Probes of structure: heavier halo systems, shell evolution and correlations in and exotic nuclei

Journées des théoriciens nucléaires
19th -20th October 2010, Institut de Physique Nucléaire de Lyon

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Faculty of Engineering and Physical Sciences
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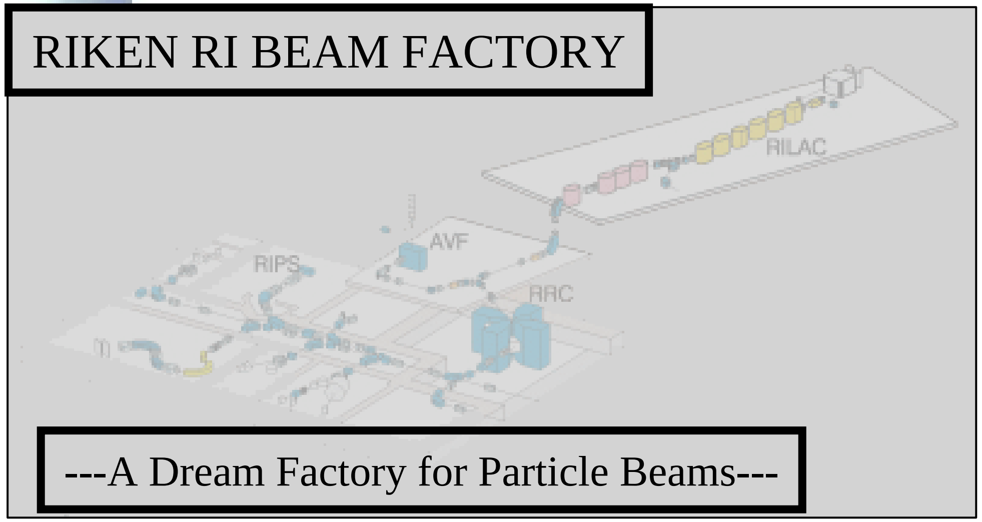
Radioactive ion-beam facilities – now and future

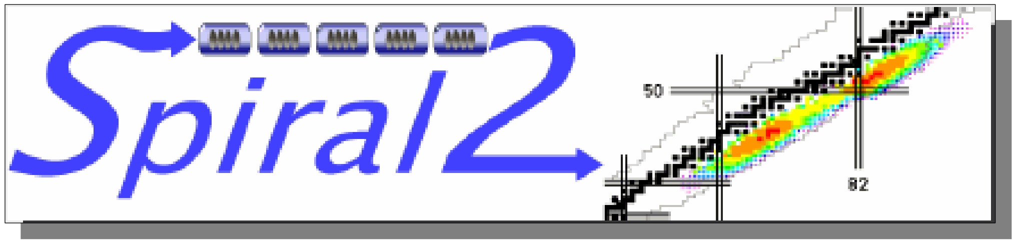


RIBF operational

RIKEN

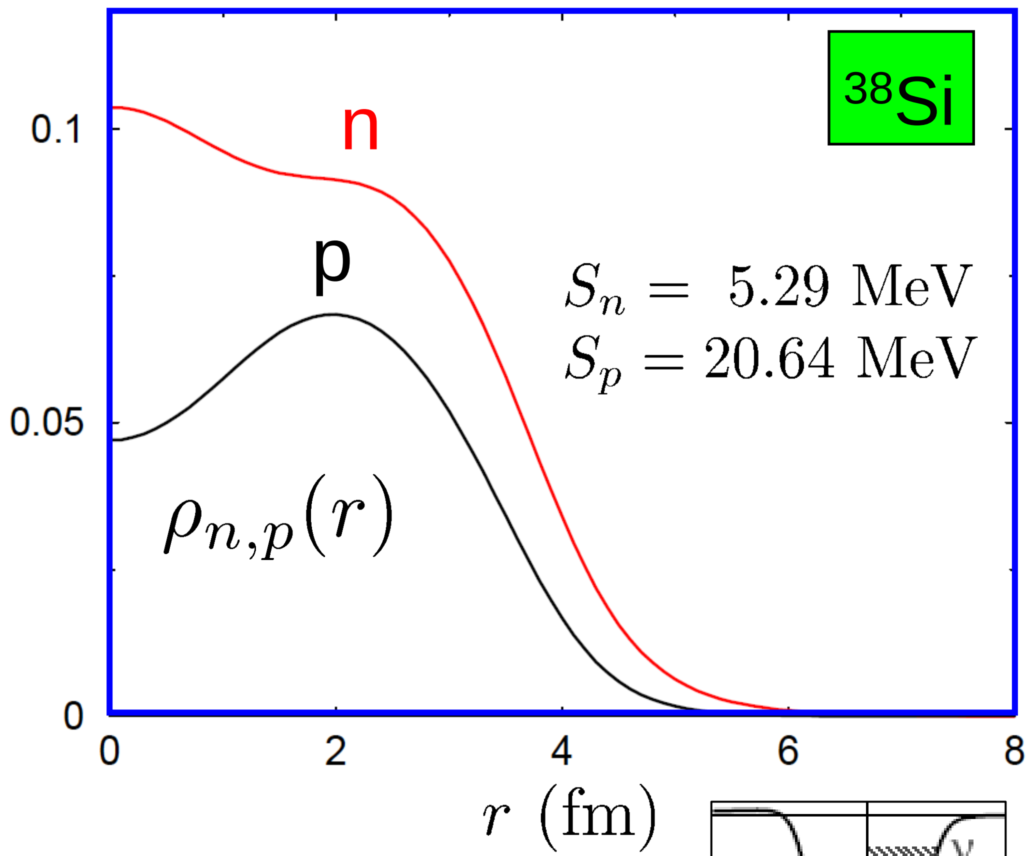
MSU -

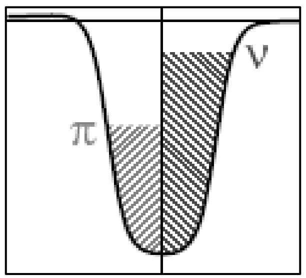
FRIB

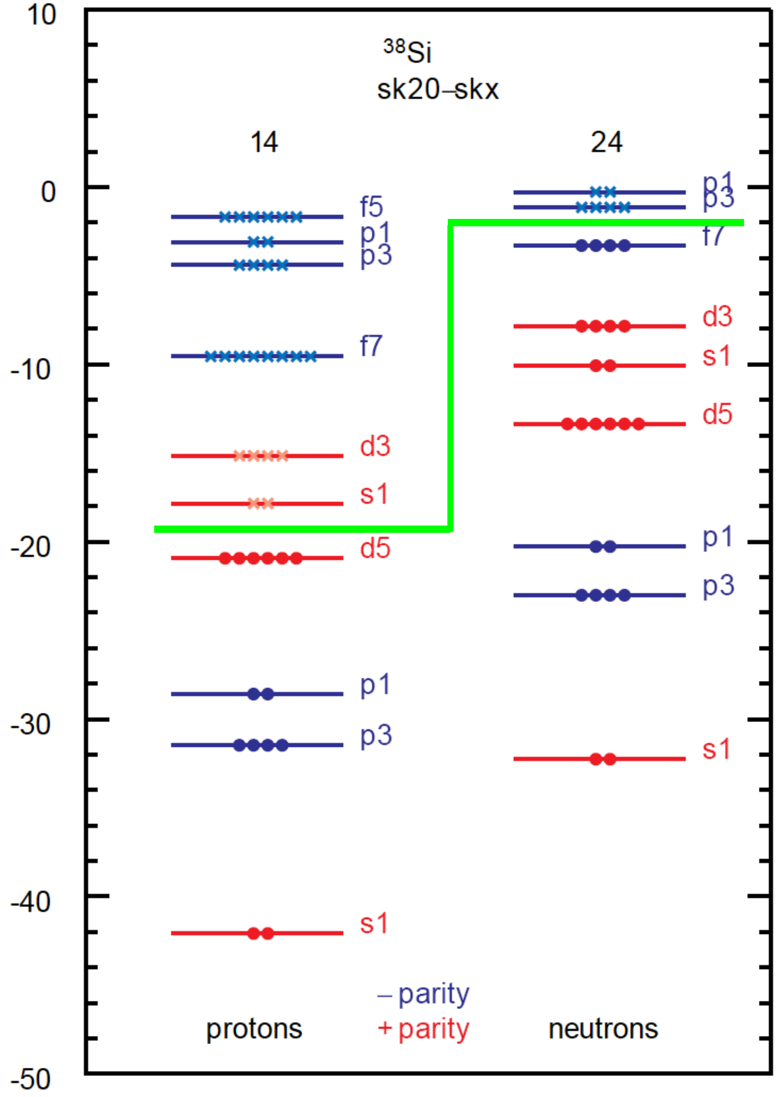


GANIL

Asymmetry → two (very) displaced Fermi surfaces







Spherical HF density (SkX)

