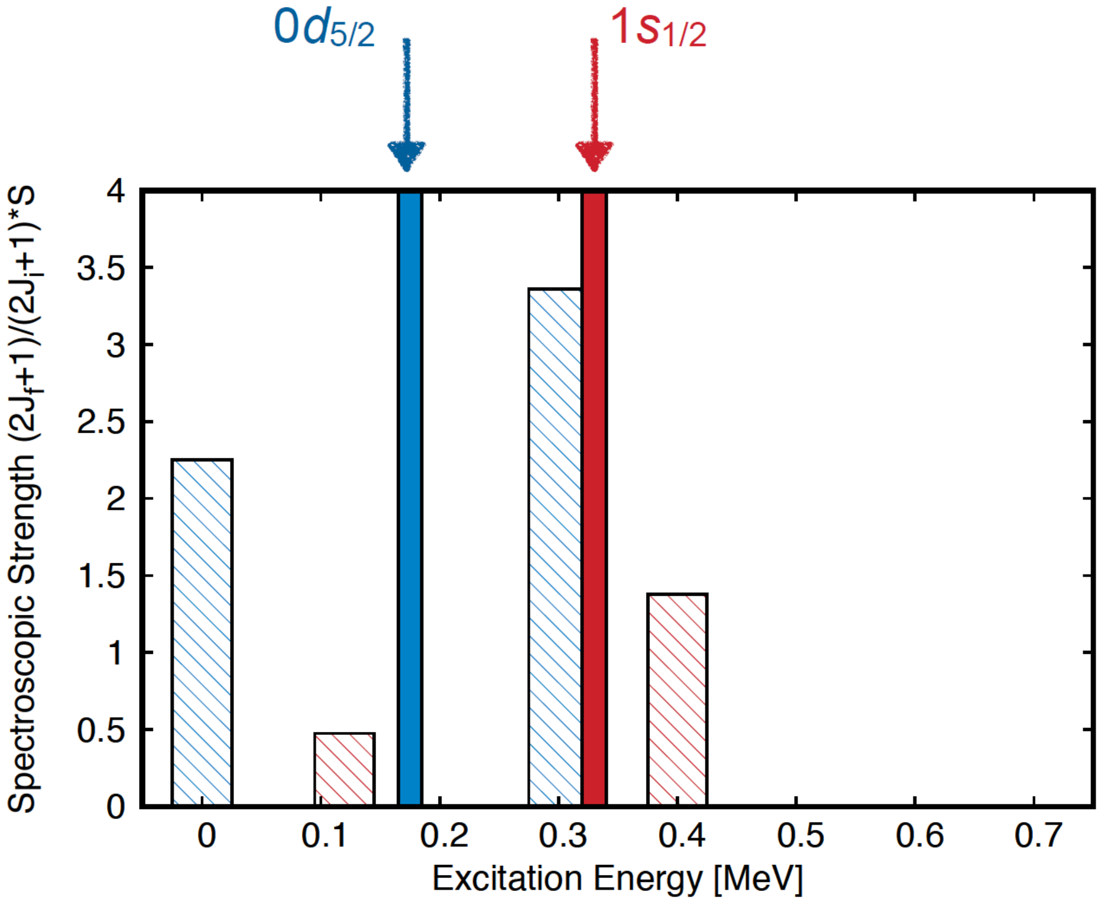
example: $j_1 = 5/2$, $j_2 = 5/2$, $J = 0 - 5$ multiplets

Average of the multiplets → monopole interaction

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

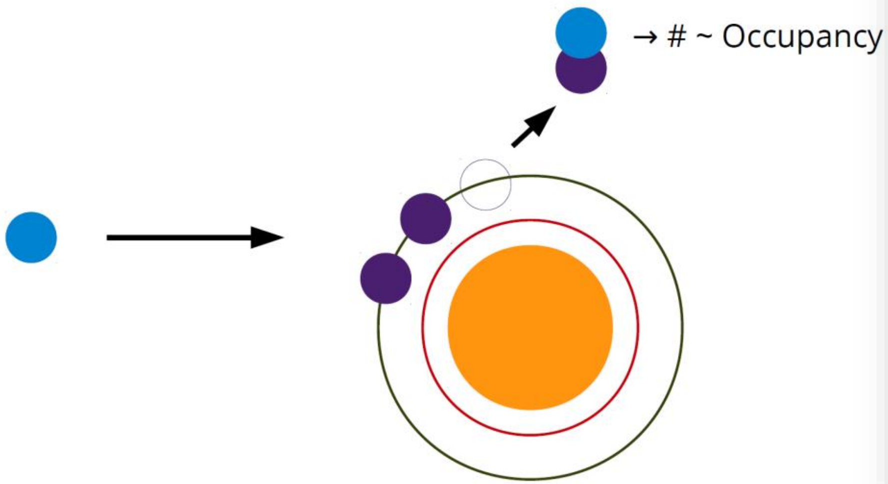


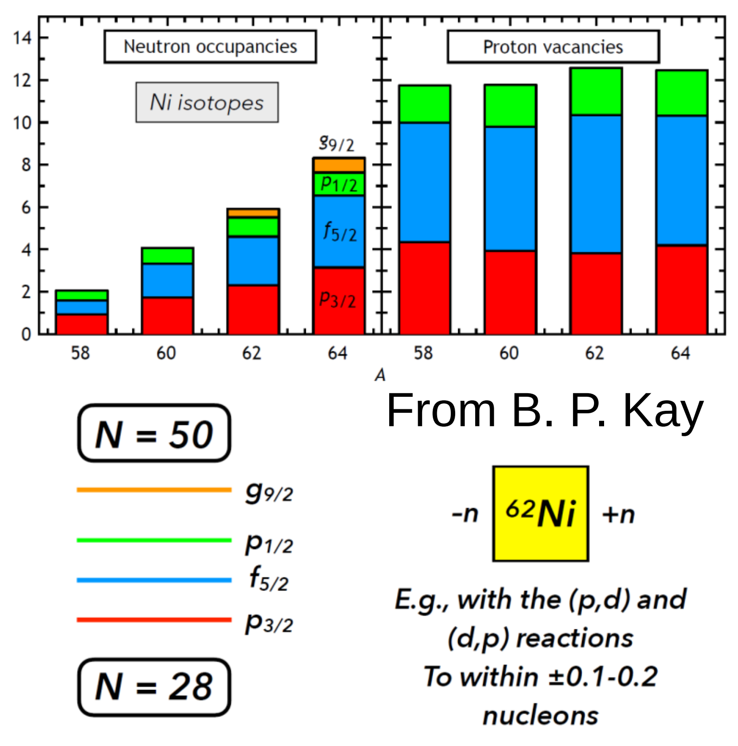
$$E_{centroid} = \frac{\sum (2j_f+1)S_{\ell j} * E_{ex}}{\sum (2j_f+1)S_{\ell j}}$$



Probing the occupancy and vacancy of the orbitals

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





Quenching factor:

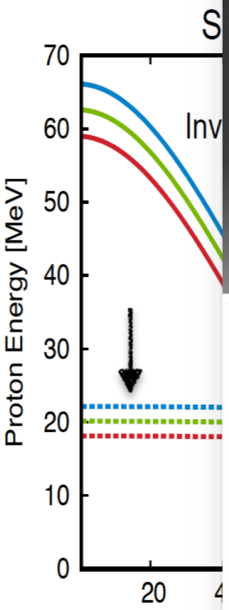
$$F_q \equiv \frac{1}{(2j+1)}\left[\Sigma\left(\frac{\sigma_{\exp}}{\sigma_{\rm DW}}\right)_j^{\rm add} + \Sigma\left(\frac{\sigma_{\exp}}{\sigma_{\rm DW}}\right)_j^{\rm rem}\right],$$

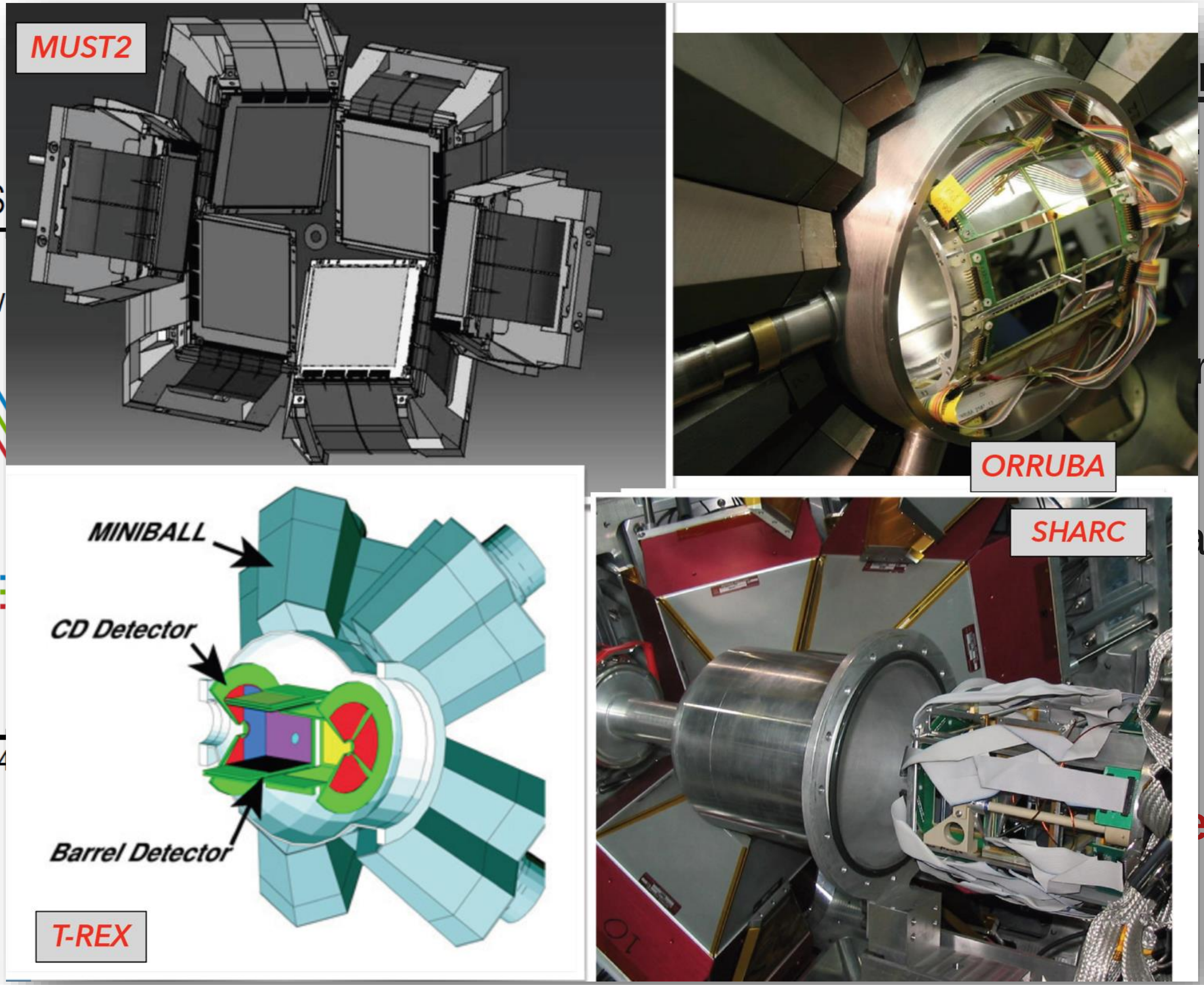
B. P. Kay et. al., PRL 111.042502 (2013)

