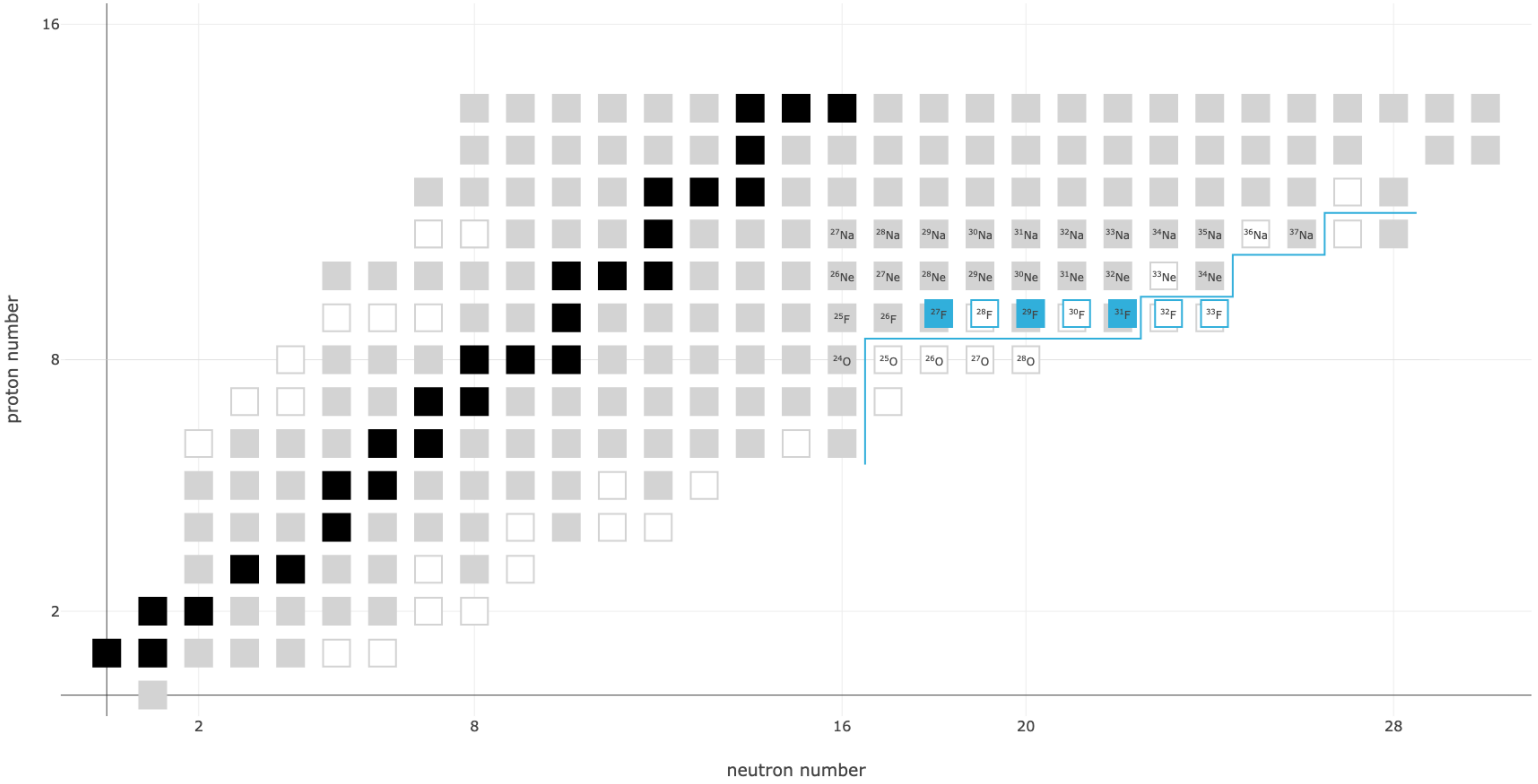
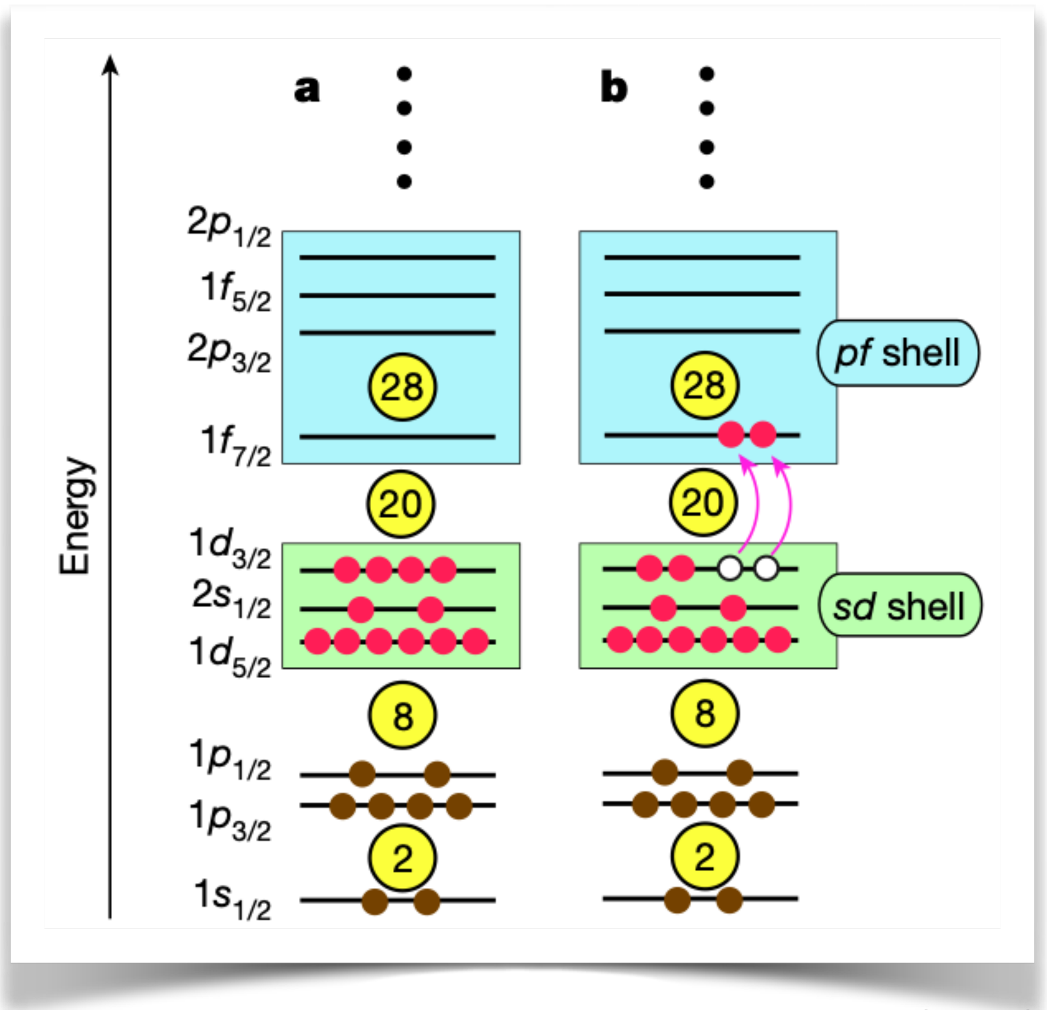
NEUTRON RESONANCE SPECTROSCOPY IN THE SD & FP SHELLS

CALEM R. HOFFMAN

FRIB-TA MAY 2023





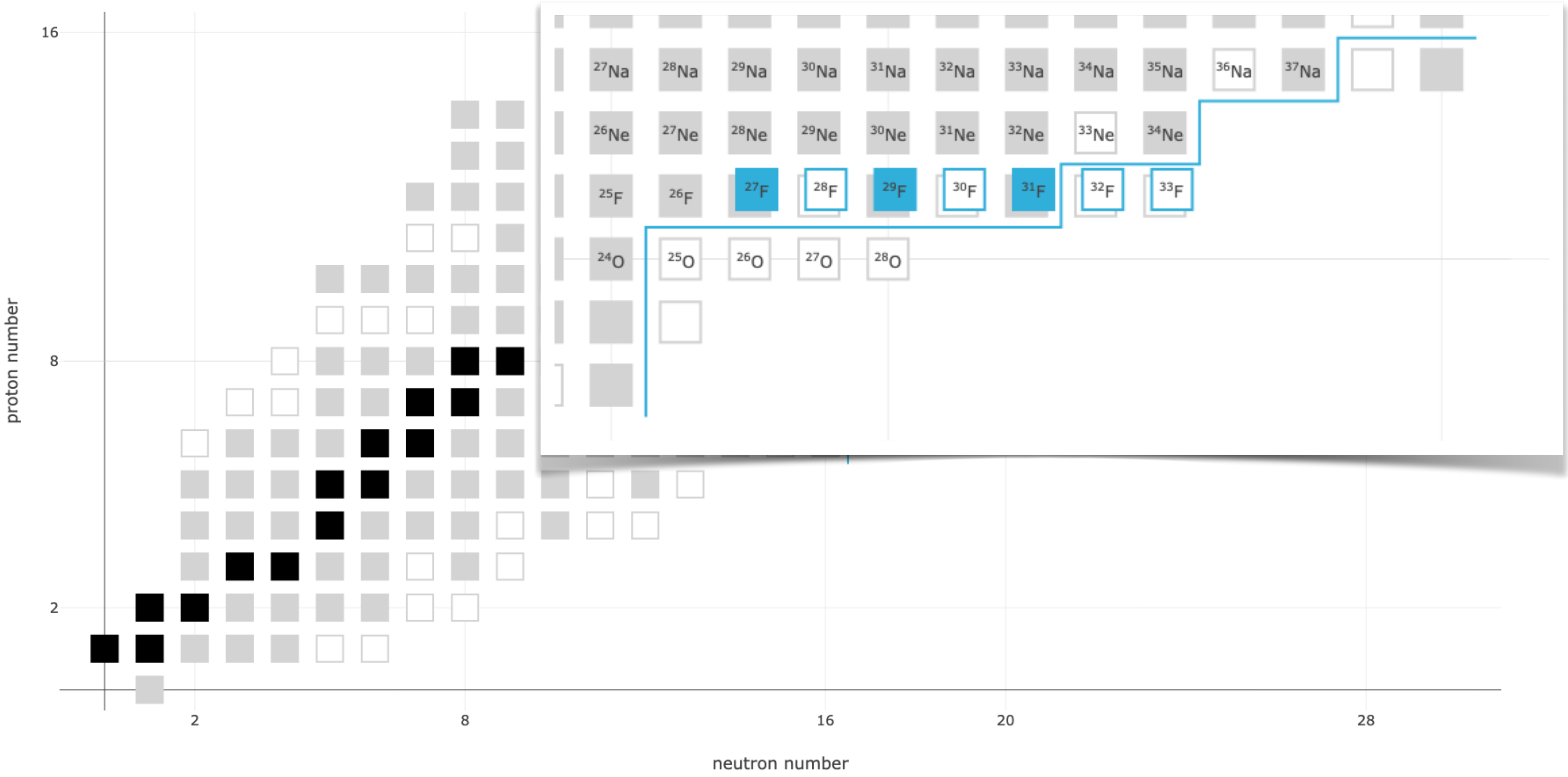
Tsunoda Nature (2020)

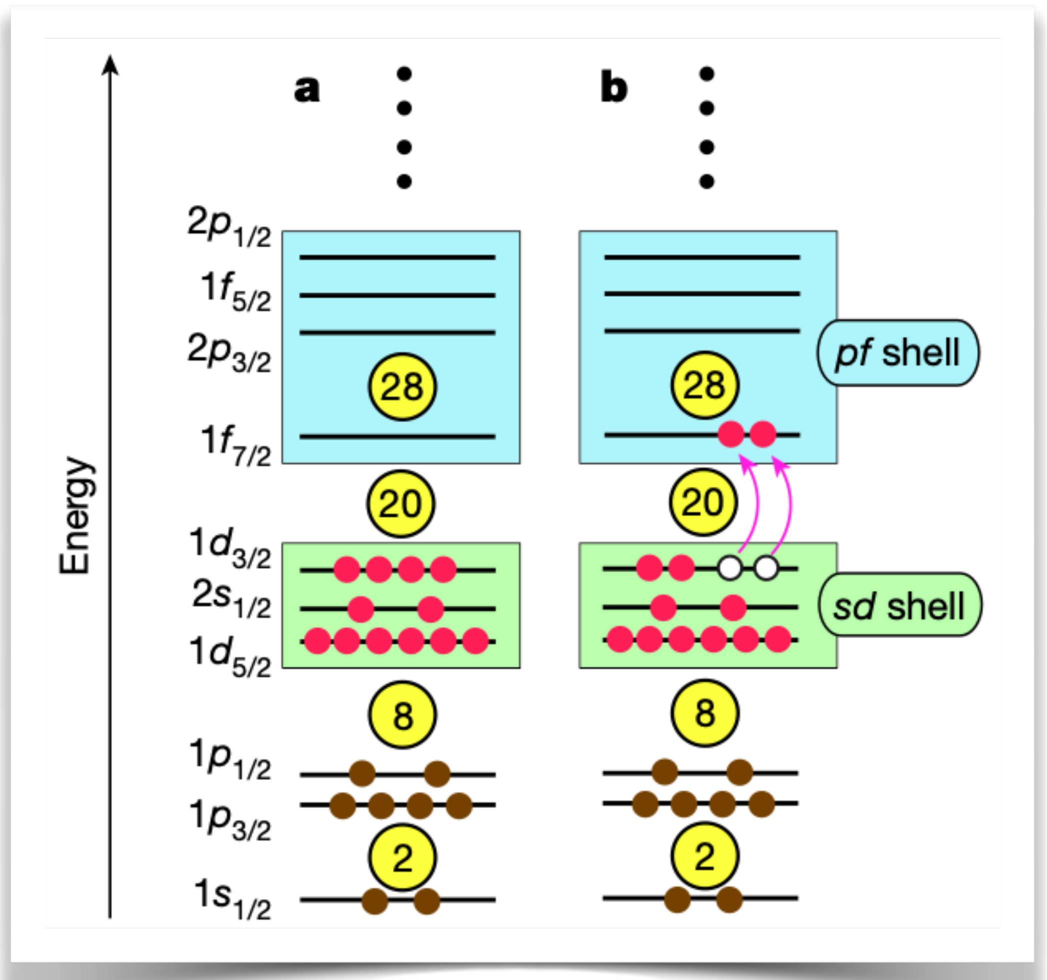
DESCRIBING THE STRUCTURE SURROUNDING & DEFINING THE OXYGEN - FLUORINE DRIP LINES

- WHAT ARE THE RELATIVE CONTRIBUTIONS FROM THE CONTINUUM, COHERENT CORRELATIONS (DEFORMATION), CENTRAL & N-BODY FORCE COMPONENTS, …

WHICH DETERMINE NOT ONLY THE DRIP LINE BUT ALSO THE SPECTROSCOPY IN THE REGION

- SPECIFIC FOCUS ON THE ROLE OF THE OF THE NEUTRON 1P$_{3/2}$ ORBITAL





Tsunoda Nature (2020)

DESCRIBING THE STRUCTURE SURROUNDING & DEFINING THE OXYGEN - FLUORINE DRIP LINES

- WHAT ARE THE RELATIVE CONTRIBUTIONS FROM THE CONTINUUM, COHERENT CORRELATIONS (DEFORMATION), CENTRAL & N-BODY FORCE COMPONENTS, …

WHICH DETERMINE NOT ONLY THE DRIP LINE BUT ALSO THE SPECTROSCOPY IN THE REGION

- SPECIFIC FOCUS ON THE ROLE OF THE OF THE NEUTRON $1P_{3/2}$ ORBITAL

ROLE OF THE NEUTRON $1P_{3/2}$ ORBITAL & THE BALANCE OF THE CONTRIBUTIONS FROM VARIOUS EFFECTS

Influence of the continuum - extended wave functions & scattering

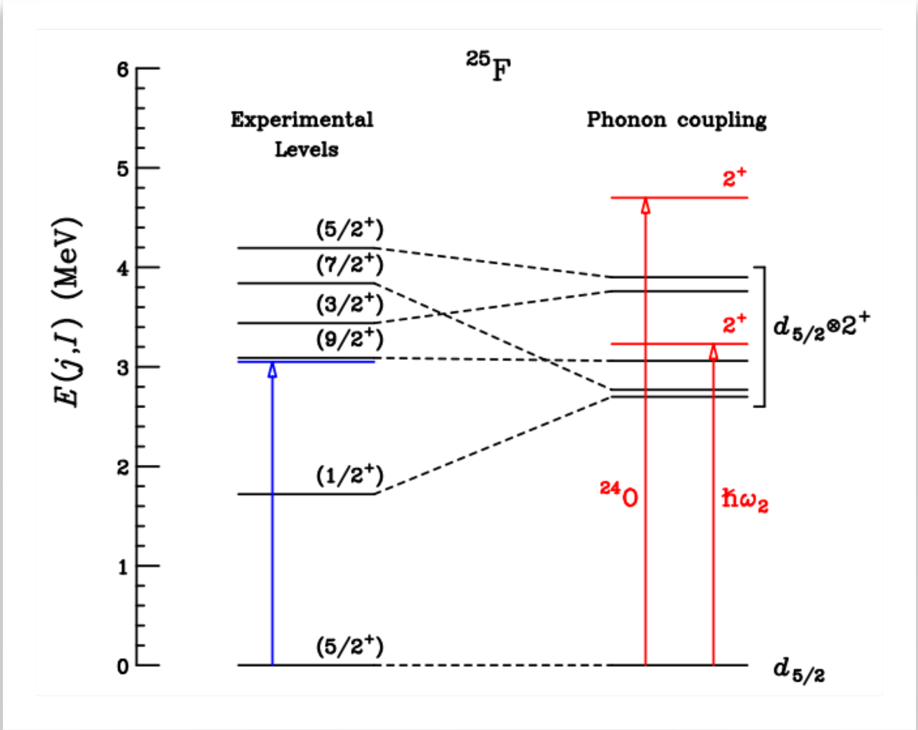
- Impact on shell structure & other observables
- Formation of neutron halo states
- Not equal for all orbitals
- …

Deformation - Coherent correlations & interplay between the neutrons & protons (& core)

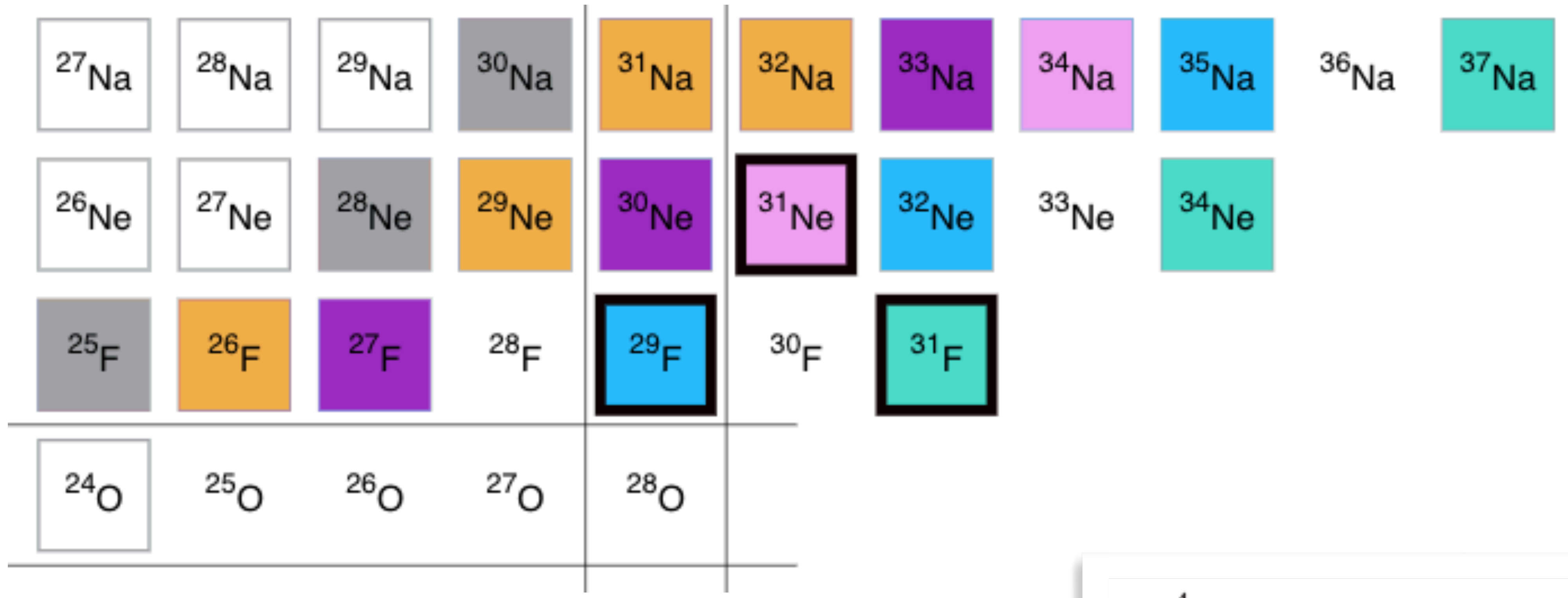
- Impact on the binding energies & enhanced correlations stabilize the $Z > 8$ drip line
- Evidence for a deformed $Z = 8$ core in Fluorine's isotopes near ^{24}O
- Provides an additional mechanism for the (two) neutron halo formation

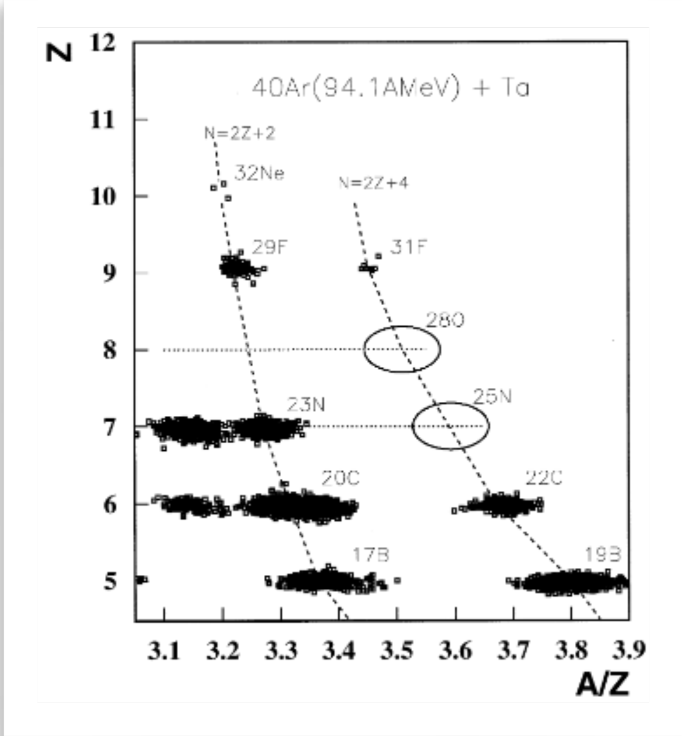
Components of the central & n-body forces

- 3 - body forces have been shown to hold influence over the $Z = 8$ drip line
- Larger role of the tensor force as it impacts the single-particle energies
- Impact of (non)modified pairing or quadrupole forces
- …

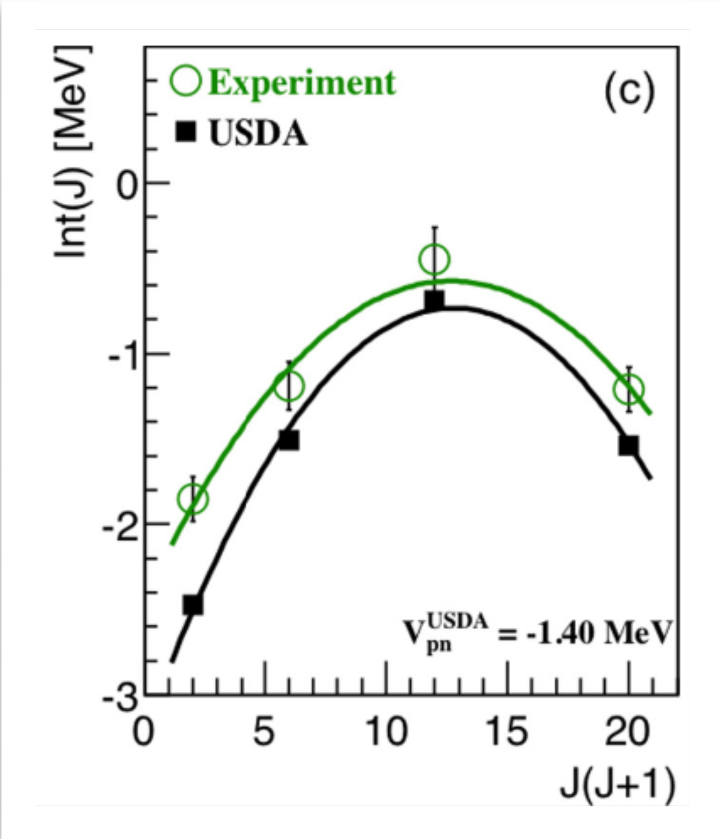


Crawford PRC(L) (2022)

