Spectroscopy and correlations probed via two-nucleon knockout reactions

DCEN Workshop
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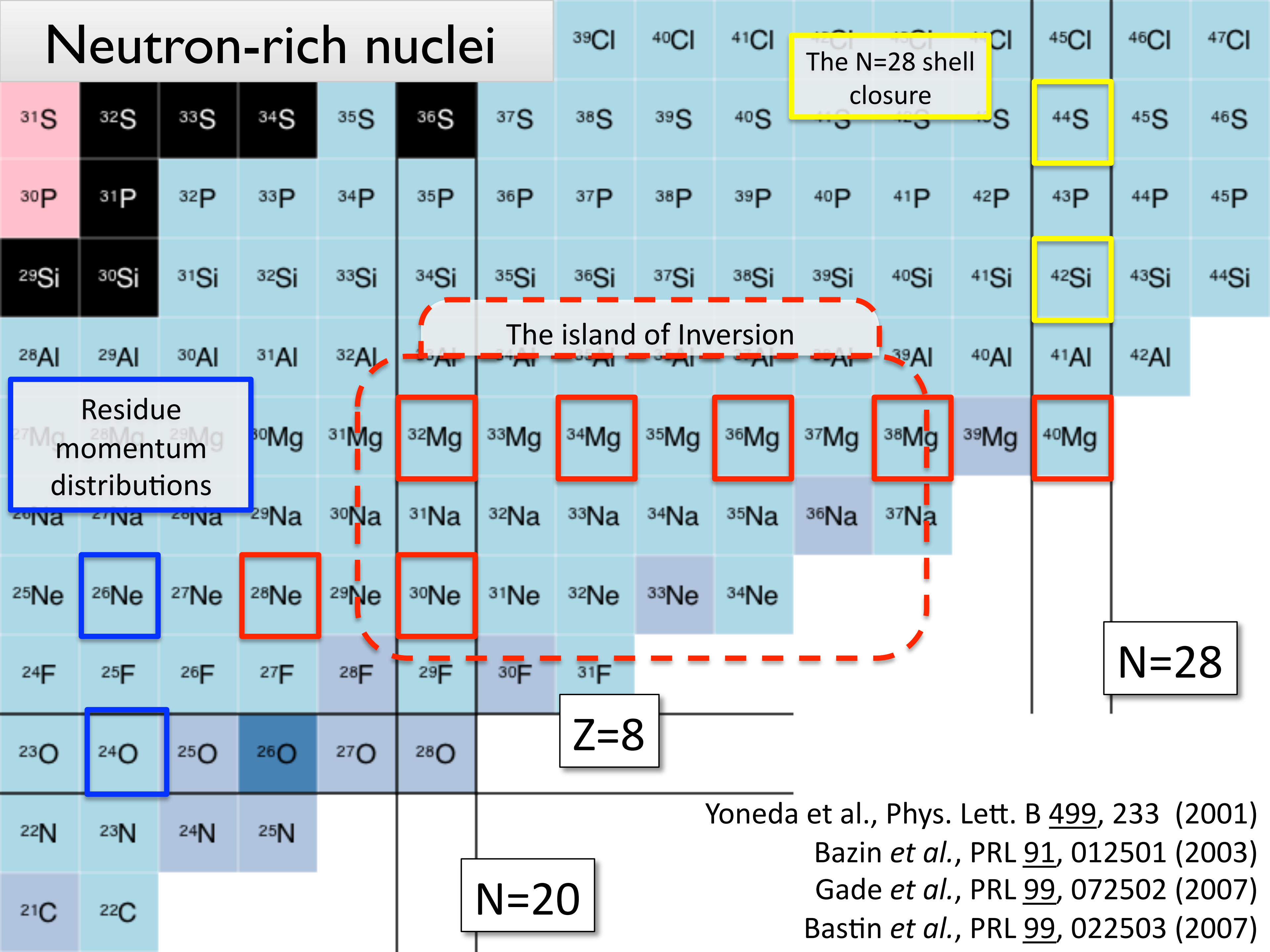
Outline

- Introduction
- Two-nucleon removal reactions
- How can we learn about structure?
  - Final state spins from momentum distributions
  - Two-nucleon spatial correlations
  - Tests of underlying structure
- N=Z nuclei
  - Stable nuclei
  - np-correlations?
- Regions of changing structure
- Conclusions

Neutron-rich nuclei



The N=28 shell closure

The island of Inversion

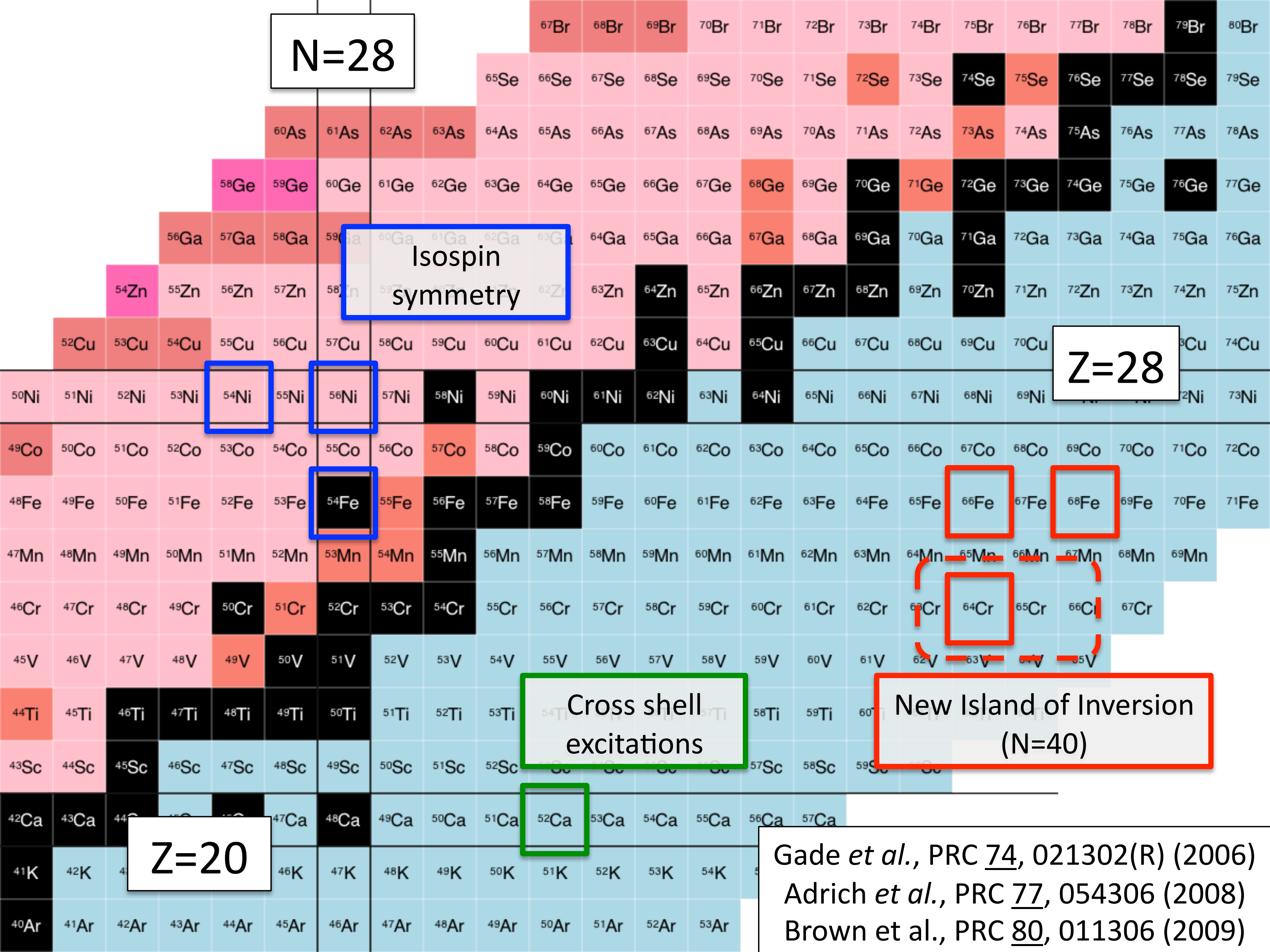
Residue momentum distributions

N=28

Z=8

N=20

Yoneda et al., Phys. Lett. B 499, 233 (2001)
Bazin *et al.*, PRL 91, 012501 (2003)
Gade *et al.*, PRL 99, 072502 (2007)
Bastin *et al.*, PRL 99, 022503 (2007)



N=28

Isospin symmetry

Z=28

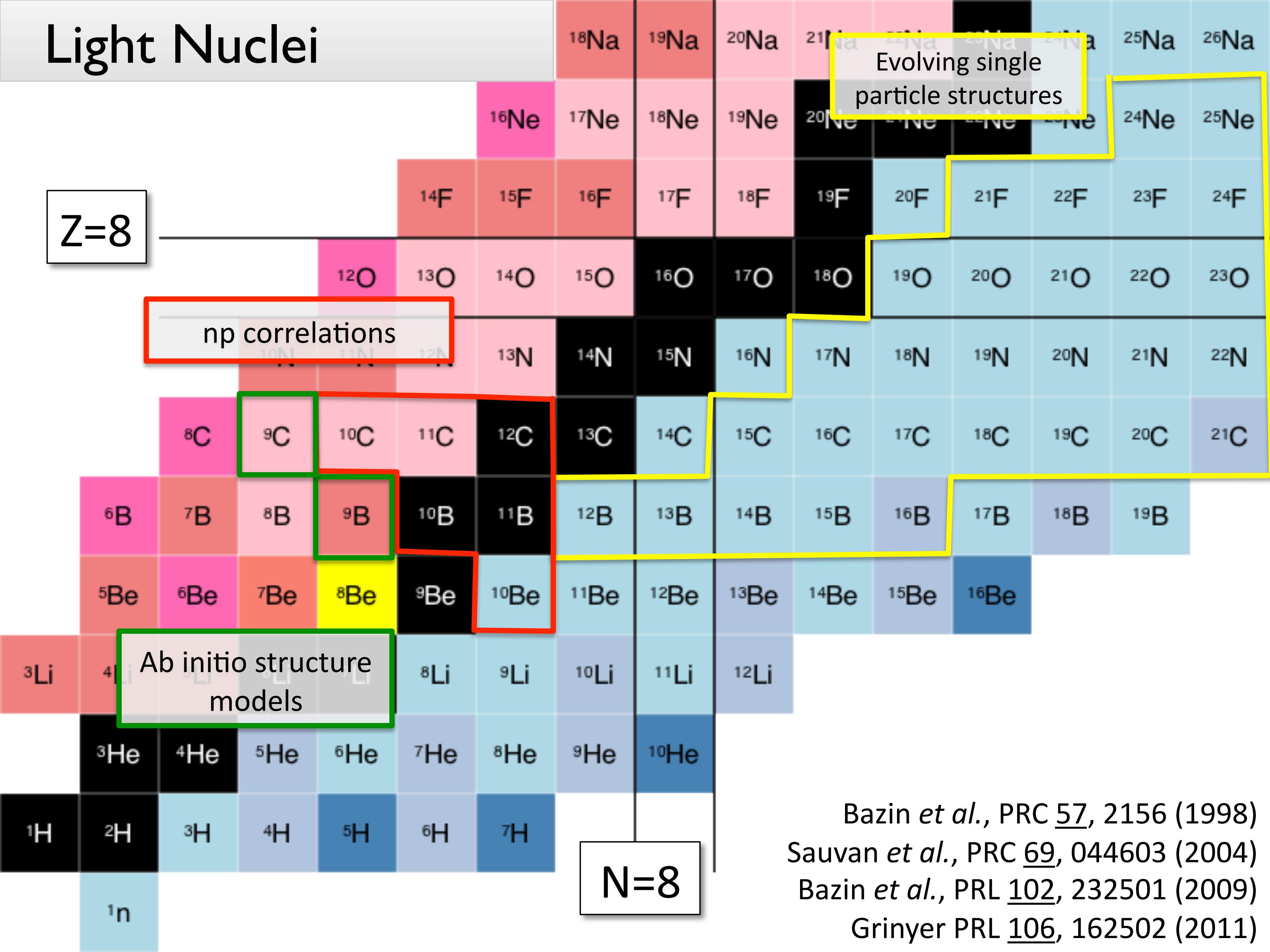
Cross shell excitations

New Island of Inversion (N=40)

Z=20

Gade *et al.*, PRC 74, 021302(R) (2006)
Adrich *et al.*, PRC 77, 054306 (2008)
Brown et al., PRC 80, 011306 (2009)

Light Nuclei



Evolving single particle structures

np correlations

Ab initio structure models

Bazin *et al.*, PRC 57, 2156 (1998)
Sauvan *et al.*, PRC 69, 044603 (2004)
Bazin *et al.*, PRL 102, 232501 (2009)
Grinyer PRL 106, 162502 (2011)

Two-nucleon removal reactions

Single-nucleon removal reactions

Removal of nucleons from a (secondary radioactive) beam at energies >80 MeV/nucleon on a light nuclear target (Be, C)

Halos: ^{15}C, ^{19}C, ^{27}P, ^{31}Ne
Magic numbers: ^{24}O, ^{42}Si
Exotic R_s: ^{23}Al, ^{23}Si, ^{27}P, ^{27}S

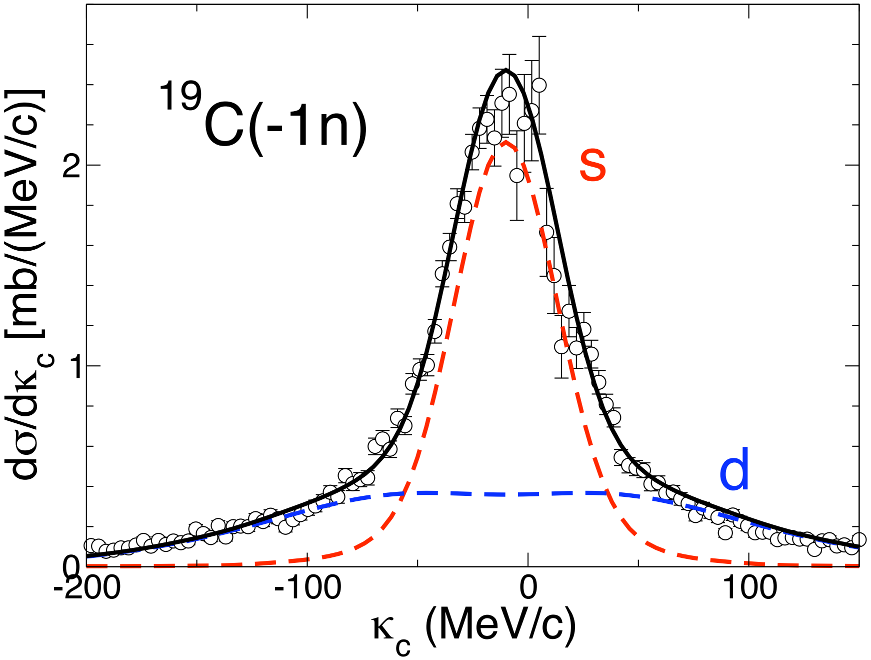
Absolute cross sections

- Cross section proportional to spectroscopic strength
- Suppression of spectroscopic strengths in asymmetric systems

$$\sigma_{-1n} = \sum_{nlj} C^2 S_{nlj}\, \sigma_{sp}$$

Beam directional momentum distributions

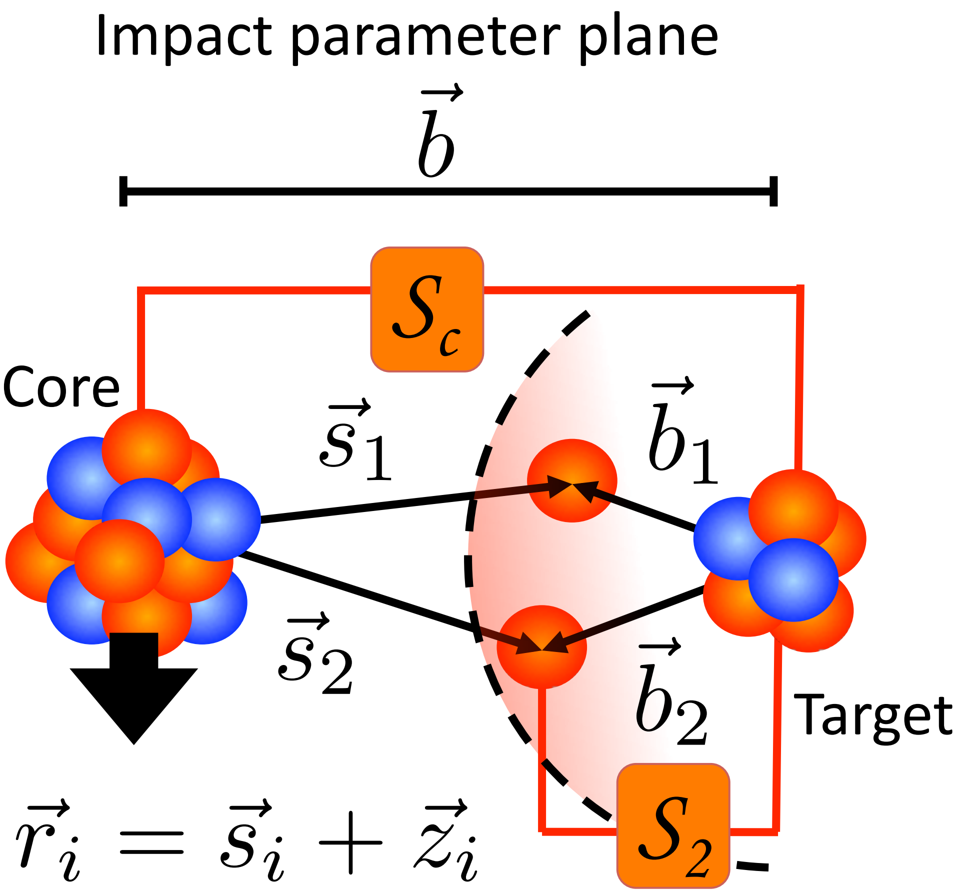
- Width → Orbital angular momentum (final state spins, evolution of shell ordering)