- 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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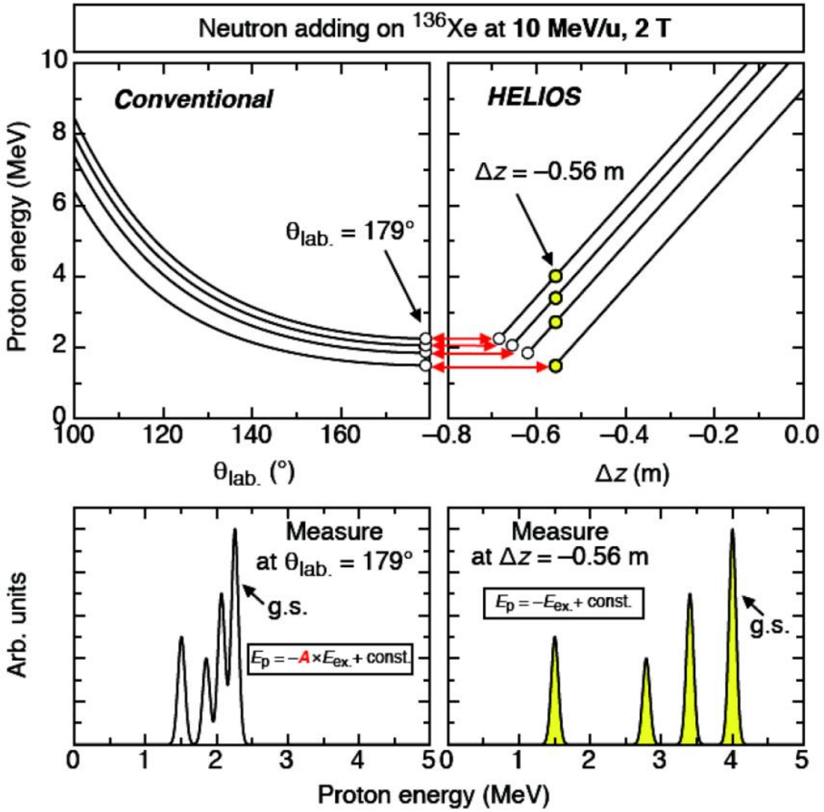

From B. P. Kay and C. Hoffman

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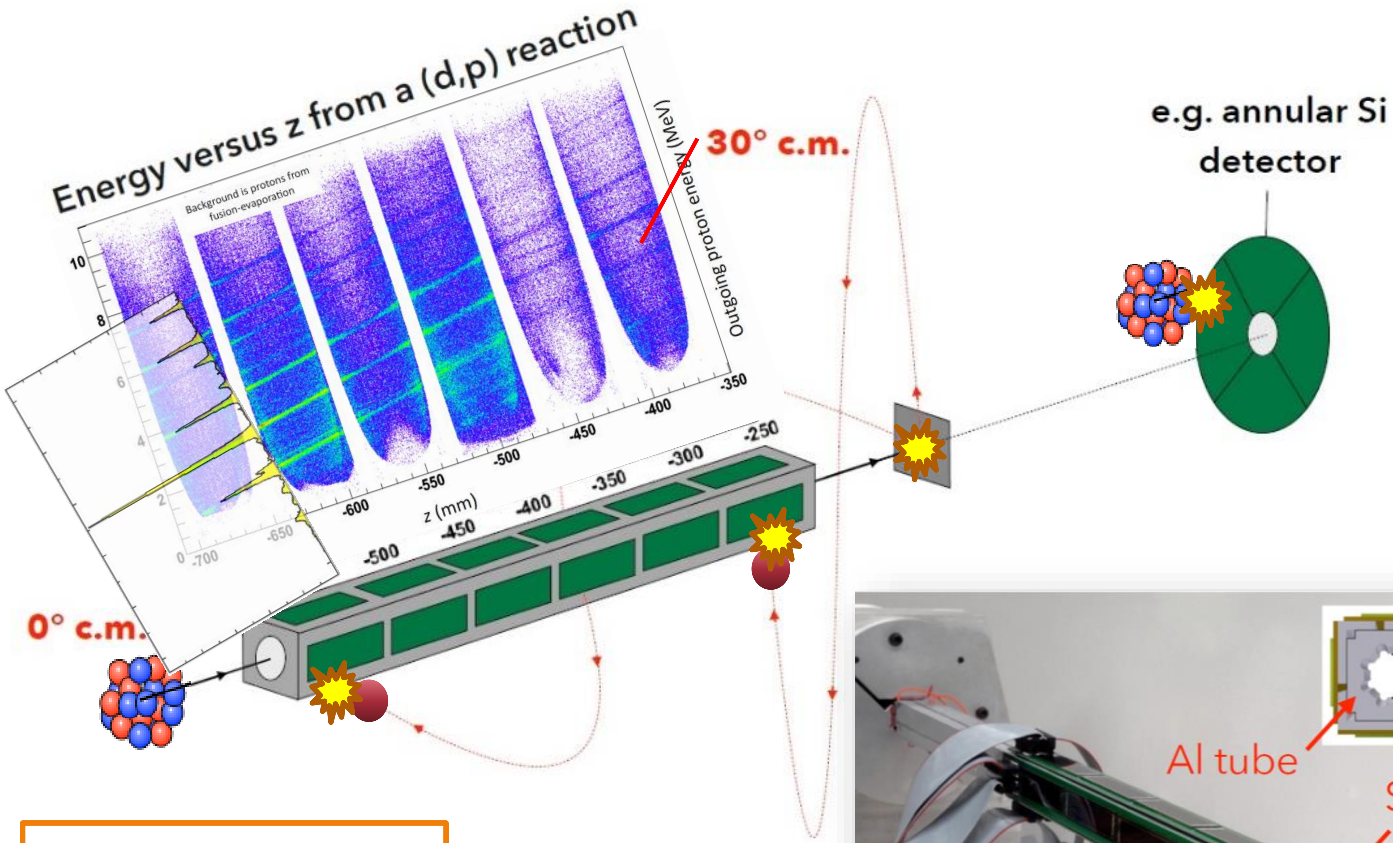
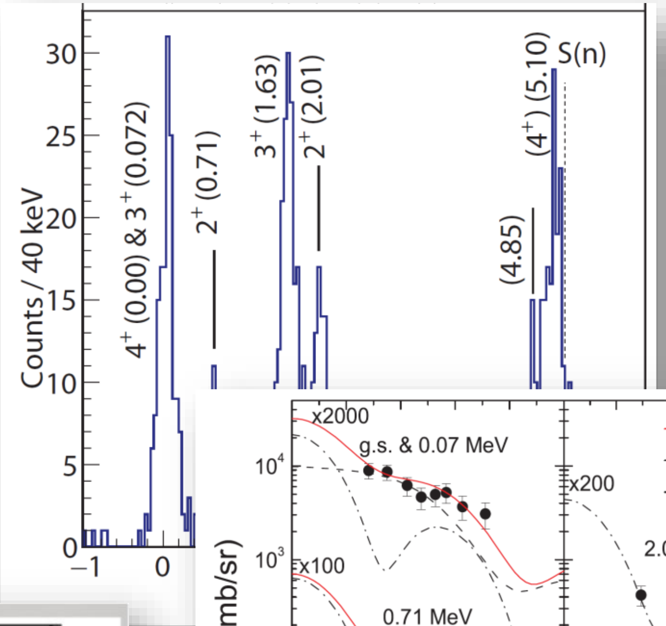
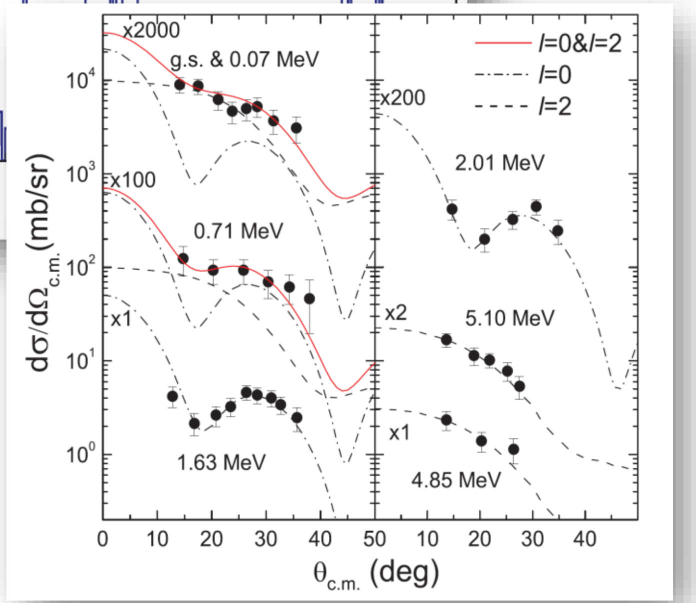
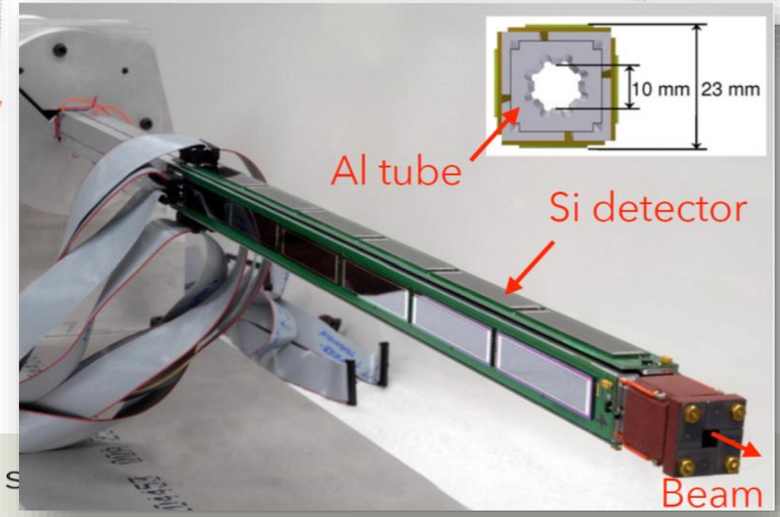
Approaching the nuclear force : N-N effective interaction





