FRIB TA "Dialogues on Nuclear Physics", 23rd June 2020

Reactions at FRIB with heavy nuclei

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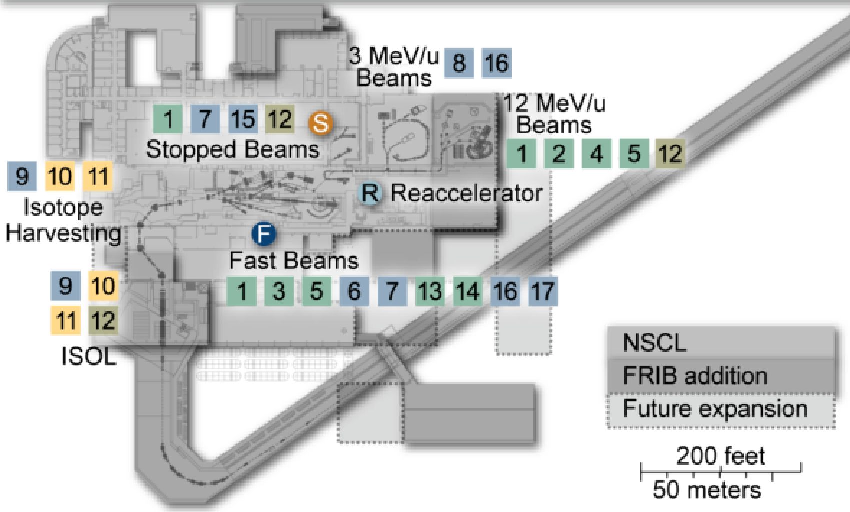
Outline

- Overview of FRIB physics capabilities for reactions studies
- Selected topics: opportunities and some theoretical challenges
  - Coulomb dissociation of halo nuclei
  - Spectroscopy of unbound nuclei
  - Indirect methods for astrophysics
  - The problem of quenching of spectroscopic factors
  - Searches for n-p pairing

The Science of FRIB

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Overarching Questions from NSAC 2007 LRP			
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?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the universe?	What are new applications of isotopes to meet the needs of society?
Overarching questions are answered by rare isotope research			
17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research			
1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe supernovae 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment	10. Medical 11. Stewardship
MSU proposed technical scope is sufficient to meet all benchmarks			



Fundamental overarching questions on:

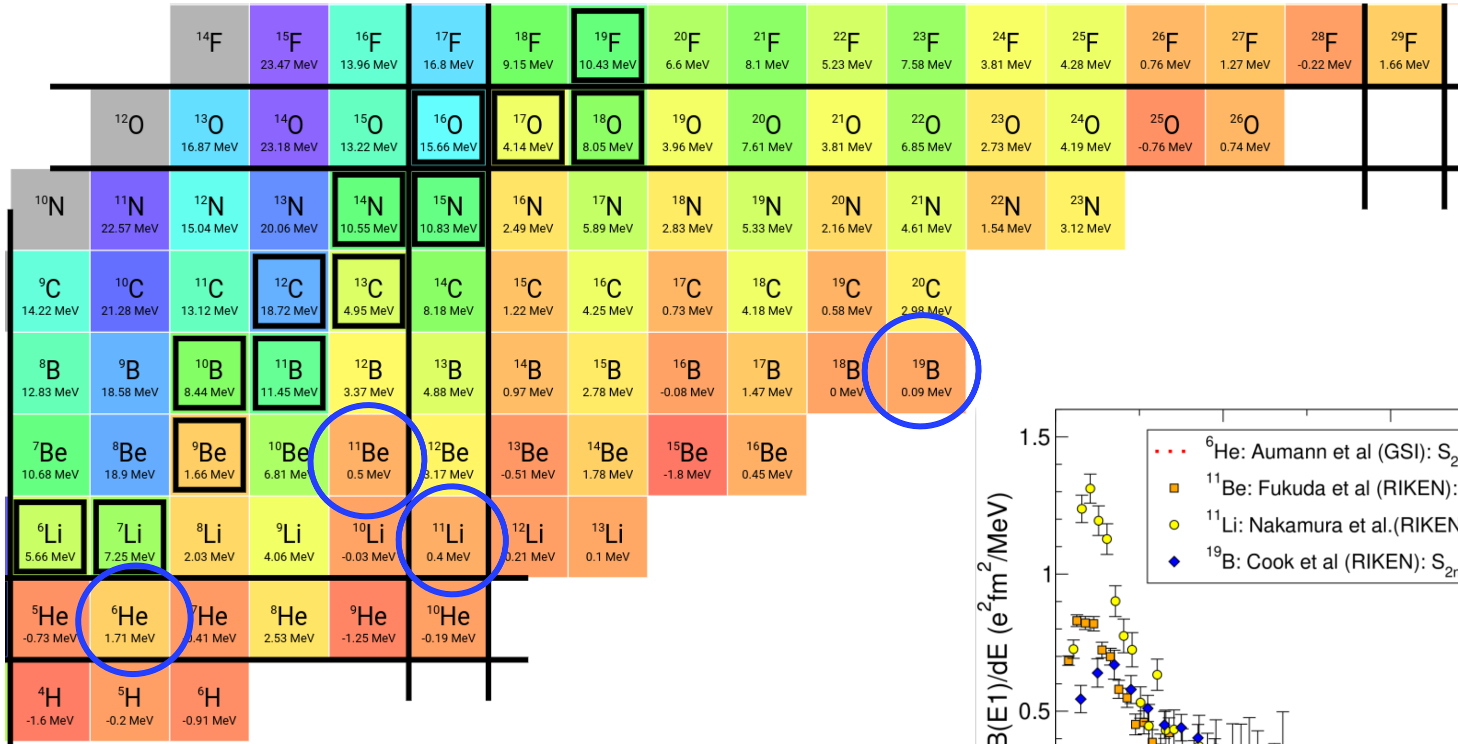
- Nuclear structure beyond stability valley and beyond driplines
- Nuclear Astrophysics

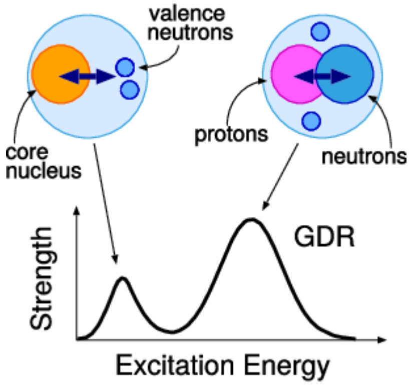
How can we use reactions with "heavy nuclei" to shed light on these problems?

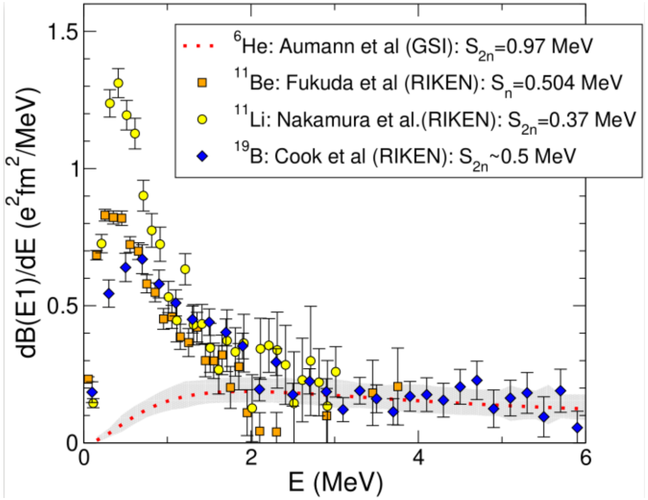
(from "FRIB Scientific and Technical Merit" - Michigan State University)

Unveling the halo structure by Coulomb dissociation

- Weak binding energy of neutron-halo nuclei enhances breakup probability near threshold in reactions with high-Z targets ⇒ mostly triggered by "stretching" caused by Coulomb E1 forces.
- Analyses of Coulomb dissociation experiments can (in principle) provide dB(E1)/dE strengths from measured breakup cross sections.