Hansen and Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003)
Bertulani and Hansen, PRC 70 034609 (2004)

Surface structure

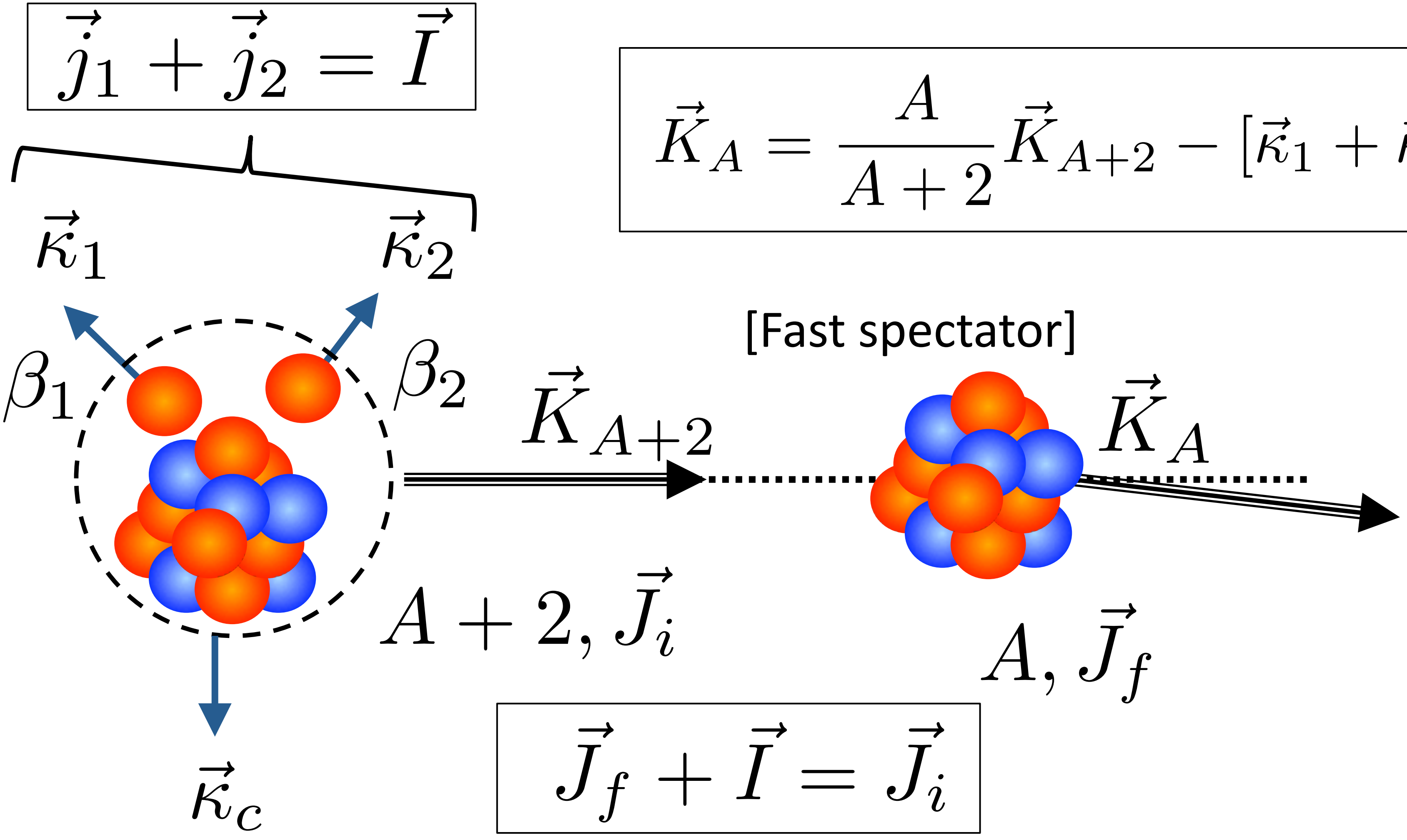
- Eikonal reaction dynamics (straight line trajectory)
- Projectile internal co-ordinates assumed fixed for the duration of the (fast) interaction
- Core assumed to act as spectator during the fast interaction
- Reaction probes the projection of the (two-) nucleon wave function on the impact parameter plane
- Final state of the valence nucleons and target unobserved



$$\vec{r}_i = \vec{s}_i + \vec{z}_i$$

$$\hat{z} || \vec{K}_{A+2} \otimes$$

Momentum distributions



$$\vec{j}_1 + \vec{j}_2 = \vec{I}$$

$$\vec{K}_A = \frac{A}{A+2}\vec{K}_{A+2} - [\vec{\kappa}_1 + \vec{\kappa}_2]$$

$$\vec{J}_f + \vec{I} = \vec{J}_i$$

K_A distribution characteristic of $\kappa_1 + \kappa_2$

Two-nucleon overlap

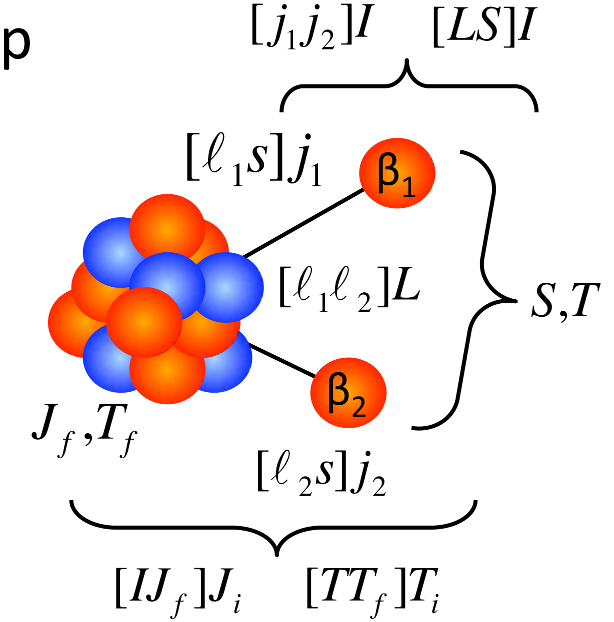
Shell-model LS-coupled two-nucleon overlap

$$\Psi_i^{(F)}(1,2) = \langle \Phi^{(F)}(A) | \Psi_i(A+2) \rangle$$

$$= \sum_{I\mu T\alpha} C_\alpha^{IT}\, (T\tau T_f\tau_f | T_i\tau_i)\, (I\mu J_f M_f | J_i M_i)$$

$$[\overline{\psi_{\beta_1}(1) \otimes \psi_{\beta_2}(2)}\,]^{T\tau}_{I\mu}$$

$$\alpha \equiv (\beta_1, \beta_2) \qquad \beta \equiv (n\ell j)$$



Two-nucleon wave function

$$[\overline{\psi_{\beta_1}(1) \otimes \psi_{\beta_2}(2)}\,]^{T\tau}_{I\mu} = D_\alpha \hat{j}_1 \hat{j}_2 \sum_{\substack{L\Lambda S\Sigma \\ \lambda_1\lambda_2}} (\ell_1\lambda_1\ell_2\lambda_2|L\Lambda)\,(L\Lambda S\Sigma|I\mu)\; \hat{L}\hat{S}\, \chi_{S\Sigma}(1,2)\chi_{T\tau}(1,2)$$

$$\times \begin{Bmatrix} \ell_1 & s & j_1 \\ \ell_2 & s & j_2 \\ L & S & I \end{Bmatrix} [\psi^{\lambda_1}_{\beta_1}(\vec{r}_1)\psi^{\lambda_2}_{\beta_2}(\vec{r}_2) - (-)^{S+T}\psi^{\lambda_1}_{\beta_1}(\vec{r}_2)\psi^{\lambda_2}_{\beta_2}(\vec{r}_1)]$$

Single-nucleon wave function

$$\psi^\lambda_\beta(\vec{r}) = u_\beta(r) Y_{\ell\lambda}(\hat{r})$$

Absorption cross section

Absorption cross section, three-body projectile

$$\sigma_{abs} = \frac{1}{\hat{J}_i^2} \sum_{M_i} \int d\vec{b}\, \langle \Psi_i | 1 - |\mathcal{S}_f \mathcal{S}_1 \mathcal{S}_2|^2 | \Psi_i \rangle$$

Two-nucleon stripping cross section

$$\sigma_{str} = \frac{1}{\hat{J}_i^2} \sum_{M_i} \int d\vec{b}\, \langle \Psi_i | |\mathcal{S}_f|^2 (1 - |\mathcal{S}_1|^2)(1 - |\mathcal{S}_2|^2) | \Psi_i \rangle$$

Also contributions to diffractive-stripping – one nucleon removed via an elastic interaction; momentum distributions expected to be very similar to pure stripping

Core assumed to be spectator – no dynamic excitation

$$\langle \Phi^{(F')}(A) | |\mathcal{S}_f|^2 | \Phi^{(F)}(A) \rangle = |\mathcal{S}_c|^2 \delta_{FF'}$$

Stripping momentum distributions

Differential two-nucleon stripping cross section

$$\frac{d\sigma^{(f)}_{str}}{d\kappa_c} = \sum_{LST} \frac{d\sigma^{(f)}_{LST}}{d\kappa_c} = \sum_{T} (T\tau T_f\tau_f|T_i\tau_i)^2 \sum_{LSI\alpha\alpha'} \frac{2\mathfrak{C}^{IT}_{\alpha LS}\mathfrak{C}^{IT}_{\alpha' LS} D_\alpha D_{\alpha'}}{\hat{L}^2}$$

$$\int d\kappa_1 \int d\kappa_2\; \delta(\kappa_c + \kappa_1 + \kappa_2) \int d\vec{b}\; |\mathcal{S}_c(b)|^2$$

$$\sum_{\Lambda\lambda_1\lambda_2\lambda_1'\lambda_2'} (\ell_1\lambda_1\ell_2\lambda_2|L\Lambda)\,(\ell_1'\lambda_1'\ell_2'\lambda_2'|L\Lambda)$$

$$\int ds_1 s_1 \int ds_2 s_2\, [direct - exchange]$$

$$direct = \left\{\mathcal{H}_{\lambda_1\lambda_1'}(1)\mathcal{R}^{\lambda_1}_{\beta_1}(1)\,\mathcal{R}^{\lambda_1'}_{\beta_1'}(1)^*\,\mathcal{H}_{\lambda_2\lambda_2'}(2)\mathcal{R}^{\lambda_2}_{\beta_2}(2)\,\mathcal{R}^{\lambda_2'}_{\beta_2'}(2)^*\right\}$$

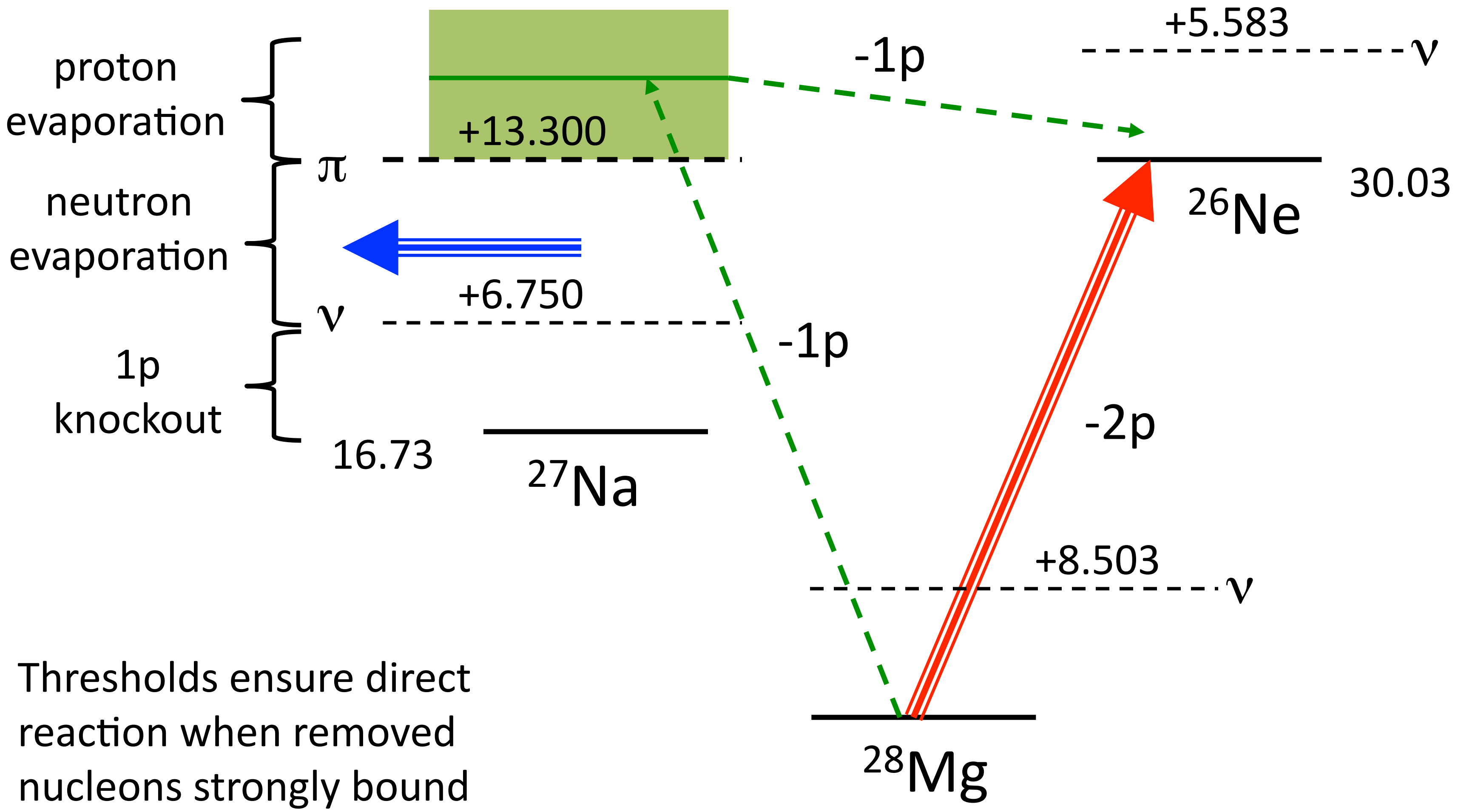
$$exchange = (-1)^{S+T}\left\{\mathcal{H}_{\lambda_2\lambda_1'}(1)\mathcal{R}^{\lambda_2}_{\beta_2}(1)\,\mathcal{R}^{\lambda_1'}_{\beta_1'}(1)^*\,\mathcal{H}_{\lambda_1\lambda_2'}(2)\mathcal{R}^{\lambda_1}_{\beta_1}(2)\,\mathcal{R}^{\lambda_2'}_{\beta_2'}(2)^*\right\}$$

LS-coupled amplitude

$$\mathfrak{C}^{IT}_{\alpha LS} = \hat{j}_1\,\hat{j}_2\,\hat{L}\,\hat{S}\left\{\begin{array}{ccc} \ell_1 & s & j_1 \\ \ell_2 & s & j_2 \\ L & S & I \end{array}\right\} C^{IT}_{\alpha}$$

Spectroscopy and structure sensitivities

Example 1: ^{28}Mg(-2p) thresholds



Thresholds ensure direct reaction when removed nucleons strongly bound

Tostevin *et al.*, PRC 70, 064602 (2004); Tostevin *et al.*, PRC 74, 064604 (2006)

Example 1: ^{28}Mg(-2p) calculation input

Radial wave functions calculated in a Woods-Saxon, the geometry of which is fitted to Hartree-Fock rms radii and binding energies.

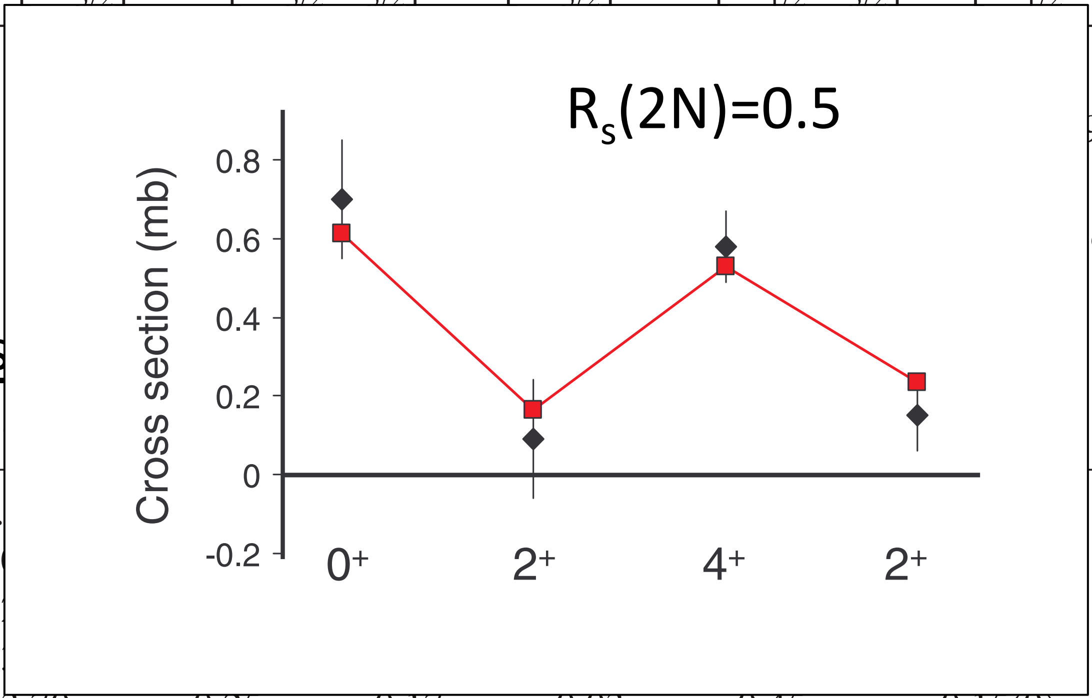
Hartree-Fock density used to calculate residue-target S-matrix.