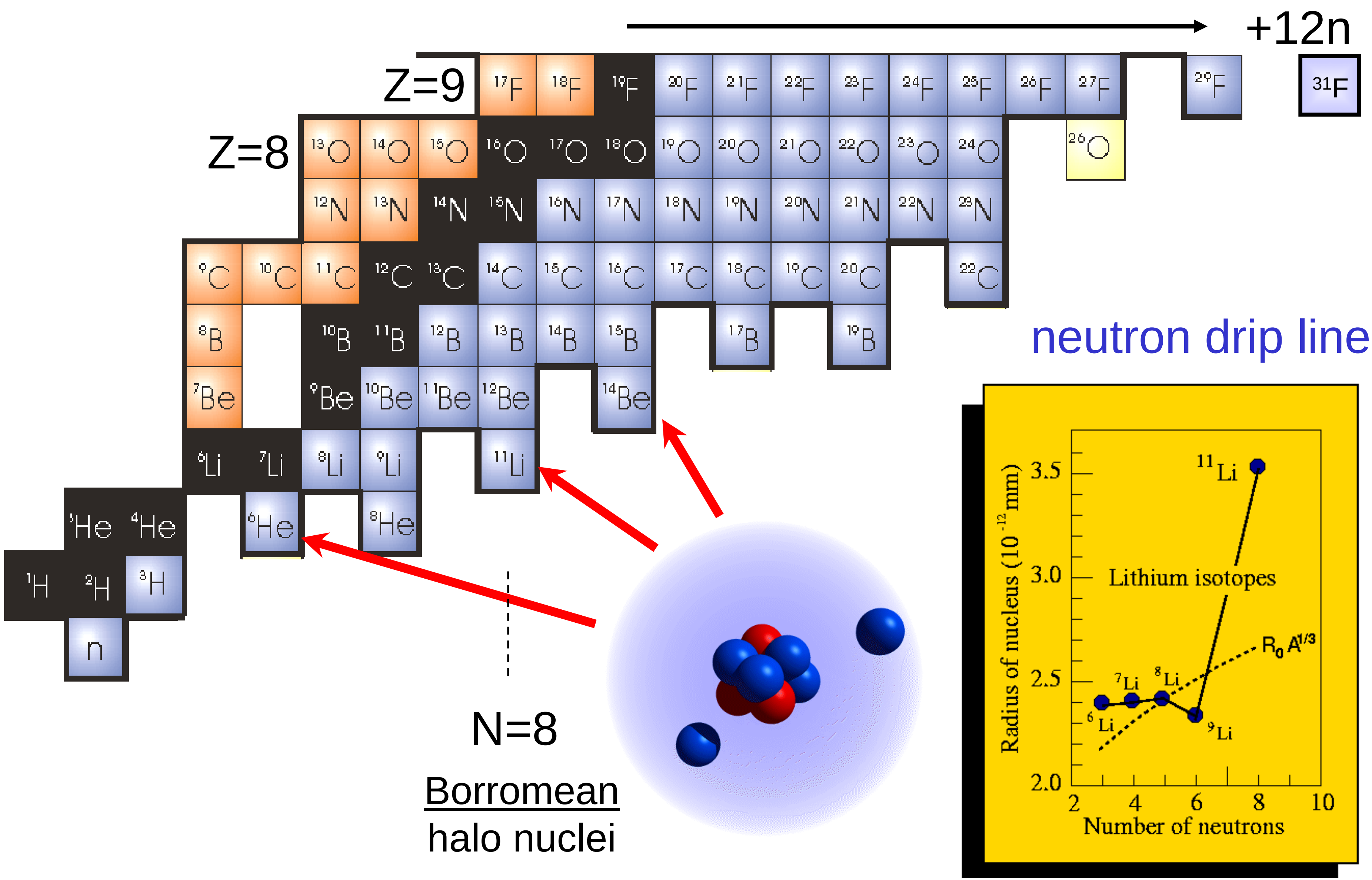
Motivations/questions/difficulties

1. Understand (i) the evolution of nuclear structure with N:Z asymmetry and (ii) the structures near the limits of binding – e.g. are there heavier halo systems?
2. Short-lived - how can we make progress with this based on simple (often inclusive) reaction data?
3. Can we pose stricter tests of many-body structure models (mostly shell-model currently) and their 1N and 2N (correlations) content? – currently, tests of the quality and predictive power of effective inter'ns in CI model calculations
4. Can we make this reaction/structure interface and methodology and testing quantitative?

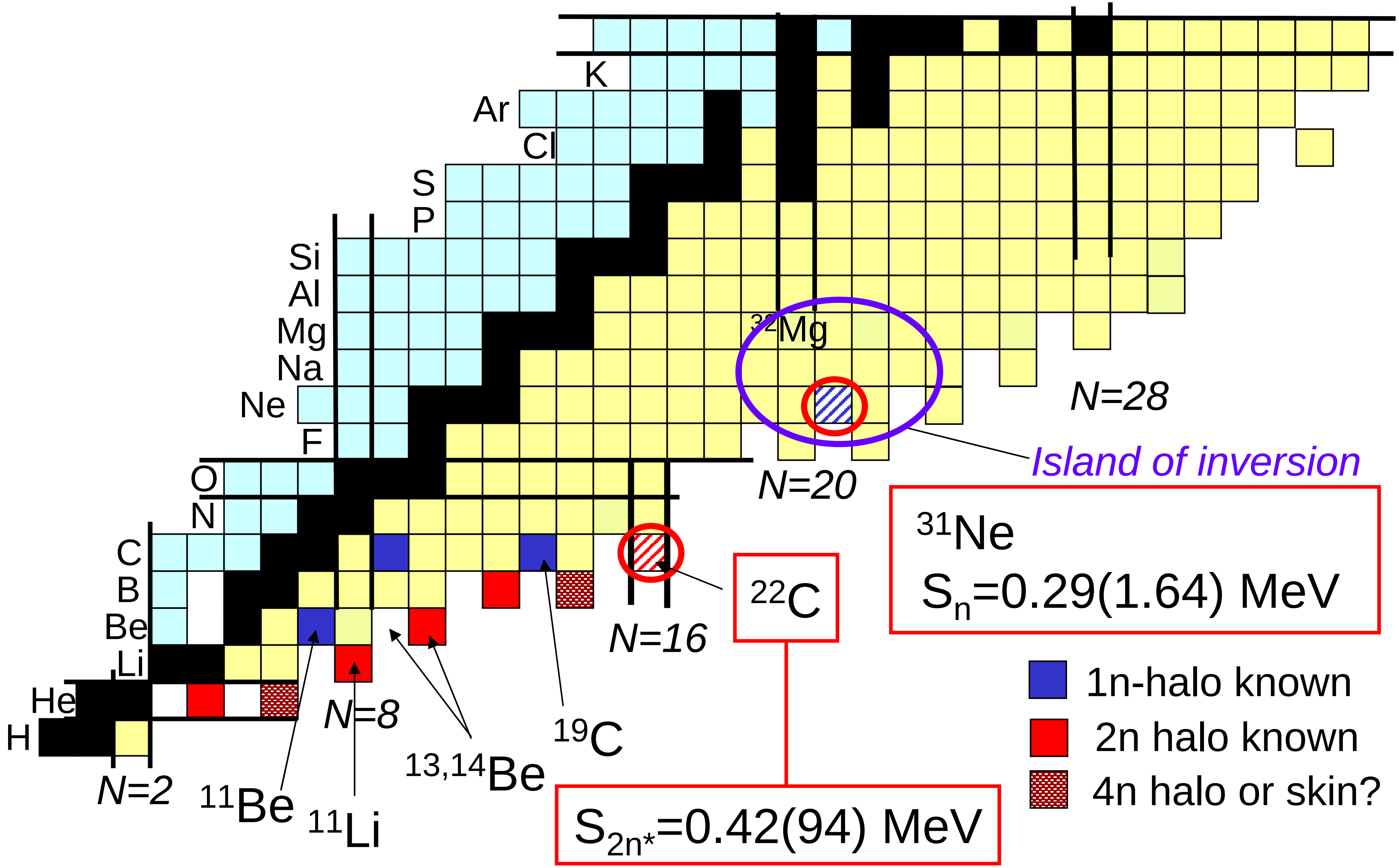
Outline of my contribution

1. Why and where halos? - mean field effects and level migration/evolution – breakdown of N=8,20
2. How do we?/can we? identify halo systems from limited and exclusive data
2. Reaction probes for weakly bound systems
3. Opportunities for (quantitative) tests of the shell model and many-body structure models – e.g. their 2N correlations content – from 2N removal data?
4. Test cases (p- and sd-shell) predictions
5. Summary comments

