S.D. Pain

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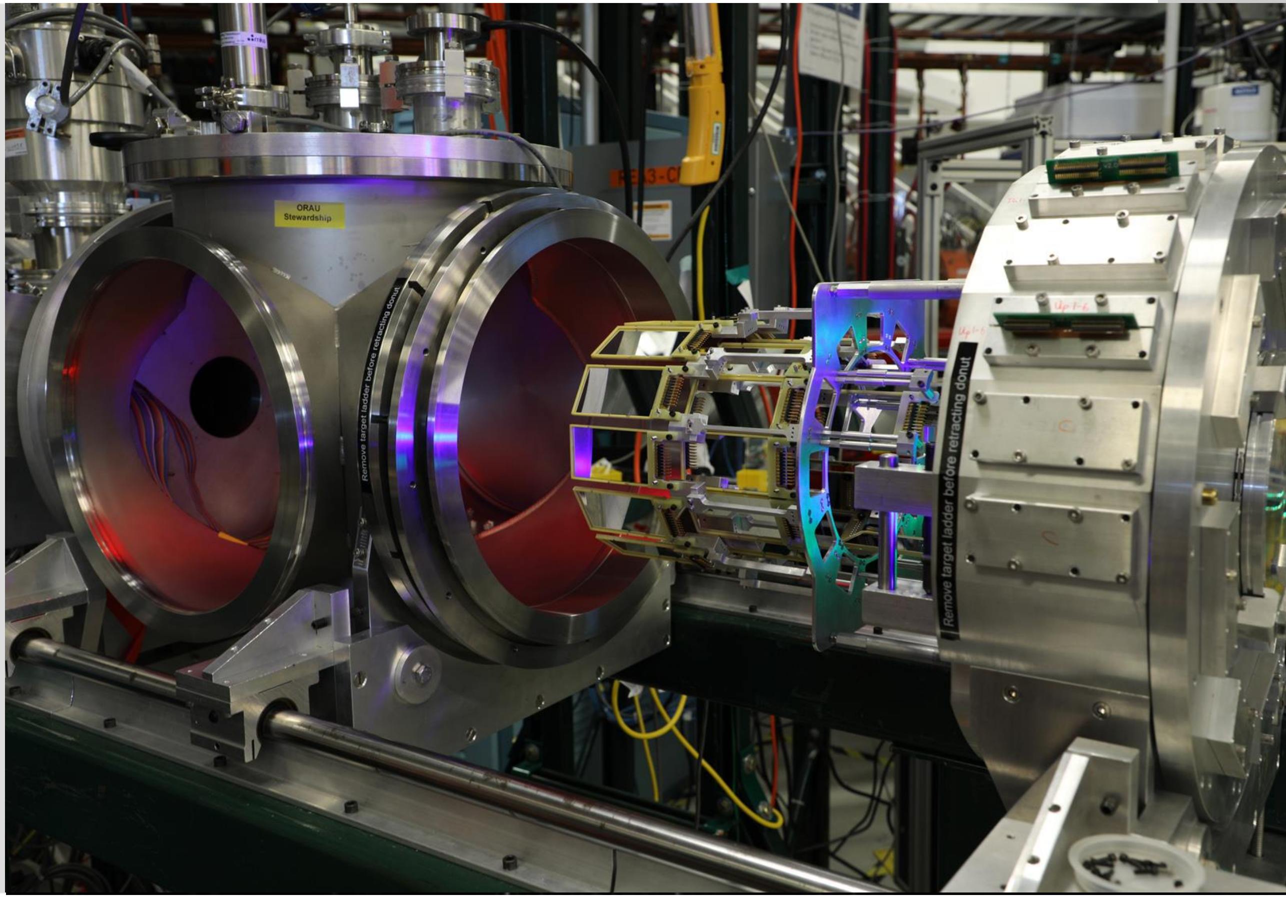
Some (selective) transfer opportunities at FRIB

- Transfer reactions for neutron capture
  - Constraining n-capture/Surrogate reactions with fast beams
- Transfer reactions on isomers
  - sd-shell nuclides
  - Constraining proton capture [(d,p) for (p,γ)]
  - Direct (α,p)
  - Comparison with SM

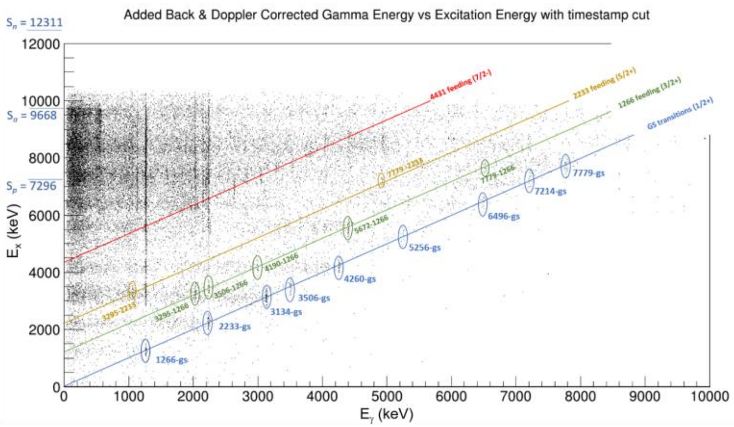


ORRUBA
Si detector array

FRIB TA Workshop, May 2023

Transfer reaction observables

- Level energies (few keV – hundreds keV, depending on reaction, beam and instrumentation)
- (Differential) cross sections
  - transferred orbital angular momenta (parity, some J)
- Decay channels of excited states
  - γ spec
  - γ/particle emission probabilities [discrete, or $P(E_x)$]
- Direct reaction analysis
  - Spectroscopic factors (C^2S)
    - Structure
    - Astrophysics
- Surrogate reactions



Selective of particle/hole states

- Stripping reactions [eg (d,p) (d,n)] probe of single-particle excitations
- Pickup reactions [eg (p,d) (d,^{3}He)] probe of hole excitations
- Spin through momentum matching (choice of probe, and beam energy)

Astrophysics

Level energies (exp. affect rates)

Spins (barrier penetrabilities – ell, not J, most important)

C^2S

Constraints on LD/GSF – eg SRM

Preferentially populates particle excitations (depending on WF, may or may not see via other probes – beta decay, KO, etc)

Branching ratios

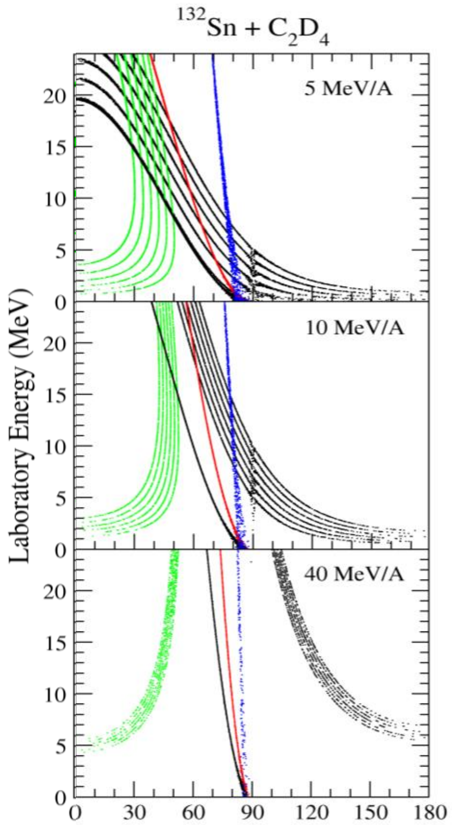
Though direct measurements are goal, need to discover important states first by some other means

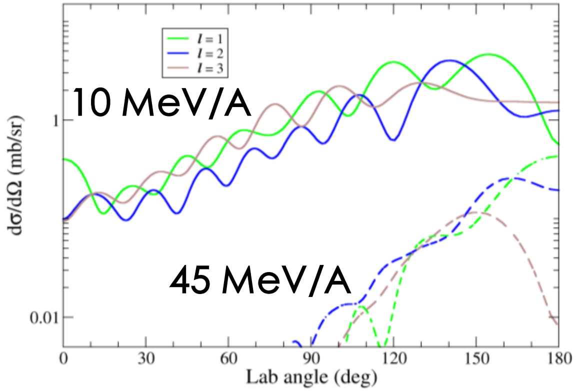
Transfer reactions at FRIB

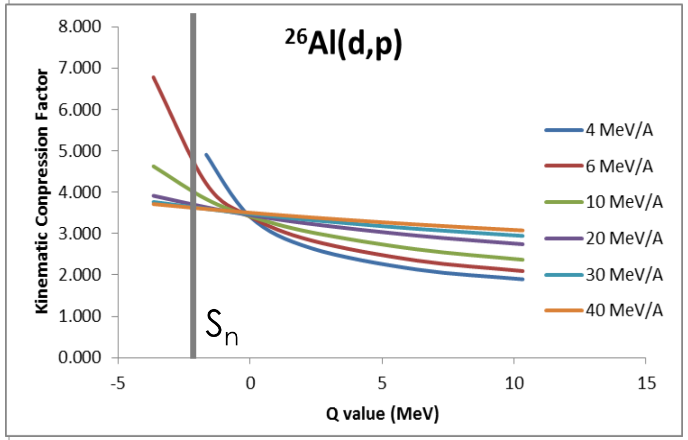
Beam energy ~3-50 MeV/A

- Cross sections (absolute and differential)
- Beam intensity
- Kinematic compression
- Beam optics
- Special cases…

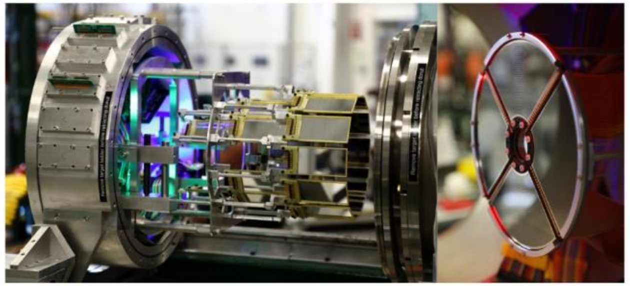
Cannot cover all – restrict to few examples of FRIB specific opportunities





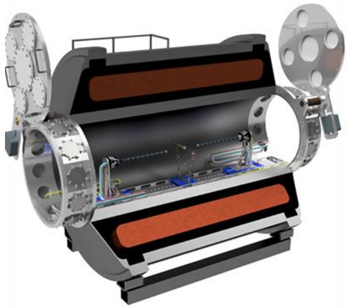


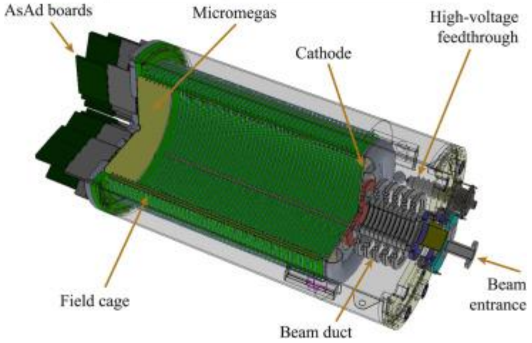
Detectors at FRIB



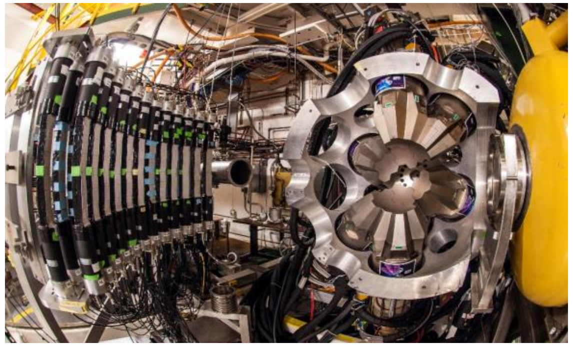
Charged-particle arrays (*HiRA, ORRUBA, …*)

Si+Solenoid arrays (*SOLARIS, HELIOS, ISIS*)

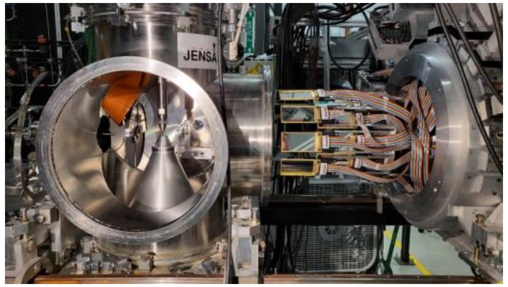




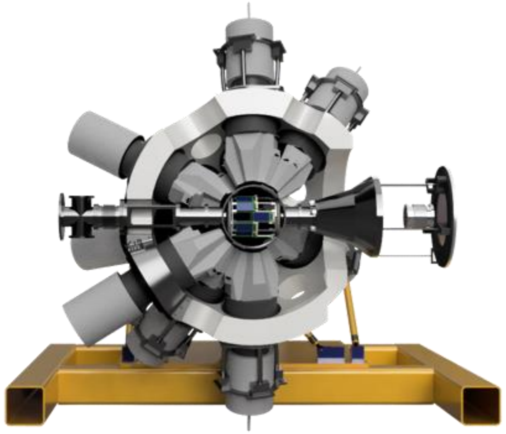
Active targets (*ATTPC*)



n arrays (*VANDLE. LENDA, NEXT, ODeSA, …*)



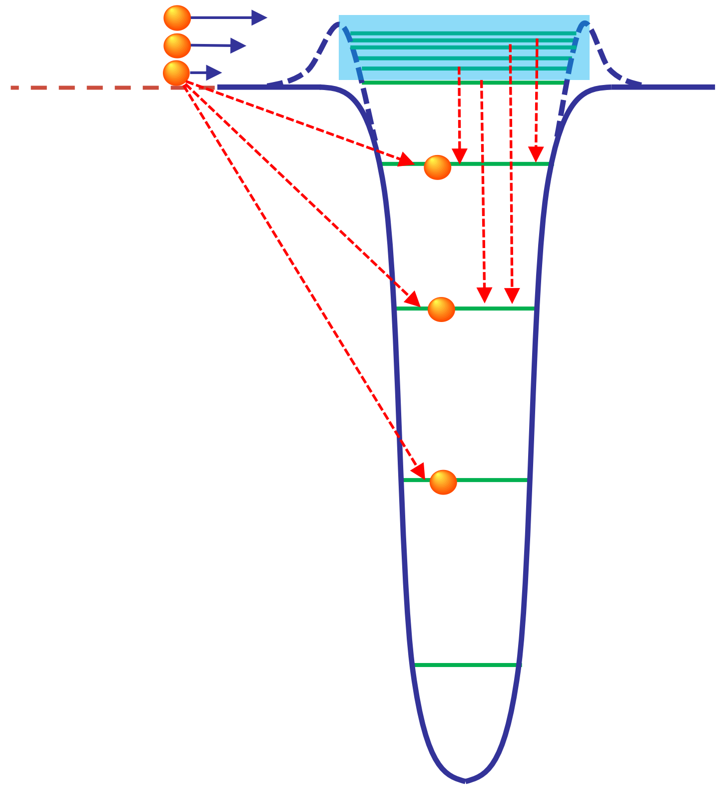
Gas jet targets (*JENSA*)

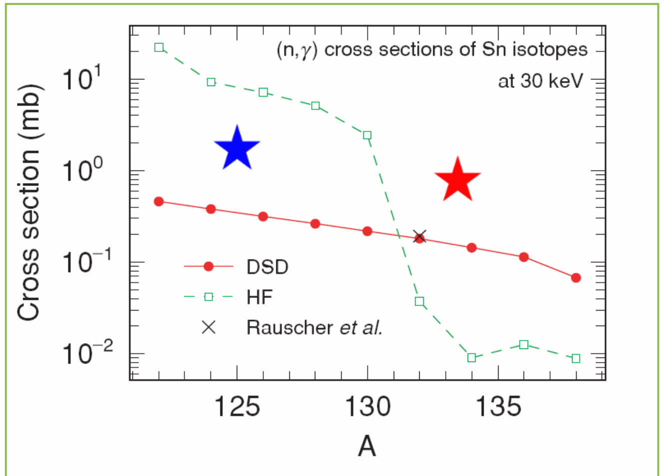


Ge arrays (*GRET(IN)A, SeGA, Clovers,…)*

Devices often coupled to recoil separators (S800, SECAR, ISLA)

Constraining neutron-capture cross sections



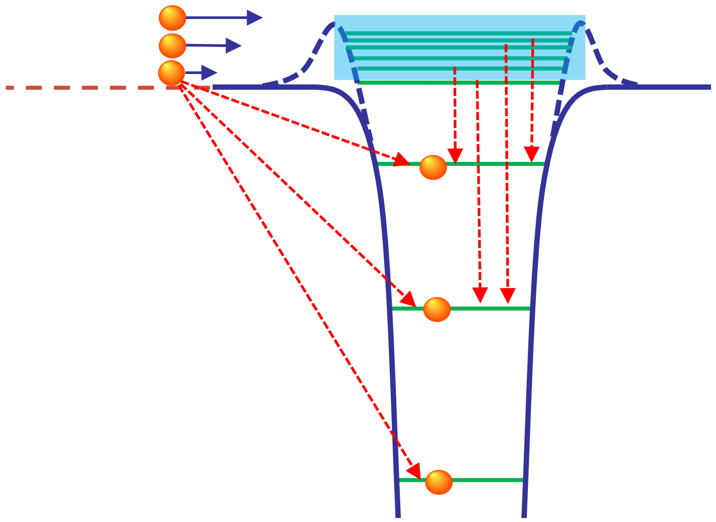


- Neutron capture can occur via resonances (eg compound nucleus formation), and direct capture to bound states
- Depending on neutron level density/strong resonances, one or other may be dominant
- In general, need methods to constrain *both* mechanisms

Neutron transfer reactions

- Selective (states with target+n wavefunctions)
- Give properties of bound states and isolated resonances (E, J^{π}, C^2S)
  - for DSD
  - Constrain structure models
- Can be used as surrogate for CN capture (SRM)