Full sd-shell USD two-nucleon amplitudes

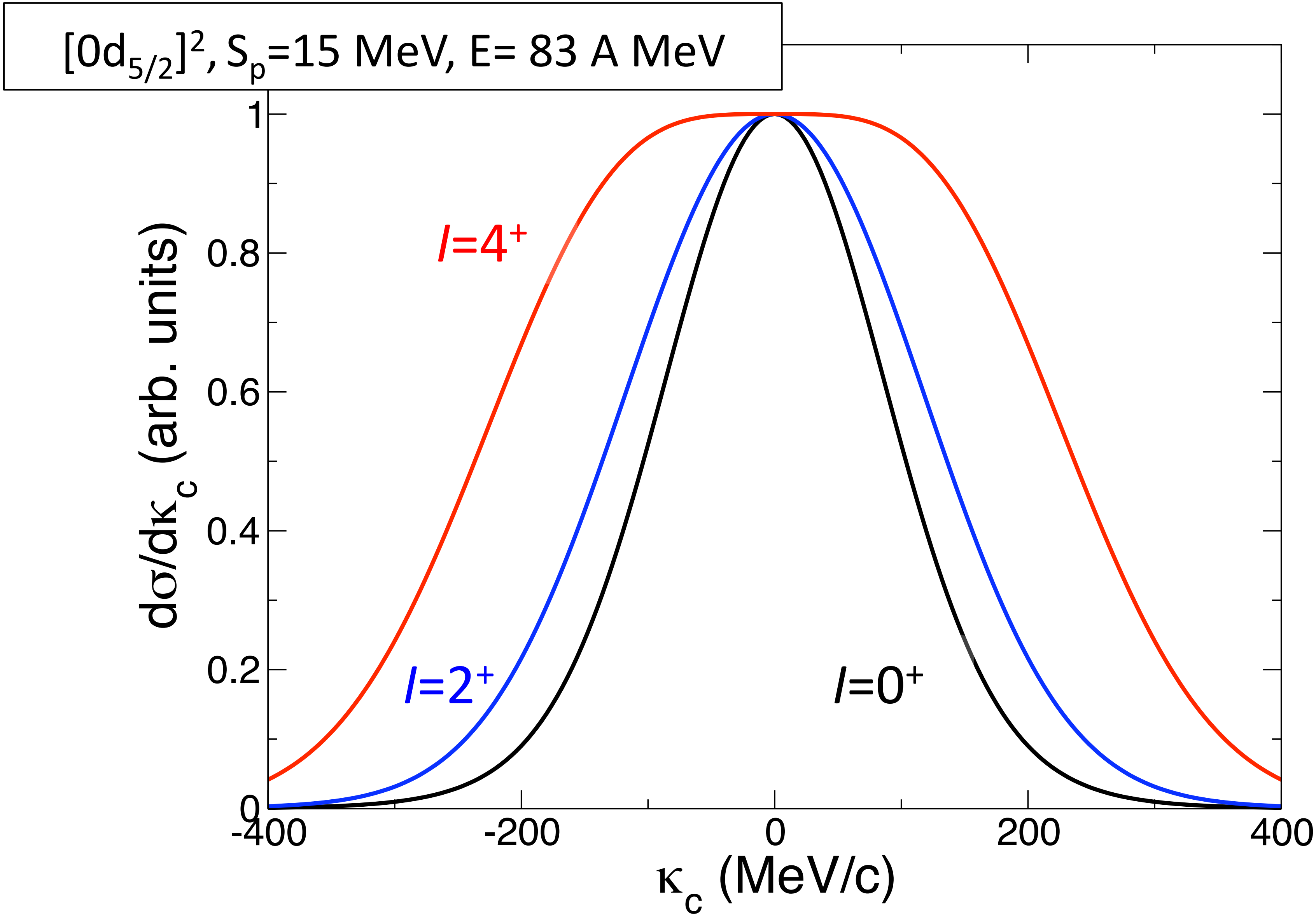
J_f^π	E^* (MeV)	$[0d_{3/2}]^2$	$[0d_{3/2}0d_{5/2}]$	$[0d_{5/2}]^2$	$[1s_{1/2}0d_{3/2}]$	$[1s_{1/2}0d_{5/2}]$	$[1s_{1/2}]^2$
0_1^+	0.0						–0.30496
2_1^+	2.02					916	—
4_1^+	3.50						—
2_2^+	3.70					90	—

Cross sections

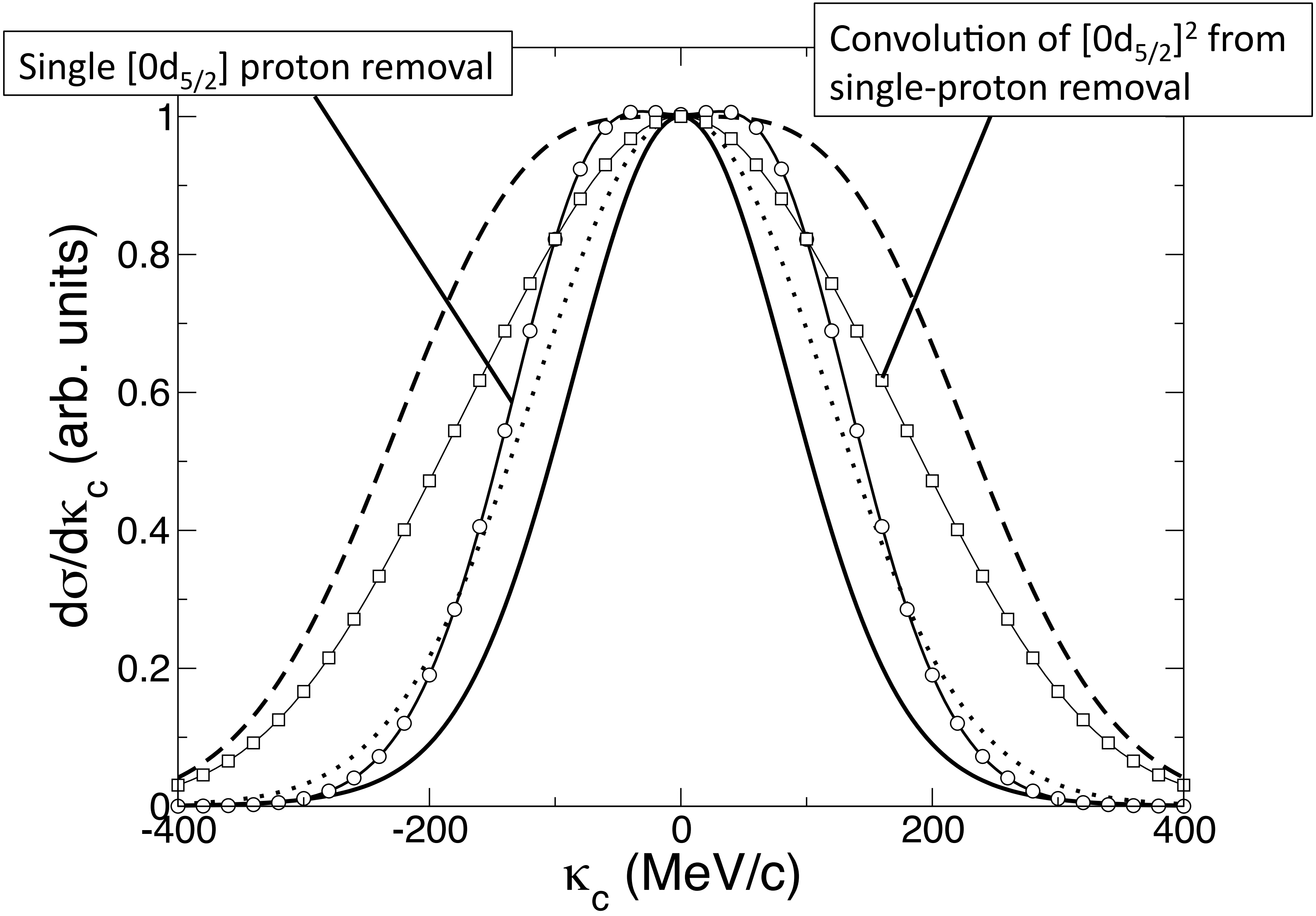
J_f^π	E						$R_s(2N)$
^{28}Mg $\rightarrow$ ^{26}Ne	83.						
0^+							0.59(13)
2_1^+							0.28(47)
4^+							0.57(9)
2_2^+	3.70	0.25	0.17	0.03	0.45	0.15(9)	0.33(20)
Incl.					2.98	1.50(10)	0.50(3)



Example I: ^{28}Mg(-2p) $[0d_{5/2}]^2$



Example 1: Single/Uncorrelated



Single $[0d_{5/2}]$ proton removal

Convolution of $[0d_{5/2}]^2$ from single-proton removal

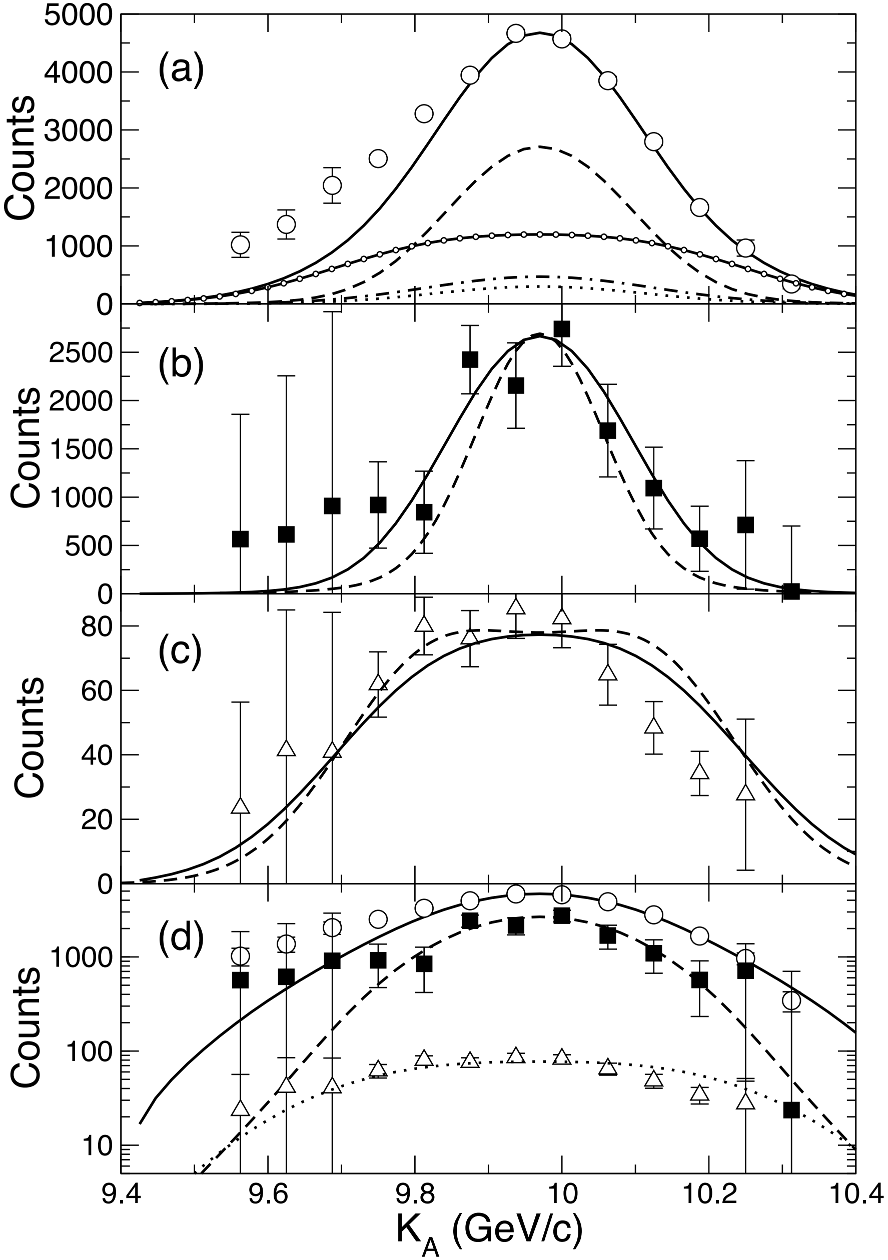
Example 1: ^{28}Mg(-2p) momentum distributions

^{28}Mg(-2p)

Beam energy
E = 82.3 A MeV

S_p = 16.8 MeV
S_n = 8.5 MeV

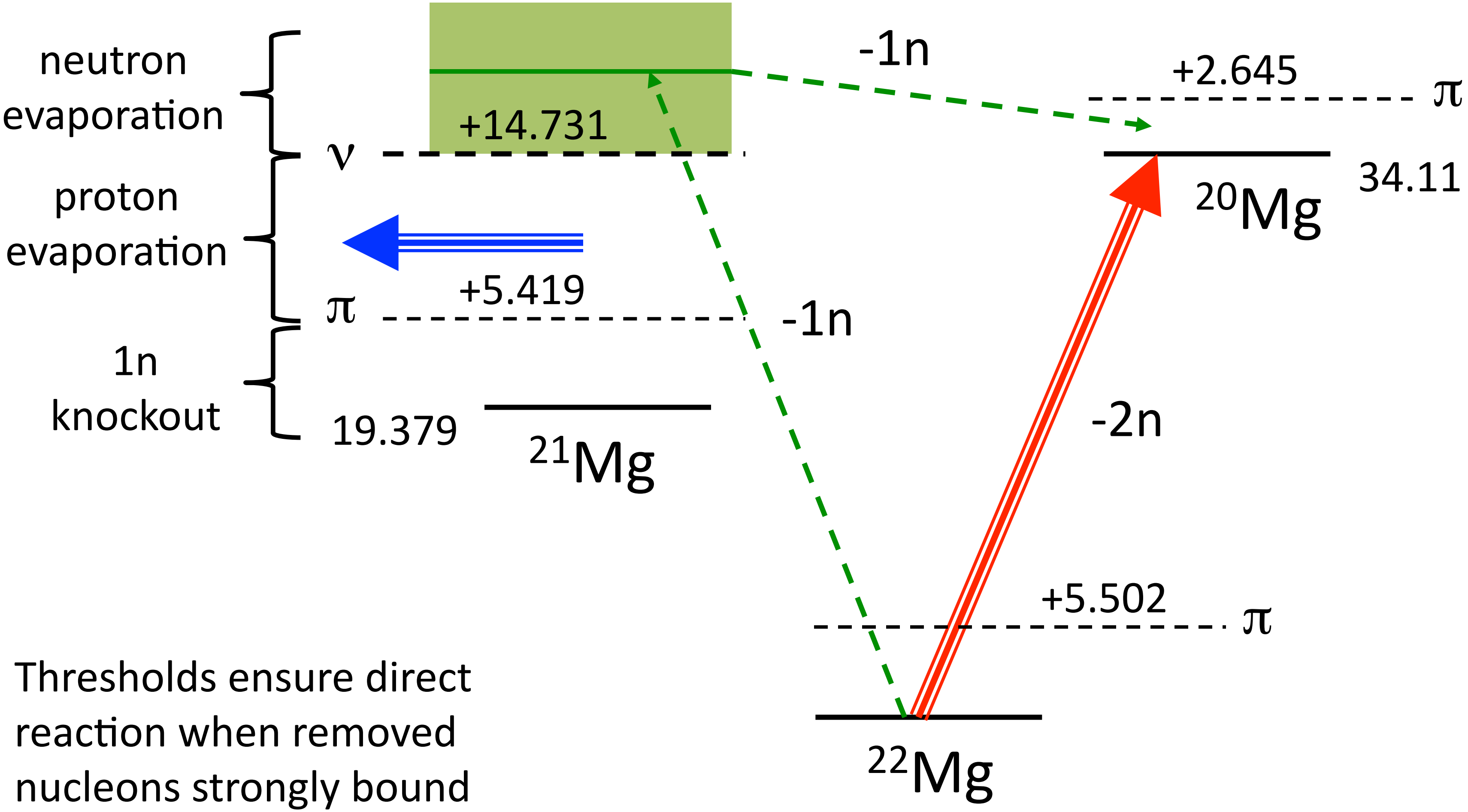
Broadening in thick reaction target
^{9}Be 375 mg/cm^2
ΔK_A = 0.29 GeV/c



Bazin *et al.*, PRL 91 012501 (2003)
Simpson *et al.*, PRL 102, 132502 (2009)

Example 2: ^{22}Mg(-2n) thresholds

^{22}Mg(-2n)



Thresholds ensure direct reaction when removed nucleons strongly bound

Tostevin *et al.*, PRC 70, 064602 (2004); Tostevin *et al.*, PRC 74, 064604 (2006)