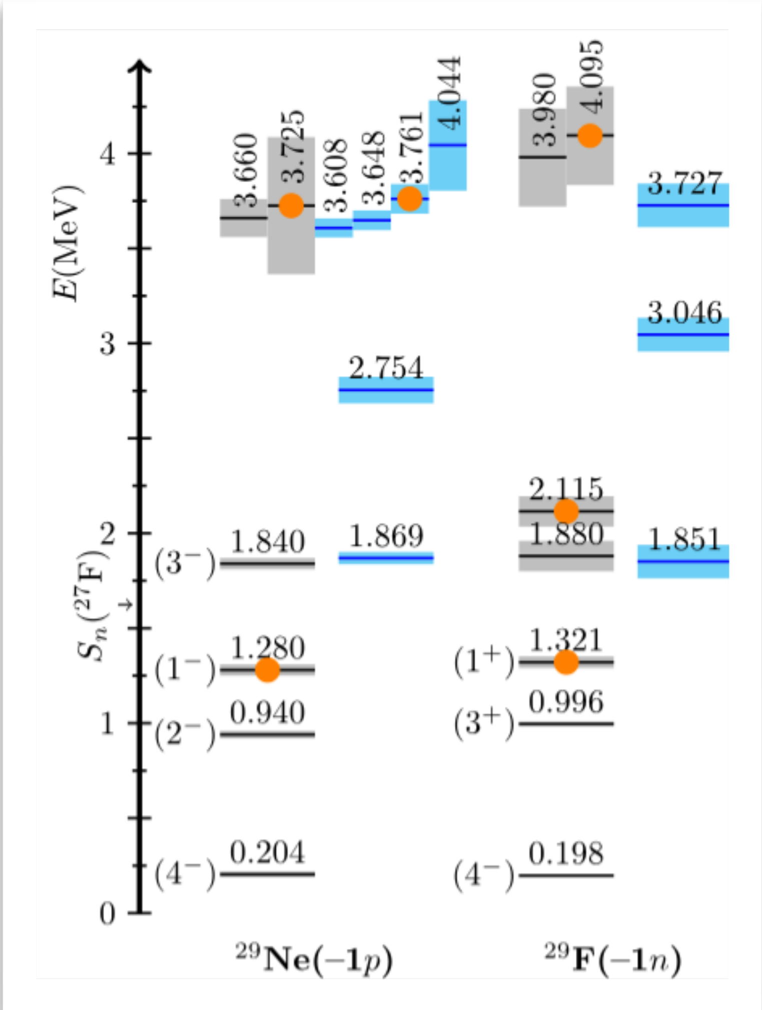




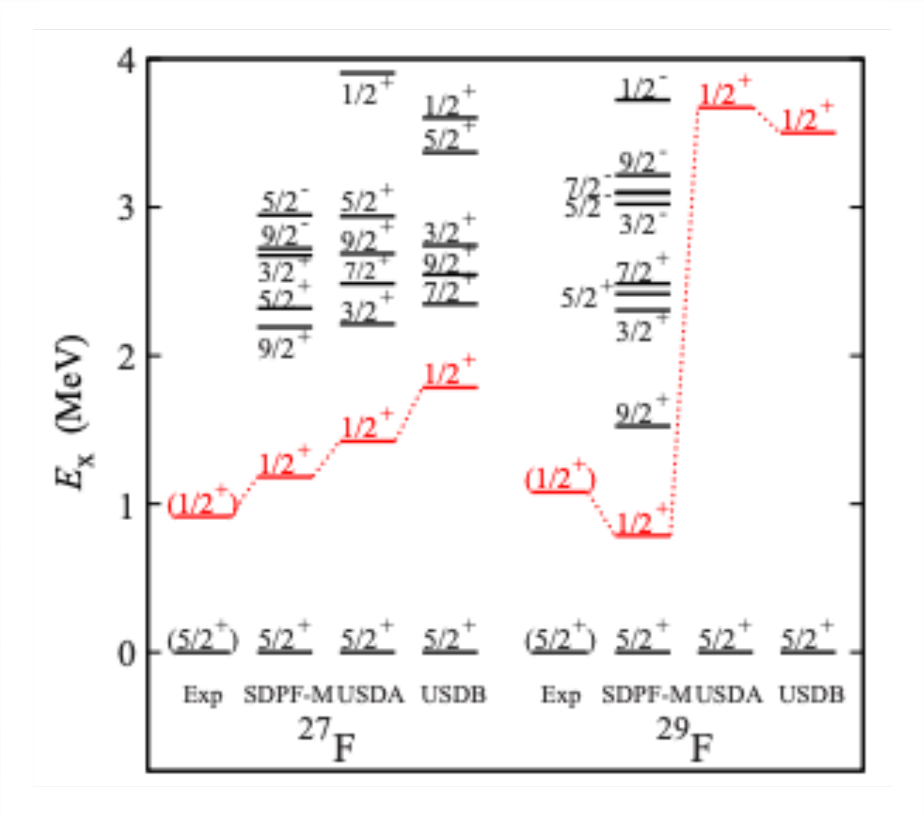
Sakurai PLB (1999)



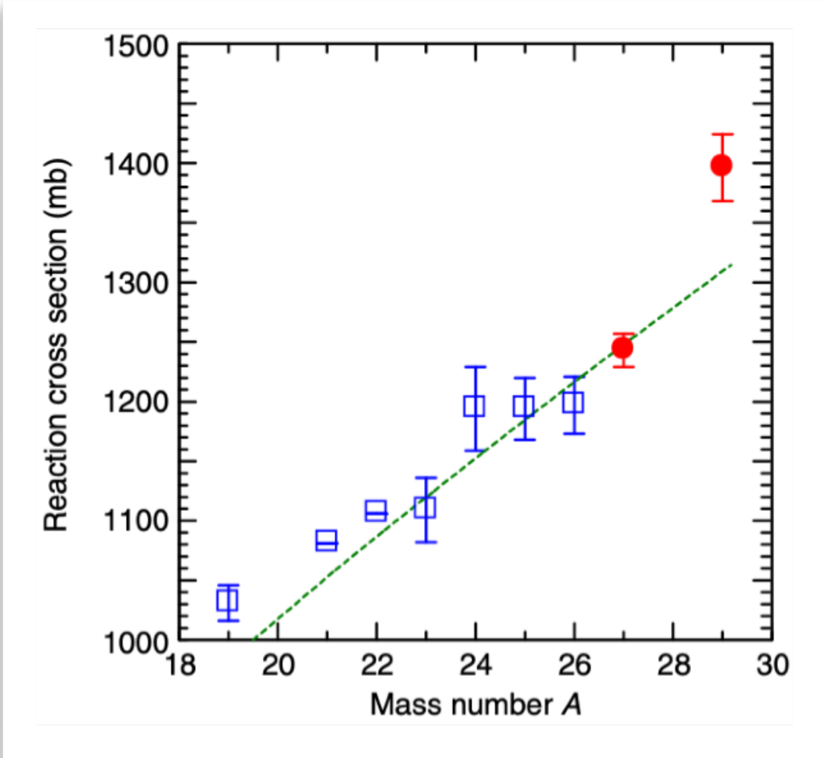
Vandebrouck PRC (2017)



Revel PRL (2020)



Doornenbal PRC(R) (2017)

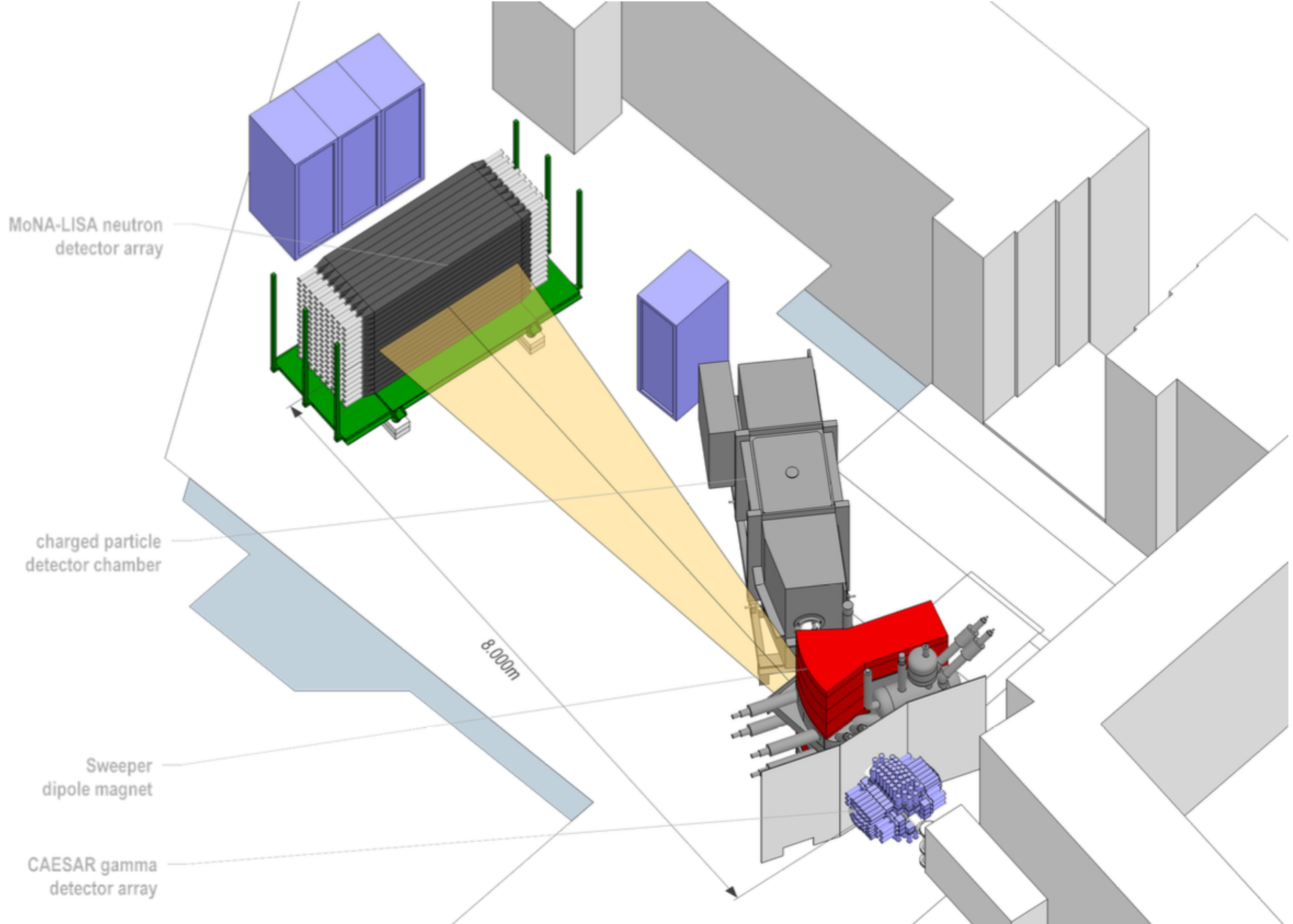


Bagchi PRL (2020)

INVARIANT MASS SPECTROSCOPY COUPLED WITH SELECTIVE REACTION MECHANISMS

- INFLUX OF EMPIRICAL INFORMATION ON THE GROUND & EXCITED STATE SPECTROSCOPY OF THE NEAR DRIP LINE FLUORINE ISOTOPES

Argonne NATIONAL LABORATORY



http://mona.wabash.edu/html/default/Collaboration.html

THE MONA-LISA+SWEEPER+CAESAR SETUP @ FRIB

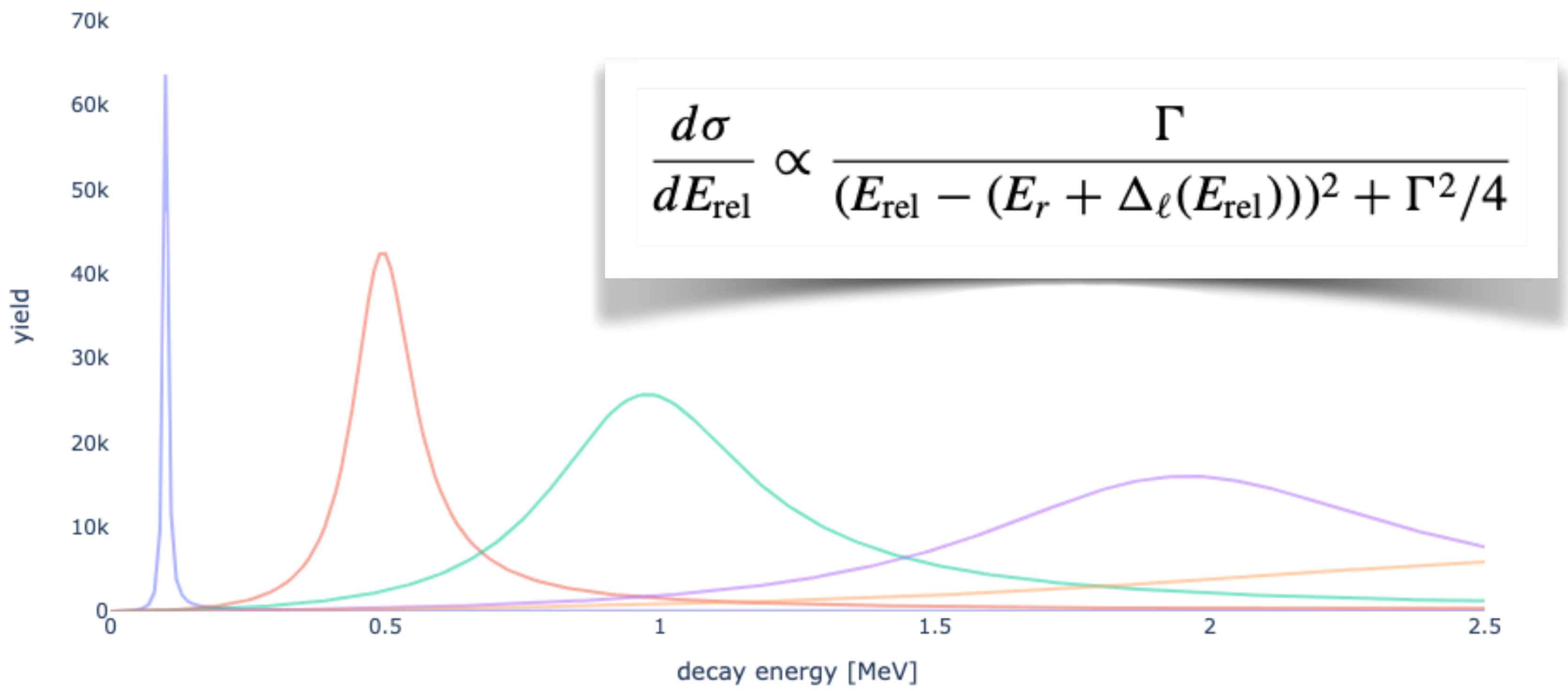
- NEUTRON & FRAGMENT (+Γ-RAY) 4-VECTOR DETERMINATION
- 4 APPROVED EXPERIMENTS [2 - PAC1, 2 - PAC2]
- TO START IN EARLY/MID CY2024

NEW DATA: STRUCTURE

Observables & derived quantities from neutron invariant mass spectroscopy & nuclear reactions

Energy-dependent Breit-Wigner expression [single-level r-matrix]

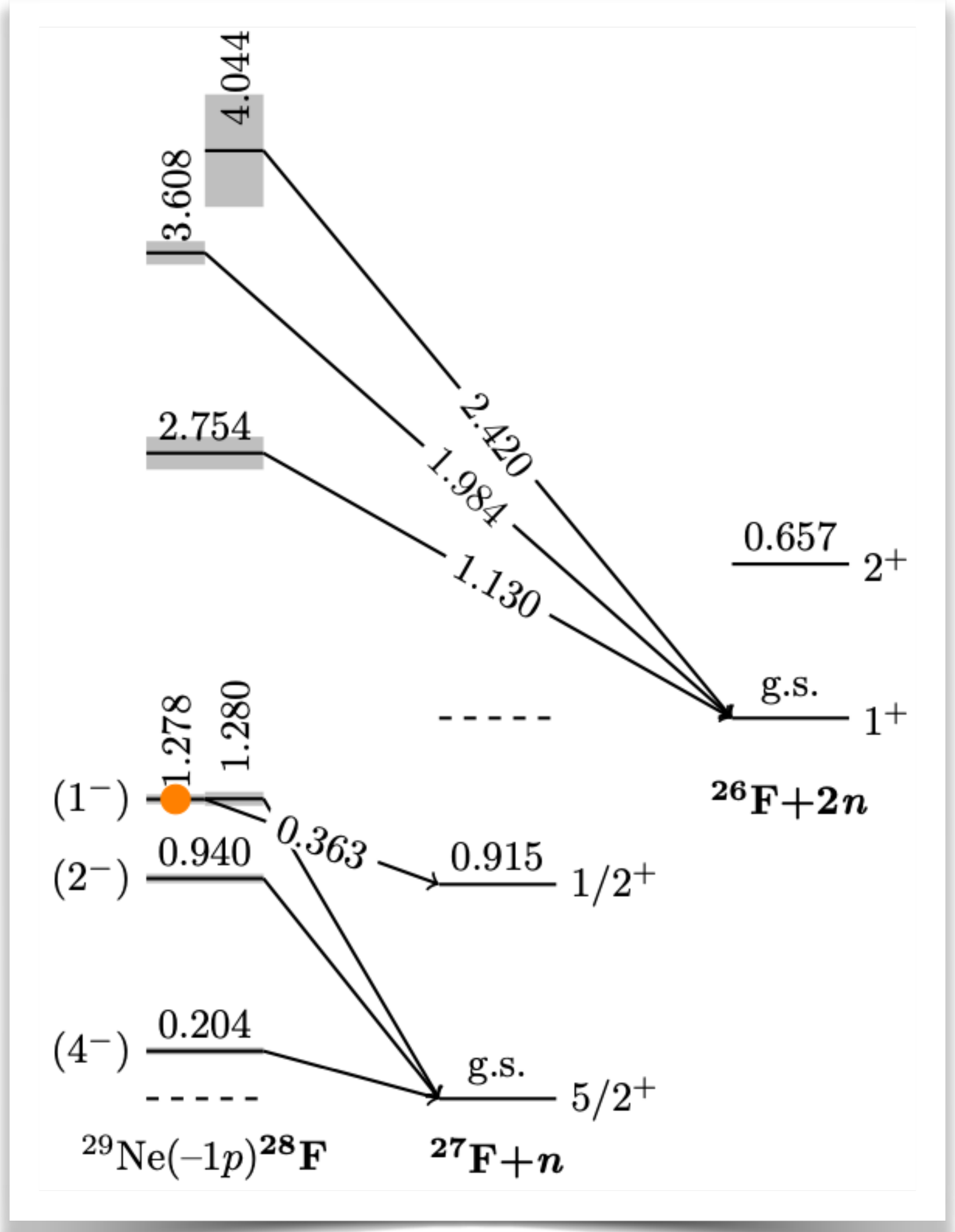
$$\frac{d\sigma}{dE_{\rm rel}} \propto \frac{\Gamma}{(E_{\rm rel} - (E_r + \Delta_\ell(E_{\rm rel})))^2 + \Gamma^2/4}$$



Orbital angular momentum dependence of partial width & extraction of single-neutron overlap

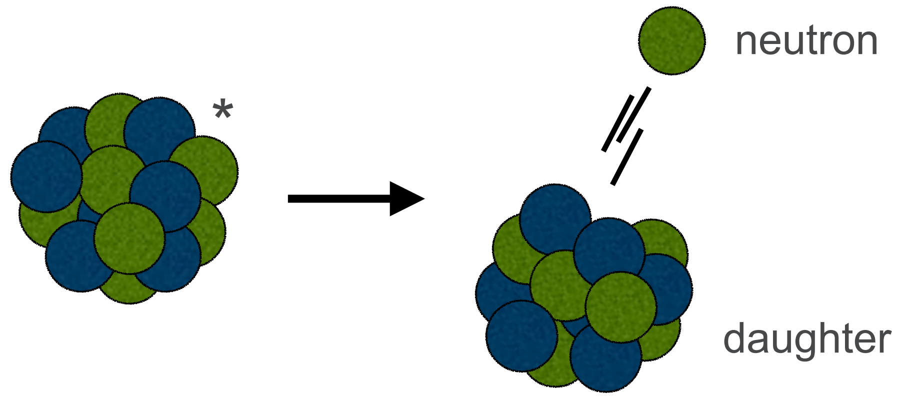
$$\Gamma = \Gamma_{\rm s.p.} C^2 S$$

$$\Gamma_{sp} = \begin{cases} \frac{2\hbar^2}{MR^2} kRv_l(kR)\frac{2l-1}{2l+1} & l > 0, kR < l^{1/2} \\ \frac{2\hbar^2}{MR^2} kR & l = 0 \end{cases}$$



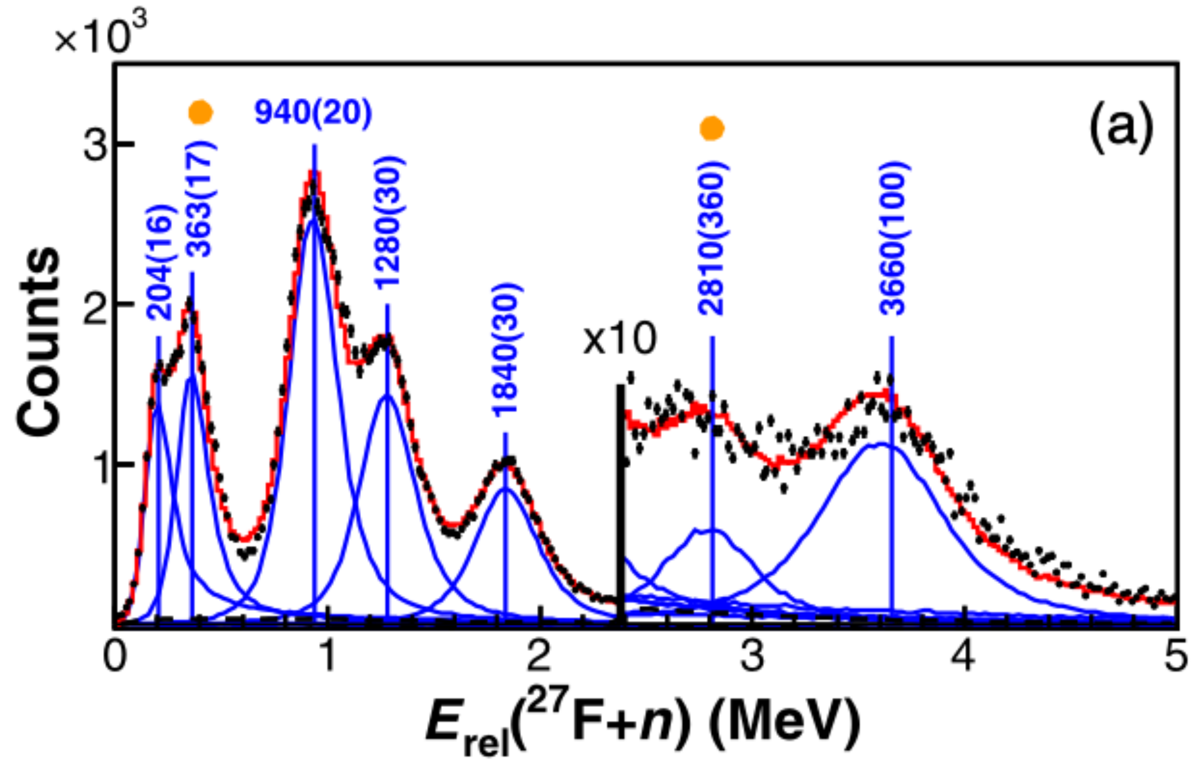
Revel PRL (2020)

Invariant mass spectroscopy: exploring above S_n



$$M_i = \sqrt{s} = \sqrt{M_f^2 + M_n^2 + 2(E_f E_n - P_f P_n cos\theta)}.$$

Relative decay energy spectra

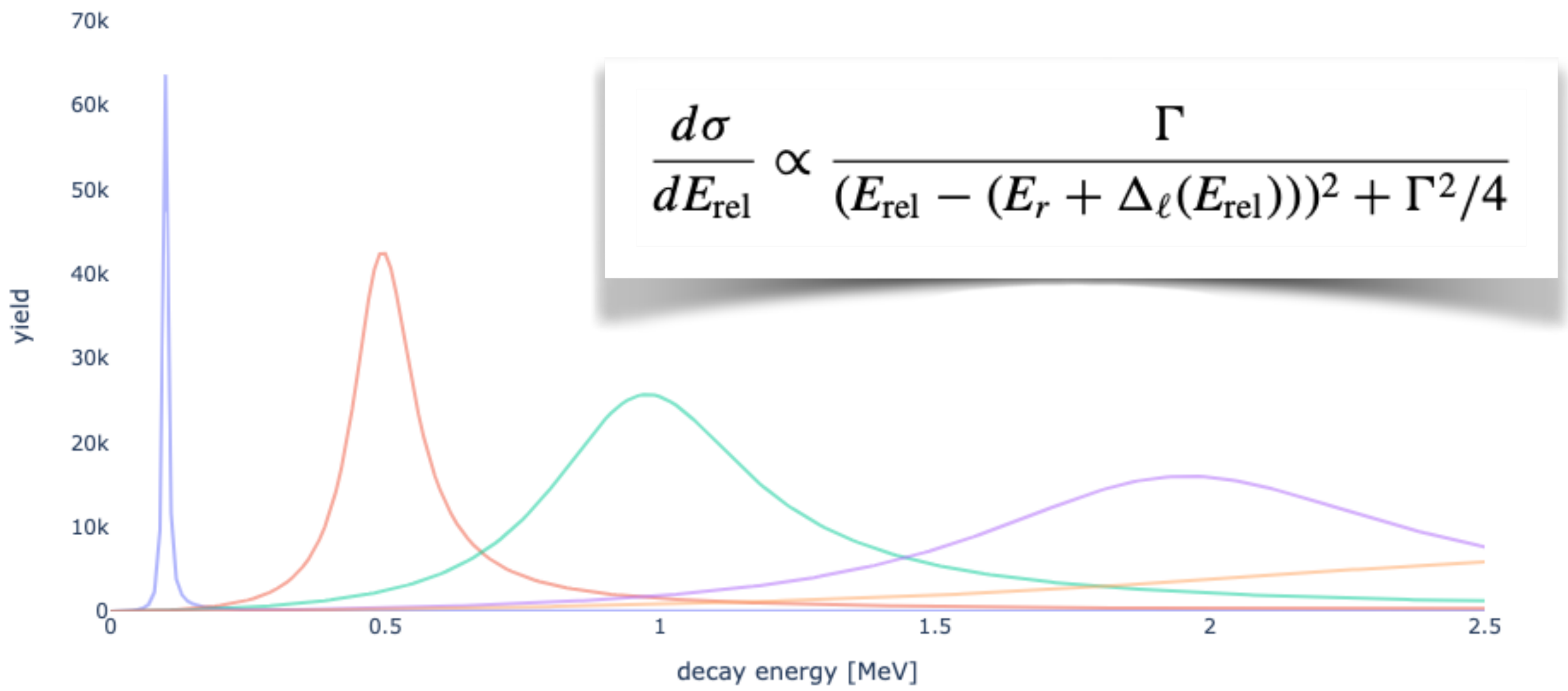


NEW DATA: STRUCTURE

Observables & derived quantities from neutron invariant mass spectroscopy & nuclear reactions

Energy-dependent Breit-Wigner expression [single-level r-matrix]