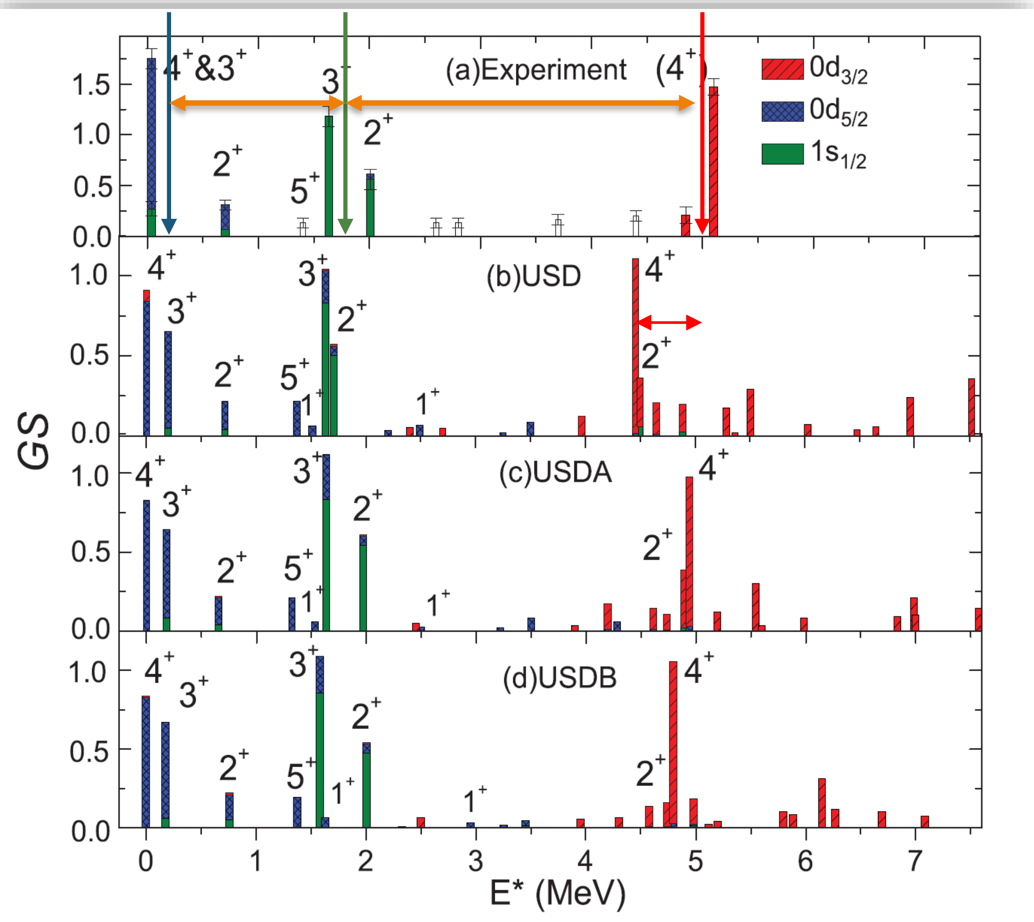




^{21}F 10 *A*MeV

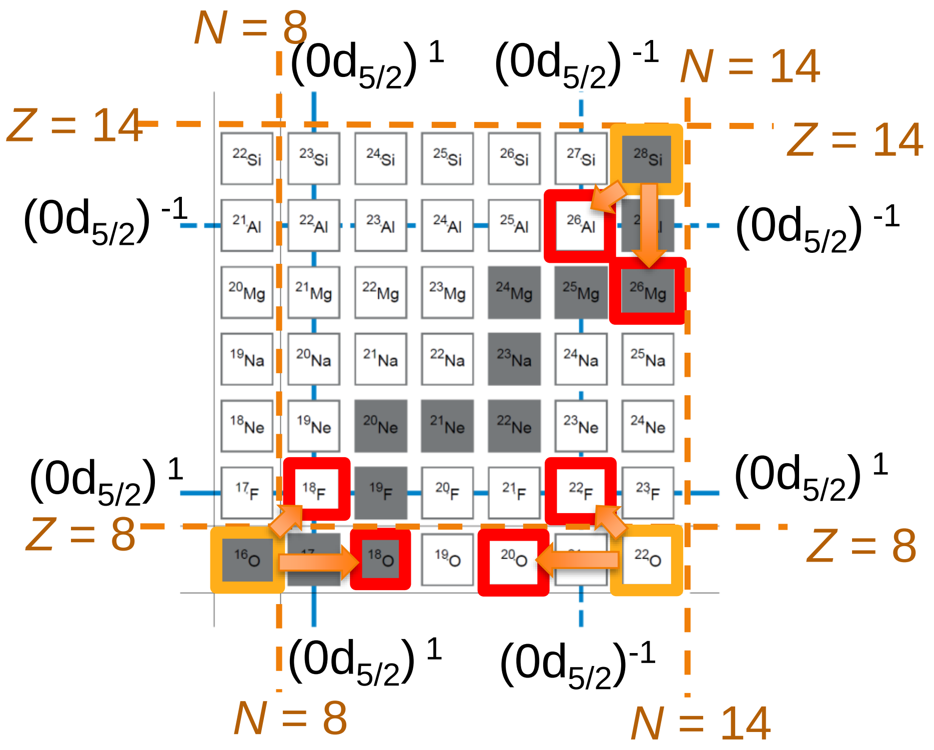
^{21}F(*d*,*p*)^{22}F

Approaching the nuclear force : N-N effective interaction



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

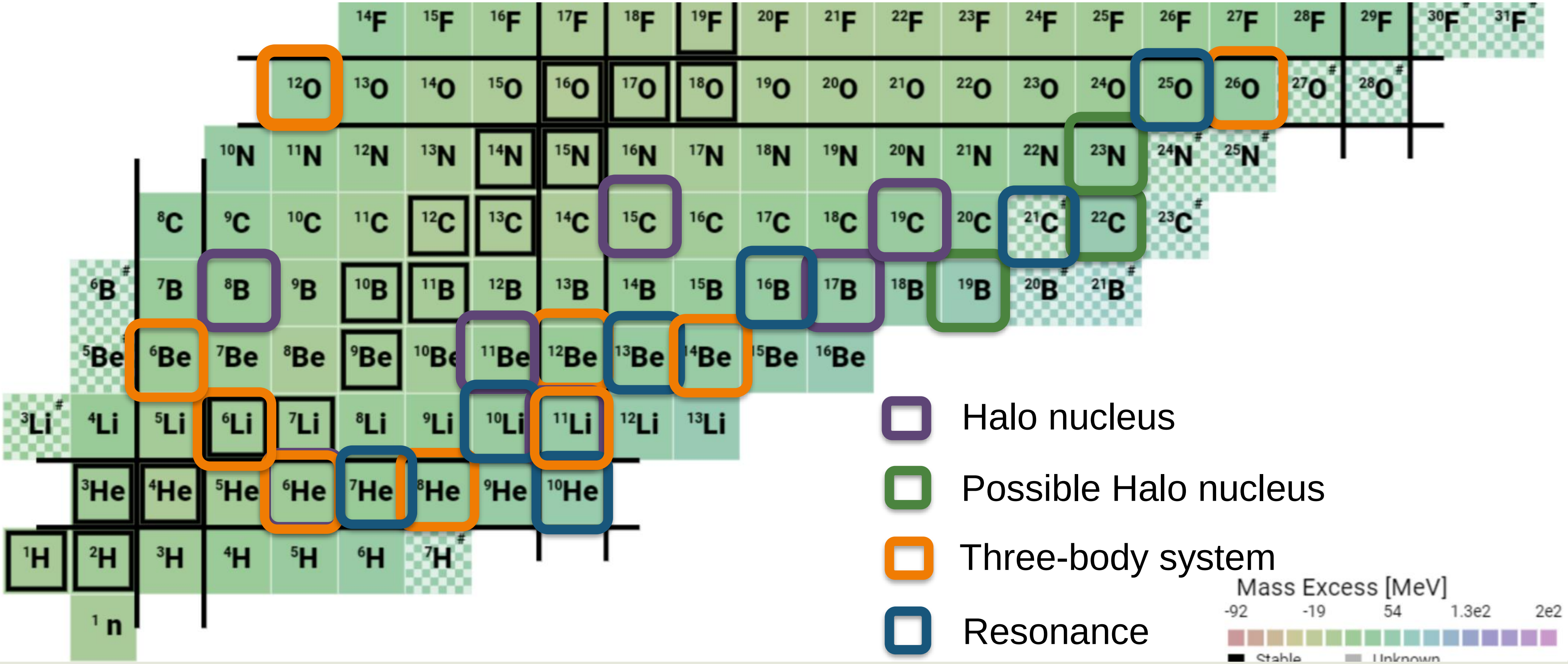
- *n-p* or *n-n* effective interactions can be obtained by the single-particle spectrum of the nuclei close to the close shells.



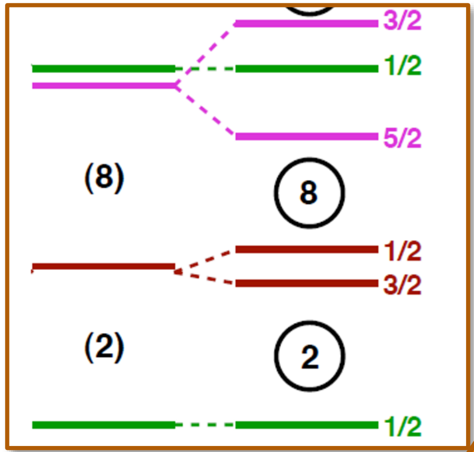
J. Chen, C. Hoffman *et al*. Phys. Rev. C 98, 014325 (2018)

Understanding of exotic nuclei

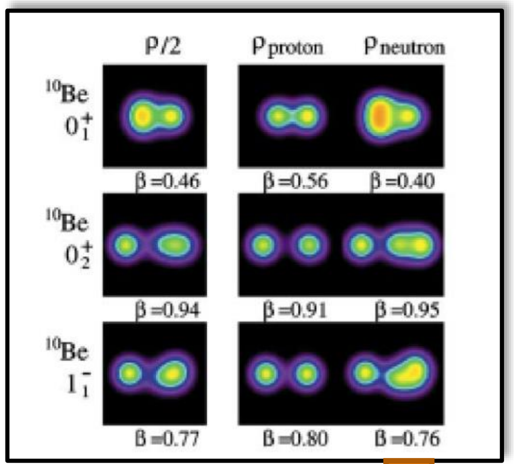
- Halo, Borromean nuclei, three body system, intruder states
- New experimental insights on rare nuclei to challenge theoretical predictions.