Example 2: ^{22}Mg(-2n) structure input

USD two-nucleon amplitudes

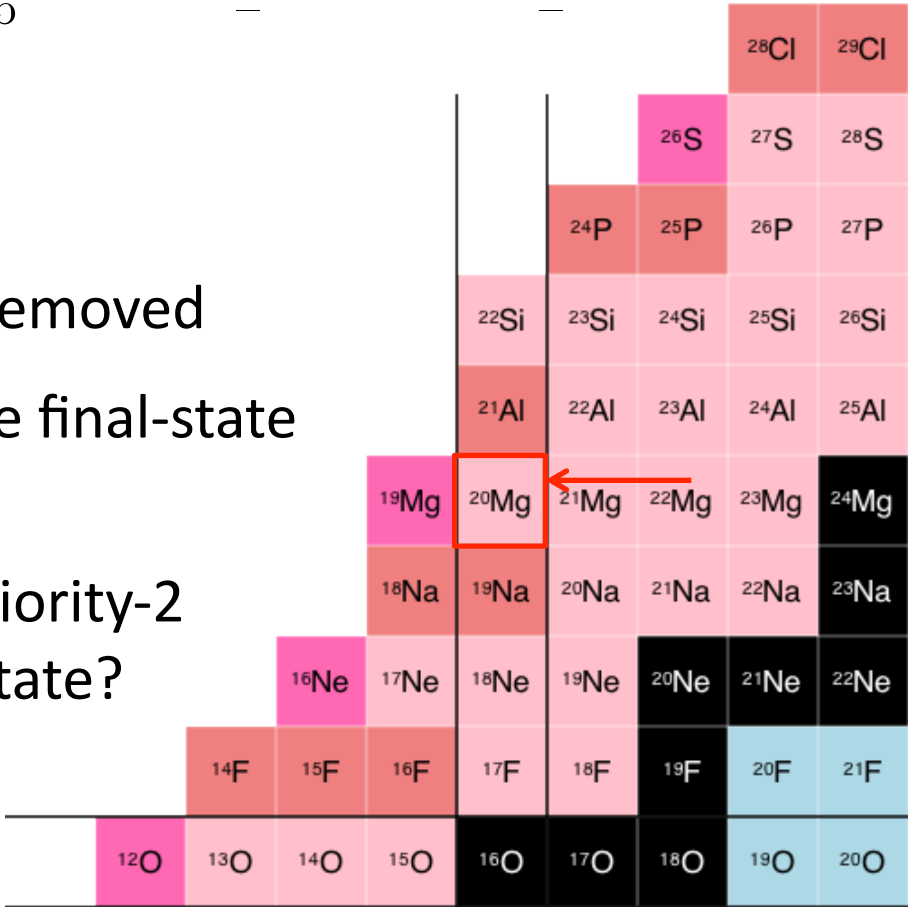
J^π_f	$[0d_{5/2}]^2$	$[0d_{3/2}]^2$	$[1s_{1/2}]^2$	$[0d_{3/2}][0d_{5/2}]$	$[0d_{5/2}][1s_{1/2}]$	$[0d_{3/2}][1s_{1/2}]$
0^+	0.8029	0.2546	0.3784	–	–	–
2^+	0.4566	0.1010	–	-0.1937	0.5244	-0.1983
4^+	-0.0153	–	–	-0.0175	–	–

N=10 → N=8

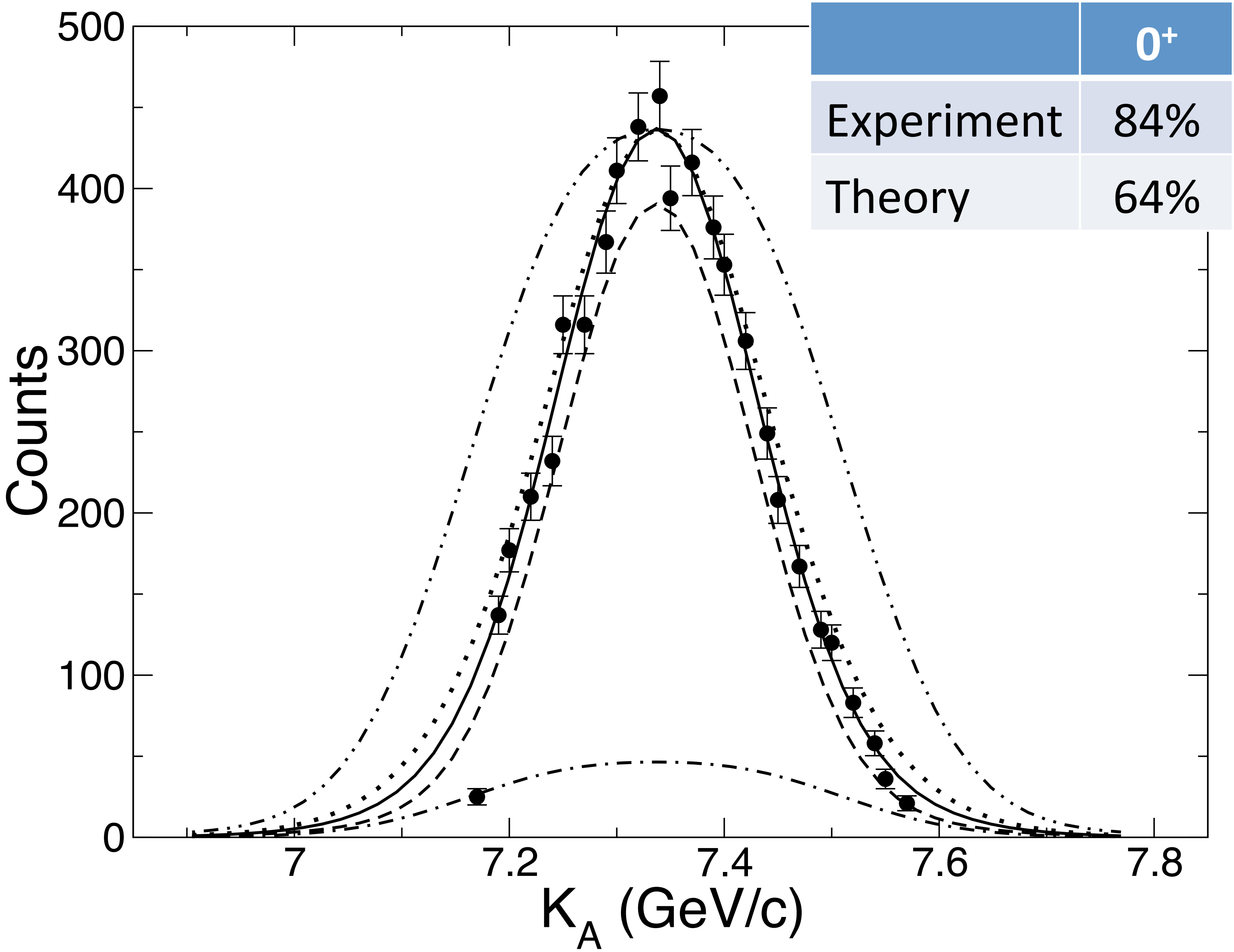
Last two neutrons in the sd-shell removed

Must necessarily be coupled to the final-state spin in the ^{22}Mg ground state

What could this tell use about seniority-2 components of the ^{22}Mg ground state?



Example 2: ^{22}Mg(-2n) momentum distributions



	0^+	2^+
Experiment	84%	16%
Theory	64%	36%

Gade *et al.*, PRC 76, 024317 (2007)

Spatial correlations

Joint position probability

Cross section in terms of joint position probability

$$\sigma_{\rm str}^{(f)} = \int d\vec{b} \int d\vec{s}_1 \int d\vec{s}_2 \, \mathcal{P}_f(\vec{s}_1, \vec{s}_2) \mathcal{O}_{\rm str}(c, 1, 2),$$

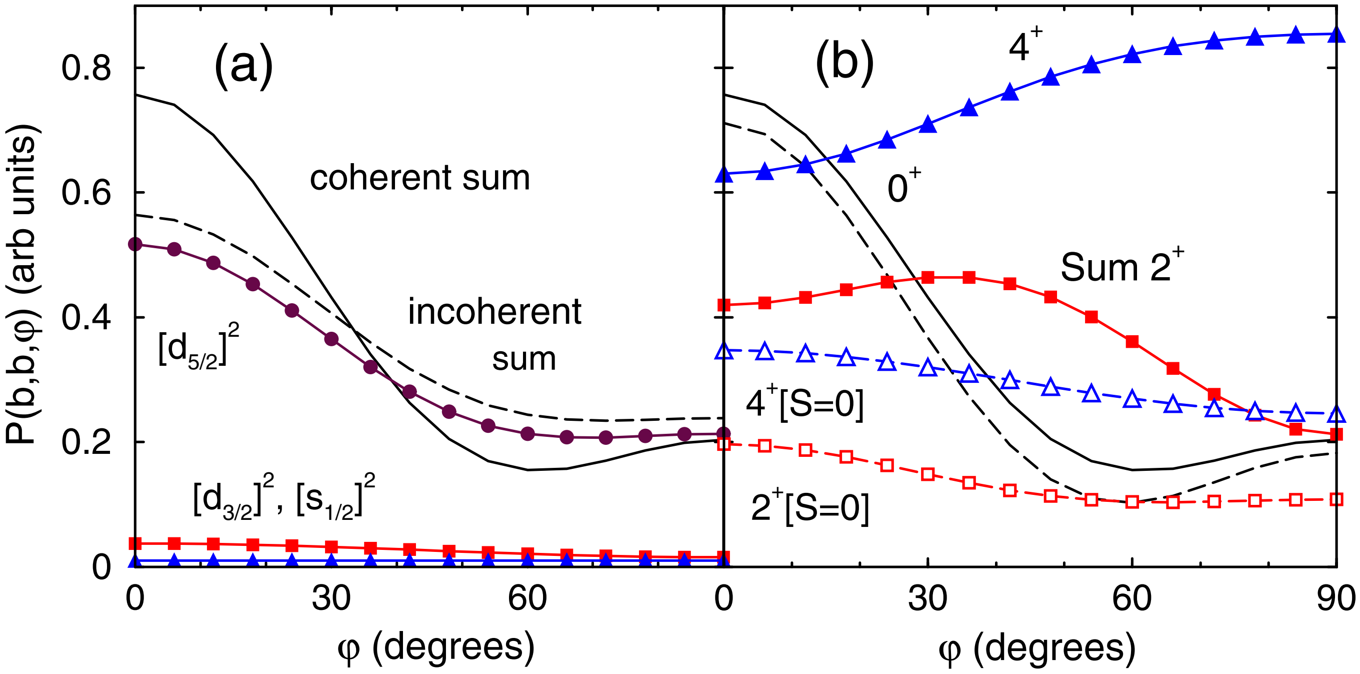
Joint position probability

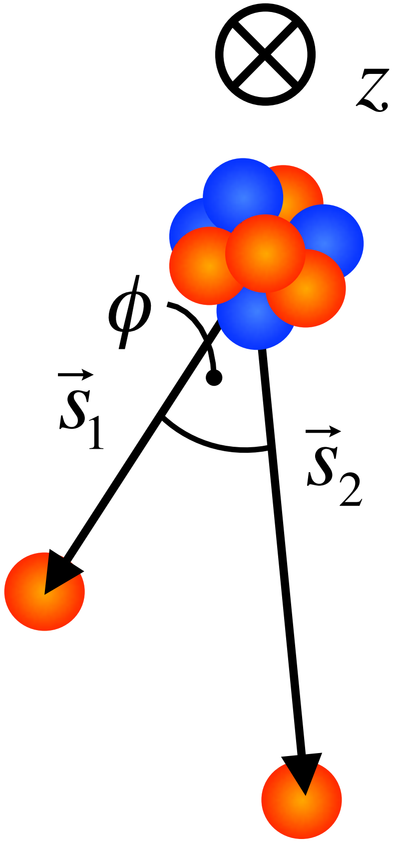
$$\mathcal{P}_f(\vec{s}_1, \vec{s}_2) = \frac{1}{\hat{J}_i^{\,2}} \sum_{M_i M_f} \int dz_1 \int dz_2 \left\langle \left| \Psi_{J_i M_i}^{(F)} \right|^2 \right\rangle_{\rm sp}.$$

Reaction probes JPP – two-nucleon overlap projected onto the impact parameter plane

Spatial correlations I

Joint position probability projected on to the impact parameter plane, displayed as the azimuthal angular separation of nucleons 1 and 2 for fixed b.

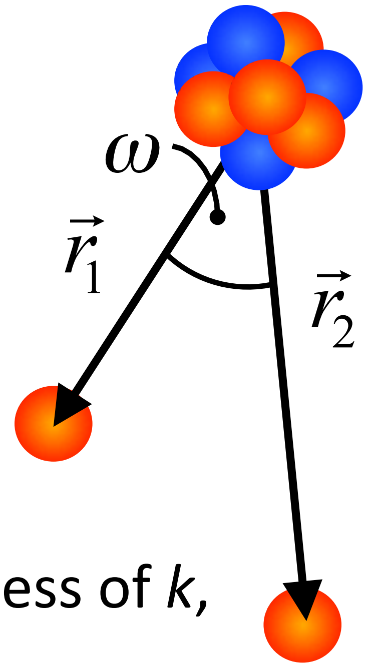




Tostevin, J. Phys. Conf. Ser. 49, 21 (2006)

Spatial correlations II

Determines the probability for angular separation, reaction geometry determines how ω is probed



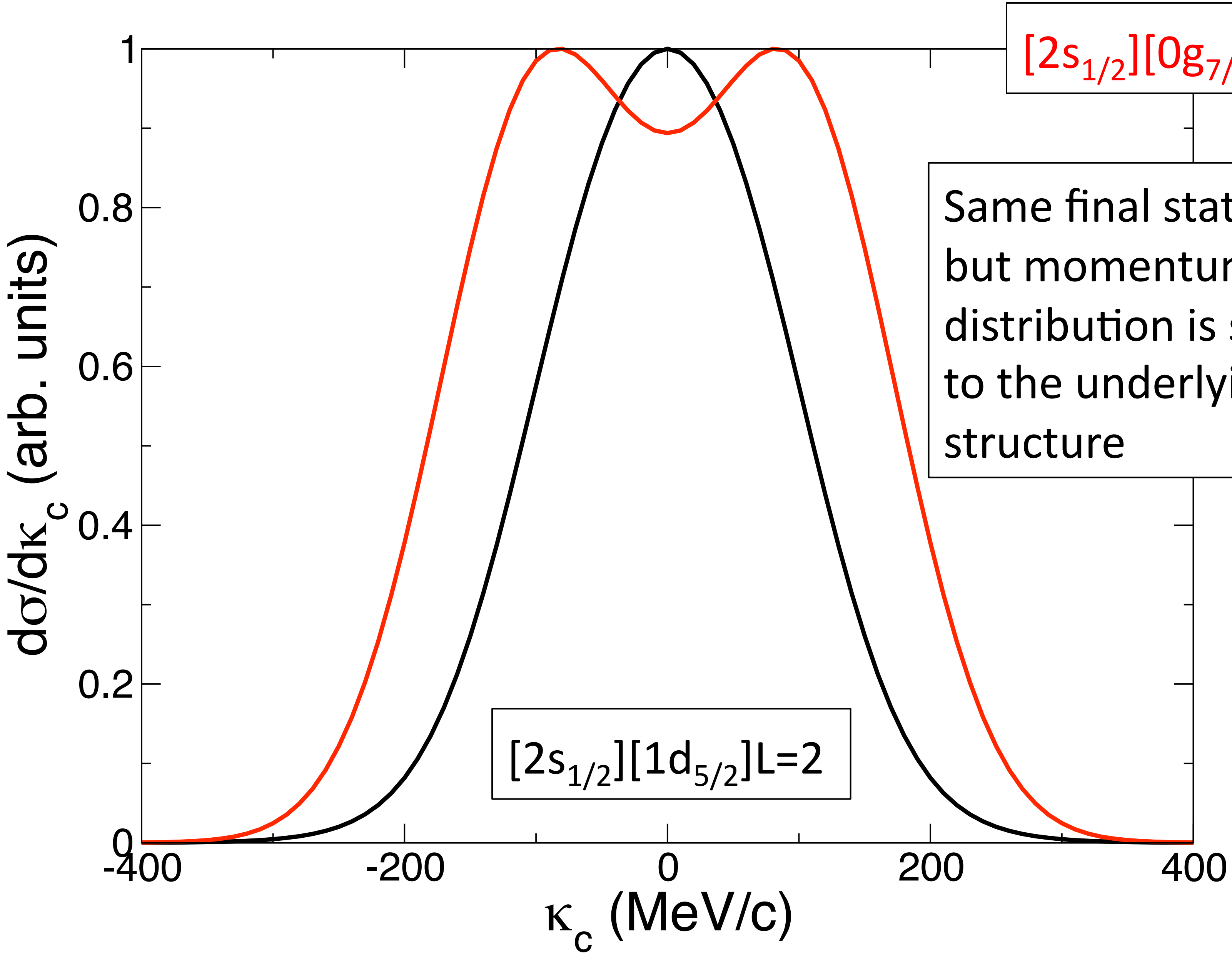
$$\Gamma^L_{\ell_1\ell_2\ell_1'\ell_2'}(\omega) = (-1)^L \frac{\hat{\ell}_1\hat{\ell}_1'\hat{\ell}_2\hat{\ell}_2'\hat{L}^2}{(4\pi)^2} \sum_k W(\ell_1\ell_2\ell_1'\ell_2'; Lk)$$
$$\times (-1)^k \, (\ell_1 0 \ell_1' 0|k0) \, (\ell_2 0 \ell_2' 0|k0) \, P_k(\cos\omega)$$

Evenness with respect to cos ω = 0 depends on evenness of *k*, itself dependent on evenness of l_1 and l_1' (l_2 and l_2')

1. Structure sensitivity of momentum distributions?
2. Large basis calculations
3. Cross-shell excitations

Catara *et al.*, PRC 29, 1091 (1984)
Pinkston, PRC 29, 1123 (1984)
Tischler *et al.*, PRC 58, 2591 (1998)

