Australian National University

Correlations probed in direct two-nucleon knockout reactions

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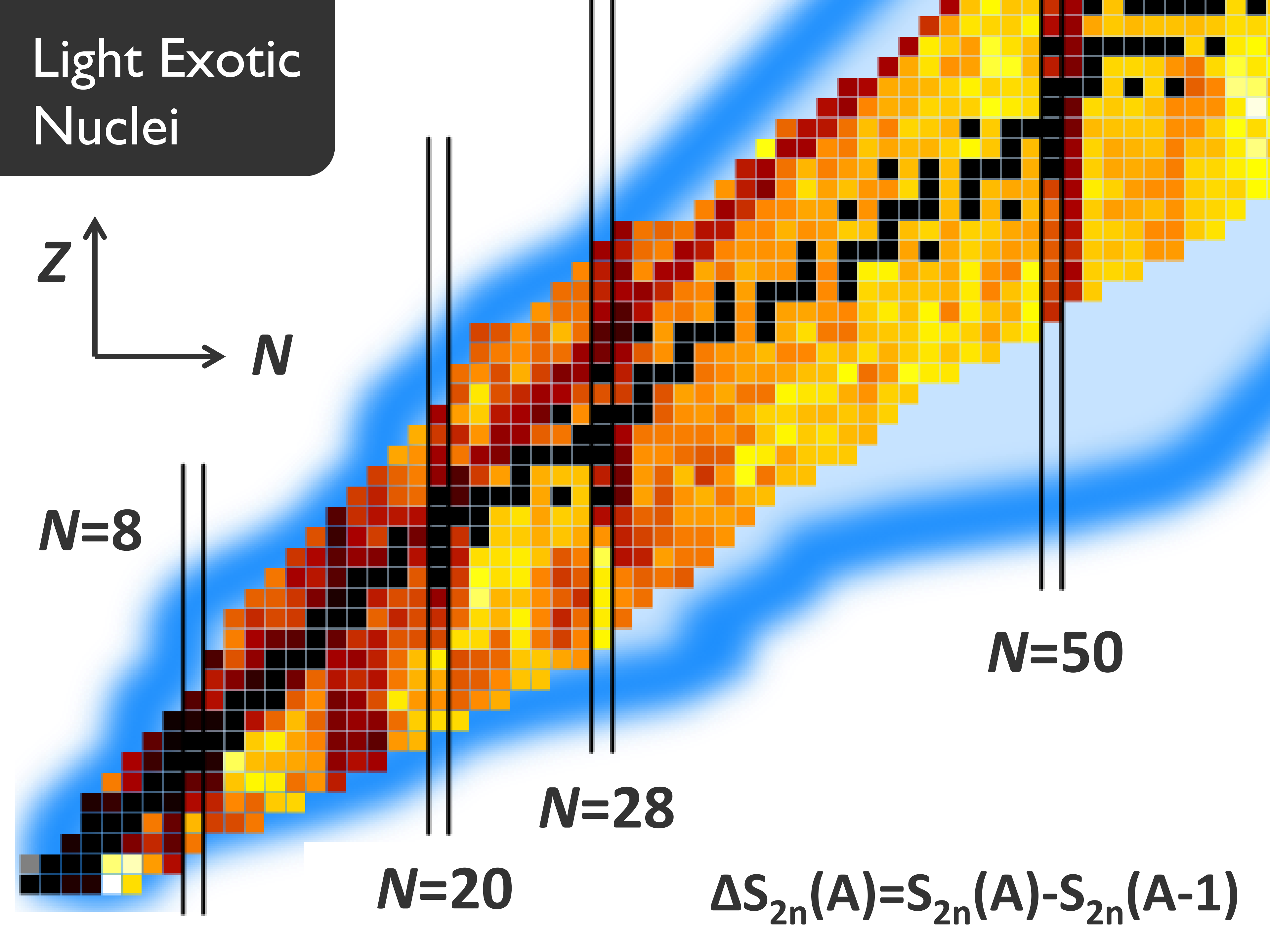
Outline

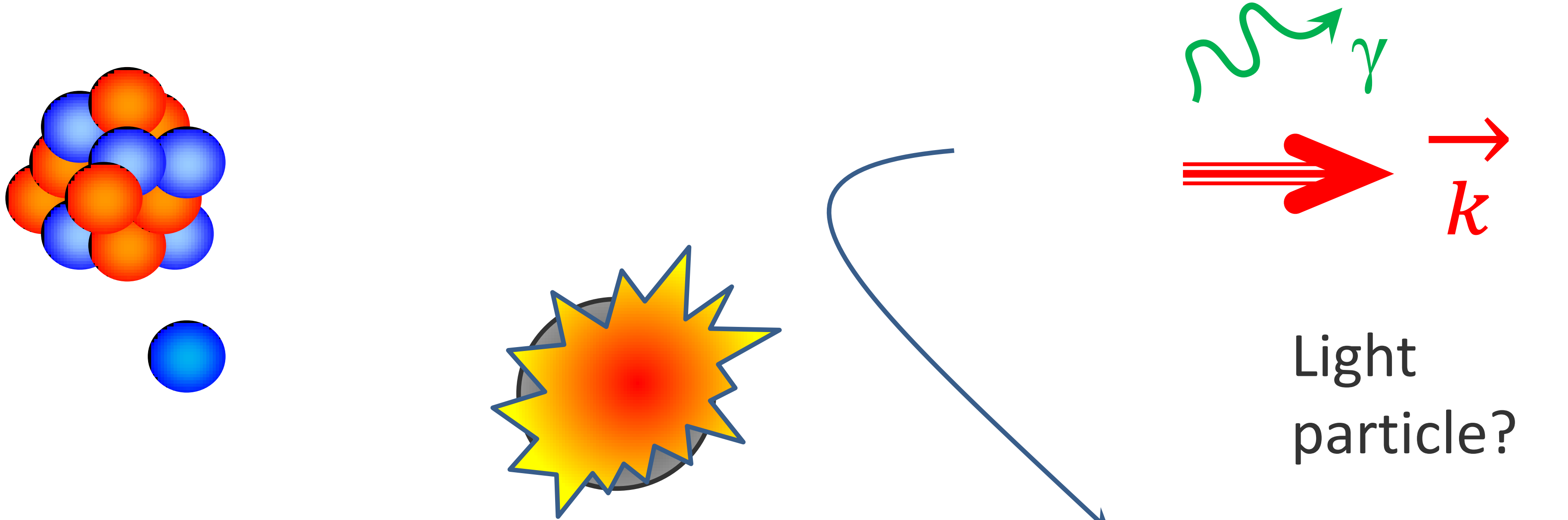
- Context and Motivation
- Two-nucleon removal
  - Overview
  - Structure and spatial correlations
  - Momentum distributions
- Recent results
  - Reactions mechanism and core recoil
- Summary