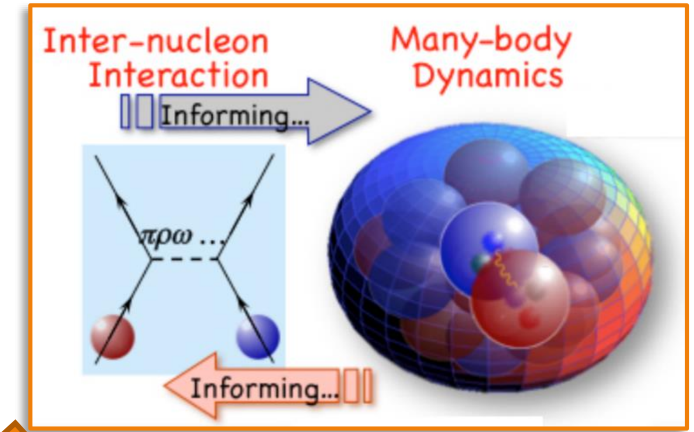
Examples: Be isotopes



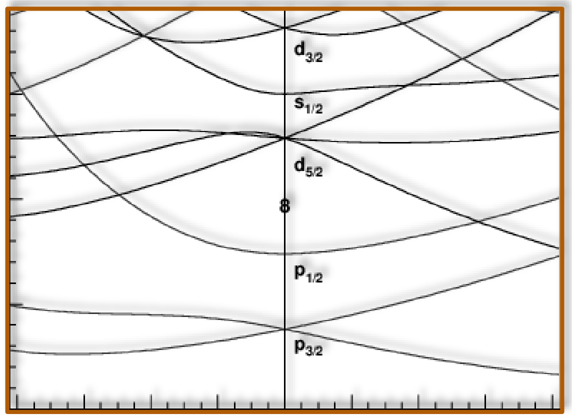
Shell model



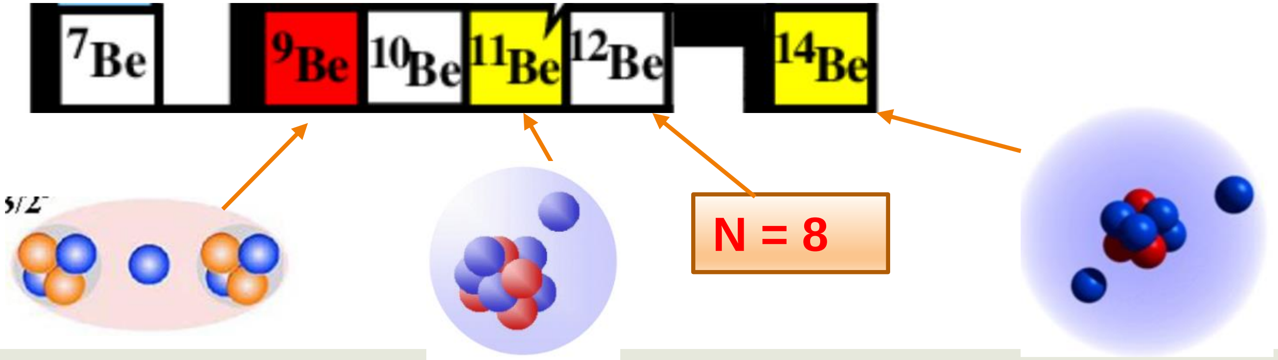
Cluster model



ab-initio



Nilsson model



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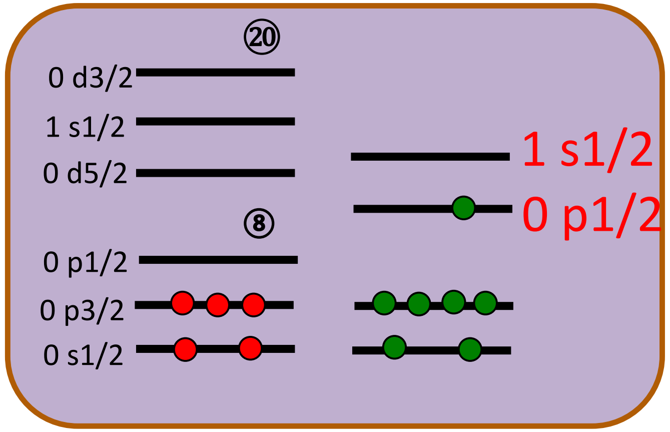
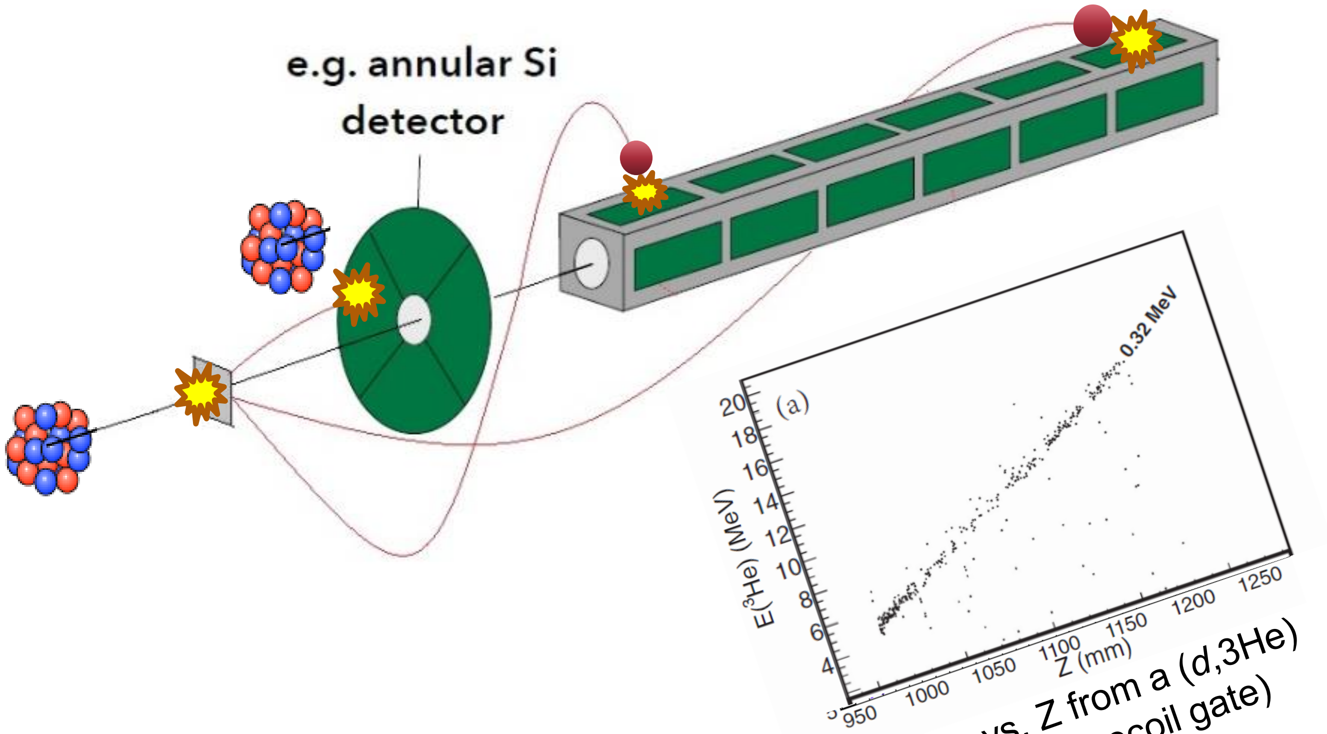
^{11}Be negative parity states

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



^{12}B (d, ^{3}He)^{11}Be
(1+)