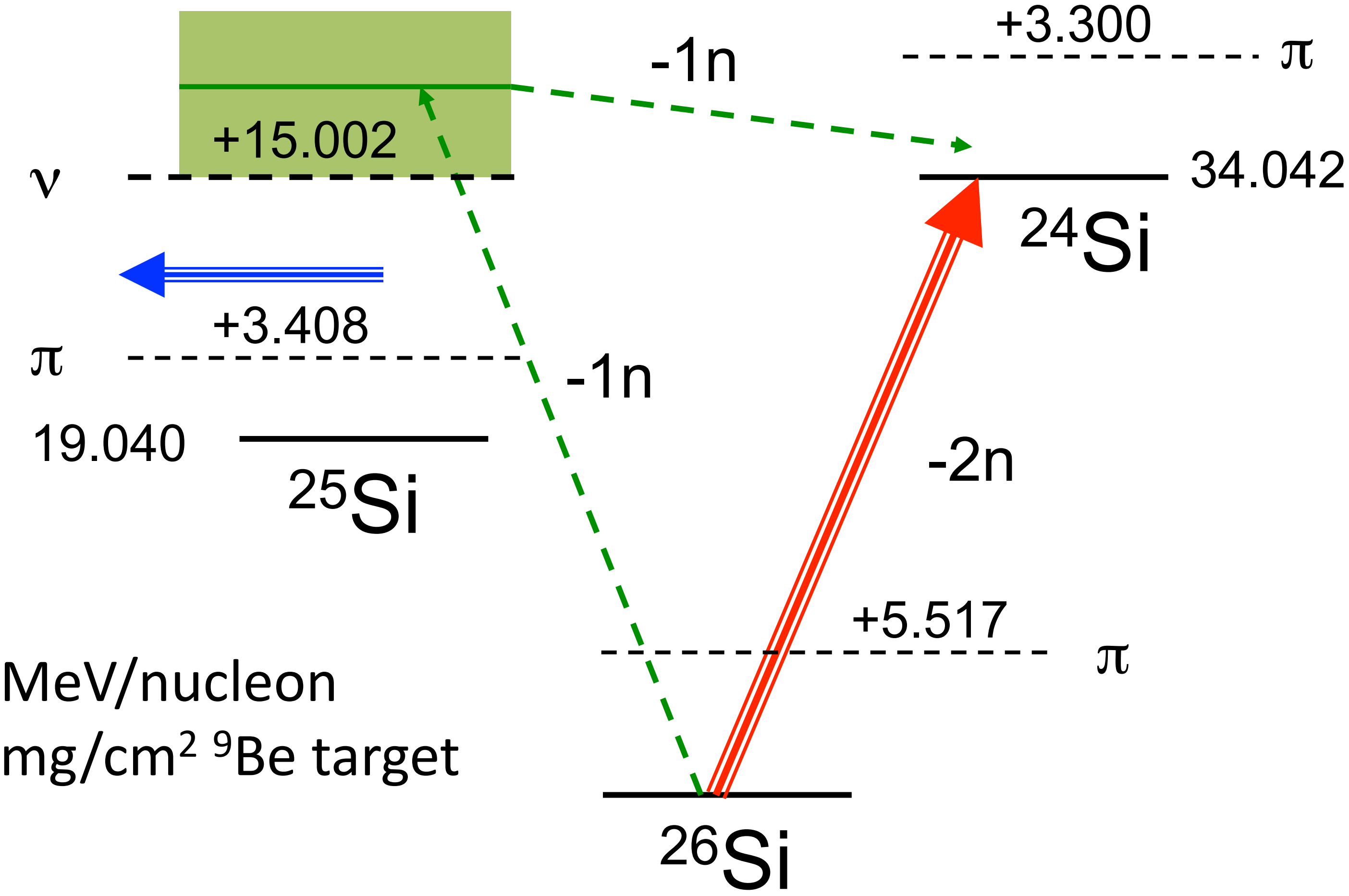
Example: ^{208}Pb(-2p) ⟶ ^{206}Hg(J_f=3$^+$)



Same final state spin, but momentum distribution is sensitive to the underlying structure

^{26}Si(-2n) → ^{24}Si separation thresholds

^{26}Si(-2n)

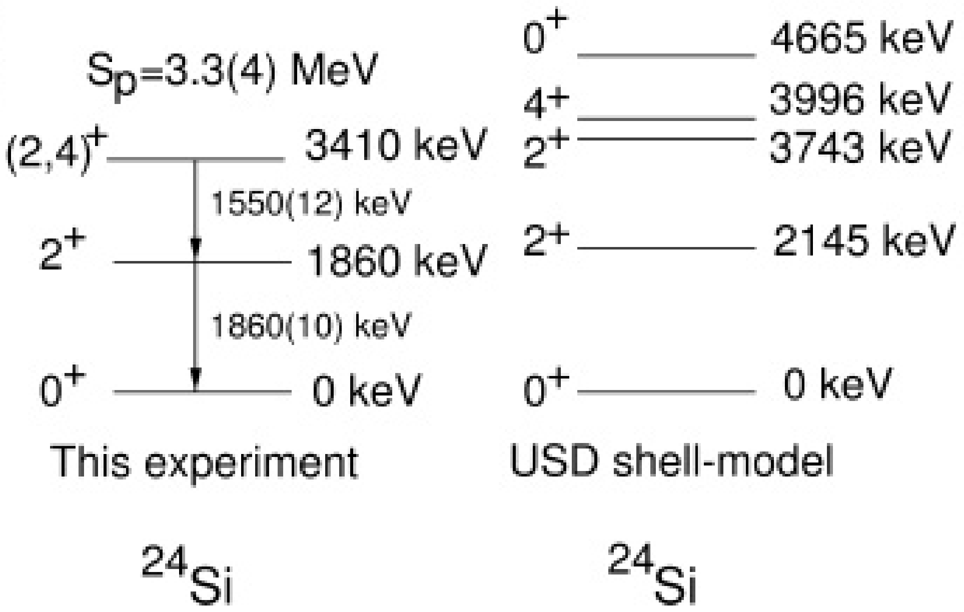


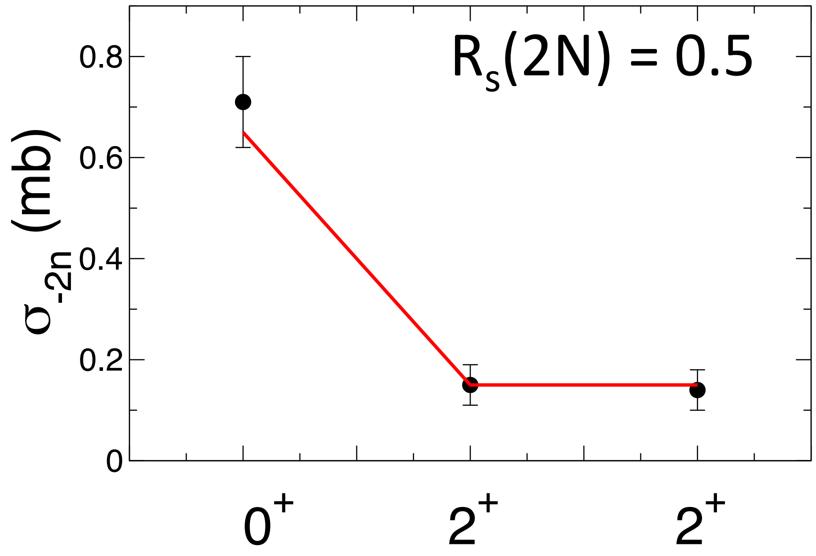
109 MeV/nucleon
376 mg/cm^2 ^{9}Be target

Yoneda *et al.*, PRC 74, 021303(R) (2006)

^{26}Si(-2n): Cross section results

Results





Shell model (sd-shell, USD) two-nucleon amplitudes

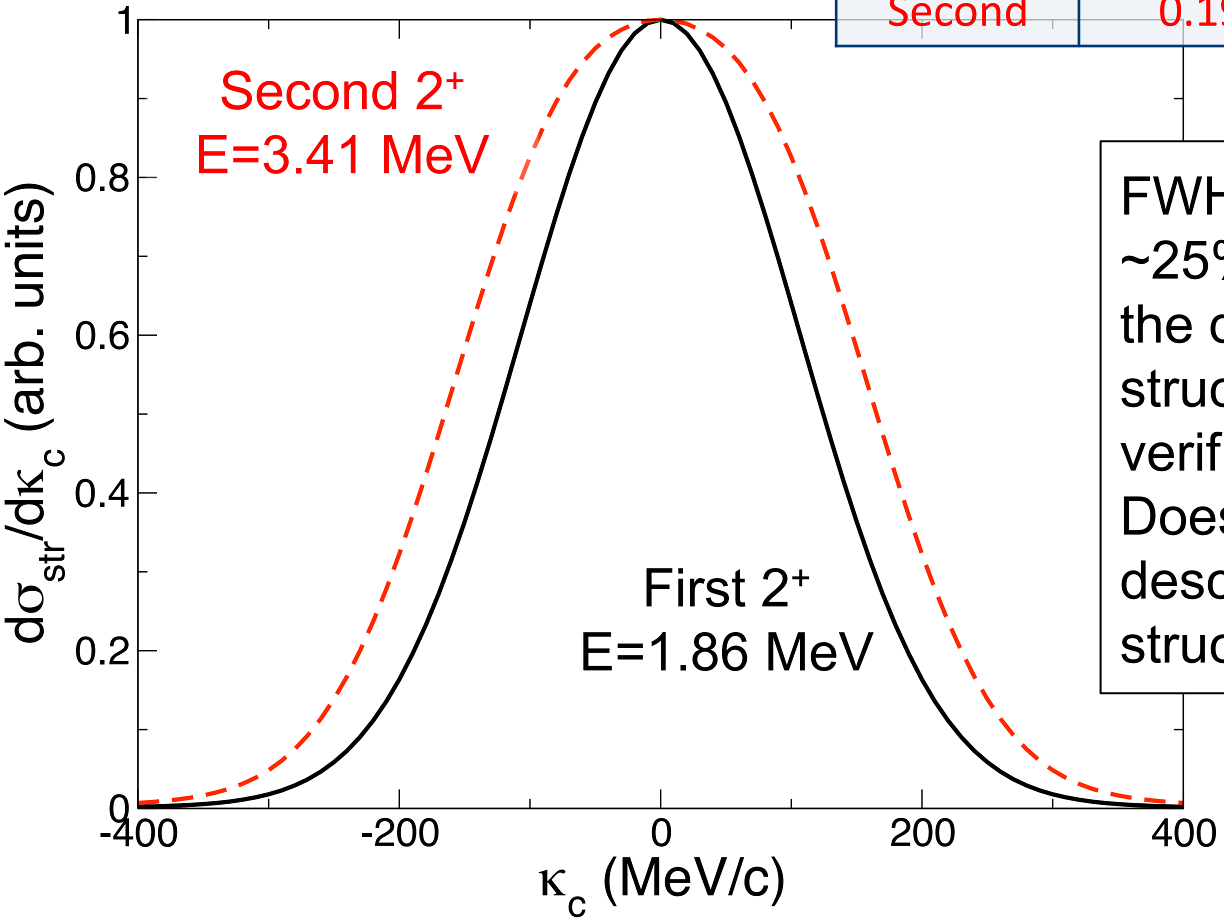
State	$[0d_{5/2}]^2$	$[0d_{5/2},0d_{3/2}]$	$[0d_{3/2}]^2$	$[1s_{1/2},0d_{3/2}]$	$[1s_{1/2},0d_{5/2}]$
2^+ (First)	-0.70074	0.43499	0.00594	-0.00188	-0.02781
2^+ (Second)	-0.38021	-0.12354	-0.12945	-0.15876	-0.58292
4+ (First)	1.57469	0.41519	-	-	-

Yoneda *et al.*, PRC 74, 021303(R) (2006)

Structure Sensitivity

^{26}Si(-2n)

2^+ states	σ_{str} (mb)	σ_{-2n} (mb)	σ_{exp} (mb)
First	0.19	0.30	0.15(4)
Second	0.19	0.30	0.14(4)



FWHM of second state is ~25% larger, attributed to the different underlying structure – can this be verified by experiment? Does the SM accurately describe the underlying structure?

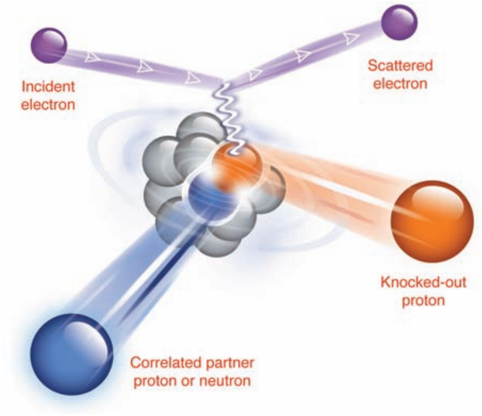
Simpson *et al.*, PRC 82, 044616 (2010)

A. Gade *et al.*, NSCL experiment 10002 (approved)

N=*Z* nuclei: knockout of a proton and neutron

Motivation…

$^{12}C(e,e'pn)^{10}B$



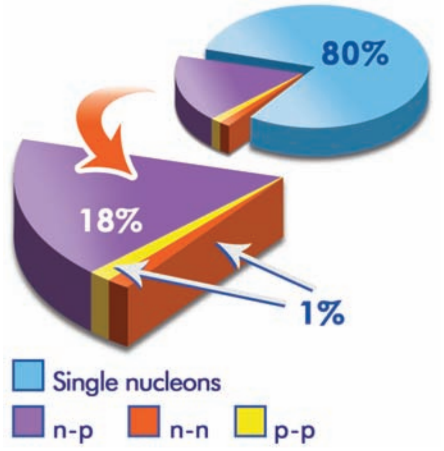


Fig. 3. The average fraction of nucleons in the various initial-state configurations of ^{12}C.

Subedi et al., Science 320, 1476 (2008)

$^{12}C(^{12}C,^{10}Z)X$ and $^{12}C(^{16}O,^{14}Z)X$

Bevatron fragmentation experiments from 1975 show very large np removal cross sections (^{12}C target)

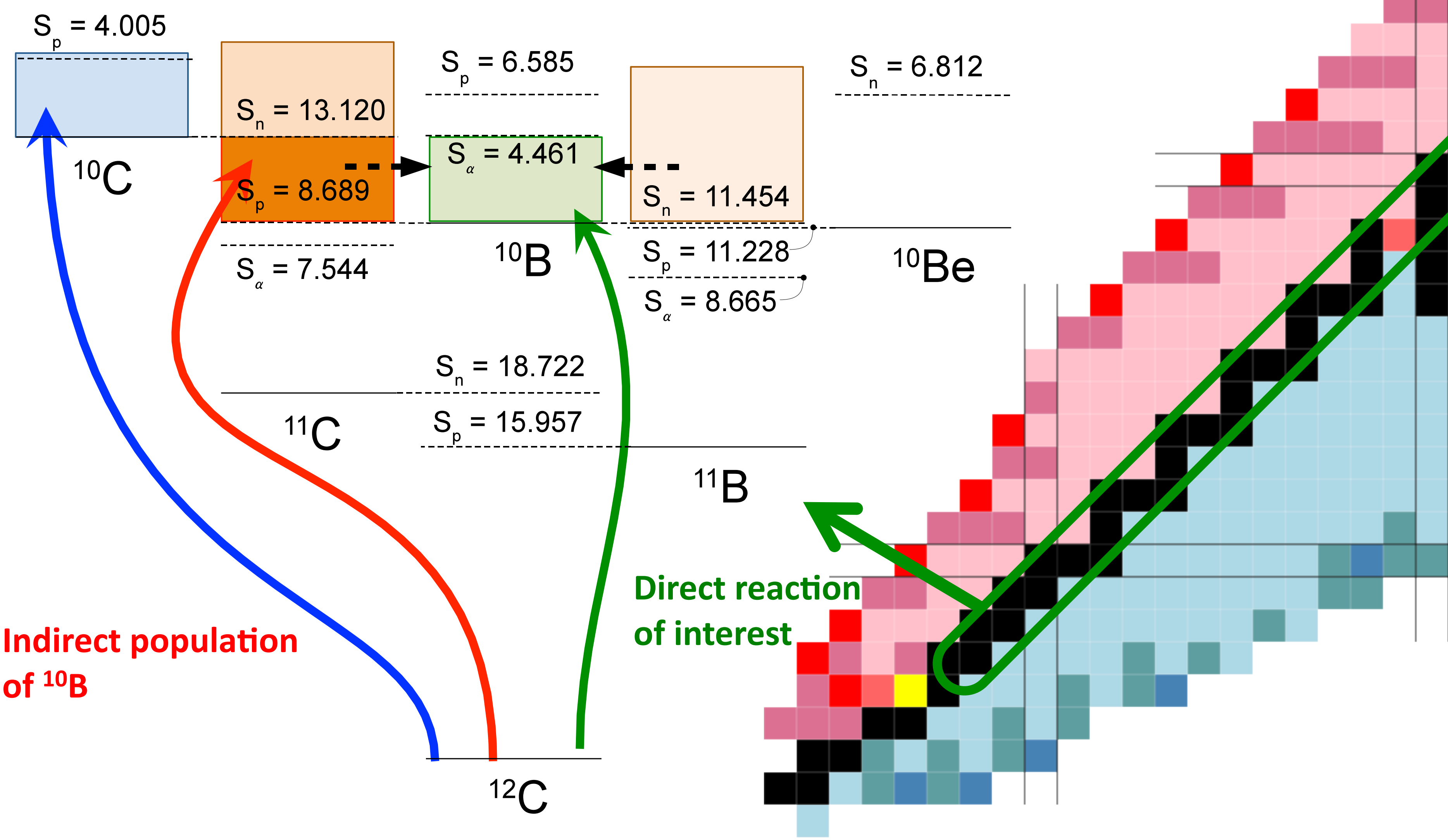
Beam	pp	nn	np
^{12}C (2100 A MeV)	5.81(29)	4.11(22)	35.1(34)
^{12}C (1050 A MeV)	6.49(48)	4.44(25)	27.9(22)
^{12}C (250 A MeV)	5.88(970)	5.33(81)	47.5(24)
^{16}O (2100 A MeV)	4.71(31)	1.67(12)	41.8(33)

Simplest $[0p_{3/2}]^8$ structure suggests $\sigma_{NN}/\sigma_{np} \approx 6/16 \approx 2.7$ for $^{12}C(-2N)$

Lindstrom *et al.*, LBNL Report 3650 (1975)
Greiner *et al.*, PRL 35, 152 (1975)
Kidd *et al.*, 37, 2613 PRC (1988)

^{12}C(-np): direct vs. indirect

Particle Separation Thresholds



S_p = 4.005

^{10}C

S_n = 13.120

S_p = 8.689

S_α = 7.544

^{11}C

S_p = 6.585

S_α = 4.461

^{10}B

S_n = 18.722

S_p = 15.957

S_n = 11.454

S_p = 11.228

S_α = 8.665

^{11}B

S_n = 6.812

^{10}Be

^{12}C

Direct reaction of interest

Indirect population of ^{10}B

^{12}C beam LBL Bevatron results (1975)