Constraining neutron-capture cross sections



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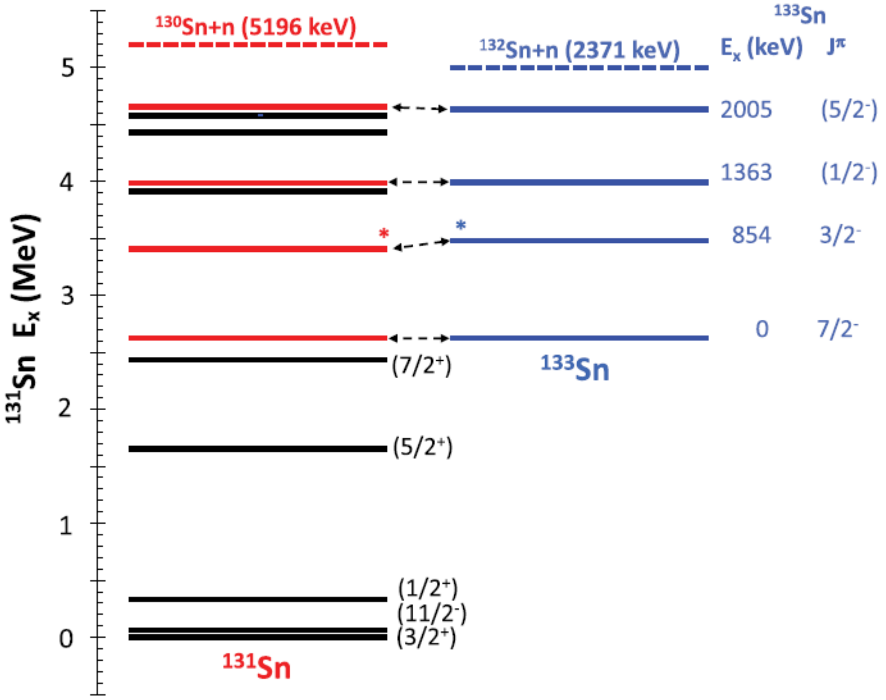
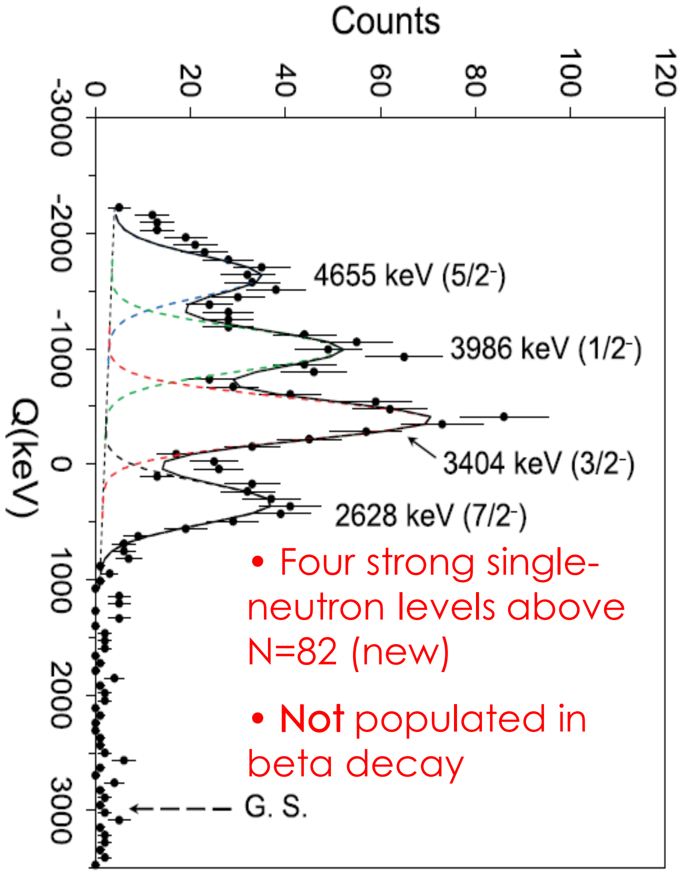
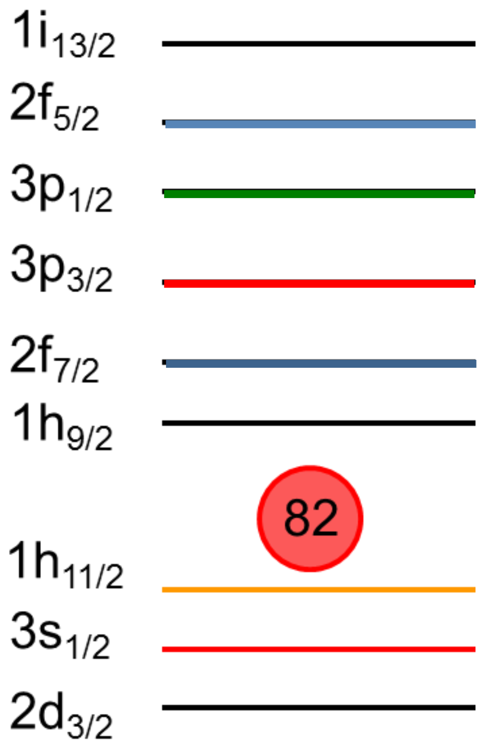


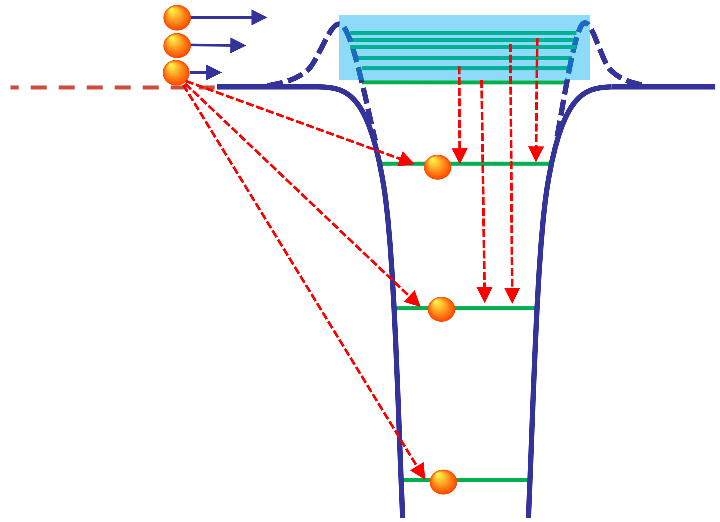


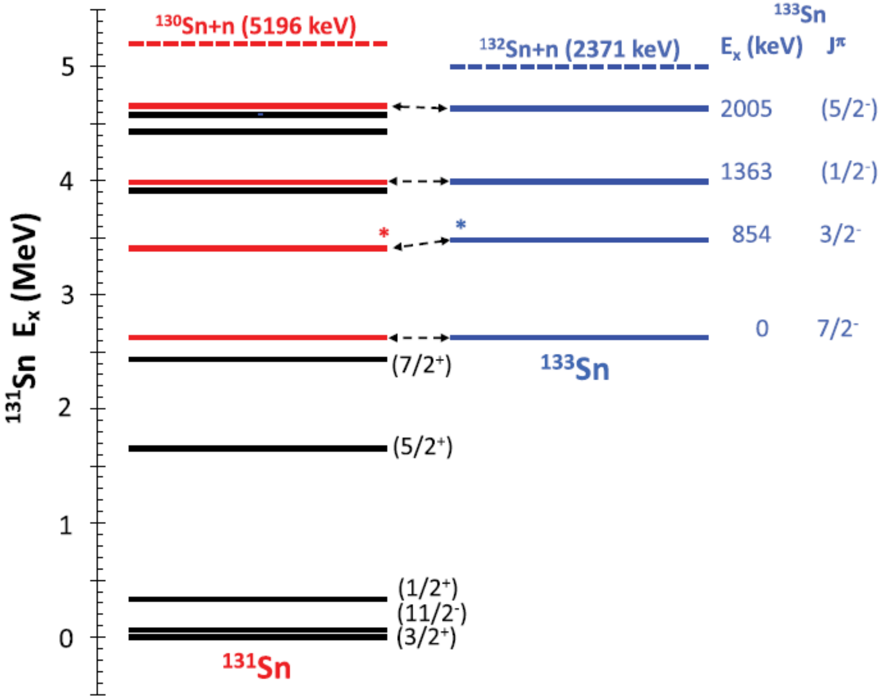
R.L. Kozub *et al*, PRL **109** 172501 (2012)

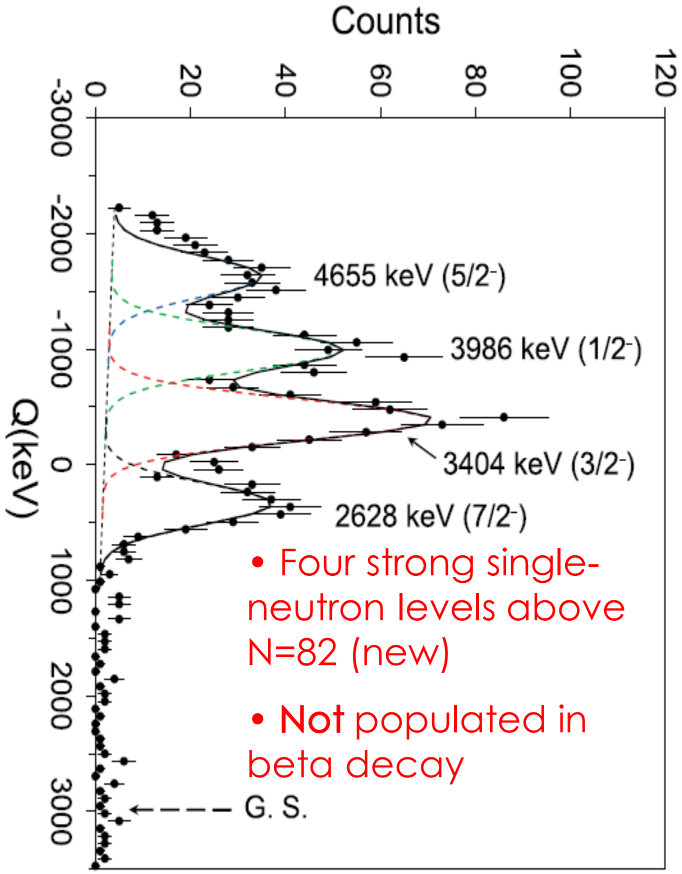


Constraining n-capture cross sections - DSD

- Neutron capture can occur via resonances (eg compound nucleus formation), and direct capture to bound states
- Depending on neutron level density, one or other may be dominant
- Ideally need methods to constrain *both* mechanisms







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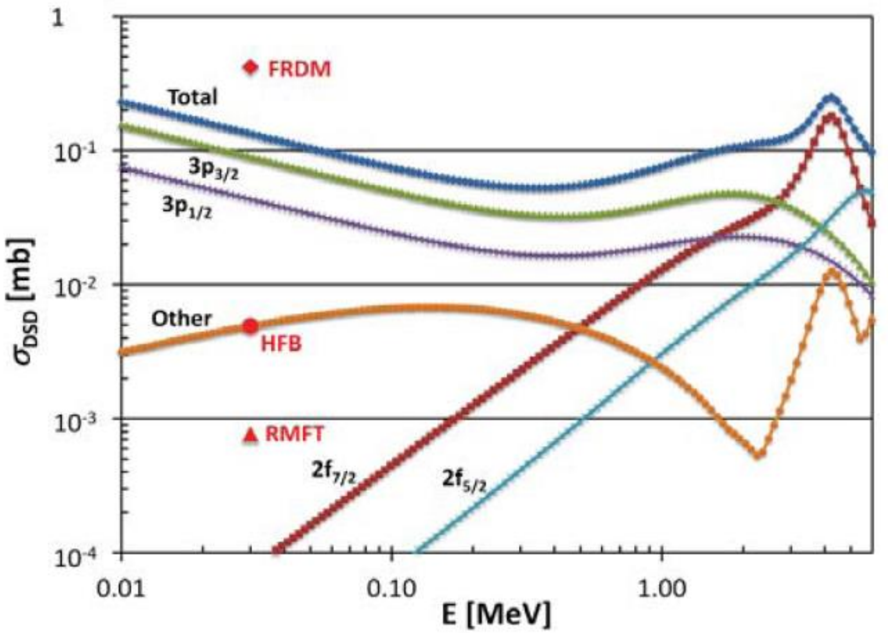
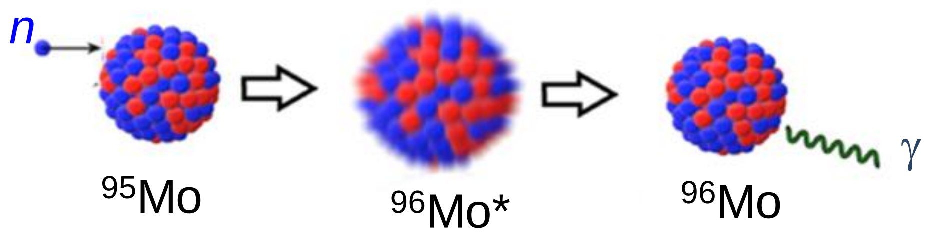


Constraining CN n-capture cross sections - SRM

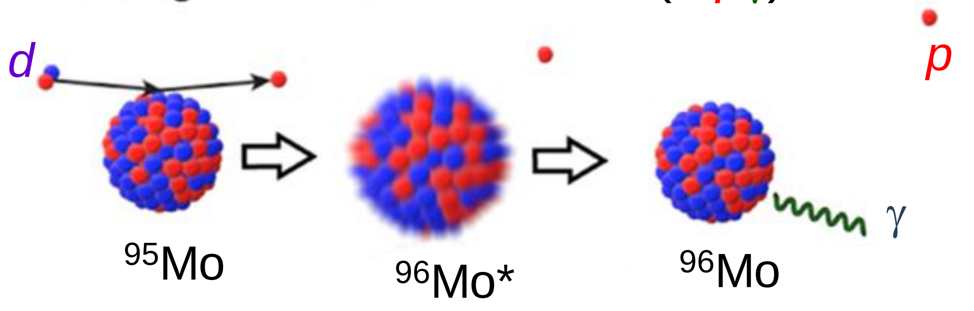
Desired Reaction $^{95}Mo(n,\gamma)^{96}Mo$



$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E_x,J,\pi) G_\gamma^{CN}(E_x,J,\pi)$$

- Model reaction in HF formalism
- Essential theory components:
  - Formation of CN (σ^{CN}) – simple
  - Decay of CN (G^{CN}) – complicated (Escher)
  - *Need to place experimental constraints on G^{CN}*

Surrogate Reaction $^{95}Mo(d,p\gamma)^{96}Mo$



$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta) G_\gamma^{CN}(E_x,J,\pi)$$

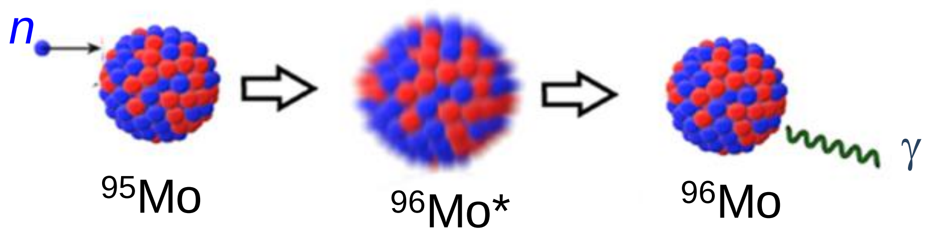
A surrogate reaction forms the "same"* compound nucleus as the desired reaction

- Model experimentally-determined $P_{p\gamma}(E_{ex})$ in HF formalism to constrain G^{CN}
- Essential theory components:
  - Decay of CN (G^{CN}) – complicated (Escher)
  - *Entry spin distribution (F^{CN}) – complicated (Potel)

Figures and equations adapted from J.E. Escher *et al.* Rev. Mod. Phys. **84,** 353 (2012).

Constraining CN n-capture cross sections - SRM

Desired Reaction $^{95}Mo(n,\gamma)^{96}Mo$



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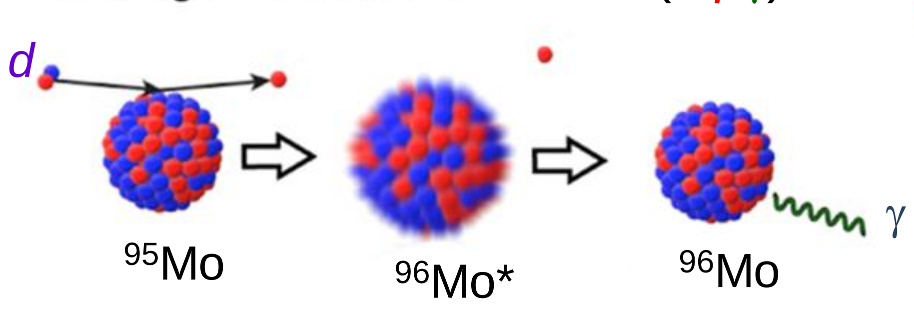
Surrogate Reaction $^{95}Mo(d,p\gamma)^{96}Mo$



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- Model reaction in HF
- Essential theory comp
  - Formation of CN (σ^{CN}) -
  - Decay of CN (G^{CN}) – c (Escher)
  - *Need to place experi constraints on G^{CN}*

forms the "same"* as the desired reaction

ally-determined lism to constrain G^{CN}

mponents:

– complicated (Escher)

on (F^{CN}) – complicated

Core experimental technique

- Measure outgoing particles, using kinematics to determine entrance E_x above S_n
- Measure γ rays to determine $P_{p\gamma}$
- Typically requires either a collecting transition, or an understanding of the γ decay scheme

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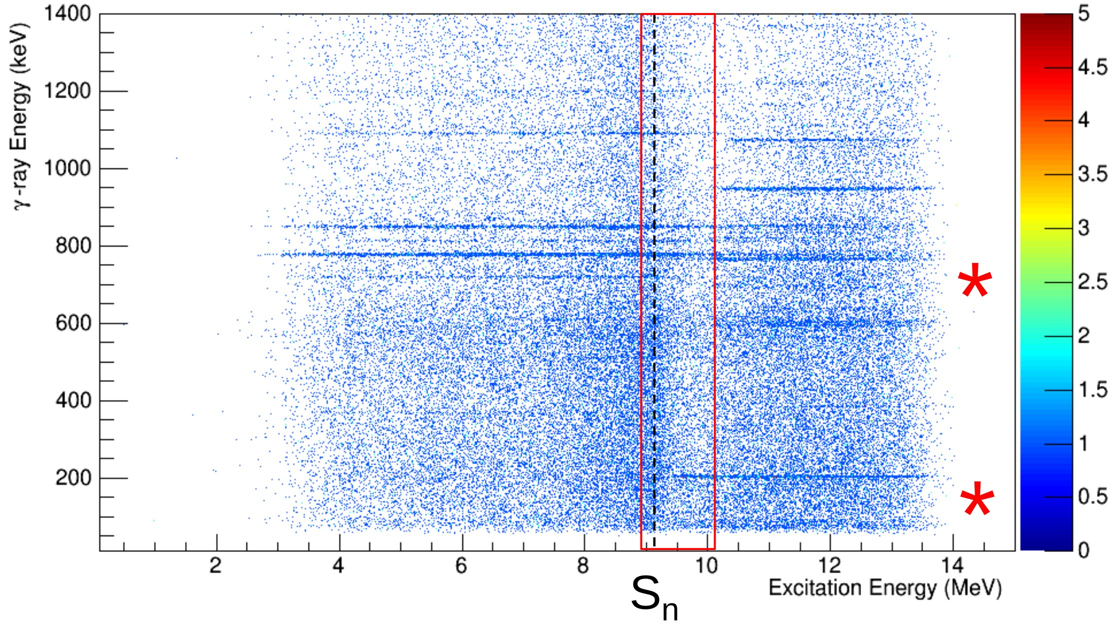
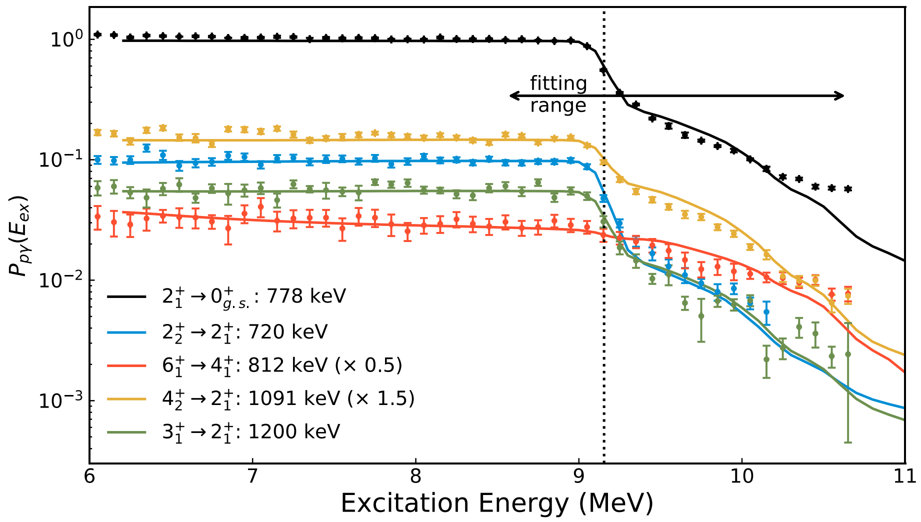
Figures and equations adapted from J.E. Escher *et al.* Rev. Mod. Phys. **84,** 353 (2012).

