Direct Reactions for Nuclear Spectroscopy

ENSAR2: NUSPIN 2016 Workshop,

San Servolo, 27^{th} June – 1^{st} July 2016

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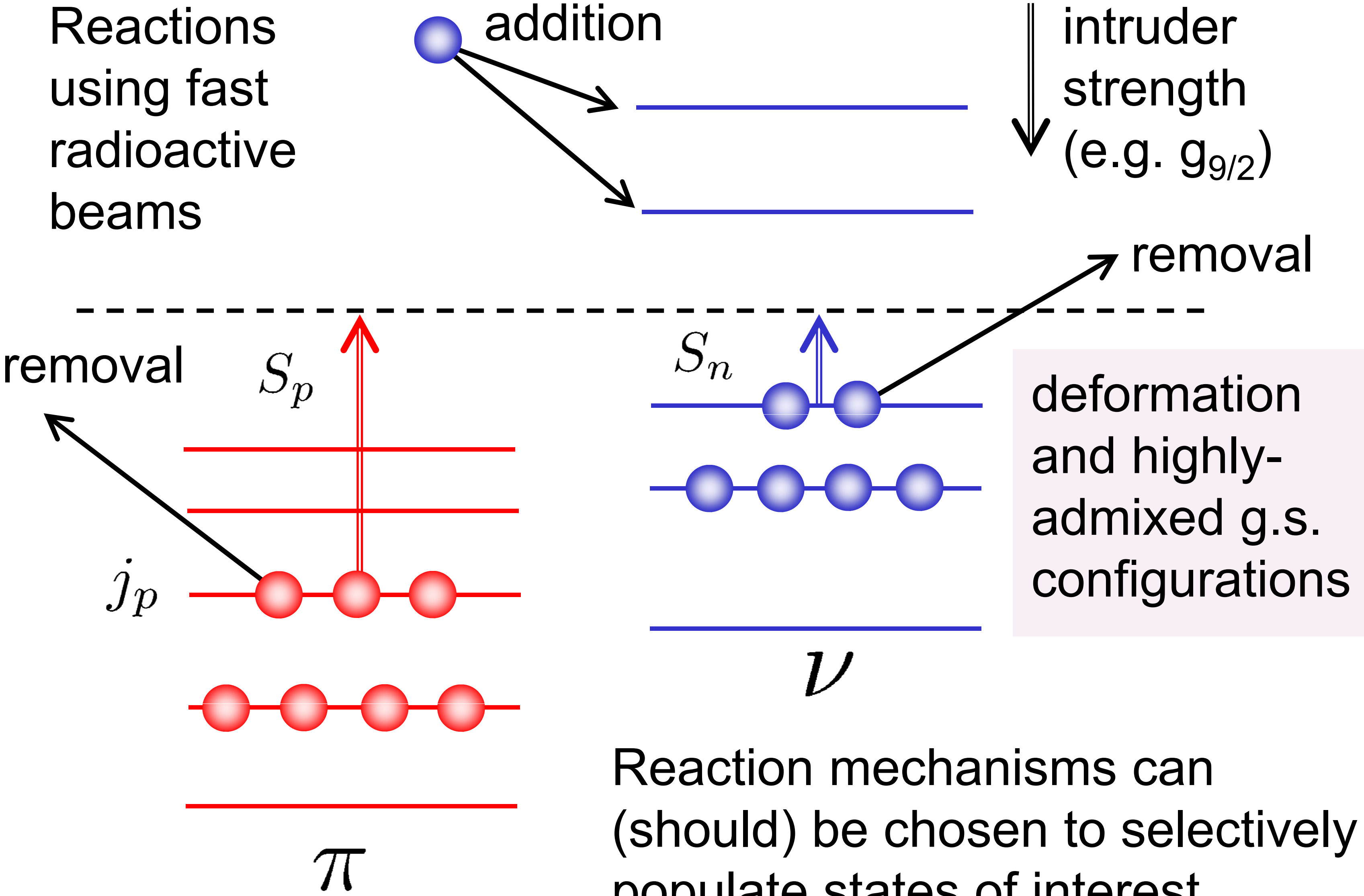
Focus is: using two recent examples

1. Determining/tracking single particle structure (level ordering and their spectroscopic strengths) at/near the N and Z Fermi surface(s)

   Reaction mechanisms:
2. Pickup (nucleon addition) from light-heavy-ion targets (e.g. C) – make use of reaction mismatch
3. Removal/breakup (nucleon removal) – make use of Coulomb and nuclear breakup selectivity
4. Interface to reactions is via shell model (or more microscopic 1N-overlaps – spectroscopic strengths
5. Spectroscopy and structure information enhanced by exploiting multiple, complementary reactions

Single-particle spectroscopy near Fermi-surfaces



Reaction mechanisms can (should) be chosen to selectively populate states of interest

Representative recent examples:

Ground-states of weakly-bound neutron rich systems

^{29}Ne(-n) [^{31}Ne(-n), ^{37}Mg(-n)]

T. Nakamura et al., Tokyo Institute of Technology:

N. Kobayashi et al., PRC **93**, 014613 (2016)

T. Nakamura et al., PRL **112**, 142501 (2014)

N. Kobayashi et al., PRL **112**, 242501 (2014)

Structure of N=29 systems near Z=20

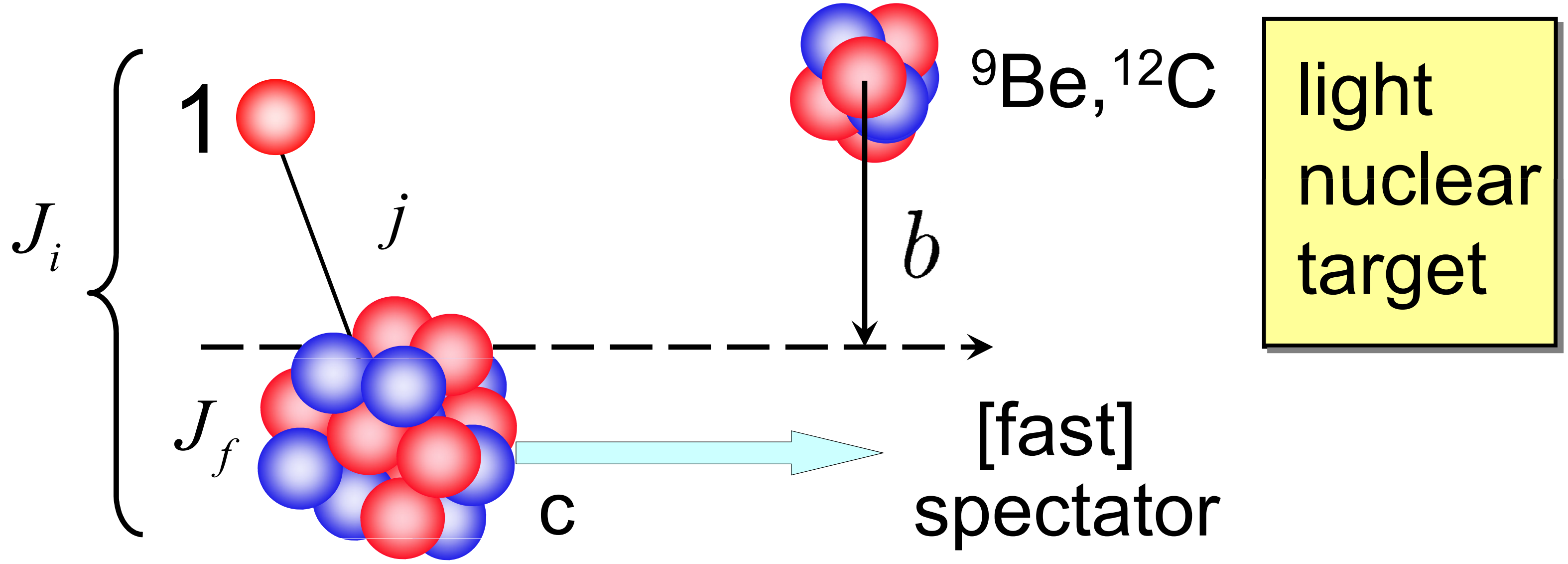
^{47}Ar [^{48}K(-p), ^{46}Ar(+n)], ^{49}Ca [^{48}Ca(+n)],