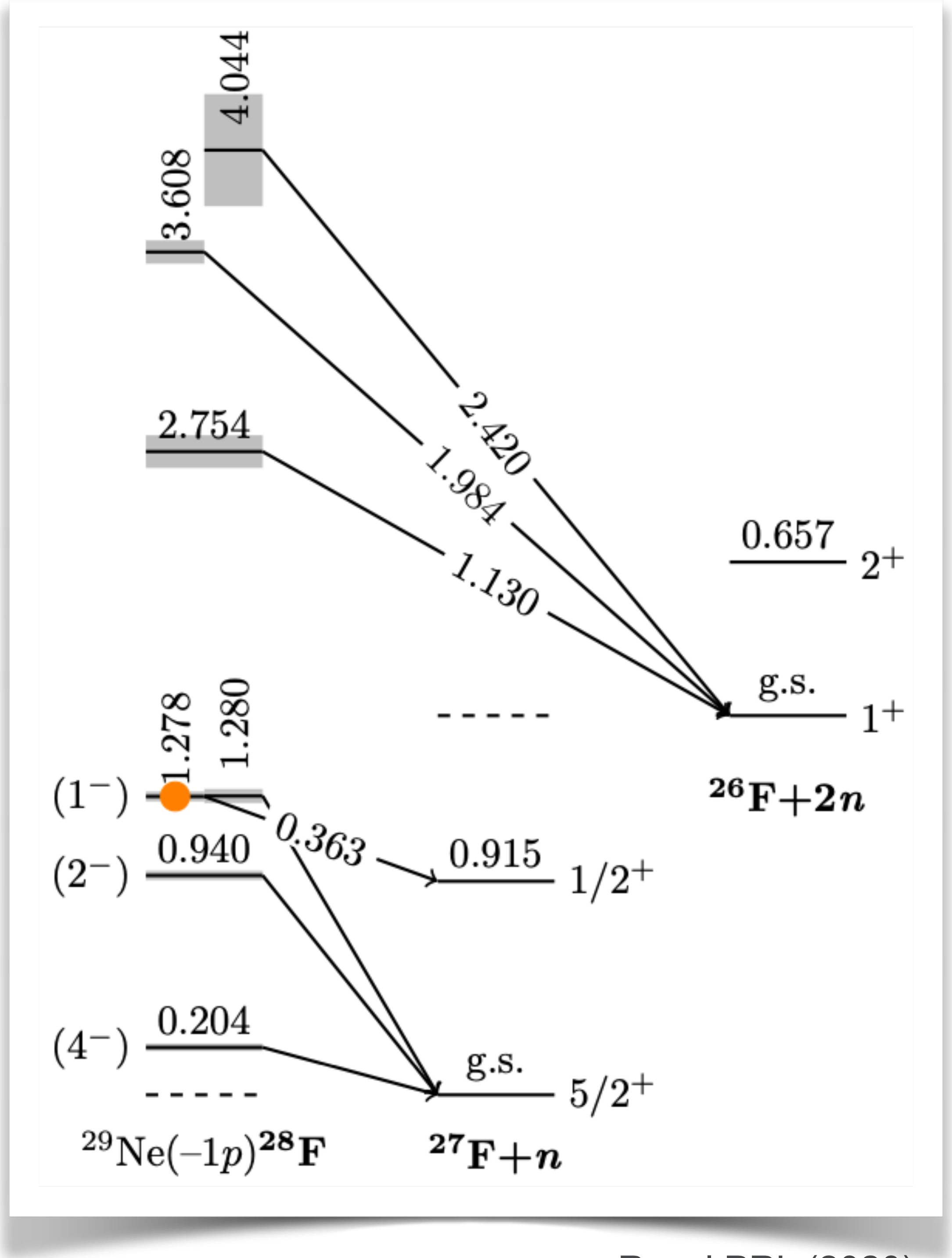
$$\frac{d\sigma}{dE_{\rm rel}} \propto \frac{\Gamma}{(E_{\rm rel} - (E_r + \Delta_\ell(E_{\rm rel})))^2 + \Gamma^2/4}$$



Orbital angular momentum dependence of partial width & extraction of single-neutron overlap

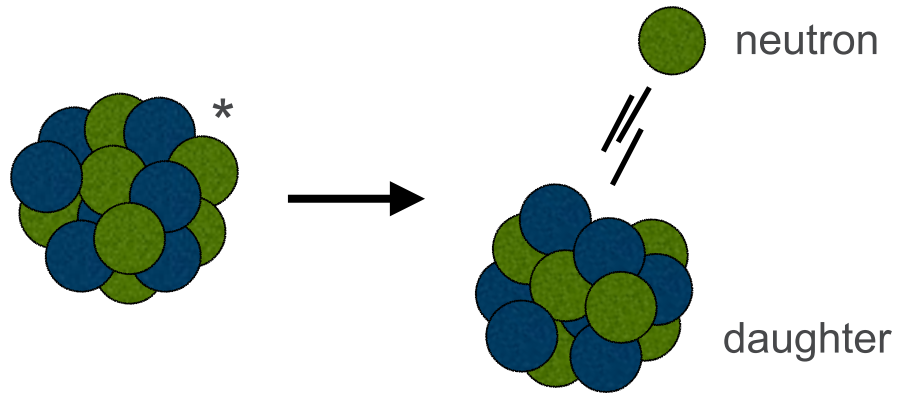
$$\Gamma = \Gamma_{\rm s.p.} C^2 S$$

$$\Gamma_{sp} = \begin{cases} \frac{2\hbar^2}{MR^2} kRv_l(kR)\frac{2l-1}{2l+1} & l > 0, kR < l^{1/2} \\ \frac{2\hbar^2}{MR^2} kR & l = 0 \end{cases}$$



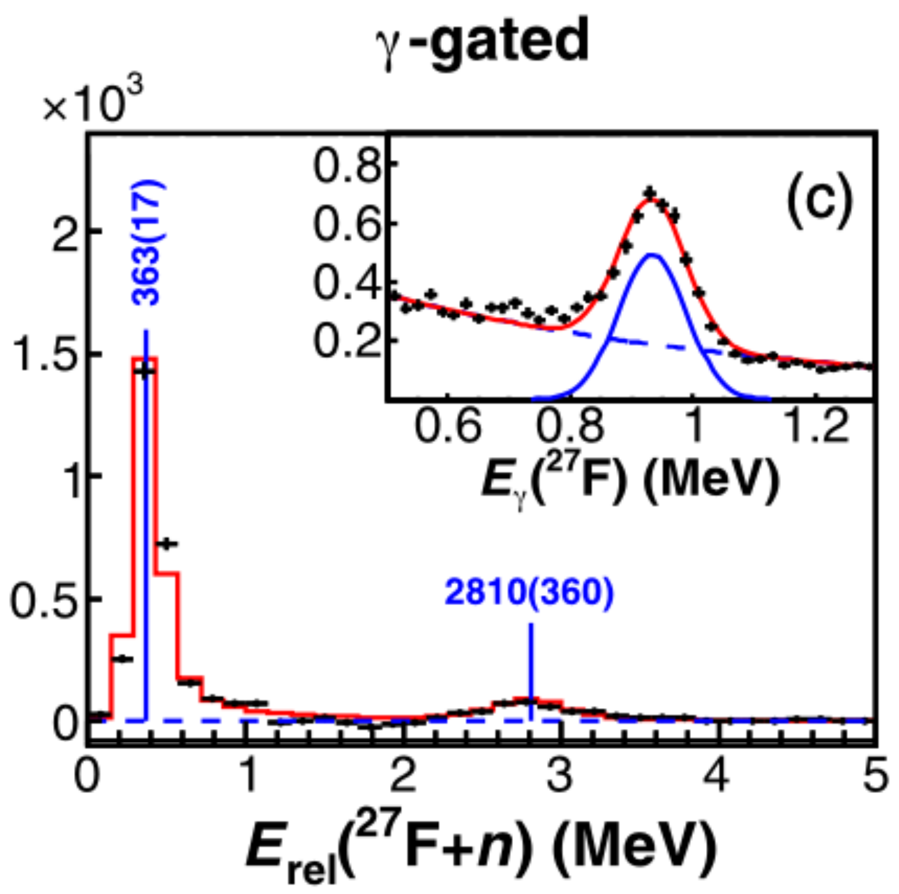
Revel PRL (2020)

Invariant mass spectroscopy: exploring above S_n



$$M_i = \sqrt{s} = \sqrt{M_f^2 + M_n^2 + 2(E_f E_n - P_f P_n cos\theta)}.$$

Relative decay energy spectra



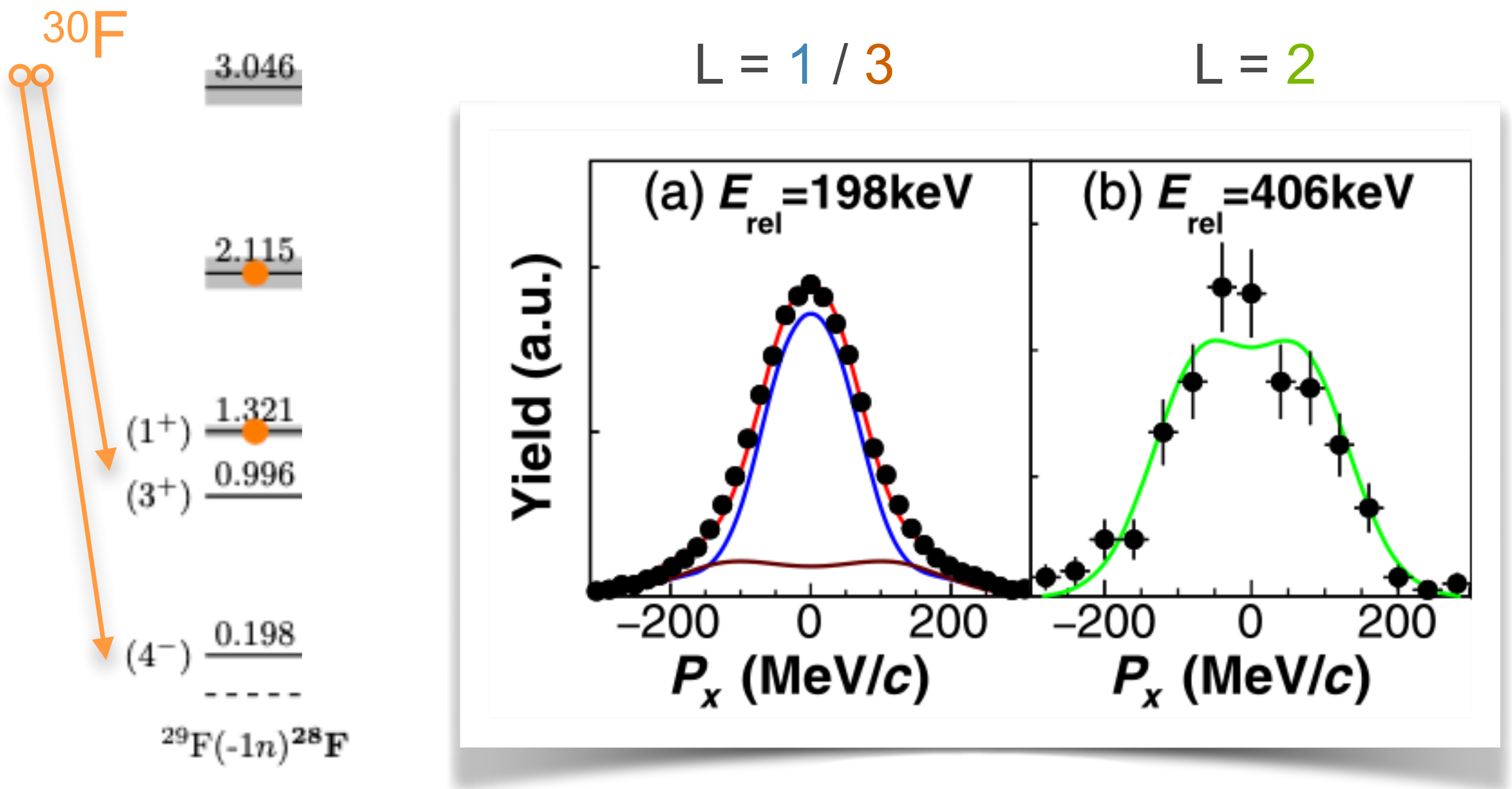
NEW DATA:REACTIONS

Various production reactions available

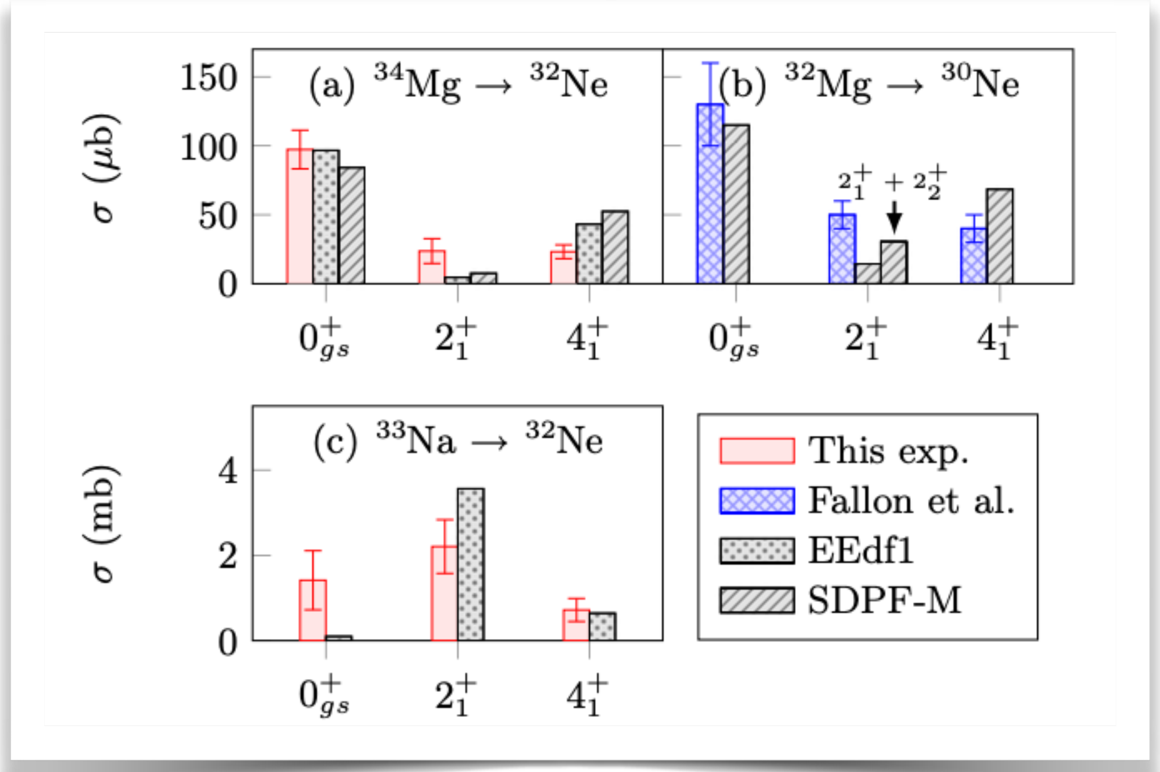
- **Nucleon removal reactions [-Xp, -Xn]**
  - Inclusive / exclusive cross sections
  - Initial to final state overlaps [C^2S]
    -> deduce initial (ground) state occupancies
    -> components of the final wave function

$$\sigma^{\mathrm{th}}_{-1\mathrm{n}}(n\ell_j, S^*_\alpha) = \left(\frac{A}{A-1}\right)^{\mathcal{N}} C^2 S(\alpha, n\ell_j)\, \sigma_{\mathrm{sp}}(n\ell_j, S^*_\alpha)$$

- **Intermediate energy inelastic reactions [(d,d'), (p,p')]**
  - Total / differential cross sections
  - Extract (matter) deformation parameters (β)
  - Deduce isovector / isoscalar contributions to various excitations
  - Search for differing coherent excitation modes [soft-, pygmy- dipole resonances]
  - …

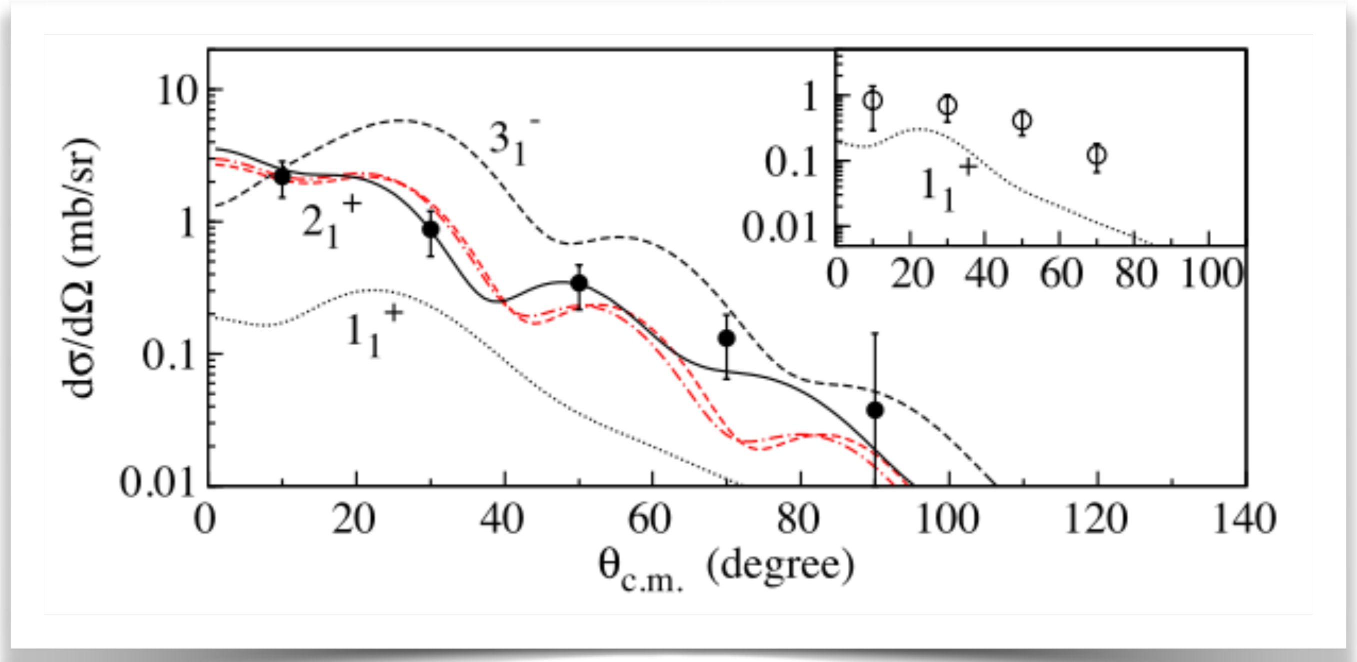


Revel PRL (2020)



Murray PRC (2019)

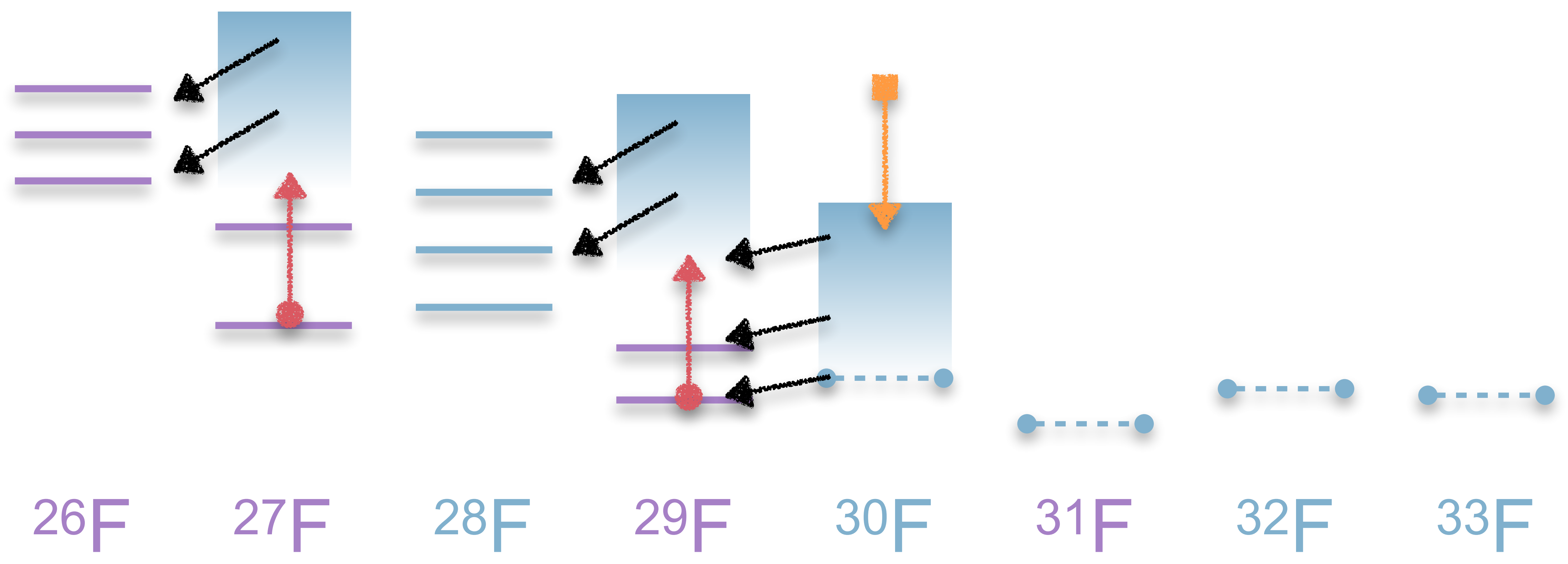
24O(p,p') @ 67 MeV/u



Tshoo PRL (2012)

NEAR-TERM MEASUREMENTS [< 3 YEARS]

PAC1/2 /(3) FRIB @ <= 20 kW

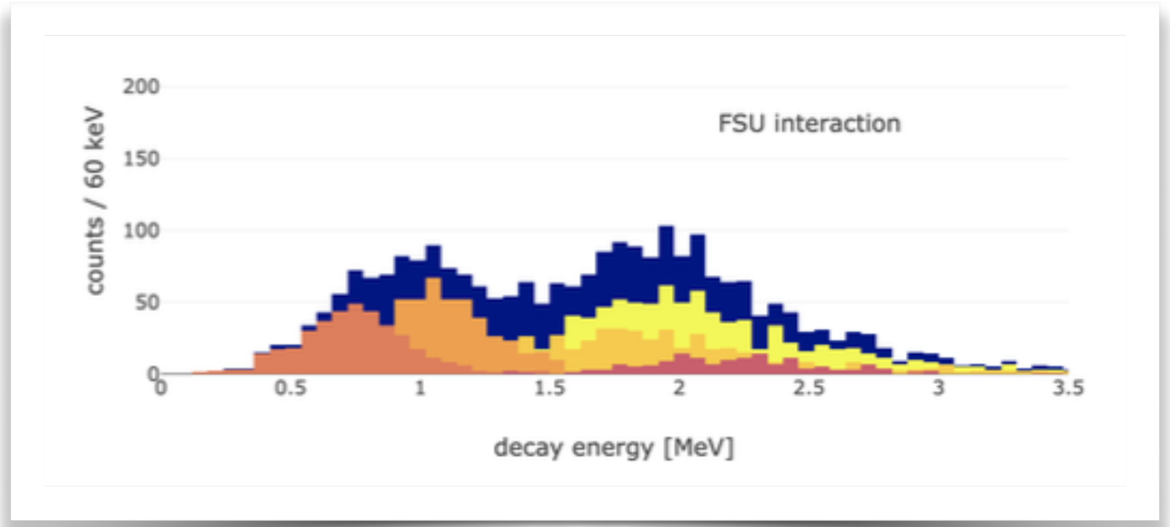


Where does the neutron $1p_{3/2}$ orbital lie in the continuum at N = 21?

$$^{31}\mathrm{Ne}(^{9}\mathrm{Be},\text{-}1p)^{30}\mathrm{F}^{*} \rightarrow {}^{29}\mathrm{F}^{(*)} + n$$

^{31}Ne g.s. $[J^{\pi} = 3/2^{-}]$:

$$\pi(0d_{5/2}1\cancel{s_{1/2}})^{2} \otimes \nu(1p_{3/2}0\cancel{f_{7/2}})^{1} \qquad {}^{30}\mathrm{F}\ [J^{\pi} = 1 - 4^{-}]$$



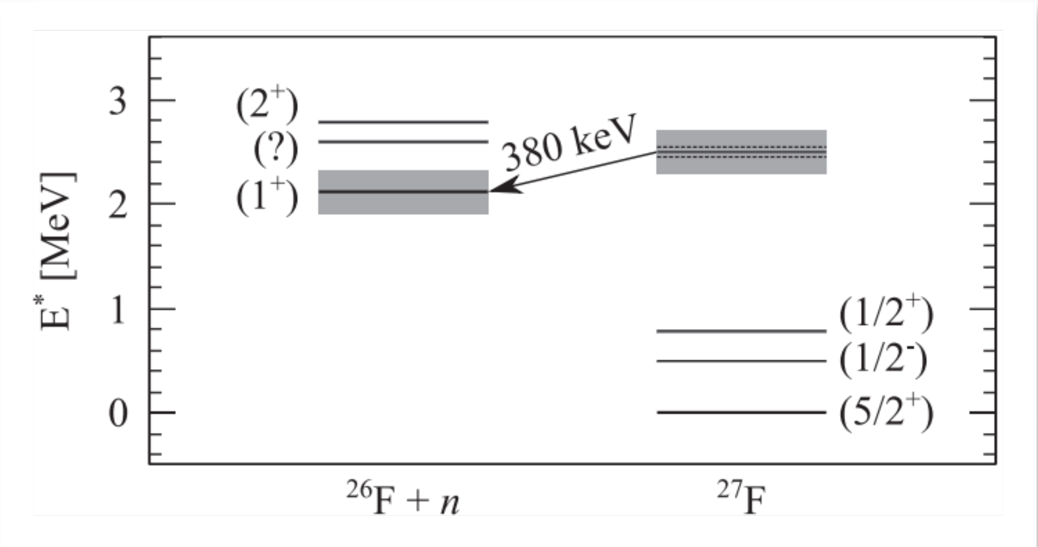
Hoffman PAC1 (2021)

^{30}F level	^{29}F(5/2+) $C^2S_{\ell=1}$	^{29}F(5/2+) $C^2S_{\ell=3}$	^{29}F(1/2+)[1] $C^2S_{\ell=1}$	^{29}F(1/2+)[1] $C^2S_{\ell=3}$
0.000, 2$^-$	0.36	0.18	0.23	0.00
0.145, 3$^-$	0.39	0.21	-	0.02
0.349, 4$^-$	0.00	0.18	-	0.43

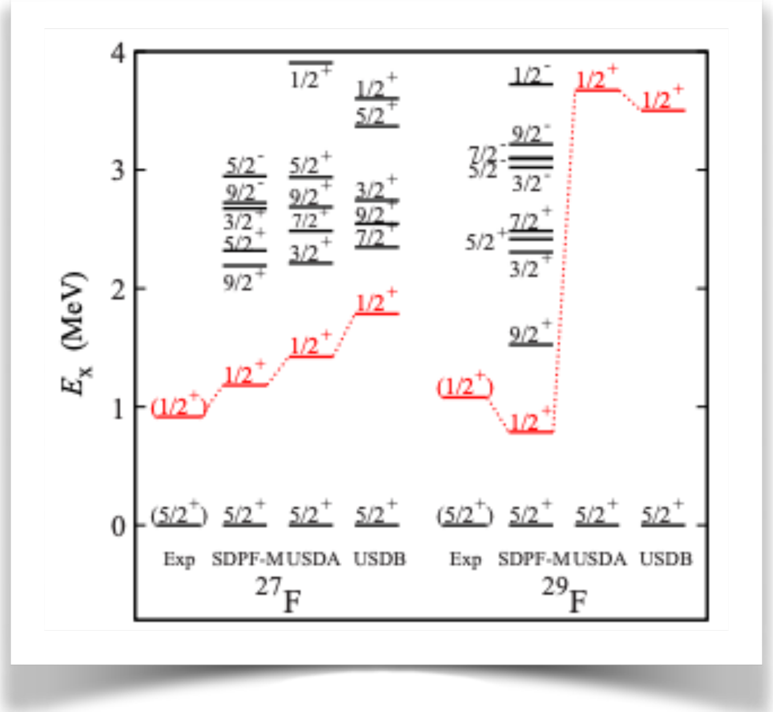
What / where are the types / locations of the collective excitations in the N = 18 & 20 systems?