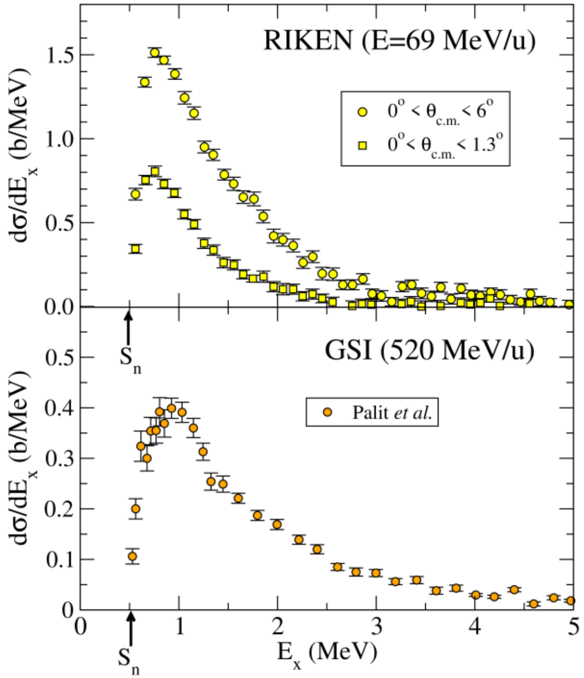
Most existing studies limited to light systems

Analysis of Coulomb dissociation experiments

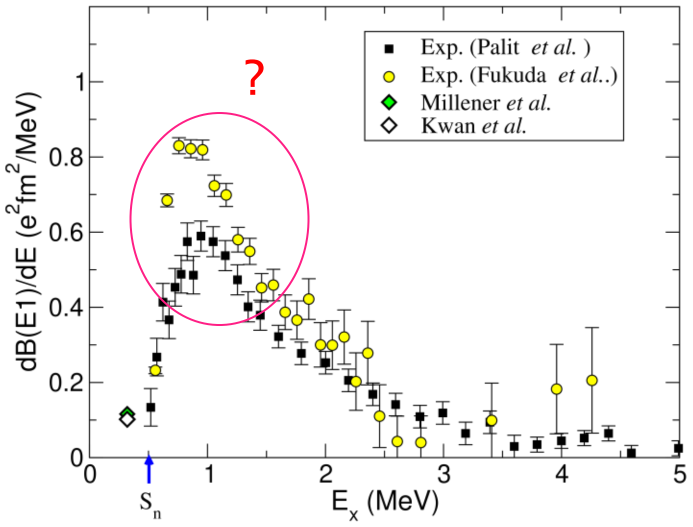
- **Goal:** extracting $dB(E1)/dE_x$ from exclusive breakup data with high-Z target
- **Standard analysis ⇒ EPM method**
  1. Only Coulomb excitation for $\theta < \theta_0$("safe" Coulomb)
  2. Coulomb part of $d^2\sigma/dEd\Omega$ proportional to dB/dE ⇒ $$\frac{d^2\sigma}{d\Omega d\varepsilon} = \frac{dB(E1,\varepsilon)}{d\varepsilon} F_1(\theta,\xi),$$ ($E_x = S_n + \varepsilon$)
  3. **Nuclear** contribution, if present, can be added incoherently.

Example: the $^{11}Be+^{208}Pb$ case

Measured



EPM



Fukuda et al, PRC70 (2004) 054606
Palit et al, PRC68 (2003) 034318.

Novel method for analysis of Coulomb dissociation experiments [arXiv:2004.14612]

Reaction framework: CDCC or extended CDCC (XCDCC) [Summers *et al*, PRC74, 014606 ('06), de Diego, PRC89, 064609 ('14)]

- Nuclear and Coulomb on equal footing and to all orders.
- Approximate relativistic kinematics.
- Much more demanding numerically than EPM.

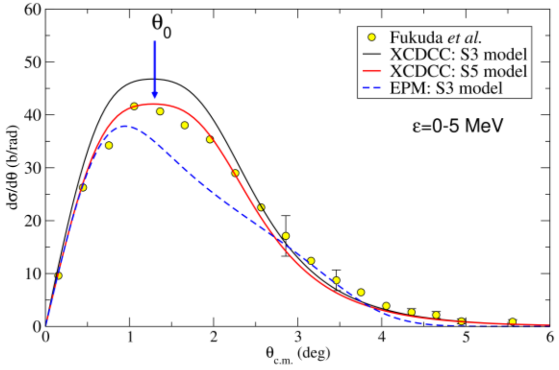
Structure model: particle-plus-core few-body model with possible core excitations.

Strategy:

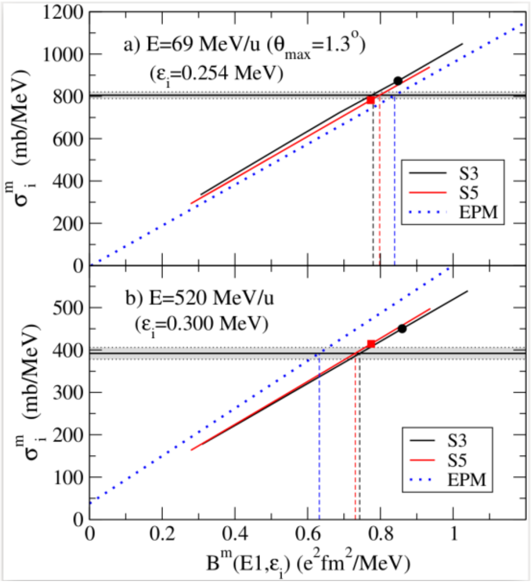
1. Using (X)CDCC, study dependence of calculated $d\sigma_{bu}/dE$ upon small variations of dB/dE of assumed structure model
2. Derive "correction" factors for each excitation energy to match measured $d\sigma_{exp}/dE$

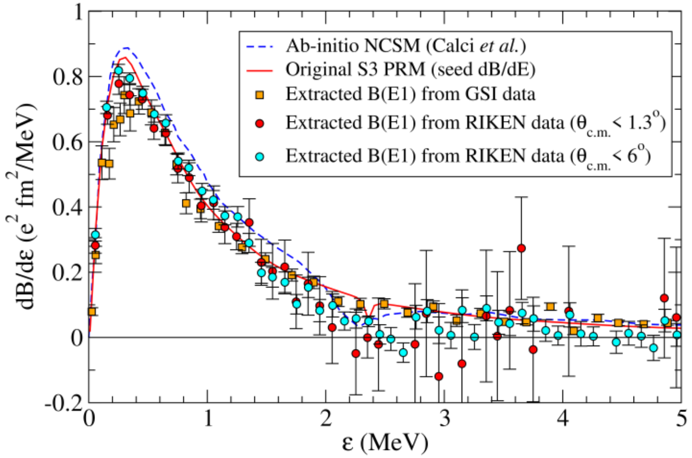
Application to $^{11}Be+^{208}Pb$

1. Nuclear excitation not negligible, even for θ <<
2. Coulomb part of $d^2\sigma/dEd\Omega$ aprox. linear with dB/dE, but NOT proportional.
3. Nuclear contribution interferes with Coulomb.



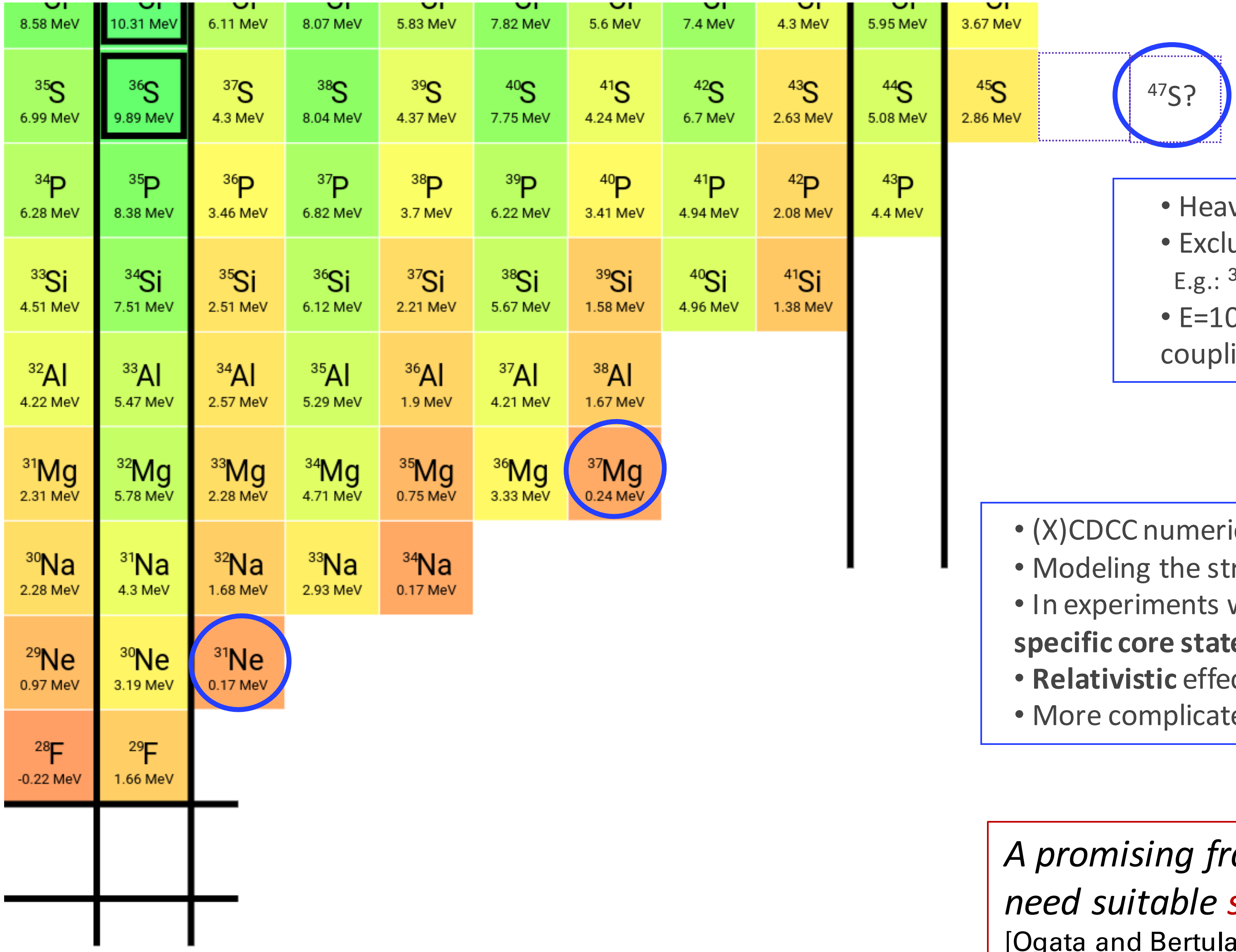
S3, S5 models from
Summers, PLB650,124 (2007)0370





A.M.M., J.A. Lay, J.Gómez-Camacho, arXiv:2004.14612

Planning future Coulomb dissociation experiments



Opportunites at FRIB

- Heavier halo candidates: ^{31}Ne,^{37}Mg, ^{47}S
- Exclusive measurements with particle and γ coincidences
  E.g.: $^{31}\text{Ne} \Rightarrow {}^{30}\text{Ne}^* + n + \gamma$
- E=100-200 MeV/u optimal for minimizing multistep couplings while keeping relativistic effects under control.