Halos – the driplines in the light nuclei

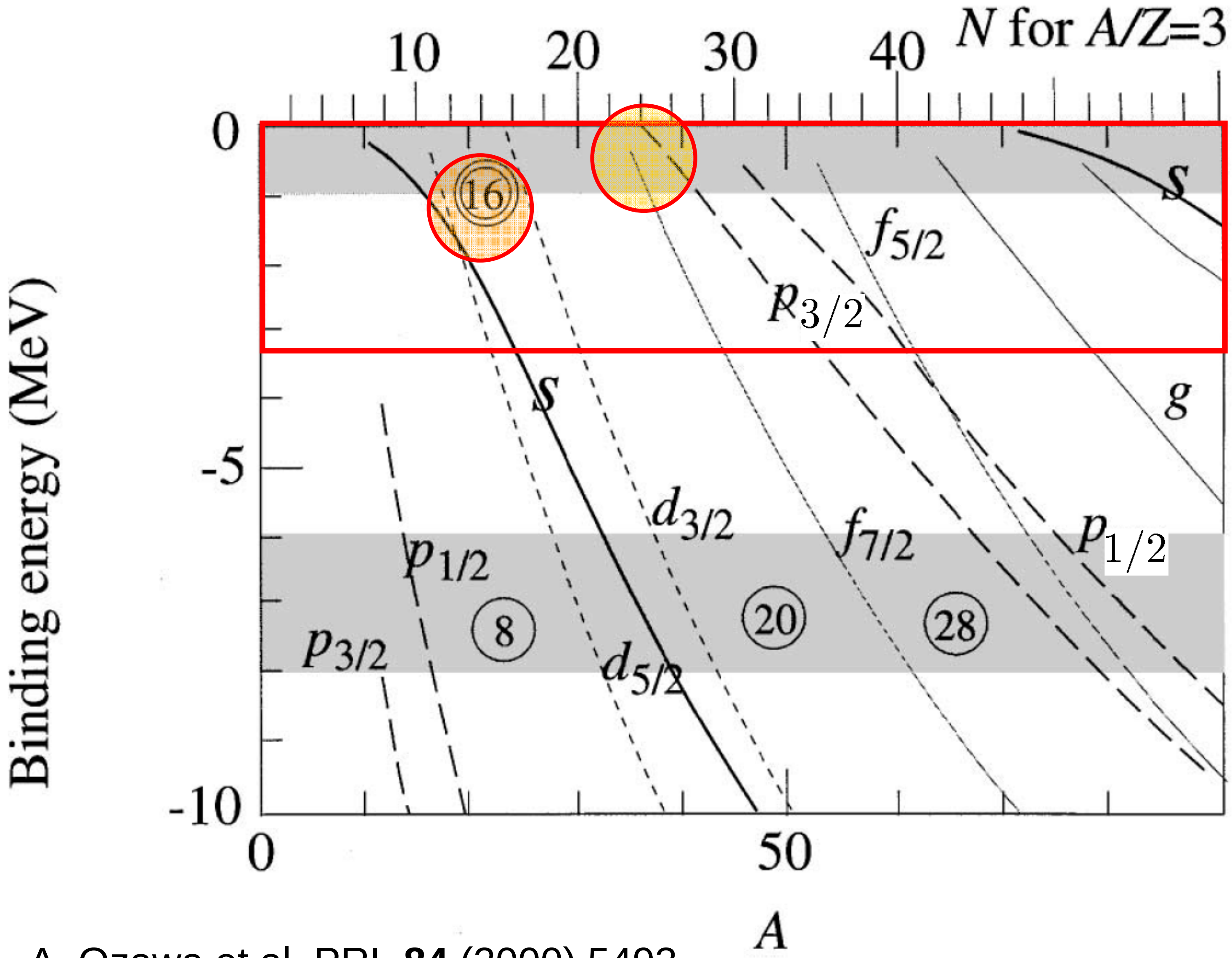


Identifying heavier halo cases: ^{22}C and ^{31}Ne



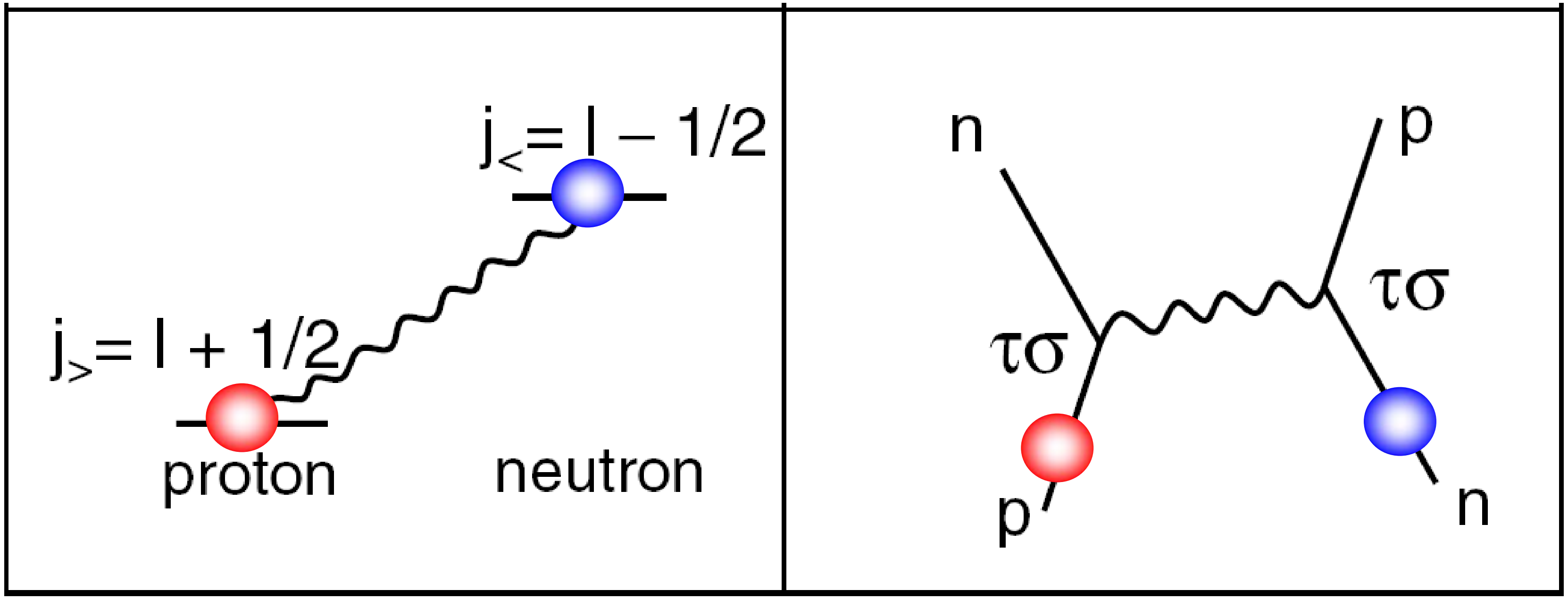
From T. Nakamura

Low angular momentum states see well diffuseness



A. Ozawa et al, PRL **84** (2000) 5493

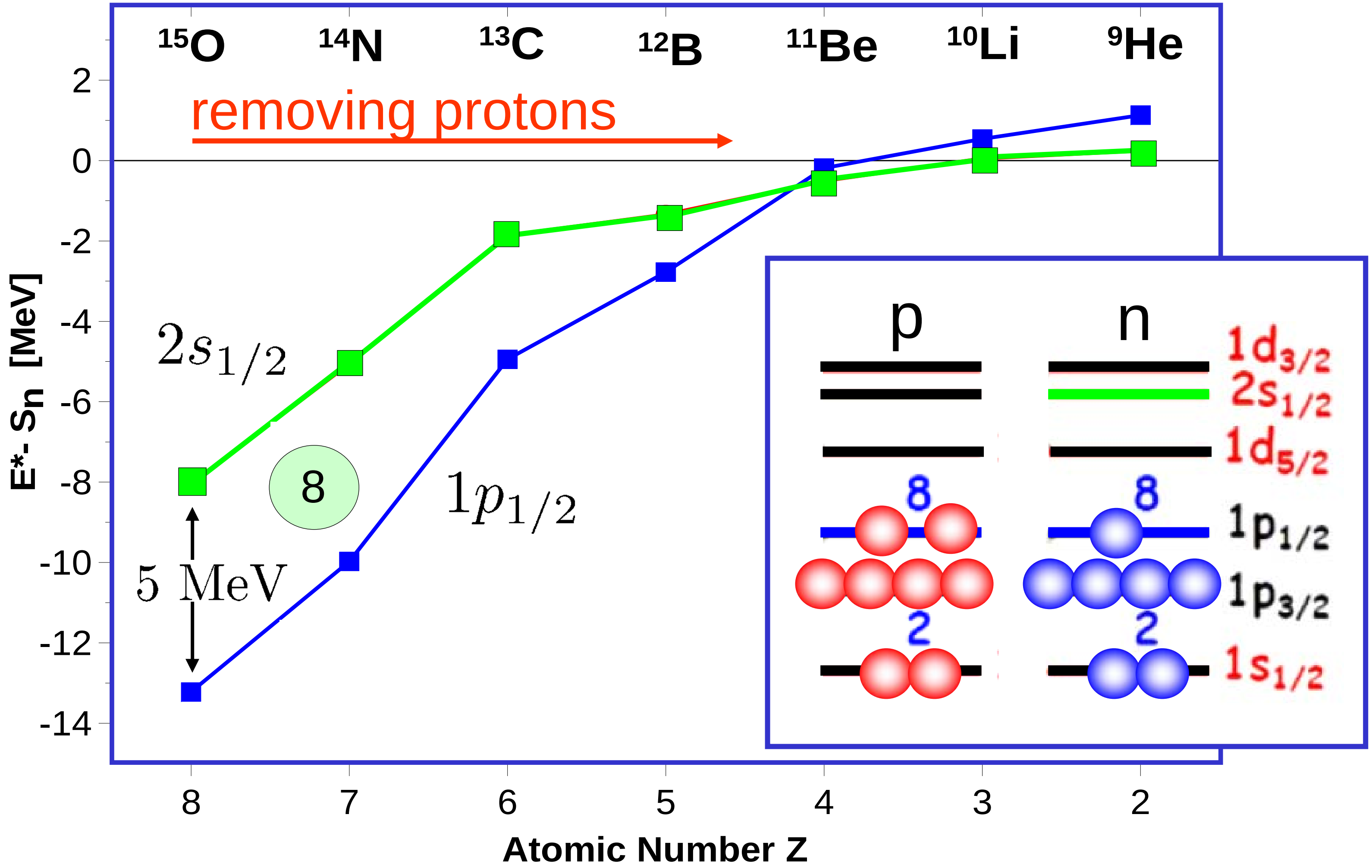
Shell structure: V_{NN} and asymmetric nuclei