Is there evidence for exotic coherent (unbound) modes?

$$^{27,29}\mathrm{F}(d,d')(p,p')$$



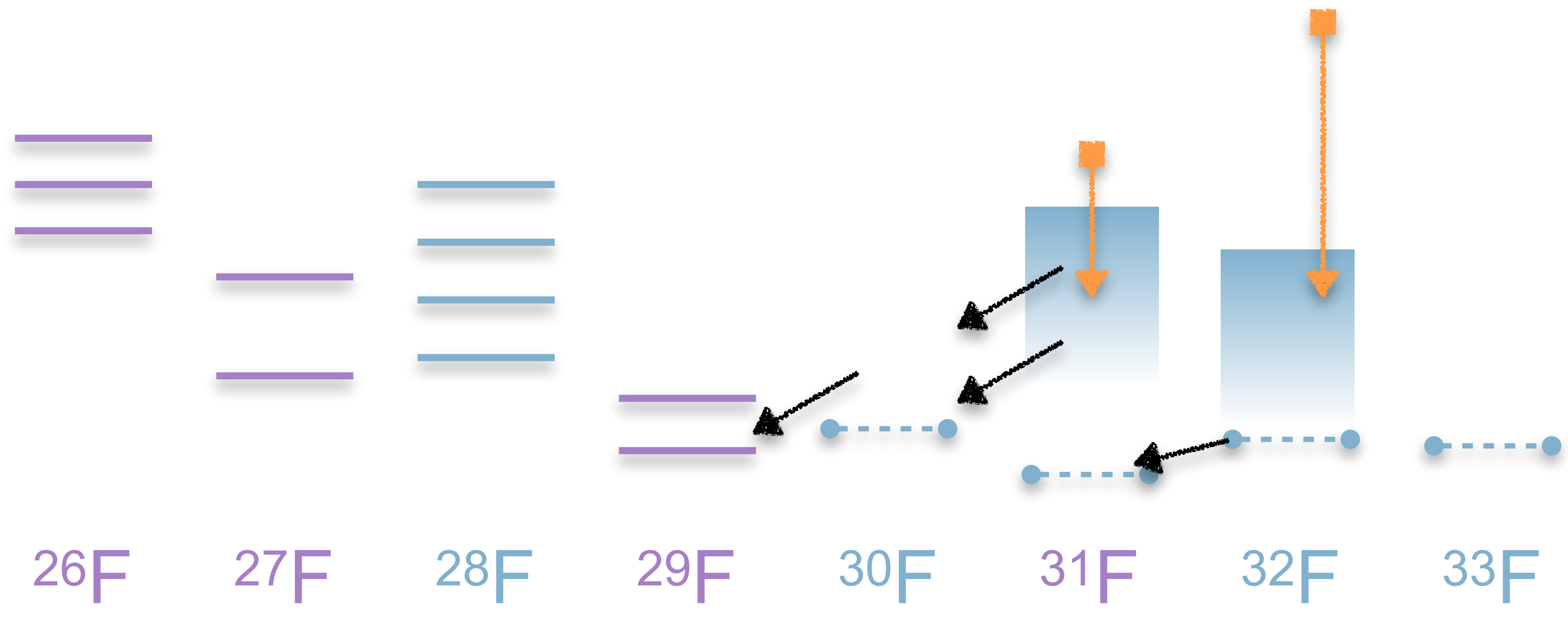
Christian PRL (2012)



Doornenbal PRC(R) (2017)

MID-TERM MEASUREMENTS [3 - 5+ YEARS]

Beyond PAC3 FRIB @ 100kW



How do the neutron $1p_{3/2}$ - $0f_{7/2}$ occupancies & the correlations evolve through ^{36}Al - ^{34}Na - ^{32}F?

- Determine nature of the ^{32}F ground state & low-lying structure
- Overlaps with bound states in ^{31}F (if any)
- Population of final state dependent upon nature of ^{34}Na g.s.
- Decay features are analogous to ^{30}F measurement

$$^{34}\mathrm{Na}(X,\text{-}2p)^{32}\mathrm{F}\rightarrow^{31}\mathrm{F}+n$$

$$\pi(0d_{5/2}1s_{1/2})^3 \otimes \ \nu(1p_{3/2})^2(0f_{7/2})^2 + \nu(1p_{3/2})^3 + \nu(0f_{7/2})^3$$

To what level do the np-nh excitations persist beyond the drip line?

- Distributed population of final states in ^{31}F
- Decays through known levels in ^{30}F aid in J assignments
- Inclusive / exclusive cross sections

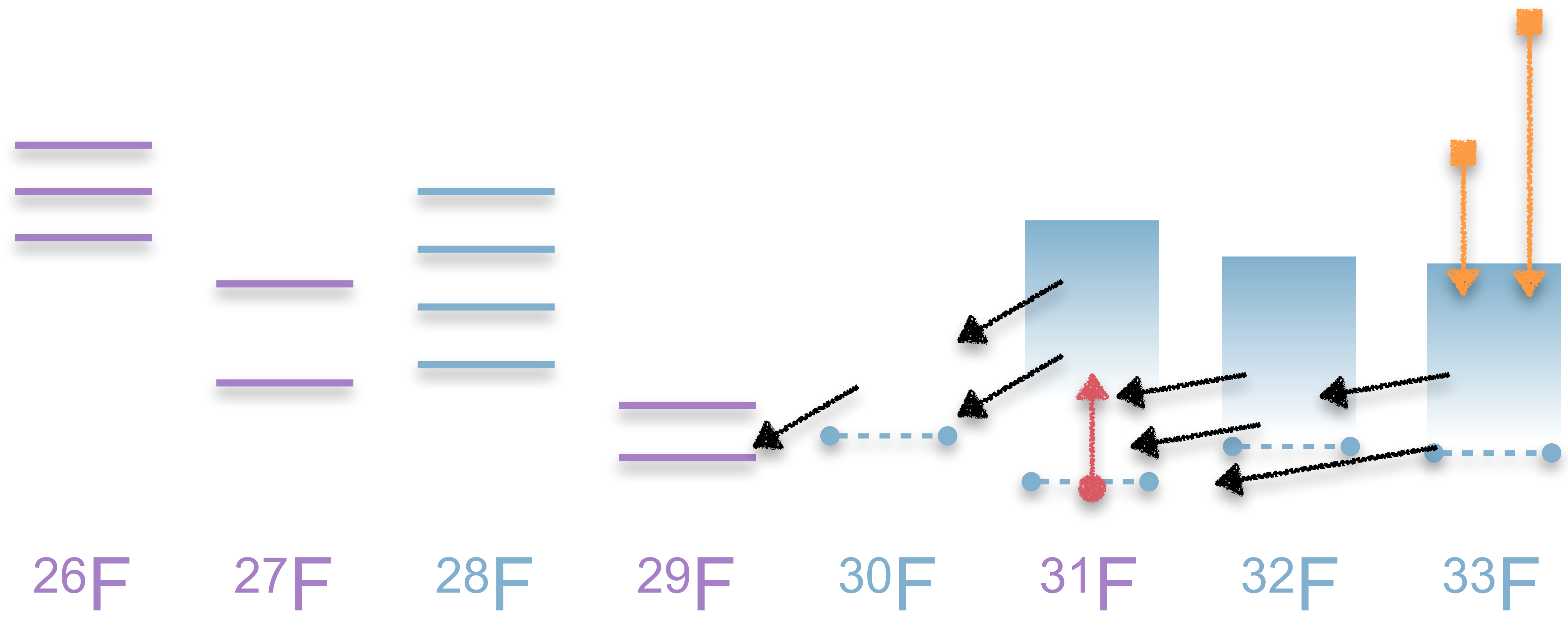
$$^{32}\mathrm{Ne}(X,\text{-}1p)^{31}\mathrm{F}\rightarrow^{29}\mathrm{F}+2n$$

	SDPF-M			EEDf1		
	0p-0h	2p-2h	4p-4h	0p-0h	2p-2h	4p-4h
^{32}Mg	4.7	82.5	12.7	1.8	36.2	51.9
^{30}Ne	3.9	74.1	22.0	0.5	19.8	68.1
^{34}Mg	9.5	82.0	8.4	1.6	49.5	43.4
^{32}Ne	10.0	76.5	13.4	1.2	43.3	50.6

Murray PRC(R) (2019)

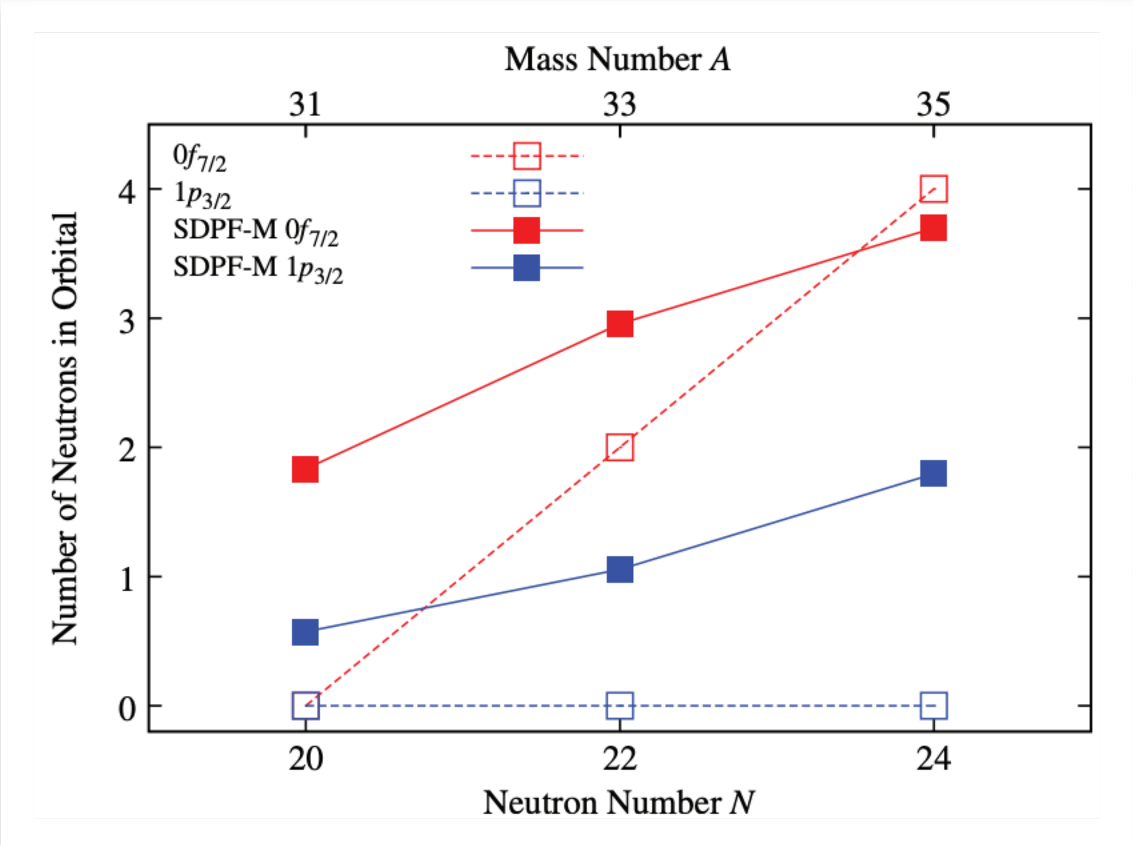
LONG-TERM MEASUREMENTS [5+ YEARS]

Ultimate rates FRIB @ ~400kW



What is the role of deformation (np-nh excitations), including continuum coupling, on the structure in the N = 24 transition region?

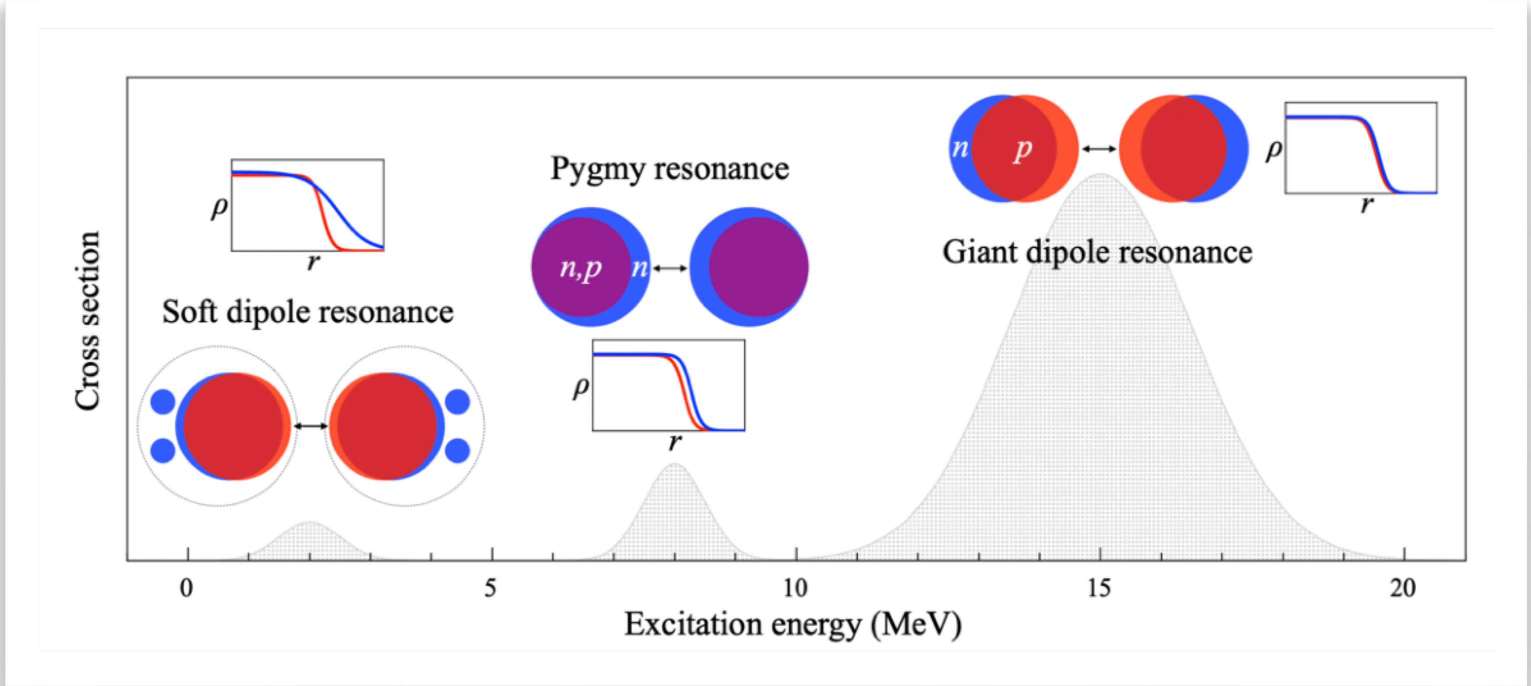
$$^{35}\mathrm{Na}(X,\text{-}2p)^{33}\mathrm{F}\rightarrow{}^{31}\mathrm{F}^{(*)}+2n$$



Doornenbal PTEP (2014)

Are there exotic excitation modes built off the "likely" extended *p*-wave ground state?

$$^{31}\mathrm{F}(d,d')(p,p')\rightarrow{}^{29}\mathrm{F}+2n$$



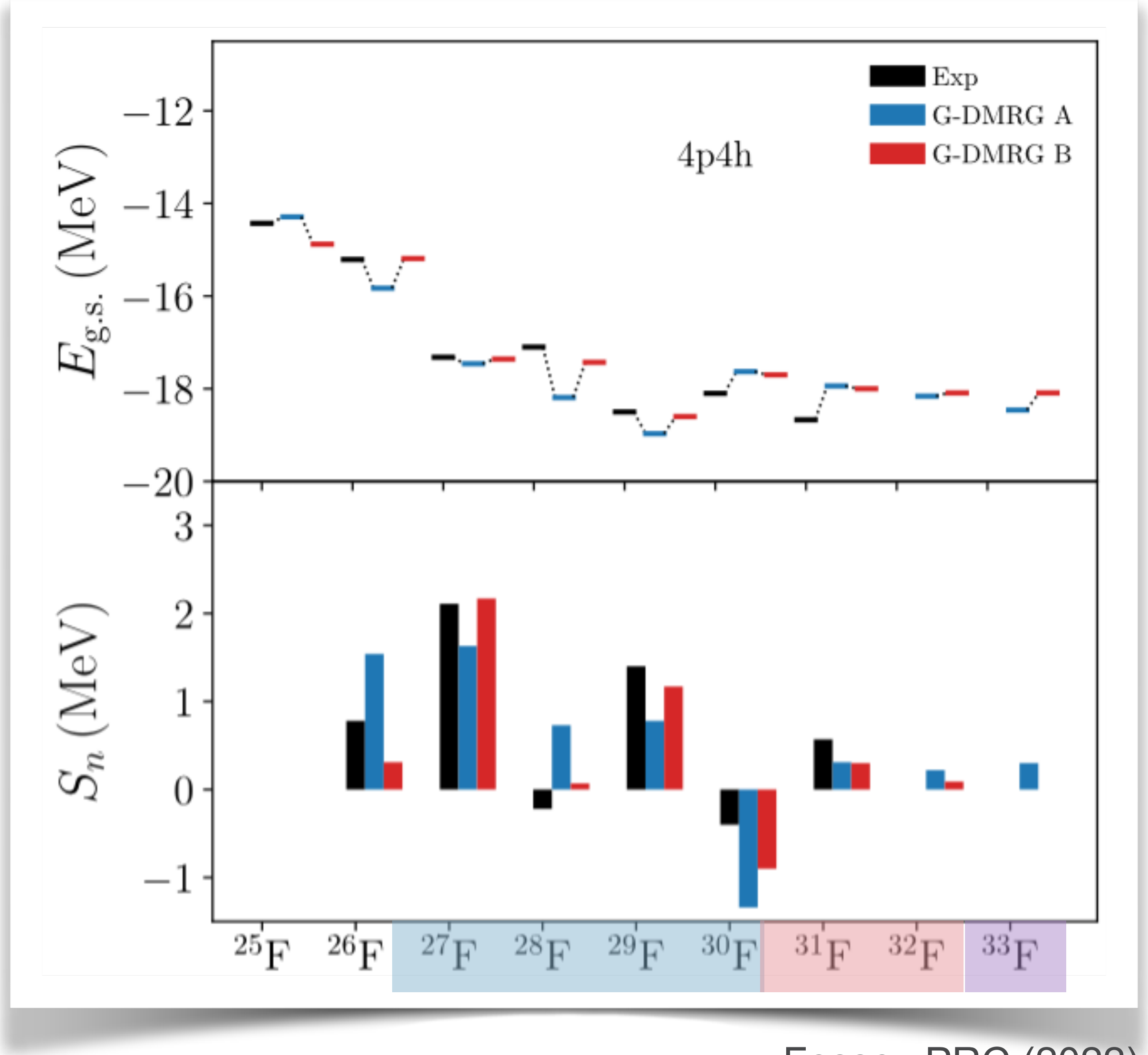
Kay,Chen ATLAS PAC (2019)

THEORETICAL WORK IN THE REGION

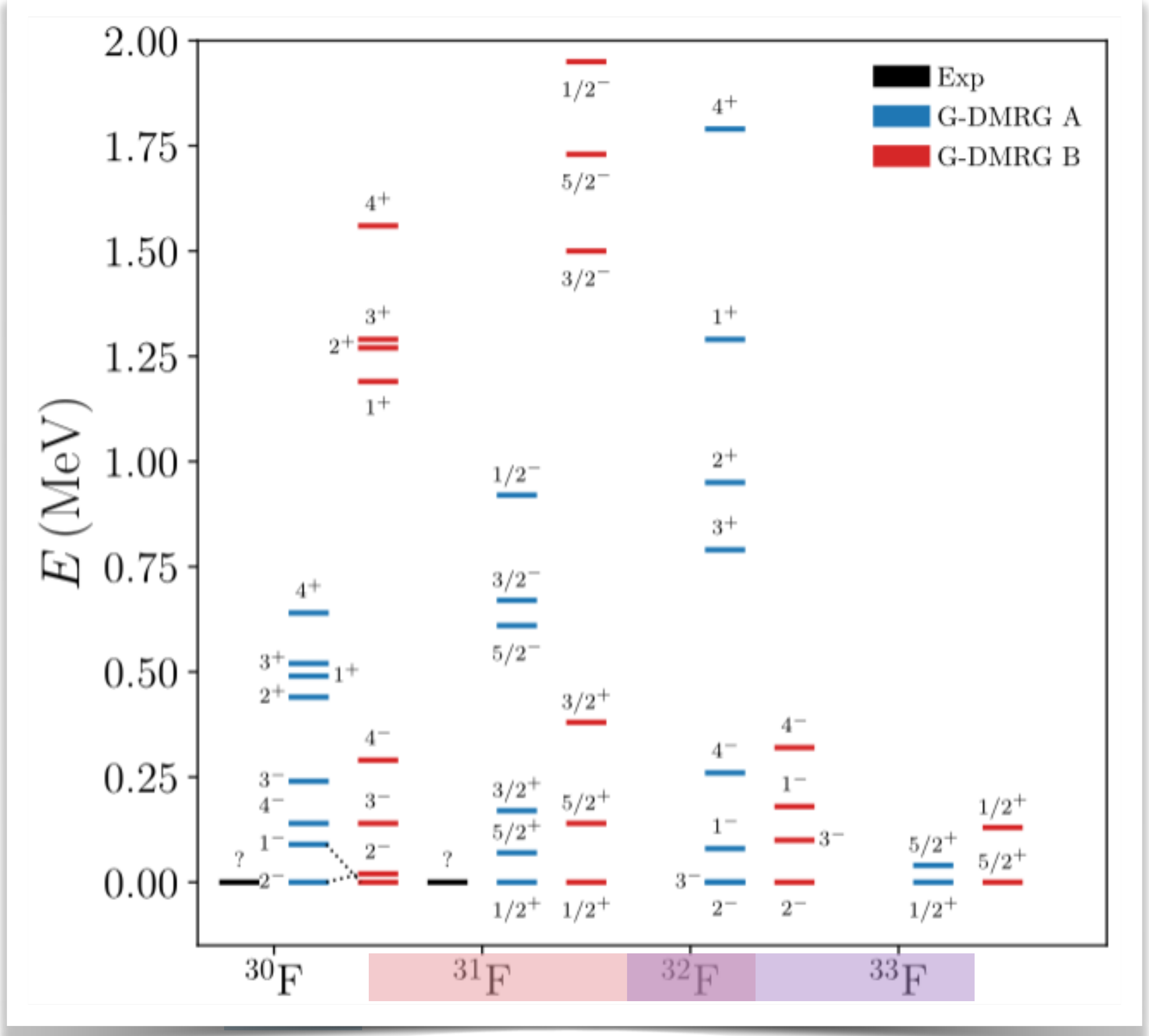
Structure

- **Place an emphasis on systematic calculations**
  - Consistent predictions across Z = 8 & 9 (N = 16 - 24)
  - Reproduce Oxygen & Fluorine spectra under single framework
  - Calculations of partial widths / decay branches (1n decay vs. multi-n decay)

- **Interest in the isolation of the role of the neutron 1p$_{3/2}$ orbital**
  - Influence on driving deformation in the Z = 14 - 16 neutron-rich region
  - Explicit role in driving deformation in Z = 9 region
  - Influences from its proximity near / in the continuum handled properly?