Context and Motivation

Light Exotic Nuclei



Nucleon knockout reactions (~100 MeV/nucleon)

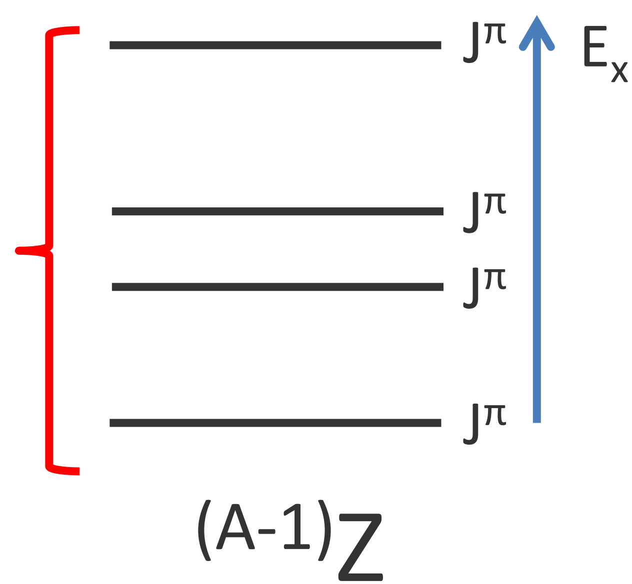


Current facilities
GANIL (France)
NSCL@MSU (USA)
RIBF@RIKEN (Japan)

Under construction
FAIR@GSI (2020, Germany)
FRIB@MSU (2020, USA)
RISP (2017, Korea)

Level energies
Orbital AM
Spectroscopic factors

In very exotic nuclei



Single-nucleon removal reactions

Knockout reactions

- Energy >80 MeV/nucleon on a light nuclear target (Be, C)
- Ideally 200 MeV/u or greater
- Cross section 5-200 mb

Absolute cross sections

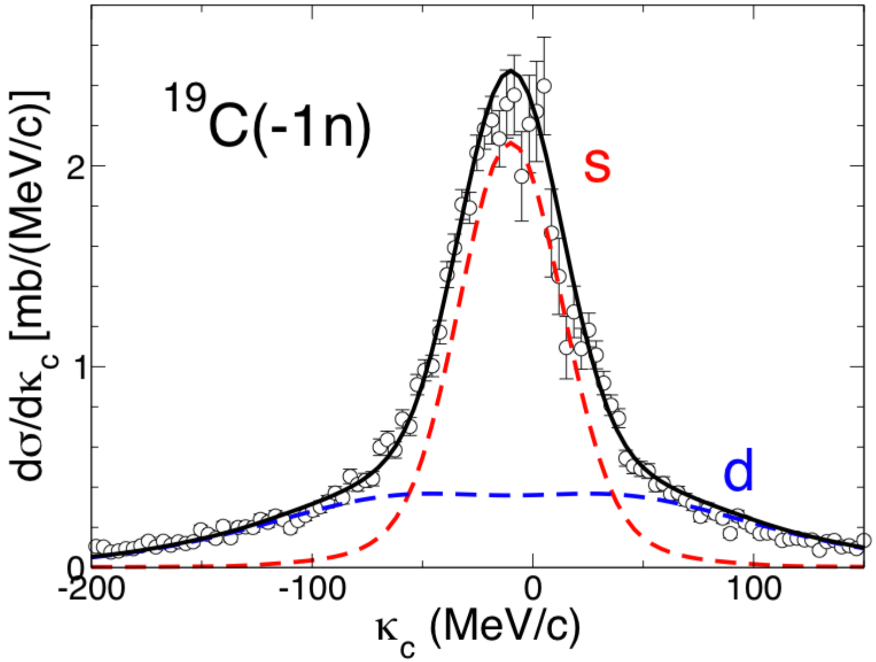
- Cross section proportional to spectroscopic strength
- Suppression of spectroscopic strengths in asymmetric systems