Attractive interaction between neutrons and protons occupying $j_>$ and $j_<$ levels, repulsive j> and j> levels – from several sources, but primarily the tensor force

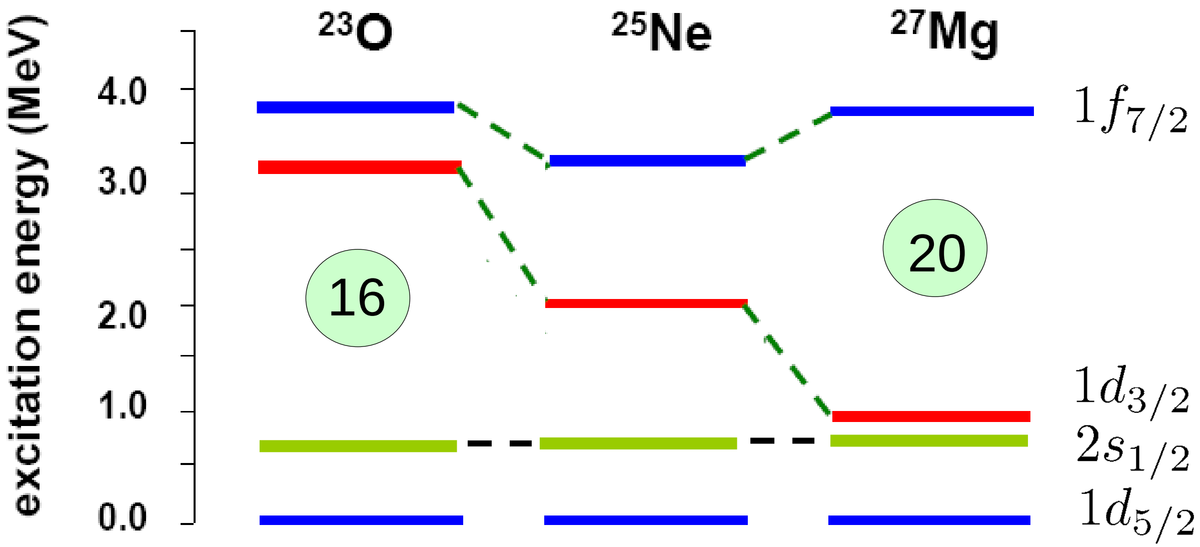
Takaharu Otsuka et al, Phys. Rev. Lett. **87**, 082502 (2001), **95**, 232502 (2005), **105**, 032501 (2010)

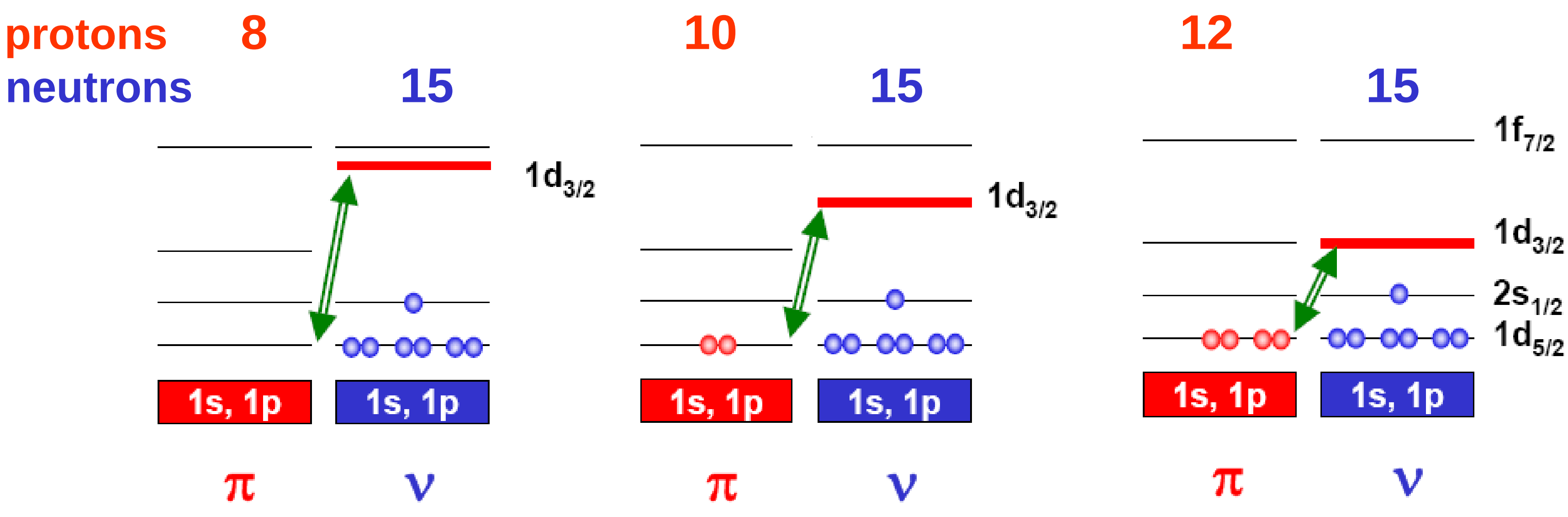
Migration of levels at N=7 – breakdown of N=8