Fossez PRC (2022)



Fossez PRC (2022)

near-, mid-, long-term measurements

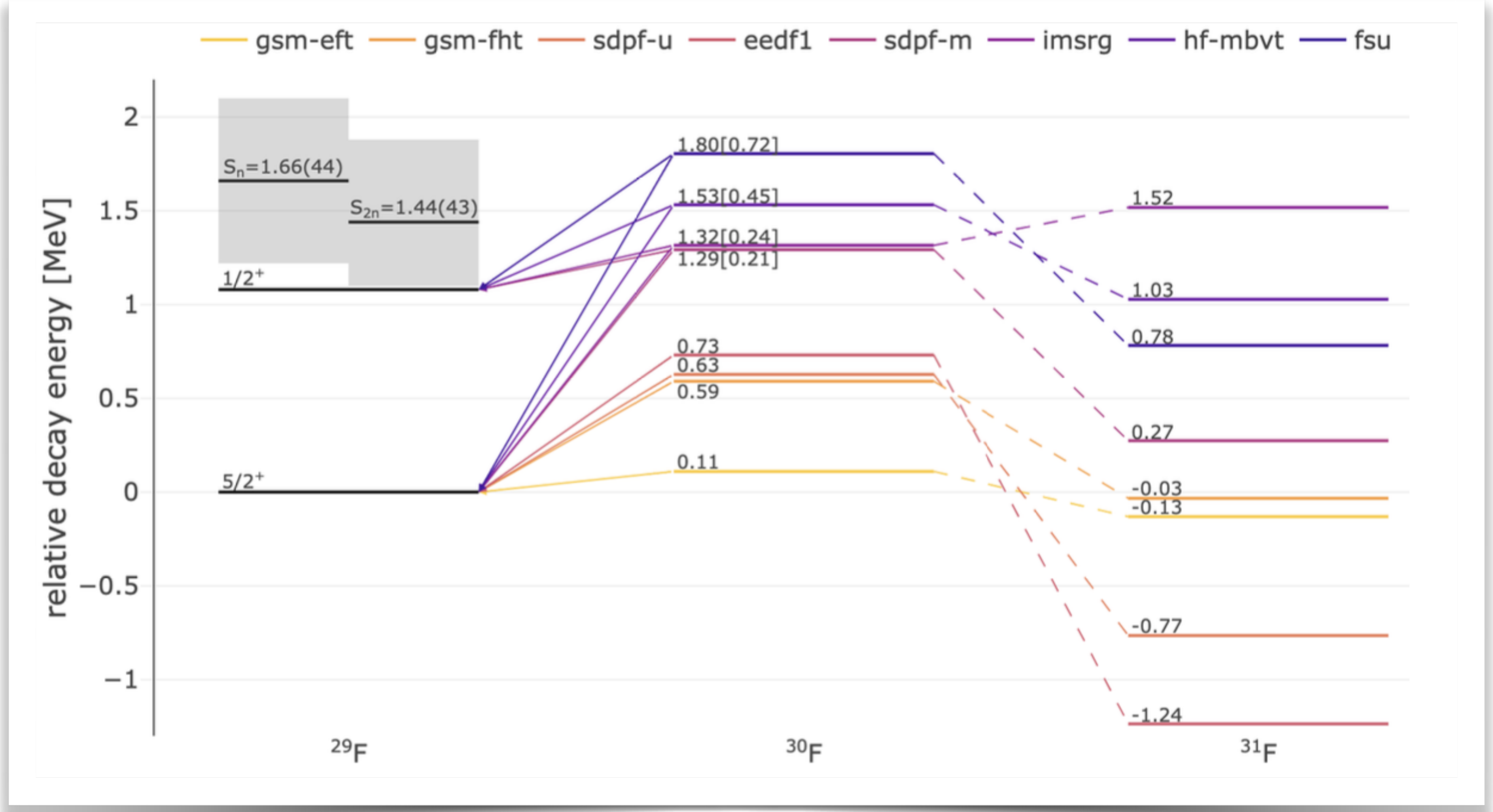
Argonne NATIONAL LABORATORY

THEORETICAL WORK IN THE REGION

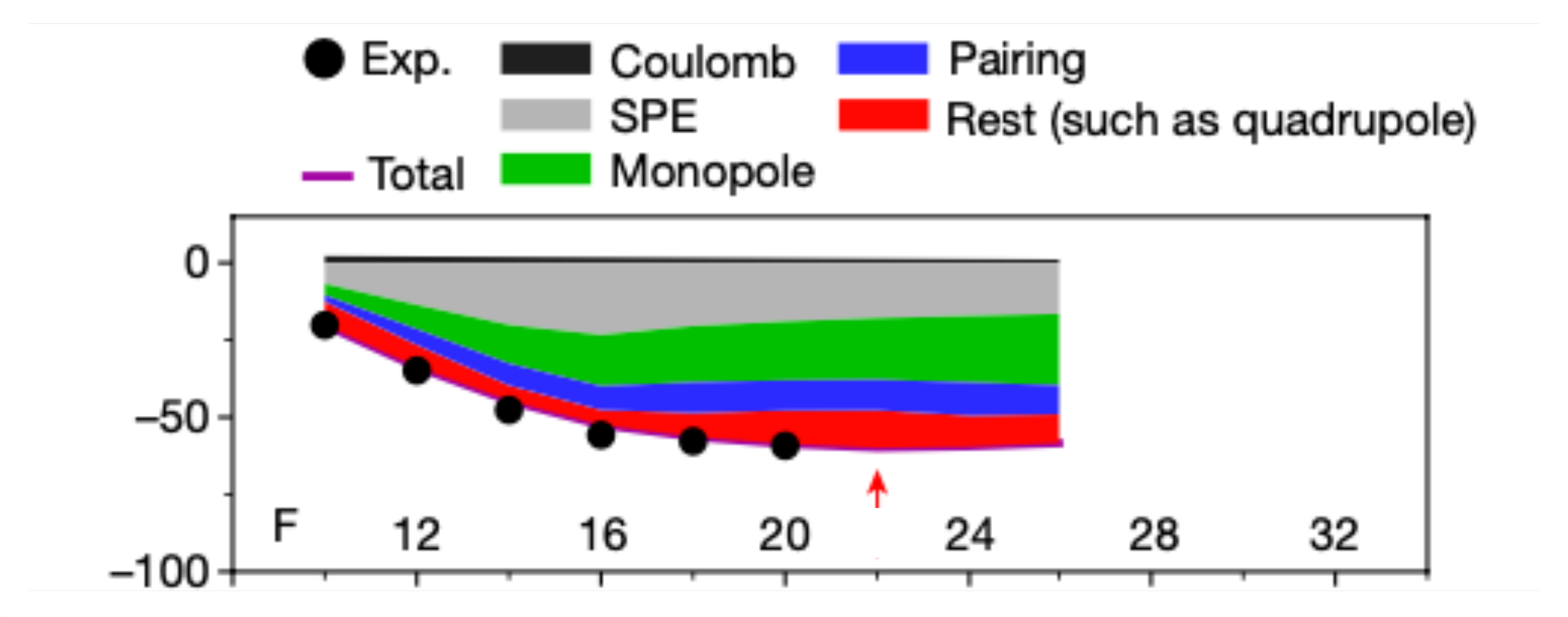
Structure

- **Place an emphasis on systematic calculations**
  - Consistent predictions across *Z* = 8 & 9 (N = 16 - 24)
  - Reproduce Oxygen & Fluorine spectra under single framework
  - Calculations of partial widths / decay branches (1n decay vs. multi-n decay)

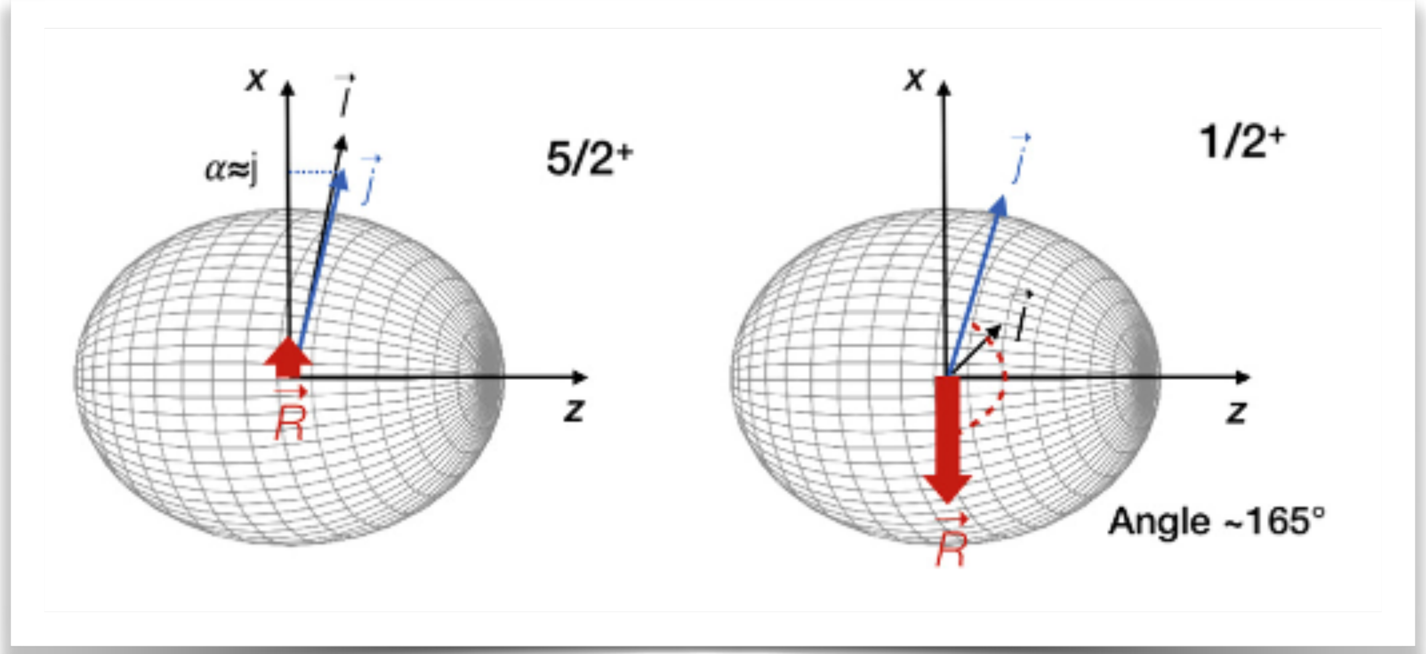
- **Interest in the isolation of the role of the neutron $1p_{3/2}$ orbital**
  - Influence on driving deformation in the *Z* = 14 - 16 neutron-rich region
  - Explicit role in driving deformation in *Z* = 9 region
  - Influences from its proximity near / in the continuum handled properly?



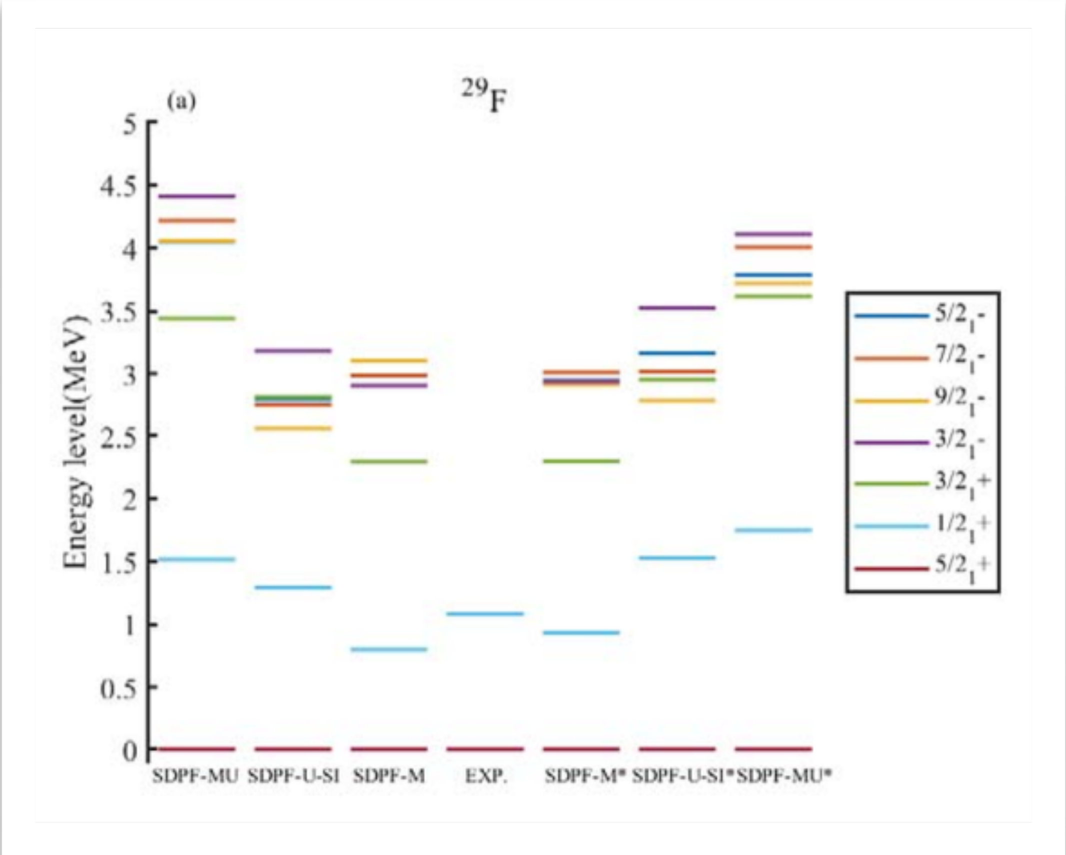
Hoffman PAC1 (2021)



Tsunoda Nature (2020)



Macchiavelli PLB (2017)



Liu Symmetry (2021)

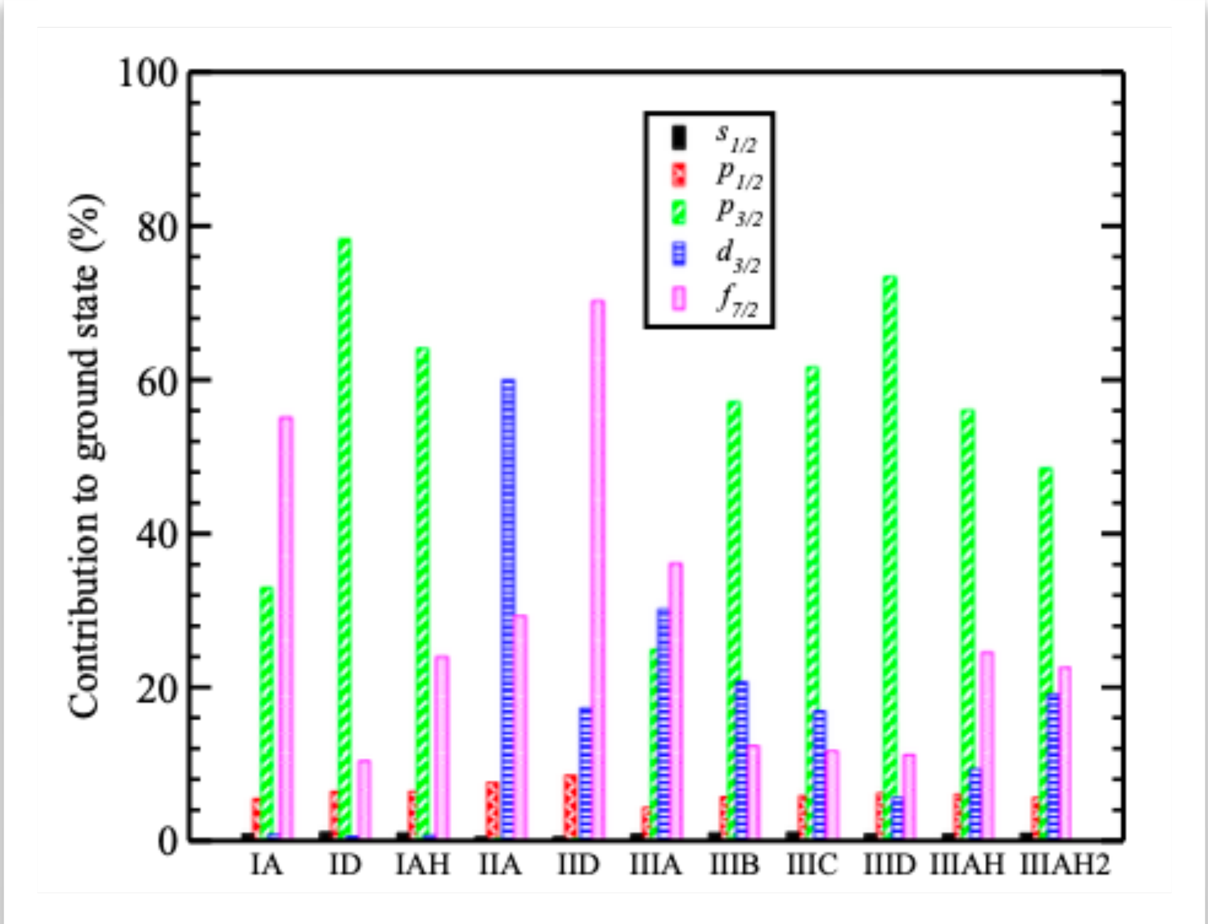
Argonne NATIONAL LABORATORY

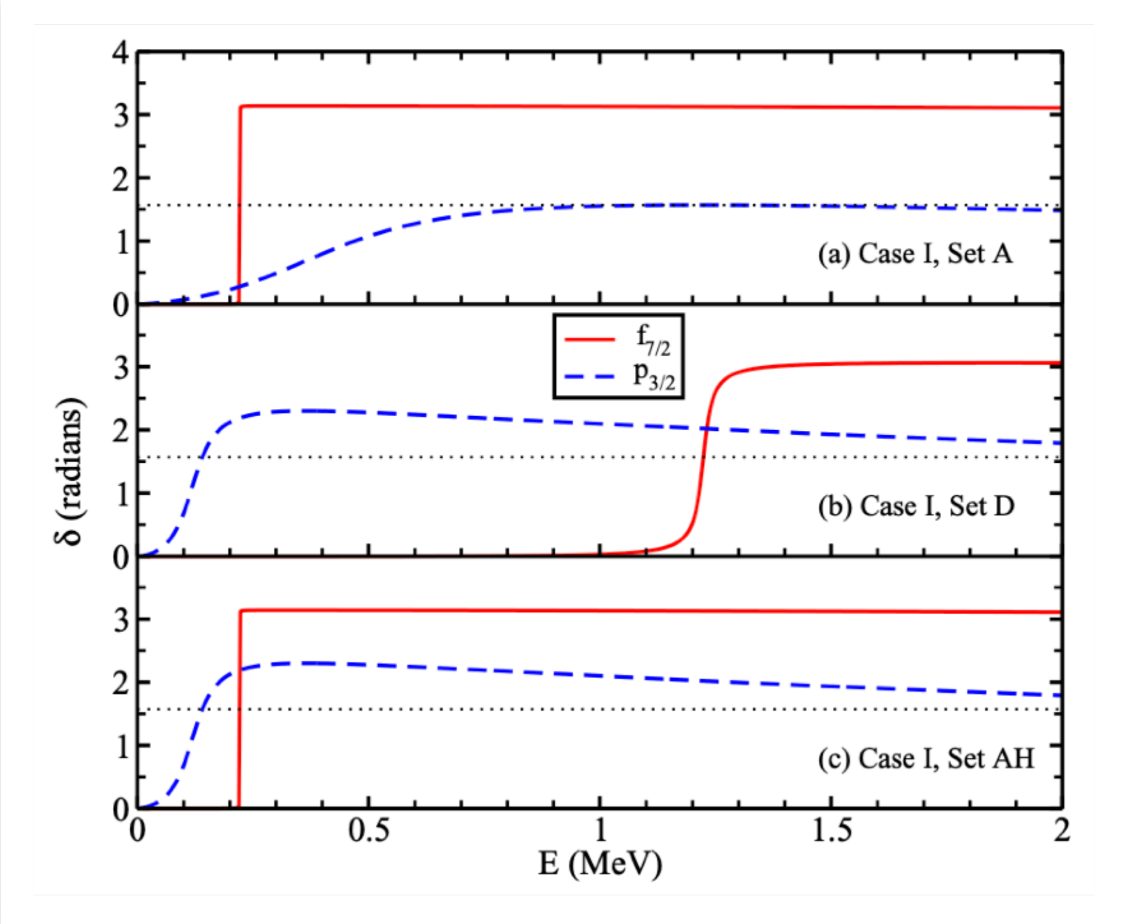
THEORETICAL WORK IN THE REGION

Structure

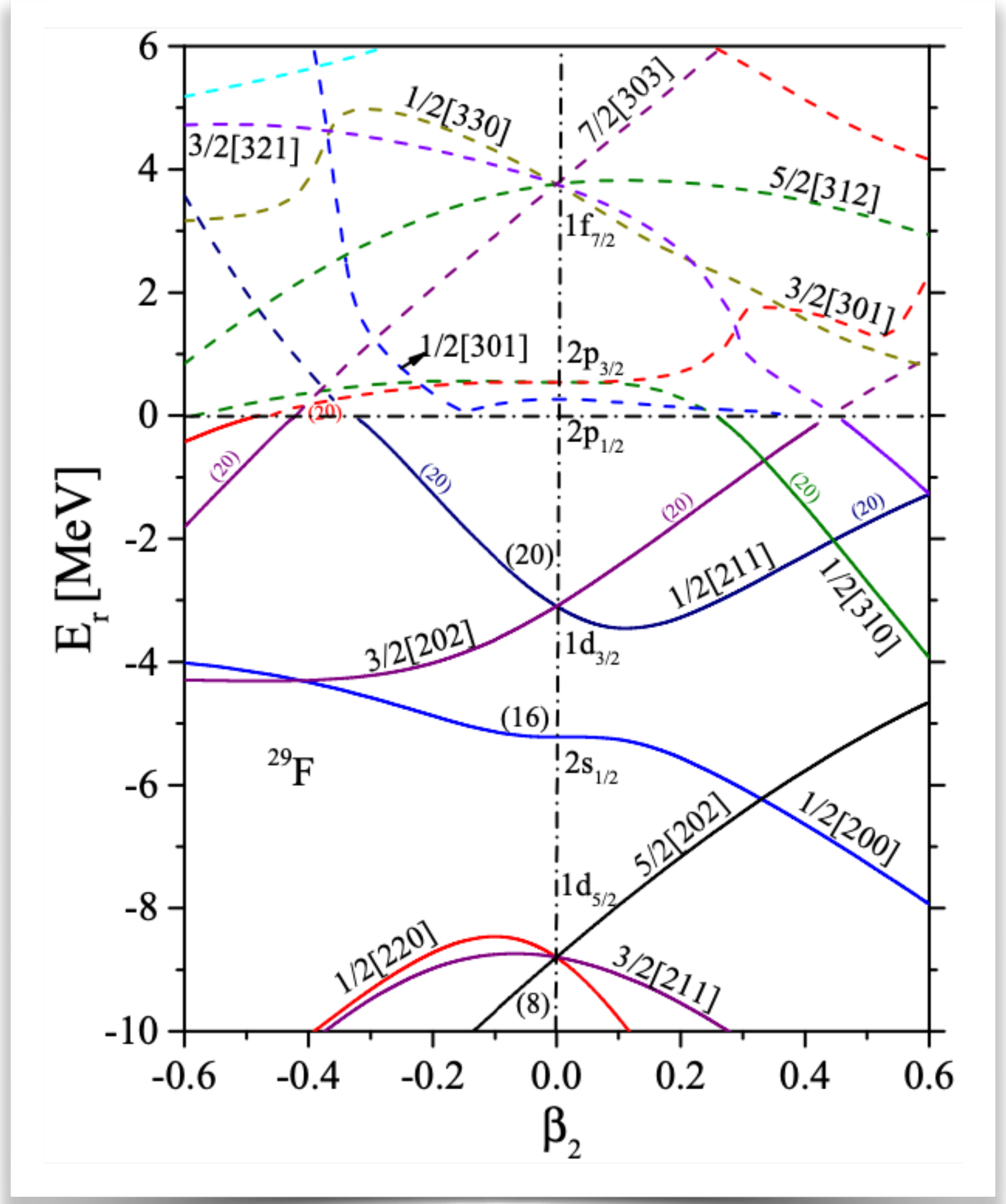
- **Place an emphasis on systematic calculations**
  - Consistent predictions across *Z* = 8 & 9 (N = 16 - 24)
  - Reproduce Oxygen & Fluorine spectra under single framework
  - Calculations of partial widths / decay branches (1n decay vs. multi-n decay)

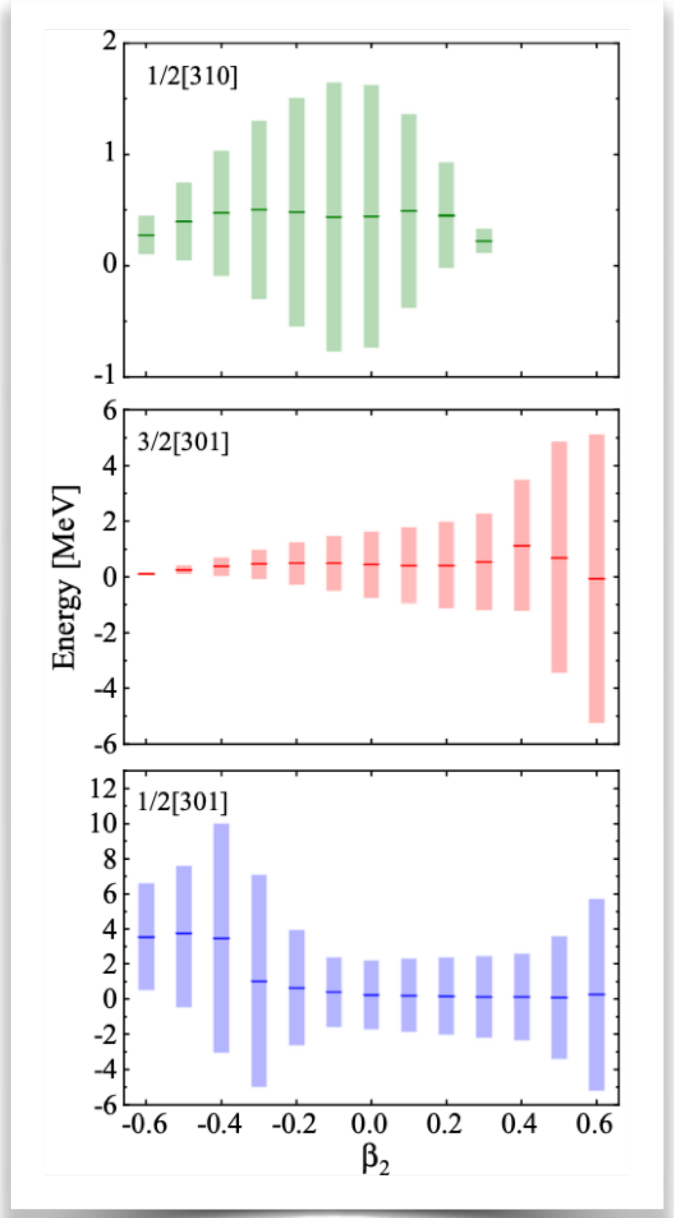
- **Interest in the isolation of the role of the neutron $1p_{3/2}$ orbital**
  - Influence on driving deformation in the *Z* = 14 - 16 neutron-rich region
  - Explicit role in driving deformation in *Z* = 9 region
  - Influences from its proximity near / in the continuum handled properly?