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

$$\beta \equiv (n\ell j)$$

Beam directional momentum distributions

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

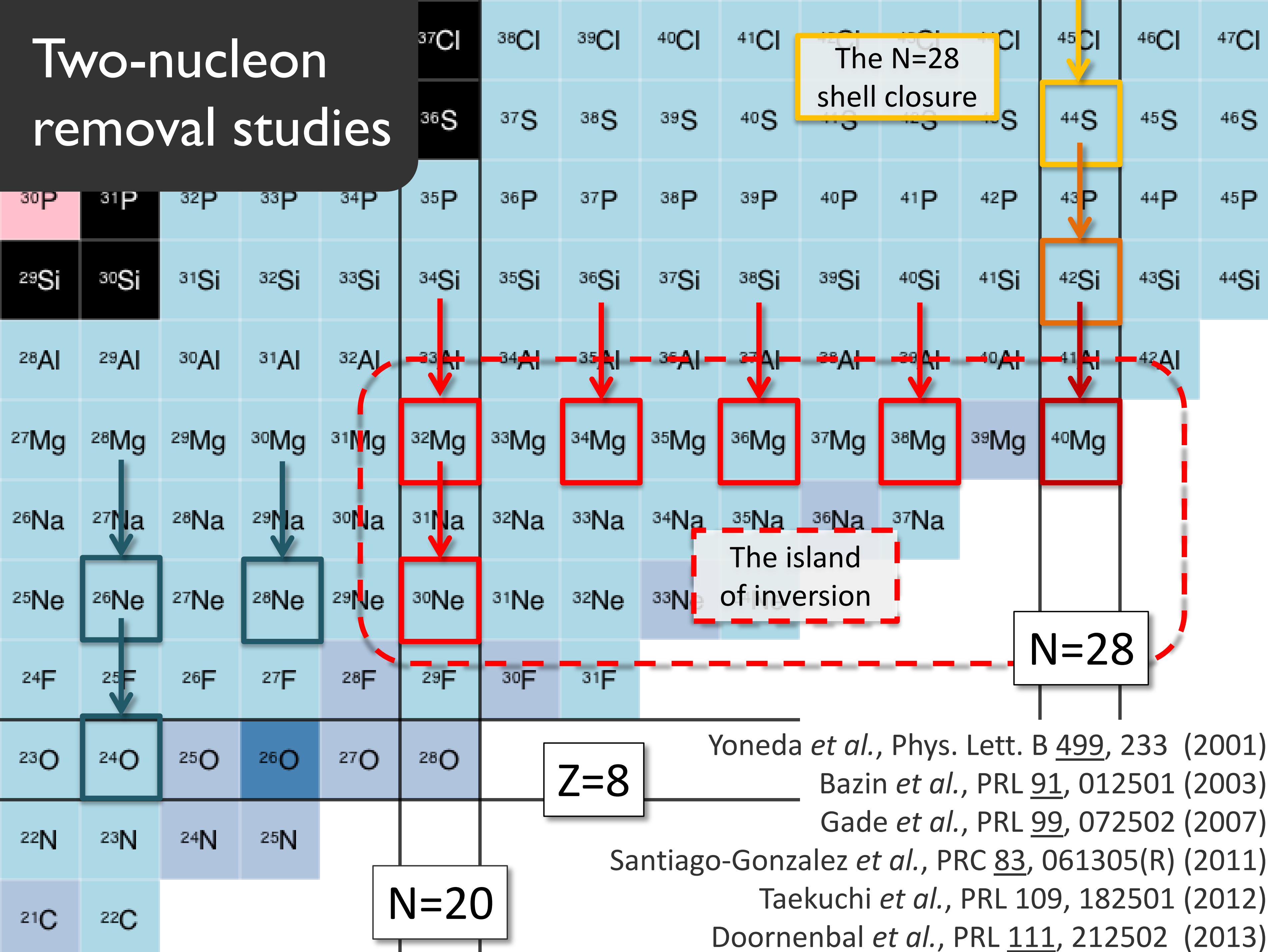


Hansen and Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003)
Bertulani and Hansen, PRC 70 034609 (2004)

Two-nucleon removal

Cross sections, momentum distributions and spatial correlations

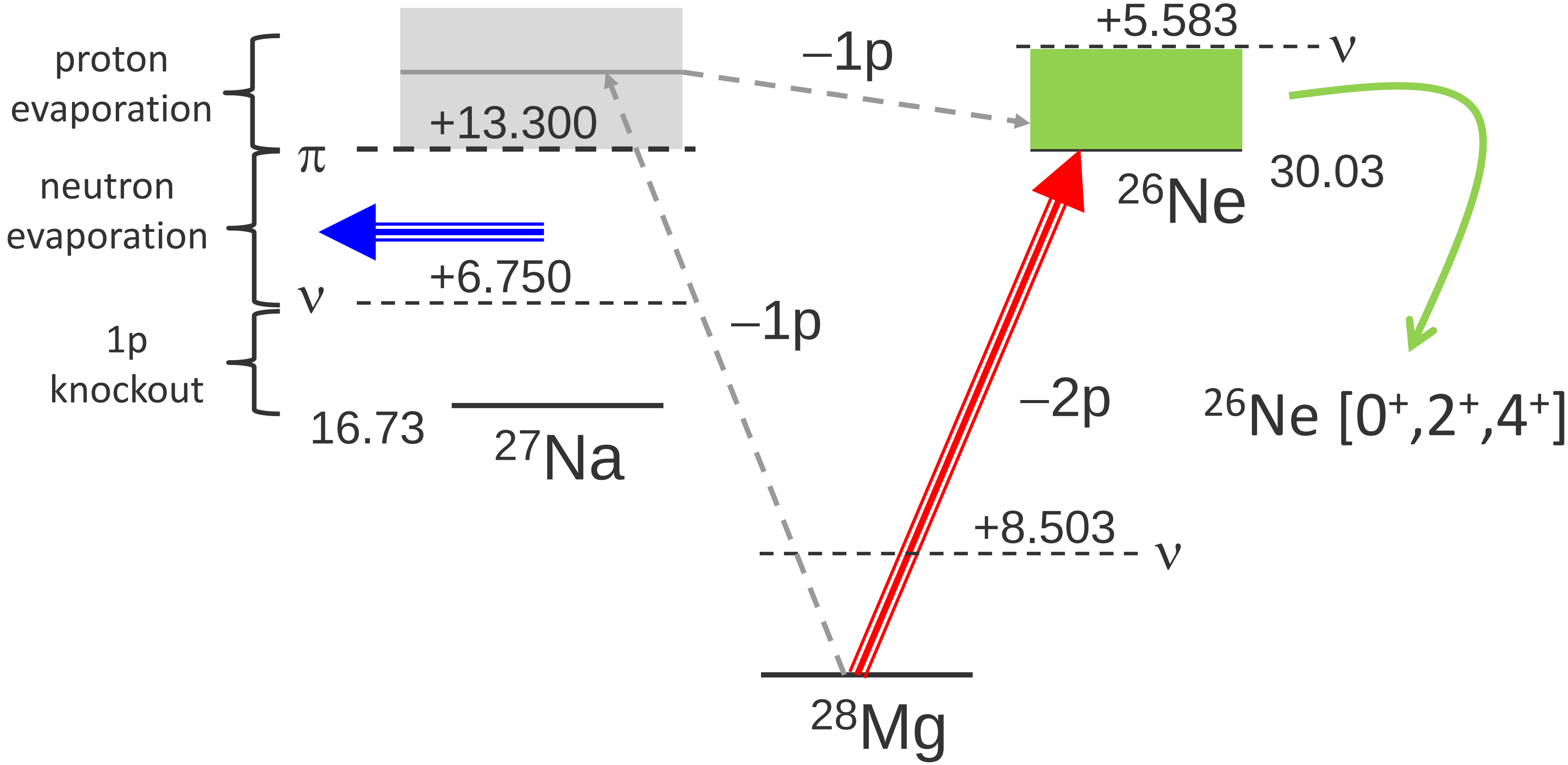
Two-nucleon removal studies



Yoneda *et al.*, Phys. Lett. B 499, 233 (2001)
Bazin *et al.*, PRL 91, 012501 (2003)
Gade *et al.*, PRL 99, 072502 (2007)
Santiago-Gonzalez *et al.*, PRC 83, 061305(R) (2011)
Taekuchi *et al.*, PRL 109, 182501 (2012)
Doornenbal *et al.*, PRL 111, 212502 (2013)