From: P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci **53** (2003) 219

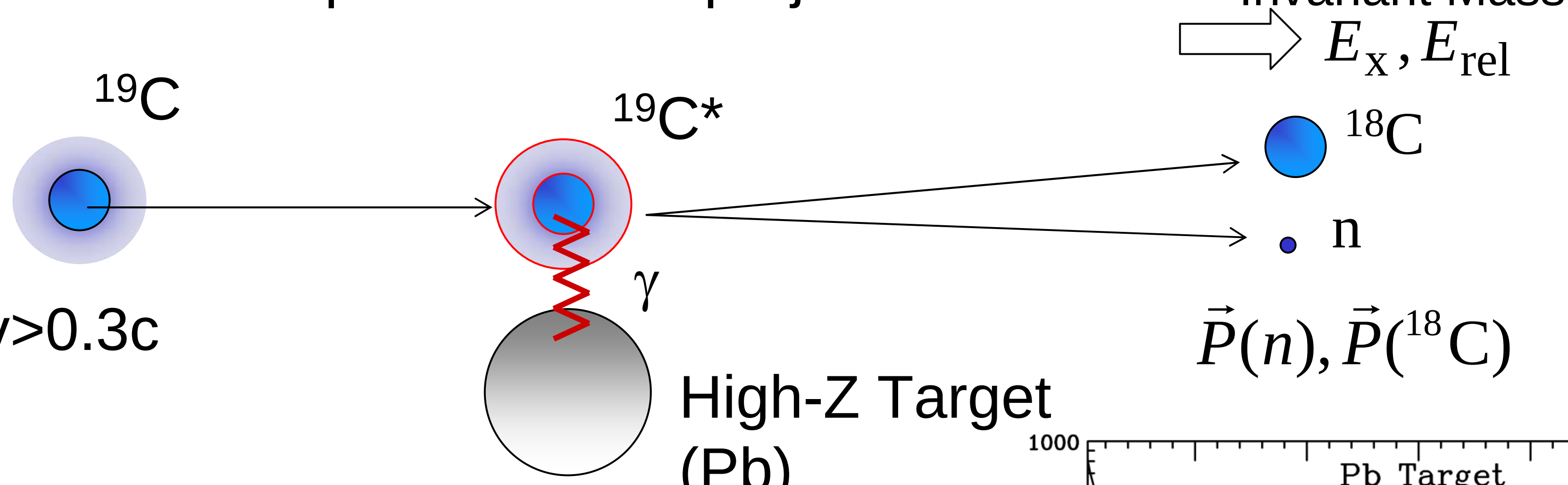
Breakdown of N=20





Coulomb excitation - breakup mechanism

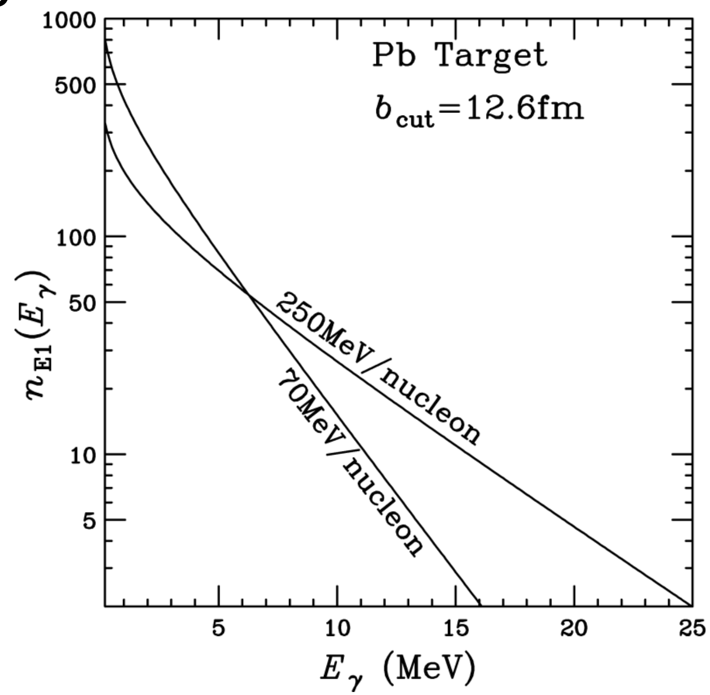
Photon absorption of a fast projectile



Equivalent Photon Method

$$\frac{d\sigma_{CD}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)x(Transition Probability)

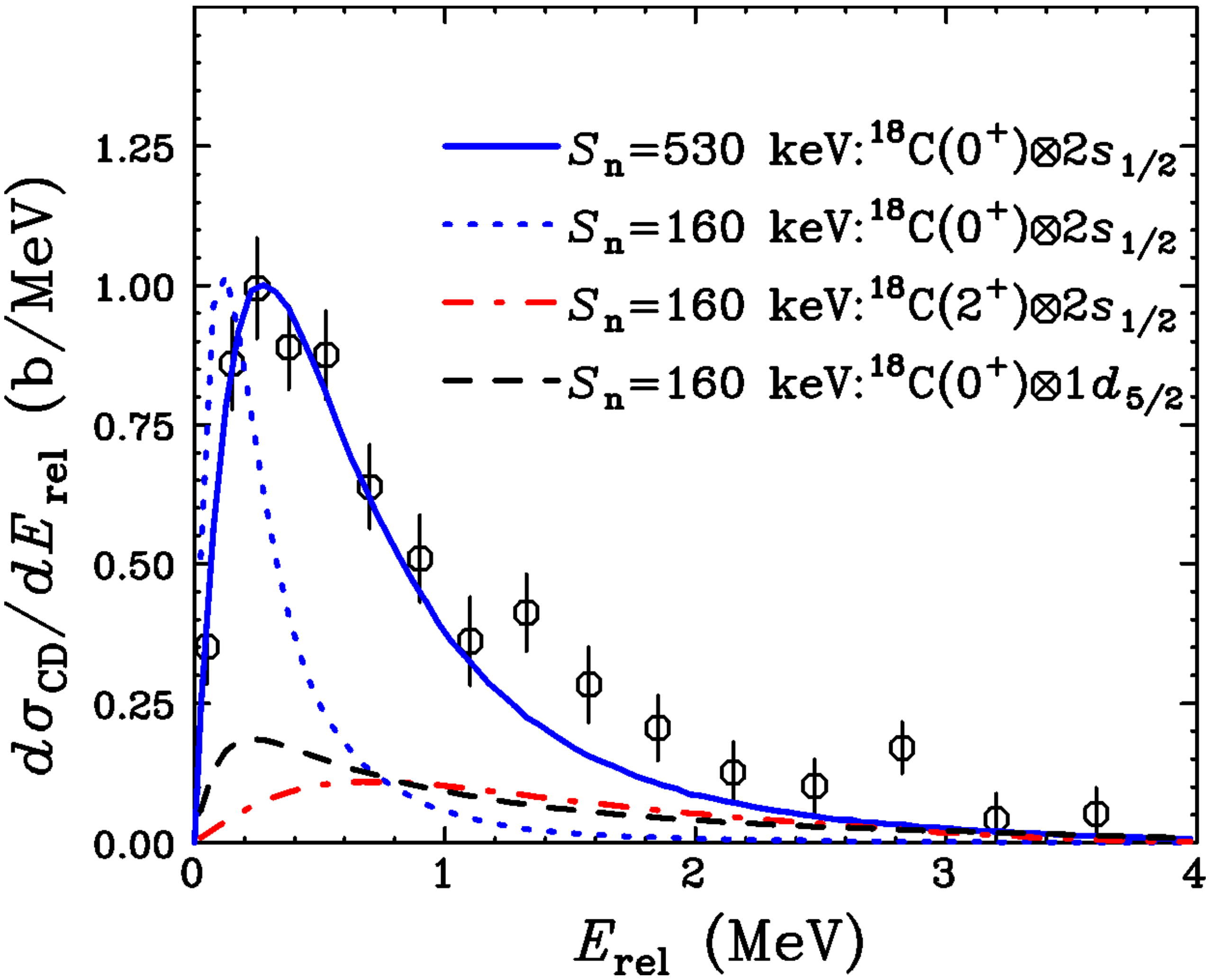


From T. Nakamura

Low energy dipole (continuum) response

^{19}C (S_n=0.53 MeV)