A. Gade et al., NSCL, Michigan State University:

A. Gade et al., PRC **93**, 031601(R) (2016)

A. Gade et al., PRC **93**, 054315 (2016)

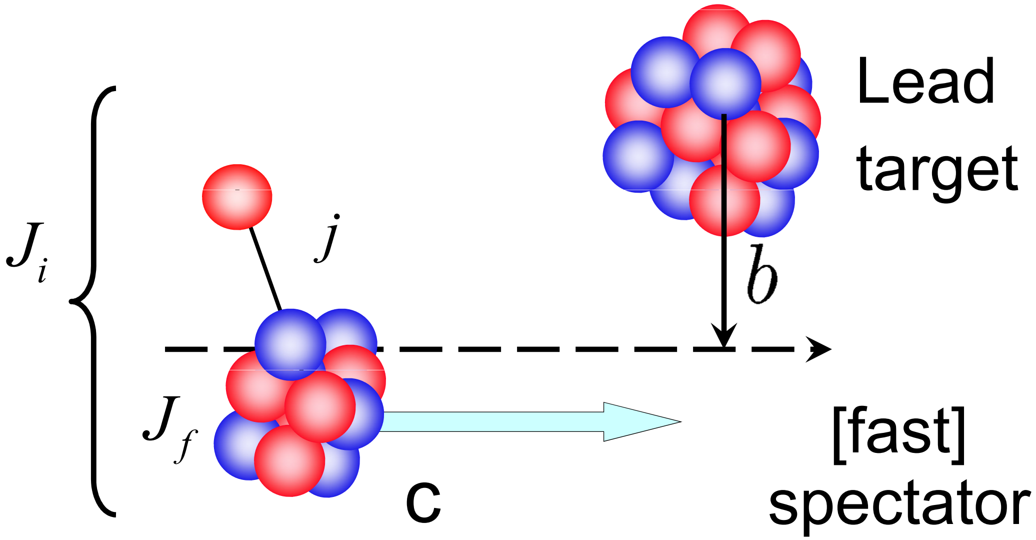
Fast nucleon removal, ~100 MeV/u and greater

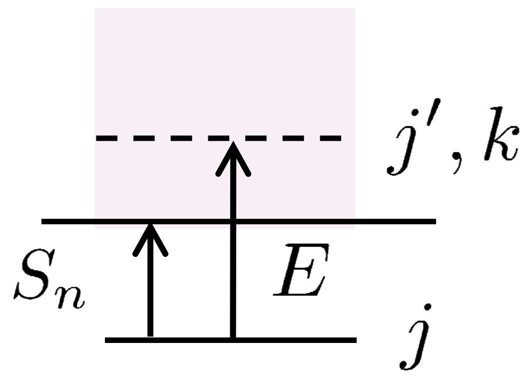


Inclusive with respect to the target final states. Gamma spectroscopy of core final states - plus the momentum distributions of these residues.

Cross sections are large and (as they probe the wave function at the surface) are relatively insensitive to the separation energy and orbital angular momentum – and so populate all available (hole-like) final states

Coulomb dissociation - 100 MeV/u and greater

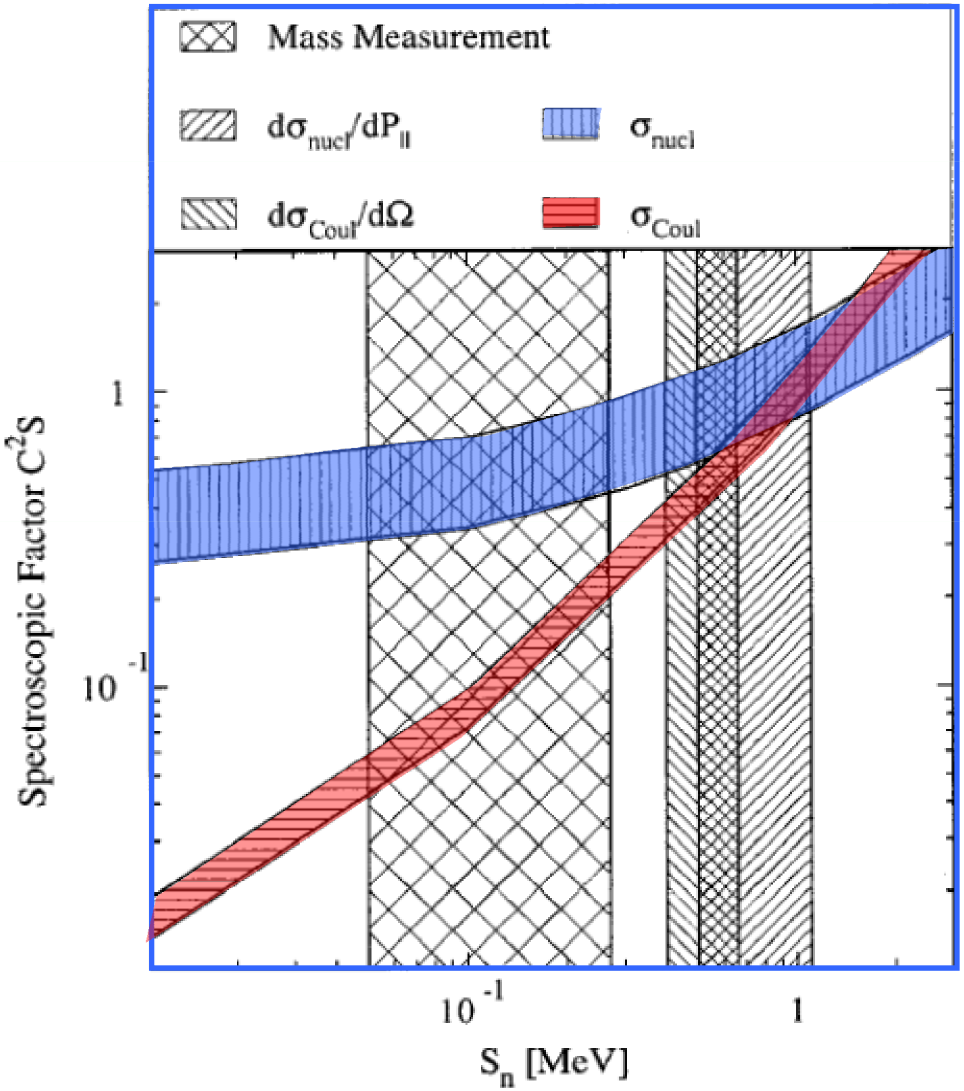




$$\frac{d\sigma}{dE} \rightarrow \frac{dB(E1,j'\ell')}{dE} = \frac{\mu k}{\hbar^2}\frac{\hat{j}'^2}{\hat{j}^2}\,\underbrace{|\langle k, j'\ell' || E1 || j\rangle|^2}_{\int dr\, r\, u_{j'\ell'}(k,r)\, u_{j\ell}(r)}$$

Mechanism is highly sensitive to ground states with small orbital angular momentum and weak binding – well suited for spectroscopy of halo-like ground-states

Nuclear and Coulomb breakup sensitivities



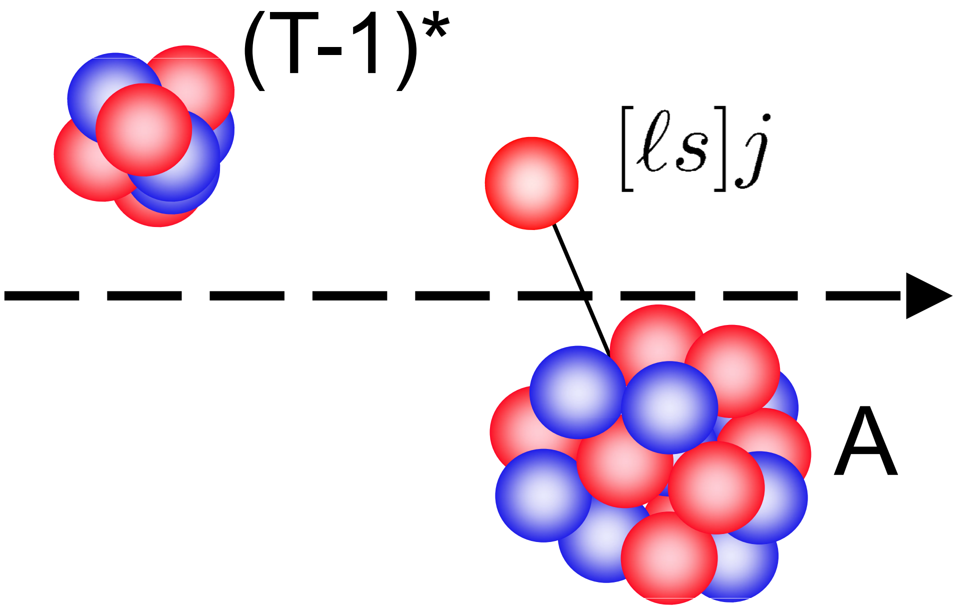
$^{19}C \rightarrow {}^{18}C+n$

Can exploit the different sensitivities of the Coulomb and nuclear (elastic and inelastic) breakup reaction mechanisms to separation energies (and orbital angular momenta) of the removed nucleon to deduce major spectroscopic strength of ground state configurations - especially halo-like configurations.