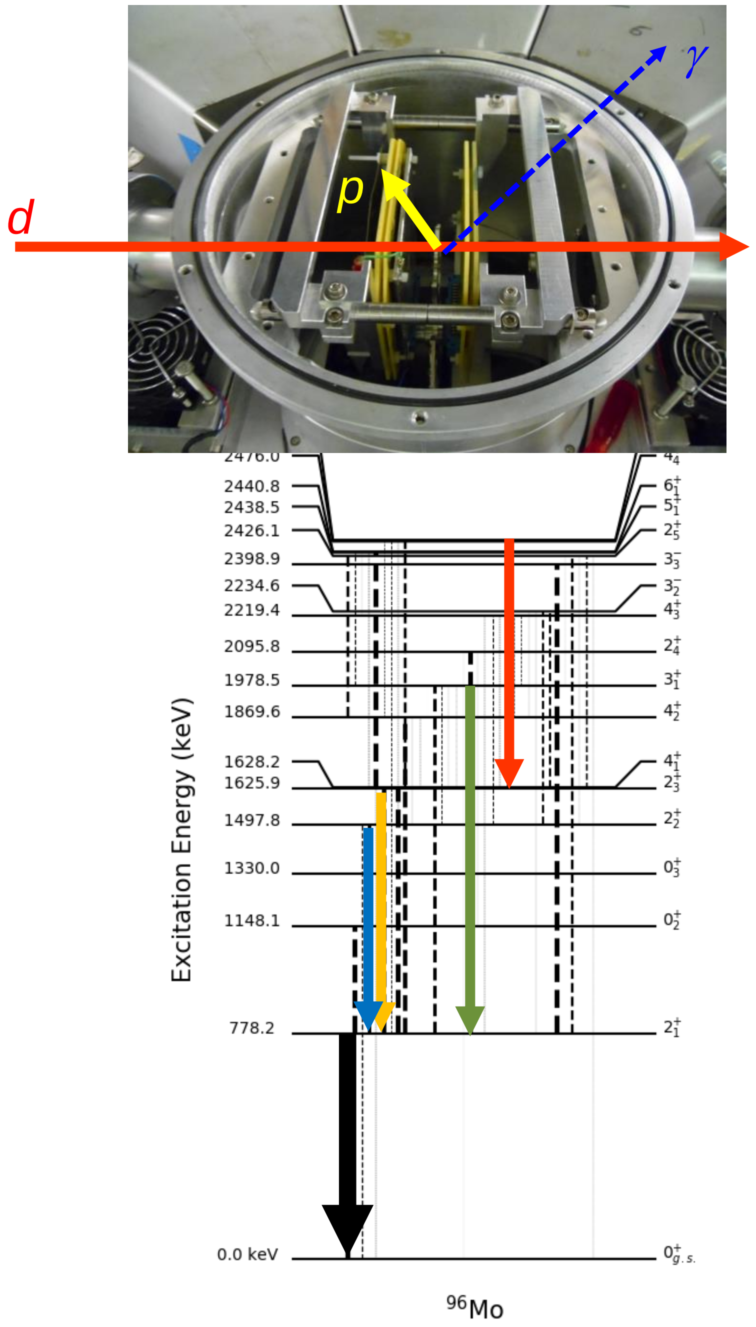
(d,p) as surrogate for (n,γ)

Ratkiewicz et al., Phys. Rev. Lett. **122**, 052502 (2019)

Experimental signature







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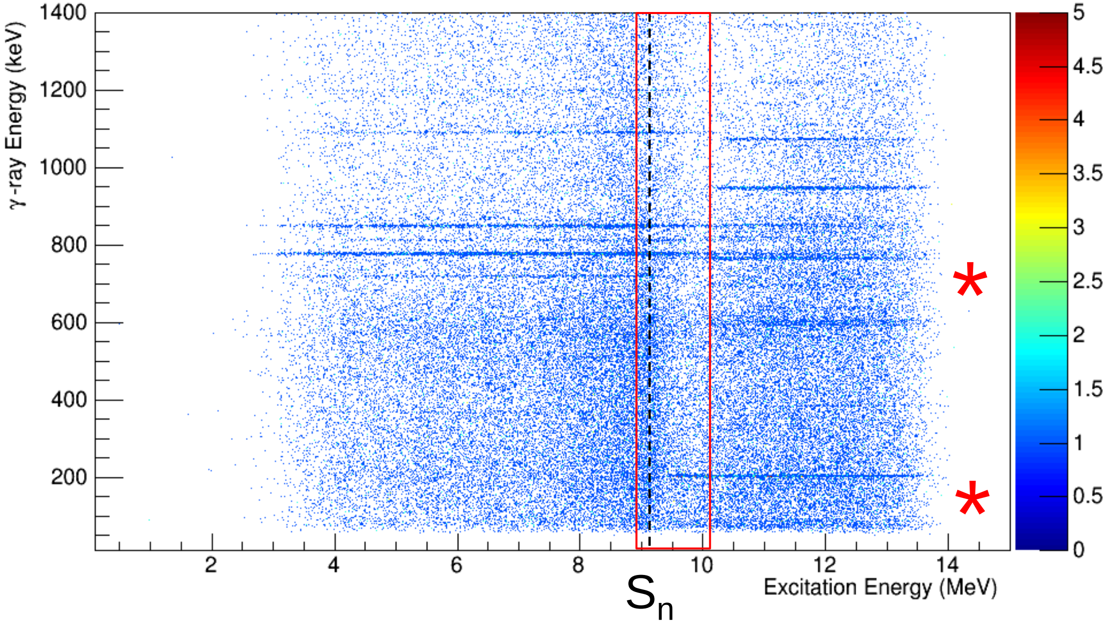

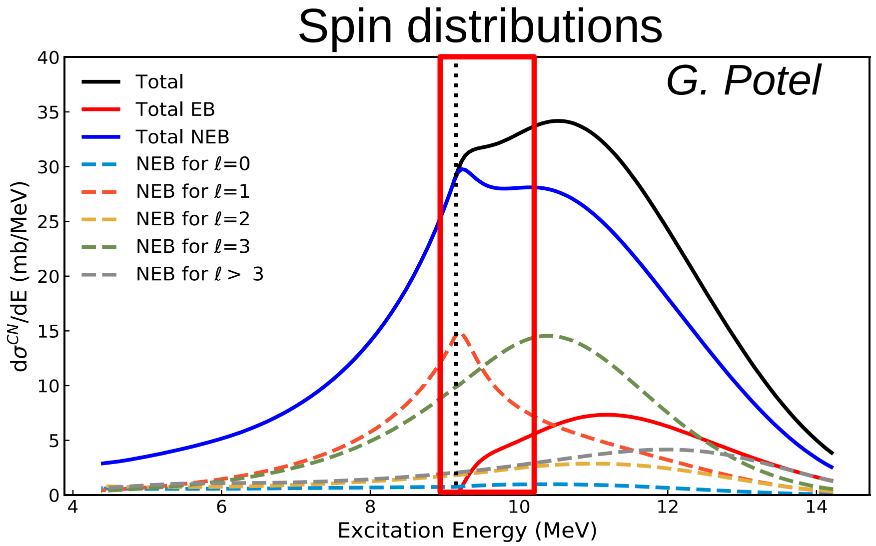

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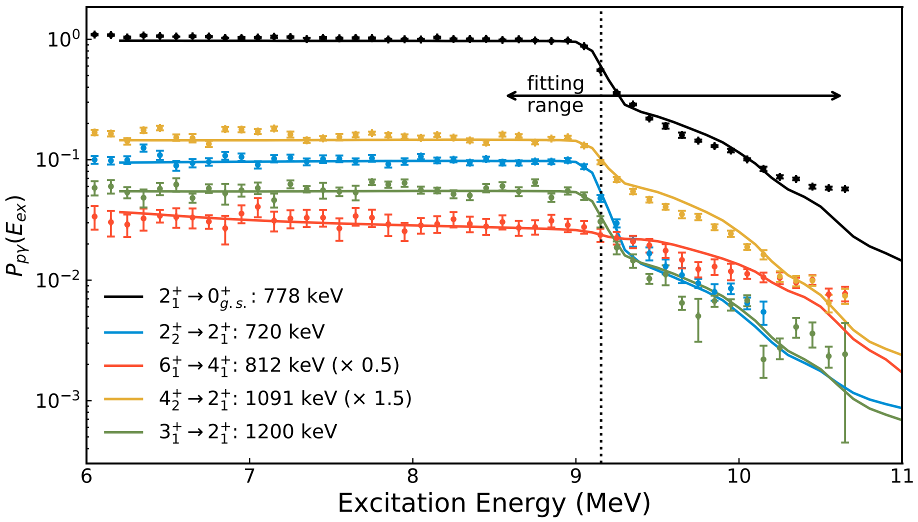
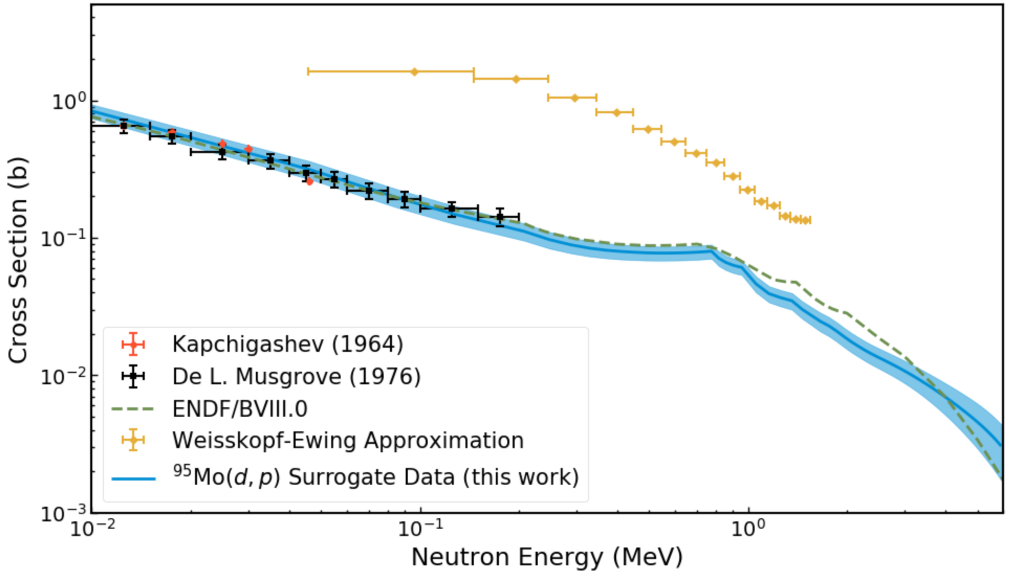
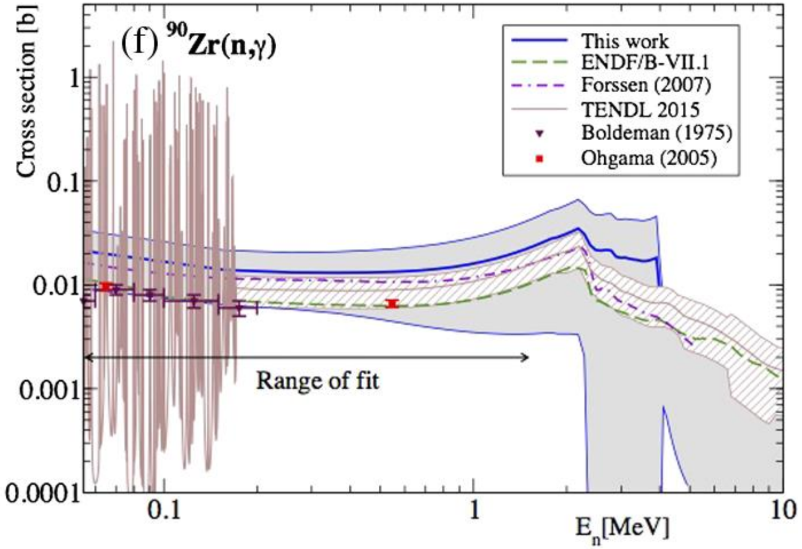




SRM outlook…

- SRM Progress
  - Validation of (d,pγ) as surrogate for (n, γ)
    - understanding J^{π} formation distributions key ingredient
  - Development of (p,d) as (n, γ) surrogate

J.E. Escher *et al.*, PRL **121** 052501 (2018)



  - Ongoing development of (p,p') as (n, γ) surrogate
  - What are the limits of the statistical approach…
  - More from Jutta next week…

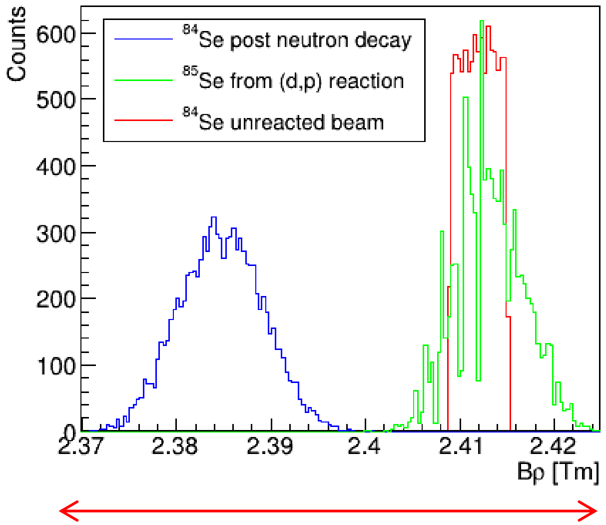
Expt. challenges moving to RIB experiments

- Resolution (target thickness, kinematic compression) (~100 keV –> 500-1000 keV)
- Contaminants (eg carbon in target – however, only need to address this 'once' – not a surprise every time)
- Luminosity (beam intensity) – statistics-limited measurements
- Limitation on nuclides that can be practically studied
  - Nuclides without a reasonably-collecting transitions are very challenging - complex γ decay schemes disperses strength over numerous γ transitions
  - Isomers (moving with beam) lead to unobserved gamma emissions

An alternative technique – uniquely suited to FRIB…

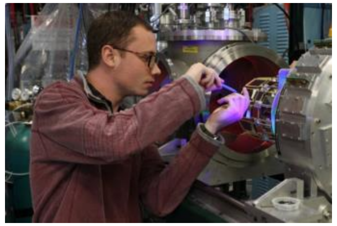
A new technique with RIBs

Developed in NSCL
$^{84}Se(d,p)^{85}Se$ experiment



...detect the recoiling nucleus to determine if decayed by n or γ

Use charged-particle [e.g (d,p)] to determine the formation E_x(as before)



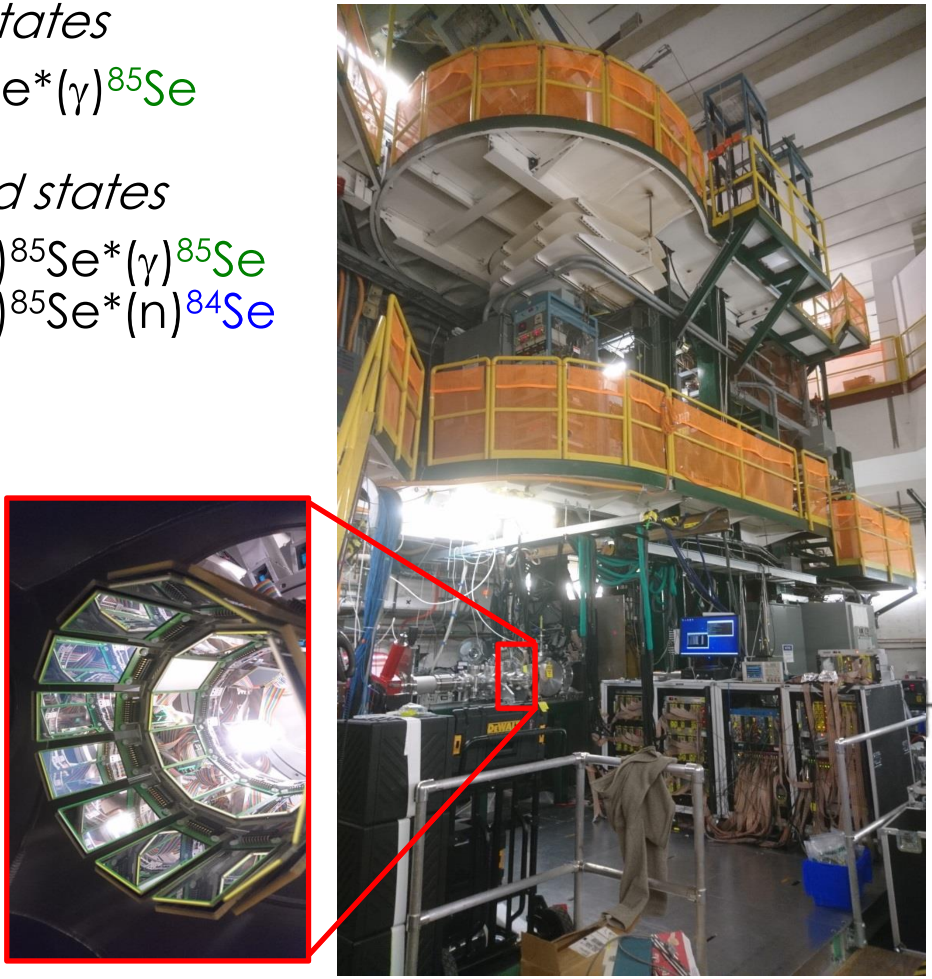
H. Sims, S.D.Pain, J.A. Cizewski, A. Ratkiewicz, et al.,