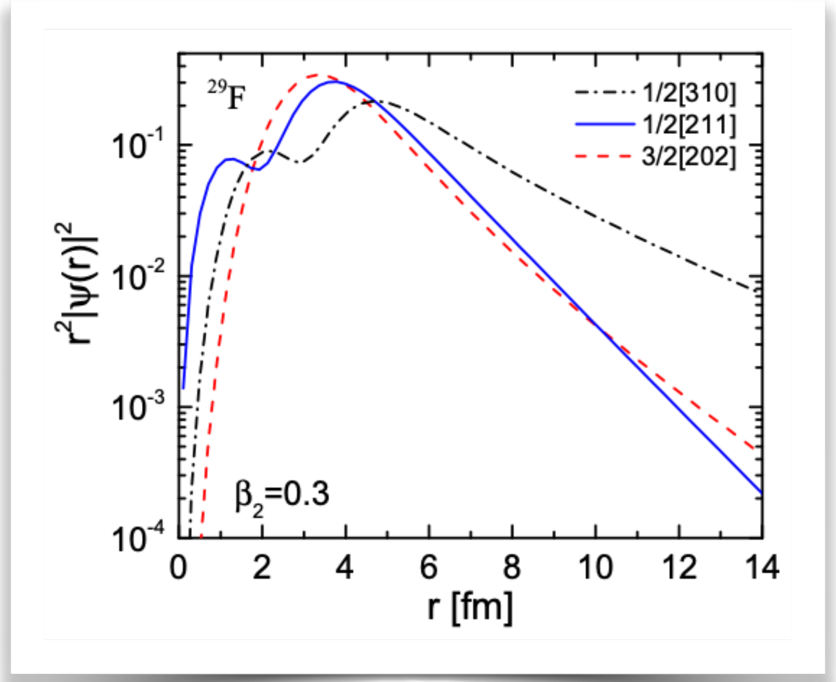


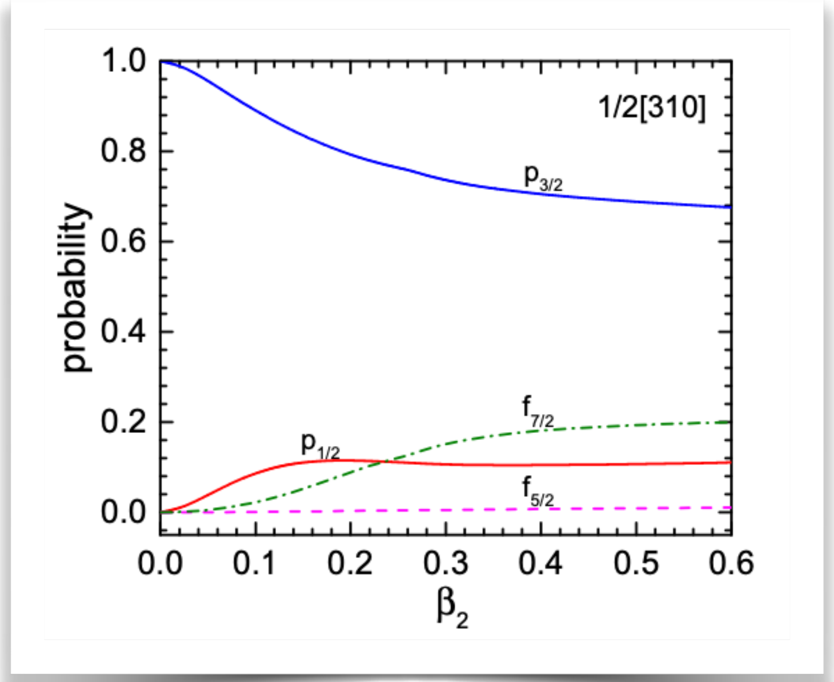


Singh PRC (2022)







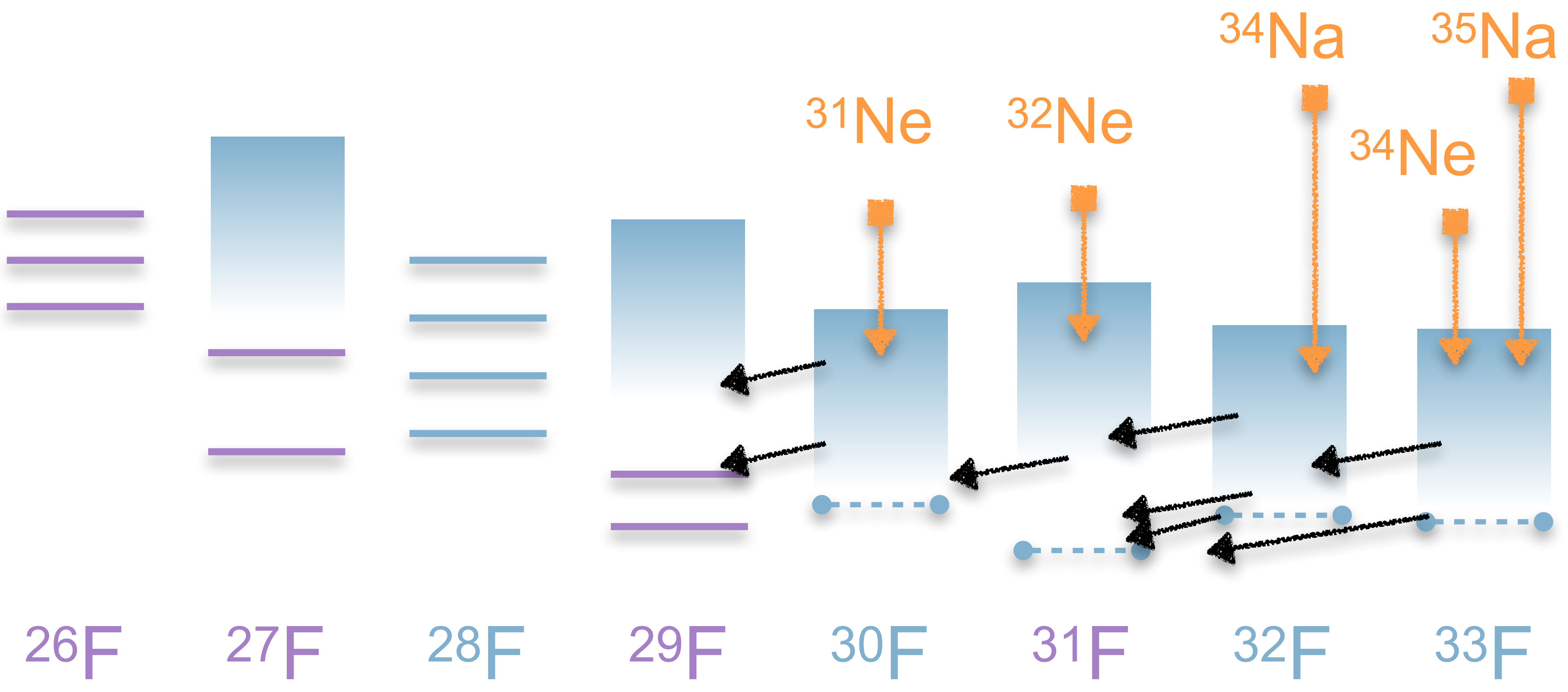


Luo PRC (2021)

Argonne NATIONAL LABORATORY

THEORETICAL OVERLAP

Reactions



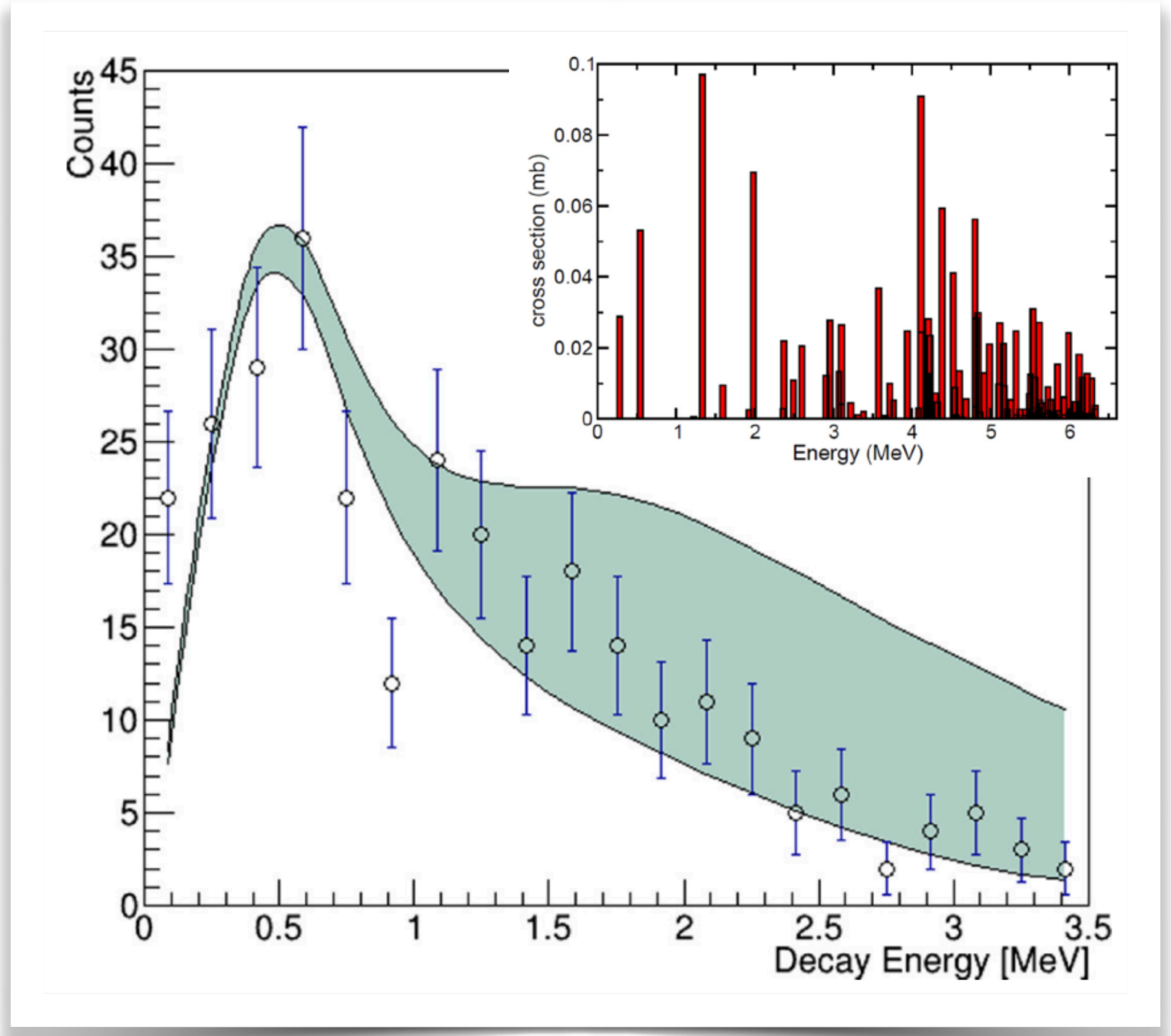
One & two proton removal reactions [H/C/Be targets]

- (Sudden) eikonal direct-reaction model calculations:
  - Calculated cross sections for the extraction of overlaps
  - Determination of the knockout orbital angular momentum
- Transition / Complement with proton reactions (p,2p) @ FRIB400

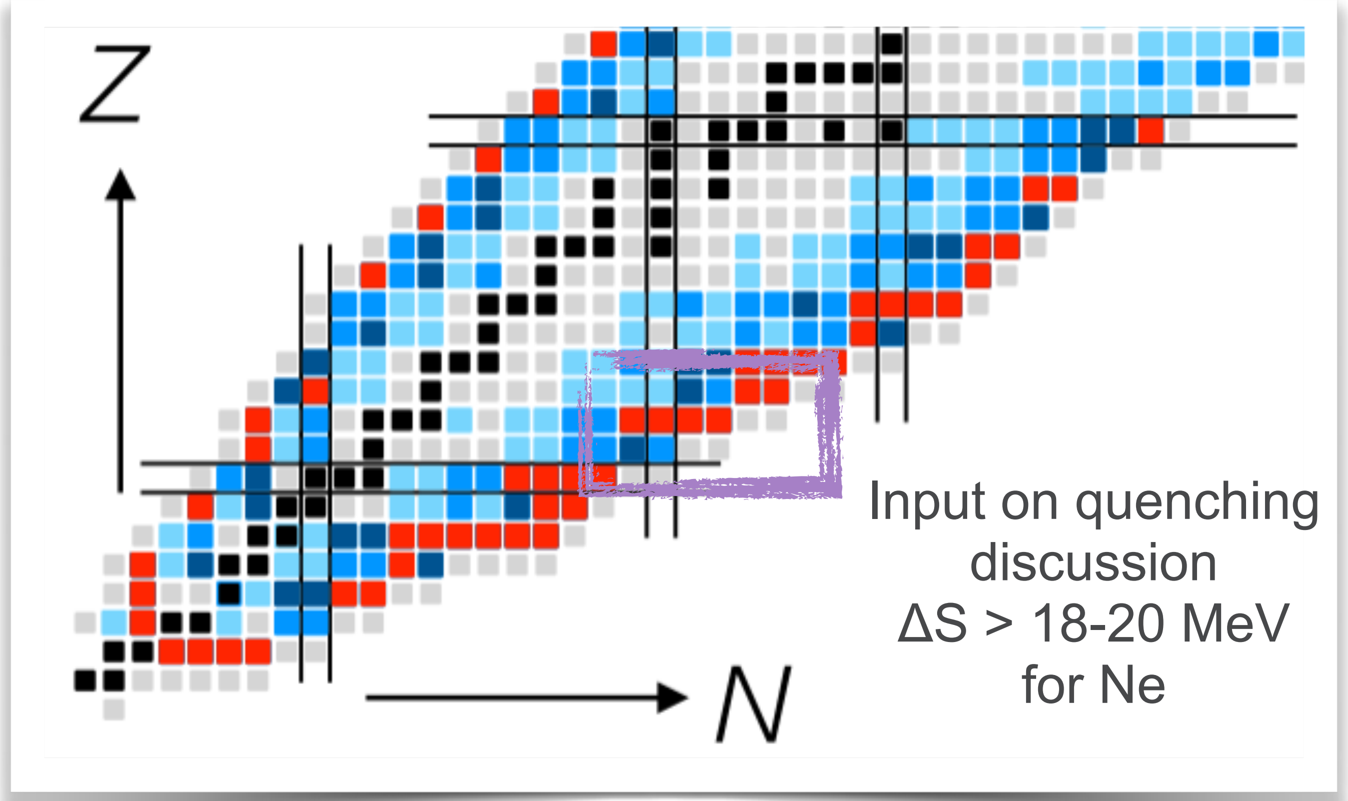
Intermediate-energy inelastic reactions [(d,d'),(p,p')]

- Relies on reaction theory to extract information
  - (Matter) deformation β, spin-parity guidance, …
- **i.e. DWBA, are optical potential parameters valid?**
  - ~100 - 150 MeV/u, "direct" population of unbound states, …

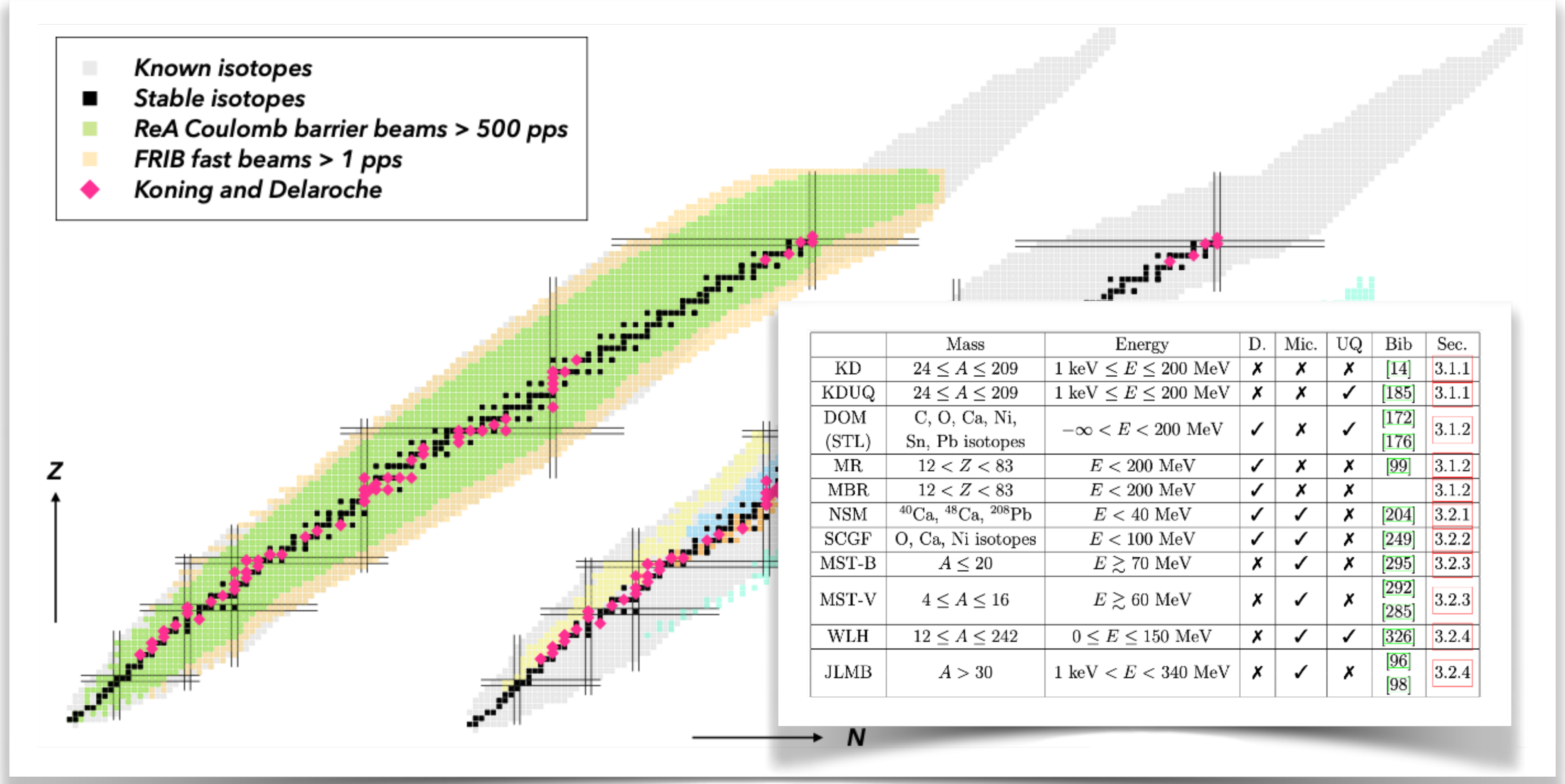
- Continued request for developments in the joining of reaction & structure theories.



Chrisman PRC (2021)



Aumann PPNP (2021)

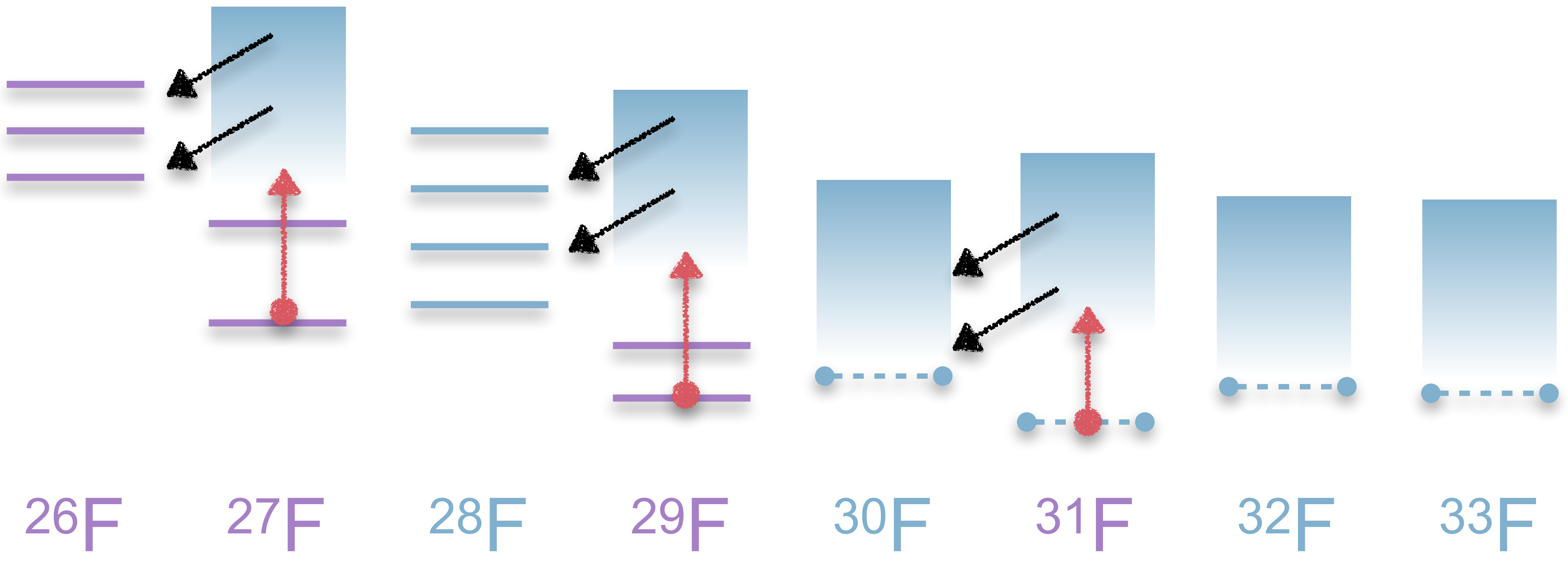


Hebron arXiv (2022)

Argonne NATIONAL LABORATORY

THEORETICAL OVERLAP

Reactions



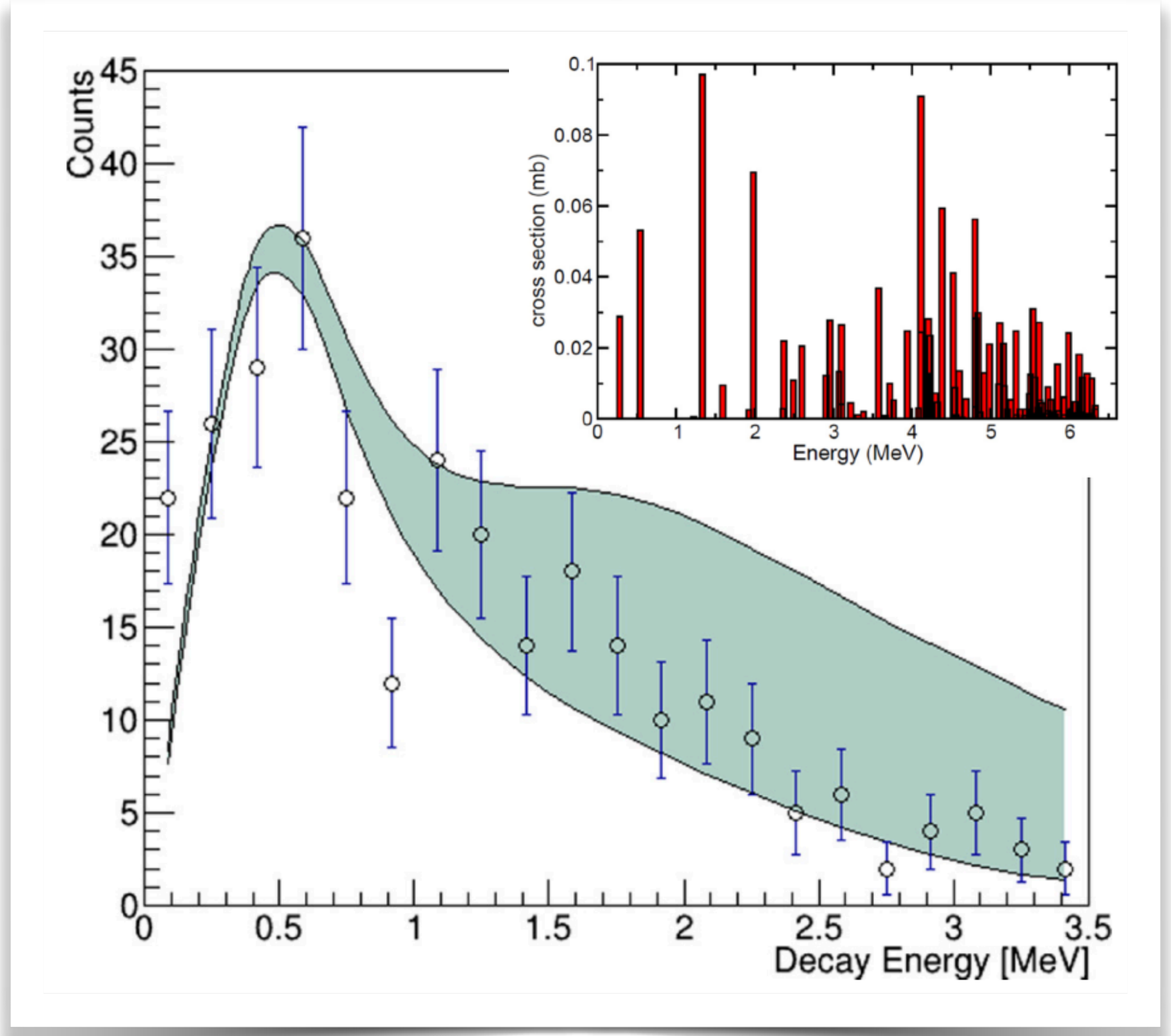
One & two proton removal reactions [H/C/Be targets]

- (Sudden) eikonal direct-reaction model calculations:
  - Calculated cross sections for the extraction of overlaps
  - Determination of the knockout orbital angular momentum
- Transition / Complement with proton reactions (p,2p) @ FRIB400

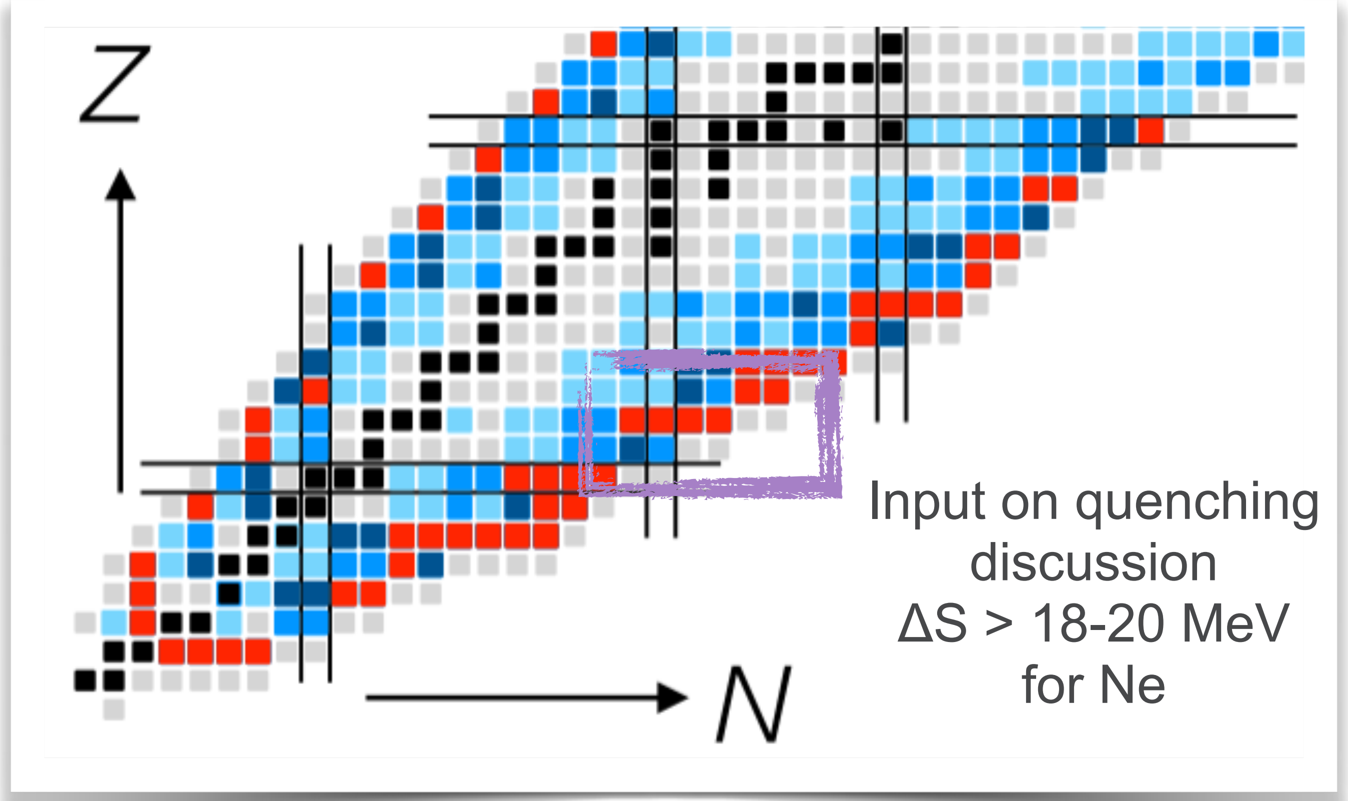
Intermediate-energy inelastic reactions [(d,d'),(p,p')]