Electric dipole response – ^{19}C

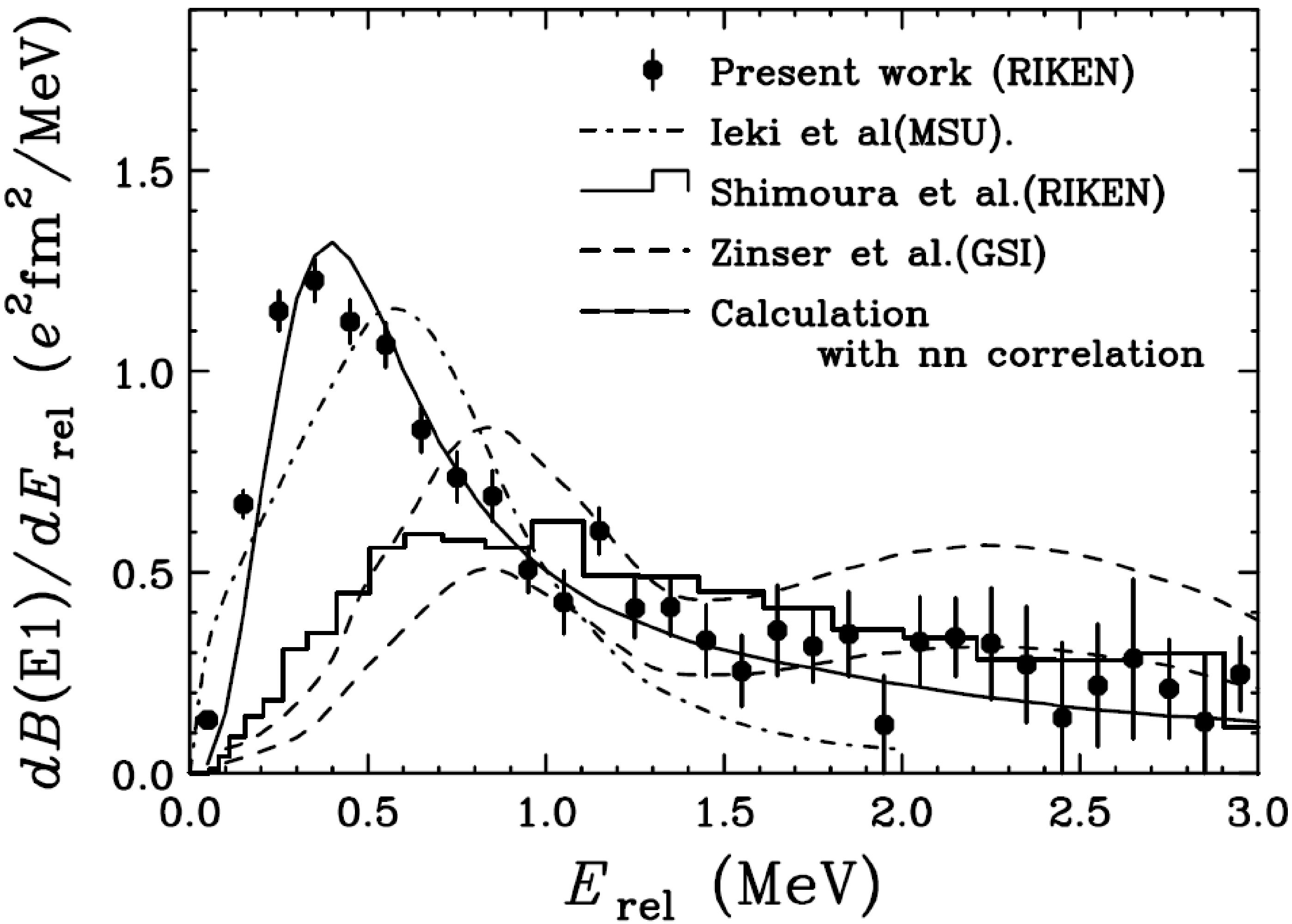


T. Nakamura et al., PRL **83**, 1112 (1999)

Low energy dipole (continuum) response

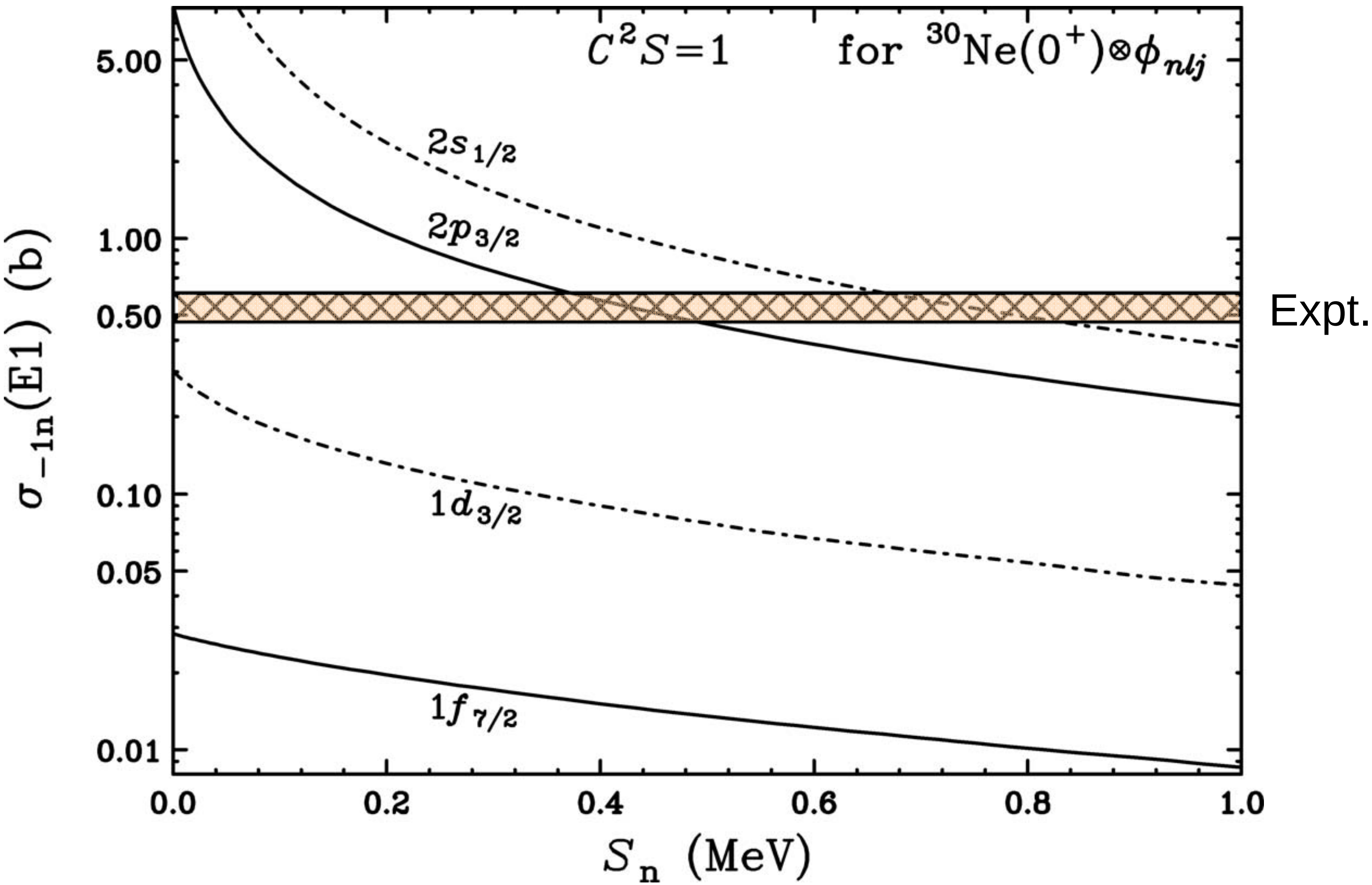
^{11}Li (S_{2n}=300 keV)

Electric dipole response – ^{11}Li



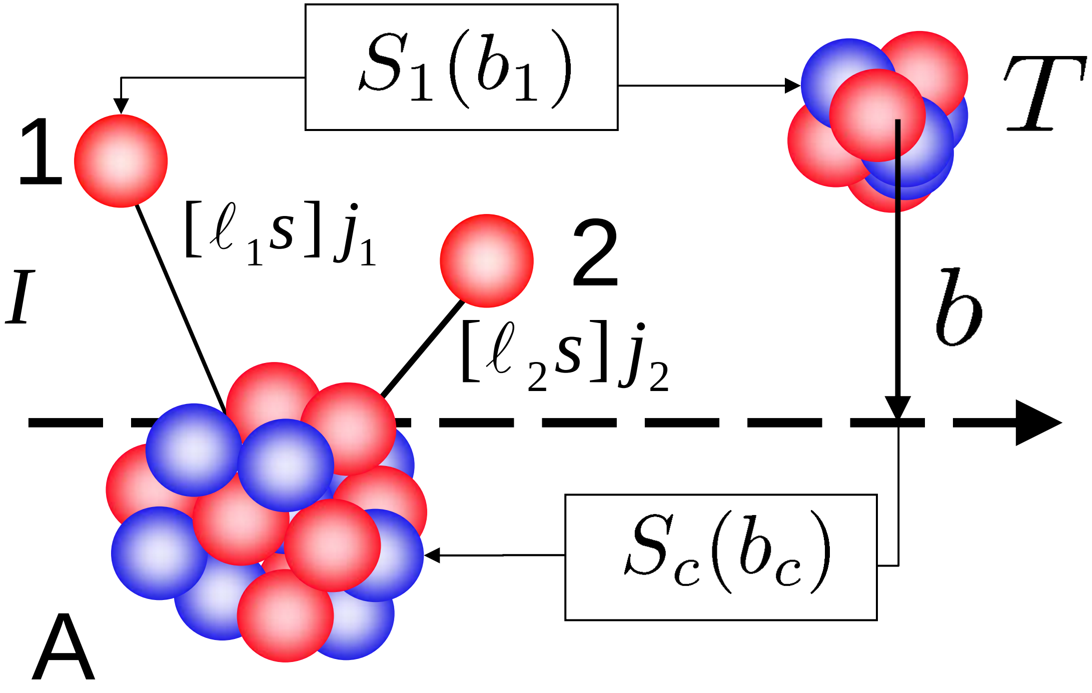
T. Nakamura et al., PRL**96**,252502 (2006)

^{31}Ne – separation energy



T. Nakamura et al., PRL **103,** 262501 (2009)

Sudden removal – eikonal reaction dynamics



Inclusive wrt target, 1 and 2 final states. Cross sections [and the *S(b)*] allow both elastic and stripping (absorptive) events that can remove the nucleon(s).