$^{9}Be(^{28}Mg,^{26}Ne^{*})X$

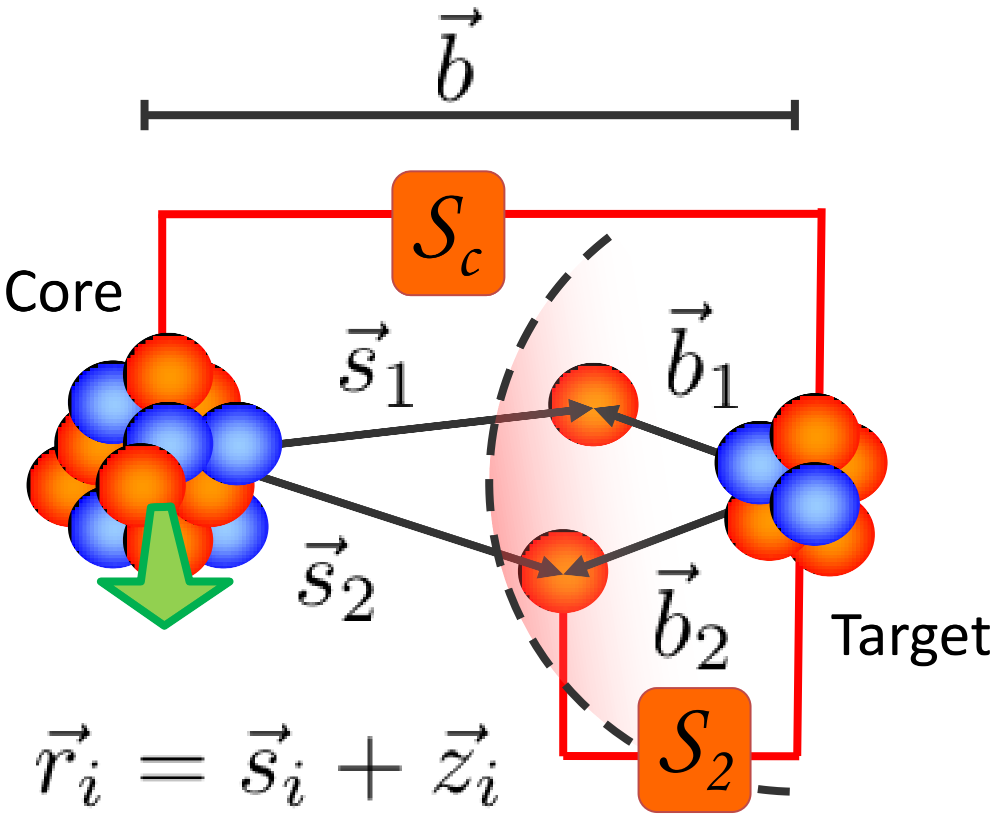
^{28}Mg thresholds



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

Two-nucleon knockout schematic

Impact parameter plane



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

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

Assumptions:

- Eikonal (straight-line) reaction dyanmics
- Spectator-core (core states not coupled)
- Sudden (internal co-ordinates frozen)
- No-recoil (massive core)

Two-nucleon stripping (pure inelastic)
Stripping-diffraction (elastic and inelastic)
Two-nucleon diffraction (pure elastic)

Two-nucleon stripping

Two-nucleon stripping cross section

$$\sigma_{ss}^{(f)} = \int d\vec{b} \int d\vec{s}_1 \int d\vec{s}_2 \;\; \mathcal{O}_{ss}(b_c, \vec{s}_1, \vec{s}_2) \;\; P_{if}(\vec{s}_1, \vec{s}_2)$$

$$\mathcal{O}_{ss} = |\mathcal{S}_c|^2 (1 - |\mathcal{S}_1|^2)(1 - |\mathcal{S}_2|^2)$$

S-matrix in the $t\rho\rho$ approximation (density-folding model)

$$\mathcal{S}_c(b) = \exp\left(- \int dZ \int d\vec{r}_p \int d\vec{r}_t \; \rho_p(r_p) \; \rho_t(r_t) \; t_{NN}(|\vec{b} + \vec{Z} + \vec{r}_p - \vec{r}_t|) \right)$$

Joint position probability

$$P_{if}(\vec{s}_1, \vec{s}_2) = \frac{1}{\hat{J}_i} \sum_{M_i M_f} \int dz_1 \int dz_2 \, \langle \Psi_{if} \mid \Psi_{if} \rangle_{sp}$$

Hartree-Fock calculations used to constrain the radial size of BOTH the density distributions and overlap function

Simpson *et al.*, PRL 102, 132502 (2009); PRC 79, 064621 (2009)

Two-nucleon overlap function

Two-nucleon overlap function

$$\Psi_{if}(1,2) = \langle \Phi_{J_f M_f}(A) | \Psi_{J_i M_i}(A+2) \rangle$$
$$= \sum_{I\mu\alpha} C_{\alpha}^{ifI} (I\mu J_f M_f | J_i M_i) [\overline{\phi_{\beta_1}(1) \otimes \phi_{\beta_2}(2)}]_{I\mu}$$

(SM) Two-nucleon amplitudes (TNA)

Parentage amplitude for two-nucleon configuration α and final state i in initial state *i*

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

Two-nucleon wave function

$$u_{n\ell j}(r)$$

^{28}Mg structure and cross sections

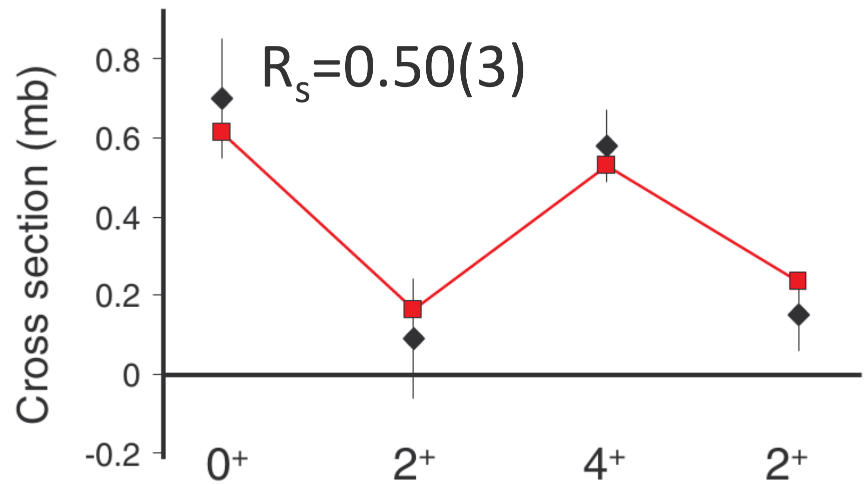
Shell model two-nucleon amplitudes

Universal sd-shell (USD) **two-nucleon amplitudes** for different coherent **two-nucleon configurations** and **final states**

J_f^π	E^* (MeV)	$[0d_{3/2}]^2$	$[0d_{3/2}0d_{5/2}]$	$[0d_{5/2}]^2$	$[1s_{1/2}0d_{3/2}]$	$[1s_{1/2}0d_{5/2}]$	$[1s_{1/2}]^2$	ΣTNA²
0_1^+	0.0	−0.30146	—	−1.04685	—	—	−0.30496	1.187
2_1^+	2.02	−0.05030	0.37358	−0.63652	−0.06084	−0.13916	—	0.570
4_1^+	3.50	—	0.33134	1.59639	—	—	—	2.658
2_2^+	3.70	0.04721	−0.07248	0.85297	0.16158	0.17590	—	0.792

Measured and **theoretical** cross sections for ^{28}Mg(-2p), including suppression factor R_s(2N)=0.5.