Challenges for theory

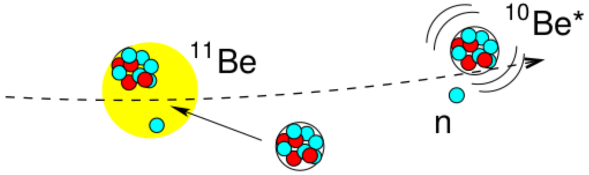
- (X)CDCC numerically demanding
- Modeling the structure of **deformed** halos?
- In experiments with γ coincidences, theory should provide population of **specific core states** and possible **core excitation/deexcitations**.
- **Relativistic** effects for E > 100 MeV/u
- More complicated excitation modes (**core+4n**?).

A promising framework is the eikonal CDCC (E-CDCC) but need suitable structure models (not always available!)
[Ogata and Bertulani, PTP 121, 1399 (2009)]

Core excitations reaction dynamics

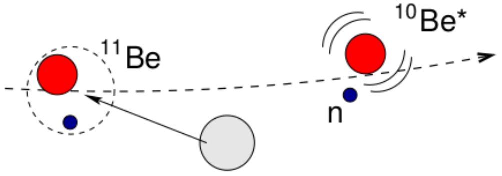
Deviations from the inert-cluster model are expected to show up when cluster d.o.f. are strongly excited during the reaction.

Microscopic models



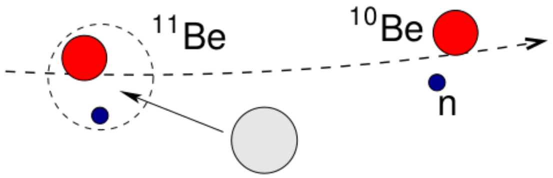
- ✔ Fragments described microscopically
- ✔ Realistic NN interactions (Pauli properly accounted for)
- ✖ Numerically demanding / not simple interpretation.

Non-inert-core few-body models



- ✔ Few-body + some relevant collective d.o.f.
- ✔ Motivated extensions of Faddeev and CDCC (XCDCC)

Inert cluster models



- ✖ Ignores cluster excitations (only few-body d.o.f).
- ✖ Phenomenological inter-cluster interactions (aprox. Pauli).
- ✔ Exactly solvable (in some cases).
- ✔ Achieved for $A \leq 5$ (eg. coupled-channels, Faddeev).

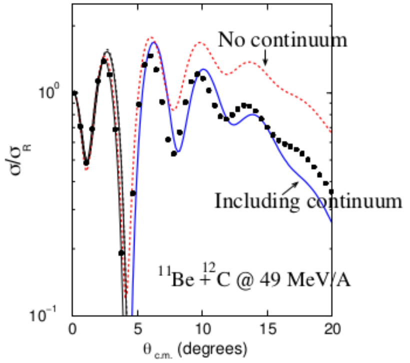
Core excitations in elastic scattering

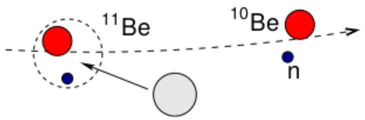
+ microscopic

CDCC with inert core

R.Johnson *et al*,

PRL79,2771(1997).



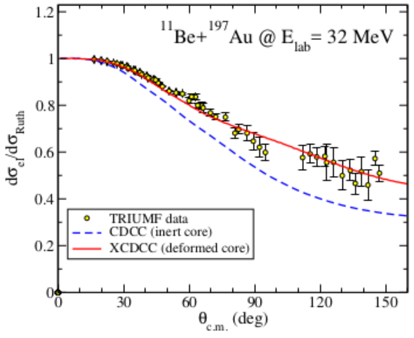


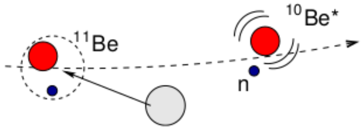
- ✔ Includes halo degre of freeom
- ✖ Clusters dynamics only through effective potentials

CDCC with deformed core

V.Pesudo *et al*,

PRL118,152502(2017)



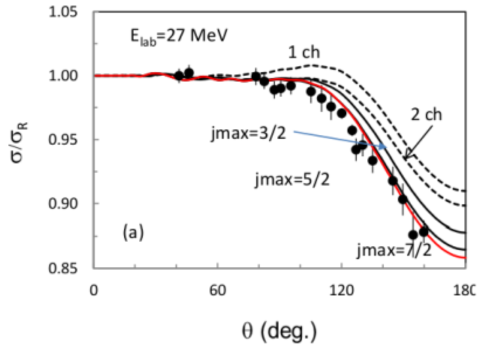


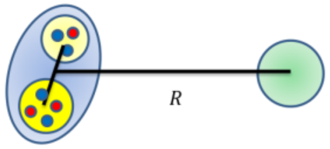
- ✔ Simple structure input (PVM, PRM, etc)
- ✘ Only collective excitations
- ✘ So far, only 2-body projetiles, coud be needed for 3-body projectiles (eg. ^{11}Li,^{14}Be)

Microscopic CDCC

P.Descouvemont,

PRL111,082701(2013)



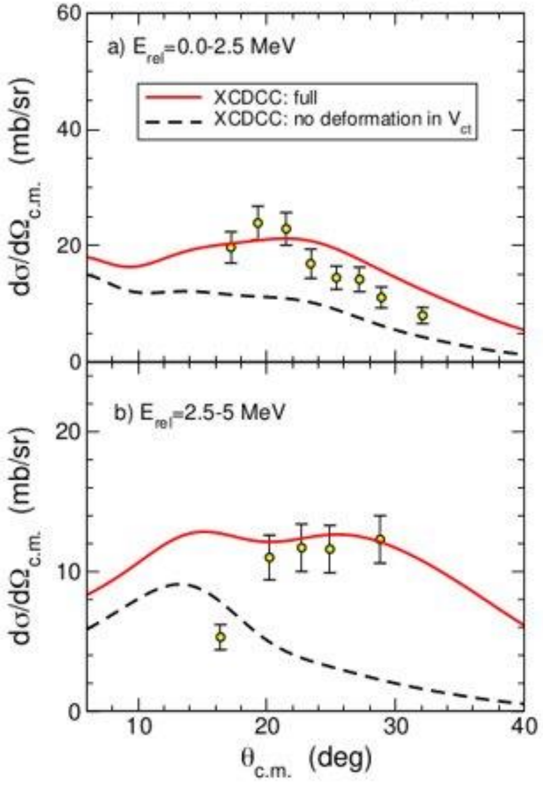


- ✔ Microscopic description of clusters.
- ✔ Core excitations "automatic"
- ✔ Collective + non-collective excitations

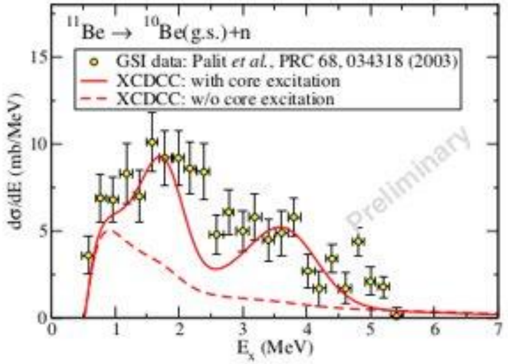
Core excitations in breakup

Core excitations may enhance dramatically the breakup cross sections in reactions of deformed halo nuclei with light targets