V. MADDALENA *et al.* PHYSICAL REVIEW C, VOLUME 63, 024613 (2001)

Nucleon pickup – populating particle-like states

Inverse kinematics – exotic beam on a light target – ^{12}C, ^{9}Be



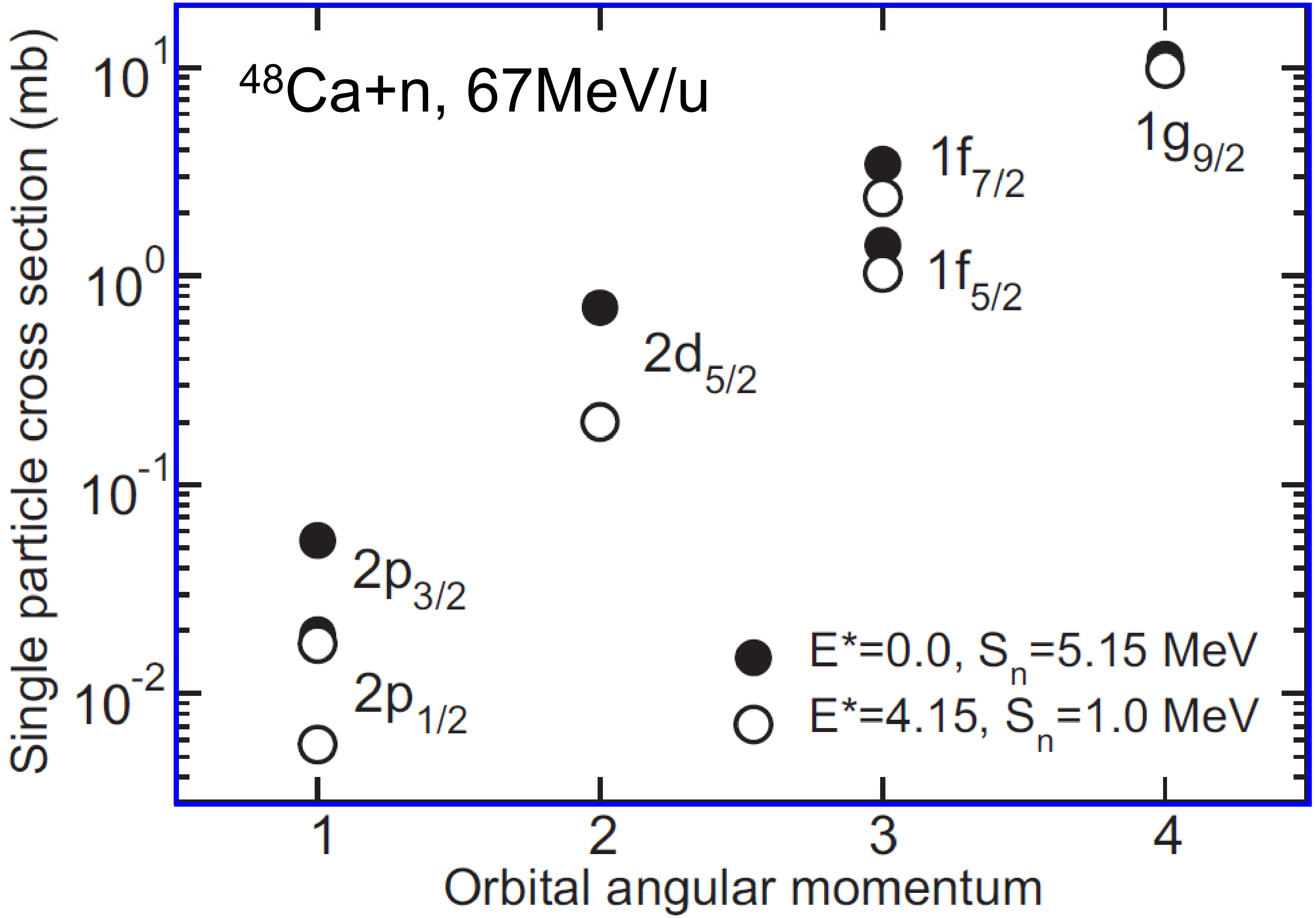
Inclusive wrt final states of the target-like fragment (T-1). T=12, the final state is 2-body. Mismatched at ~60 MeV per nucleon - is useful.

A. Gade *et al.*, PRC **83,** 057304 (2011)

State of pickup residue using gamma-ray spectroscopy

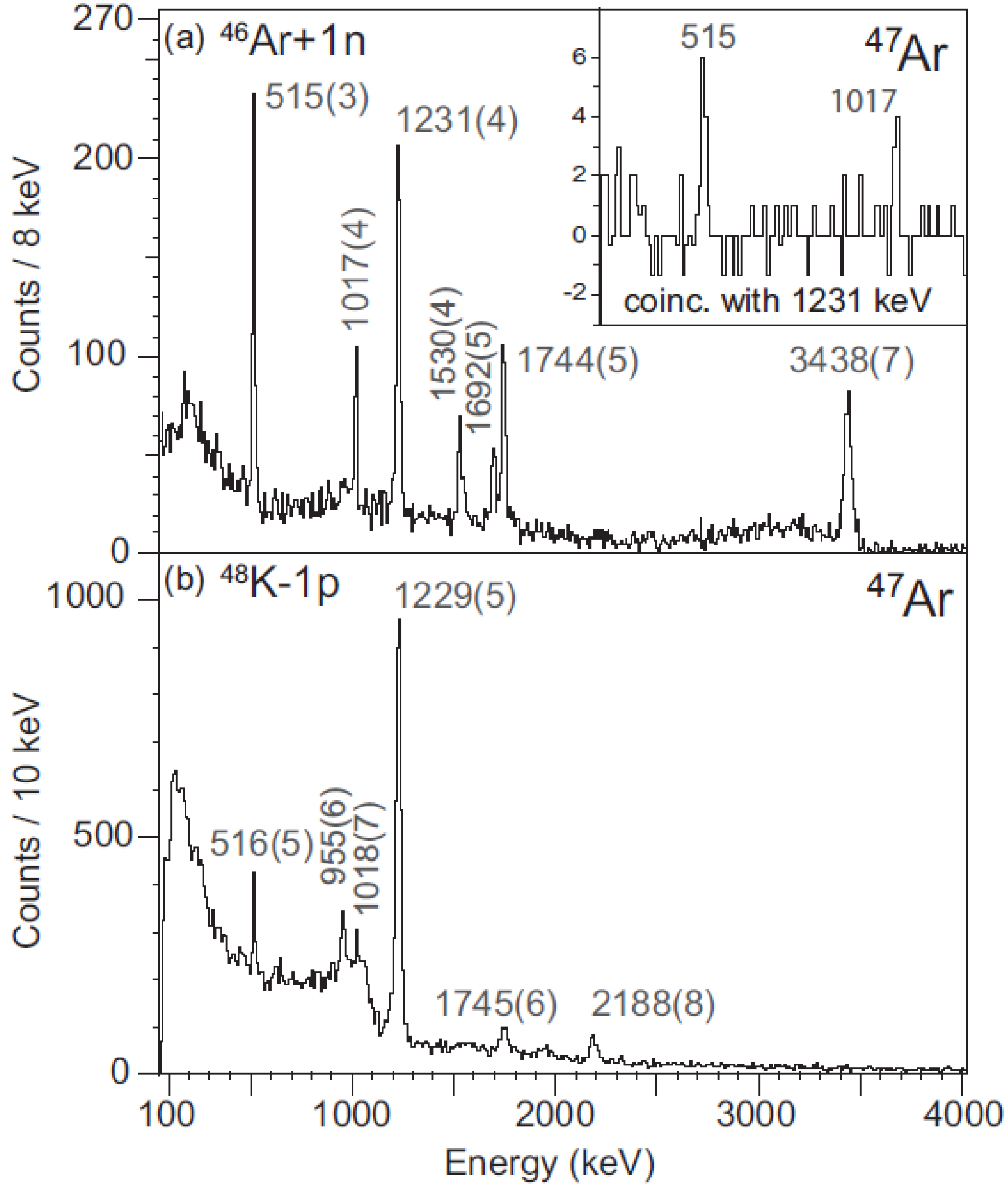
The highly absorptive nature of the high-energy ion-ion (60-70 MeV/u) projectile-target interactions localize reactions at the surface – where nucleon wave functions are probed