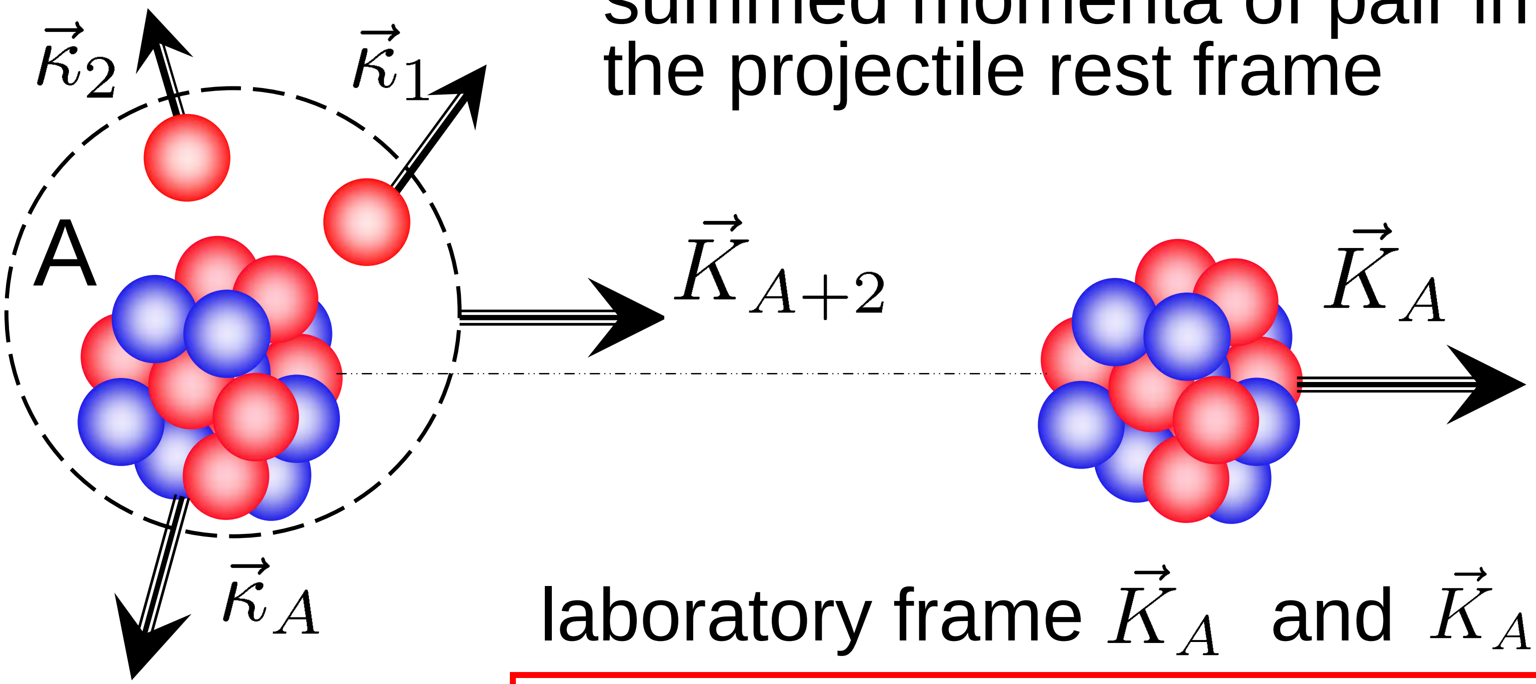
$$\sigma_I = \frac{1}{2I+1} \sum_M \int d\vec{b} \, \langle F_{IM} | \hat{O}(c,1,2) | F_{IM} \rangle$$

$$\text{2N stripping} : \hat{O}(c,1,2) = |S_c|^2 (1 - |S_1|^2)(1 - |S_2|^2)$$

J.A. Tostevin *et al.*, PRC 70 (2004) 064602 and PRC 74 (2006) 064604
P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci **53** (2003) 219

Sudden 2N removal from the mass A residue

Sudden removal: residue momenta probe the summed momenta of pair in the projectile rest frame