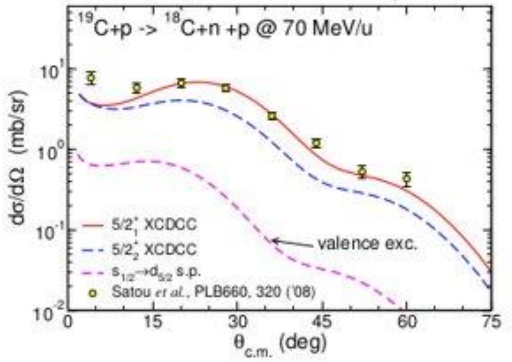
^{11}Be+ p @ 64 MeV/u

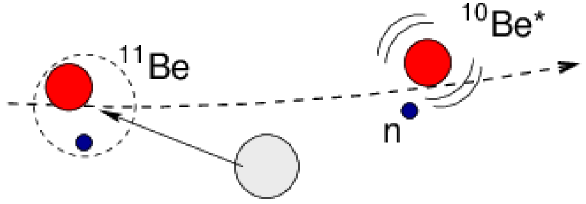


^{11}Be+ ^{12}C @ 520 MeV/u



^{19}C+ p @ 69 MeV/u

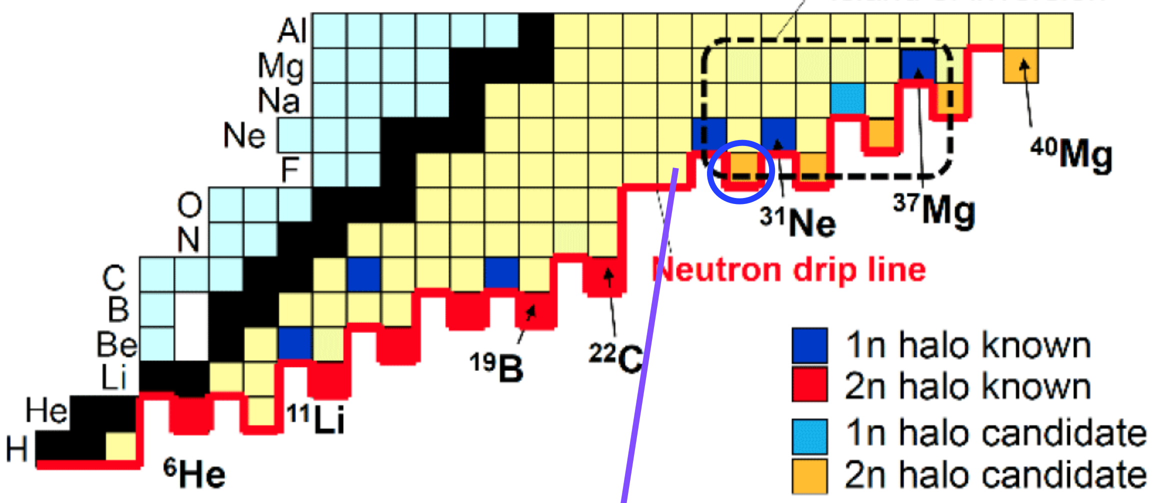




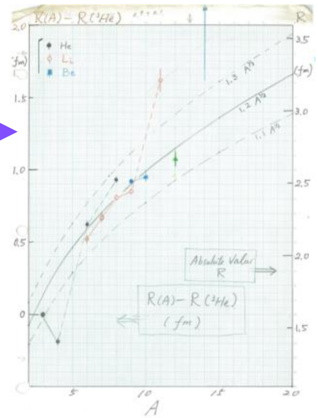
What are the limits of formation of 2n-haloes

(by I. Tanihata)

(by T. Nakamura)



^{29}F



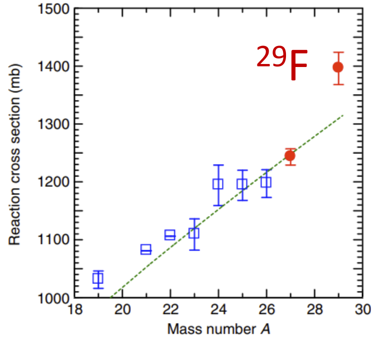
^{6}He, ^{11}Li: Tanihata (1980s). σ_{int}
^{22}C: Togano, PLB761,412(2016). σ_{reac}
^{19}B: Cook, PRL 124, 212503 (2020). Coulex
^{29}F: Baghi, PRL124, 222504 (2020). σ_{reac}
(heaviest confirmed 2n-halo)

Key open questions

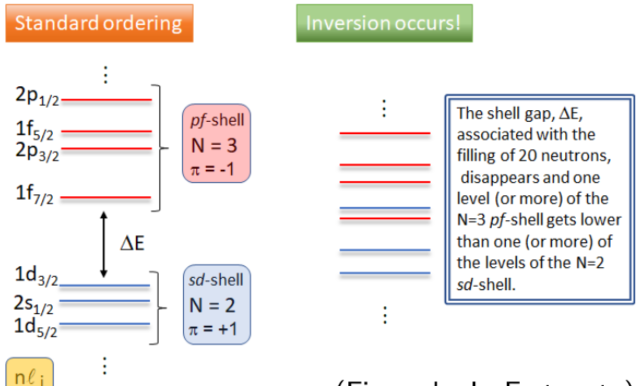
- Where are the limits of the driplines in the island of inversion?
- What are the mechanisms leading to 2n-haloes?
  (pairing, intruder states, core excitations, ...)

Opportunites at FRIB

- Reaction cross sections measurements of halo candidates
- Coulomb dissociation experiments
- One, two-particle transfer?



Baghi, PRL124, 222504 (2020)



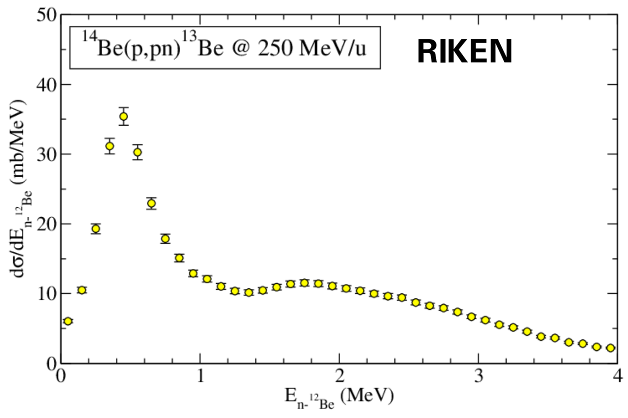
(Figure by L. Fortunato)

lowering of intruder $2p_{32}$ level enhances halo formation

[Singh et al, Phys. Rev. C 101 (2020) 024310]

Spectroscopy of unbound systems

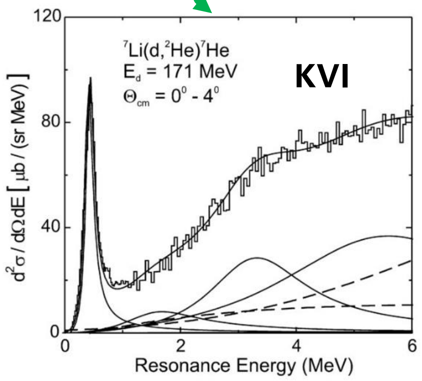
	^{12}O	^{13}O 16.87 MeV	^{14}O 23.18 MeV	^{15}O 13.22 MeV	^{16}O 15.66 MeV	^{17}O 4.14 MeV	^{18}O 8.05 MeV	^{19}O 3.96 MeV	^{20}O 7.61 MeV	^{21}O 3.81 MeV	^{22}O 6.85 MeV	^{23}O 2.73 MeV	^{24}O 4.19 MeV
^{10}N	^{11}N 22.57 MeV	^{12}N 15.04 MeV	^{13}N 20.06 MeV	^{14}N 10.55 MeV	^{15}N 10.83 MeV	^{16}N 2.49 MeV	^{17}N 5.89 MeV	^{18}N 2.83 MeV	^{19}N 5.33 MeV	^{20}N 2.16 MeV	^{21}N 4.61 MeV	^{22}N 1.54 MeV	^{23}N 3.12 MeV
^{9}C 14.22 MeV	^{10}C 21.28 MeV	^{11}C 13.12 MeV	^{12}C 18.72 MeV	^{13}C 4.95 MeV	^{14}C 8.18 MeV	^{15}C 1.22 MeV	^{16}C 4.25 MeV	^{17}C 0.73 MeV	^{18}C 4.18 MeV	^{19}C 0.58 MeV	^{20}C 2.98 MeV		
^{8}B 12.83 MeV	^{9}B 18.58 MeV	^{10}B 8.44 MeV	^{11}B 11.45 MeV	^{12}B 3.37 MeV	^{13}B 4.88 MeV	^{14}B 0.97 MeV	^{15}B 2.78 MeV	^{16}B -0.08 MeV	^{17}B 1.47 MeV	^{18}B 0 MeV	^{19}B 0.09 MeV		
^{7}Be 10.68 MeV	^{8}Be 18.9 MeV	^{9}Be 1.66 MeV	^{10}Be 6.81 MeV	^{11}Be 0.5 MeV	^{12}Be 3.17 MeV	^{13}Be -0.51 MeV	^{14}Be 1.78 MeV	^{15}Be -1.8 MeV	^{16}Be 0.45 MeV				
^{6}Li 5.66 MeV	^{7}Li 7.25 MeV	^{8}Li 2.03 MeV	^{9}Li 4.06 MeV	^{10}Li -0.03 MeV	^{11}Li 0.4 MeV	^{12}Li -0.21 MeV	^{13}Li 0.1 MeV						
^{5}He -0.73 MeV	^{6}He 1.71 MeV	^{7}He -0.41 MeV	^{8}He 2.53 MeV	^{9}He -1.25 MeV	^{10}He -0.19 MeV								
^{4}H -1.6 MeV	^{5}H -0.2 MeV	^{6}H -0.91 MeV											