To bound states

$^{84}Se(d,p)^{85}Se^{*}(\gamma)^{85}Se$

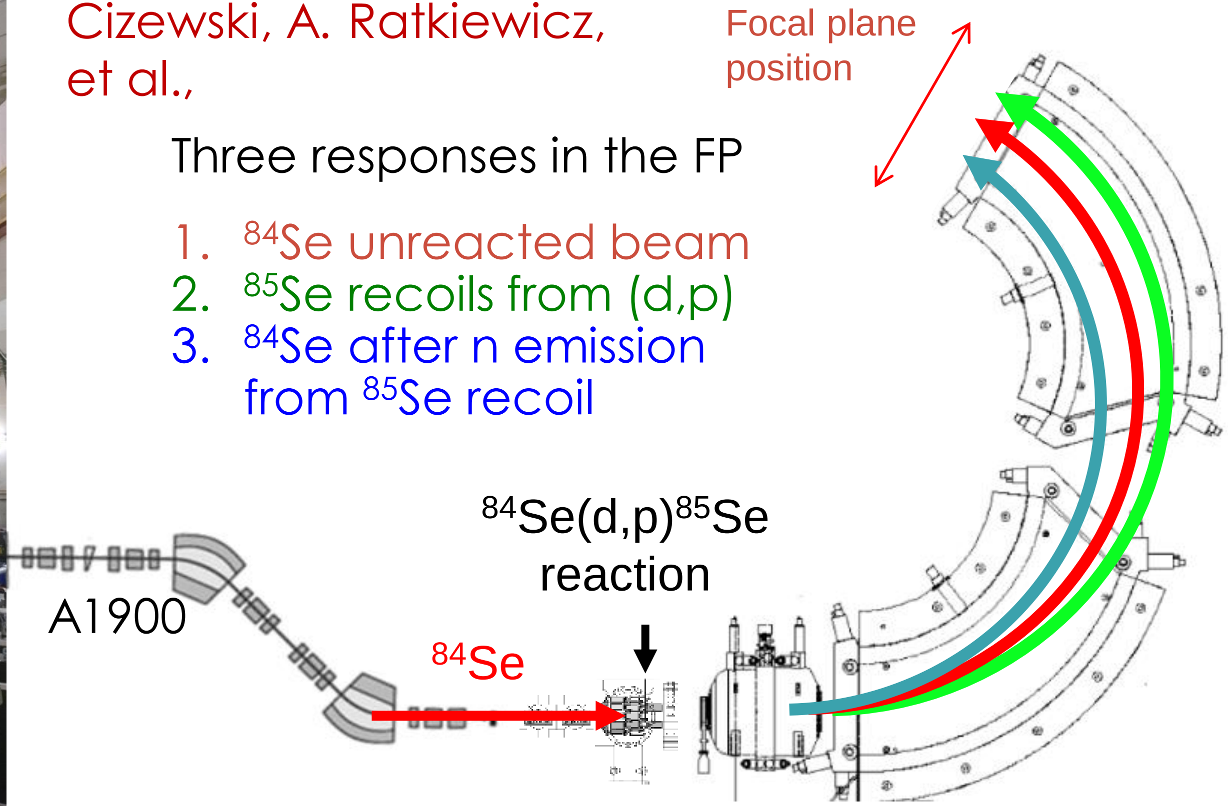
To unbound states

- $^{84}Se(d,p)^{85}Se^{*}(\gamma)^{85}Se$
- $^{84}Se(d,p)^{85}Se^{*}(n)^{84}Se$



Three responses in the FP

1. ^{84}Se unreacted beam
2. ^{85}Se recoils from (d,p)
3. ^{84}Se after n emission from ^{85}Se recoil



A new technique with RIBs

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^{84}Se(d,p)^{85}Se experiment

...detect the recoiling nucleus to determine if decayed by n or γ

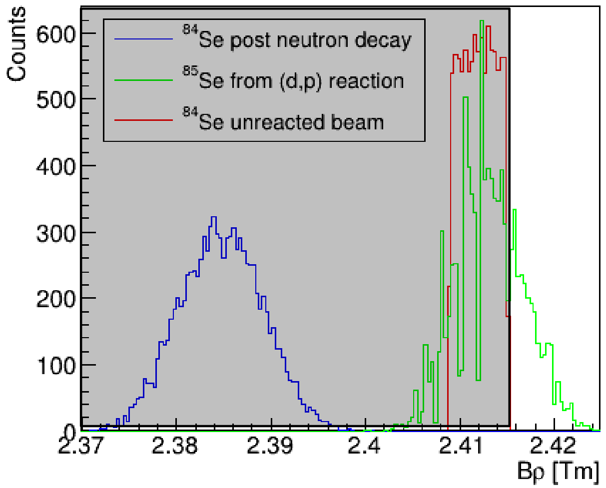
Use charged-particle [e.g (d,p)] to determine the formation E_x(as before)

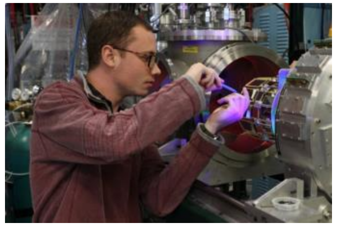
To bound states

^{84}Se(d,p)^{85}Se*(γ)^{85}Se

To unbound states

- ^{84}Se(d,p)^{85}Se*(γ)^{85}Se
- ^{84}Se(d,p)^{85}Se*(n)^{84}Se





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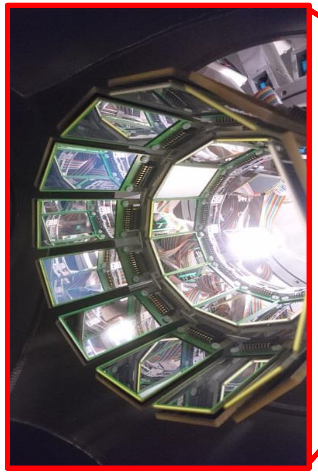

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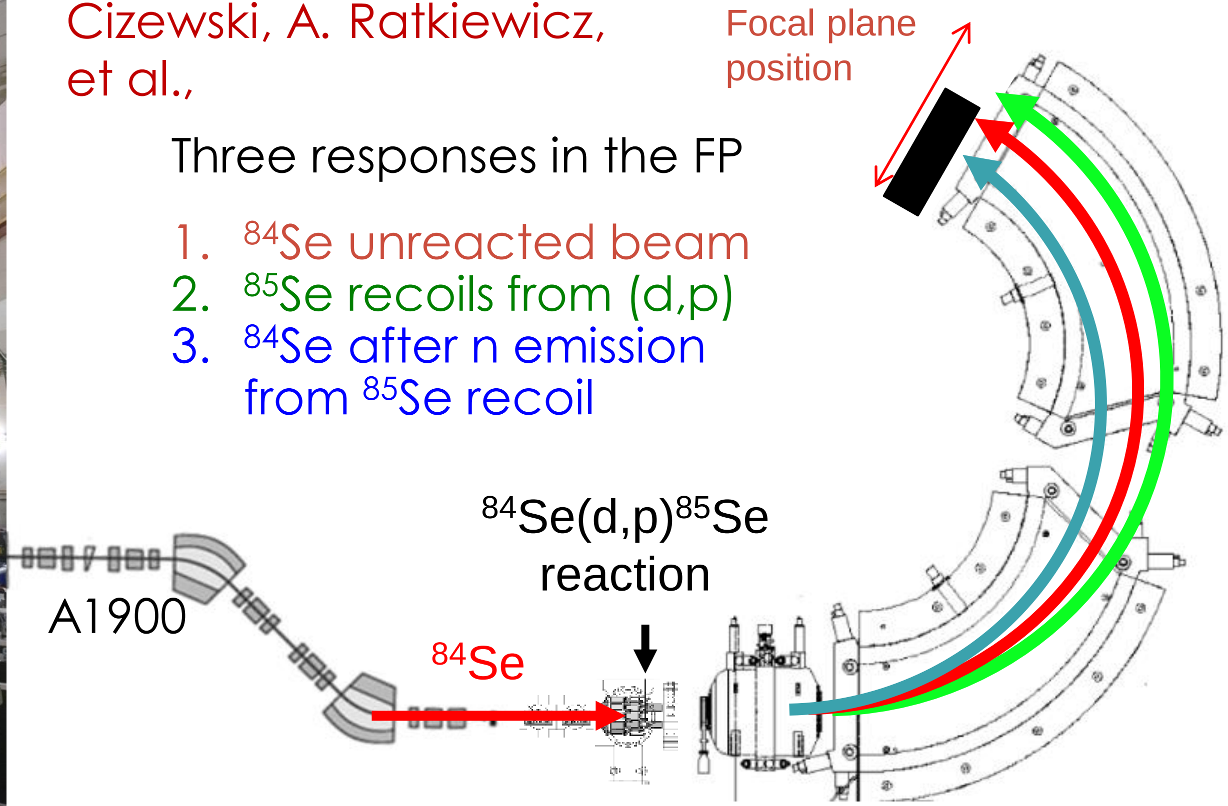
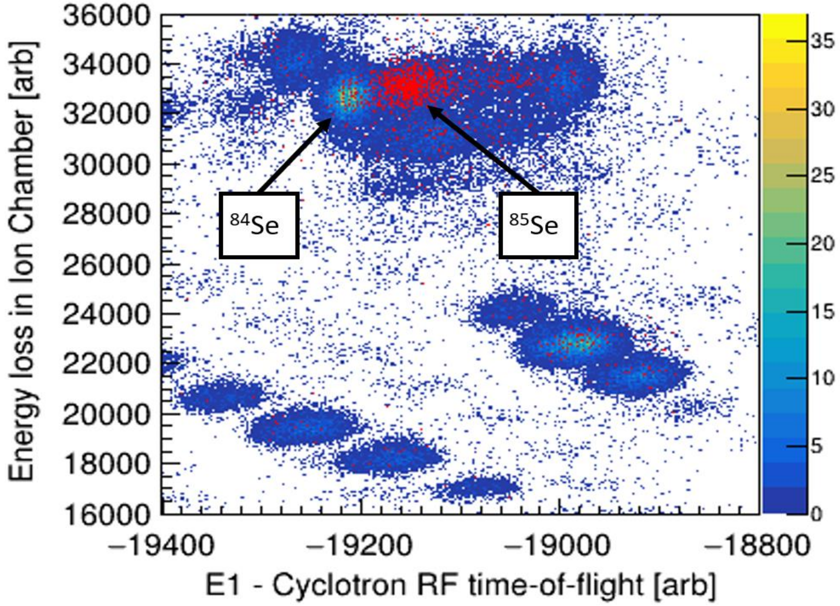


An alternative with RIBs…



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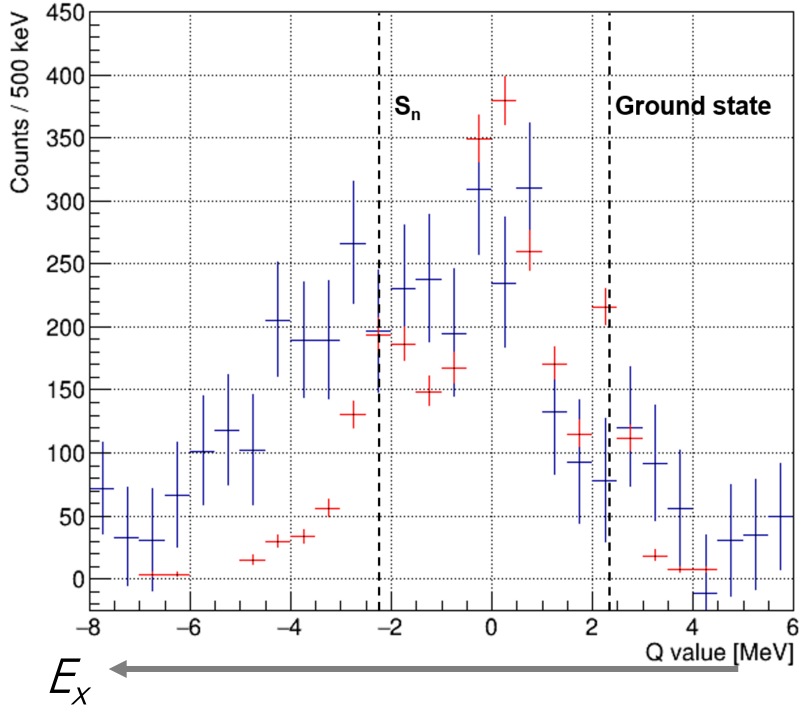
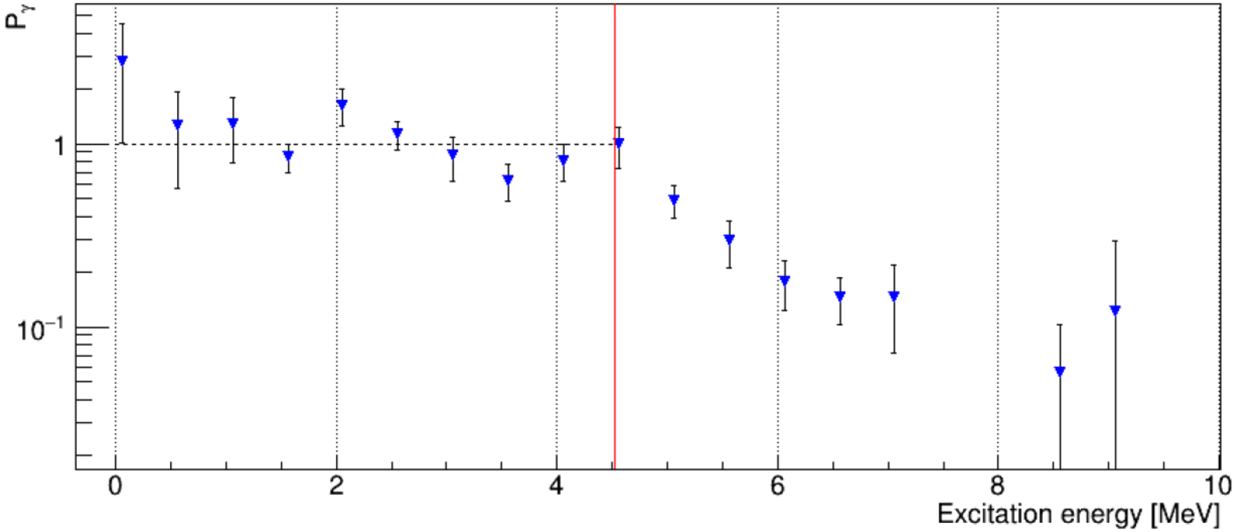


Advantages

- concentrates all statistics in a single observable
- high (25-50%), simple and experimentally-determinable detection efficiency (cf γ cascades)
- Enables measurements on (almost) any nucleus on same footing

Challenges

- need careful characterization of BG reactions on C in target



Work ongoing with Jutta to extract (n,γ) cross section

Unique opportunity at FRIB

Combination

- FRIB n-rich beams
- S800
- GODDESS [ORRUBA+GRET(IN)A]

Two approved experiments

- ^{80}Ge (Sims, Grinder, Cizewski, Pain, et al) – *weak r process*
- ^{75}Ga (Pain, Balakrishnan, et al) – *i-process*

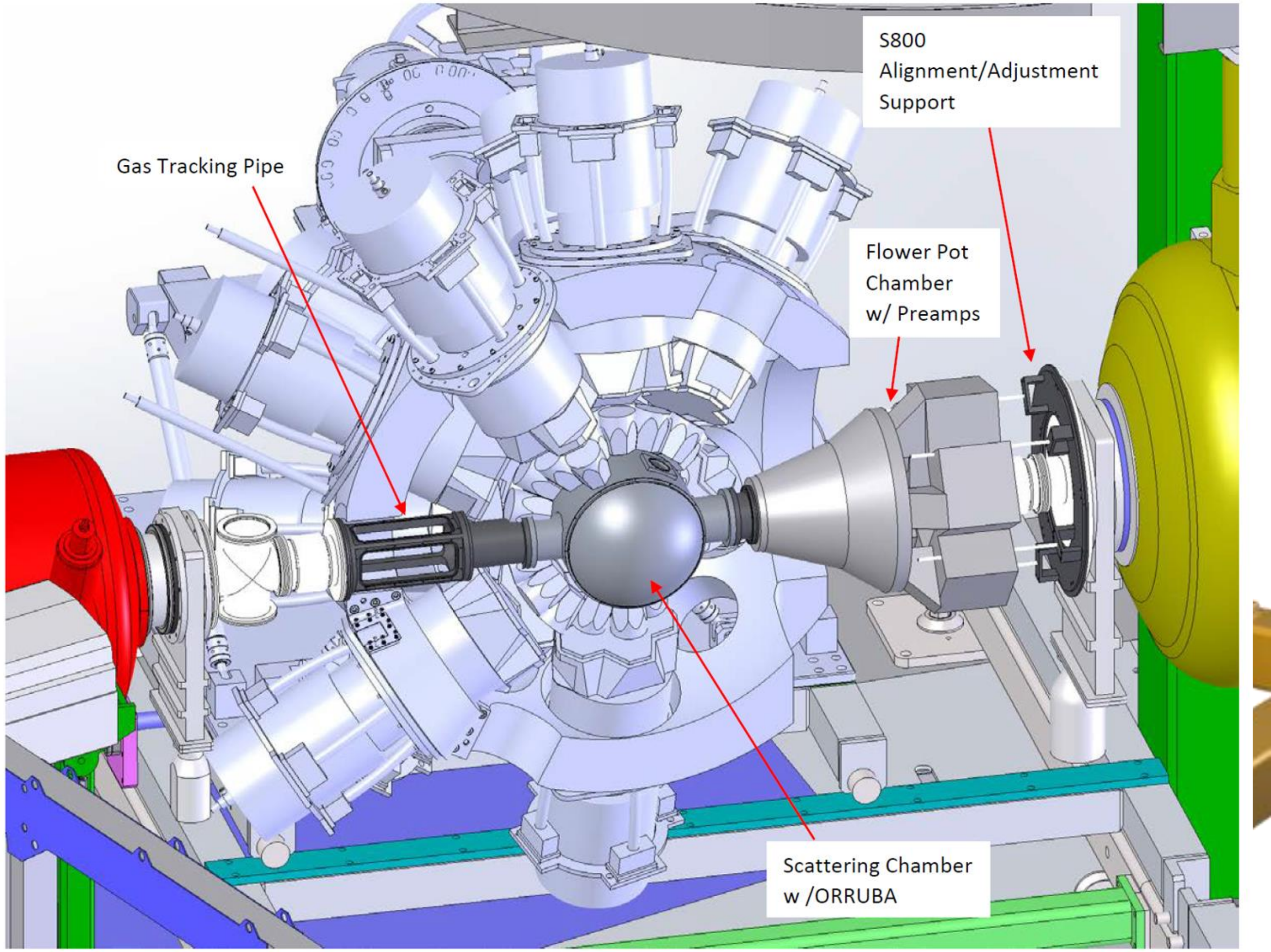
Cannot measure all; target specific interesting cases

Ideally like to have (empirical) predictive model of (n,γ) cross sections

- Model constrained by experiment in sensitive cases?