Exploit high-ℓ transition selectivity

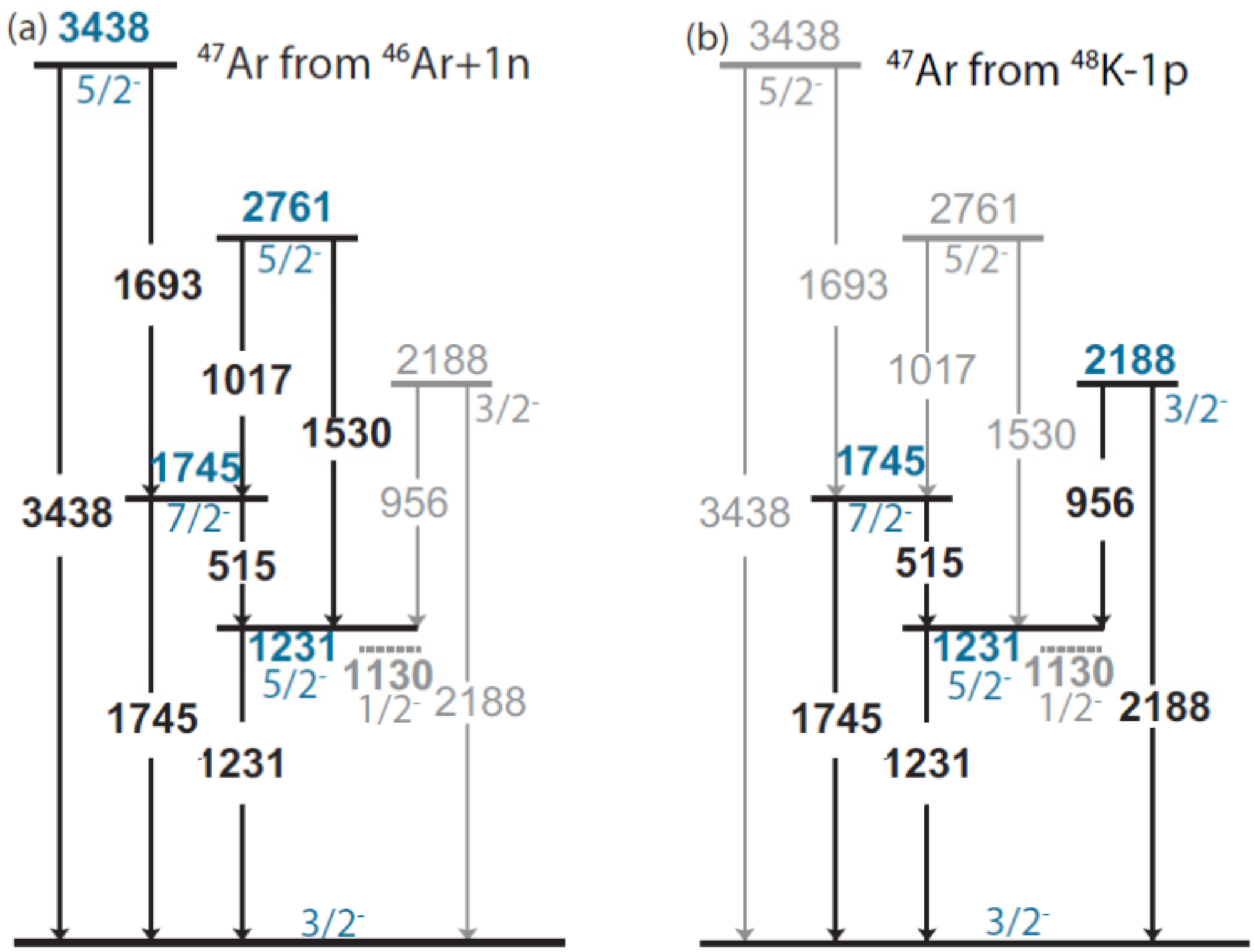


PHYSICAL REVIEW C **93**, 031601(R) (2016)

Complementary mechanisms – ^{47}Ar spectra

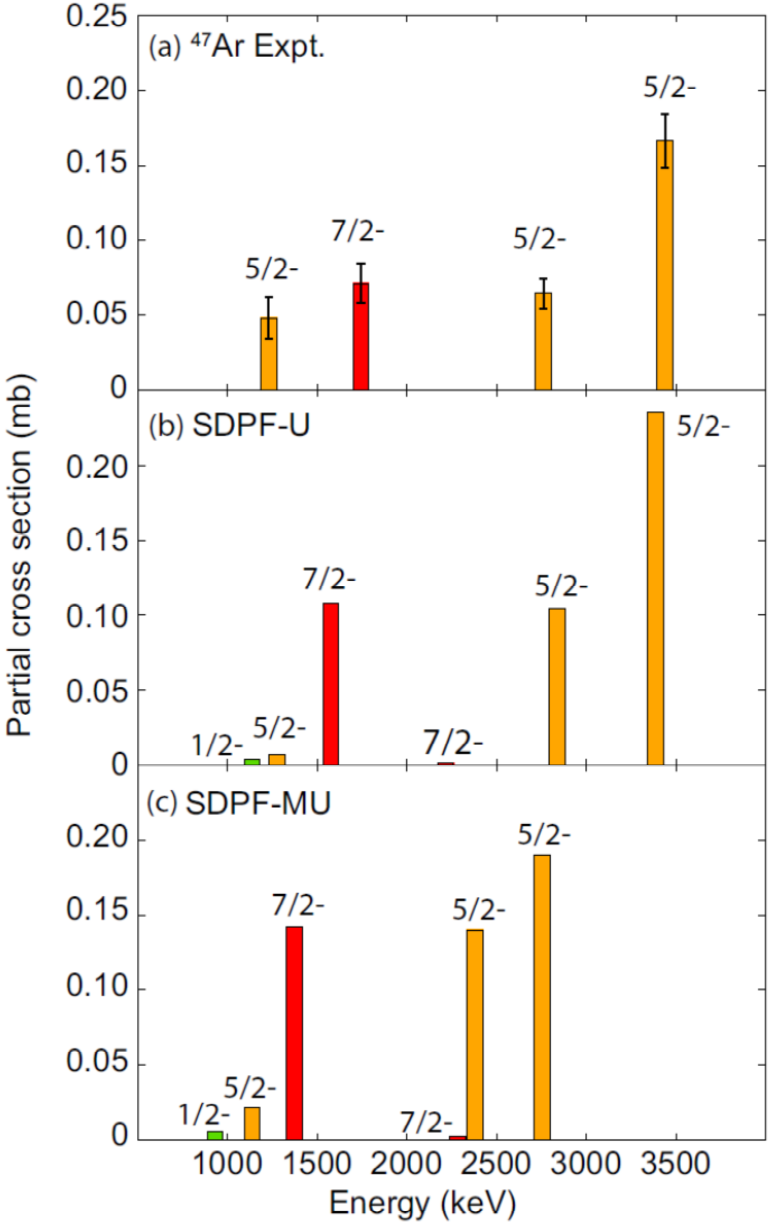


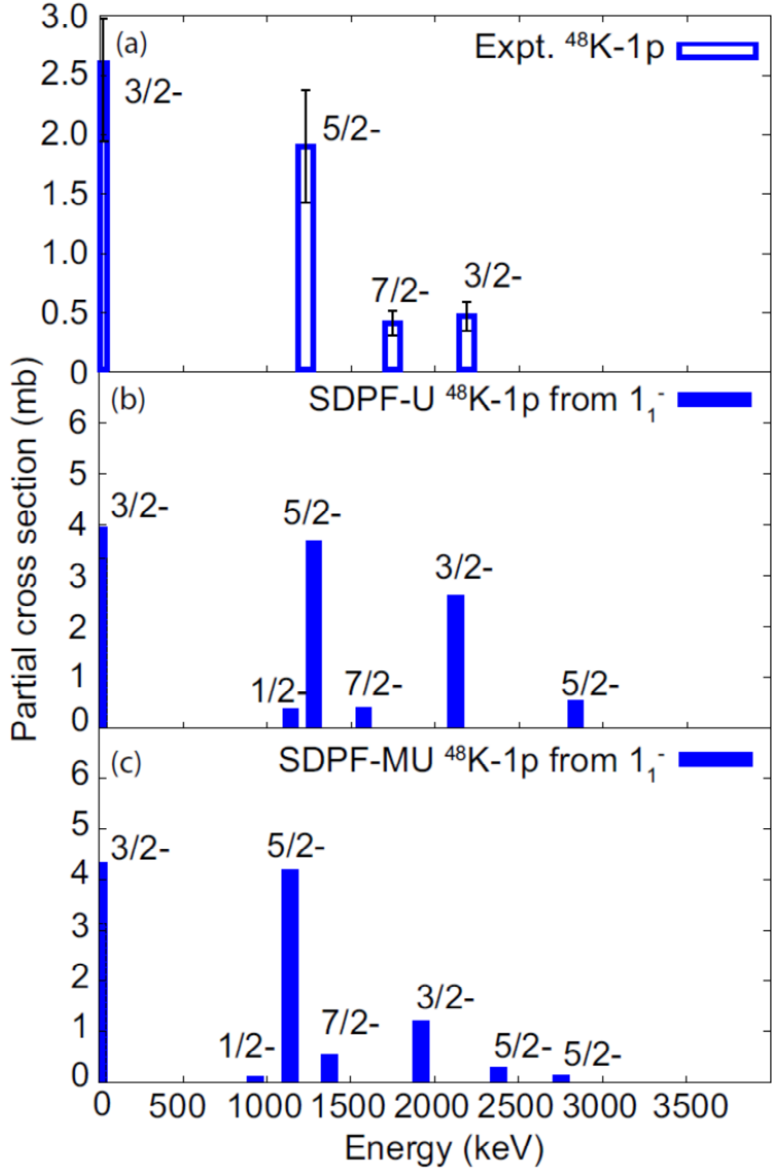
Complementary mechanisms: ^{47}Ar



PHYSICAL REVIEW C **93**, 054315 (2016)