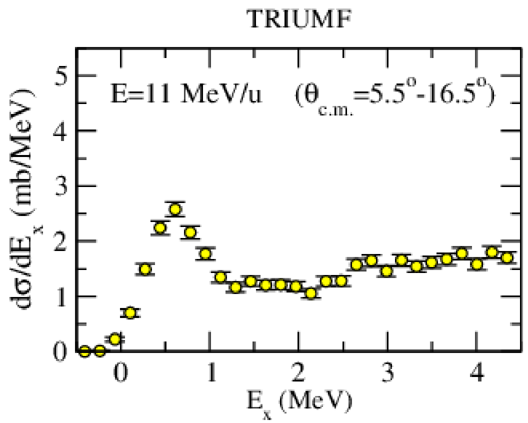


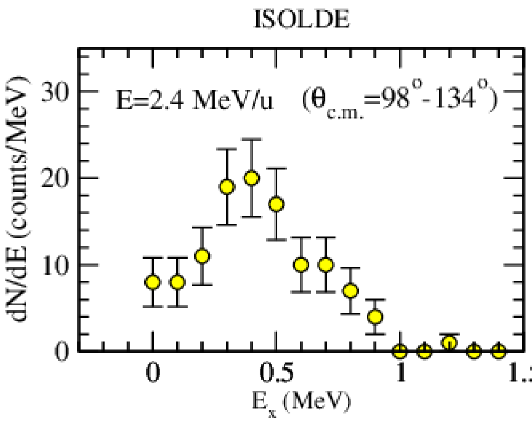
^{9}Li(d,p)^{10}Li

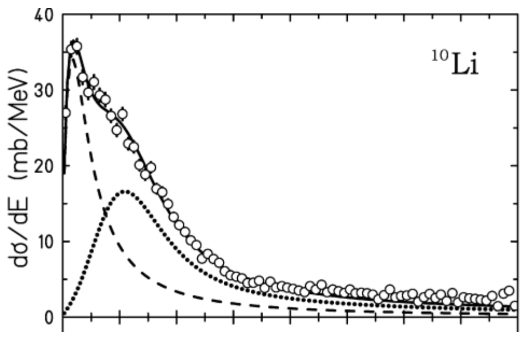
^{11}Li(p,pn)

GSI-LAND @ 280 MeV/u









Beck, PLB 645(2007)128

Cavallaro,PRL118 (2017) 012701

Jeppesen, PLB 642 (2006) 449

Aksyutina,PLB 666,430('08)

Spectroscopy of unbound systems: from cross sections to structure

Using a single probe can lead to misleading or even contradictory information

Example: The ^{9}Li(d,p)^{10}Li transfer reaction:

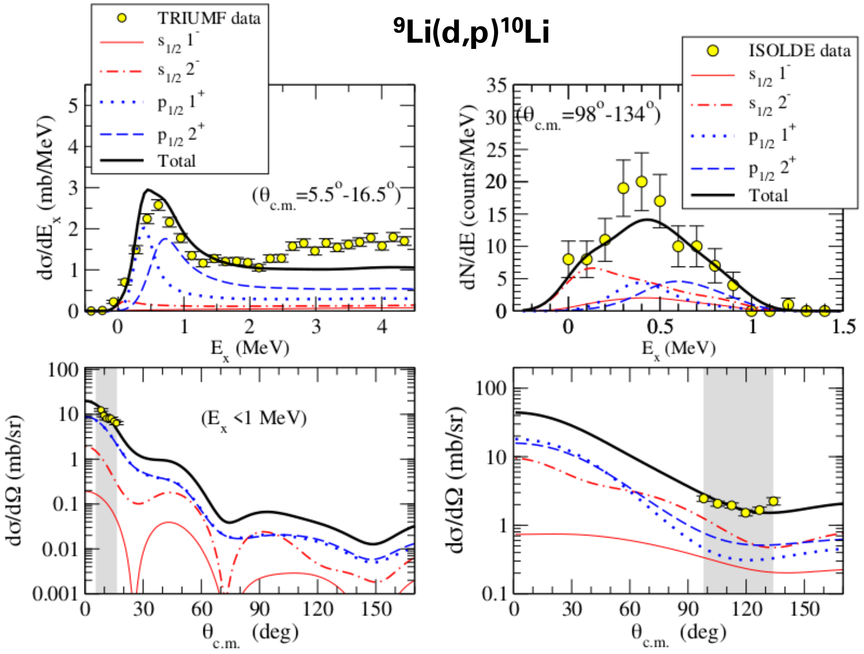
- ISOLDE (E=2.4 MeV/u)
  ⇒ large s-wave near-threshold strength (virtual state)

- TRIUMF (E~11 MeV/u)
  ⇒ cross section dominated by p-wave resonance
  ⇒ no apparent evicence of near-threshold virtual state

⇓

- The two sets of cross sections can be reproduced with the same reaction theory (transfer to continuum) and structure model (with both s-wave v.s. and p-wave resonances)

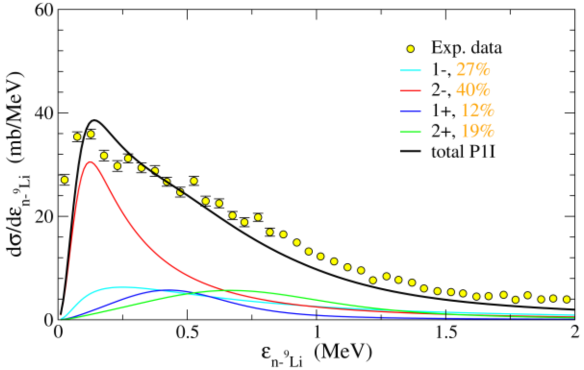
- These **structure** properties manifest themselves very differently in the **reaction observables** depending on the experimental probe and conditions (incident energy, angular range).



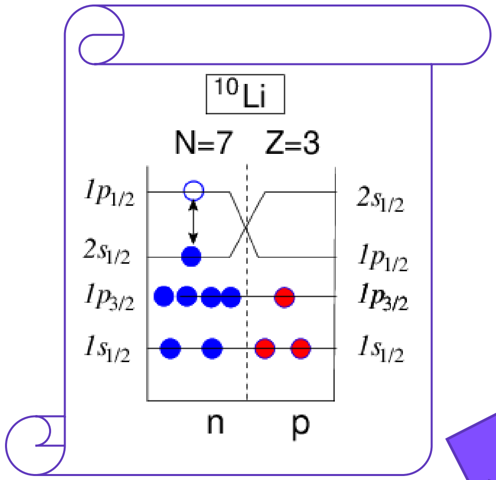
AMM, Casal, Gomez-Ramos, PLB 793 (2019) 13

Complementing different mechanisms: the ^{10}Li case

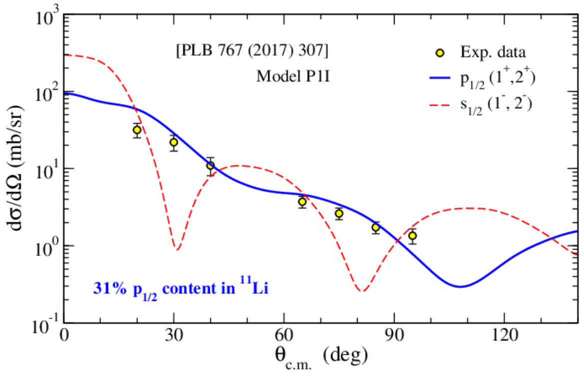
^{11}Li(p,pn)^{10}Li @ 280 MeV/u (GSI)



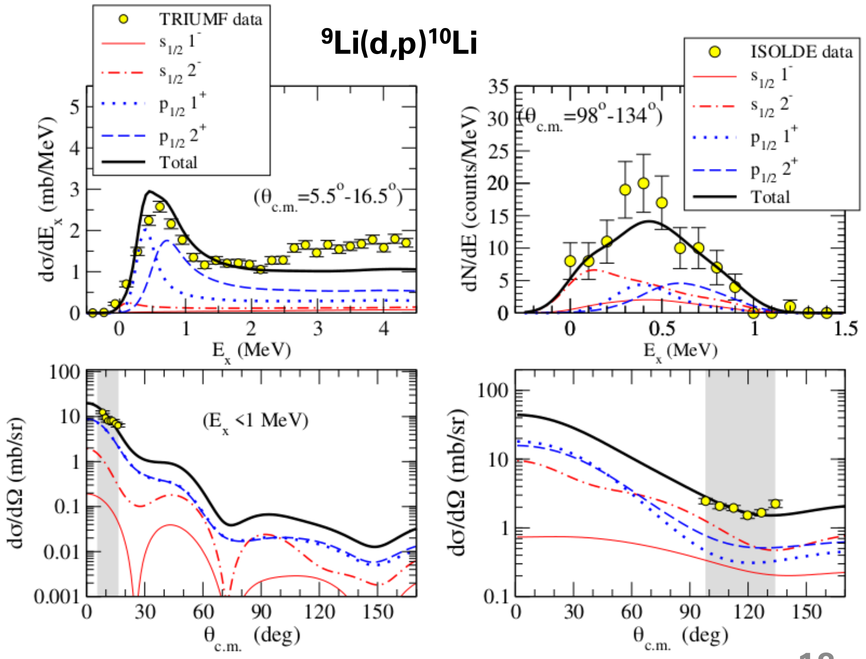
Gomez-Ramos et al,
PLB772, 115 (2017)



^{11}Li(p,d)^{10}Li @ 5.7 MeV/u (TRIUMF)