Detect ***protons, gammas and recoils***

- Discrete particle-γ spectroscopy
- SRM with recoils
- SRM with γ



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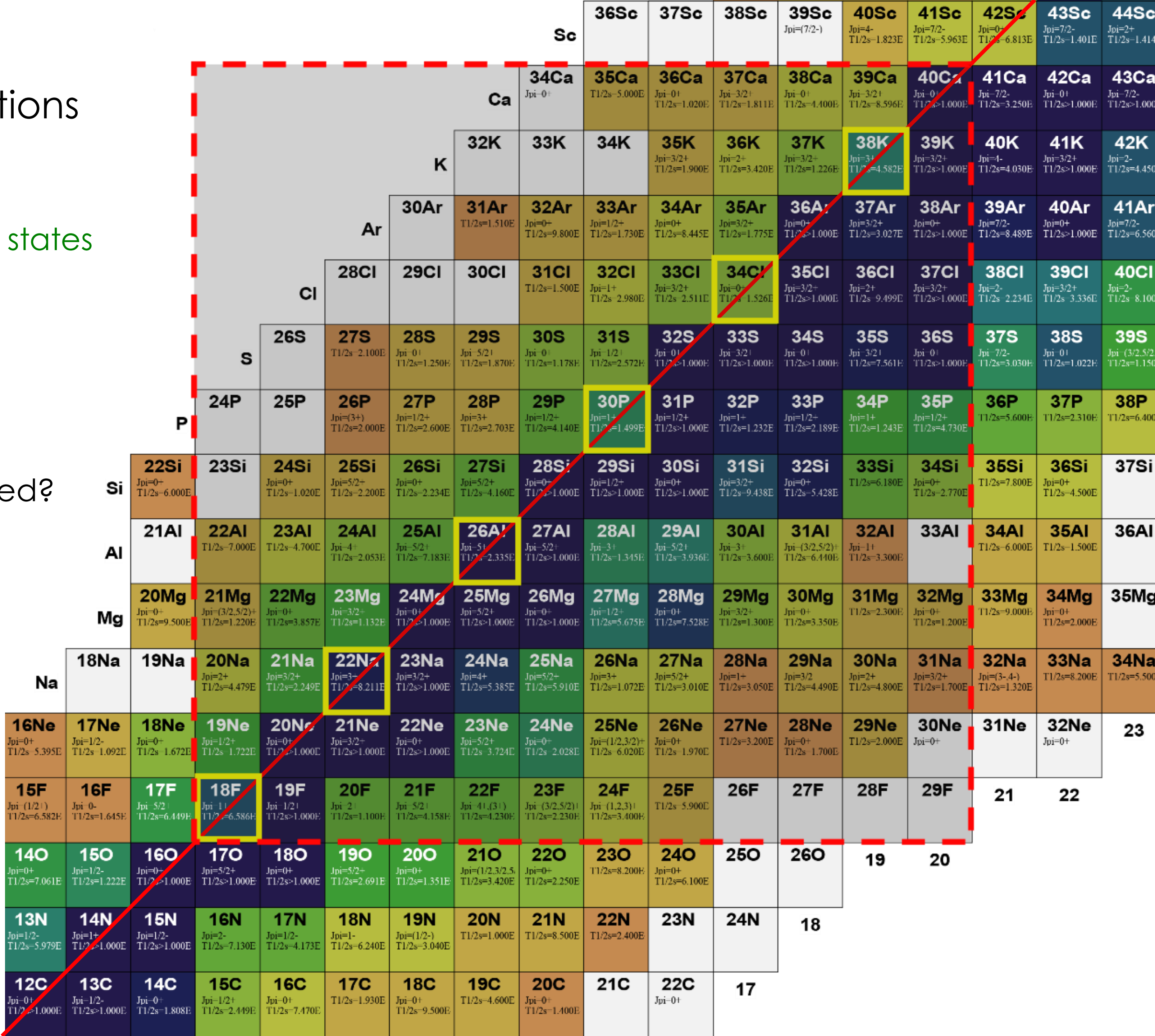
Transfer on sd nuclei

- Testing ground of LBSM calculations
  - Wealth of experimental data (near stability)
  - Well-constrained interactions for sd states (eg USDb)
  - Mid shell
    - highly mixed states
    - non-zero J^{π} ground states
    - non-spherical systems
  - How well are *fp* excitations described?

- Reaction models
  - Lower-end of well-constrained nucleon-nucleus global potentials (near stability)
  - ADWA vs DWBA?
  - Finite range effects?
  - …

- Beautiful experiments

- Astrophysical motivation



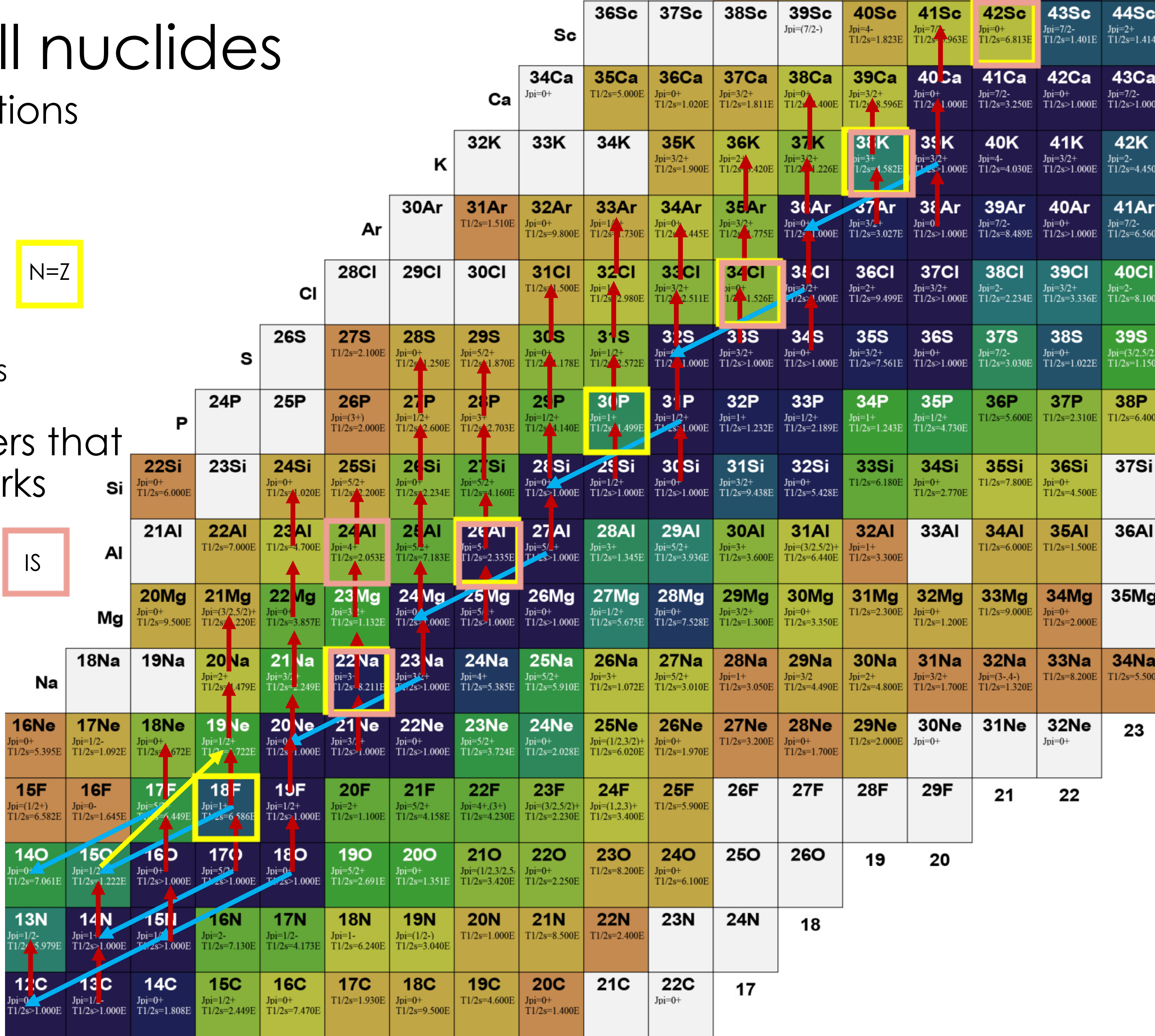
Odd-odd N=Z sd-shell nuclides

- Networks of (p,γ) and (p,α) reactions (beta decays omitted) in novae
- (p,γ) on odd-odd $N=Z$ nuclides particularly important
  - bottleneck reactions
  - impact on astronomical observables
- Many have long-lived spin isomers that can play roles in reaction networks (astromers)

N=Z

IS

Species	t(GS)	t(IS)	J^{π}(GS)	J^{π}(IS)
– ^{22}Na	2.6 y	240 ns	3^+	1^+
– ^{24}Al	2 s	130 ms	4^+	1^+
– ^{26}Al	0.7 My	6.3 s	5^+	0^+
– ^{30}P	2.5 m	96 fs	1^+	0^+
– ^{34}Cl	1.5 s	32 m	0^+	3^+
– ^{38}K	6.7 m	0.9 s	3^+	0^+
– ^{42}Sc	0.7 s	1 m	0^+	7^+



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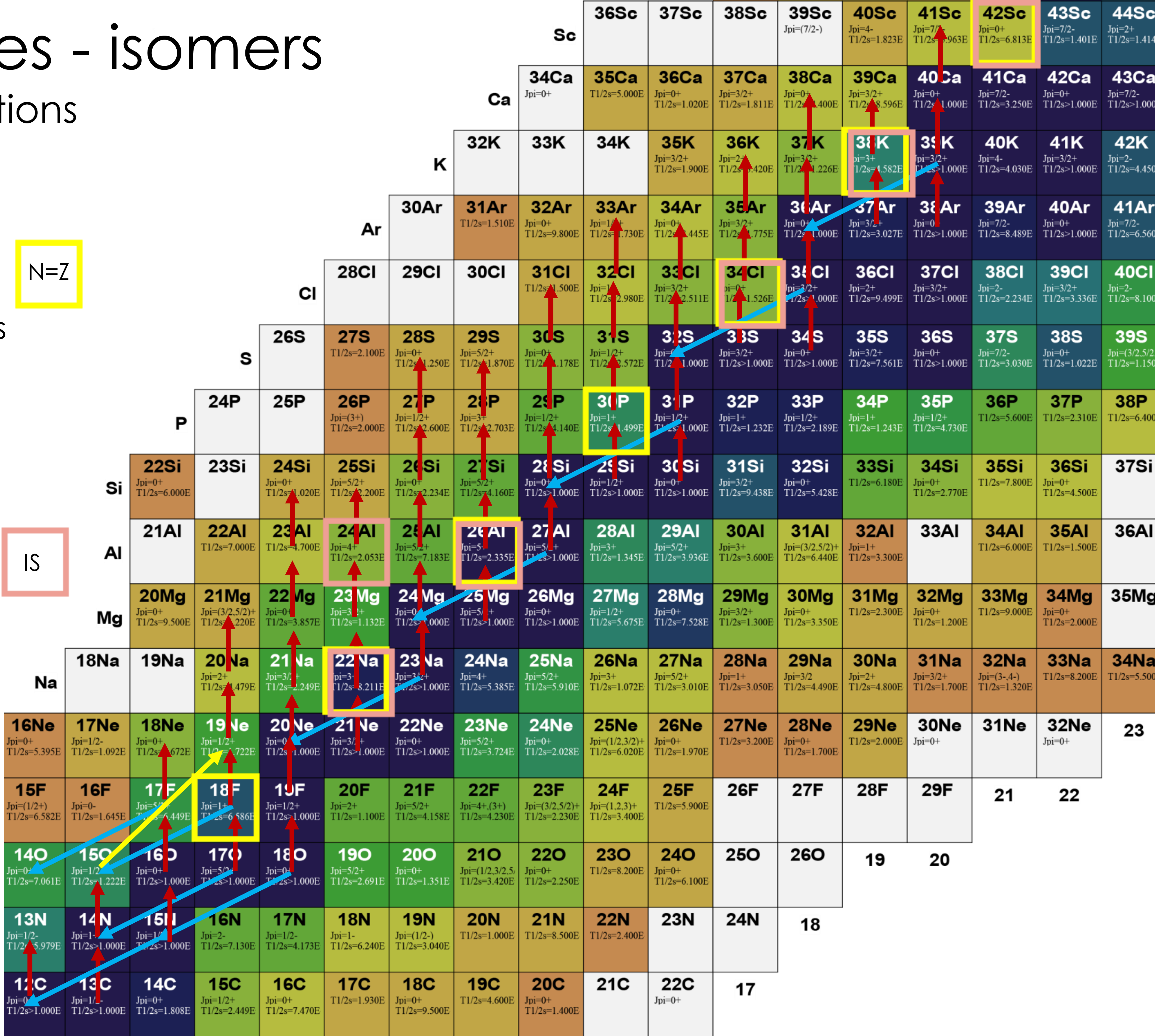
Odd-odd N=Z nuclides - isomers

- Networks of (p,γ) and (p,α) reactions (beta decays omitted) in novae
- (p,γ) on odd-odd $N = Z$ nuclides
  - bottleneck reactions
  - impact on astronomical observables
- Reaction networks
  - independent
  - or thermal coupling at high T
- Want reaction rates on both GS and IS
  - v. different SP structure, limited expt
  - sdpf states
- General rule
  - Insufficient beam intensities for direct (p,γ) measurements currently (some at FRIB)
  - indirect techniques within reach

N=Z

IS



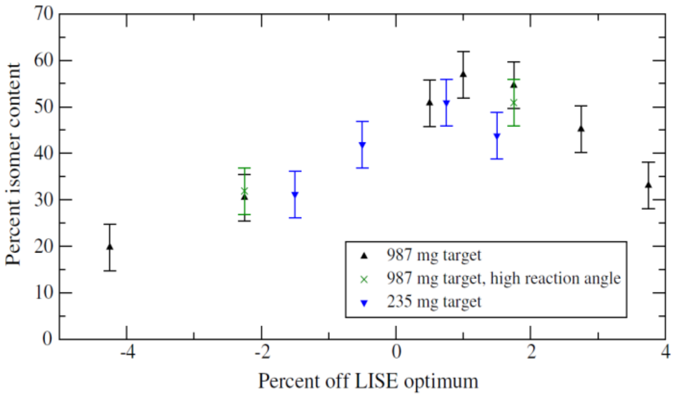
OAK RIDGE National Laboratory

Transfer reactions on isomeric beams at FRIB

- Unique design of FRIB gives opportunities for producing beams of long-lived (>ms) nuclear isomers at ideal beam energies/optics for transfer reactions - ReA
- Produce GS and IS with fragmentation, reaccelerate
- Control the ground:isomer composition via
  - selection of production yields, via fragment separator (spin, though not specifically that of final state)
  - Adjustment of hold-up times inherent to ReA (lifetimes)

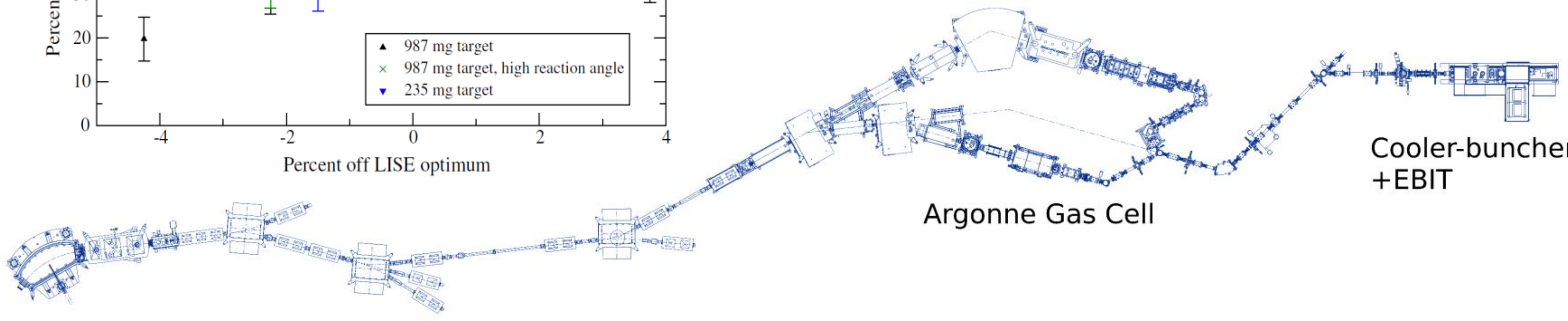
- Transfer, charge-exchange, Coulex,… for structure/indirect astrophysics (ORRUBA, SOLARIS, GODDESS, GRETA, LENDA, SeGA, Clarion2, ….)
- Direct measurements of astrophysical reactions [eg (*p*,g) with SECAR, or (a,*p*) (a,*n*) with JENSA, MUSIC, HabaNERO, …]

Selection on production

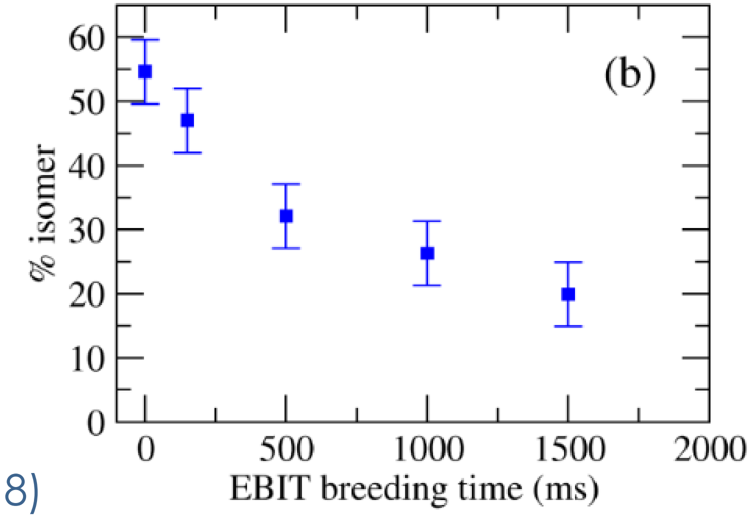


^{38}K

GS	3^+		$t_{1/2}$ ~ 7.6 min
Isomer	0^+	(130 keV)	$t_{1/2}$ ~ 1 sec



Selection by charge-breeding

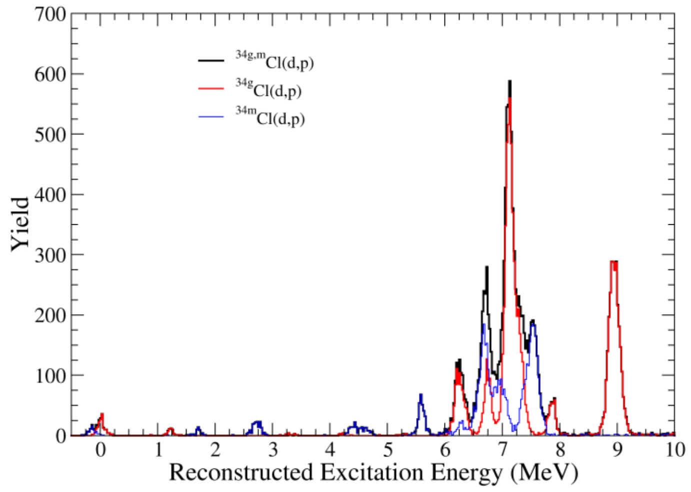


K.A. Chipps *et al.,* Phys. Rev. Acc. and Beams **21**, 121301 (2018)