Fragmentation of ^{16}O and ^{12}C projectiles studies at LBNL; beam energies 2.1 GeV/nucleon; cross sections and momentum distribution widths published (though averaged over targets)

Oxbash p-shell shell model structure input using WBP (and PJT interactions)

^{12}C projectile, WBP interaction

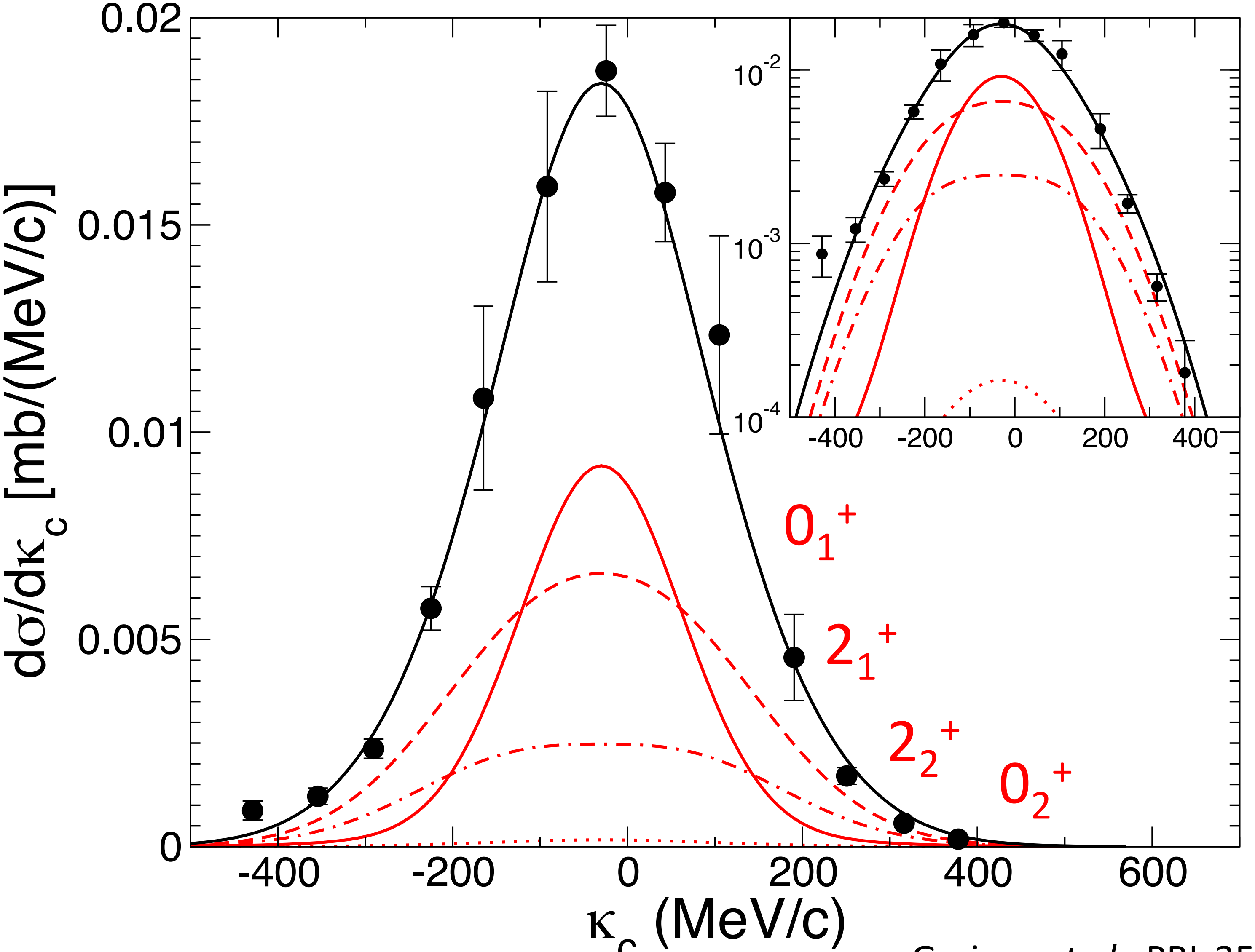
Residue	**^{10}C**		**^{10}Be**		**^{10}B**	
	exp.	theory	exp.	theory	exp.	theory
σ_{-2N} (mb)	4.11±0.22	5.04	5.81±0.29	6.52	35.1±3.4	19.02
Width (MeV/c)*	121±6	120	129±4	127	134±3	132

*Target averaged

Lindstrom *et al.*, LBNL Report 3650 (1975)
Greiner *et al.*, PRL 35, 152 (1975)

$^{12}C(-2p) \rightarrow {}^{10}Be$ momentum distribution

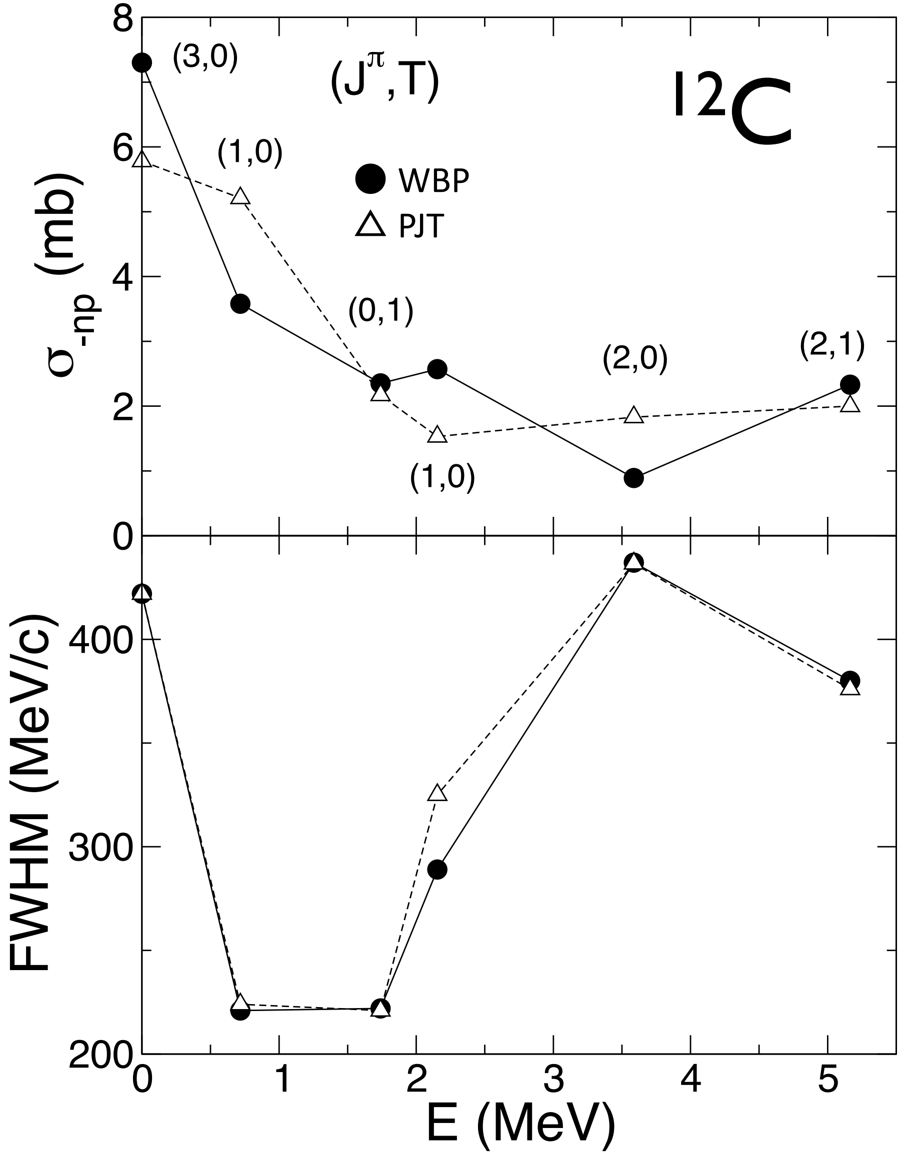
^{10}Be final state inclusive



Greiner *et al.*, PRL 35, 152 (1975)

np-knockout: ^{12}C

- Cross section underestimated: T=1 removal apparently well described (^{10}C, ^{10}Be), so deficiency with T=1 states?
- Some interaction sensitivity for T=0 states, weaker for T=1 states
- Distinct pattern of momentum distributions widths
  - Sensitivity to underlying structure
  - Indications of indirection removal
- Calculations using NCSM amplitudes are underway – can these large basis (N_{max}=6) account for the cross section deficit?

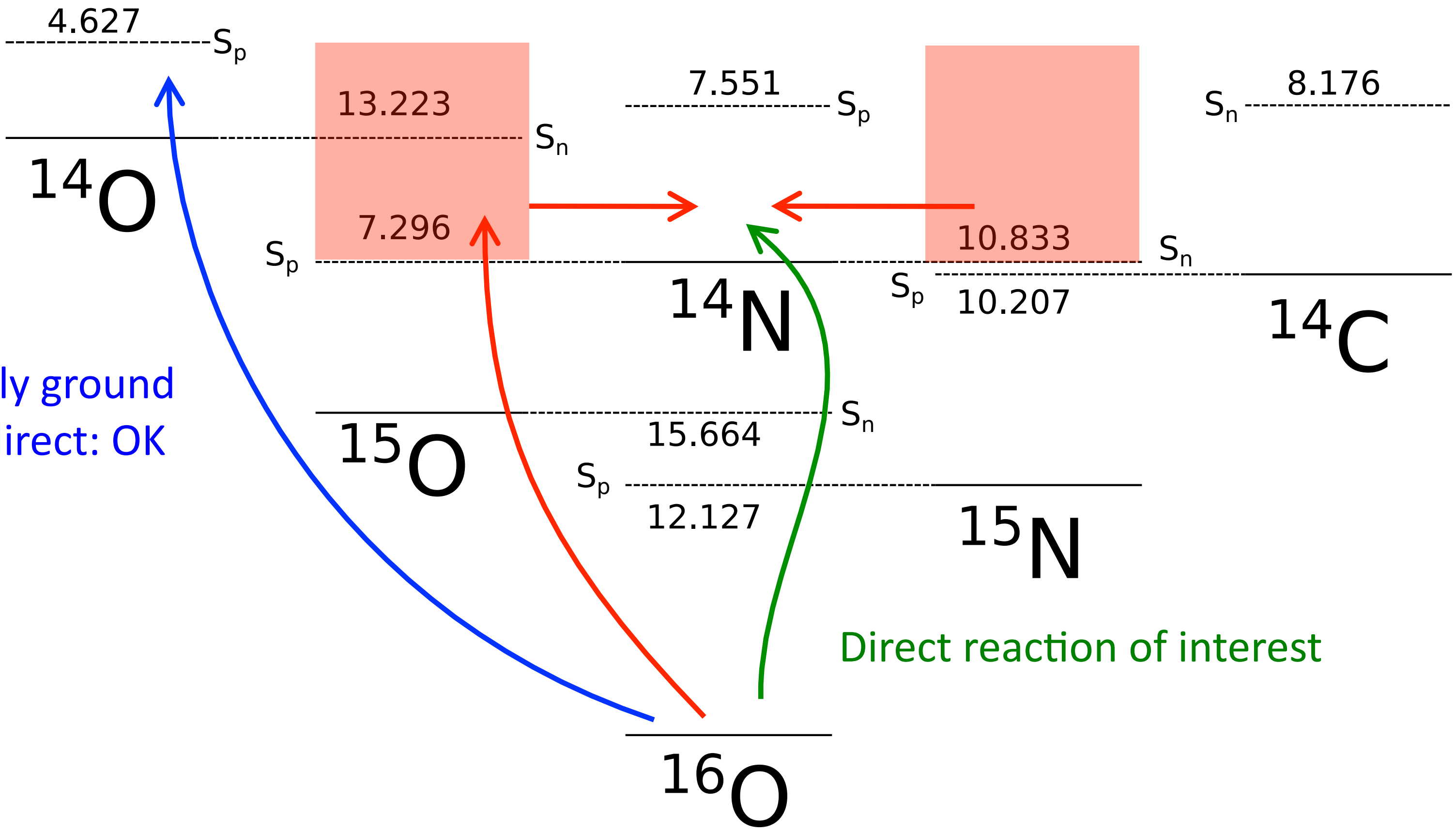


Simpson and Tostevin, PRC 83, 014605 (2011)

^{16}O(-np): direct vs. indirect

<u>Nucleon separation thresholds</u>

Possible indirect contributions to removal,
(though little predicted by SM)



-2n: only ground
state, direct: OK

Direct reaction of interest

<u>Oxbash shell model input</u>: spspdpf, wbt

Truncate to p-shell (0 ħω) (also 0+2 ħω, 0+2+4 ħω)

Harmonic oscillator wave functions used, $\hbar\omega = 45A^{-1/3} - 25A^{-2/3}$

$^{16}O(-2n) \rightarrow {}^{14}O$

Preliminary Results

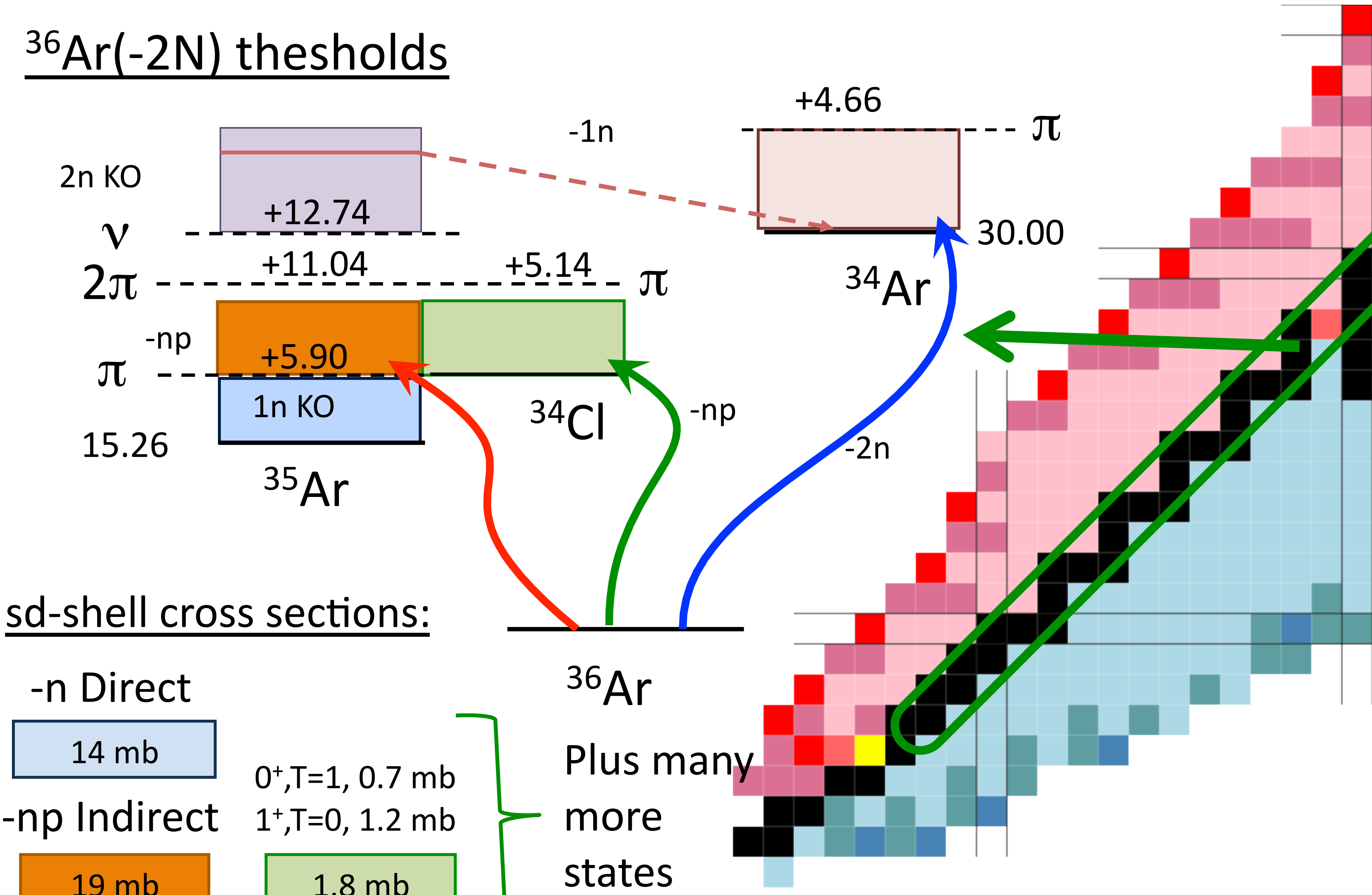
^{14}O	Experiment	0ħω (WBT)	2ħω (WBT)	4ħω (WBT)
σ (mb)	1.67±0.12	1.36	1.36	1.39
Width (MeV/c)	99±6	99.6	96.5	94.4
$\Sigma(TNA)^2$	-	1.00	0.90	0.83

- Good agreement for (very narrow) momentum distribution
- 0ħω theory underestimates experiment in contrast to exotic sd-shell cases and $^{12}C(-2N)$
  - Sizes of core and radial wave functions?
  - Centre of mass corrections to TNA?
- How important are cross-shell excitations?
  - Overlap smaller, cross-shell components enhance spatial correlations, maintaining cross section

see also Warburton *et al.*, PLB 293, 7 (1992)

Along the *N*=*Z* line?