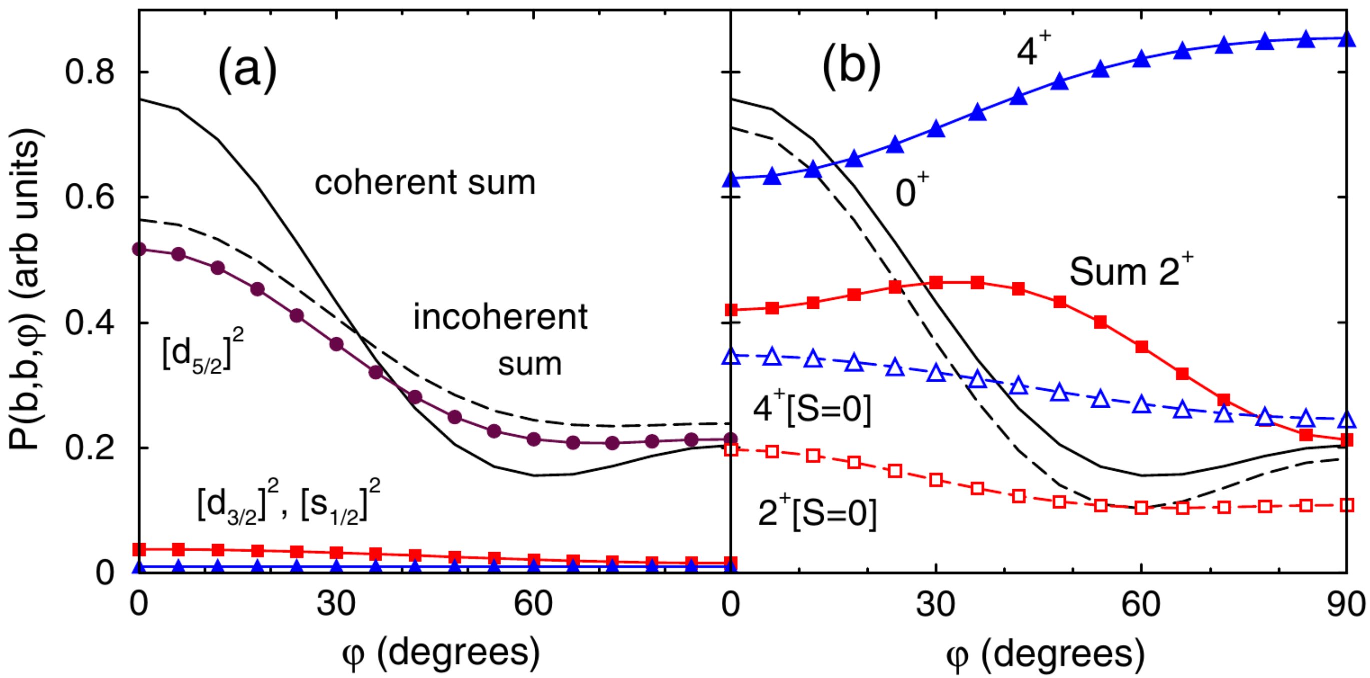
Branching ratios very well reproduced

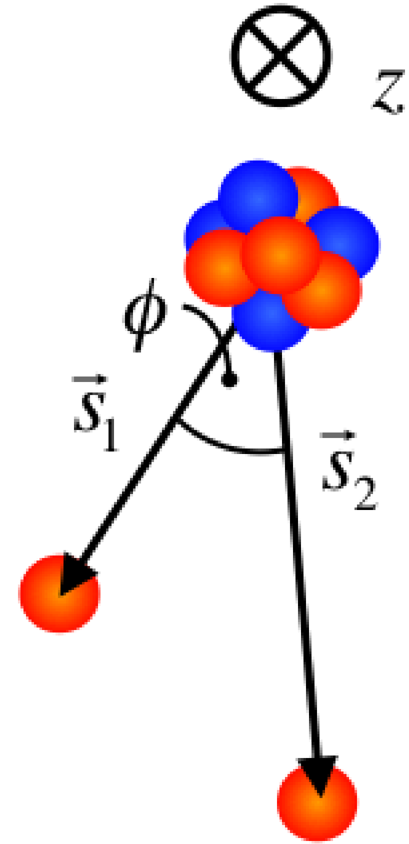


Tostevin *et al.*, PRC 70, 064602 (2004)

Spatial Correlations

<u>^{28}Mg(-2p)</u> using USD shell model TNA





<u>Compared to uncorrelated calculations</u>:

0^+ enhanced by 70%

4^+ suppressed by 23%

Pinkston, PRC 29, 1123 (1984); Insolia *et al.*, J. Phys. G <u>15</u>, 1249 (1989)
Tostevin, J. Phys. Conf. Ser. <u>49</u>, 21 (2006); Simpson and Tostevin, PRC <u>82</u>, 044616 (2010)