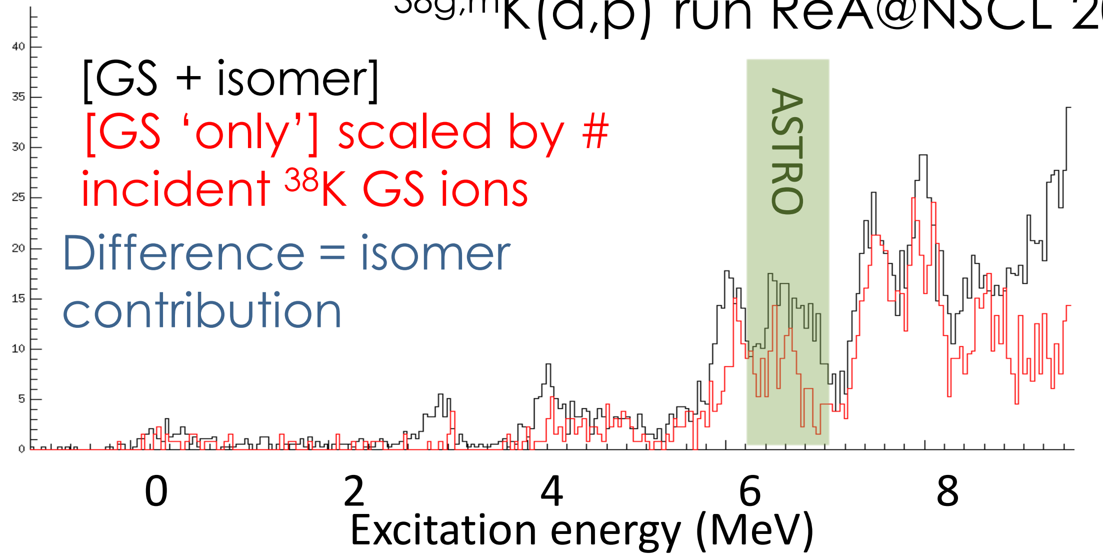
Previous and upcoming isomer expts

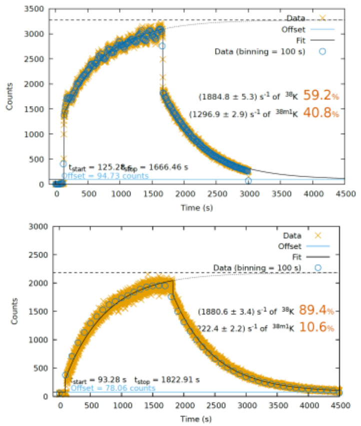
Nova nucleosynthesis

^{34g,m}Cl(d,p) FRIB PAC1 approved

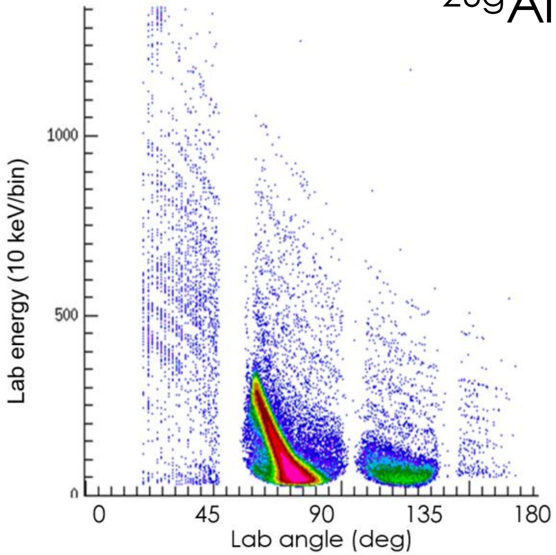


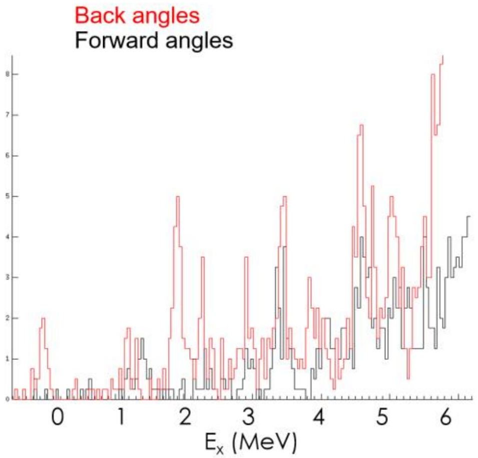
^{38g,m}K(d,p) run ReA@NSCL 2020





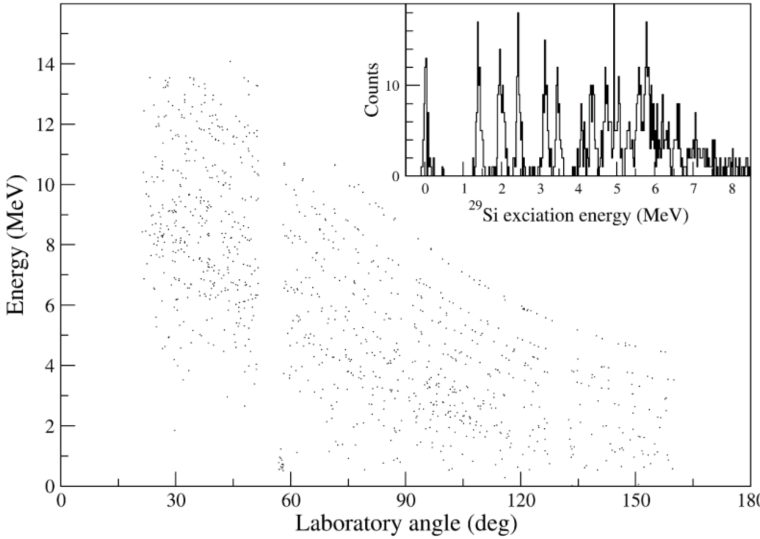
^{26g}Al(a,p) run ReA 2022





Direct measurements for XRB and SN nucleosynthesis

^{26m}Al(a,p) FRIB PAC2 approved



Indirect constraints on (p,γ) reactions

- Dominated by isolated resonances (some too low for direct measurements)
- Locate states E_r
- To constrain resonance strength, determine:
  - Spins
    - ℓ_p (constrains barrier, Γ_{sp})
  - Determine reduced width (10^2) $\Gamma_p = C^2 S.\Gamma_{sp}$

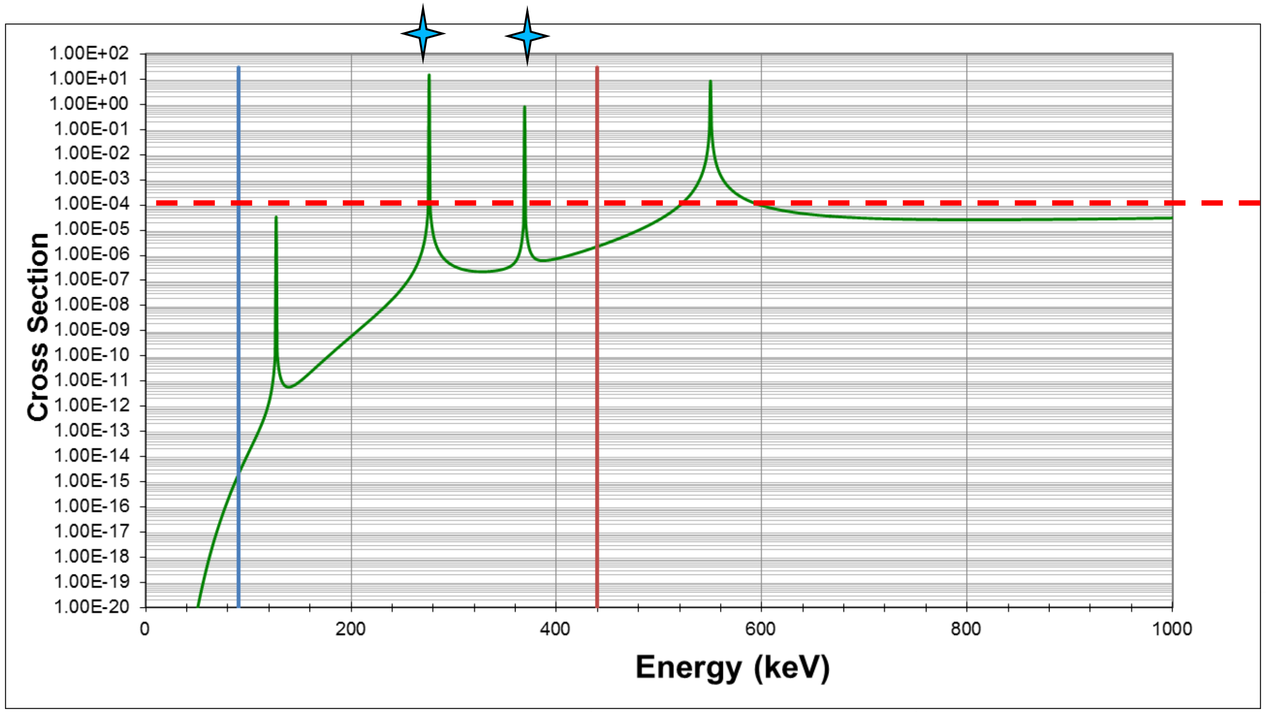
$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \eta^2 \omega\gamma \exp\left(-\frac{E}{kT} \right)$$

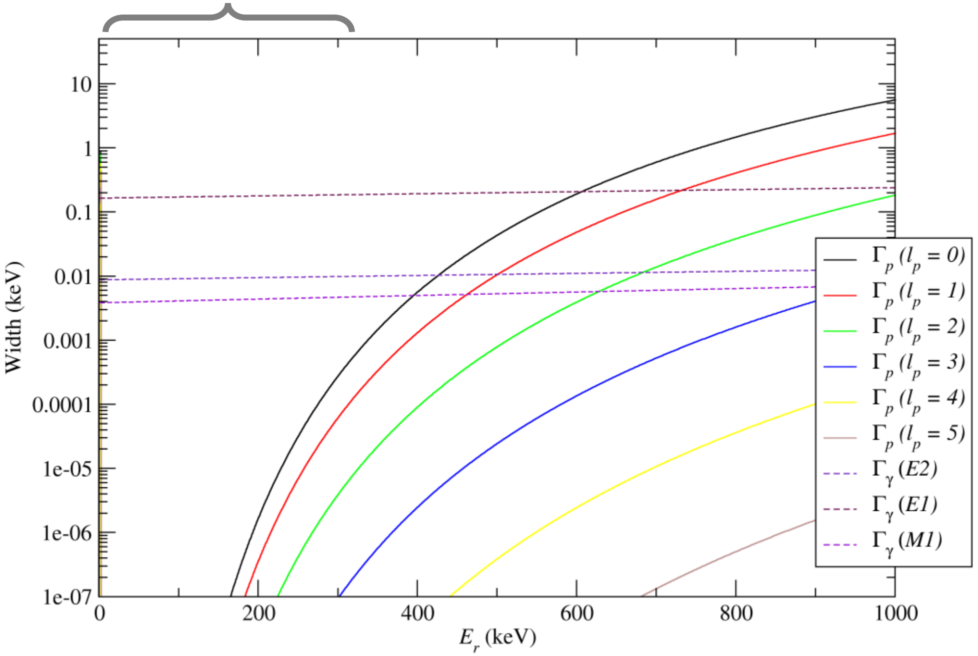
$$\omega = \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12}) \qquad \gamma = \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$

low-energy limit

$$\Gamma_p \ll \Gamma_\gamma$$

$$\omega\gamma \approx \omega\Gamma_p$$





What can we learn from transfer?

- Proton transfer ideal (d,n) or (^{3}He,d)
  - *Selectivity*
  - *Energies 10s of keV*
  - ℓ_p
  - C^2S

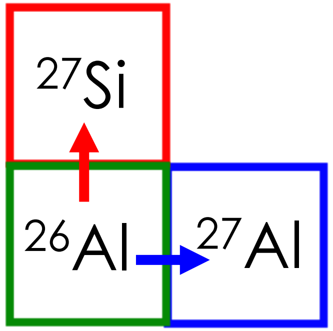
- ***Experimental challenges***
  - *Neutron detection*
  - *Inclusive measurements*
    - *Gamma tagging*
    - *Non-spin-zero ground/isomeric states*
  - *^{3}He targets*

- Infer C^{2}S for *single-proton states* via ***mirror symmetry***
  - Guide by SMEC
  - 10-20% effect

$$C^2S_p \approx C^2S_n$$

$$\Gamma_p = C^2S.\Gamma_{sp}$$

$$\omega\gamma \approx \omega\Gamma_p$$



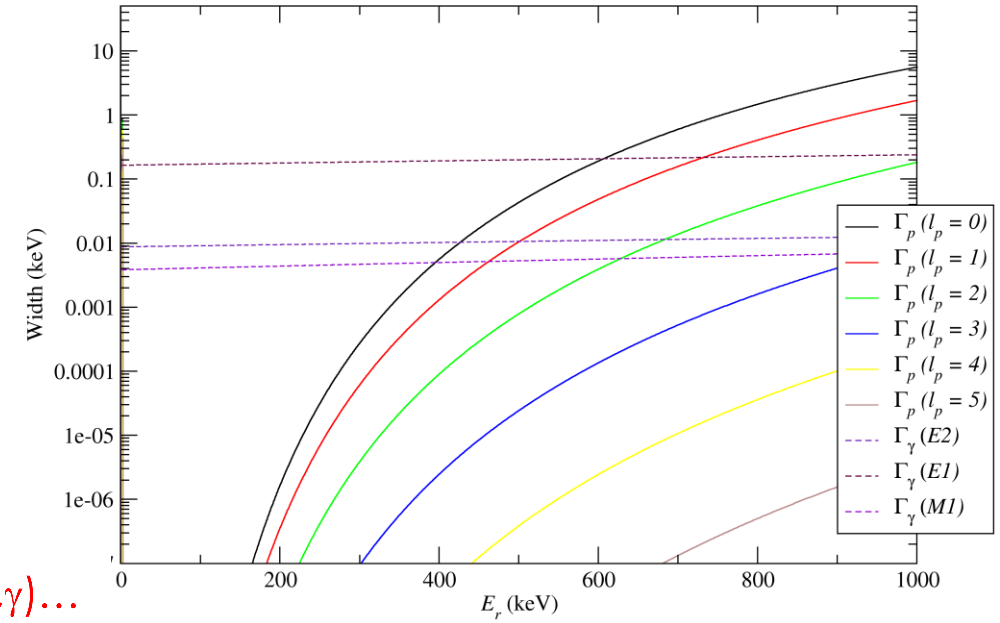
Benchmark against ^{26}Al(p,γ)…

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \eta^2 \omega\gamma \exp\left(-\frac{E}{kT}\right)$$

$$\omega = \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12}) \qquad \gamma = \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$

$$\Gamma_p \ll \Gamma_\gamma$$

$$\omega\gamma \approx \omega\Gamma_p$$

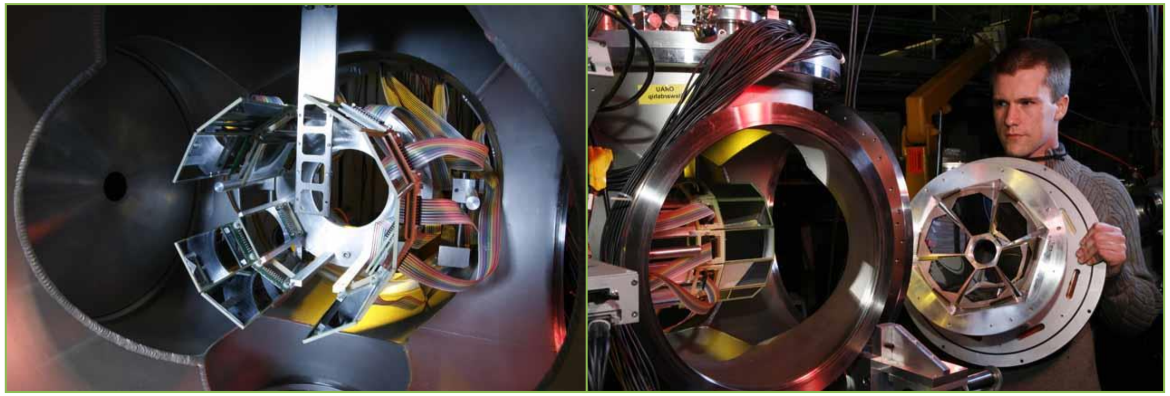


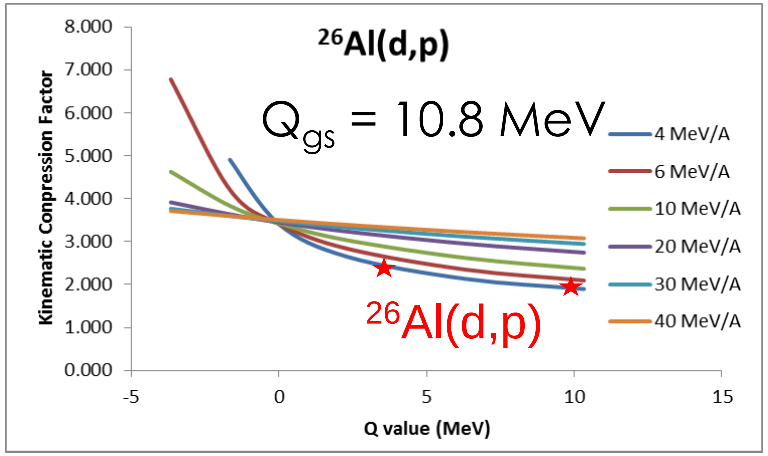
$^{26}Al(d,p)^{27}Al$ experiment

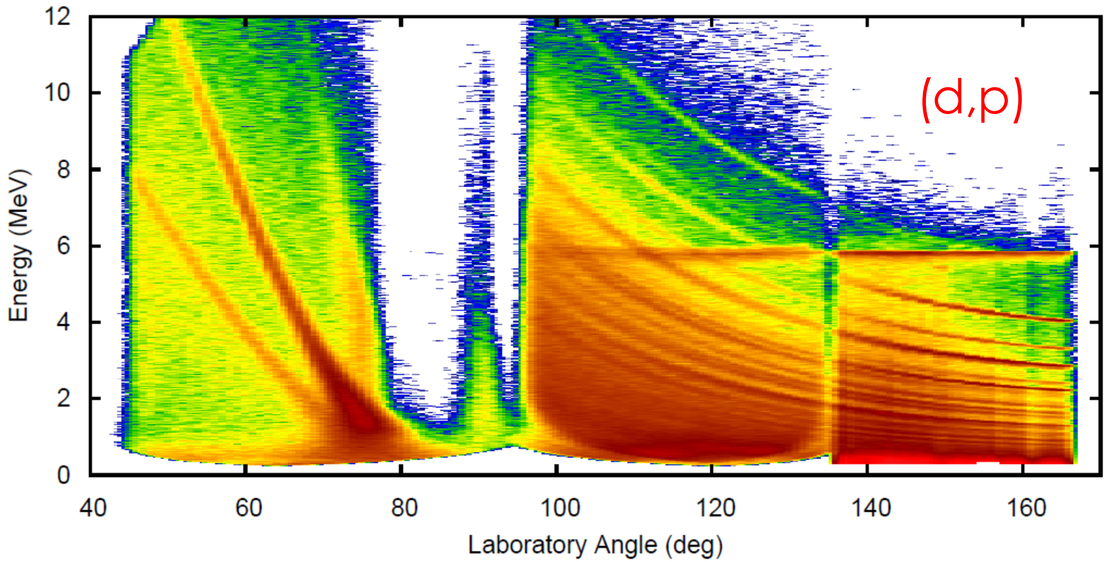
ORRUBA

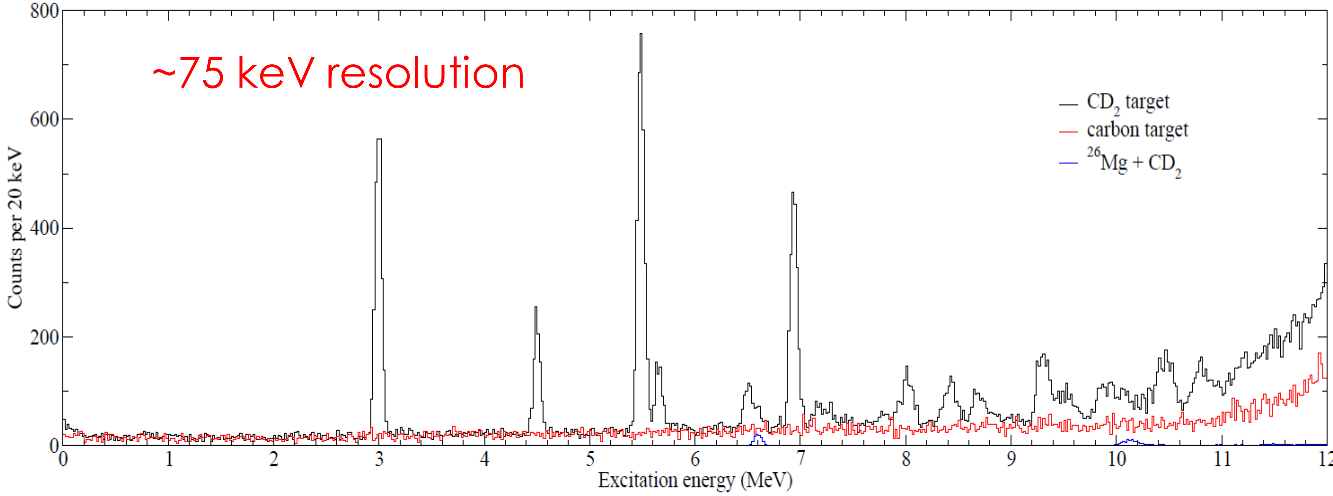
- 4.5 MeV/u ^{26}Al (Oak Ridge Tandem)
- $5x10^6$ pps
- 150 μg/cm² CD_2
- MCP normalization (200 kHz)