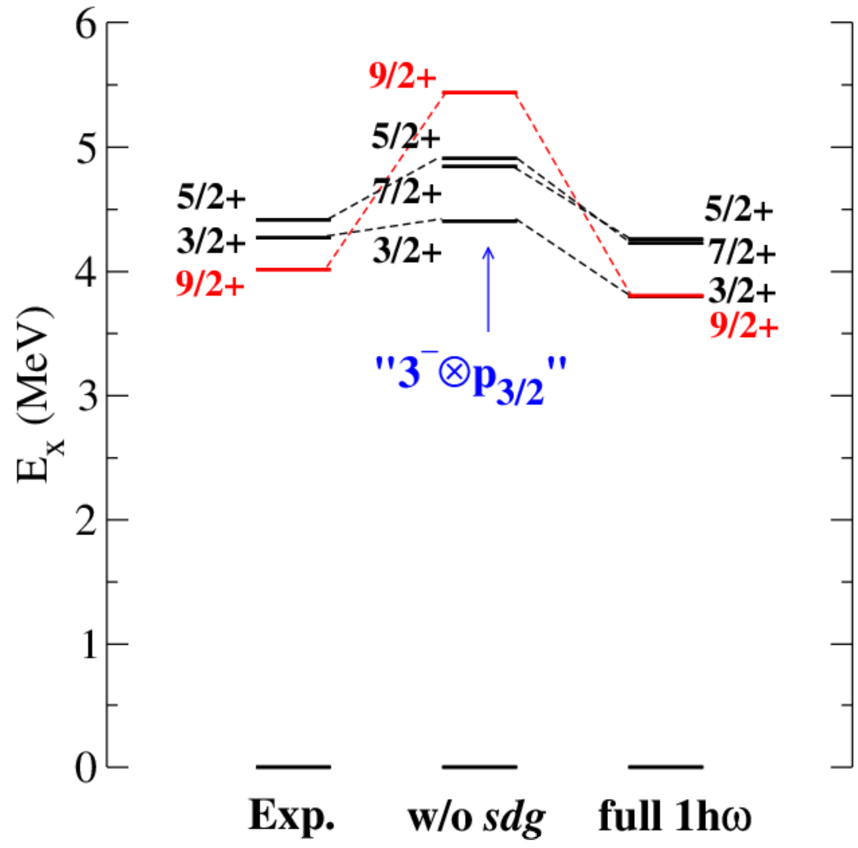
Shell-model interactions at N=29: Z=18





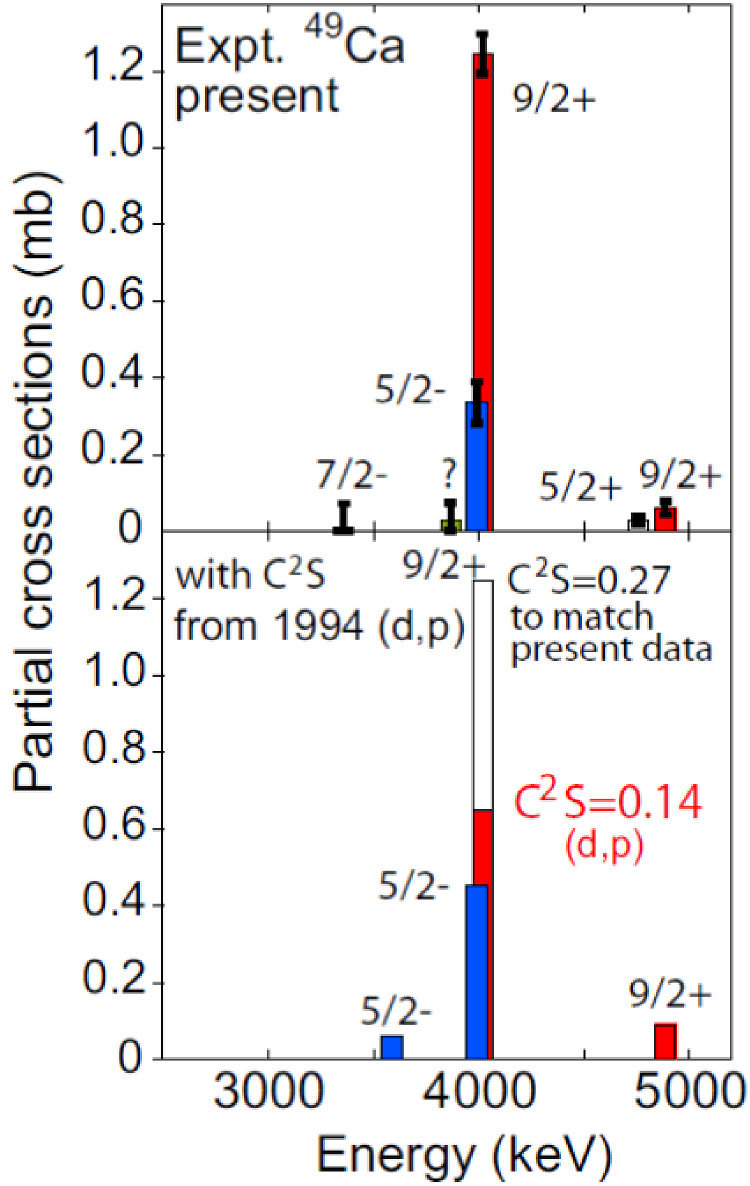
Positive-parity states of ^{49}Ca (Utsuno)

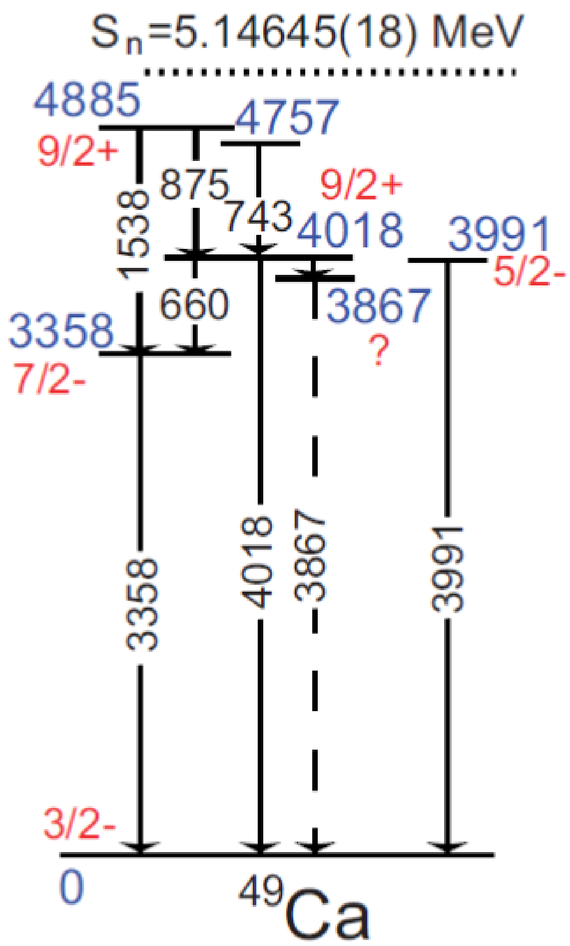
- $9/2^+$ at 4.017 MeV
  - Spin-parity has been recently established (D. Montanari et al., Phys. Lett. B 697, 288 (2011).).
  - Probably the lowest positive-parity state
    - Low-spin states must be observed via the b decay.
  - Without the sdg shell, $9/2^+$ is the highest among the multiplet.
  - A strong mixing with pf-to-sdg excitation associated only with $9/2^+$ accounts for the ordering.



	$3/2^+_1$	$5/2^+_1$	$7/2^+_1$	$9/2^+_1$
% of sdg	6	9	7	**51**

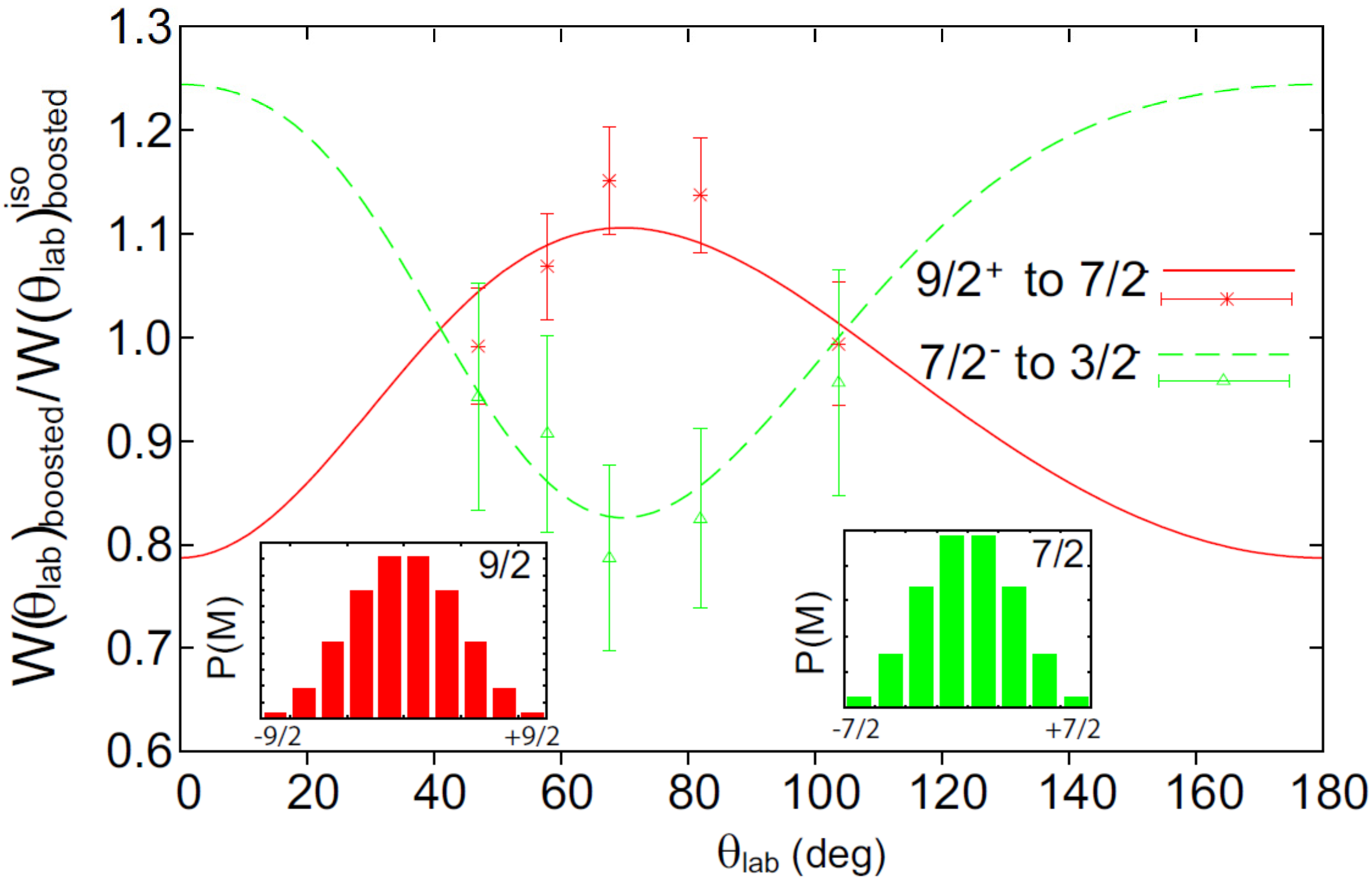
Role of the g9/2 orbital at N=29 at Z=20