Momentum distributions

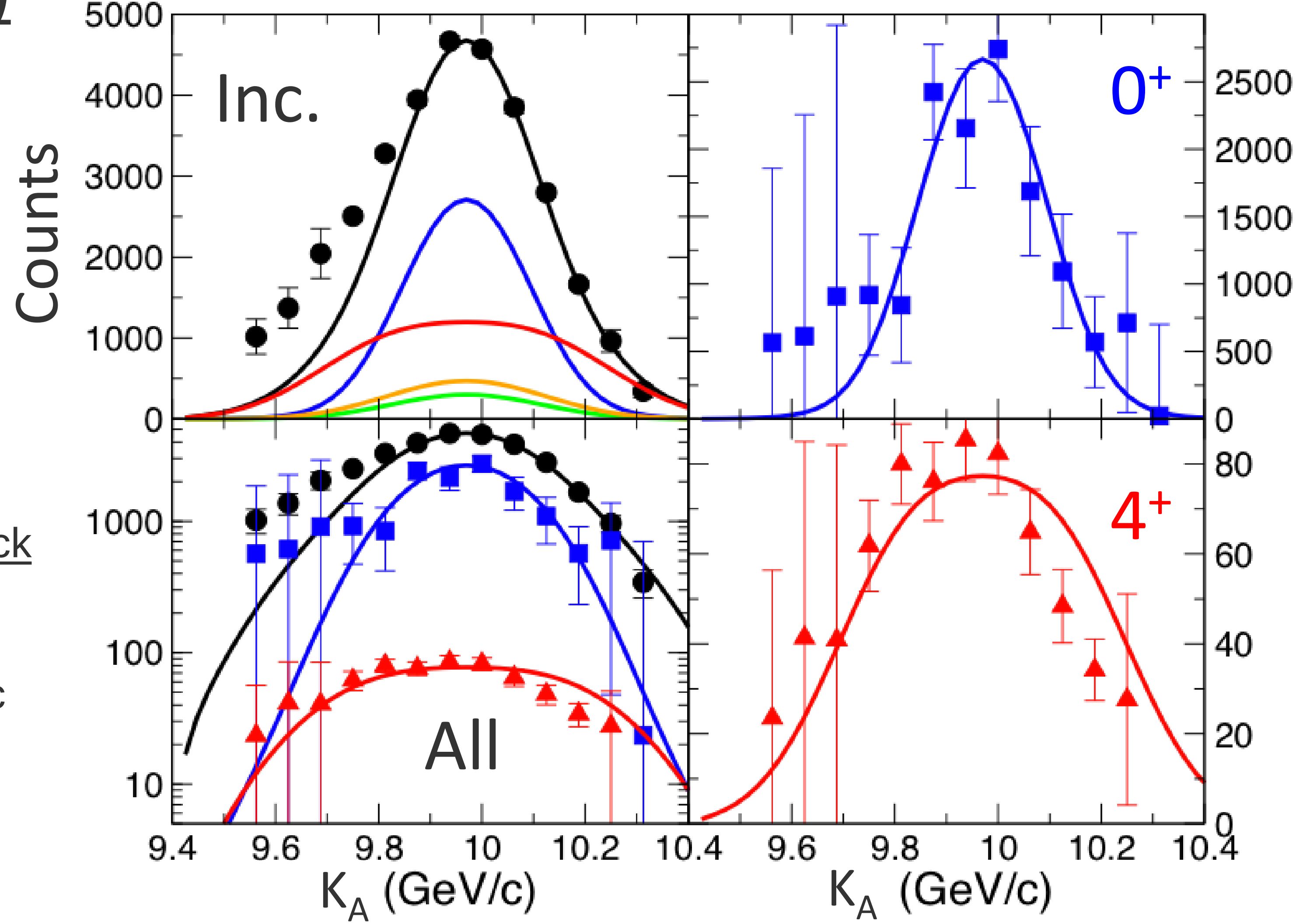
<u>^{28}Mg(-2p)</u>

Width --> Final state spin

S_p = 16.8 MeV
S_n = 8.5 MeV

<u>Beam energy</u>
E = 82.3 A MeV

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



Bazin *et al.*, PRL <u>91</u> 012501 (2003); Simpson *et al.*, PRL <u>102</u>, 132502 (2009)

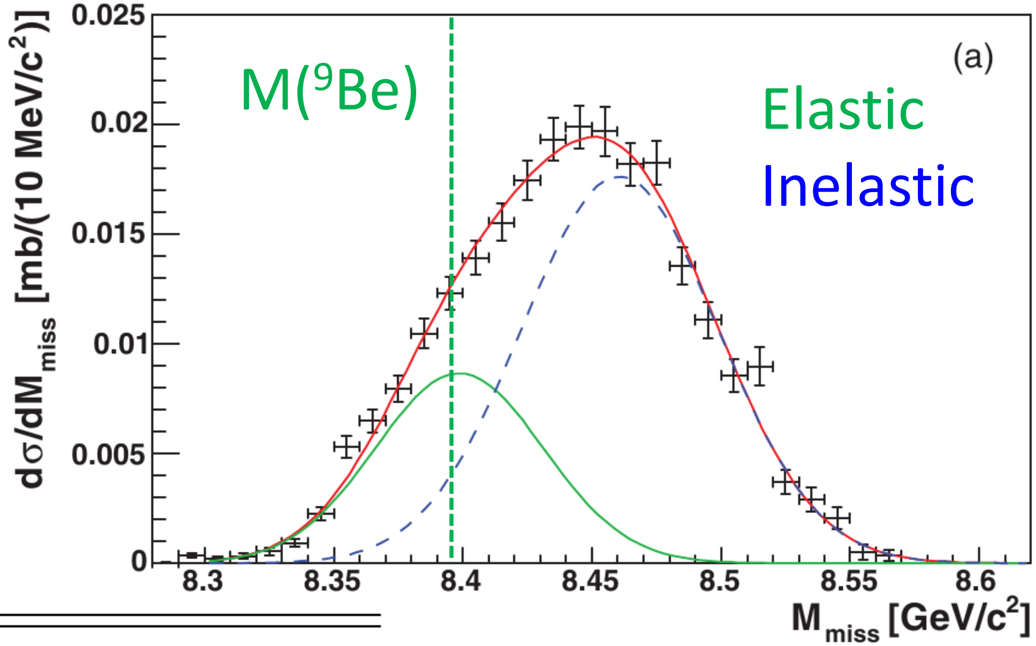
Recent results

Reaction mechanisms and core recoil

^{28}Mg(-2p): Reaction mechanisms in 2KO

Missing mass spectrum for ^{26}Ne+2p

Peak at M(^{9}Be) is elastic breakup, the rest a mixture of inelastic and elastic mechanisms



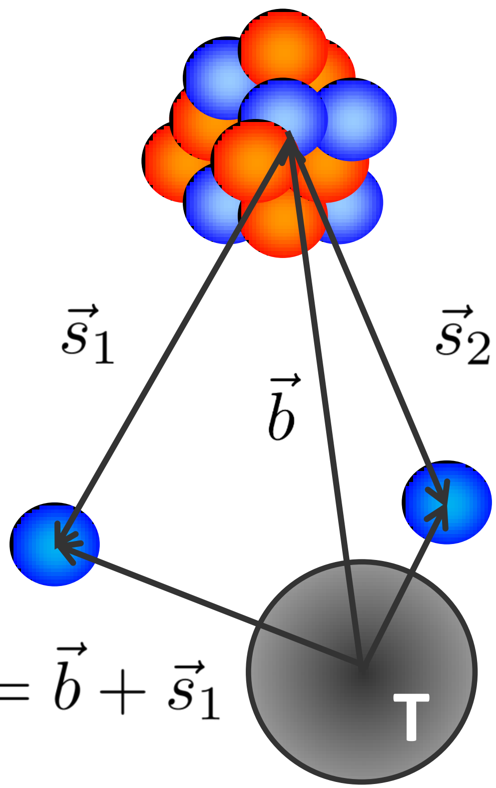
	diff	diff-str	str	tot
σ_{obs} (mb)	0.07(2)	0.27(14)	0.54(14)	0.88(2)
σ_{extr} (mb)	0.11(3)	0.44(23)	0.87(23)	1.43(5)
fraction (%)	8(2)	31(16)	61(16)	
σ^{inc} (mb)				1.475(18)
σ_{theo} incl. (mb)	0.19	1.13	1.70	3.02
$\sigma_{theo} R_S$(2N) (mb)	0.09	0.55	0.83	1.475
fraction$_{theo}$ (%)	6.3	37.4	56.3	