- Large Q value = low kinematic compression

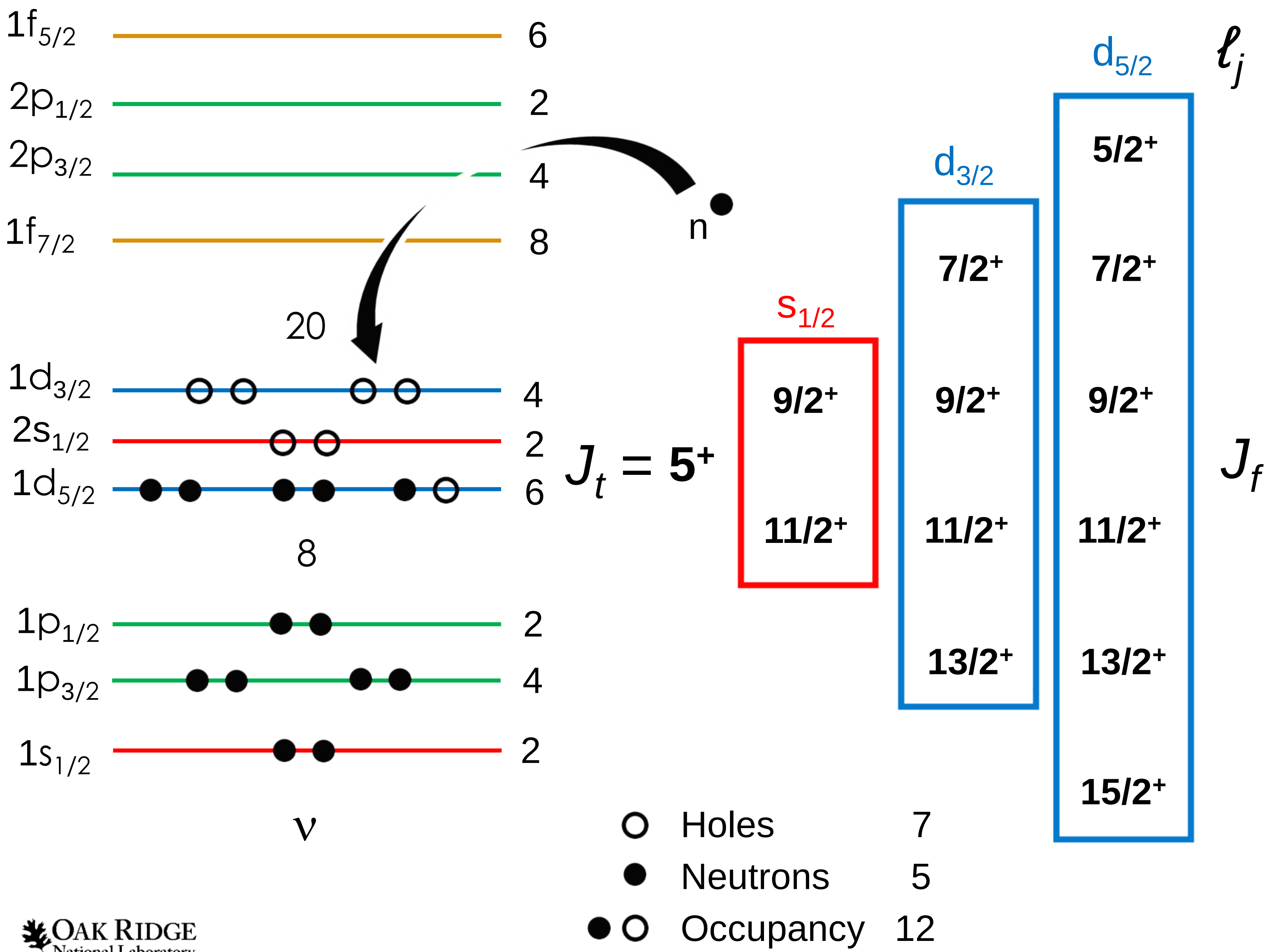








^{26}Al *sd*-shell states

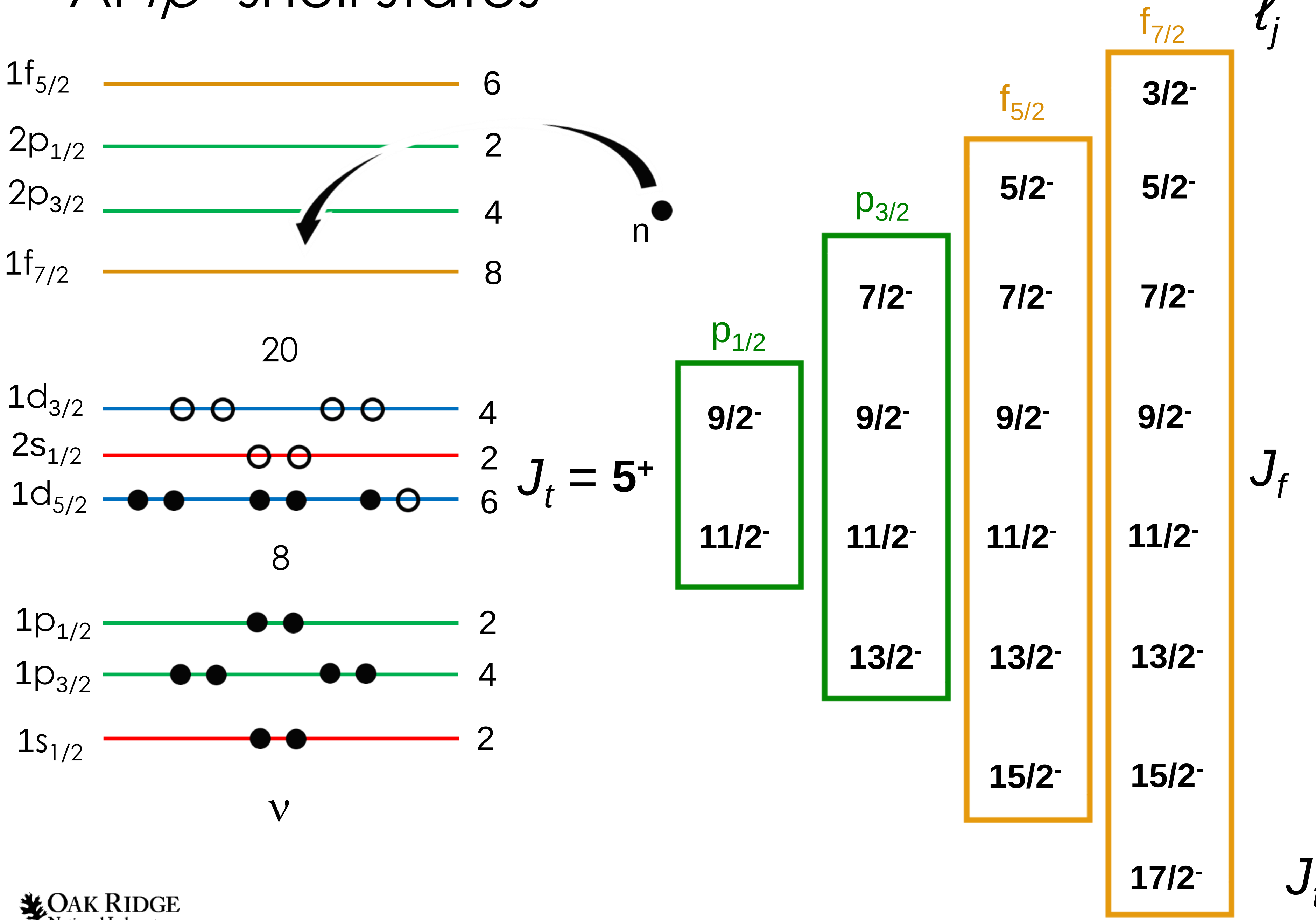


What to expect?

- *sd*-shell excitations
- *fp*-shell excitations at higher E_x

$$J_t - j \leq J_f \leq J_t + j$$

^{26}Al *fp* -shell states



What to expect?

- *sd*-shell excitations
- *fp*-shell excitations at higher E_x

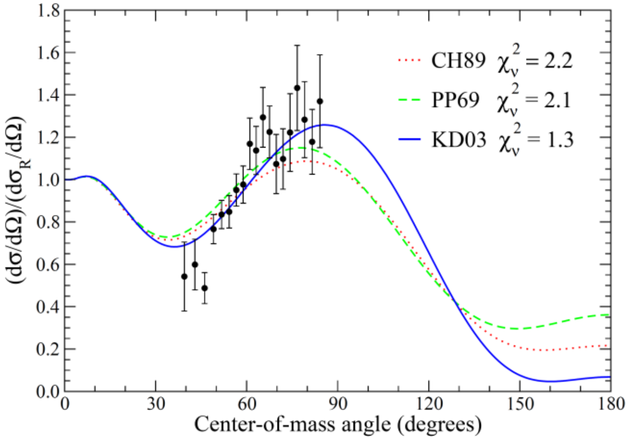
$$J_t - j \le J_f \le J_t + j$$

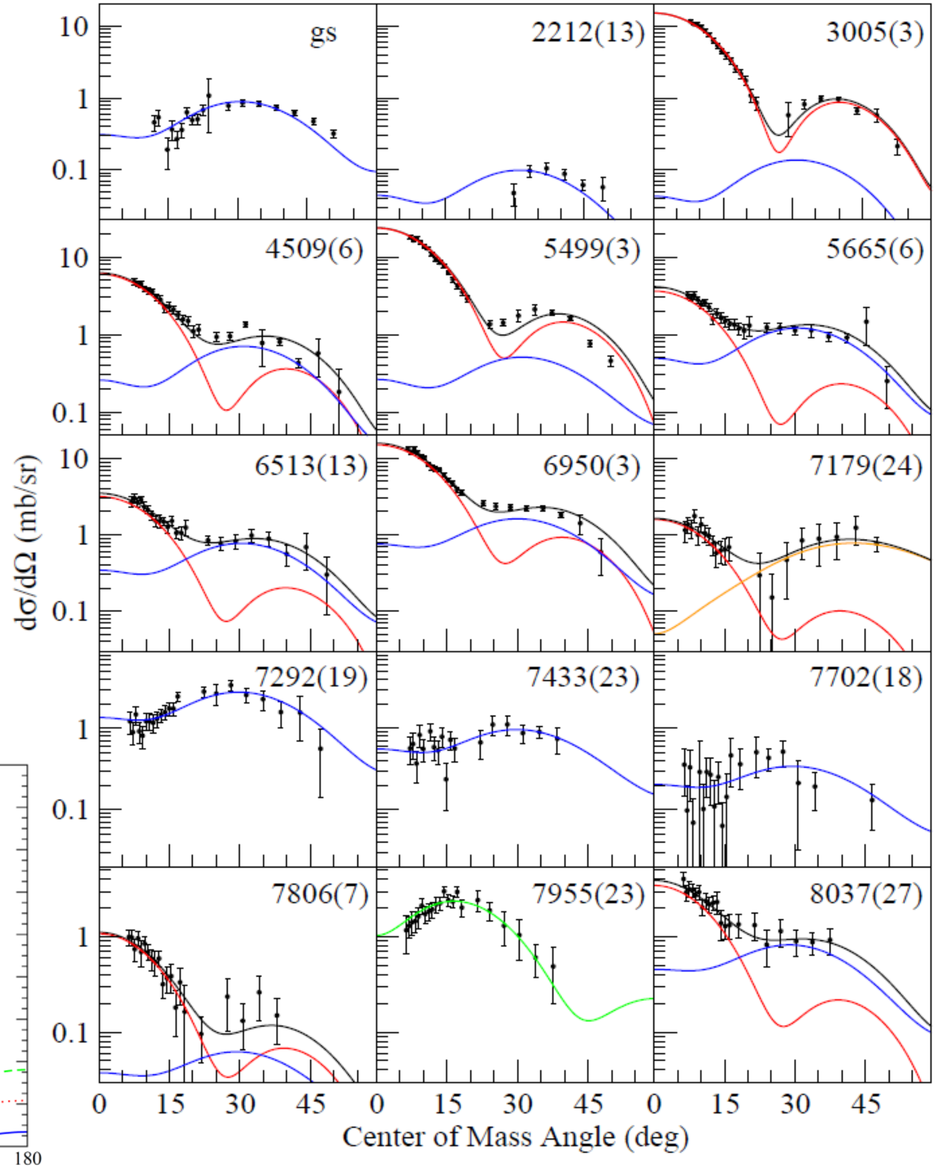
$^{26}Al(d,p)^{27}Al$ angular distributions

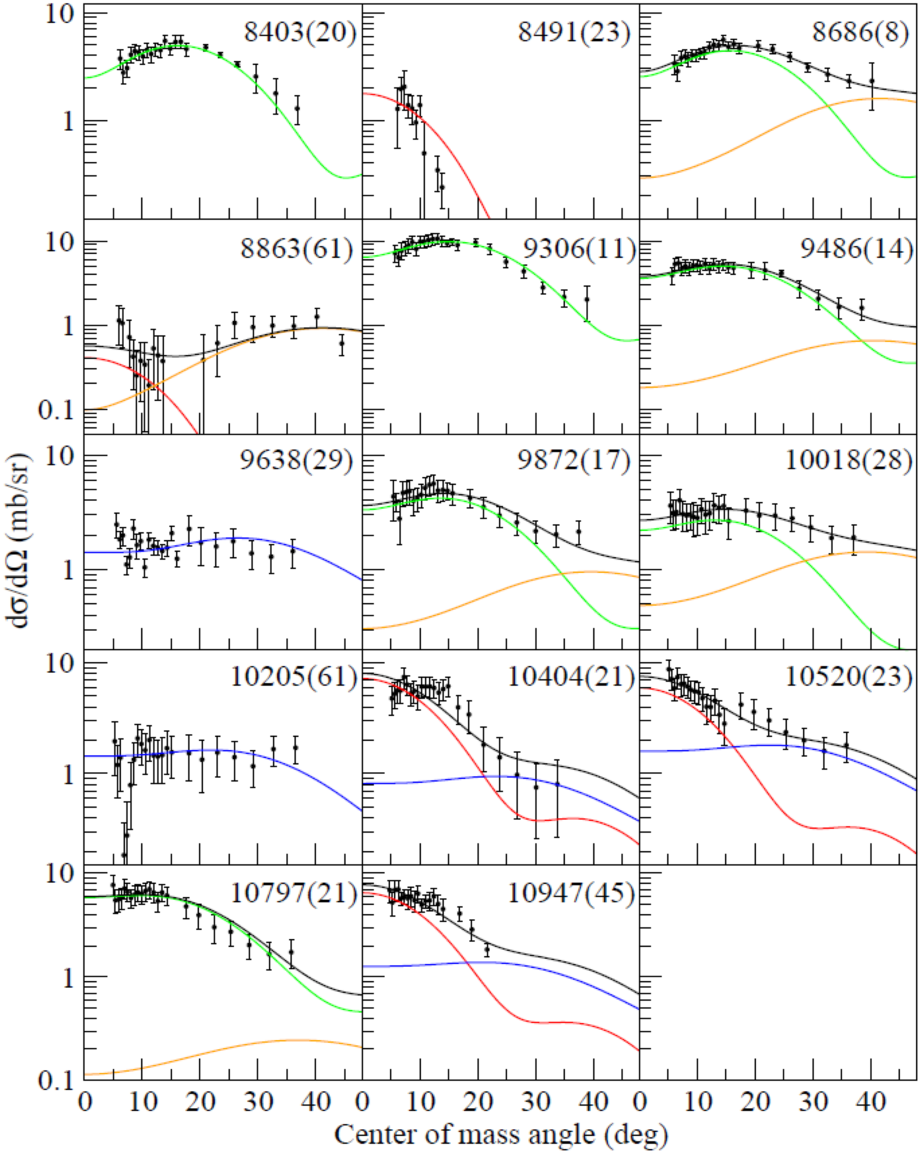
total
s wave
p wave
d wave
f wave

Important for quality analysis of transfer data

- *Good coverage of first stripping peak*
- *ADWA*
- *Finite Range (d and T)*
- *KD nucleon-nucleus OMPs*
- *Standard geometry parameters*





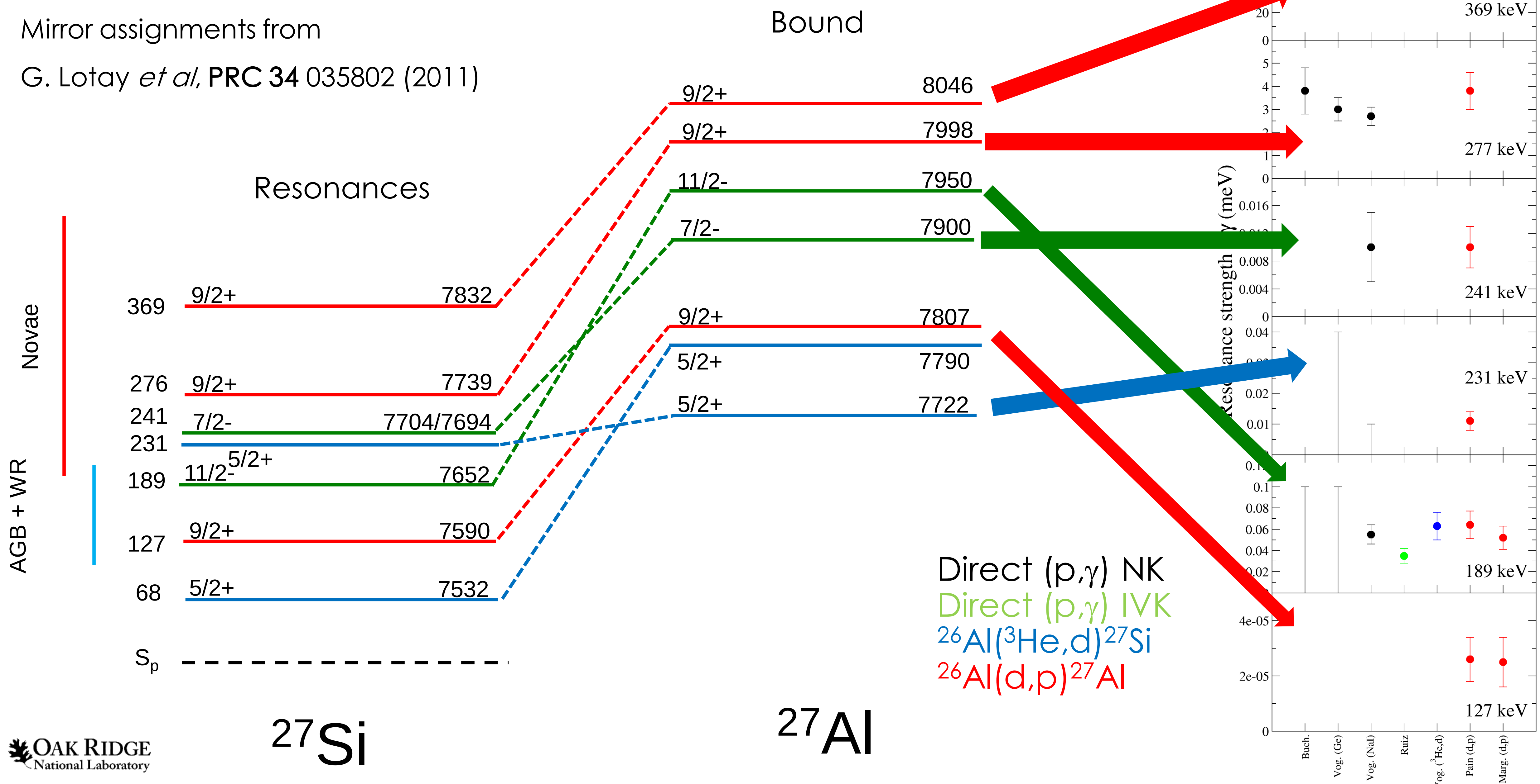


Resonance strengths from (d,p)