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

^{11}Be negative parity states

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

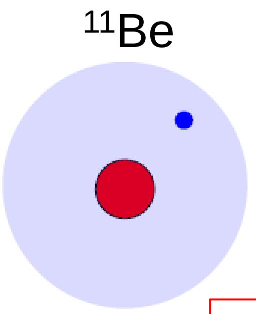
- Testing of various theories

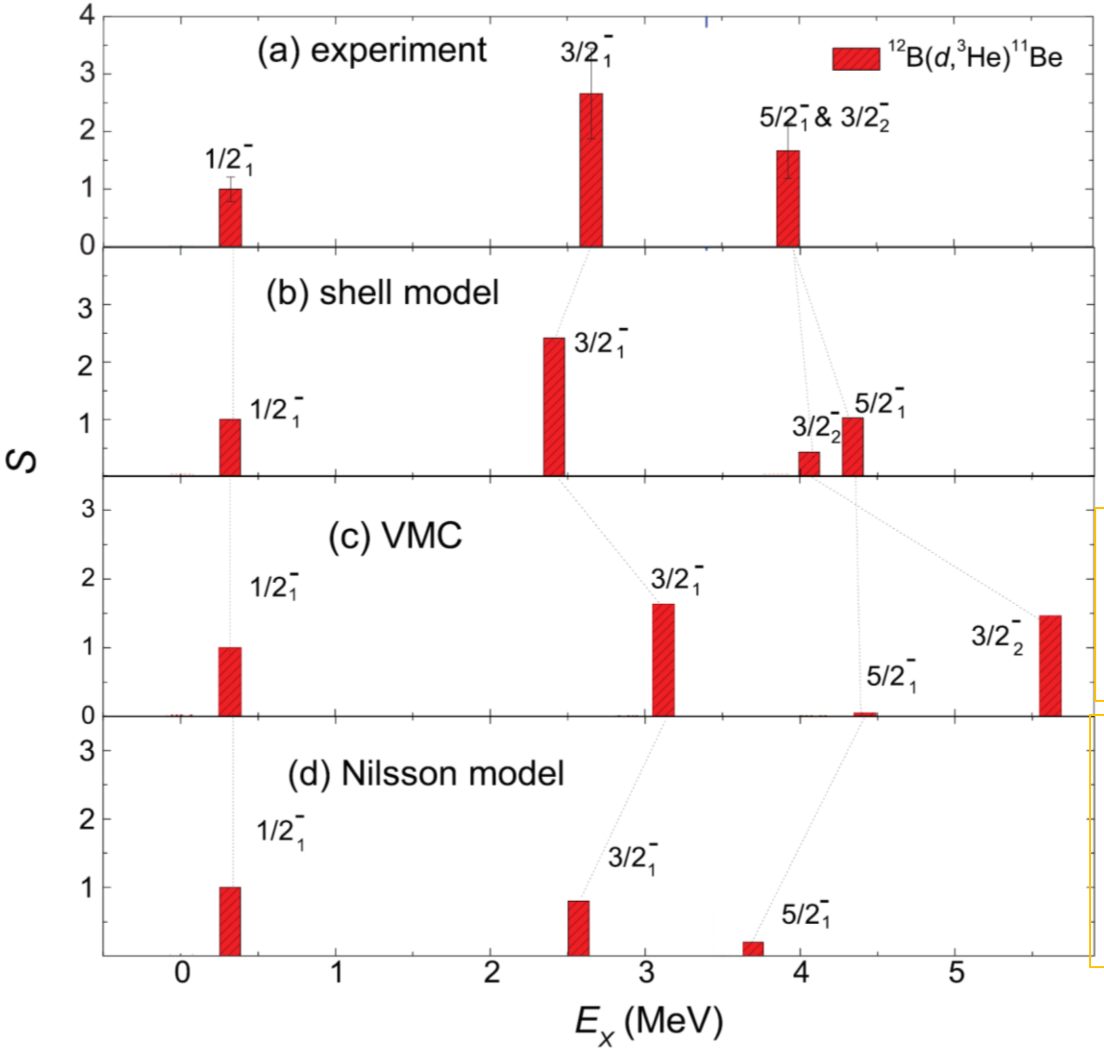
Shell model

Nilsson model

VMC

No-Core Shell model





More mixing with 3/2- states

Not a pure strong coupling picture

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

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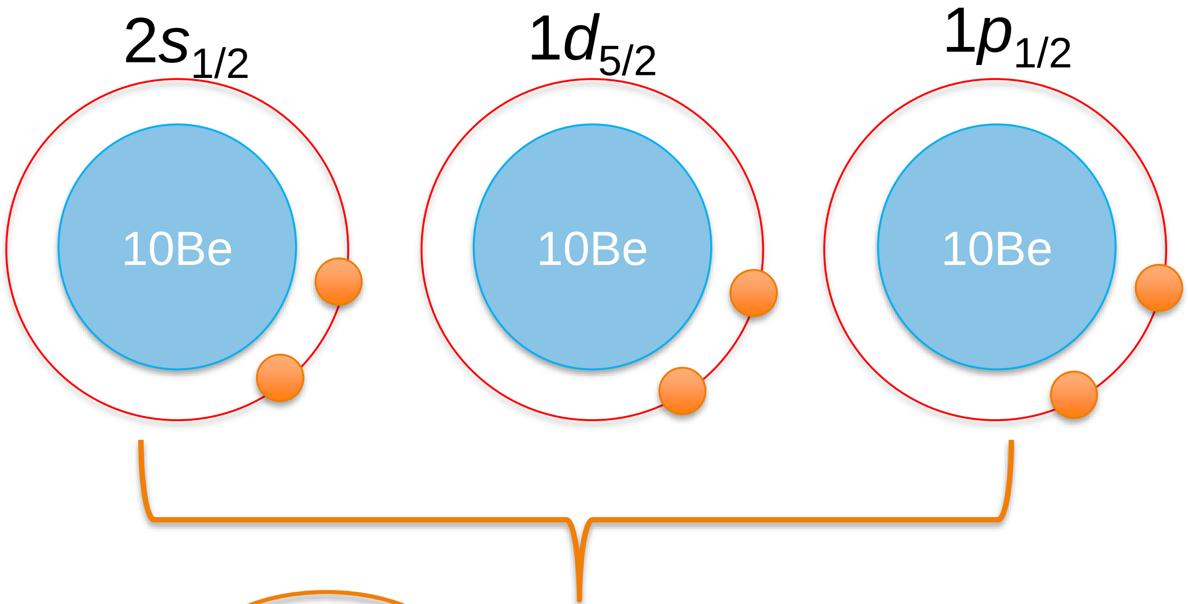
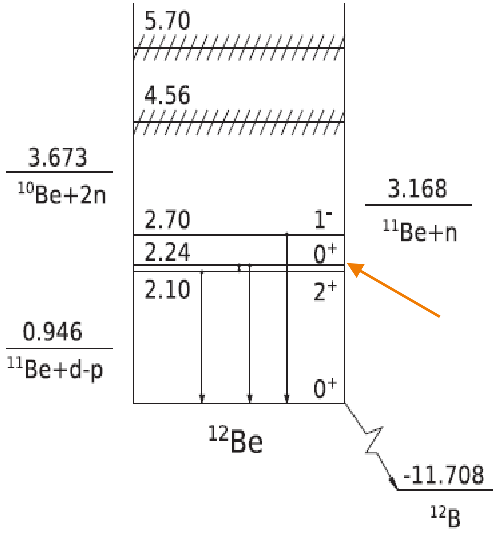
^{12}Be intruder states and single-particle configuration mixing

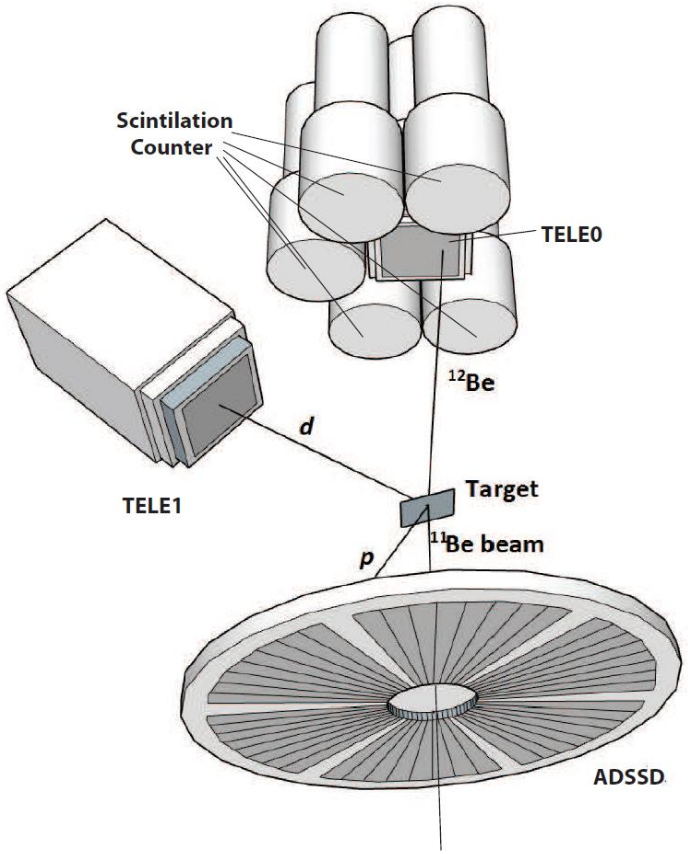
- **Breakdown** of conventional magic number： N=8
- **Isomeric state**： 0_2^+ 331(12) ns

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



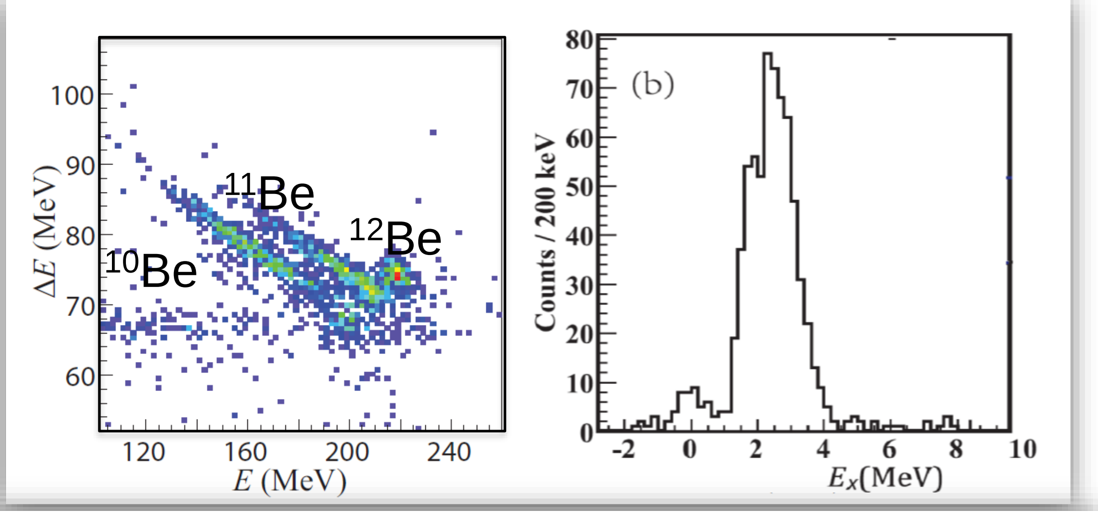
$$|0_i^+\rangle = a_i|1s_{1/2}^2\rangle + b_i|0d_{5/2}^2\rangle + c_i|0p_{1/2}^2\rangle \ (i = 1, 2)$$

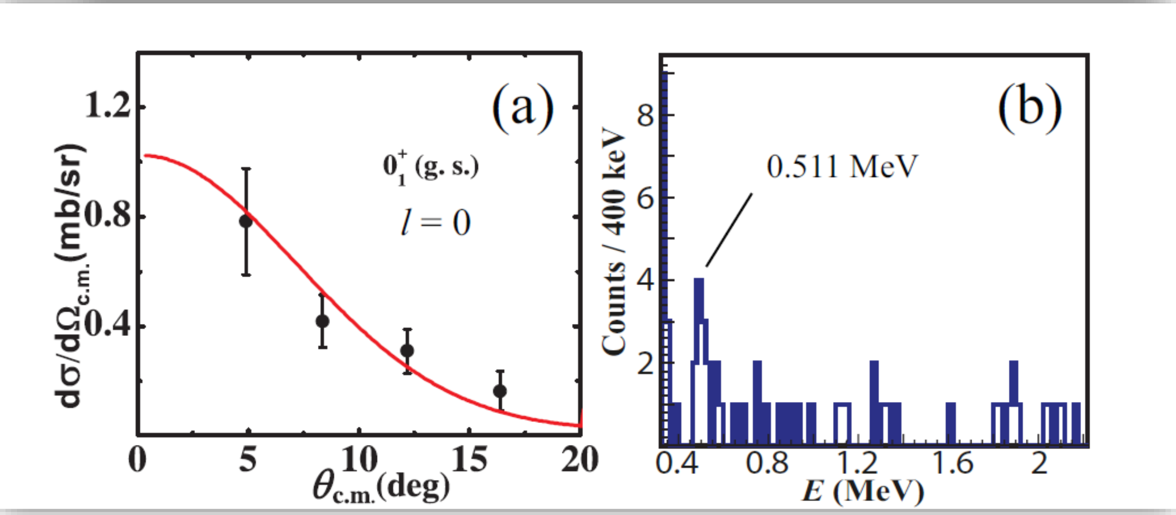




^{11}Be(*d,p*)^{12}Be
J. L. Lou, J. Chen *et al*. RCNP E407

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





ADWA calculation From D. Y. Pang

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

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

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

$$\alpha_1/\alpha_2 = 0.20/0.41 = 0.49^{+0.15}_{-0.16}$$

charge-exchange : γ_1= 0.24 and γ_2= 0.59

0_1^+			0_2^+		
$\alpha_1(\%)$	$\beta_1(\%)$	$\gamma_1(\%)$	$\alpha_2(\%)$	$\beta_2(\%)$	$\gamma_2(\%)$
19±7	57 ± 7		39 ± 2	2 ± 2	