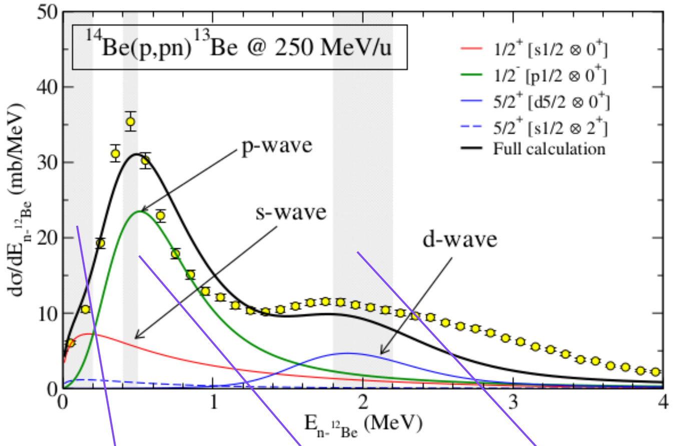
Casal et al,
PLB767, 307 (2017)



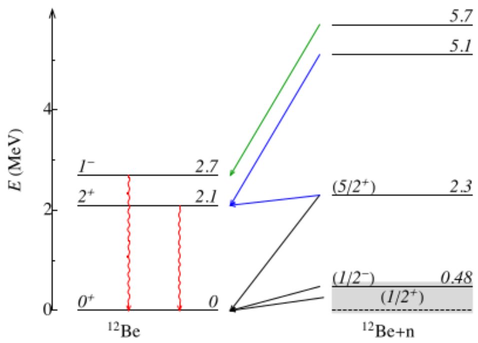
AMM, Casal, Gomez-Ramos, PLB 793 (2019) 13

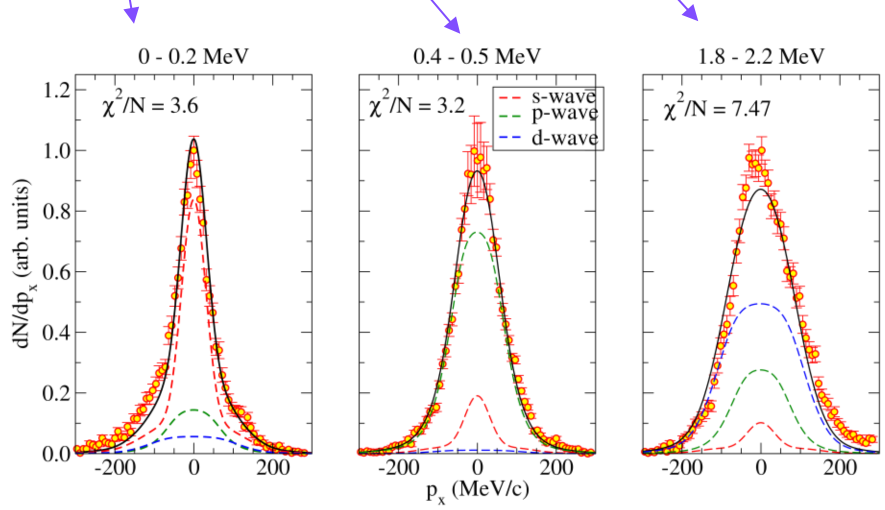
FRIB can provide unique possibilites combining information from low-energy reactions (eg. transfer) with fast beams (eg. (p,pn))

Challenges for future spectroscopic studies in the continuum



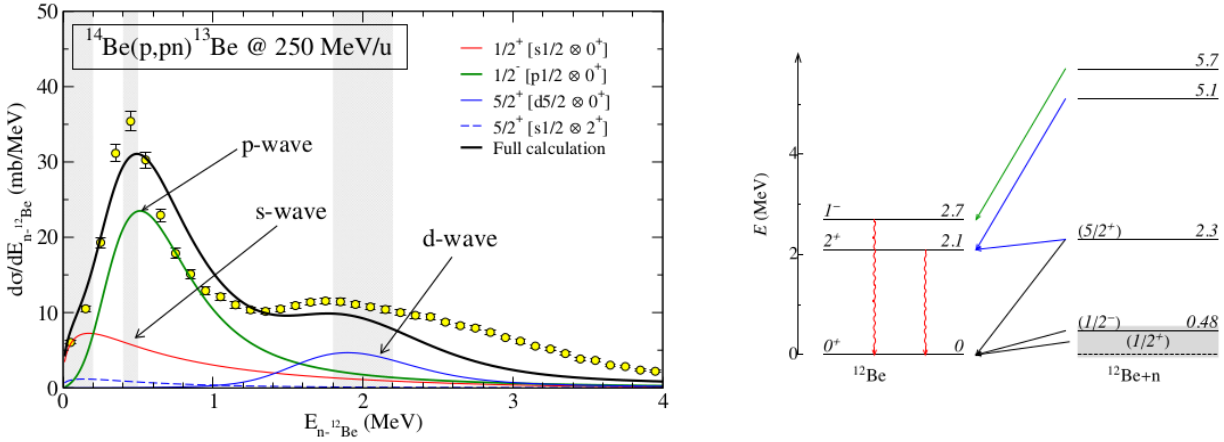
Corsi et a, PLB797(2019) (SAMURAI)





- Open-shell cores produce complex n+core spectra (eg. ^{13}Be=^{12}Be+n)
- Experimentally, the interpretation can be assisted by:
  - γ-ray coincidences.
  - momentum distributions.
- **Theoretically**, usual "Breit-Wigner" fitting may become impractical and should be bettter replaced by a proper modeling of the reaction dynamics and structure overlaps.
- **Eg.:** ^{14}Be(p,pn)^{13}Be analysed with TC method and 3-body model of ^{14}Be with ^{12}Be(0$^+$,2$^+$) core excitations

Challenges for future spectroscopic studies in the continuum



Corsi et a, PLB797(2019) 134843 (SAMURAI)

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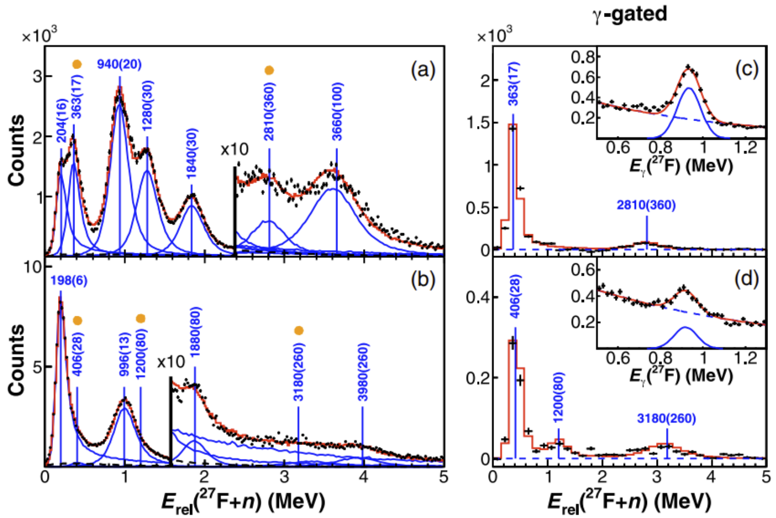
- More complicated spectra observed around the islands of inversion
- Not simple "collective" excitations expected
- May need core+4n models:
  ^{8}He= ^{4}He+4n instead of ^{6}He+2n?
  ^{19}B= ^{15}B+4n instead of ^{17}B+2n?

Eg.: ^{28}F populated via ^{29}Ne(-1p), ^{29}F(-1n)

Revel, PRL124, 152502 (2020)



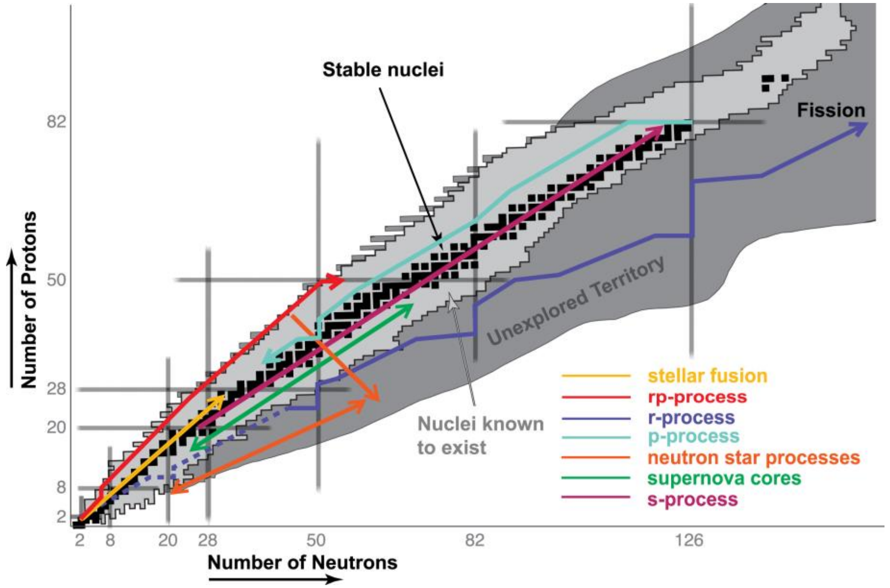
(a) ^{29}Ne(-1p)
(b) ^{29}F(-1n)

Indirect methods for neutron-induced reactions

Neutron-induced cross sections on unstable nuclei needed for:

- Nuclear astrophysics (e.g. s-and r-processes)
- Nuclear reactors for transmutation of nuclear waste
- New generation of reactors based on Th/U cycle