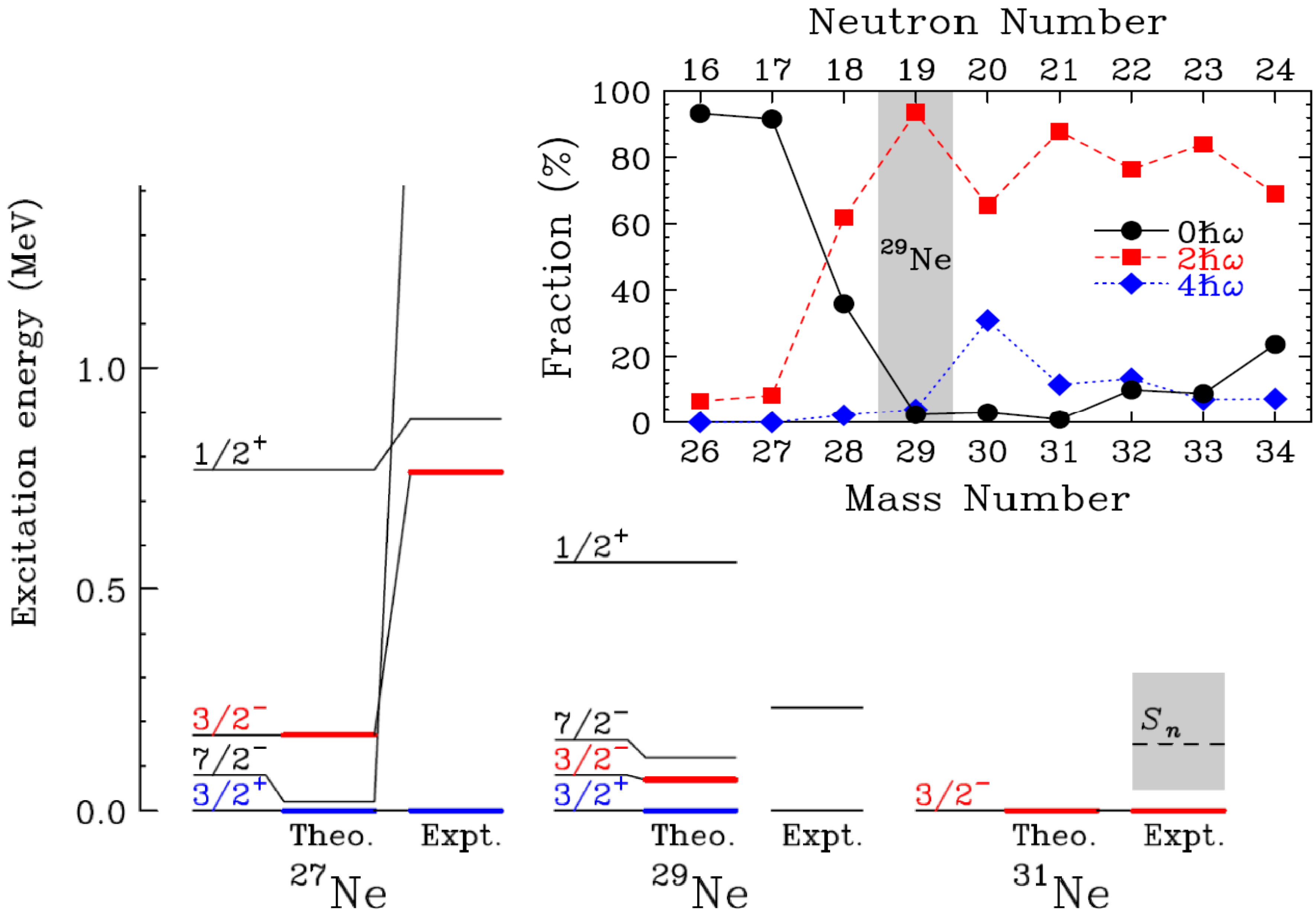
PHYSICAL REVIEW C **93**, 031601(R) (2016)

GRETINA → ^{49}Ca spin-substate alignment



PHYSICAL REVIEW C **93**, 031601(R) (2016)