Agreement within (large) experimental uncertainties

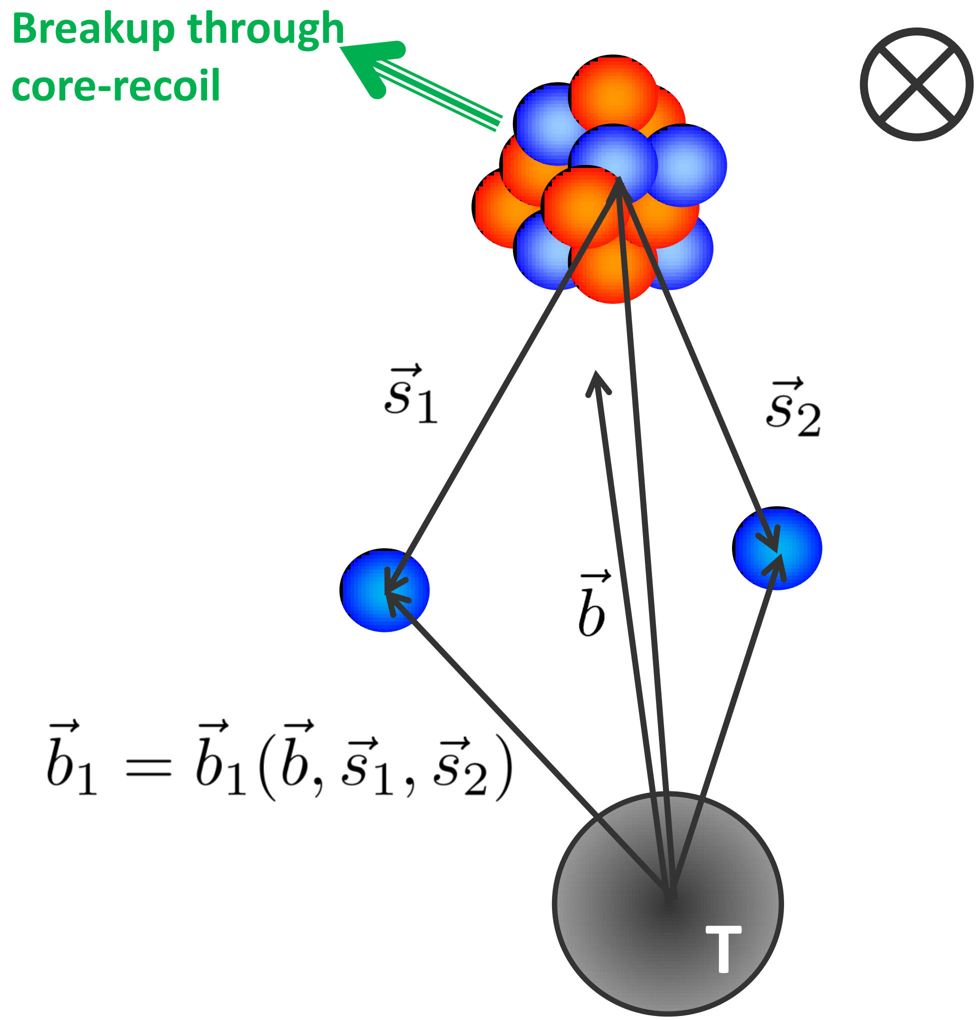
Wimmer *et al.*, PRC 85, 051603(R) (2012)

Stripping-diffraction: core recoil

The no-recoil (heavy core) approximation:



$$\vec{b}_1 = \vec{b} + \vec{s}_1$$



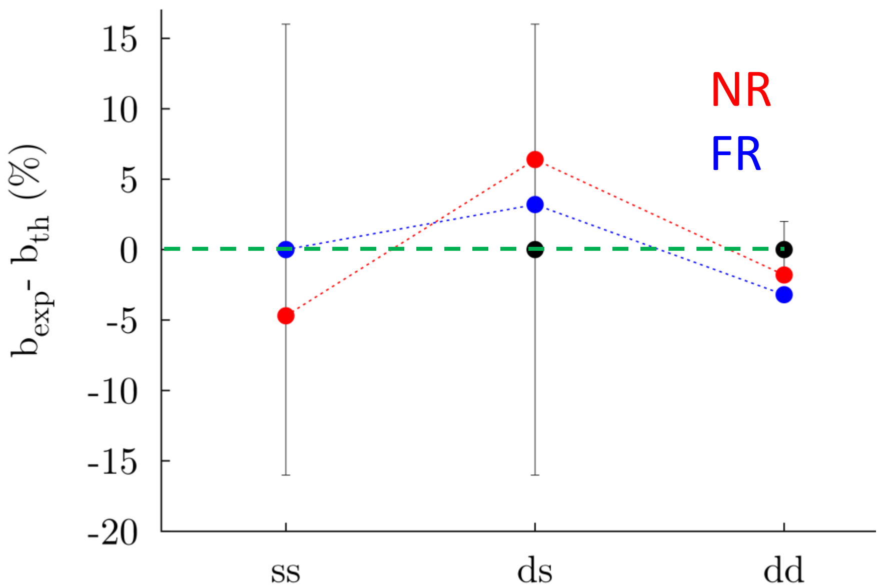
$$\vec{b}_1 = \vec{b}_1(\vec{b}, \vec{s}_1, \vec{s}_2)$$

No-recoil **$\sigma_{2N\text{-}NR} > \sigma_{2N}$** Including core-recoil

Reaction mechanisms: NR vs. FR in ^{28}Mg(-2p)

Inclusive cross sections and mechanism-fractions

	dd	ds	ss	tot
σ_{exp}	0.11(3)	0.44(23)	0.87 (23)	1.43(5)
σ_{th} (NR)	0.188	1.130	1.706	3.025
σ_{th} (FR)	0.135	0.958	1.706	2.798
b_{exp} (%)	8(2)	31(16)	61(16)	
b_{th} (NR) (%)	6.2	37.4	56.3	
b_{th} (FR) (%)	4.8	34.2	61.0	