Arcones et al, PPNP 94, (2017)



J.E. Escher, LLNL - FRIB Day 1 – 5/8/2020

Direct measurements not feasible for short-lived nuclei

Indirect methods

Trojan Horse Method

$x + A \Rightarrow y + B$

Surrogate method

$x + A \Rightarrow [C]^* \Rightarrow$ decay

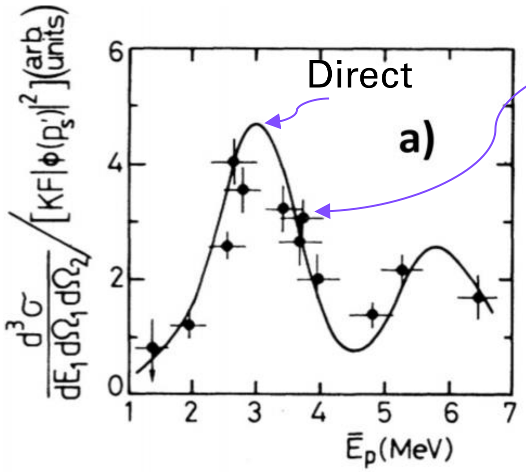
$a(=b+x) + A \Rightarrow b + (x + A)$ *(if "a" is stable, can be performed in **inverse kinematics**)*

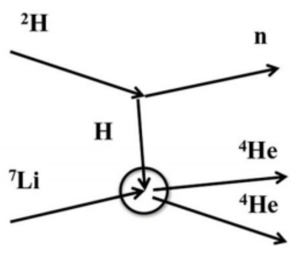
THM: successes and limitations

A successful application: $^7Li(p,\alpha)\alpha$

$$\frac{d^3\sigma}{dE_y d\Omega_y d\Omega_B} \propto KF\,|\Phi(p_{bx})|^2 \left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{A-x}$$

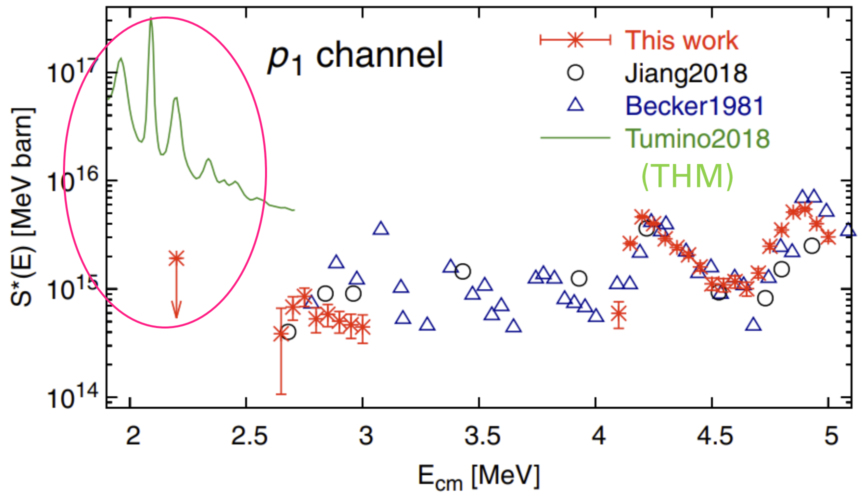
measured — extracted





Possible limitations of the THM:

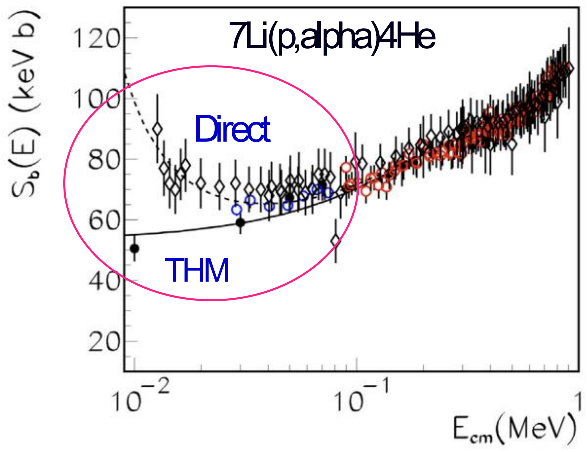
Possible failure of PWIA approximation?



$^{12}C+^{12}C$

Tan et al,
PRL124, 192702 (2020)

The electron screening puzzle

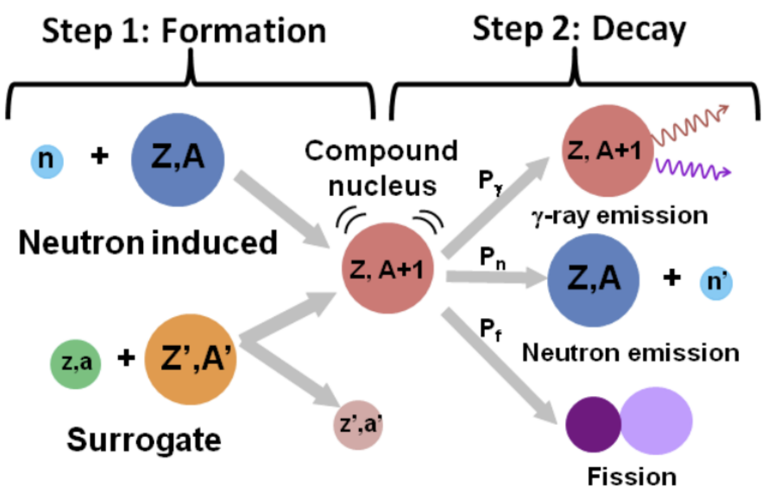


Lamia, A&A 541, A158 (2012)

Surrogate method: the A(d,pχ) case

Goal:
- Determine the A(n,χ) cross section from A(d,pχ) cross section

(figure by B. Jurado)



(aimed) $$\sigma_{(n,\chi)} = \sum_{J,\pi} \sigma^{CN}_{n+A}(E,J,\pi) G^{CN}_{\chi}(E,J,\pi)$$

(measured) $$P_{(d,p\chi)}(E) = \sum_{J,\pi} F^{CN}_{(d,p)}(E,J,\pi) G^{CN}_{\chi}(E,J,\pi)$$

Theory requirements:
- A reaction model for the formation process: d+ A ⇒ p+ B*, encoded in the function $F^{CN}_{(d,p)}(E,J,\pi)$
  - Angular/energy distribution of "p" fragments
  - Spin distribution of (n+A)=B* compound
  - Understanding of competing channels not leading to CN (e.g. deuteron breakup)

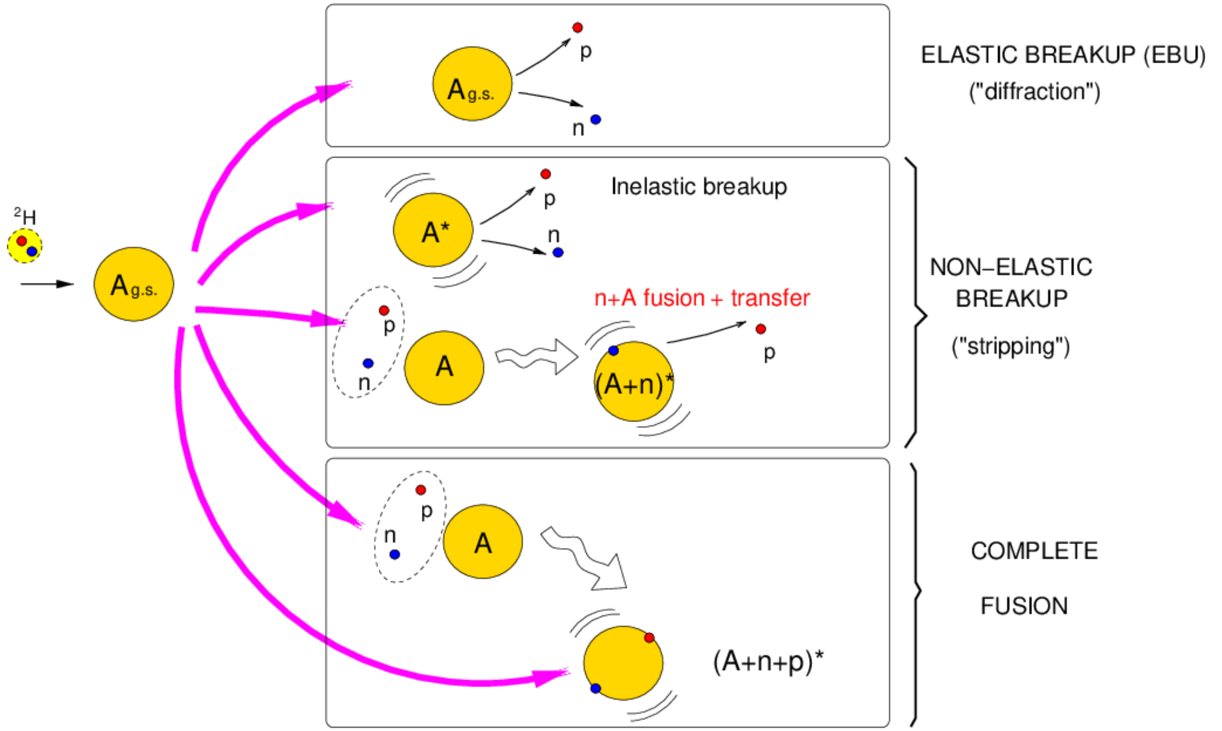
  Ichimura-Austern-Vincent (IAV) model [PRC32, 431 ('85)]
  (recently implemented by Lei et al, Potel et al, Carlson et al)