- Relies on reaction theory to extract information
  - (Matter) deformation β, spin-parity guidance, …
- **i.e. DWBA, are optical potential parameters valid?**
  - ~100 - 150 MeV/u, "direct" population of unbound states, …

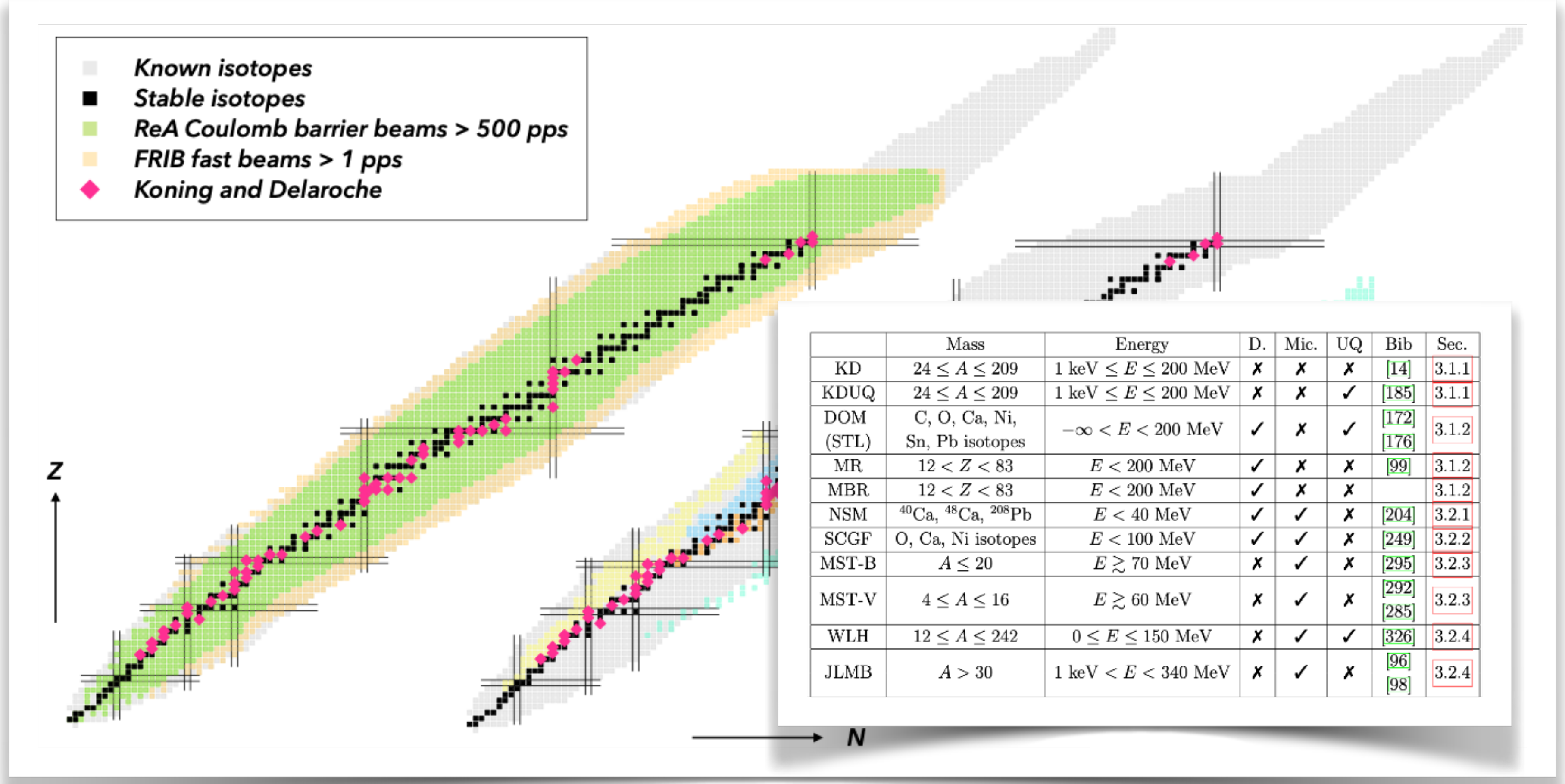
- Continued request for developments in the joining of reaction & structure theories.



Chrisman PRC (2021)



Aumann PPNP (2021)

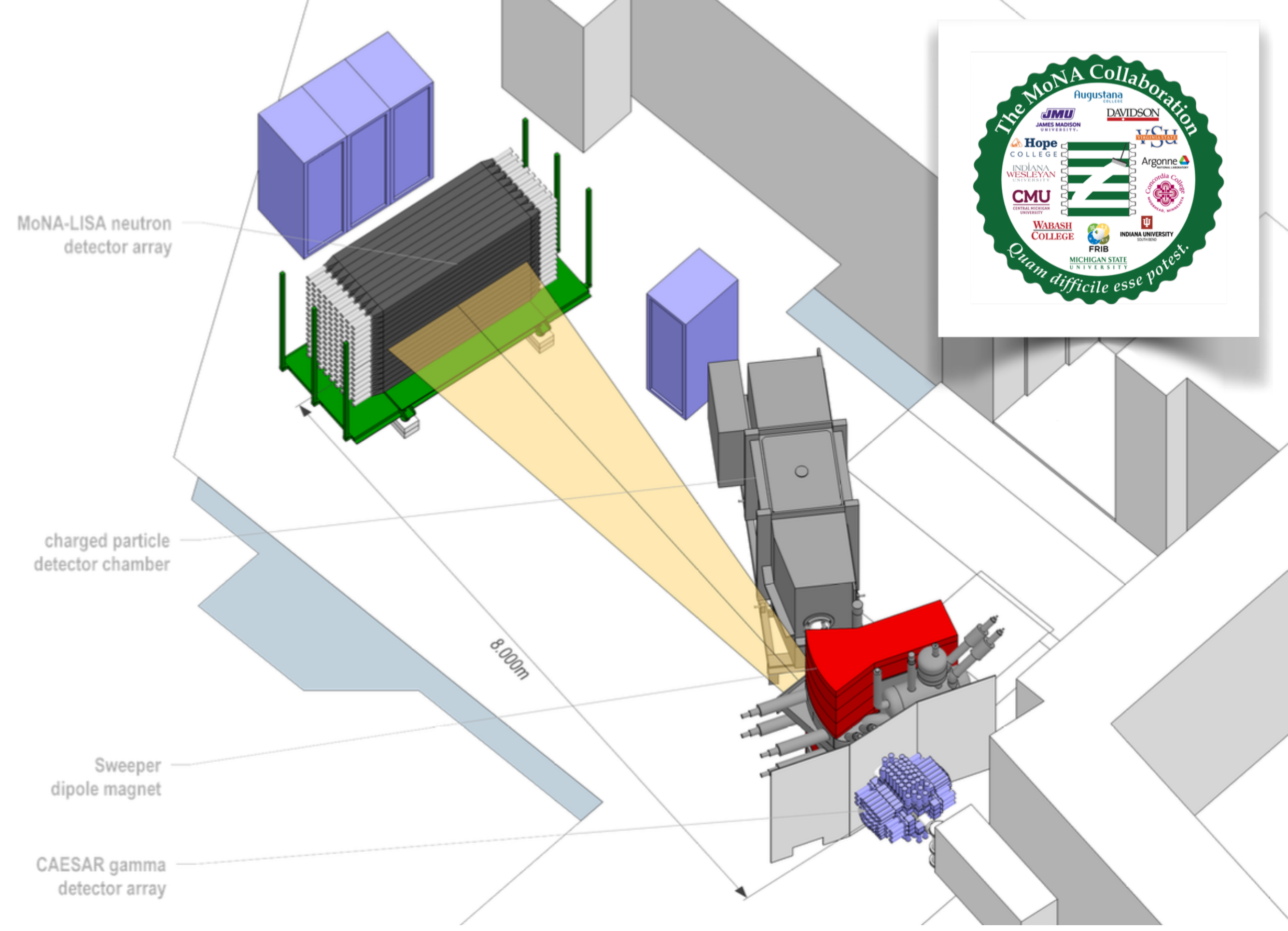


	Mass	Energy	D.	Mic.	UQ	Bib	Sec.
KD	$24 \leq A \leq 209$	$1\ \mathrm{keV} \leq E \leq 200\ \mathrm{MeV}$	✗	✗	✗	[14]	3.1.1
KDUQ	$24 \leq A \leq 209$	$1\ \mathrm{keV} \leq E \leq 200\ \mathrm{MeV}$	✗	✗	✓	[185]	3.1.1
DOM (STL)	C, O, Ca, Ni, Sn, Pb isotopes	$-\infty < E < 200\ \mathrm{MeV}$	✓	✗	✓	[172] [176]	3.1.2
MR	$12 < Z < 83$	$E < 200\ \mathrm{MeV}$	✓	✗	✗	[99]	3.1.2
MBR	$12 < Z < 83$	$E < 200\ \mathrm{MeV}$	✓	✗	✗		3.1.2
NSM	^{40}Ca, ^{48}Ca, ^{208}Pb	$E < 40\ \mathrm{MeV}$	✓	✓	✗	[204]	3.2.1
SCGF	O, Ca, Ni isotopes	$E < 100\ \mathrm{MeV}$	✓	✓	✗	[249]	3.2.2
MST-B	$A \leq 20$	$E \gtrsim 70\ \mathrm{MeV}$	✗	✓	✗	[295]	3.2.3
MST-V	$4 \leq A \leq 16$	$E \gtrsim 60\ \mathrm{MeV}$	✗	✓	✗	[292] [285]	3.2.3
WLH	$12 \leq A \leq 242$	$0 \leq E \leq 150\ \mathrm{MeV}$	✗	✓	✓	[326]	3.2.4
JLMB	$A > 30$	$1\ \mathrm{keV} < E < 340\ \mathrm{MeV}$	✗	✓	✗	[96] [98]	3.2.4

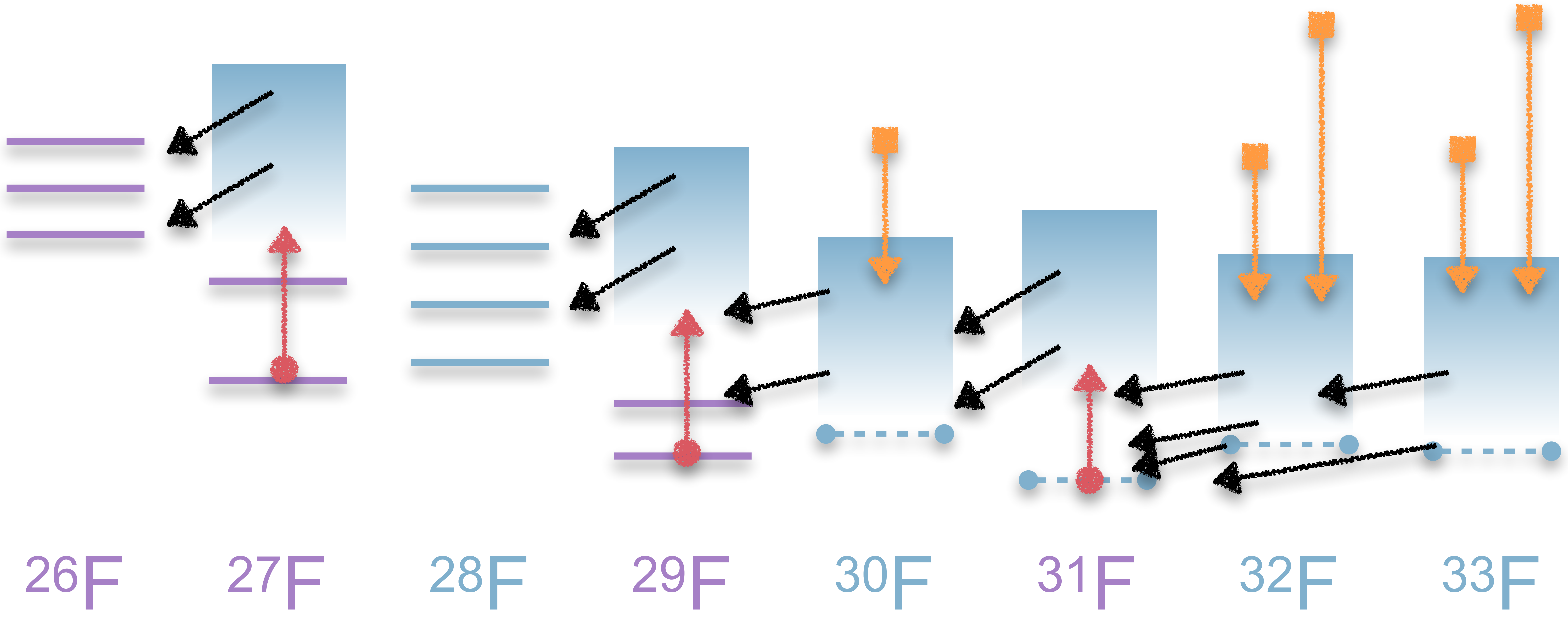
Hebron arXiv (2022)

PARTING COMMENTS

Spectroscopy involving the population & decay of neutron-unbound states

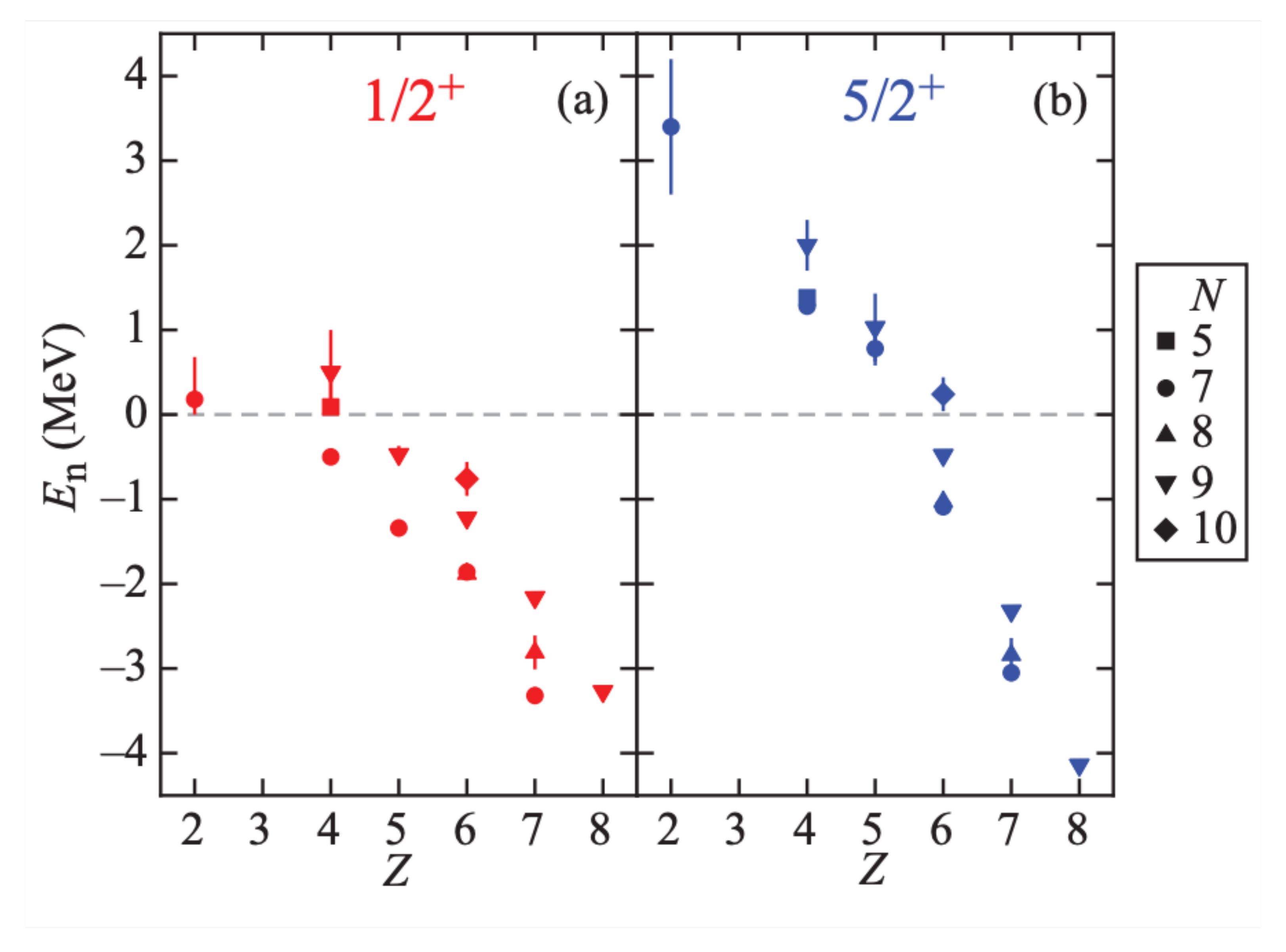


- Determine energies, spin-parity & orbital angular momenta constraints, neutron decay branches, partial widths, and overlaps
- Request for (continued) systematic calculations - Z & N, …
- High interest in the isolation of the neutron $1p_{3/2}$, orbital - influences from the continuum, deformation effects (correlations), …
- Establish the understanding of the oxygen - fluorine drip lines in the early FRIB era

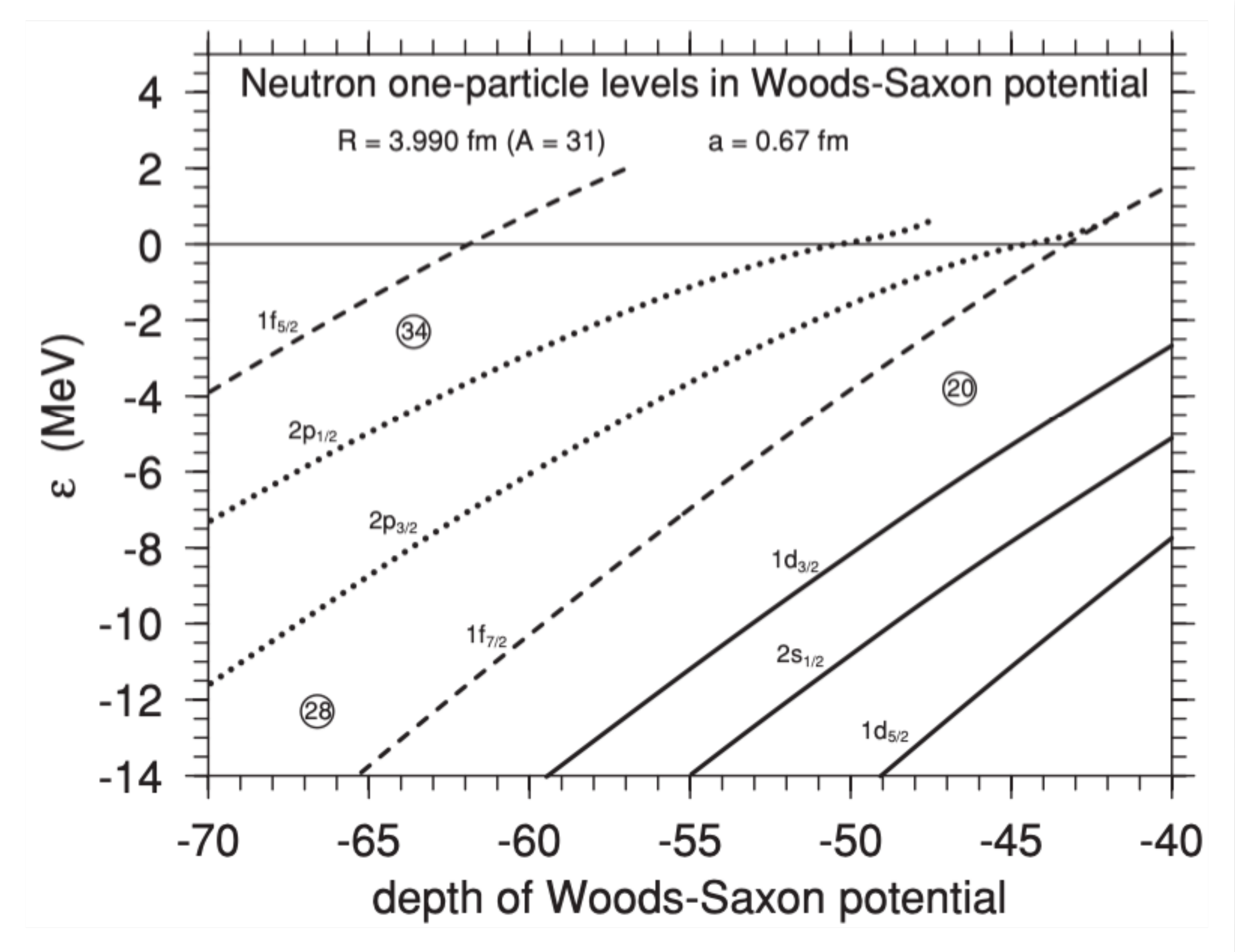


Reaction cross sections, β-delayed γ-ray & neutron spectroscopy, prompt γ-ray spectroscopy, mass measurements, transfer reactions, …

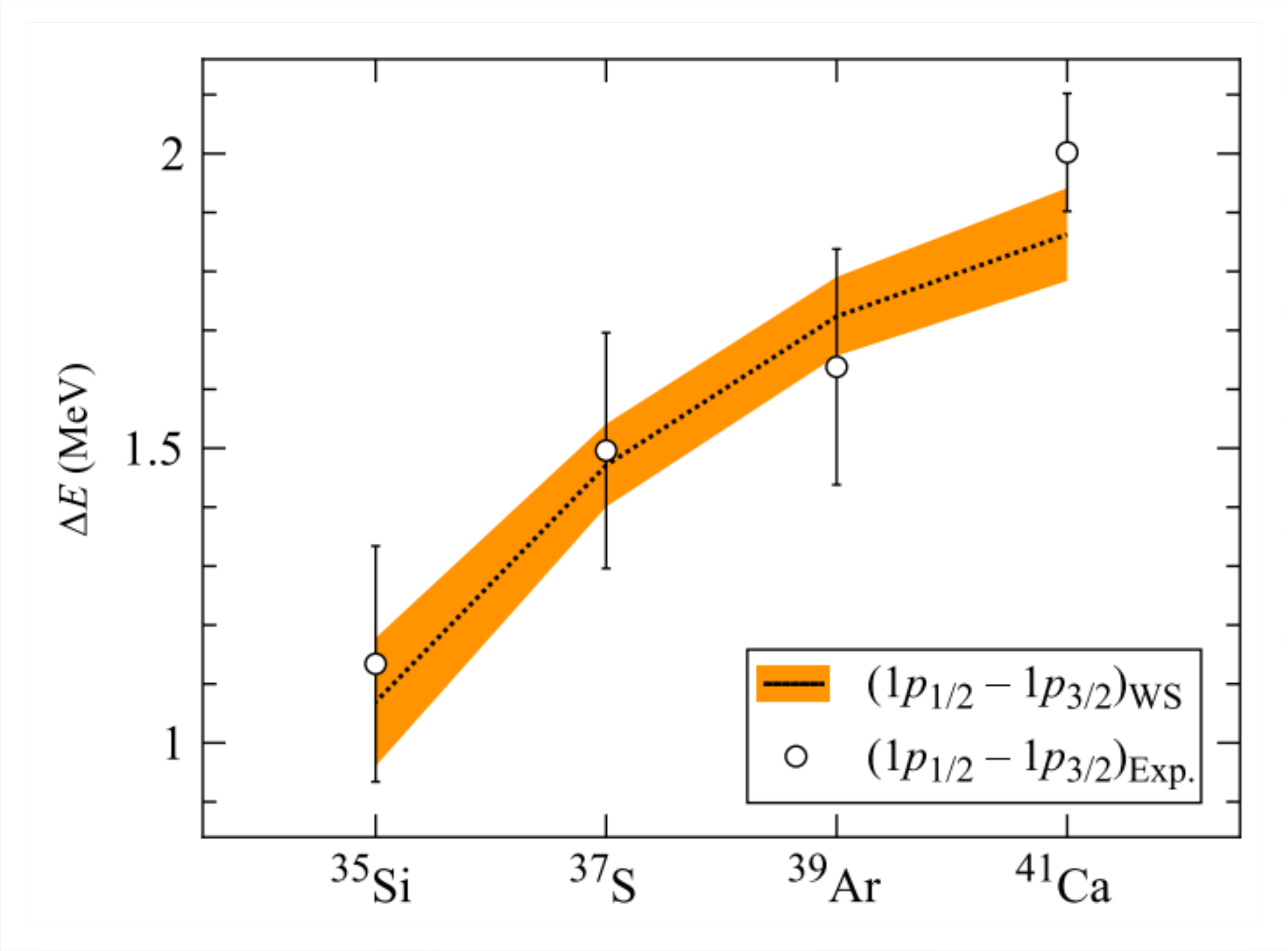
SINGLE & MULTI-NUCLEON TRANSFER REACTIONS AT REA



Hoffman PRC (2012)



Hamamoto PRC (2007)



Kay PRL (2017)