Island of Inversion – the neutron-rich Ne isotopes

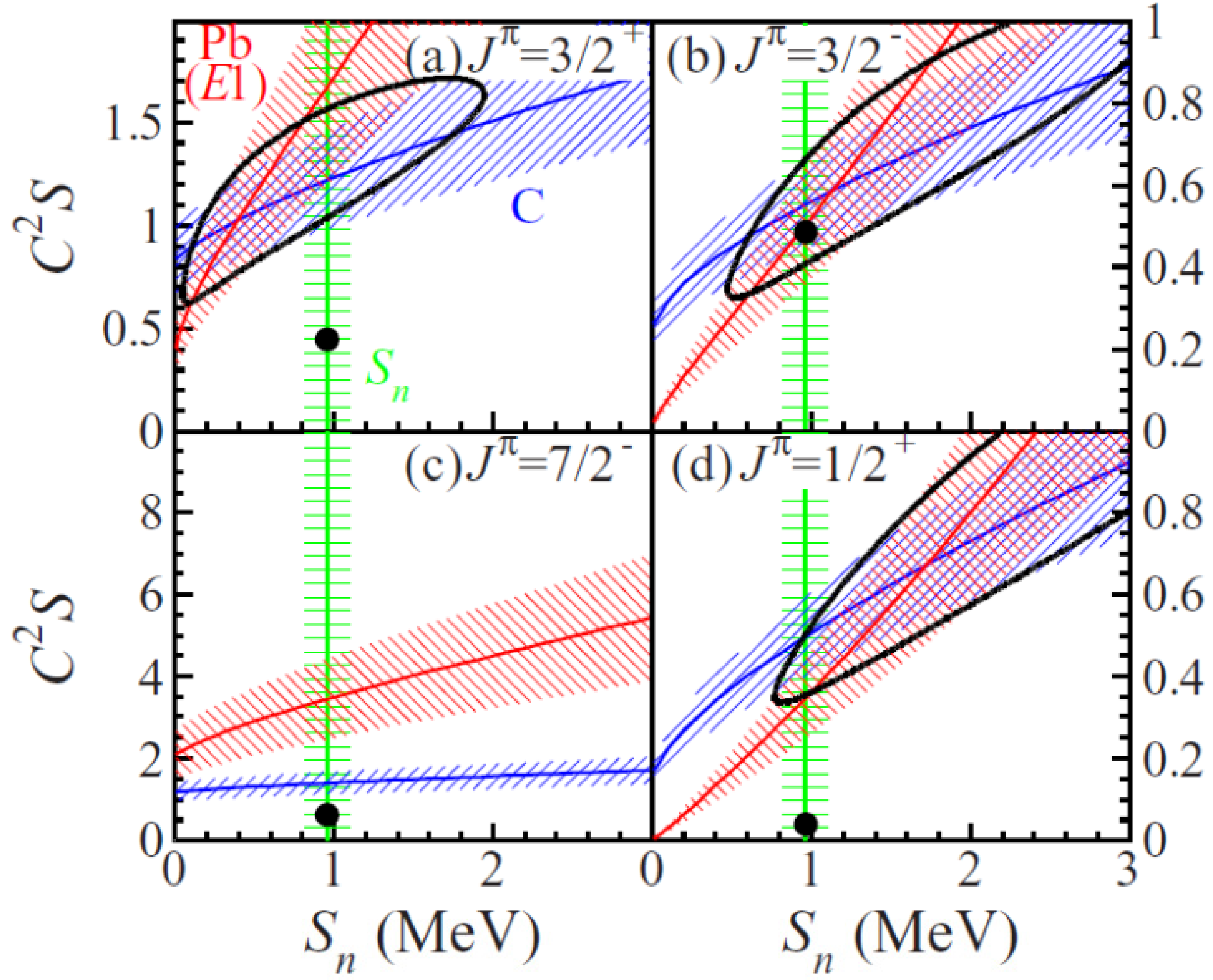


Cross sections – ground- and excited-states

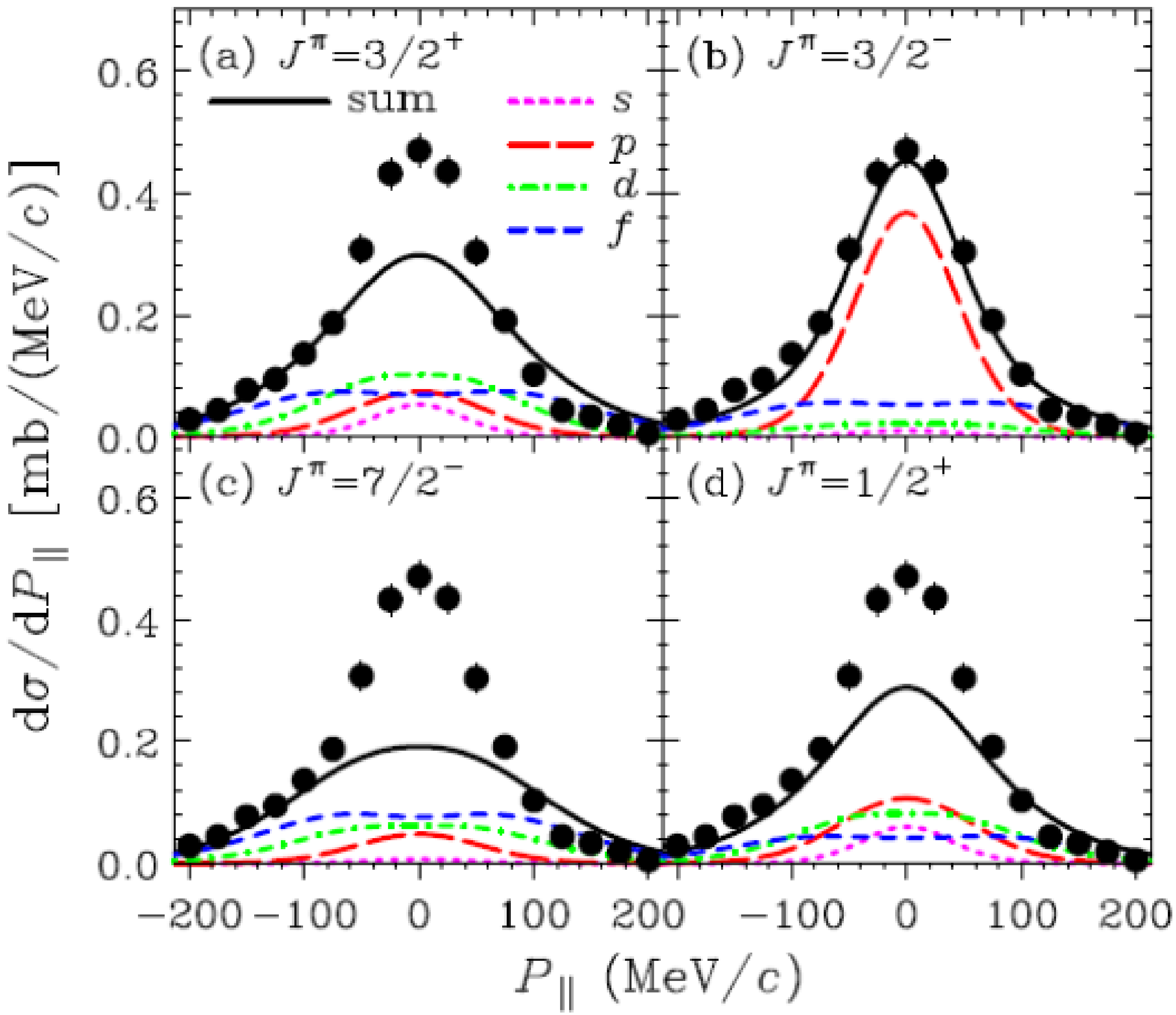
	^{29}Ne: J^{π}				
	$3/2^+$	$3/2^-$	$7/2^-$	$1/2^+$	Expt.
$\sigma_{-1n}(E1)$ (mb)					
^{28}Ne(0_1^+)	48.0	169.6	29.1	19.0	176(50)
^{28}Ne*	92.4	67.0	58.3	107.1	46(49)
Inclusive	140.3	236.6	87.4	126.0	222(36)
g.s. fraction	34%	72%	33%	15%	79(26)%

	$3/2^+$	$3/2^-$	$7/2^-$	$1/2^+$	Expt.
σ_{-1n}^{th} (mb)					
^{28}Ne(0_1^+)	13.25	31.60	15.87	2.71	36(7)
^{28}Ne*	49.82	37.41	32.24	52.41	38(7)
Inclusive	63.07	69.01	48.11	55.13	74(2)
g.s. fraction	21%	46%	33%	5%	49(9)%