SMEC gives ~10-20% reduction in C^2S for ^{27}Si unbound states

Mirror assignments from

G. Lotay *et al*, **PRC 34** 035802 (2011)



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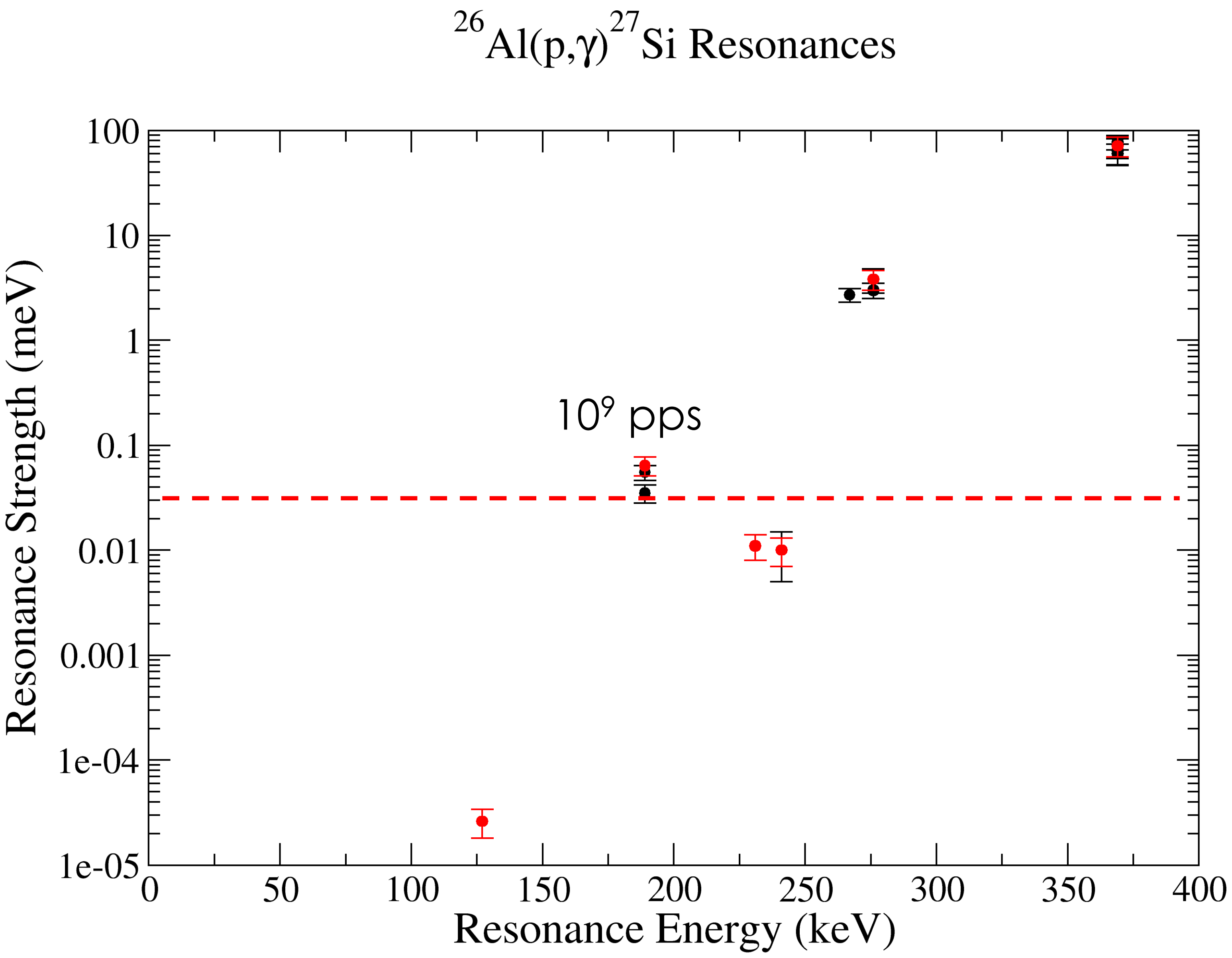
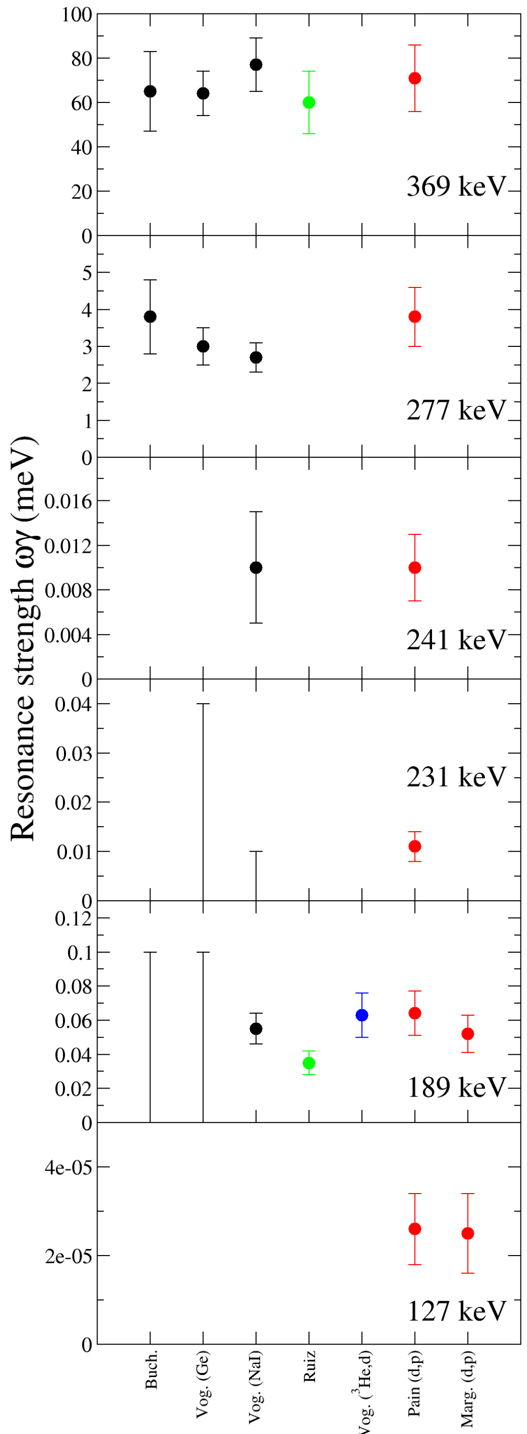
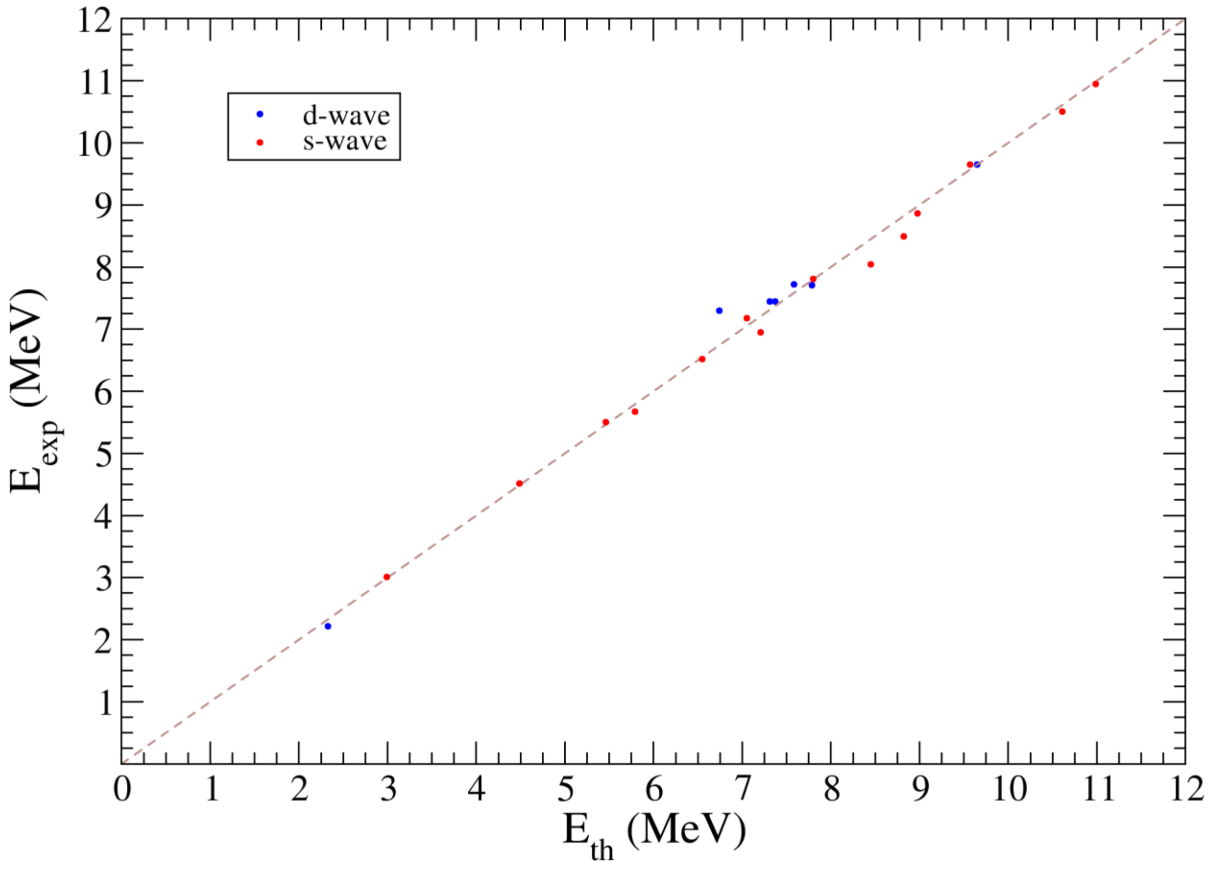
Resonance strengths





Comparison with USDB - energies

- Using NuShellX@MSU
- Calculated the first 40 states of each positive parity (5/2+ - 17/2+) in ^{27}Al (dim 80,000) and calculate overlaps with ^{26}Al 5+ ground state (dim 70,000) (few minutes with 6-core/12-threads (280 states total)
- Match by comparing C^2S and energy



Excellent agreement in energies

- Perhaps unsurprising, as USDb fitted to energy levels in the SD shell (608 states, 77 nuclei, incl ^{26,27}Al)
  - Only fitted up until J^π becomes ambiguous - typically around 6-7 MeV
  - Agreement up to 11 MeV in expt

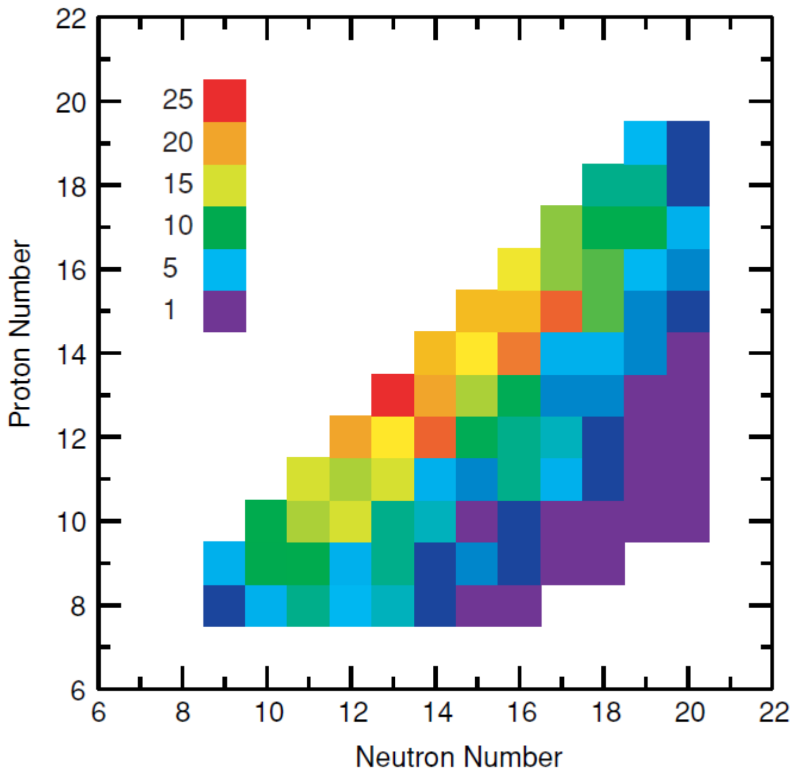
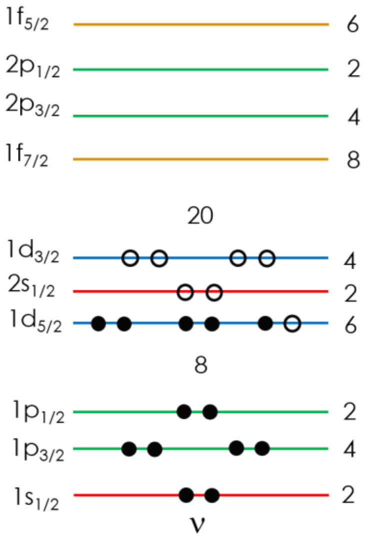


FIG. 2. (Color) Number of states used for the USDA and USDB Hamiltonians for each nucleus.

Comparison with USDb

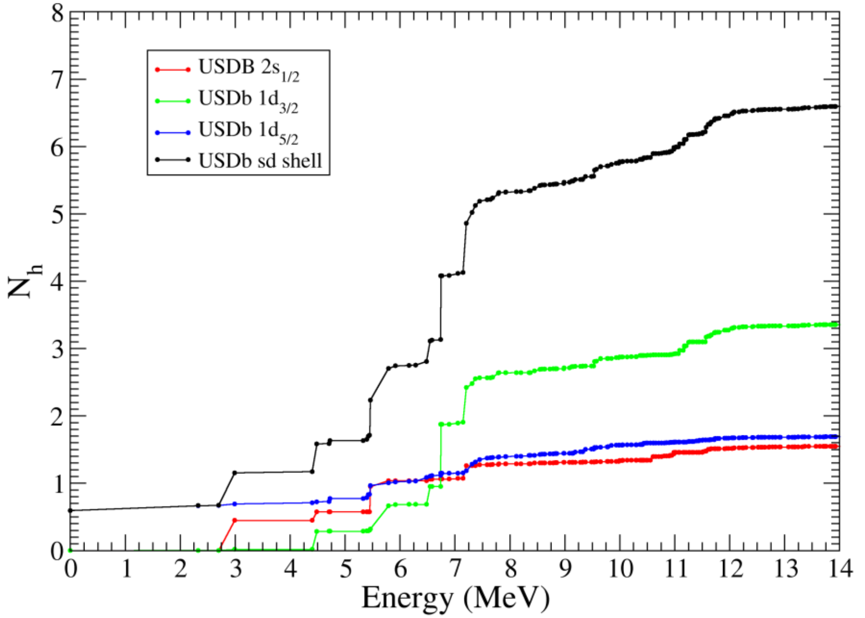


Macfarlane & French sum rules

$$N_h = \sum_E \frac{2J_f + 1}{2J_t + 1} C^2 S_{(d,p)}$$

$N_n + N_h = 12$ (for sd shell)

- ○ Vacancies 7
- ● Occupancies 5
- ● ○ sd-shell space 12



Summary

- Impossibly broad scope of FRIB transfer reaction program - focus on a couple of unique opportunities
- Developments in SRM: (d,p) for (n,γ)
- Opportunities for (d,p) measurements at the S800
  - strong beams in the mass ~80 region
  - discrete particle and particle-γ spectroscopy
  - New technique: SRM for CN neutron transfer using recoils, and γs
  - Two approved experiments GODDESS+S800 upcoming
- Ability to produce high-quality Reacc. beams with controllable isomer content
  - Mirror studies for (p, γ) reactions on isomers, ultimately (p, γ) SECAR
  - Direct (α,p) measurements (JENSA) on isomers, ultimately SECAR
  - Two approved ReA experiments – ^{34}Cl(d,p) and ^{26}Al/^{26}Si(a,p)
  - expt/SM across the sd N=Z (^{22}Na, ^{30}P, ^{34g,m}Cl, ^{26g,m}Al, ^{38g,m}K)

Thanks

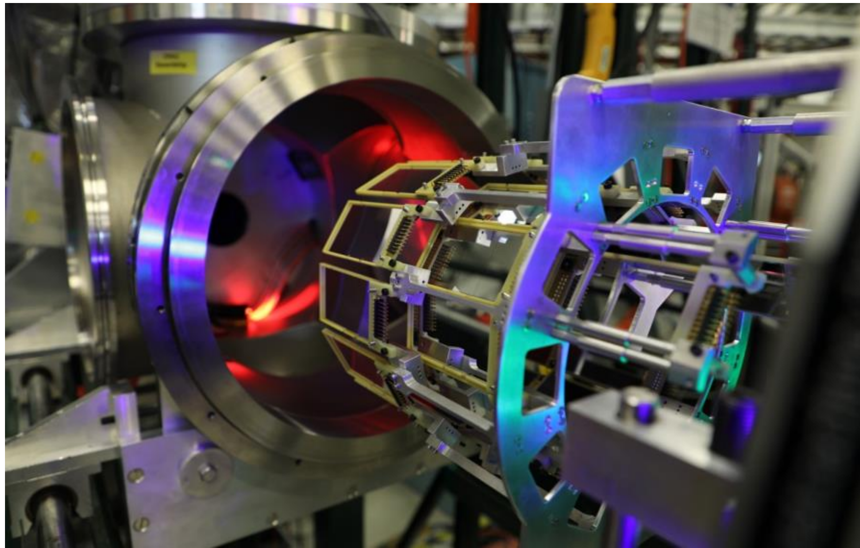
ORRUBA, GODDESS, JENSA and SECAR Collaborations
Esp. H. Sims, A. Ratkiewicz, J.A. Cizewski

ReA: A. Henriques, A. Lapierre, K. Lund, Y. Liu, S. Nash, C. Sumithrarachchi, A. Villari

ORRUBA
Si detector array

JENSA

SECAR



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