BEHAVIOR OF THE ORBITAL ENERGIES NEAR THRESHOLD

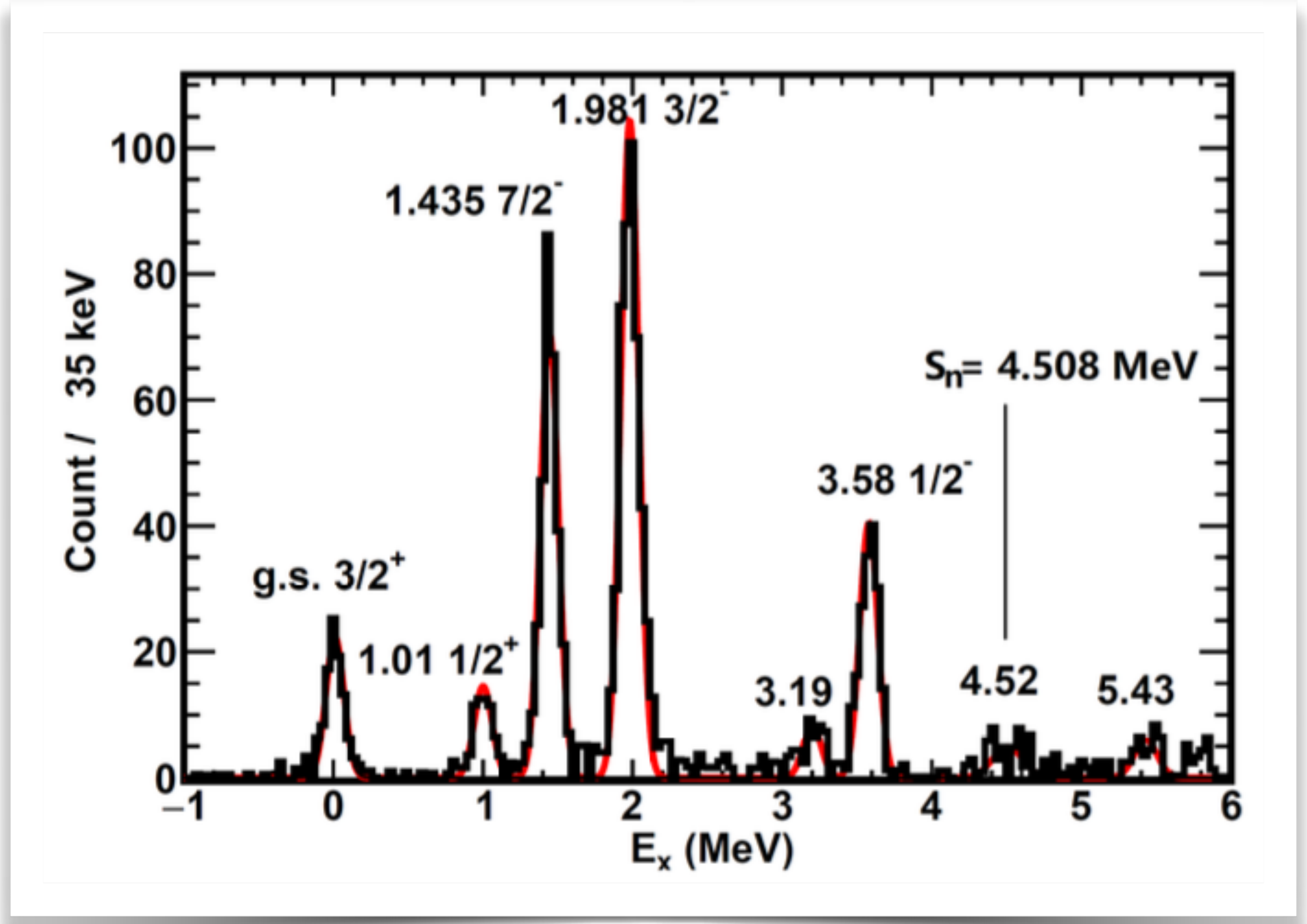
- S-WAVE: MOST DISTINCT BEHAVIOR AT $S_N \sim 0$
- PERSISTS FOR ALL ORBITS NEAR THEIR BARRIER THRESHOLDS IN THE CONTINUUM [COULOMB BARRIER PROTONS, L>0]

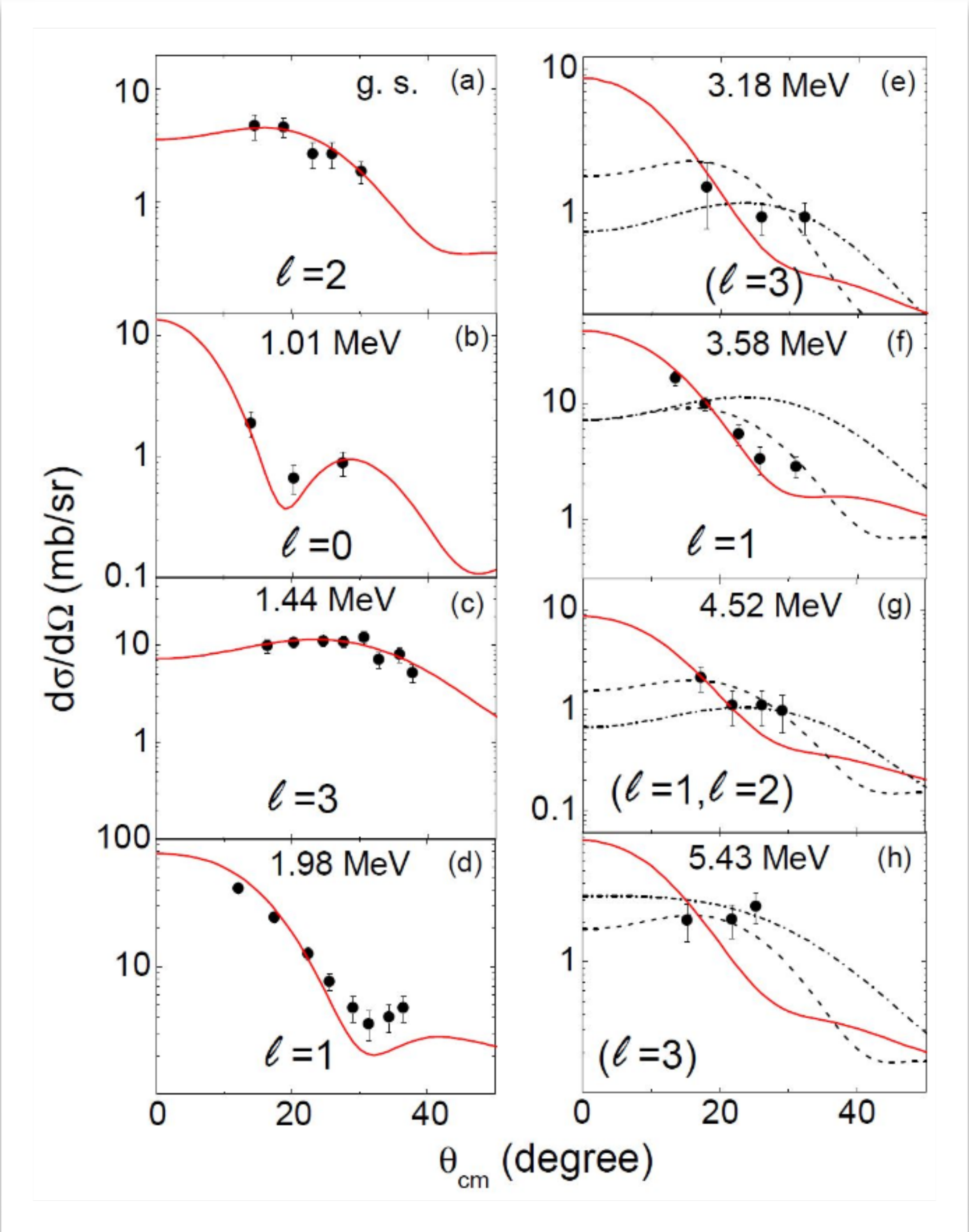
Argonne NATIONAL LABORATORY

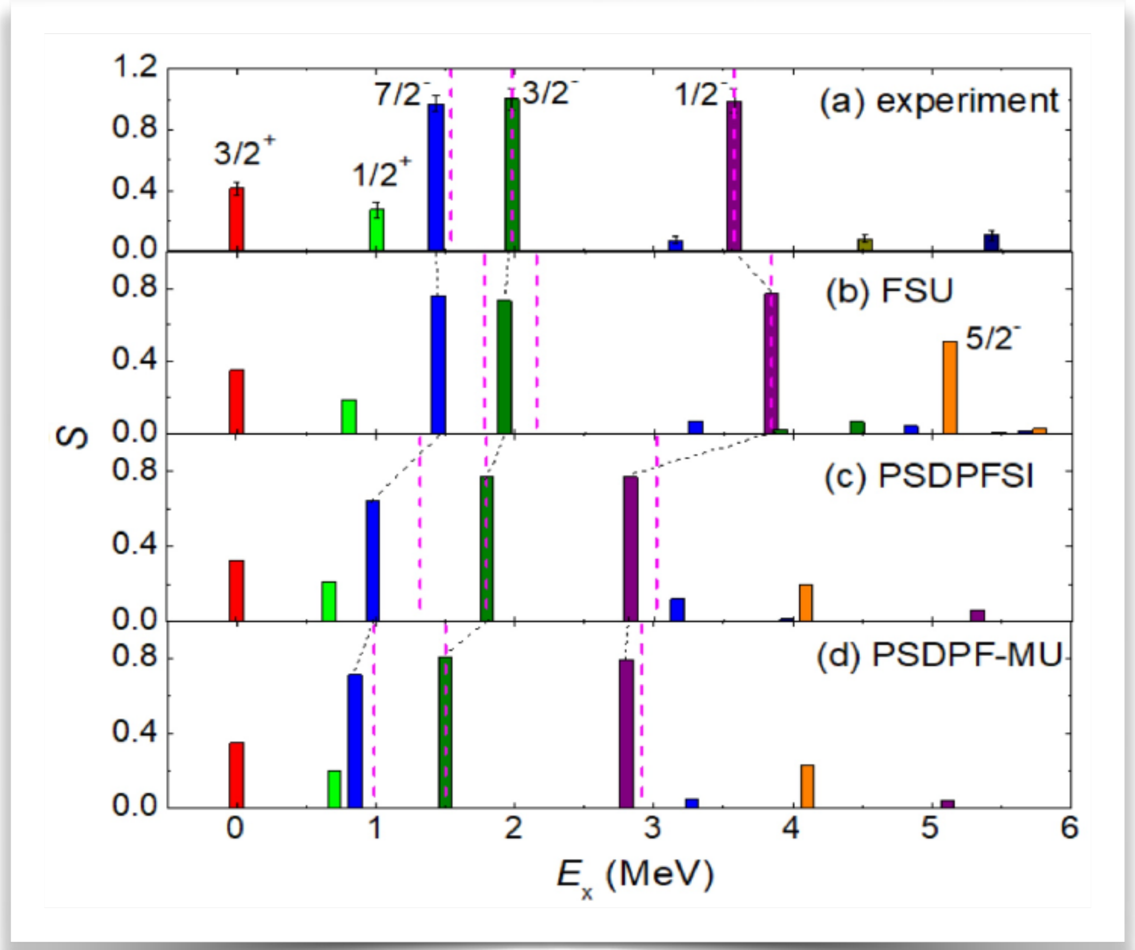
DATA & THEORY

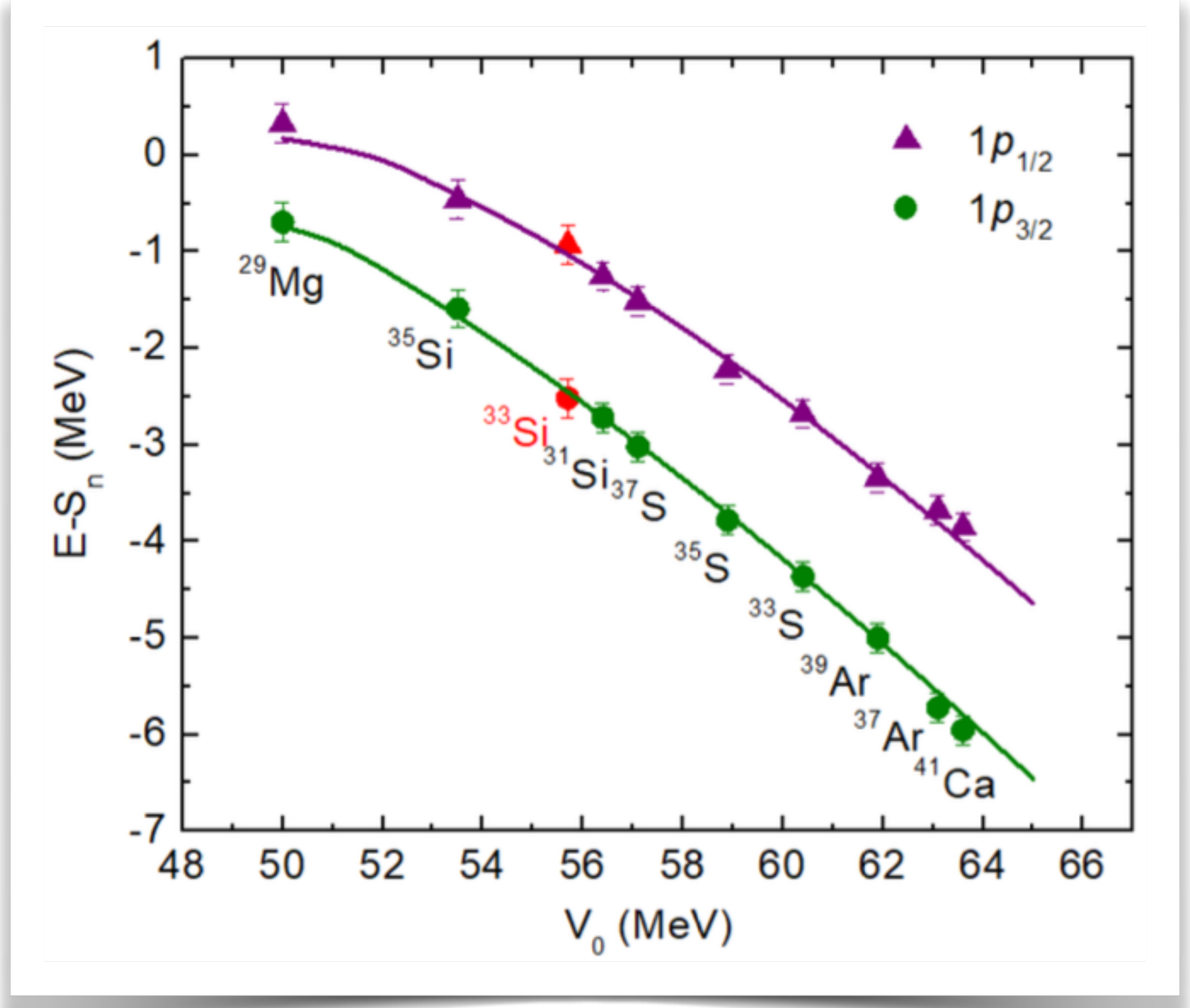
Extraction of strength distributions @ ~10 MeV/u via transfer reactions

- Example with the single-neutron adding reaction ^{32}Si(d,p)^{33}Si carried out w/ SOLARIS@ReA using a long-lived sample









Chen (2023)

Observe Q-values & yields
- determine excitation energies & differential cross section

Reaction theory [DWBA] applied to extract orbital angular momenta transfer & overlaps

Deduce strength distributions (fragmentation), occupancy, & single-particle energy centroids

Similar methods with nucleon removal & pair transfer
- key on $0^+_{1,2(3)}$ mixing, and $J^\pi = 3^- / 5^-$ population

WHAT NEW DATA CAN WE PROVIDE IN OTHER REGIONS?

Z ~ 13 - 14

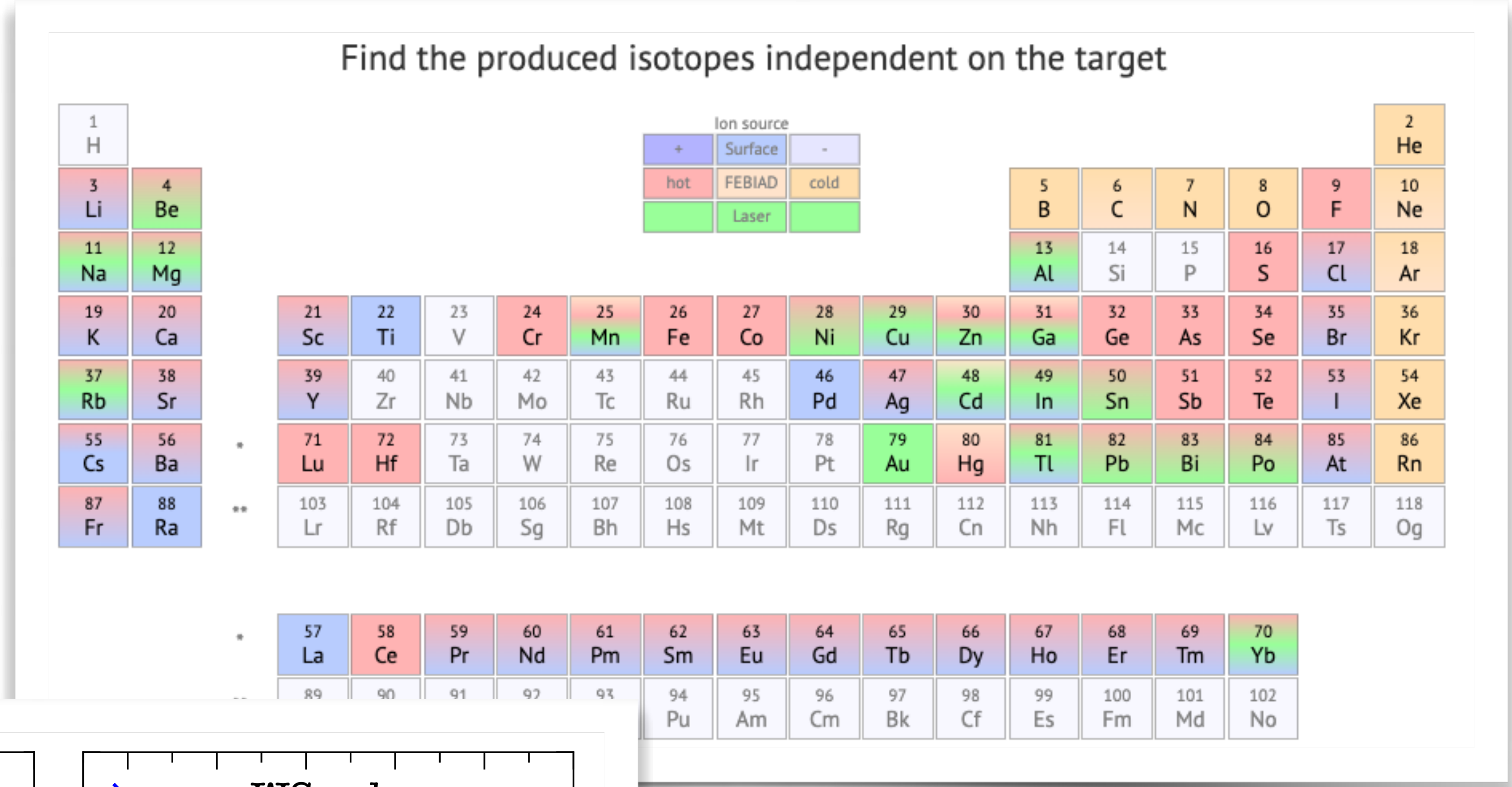
- Characterize the single-neutron energies through the N = 20 & 28 regions [tests correlations as well]
- $^{35-43}$P & $^{34-40}$Si neutron adding & removal [(d,t) & (d,p)]
- Two-neutron (pn) pairing probe [(t,p)]

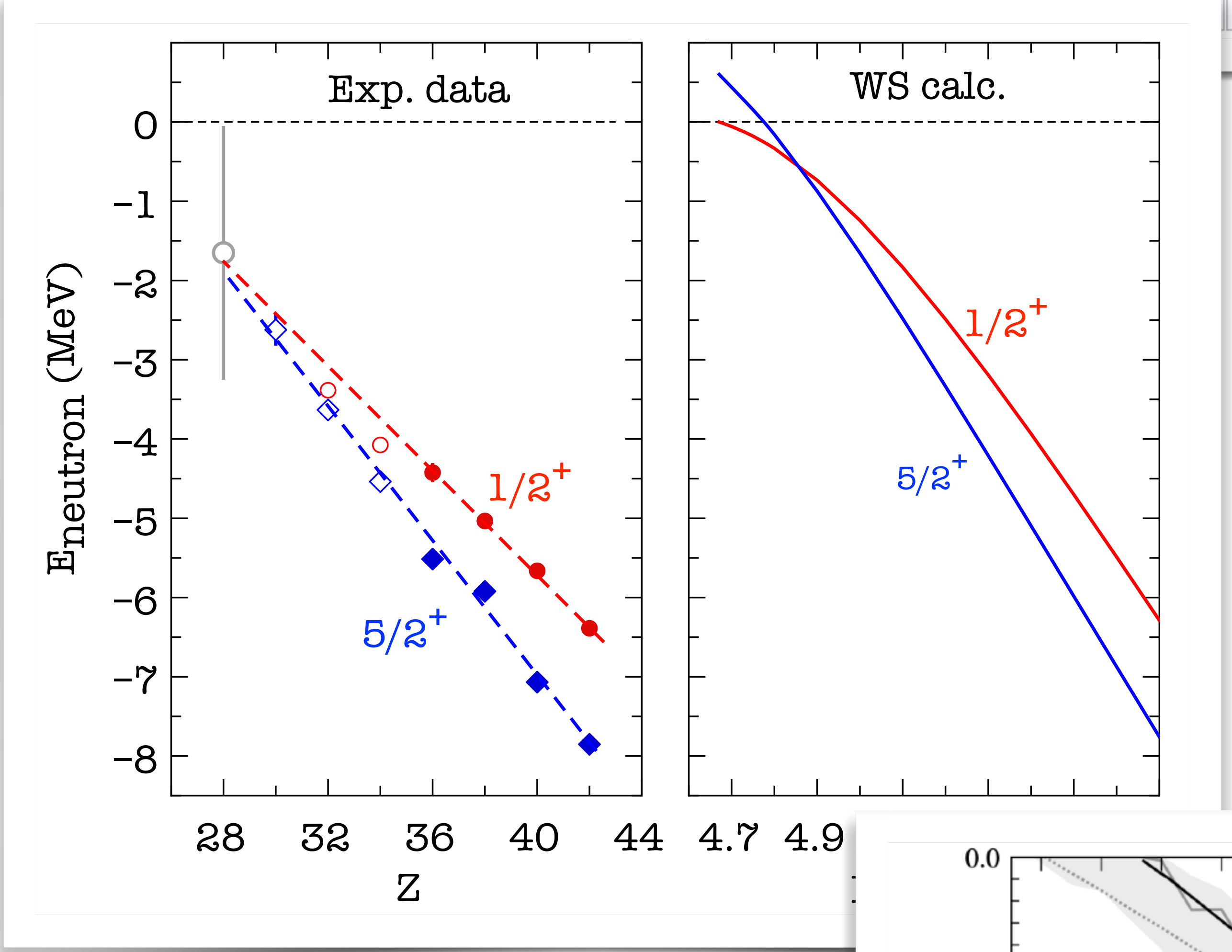
N ~ 40 & 50

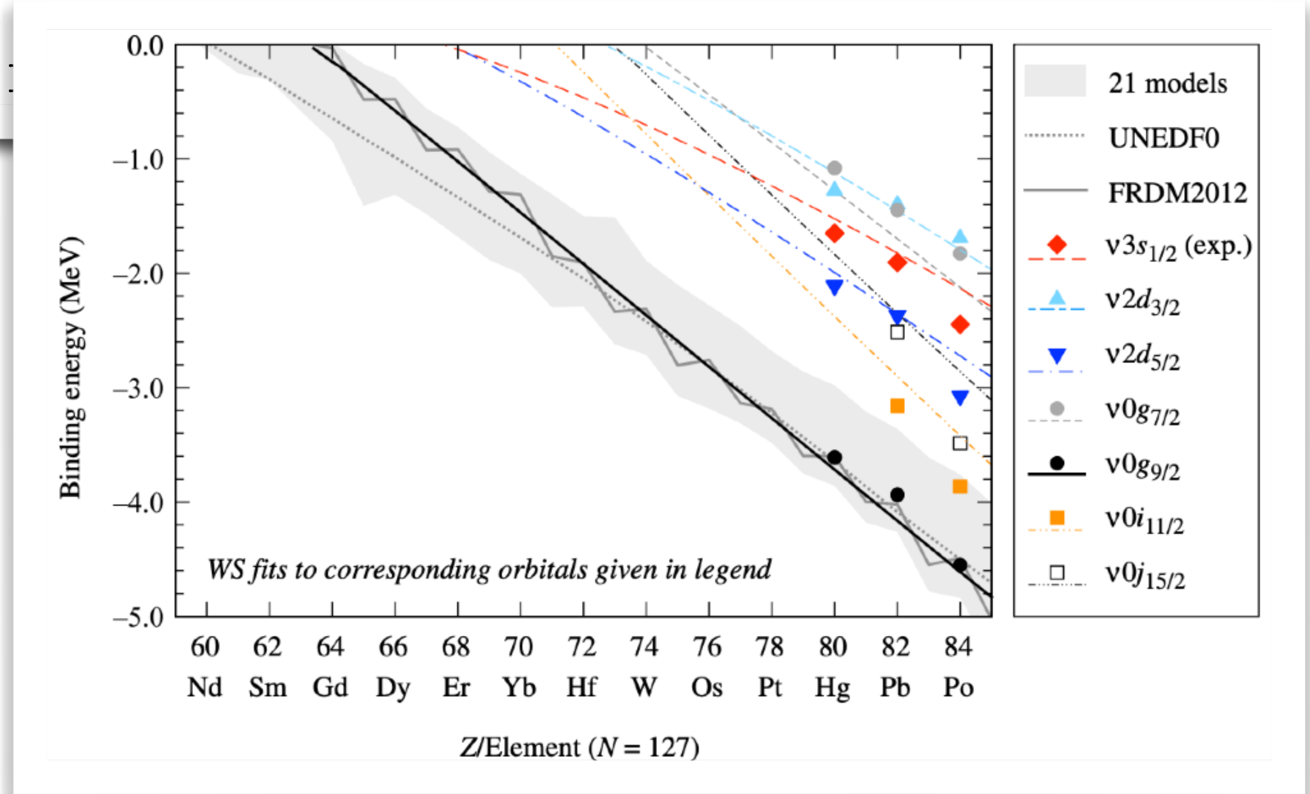
- Single-particle evolution towards ^{60}Ca & ^{78}Ni
  - Role of the s-wave on ordering & sustaining a neutron halo/skin
- ^{64}Cr - ^{66}Fe & ^{84}Se - ^{80}Zn neutron adding & removal [(d,t) & (d,p)]

N ~ 126

- Evolution of the levels south-east of ^{208}Pb
- Build upon ^{206}Hg(d,p) results from HIE-ISOLDE
- Reactions on ^{204}Pt beam







Tang PRL (2020)

Argonne NATIONAL LABORATORY

END