^{36}Ar(-2N) thesholds



2n KO

+12.74

ν

-1n

+4.66

π

30.00

^{34}Ar

2π

+11.04

+5.14

π

-np

π

+5.90

1n KO

15.26

^{35}Ar

^{34}Cl

-np

-2n

^{36}Ar

sd-shell cross sections:

-n Direct

14 mb

-np Indirect

19 mb

0⁺,T=1, 0.7 mb

1⁺,T=0, 1.2 mb

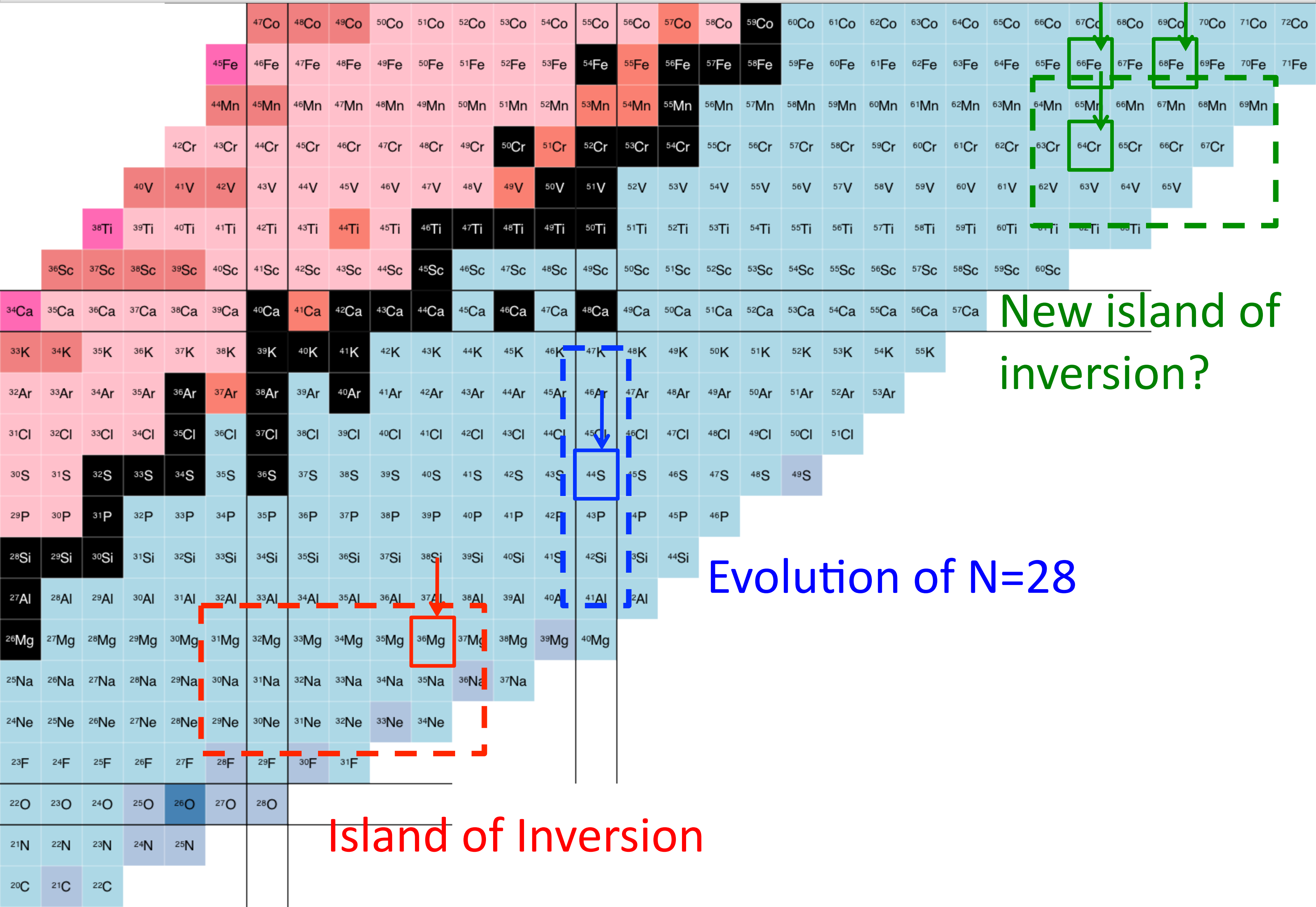
1.8 mb

Plus many more states

Tostevin (personal communication)

Rapid structural change: applications and further work

Structure changes in exotic nuclei



^{47}Co ^{48}Co ^{49}Co ^{50}Co ^{51}Co ^{52}Co ^{53}Co ^{54}Co ^{55}Co ^{56}Co ^{57}Co ^{58}Co ^{59}Co ^{60}Co ^{61}Co ^{62}Co ^{63}Co ^{64}Co ^{65}Co ^{66}Co ^{67}Co ^{68}Co ^{69}Co ^{70}Co ^{71}Co ^{72}Co

^{45}Fe ^{46}Fe ^{47}Fe ^{48}Fe ^{49}Fe ^{50}Fe ^{51}Fe ^{52}Fe ^{53}Fe ^{54}Fe ^{55}Fe ^{56}Fe ^{57}Fe ^{58}Fe ^{59}Fe ^{60}Fe ^{61}Fe ^{62}Fe ^{63}Fe ^{64}Fe ^{65}Fe ^{66}Fe ^{67}Fe ^{68}Fe ^{69}Fe ^{70}Fe ^{71}Fe

^{44}Mn ^{45}Mn ^{46}Mn ^{47}Mn ^{48}Mn ^{49}Mn ^{50}Mn ^{51}Mn ^{52}Mn ^{53}Mn ^{54}Mn ^{55}Mn ^{56}Mn ^{57}Mn ^{58}Mn ^{59}Mn ^{60}Mn ^{61}Mn ^{62}Mn ^{63}Mn ^{64}Mn ^{65}Mn ^{66}Mn ^{67}Mn ^{68}Mn ^{69}Mn

^{42}Cr ^{43}Cr ^{44}Cr ^{45}Cr ^{46}Cr ^{47}Cr ^{48}Cr ^{49}Cr ^{50}Cr ^{51}Cr ^{52}Cr ^{53}Cr ^{54}Cr ^{55}Cr ^{56}Cr ^{57}Cr ^{58}Cr ^{59}Cr ^{60}Cr ^{61}Cr ^{62}Cr ^{63}Cr ^{64}Cr ^{65}Cr ^{66}Cr ^{67}Cr

^{40}V ^{41}V ^{42}V ^{43}V ^{44}V ^{45}V ^{46}V ^{47}V ^{48}V ^{49}V ^{50}V ^{51}V ^{52}V ^{53}V ^{54}V ^{55}V ^{56}V ^{57}V ^{58}V ^{59}V ^{60}V ^{61}V ^{62}V ^{63}V ^{64}V ^{65}V

^{38}Ti ^{39}Ti ^{40}Ti ^{41}Ti ^{42}Ti ^{43}Ti ^{44}Ti ^{45}Ti ^{46}Ti ^{47}Ti ^{48}Ti ^{49}Ti ^{50}Ti ^{51}Ti ^{52}Ti ^{53}Ti ^{54}Ti ^{55}Ti ^{56}Ti ^{57}Ti ^{58}Ti ^{59}Ti ^{60}Ti ^{61}Ti ^{62}Ti ^{63}Ti

^{36}Sc ^{37}Sc ^{38}Sc ^{39}Sc ^{40}Sc ^{41}Sc ^{42}Sc ^{43}Sc ^{44}Sc ^{45}Sc ^{46}Sc ^{47}Sc ^{48}Sc ^{49}Sc ^{50}Sc ^{51}Sc ^{52}Sc ^{53}Sc ^{54}Sc ^{55}Sc ^{56}Sc ^{57}Sc ^{58}Sc ^{59}Sc ^{60}Sc

^{34}Ca ^{35}Ca ^{36}Ca ^{37}Ca ^{38}Ca ^{39}Ca ^{40}Ca ^{41}Ca ^{42}Ca ^{43}Ca ^{44}Ca ^{45}Ca ^{46}Ca ^{47}Ca ^{48}Ca ^{49}Ca ^{50}Ca ^{51}Ca ^{52}Ca ^{53}Ca ^{54}Ca ^{55}Ca ^{56}Ca ^{57}Ca

^{33}K ^{34}K ^{35}K ^{36}K ^{37}K ^{38}K ^{39}K ^{40}K ^{41}K ^{42}K ^{43}K ^{44}K ^{45}K ^{46}K ^{47}K ^{48}K ^{49}K ^{50}K ^{51}K ^{52}K ^{53}K ^{54}K ^{55}K

^{32}Ar ^{33}Ar ^{34}Ar ^{35}Ar ^{36}Ar ^{37}Ar ^{38}Ar ^{39}Ar ^{40}Ar ^{41}Ar ^{42}Ar ^{43}Ar ^{44}Ar ^{45}Ar ^{46}Ar ^{47}Ar ^{48}Ar ^{49}Ar ^{50}Ar ^{51}Ar ^{52}Ar ^{53}Ar

^{31}Cl ^{32}Cl ^{33}Cl ^{34}Cl ^{35}Cl ^{36}Cl ^{37}Cl ^{38}Cl ^{39}Cl ^{40}Cl ^{41}Cl ^{42}Cl ^{43}Cl ^{44}Cl ^{45}Cl ^{46}Cl ^{47}Cl ^{48}Cl ^{49}Cl ^{50}Cl ^{51}Cl

^{30}S ^{31}S ^{32}S ^{33}S ^{34}S ^{35}S ^{36}S ^{37}S ^{38}S ^{39}S ^{40}S ^{41}S ^{42}S ^{43}S ^{44}S ^{45}S ^{46}S ^{47}S ^{48}S ^{49}S

^{29}P ^{30}P ^{31}P ^{32}P ^{33}P ^{34}P ^{35}P ^{36}P ^{37}P ^{38}P ^{39}P ^{40}P ^{41}P ^{42}P ^{43}P ^{44}P ^{45}P ^{46}P

^{28}Si ^{29}Si ^{30}Si ^{31}Si ^{32}Si ^{33}Si ^{34}Si ^{35}Si ^{36}Si ^{37}Si ^{38}Si ^{39}Si ^{40}Si ^{41}Si ^{42}Si ^{43}Si ^{44}Si

^{27}Al ^{28}Al ^{29}Al ^{30}Al ^{31}Al ^{32}Al ^{33}Al ^{34}Al ^{35}Al ^{36}Al ^{37}Al ^{38}Al ^{39}Al ^{40}Al ^{41}Al ^{42}Al

^{26}Mg ^{27}Mg ^{28}Mg ^{29}Mg ^{30}Mg ^{31}Mg ^{32}Mg ^{33}Mg ^{34}Mg ^{35}Mg ^{36}Mg ^{37}Mg ^{38}Mg ^{39}Mg ^{40}Mg

^{25}Na ^{26}Na ^{27}Na ^{28}Na ^{29}Na ^{30}Na ^{31}Na ^{32}Na ^{33}Na ^{34}Na ^{35}Na ^{36}Na ^{37}Na

^{24}Ne ^{25}Ne ^{26}Ne ^{27}Ne ^{28}Ne ^{29}Ne ^{30}Ne ^{31}Ne ^{32}Ne ^{33}Ne ^{34}Ne

^{23}F ^{24}F ^{25}F ^{26}F ^{27}F ^{28}F ^{29}F ^{30}F ^{31}F

^{22}O ^{23}O ^{24}O ^{25}O ^{26}O ^{27}O ^{28}O

^{21}N ^{22}N ^{23}N ^{24}N ^{25}N

^{20}C ^{21}C ^{22}C

New island of inversion?

Evolution of N=28

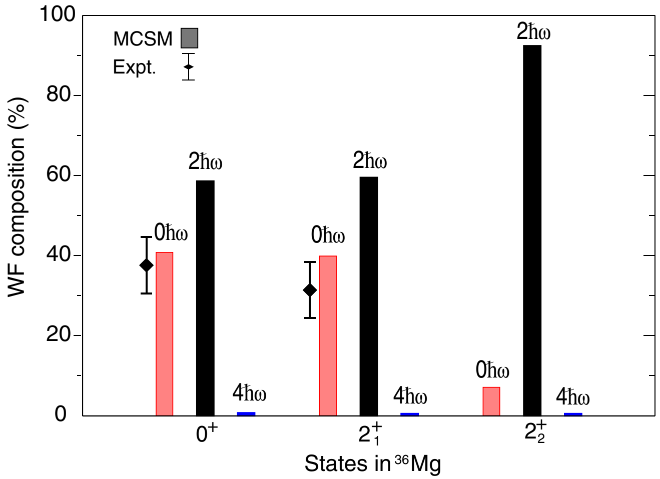
Island of Inversion

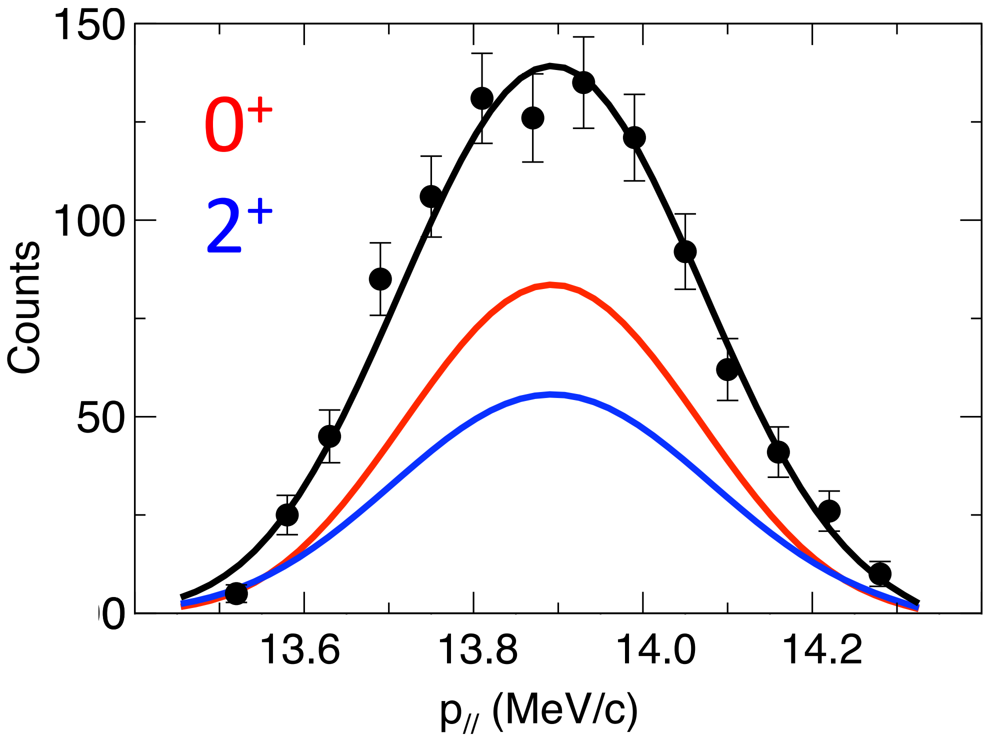
Island of Inversion: ^{38}Si(-2p) → ^{36}Mg

^{38}Si(-2p) → ^{36}Mg

Exp. (mb)	0 ħω Theory (mb)
0.10±0.01	0.28

Ratio of experimental to pure 0 ħω theoretical cross sections gives indications of fraction of 2 ħω components, agreeing with MCSM calculations





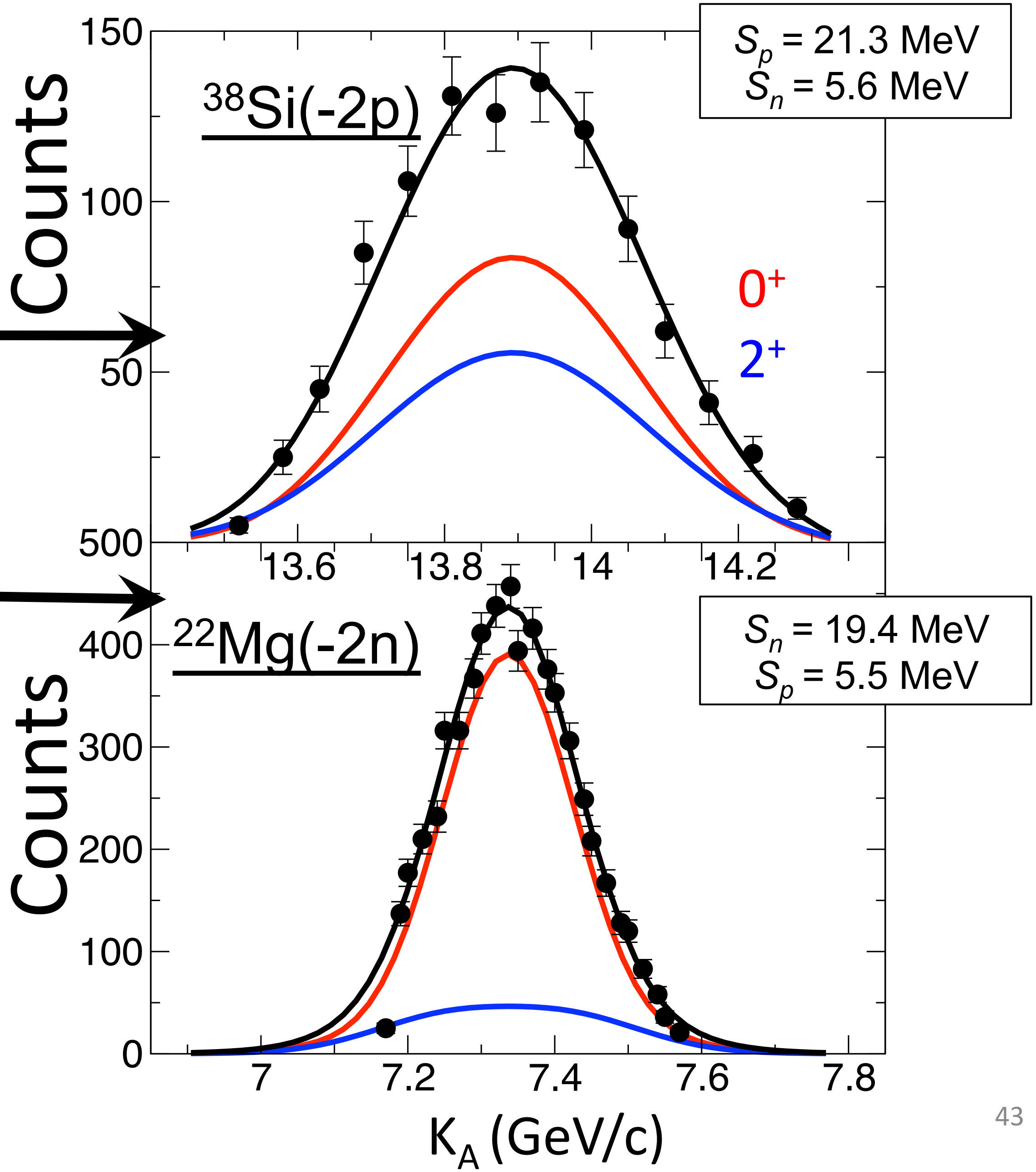
Gade et al., PRC 77, 044306 (2008)