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

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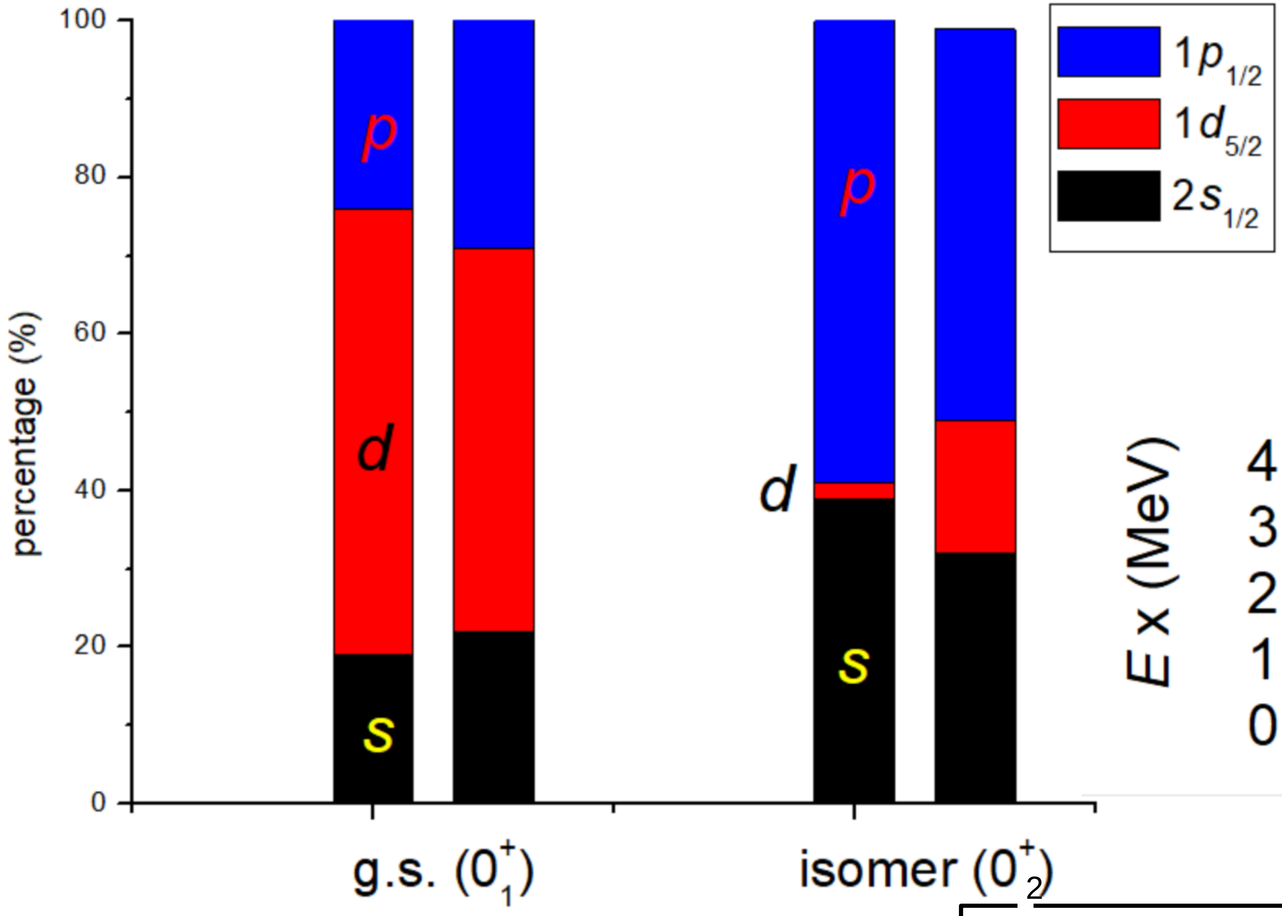
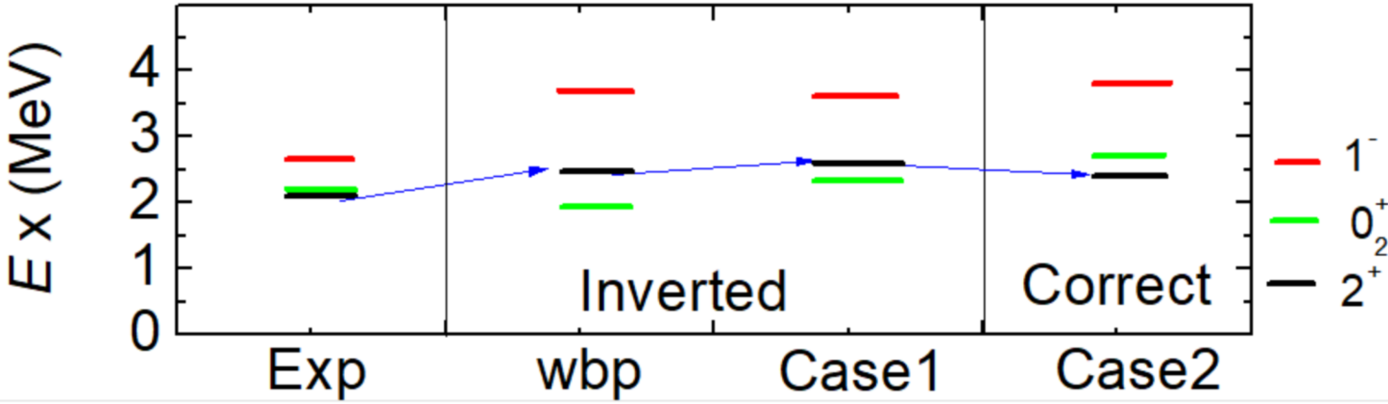
^{12}Be intruder states and single-particle configuration mixing



- 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.



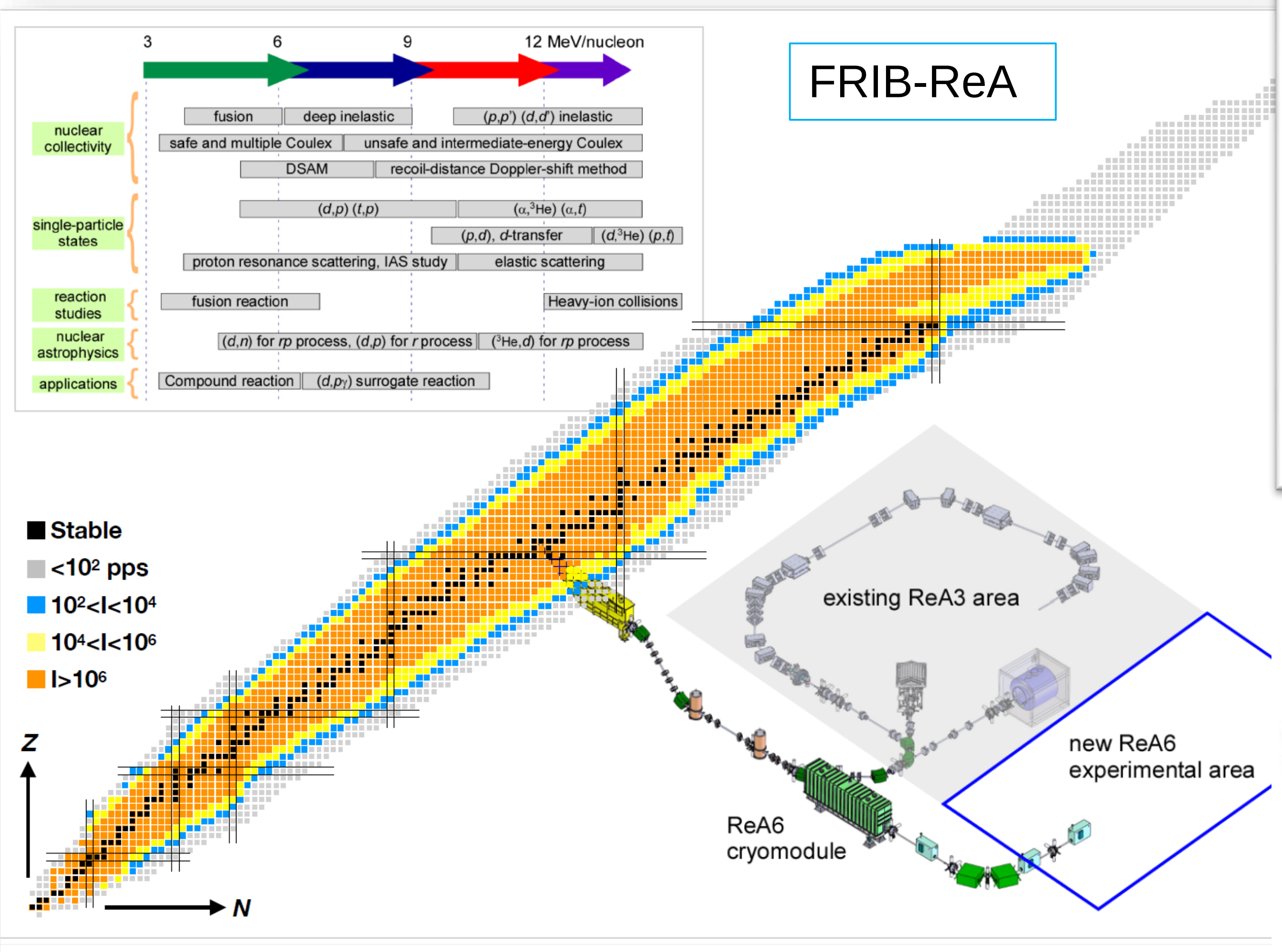
J. Chen *et al.* Phys. Lett. B 781 (2018) 412 - 416

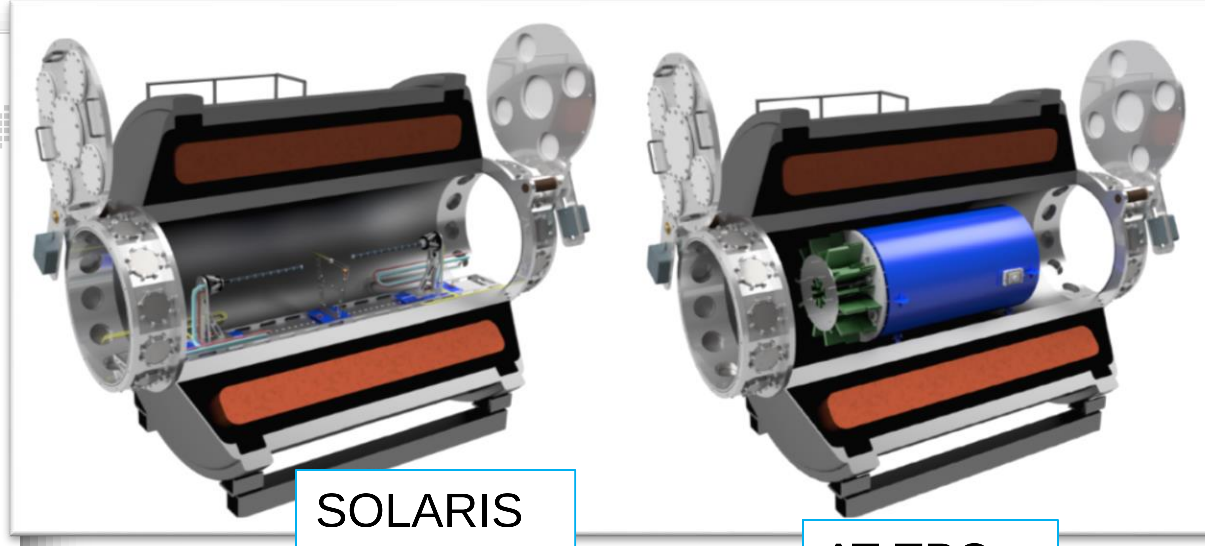
J. Chen *et al.* Phys. Rev. C 94, 064620 (2016)