Improvement (modest) in the calculated ss and ds branches

ss: b_{th}(FR)-b_{th}(NR) = +4.7%

ds: b_{th}(FR)-b_{th}(NR) = -3.2%

dd: b_{th}(FR)-b_{th}(NR) = -1.4%

Wimmer *et al.*, PRC 85, 051603(R) (2012)

Simpson (in preparation)

^{28}Mg(-2p) final-state-exclusive cross sections

			No-recoil ($A+2=10^5$)		
State	σ_{ss}	σ_{ds}	σ_{dd}	σ_{tot}	σ_{exp}
0_1^+	0.633	$\boxed{0.465}$	0.085	1.183	0.70(15)
2_1^+	0.180	0.121	0.020	0.322	0.09(15)
4_1^+	0.586	$\boxed{0.374}$	0.060	1.020	0.58(9)
2_2^+	0.252	0.170	0.029	0.450	0.15(9)
Total	1.651	$\boxed{1.130}$	0.194	$\boxed{2.975}$	1.50(10)
			Full-recoil ($A+2=28$)		
State	σ_{ss}	σ_{ds}	σ_{dd}	σ_{tot}	σ_{exp}
0_1^+	0.633	$\boxed{0.367}$	0.053	1.053	0.70(15)
2_1^+	0.180	0.106	0.016	0.302	0.09(15)
4_1^+	0.586	$\boxed{0.355}$	0.054	0.995	0.58(9)
2_2^+	0.252	0.146	0.021	0.419	0.15(9)
Total	1.651	$\boxed{0.974}$	0.144	$\boxed{2.769}$	1.50(10)

Recoil effects depend on the state

0^+ = -21%

4^+ = -5%

Total = -14%

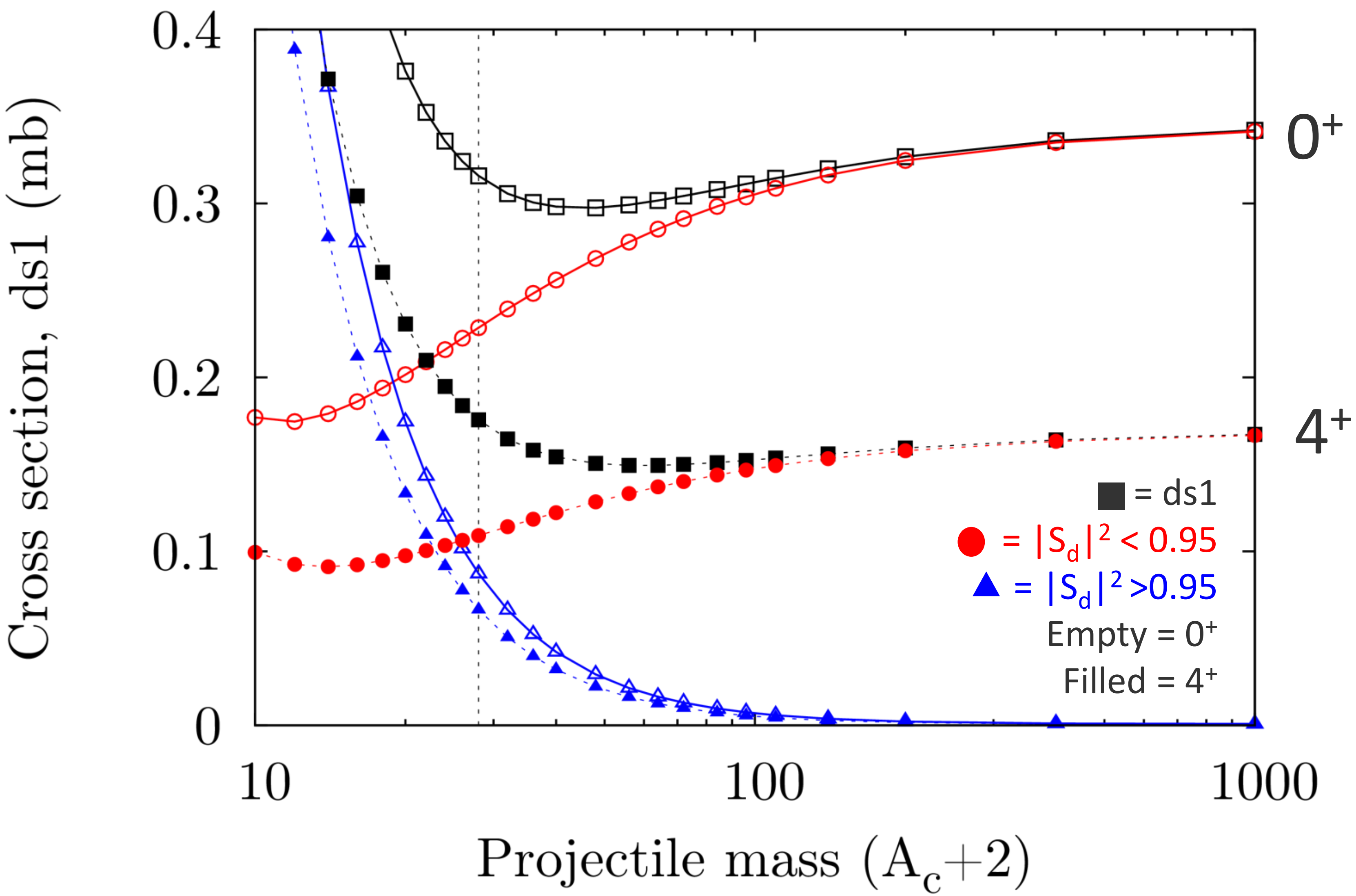
R_s(NR)=0.50(3)

R_s(FR)=0.54(4)

Total cross sections = -7%

$[d_{5/2}]^2$ unit normalised overlaps

$$\mathcal{S}_c\mathcal{A}_s\mathcal{S}_d \rightarrow \mathcal{S}_c\mathcal{A}_s\mathcal{S}_d - \mathcal{S}_c^{(1)}\mathcal{A}_s^{(1)}$$



Conclusions

Conclusions

Two-nucleon removal

- Key tool for studying the structure of exotic nuclei
  - Efficient access to basic nuclear spectroscopy
  - Sensitive to structure and two-nucleon spatial correlations
  - In specific cases, structure (configuration mixing) effects evident in momentum distributions

Mechanisms and recoil

- New calculations in good agreement with observed reaction mechanism branches (within large errors)
- High precision tests (with γs) required, with best test:
  - High J in light nuclei
  - Low J in heavier nuclei

Thanks for listening