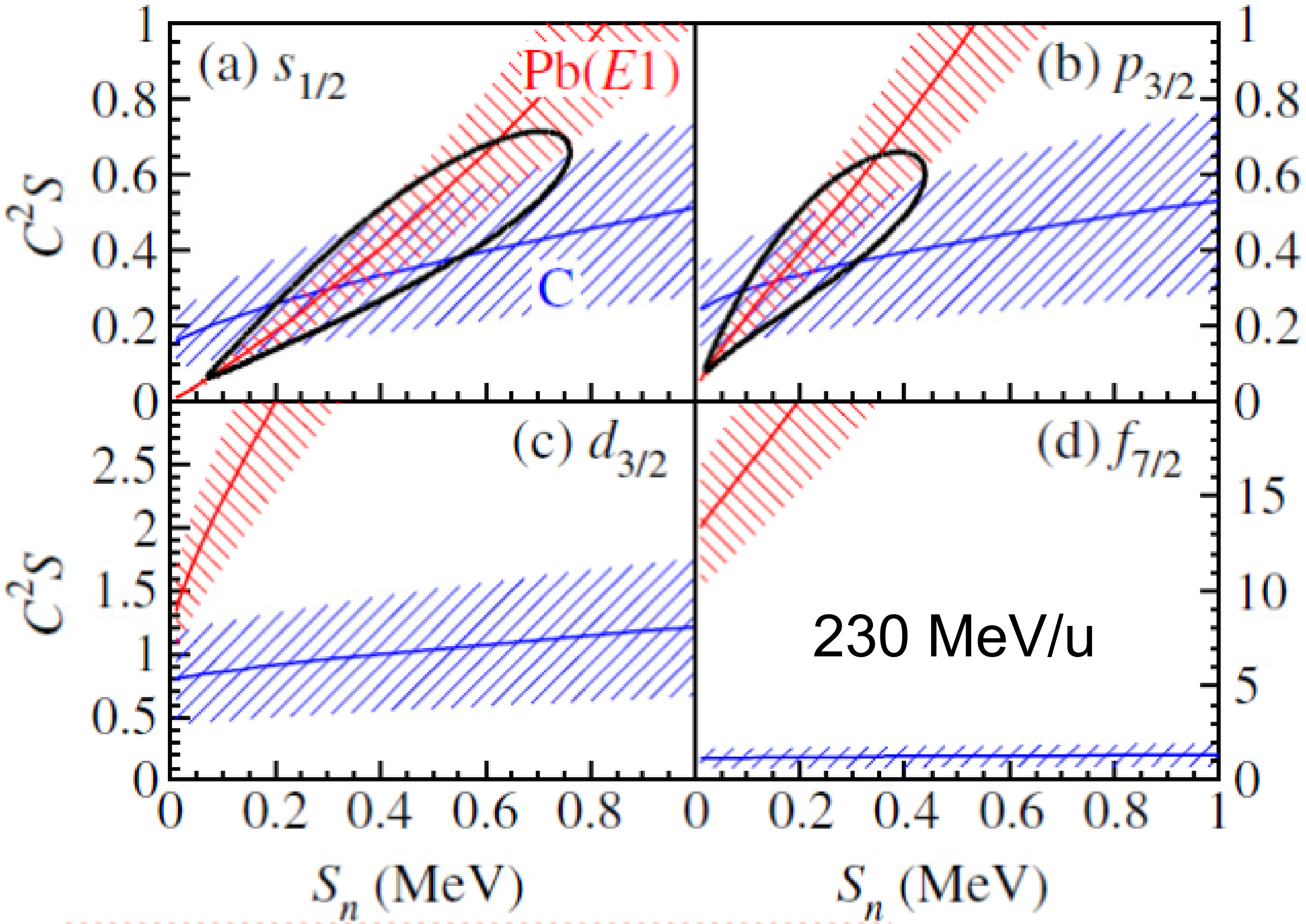
Complementary – Coulomb/nuclear



Momentum distributions also add consistency



Halo-components in heavier n-rich systems: 31Ne

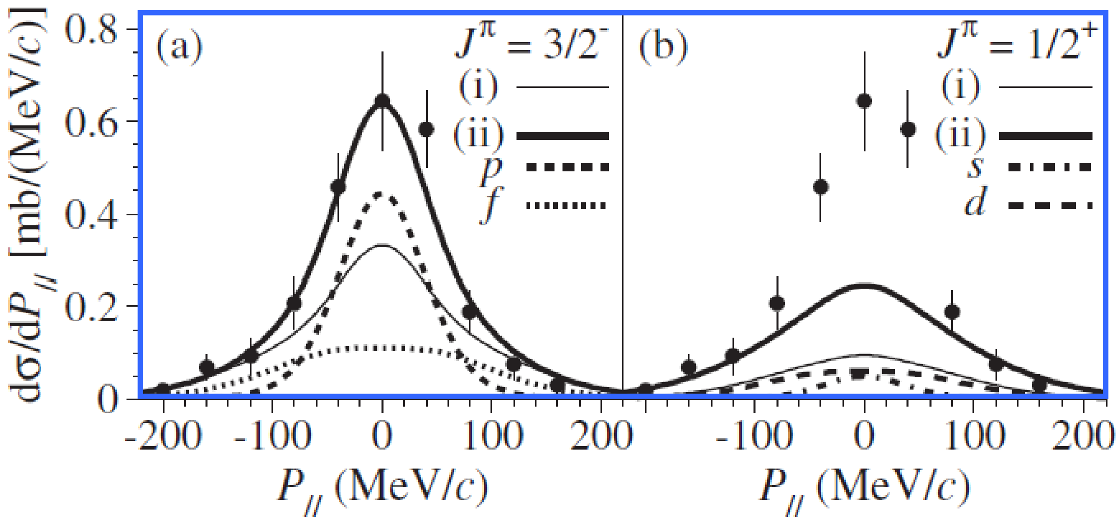


$\sigma_{-1n}(E1;0_1^+)/\sigma_{SP}(E1;n\ell j)$

T. Nakamura et. al. PRL **112,** 142501 (2014)

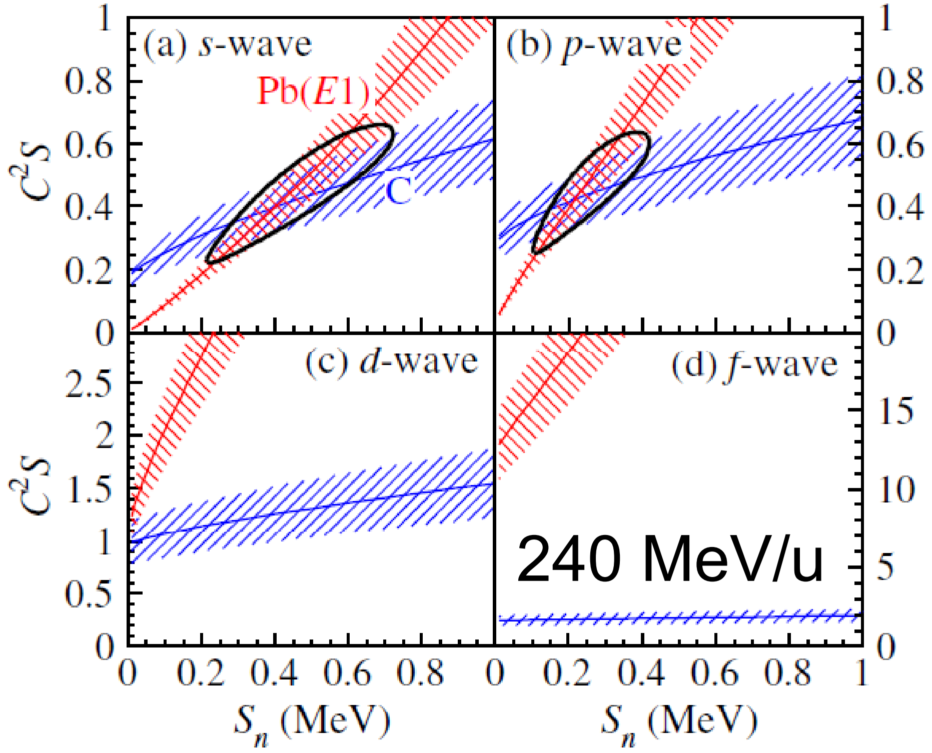
^{31}Ne: configuration mixing – spherical basis

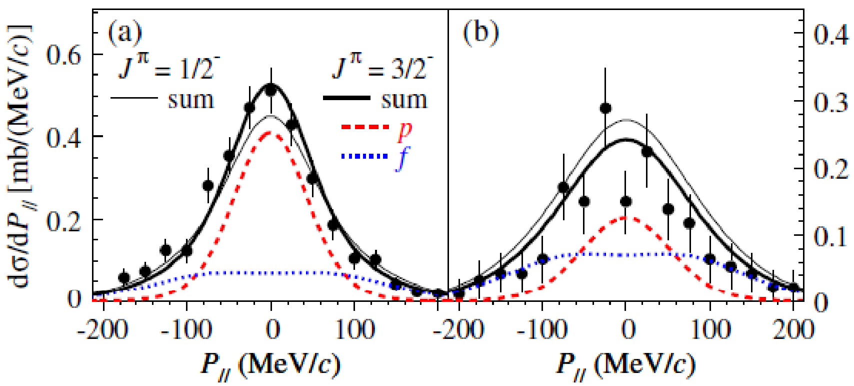
Shell-model configuration	σ_{-1n}(C) (mb)	SM(i) C^2S	WBMB σ^{th}_{-1n}(C) (mb)	SM(ii) C^2S	SDPF-M σ^{th}_{-1n}(C) (mb)
C(^{31}Ne($3/2^-$), ^{30}Ne)					
^{30}Ne(0^+_1) $\otimes$ $2p_{3/2}$	33(15)	0.080	9.2	0.21	24.3
^{30}Ne* $\otimes$ $2p_{3/2}$		0.21	14.4	0.34	21.4
^{30}Ne* $\otimes$ $1f_{7/2}$		1.36	32.9	0.80	18.8
Inclusive	90(7)		58.3		93.3
C(^{31}Ne($1/2^+$), ^{30}Ne)					
^{30}Ne(0^+_1) $\otimes$ $2s_{1/2}$	33(15)	0.011	1.3	0.011	1.3
^{30}Ne* $\otimes$ $1d_{3/2}$		0.76	16.2	0.55	12.8
Inclusive	90(7)		18.1		51.1



T. Nakamura et. al. PRL **112**, 142501 (2014)

Halo-component in heavier n-rich system: ^{37}Mg





N. Kobayashi et al.
PRL **112,** 242501 (2014)

$$\sigma_{-1n}(E1;0_1^+)/\sigma_{\rm SP}(E1;n\ell j)$$

$$\mathrm{SDPF-M}+p_{1/2}$$

Configuration	σ_{sp} (mb)	C^2S	σ^{th}_{-1n}(C) (mb)	σ_{-1n}(C)
C[^{37}Mg(3/2$^-$), ^{36}Mg]				
^{36}Mg(0_1^+) ⊗ 2$p_{3/2}$	89.4	0.31	30.1	38(8)
^{36}Mg* ⊗ 2p	⋯	0.47	17.4	
^{36}Mg* ⊗ 1f	⋯	1.35	23.0	
Inclusive			80.6	80(4)
C[^{37}Mg(1/2$^-$), ^{36}Mg]				
^{36}Mg(0_1^+) ⊗ 2$p_{1/2}$	88.1	0.20	18.9	38(8)
^{36}Mg* ⊗ 2p	⋯	0.44	17.4	
^{36}Mg* ⊗ 1f	⋯	1.80	28.4	
Inclusive			77.6	80(4)
C[^{37}Mg(1/2$^+$), ^{36}Mg]				
^{36}Mg(0_1^+) ⊗ 2$s_{1/2}$	95.3	0.001	0.1	38(8)
^{36}Mg* ⊗ 1d	⋯	0.85	15.7	
^{36}Mg* ⊗ 2p	⋯	0.17	5.1	
^{36}Mg* ⊗ 1f	⋯	1.00	15.4	
Inclusive			37.0	80(4)

Summary

Tracking of single particle structure (level ordering and spectroscopic strengths) at and near the N and Z Fermi surface(s) can be advanced using:

Pickup (nucleon addition) reactions from light-heavy-ion targets (C works well) – *exploiting mismatch*

Removal/breakup (nucleon removal) – exploiting Coulomb/nuclear *breakup mechanism selectivity*

Shell-model interface with reactions allows a detailed *assessment of calculations/interactions*

Deduced spectroscopy and structure information is enhanced using multiple, *complementary* reactions