- A realistic OMP for relevant range of n+A energies

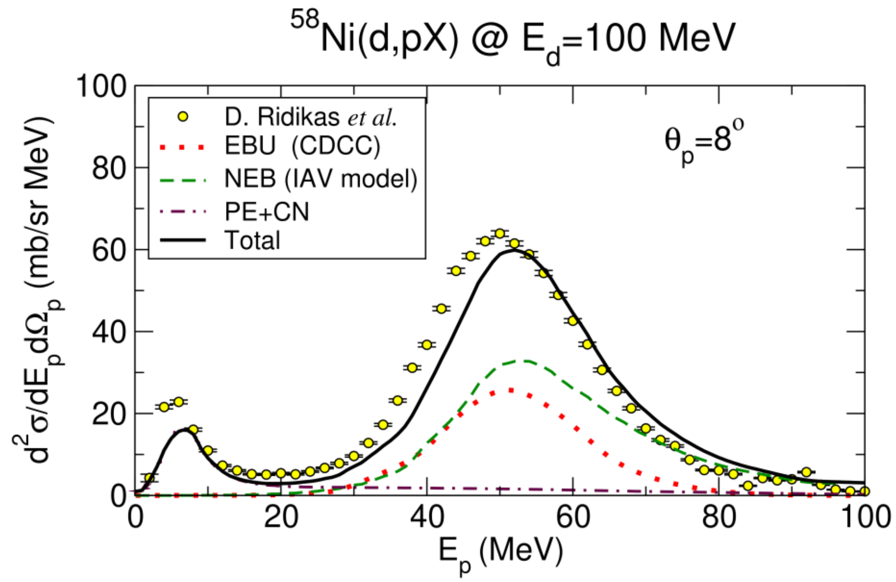
  Dispersive optical model (Mahaux & Sartor, 1991)
  (and modern implementations: Dickhoff, Charity, etc)

Difficulties and challenges of SRM

The A(d,pχ) as surrogate reaction



- Not all produced protons are associated with the desired (n+A)* CN channel:
  - Elastic breakup: A(d,pn)A(gs)
  - Inelastic breakup: A(d,pn)A*
  - PE + CF
- The IAV theory provides the total "nonelastic breakup", rather than n+A CN
- Extension of IAV to (p,d) and other reactions theoretically feasible but not implemented yet.



J.Lei, AMM, PRC.92.044616

The (long-standing) problem of quenching of spectroscopic factors

knockout, transfer and proton knockout SFs

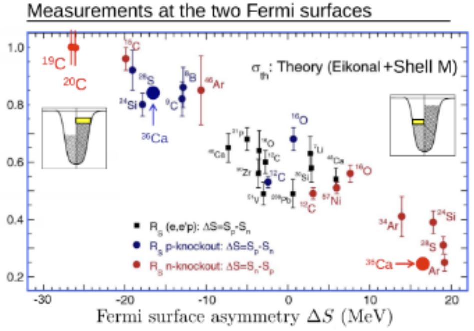
- Agreement theory vs experiment quantified in reduction factor:

$$R_s = \frac{\sigma_{\text{theor}}}{\sigma_{\text{exp}}}$$

- $R_s < 1 \Rightarrow$ correlations (long-range, short-range, tensor,...) not included in σ_{theor}?

HI knockout ($\sim$100 MeV/u)

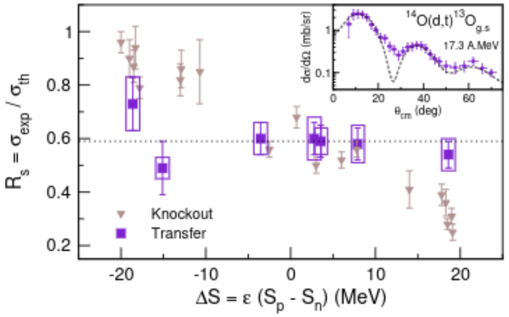
Tostevin, PRC90,057602(2014)



- Reaction model: eikonal + adiabatic
- R_s strongly dependent on $S_p - S_n$.

Low-energy transfer

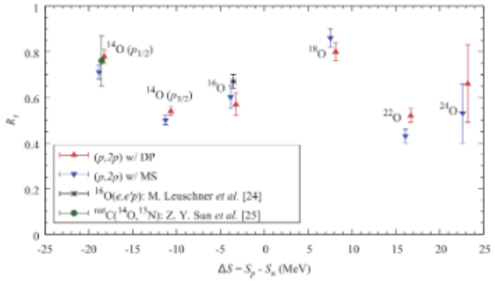
Flavigny, PRL110, 122503(2013)



- Reaction model: ADWA, DWBA, CRC
- $R_s \sim$ constant.

(p, pN) @ 200-250 MeV/u

Wakase, PTEP 021D01 (2018)



- Reaction model: DWIA
- $R_s \sim$ constant.
- ☞ Similar resuts from GSI:Atar *et al*, PRL120, 052501 (2018).

R_s from knockout disagree with those from transfer and (p, pN)

FRIB opportunities

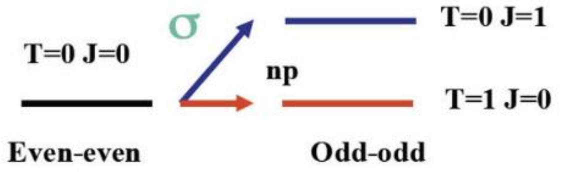
1. Systematic studies with the same projectile and different probes: knockout, *(p,pN)*, transfer
2. Extend "Gade plot" to more exotic (larger |ΔS| cases.

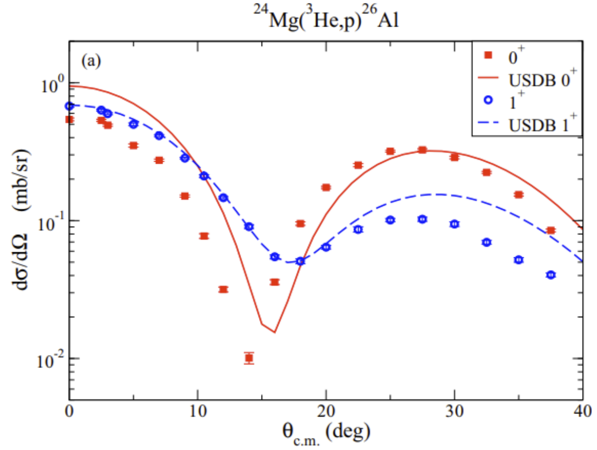
Searches for the elusive n-p pairing

Isovector T=1 (p-p and n-n) pairing well understood
⇒ Can be probed via 2n transfer reactions

Isoscalar T=0 (p-n) predicted but not clearly identified
⇒ Can be in principle be probed via np-transfer reactions. Eg: (^{3}He,p), (^{6}Li,α)
⇒ Expected to dominate for N~Z nuclei (departs from stability valley as A increases)

T=0 (T=1) pairing:
enhanced transfer probabilities
0+ → 1+ (0+ → 0+) levels





Ayyad, PRC 96, 021303(R) (2017)

Theory requirements:

- Second order DWBA (at least)
- Reliable structure inputs (e.g. shell-model) for two-nucleon amplitudes

Eg.: Pioneering study for ^{26}Mg(^{3}He,p)^{27}Al @ RCNP suggests T=0 pairing strength underestimated by available SM calculations.

More exotic candidates predicted near driplines for large A (reachable at FRIB?):

PHYSICAL REVIEW C **81**, 064320 (2010)

Spin-triplet pairing in large nuclei

G. F. Bertsch and Y. Luo

The candidate for the smallest nuclei with a well-developed condensate, $A \sim 130$–140, is tantalizingly close to the region of physical nuclei defined by the single-nucleon driplines.

Conclusions

- FRIB promises to provide unique opportunies for a wide range of physics cases, extending our present knowledge to unexplored areas of nuclear chart and tacking unsolved problems.
- Isotopes can be studied at different energy regimes and using different probes:
  - Some features may show up in specific observables, but not in others
  - Coulomb dissociation, quasi-free (p,pN).. .more suited at intermediate energies (100-200 MeV/u).
  - Transfer reactions better suited a few MeV/u

Many other interesting topics not covered here:

- fusion (complete & incomplete, interplay with transfer, competition with quasifission, role of dissipation…)
- multinucleon transfer and DIC (production of new isotopes, EOS studies...)
- fission (shell effects, similarities with quasifission…)
- *(p,3p)* reactions and relation to short-range correlations
- charge-exchange
- … and many other

Special thanks to:

- Jesús Casal (U. Padova)
- José Antonio Lay (U. Sevilla)
- Mario Gómez-Ramos (TU Darmstadt)
- Joaquín Gómez-Camacho (U. Sevilla)
- Alexandre Obertelli (CEA,TU Darmstadt)
- Cedric Simenel (ANU)
- Kaitlin Cook (MSU)

*And to the **FRIB Theory Alliance** for the invitation and the initiative!*

Nuclear charts credits: Ed Simpson (ANU)

(https://people.physics.anu.edu.au/~ecs103/chart/)