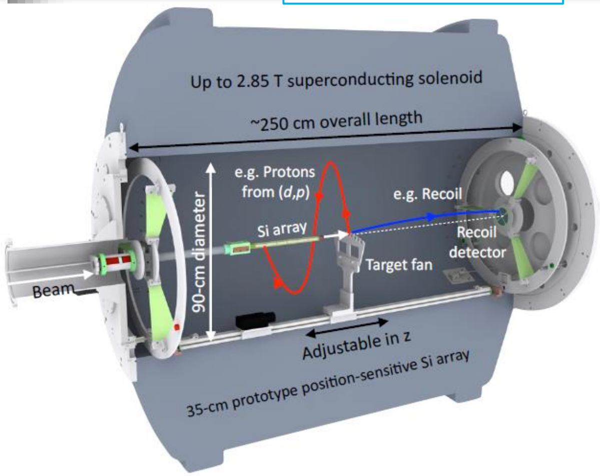
J. Chen *et al.* Phys. Rev. C 98, 014616 (2018)

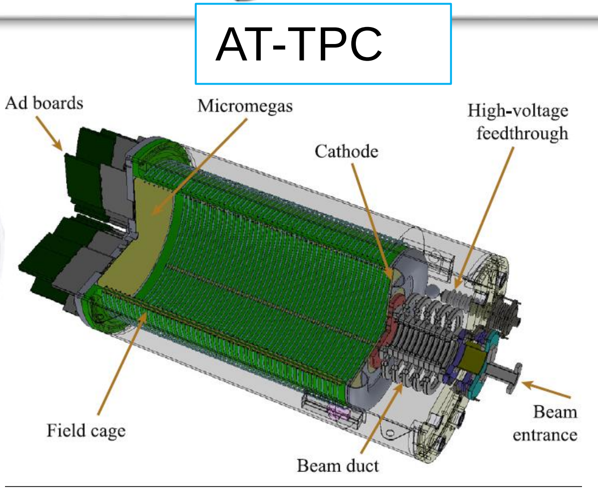
J. Chen *et al.* Phys. Rev. C 93, 034623 (2016)

New opportunities with ReA coupling to AT-TPC and SOLARIS





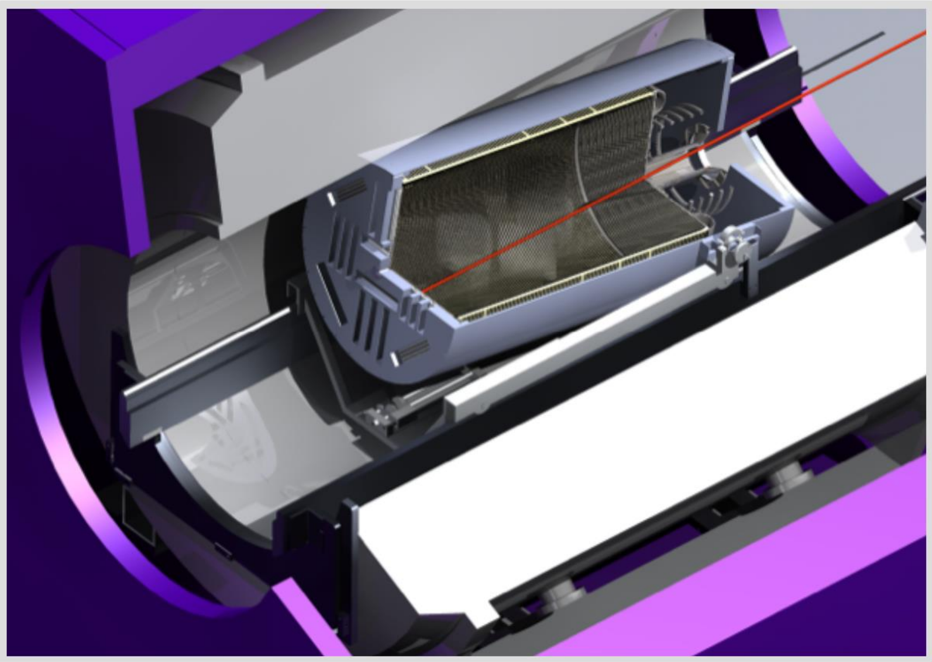


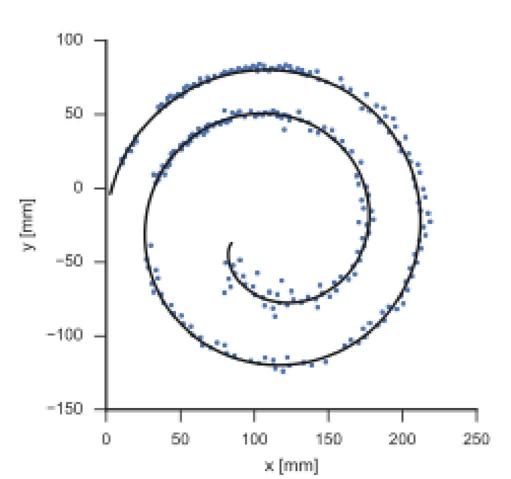


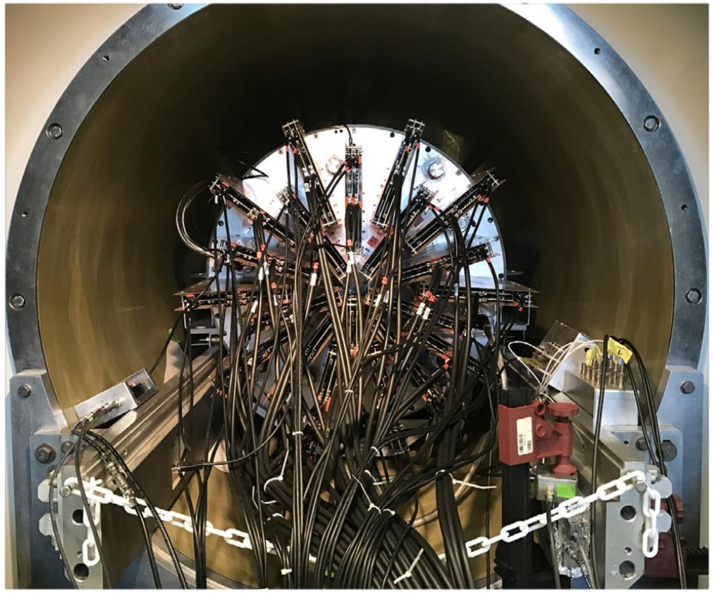
https://indico.frib.msu.edu/event/20/page/268-program,
https://www.anl.gov/phy/solaris

New opportunities with ReA coupling to AT-TPC and SOLARIS

- large-volume gas-filled detector ⟷ target isotopes as well as the tracking medium
- a large effective luminosity ⟷ beams as low as hundreds of pps





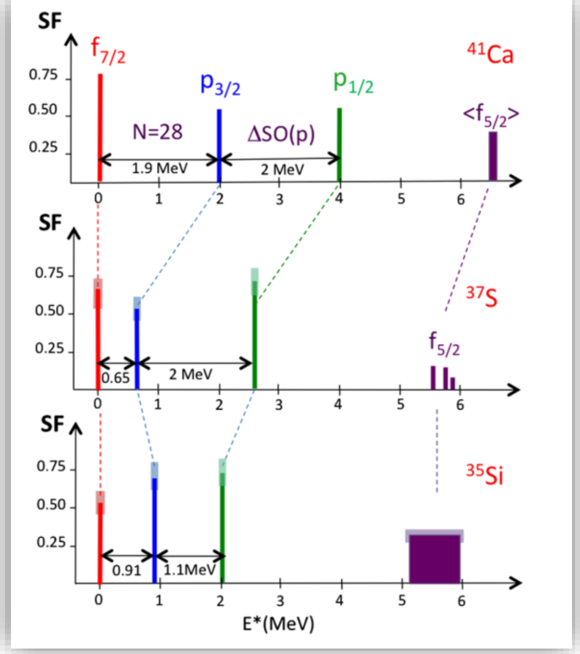


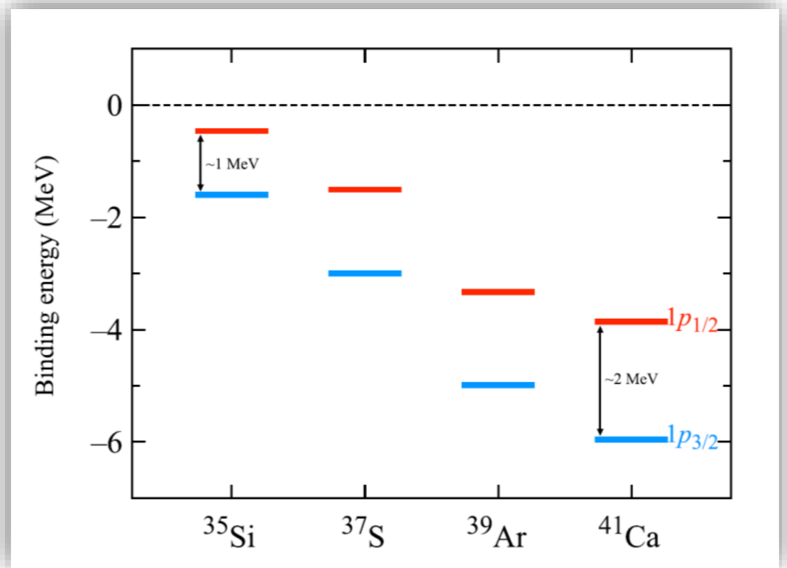
J. Bradt, D. Bazin et al., Nucl. Instrum. and Methods in Phys. Res. A 875, 65 (2017)

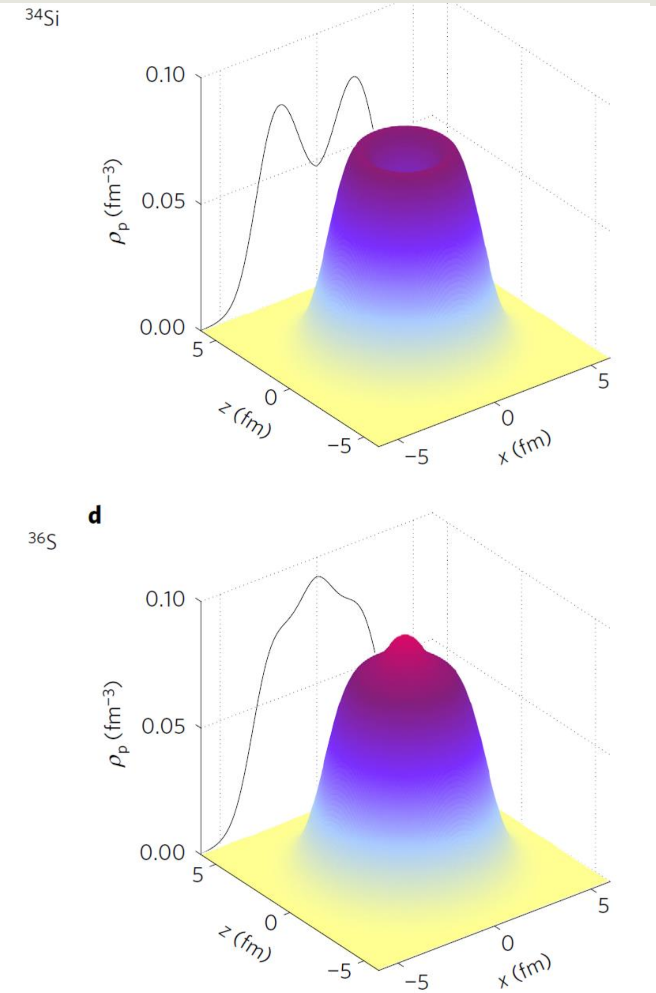
longer trajectories can be recorded

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

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).