Spherical model does not track structural changes

^{22}Mg(-2n) vs. ^{38}Si(-2p)

Target: ^{9}Be 376 mg/cm^{2}
Energy: 83 A MeV
Beam: ΔK = 1.66%
Target: ΔK = 0.29 GeV/c

Target: ^{9}Be 188 mg/cm^{2}
Energy: 75.1 MeV
Beam: ΔK = 0.5%



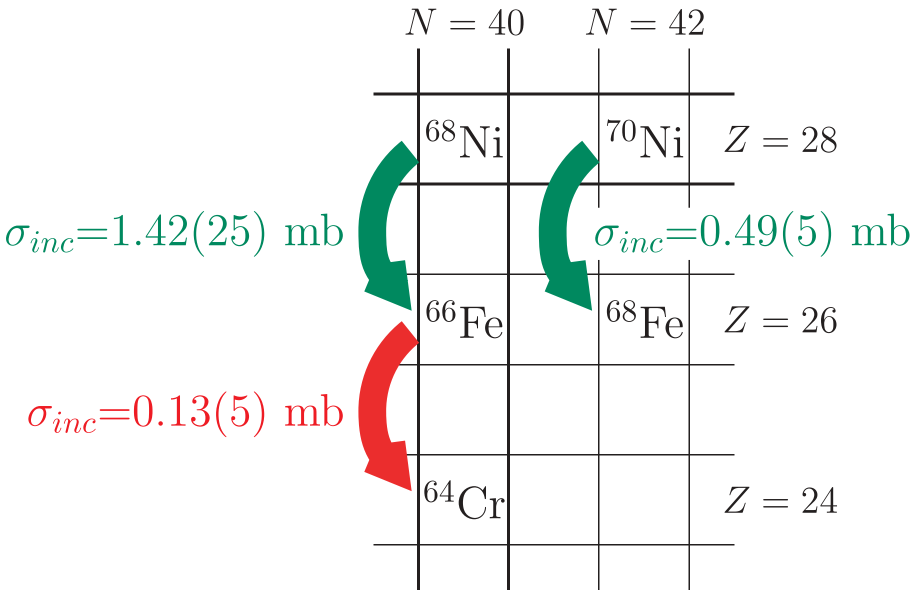
Gade *et al.*, PRC 76, 024317 (2007)
Gade *et al.*, PRL 99, 072502 (2007)

New island of inversion? N=40

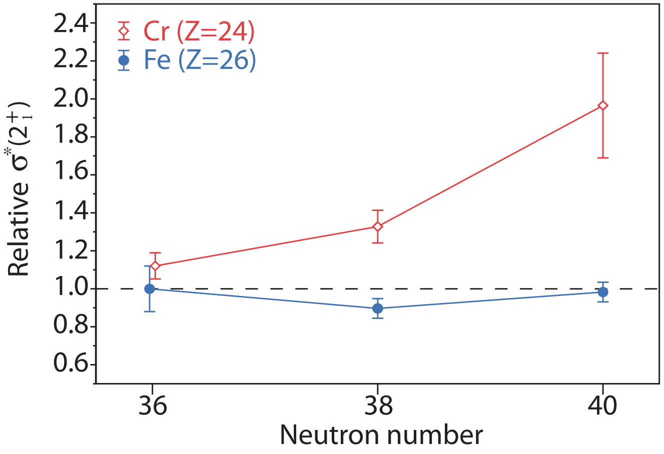
Two-proton removal

- Cross section for ^{66}Fe(-2p) strongly suppressed relative to spherical theory and ^{68}Ni (-2p)
- Symptomatic of reduced structure overlap
  - Rapid structure changes
  - Onset of deformation
- Inelastic scattering measurements indicate increasing deformation

Adrich et al., PRC 77, 054306 (2008)



Inelastic scattering



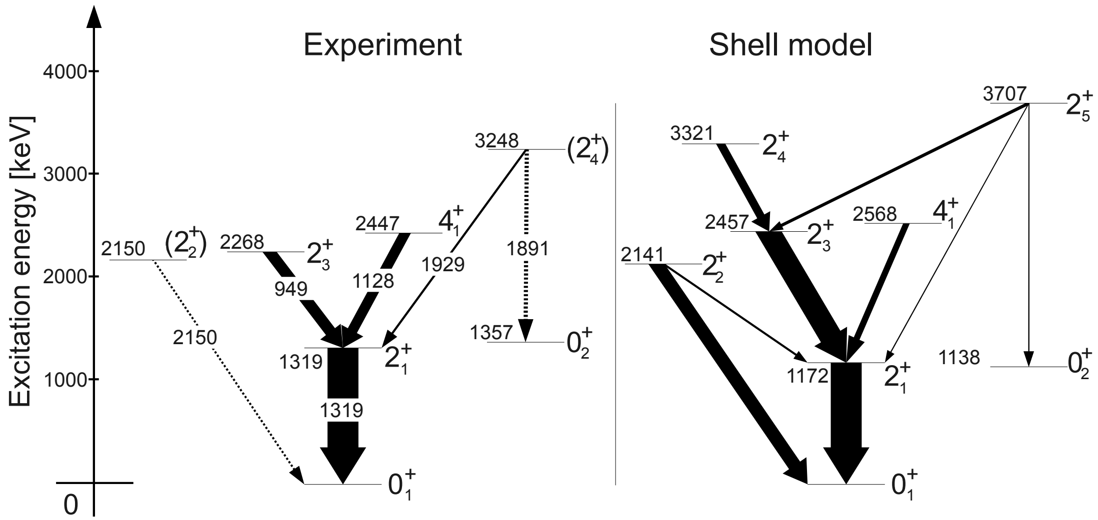
Gade et al., PRC 81, 051304(R) (2010)

N=28 shell closure: ^{46}Ar(-2p) → ^{44}S

^{46}Ar(-2p)

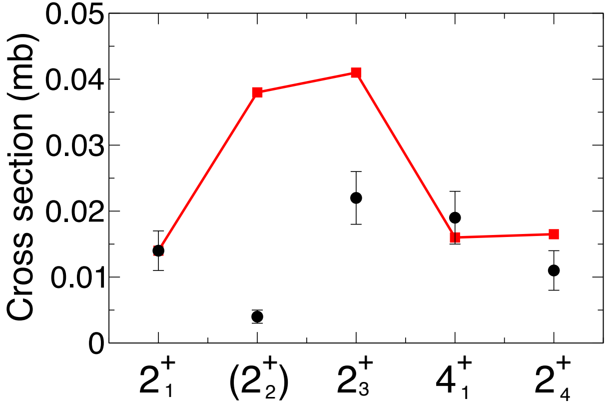
Structure down the N=28 shell closure

- $0_1^+\ \nu[2p2h]$
- $2_1^+\ \nu[2p2h]$
- $0_2^+\ \nu[0p0h]$
- $4_1^+\ \nu[1p1h]$



E_{level} (keV)	J^π	E_γ (keV)	J^π_{final}	σ (mb)	σ_{theory} (mb)
0	0^+				0.334
1319(7)	2_1^+	1319(7)	0_1^+	0.014(3)	0.028
1357(15)	0_2^+				0.163
2150(11)*	(2_2^+)	2150(11)	0_1^{+*}	0.004(1)	0.076
2268(8)	2_3^+	949(5)	2_1^+	0.022(4)	0.082
2447(9)	4_1^+	1128(6)	2_1^+	0.019(4)	0.032
3248(12)	(2_4^+)	1891(10)	0_2^{+*}	0.011(3)	0.033
		1929(7)	2_1^+		

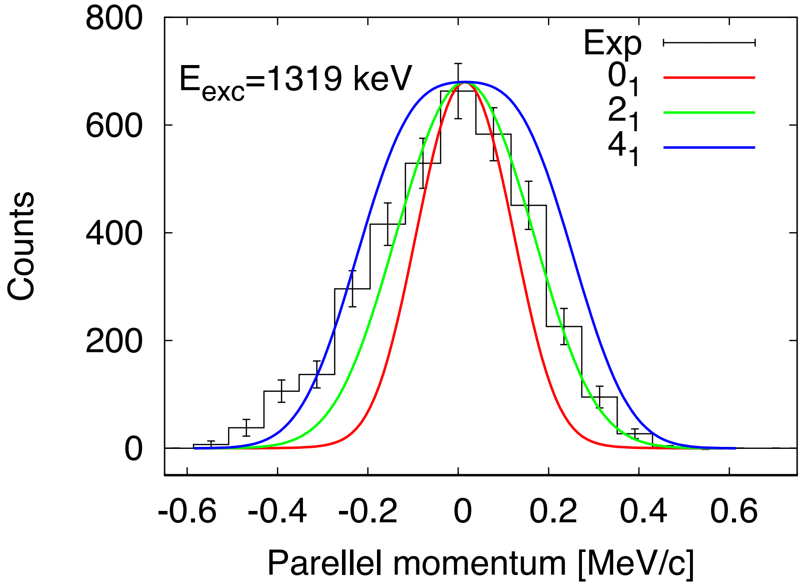
$R_s(2N) = 0.5$

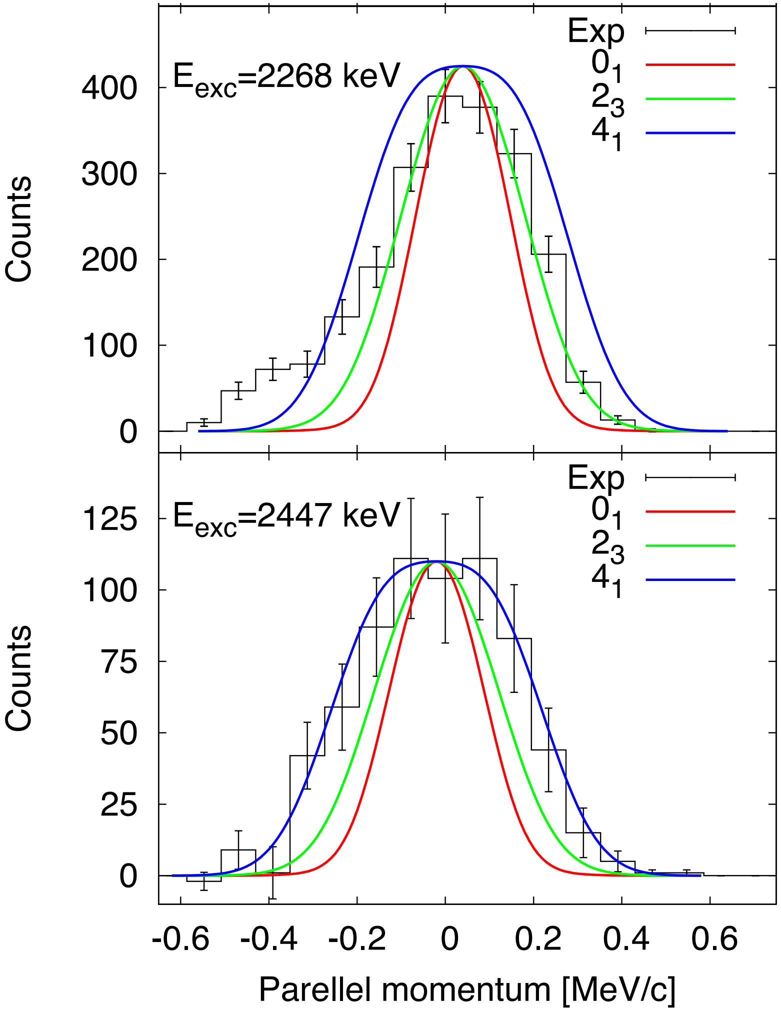


Santiago-Gonzalez et al., PRC 83 061305 (2011)

N=28 shell closure: ^{46}Ar(-2p) → ^{44}S

Residue momentum distributions





YKIS talk by Dario Vretenar:

$\beta(^{34}\mathrm{Ar}) = -0.19$

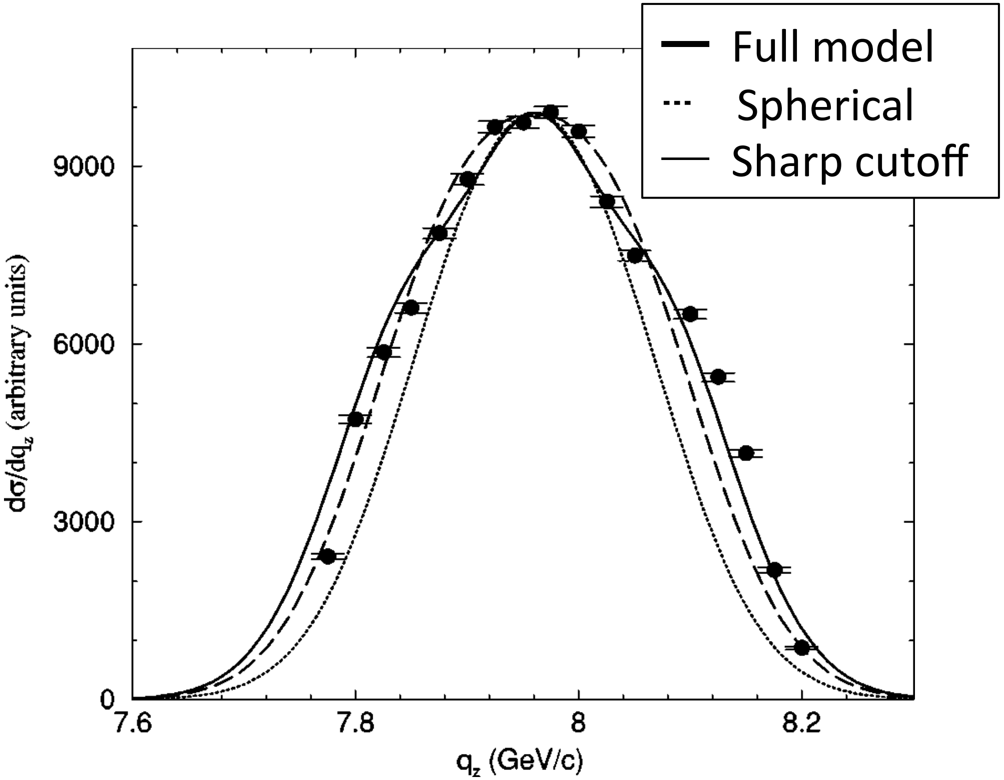
$\beta(^{44}\mathrm{S}) = 0.34$

BUT ^{44}S and other N=28 isotones are strongly deformed

Deformation

^{25}Al(-1p) [202]5/2, δ=0.34

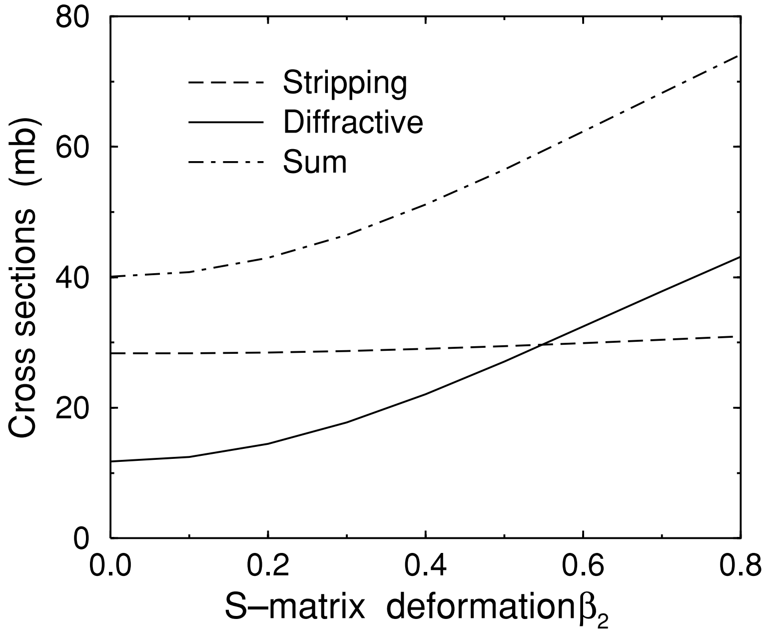
Dynamic core excitation required for momentum distribution shoulders



Sakharuk and Zelavinsky, PRC 61, 014609 (1999)

^{17}C(-1n)

Stripping and diffractive cross sections as a function of deformation



Batham *et al.*, PRC 71 064608 (2005)

Conclusions

Conclusions

- Two-nucleon removal offers an efficient route to detailed spectroscopic information on low-lying states in highly exotic nuclei
- Momentum distributions offer detailed tests of structure models
  - NSCL proposal on ^{26}Si(-2n)
- Odd-odd systems more complicated (mixed *l*), but may yet exhibit structure sensitivity
- KO from N=Z nuclei are intriguing: new final-state exclusive measurements are required to provide robust tests in stable nuclei
  - RIKEN proposal on ^{12}C(-np)
- Rapid structural changes:
  - New (deformed) structure input (PSM, BCS+Nilsson)
  - Deformed reaction dynamics descriptions
  - Dynamic core excitation

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