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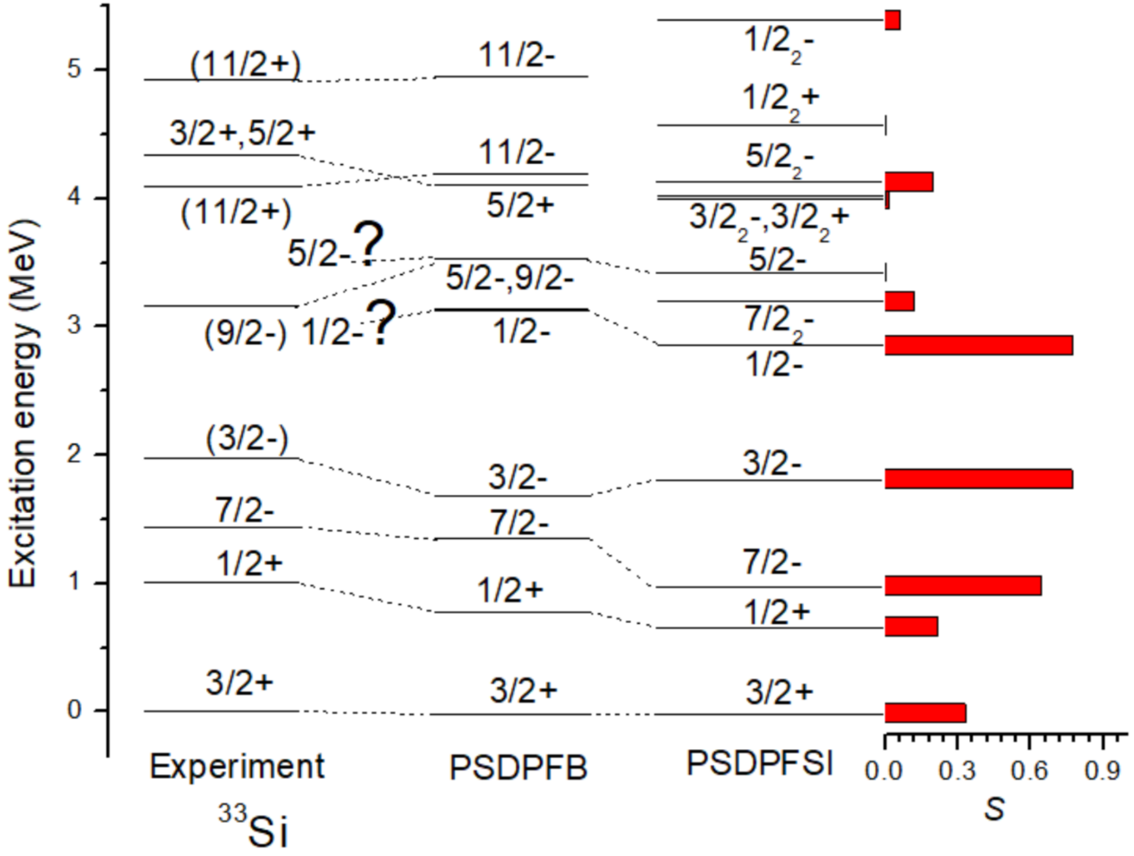
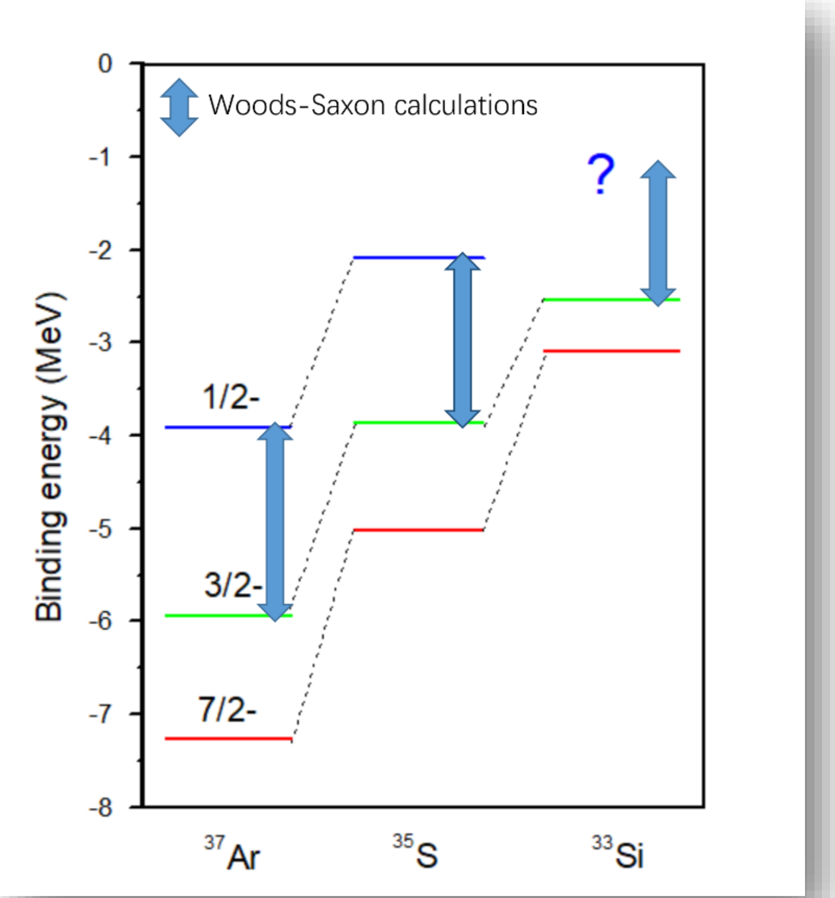


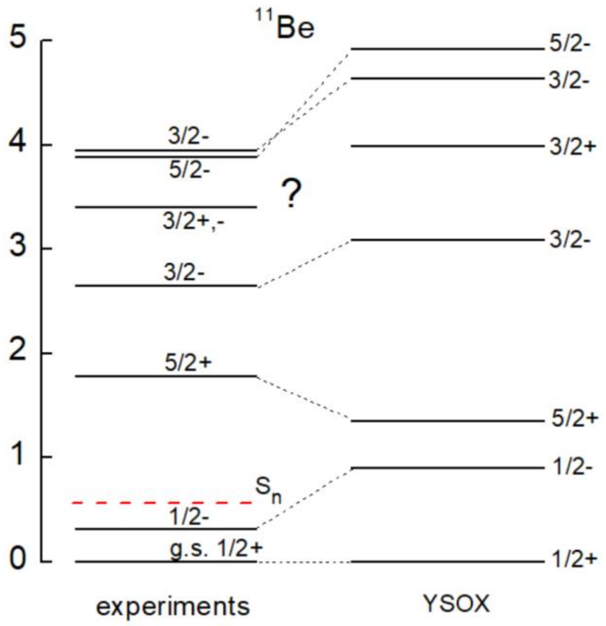


- Approved by NSCL PAC

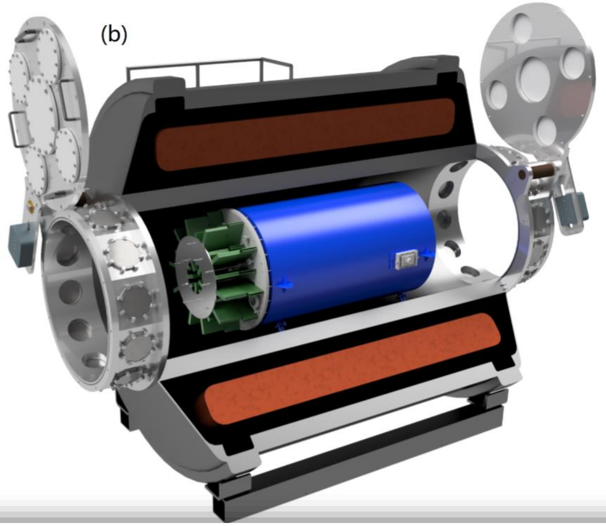
J. Chen, D. Bazin, et al,

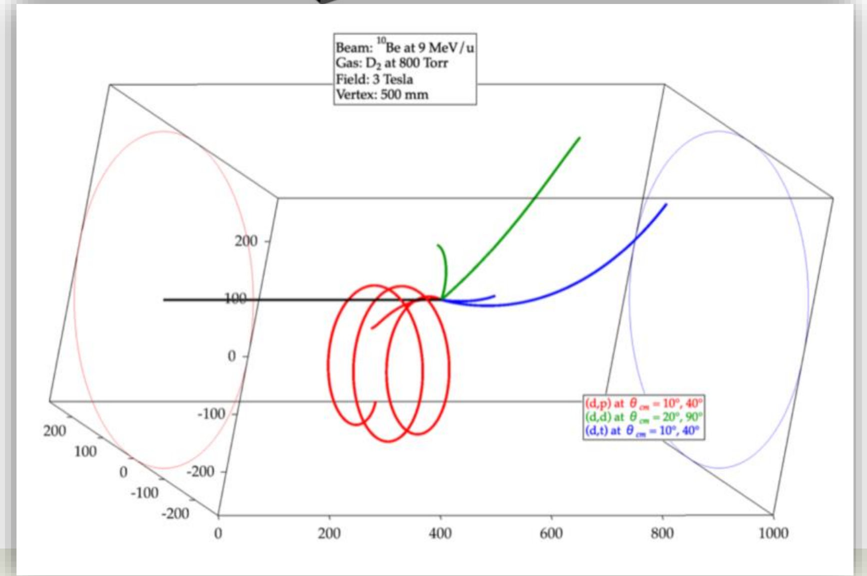
Commissioning of the AT-TPC and SOLARIS using long-lived beams

- ➢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



D. Bazin, J. Chen, et al,





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

Summary

- Overarching questions of nuclear physics:
  - nature of the nuclear force
  - origin of simple patterns in nuclear structures
- Experimental approach to study the nuclear single-particle structures
  - Probing nuclear forces in weak-binding system
- Testing various theories using ^{11}Be negative parity states
  - *ab-initio* approach, shell model, Nilsson model
- Determine 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 the 1$d_{5/2}$-orbital
- Test the role of continuum by measuring unbound state of ^{12}Be.
  - Three-body description is essential in ^{12}Be.
- New opportunities with ReA coupling to AT-TPC and SOLARIS

New experimental insights on rare nuclei to guide theoretical developments.

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

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