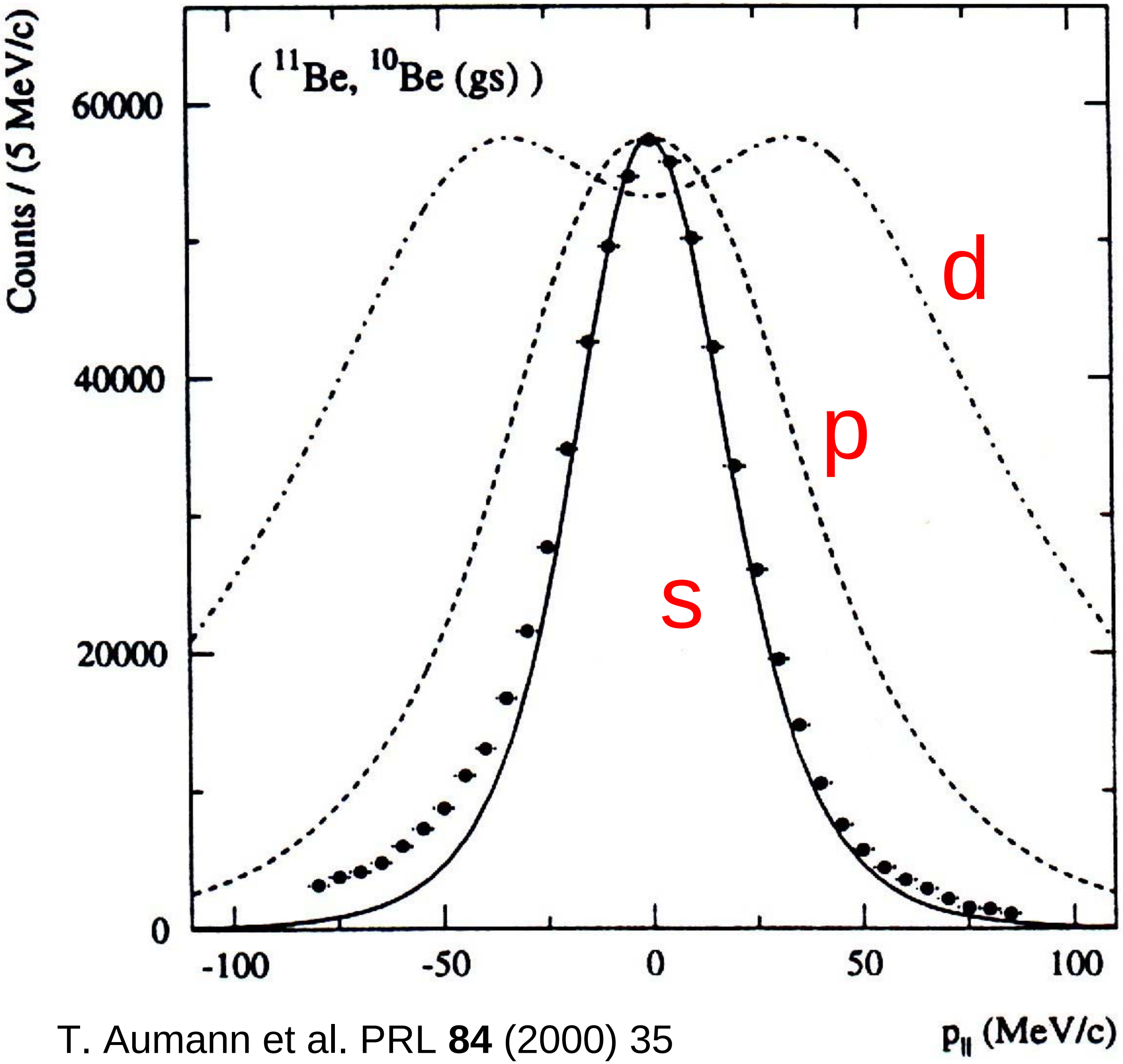
Projectile rest frame

laboratory frame $\vec{K}_A$ and $\vec{K}_{A+2}$

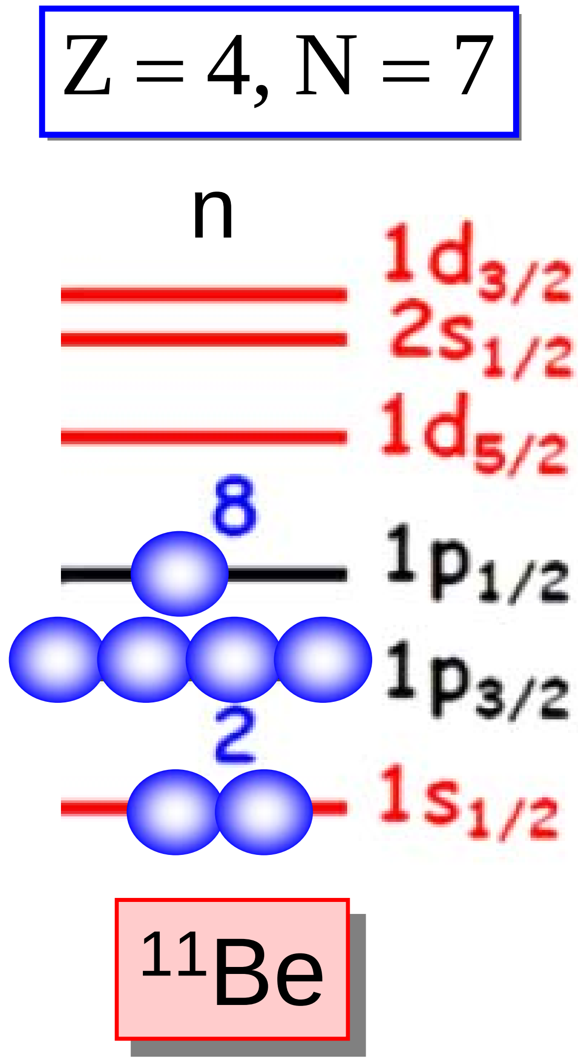
$$\boxed{\vec{K}_A = \frac{A}{A+2}\vec{K}_{A+2} - [\vec{\kappa}_1 + \vec{\kappa}_2]}$$

and component equations

Residue momentum $^{11}Be \rightarrow {}^{10}Be$ – halo case



T. Aumann et al. PRL **84** (2000) 35



^{11}Li – ground state wavefunction admixtures

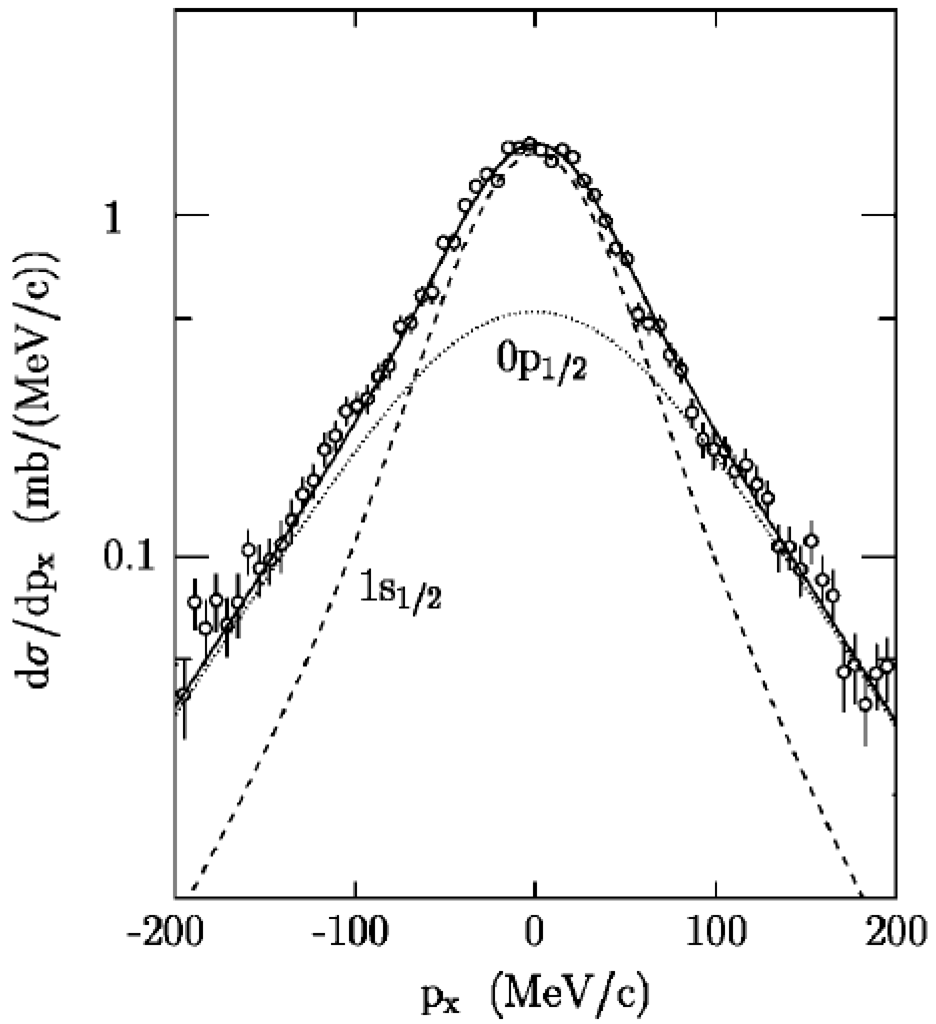
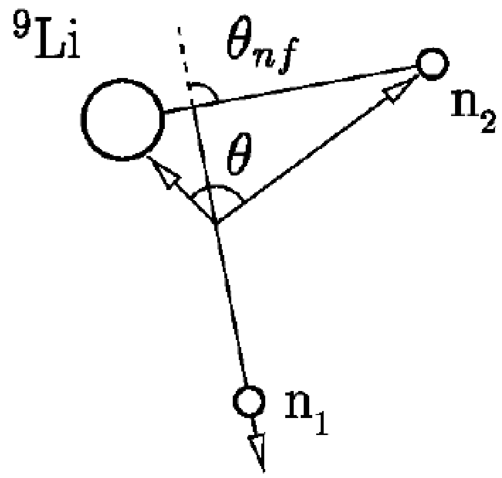


FIG. 1. Transverse momentum distribution of ^{10}Li, reconstructed from the momenta of ^{9}Li, and the neutron measured in coincidence after neutron knockout from ^{11}Li (C target).



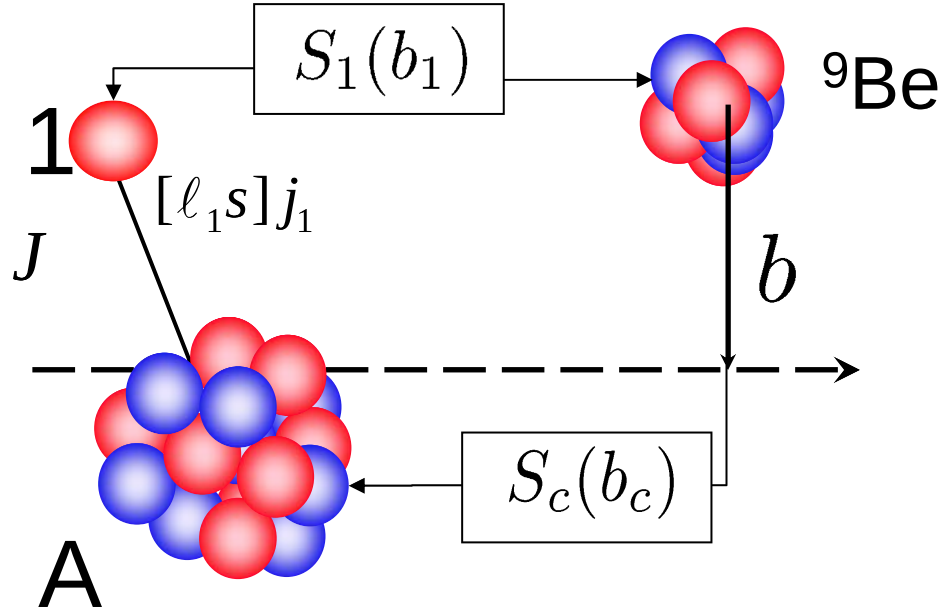
$$\mathbf{p}_{n_1} = \mathbf{p}_{n(nf)} = -(\mathbf{p}_{n_2} + \mathbf{p}_f) = -\mathbf{p}(^9\mathrm{Li} + n_2)$$

H. Simon et al,
PRL **83** (1999) 496

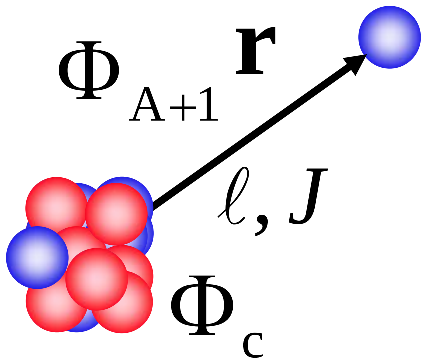
Eikonal and sudden model - requires two 'sizes'

(i) Interactions

$$\rho_T(r)$$
$$\rho_A(r)$$



(ii) Overlaps



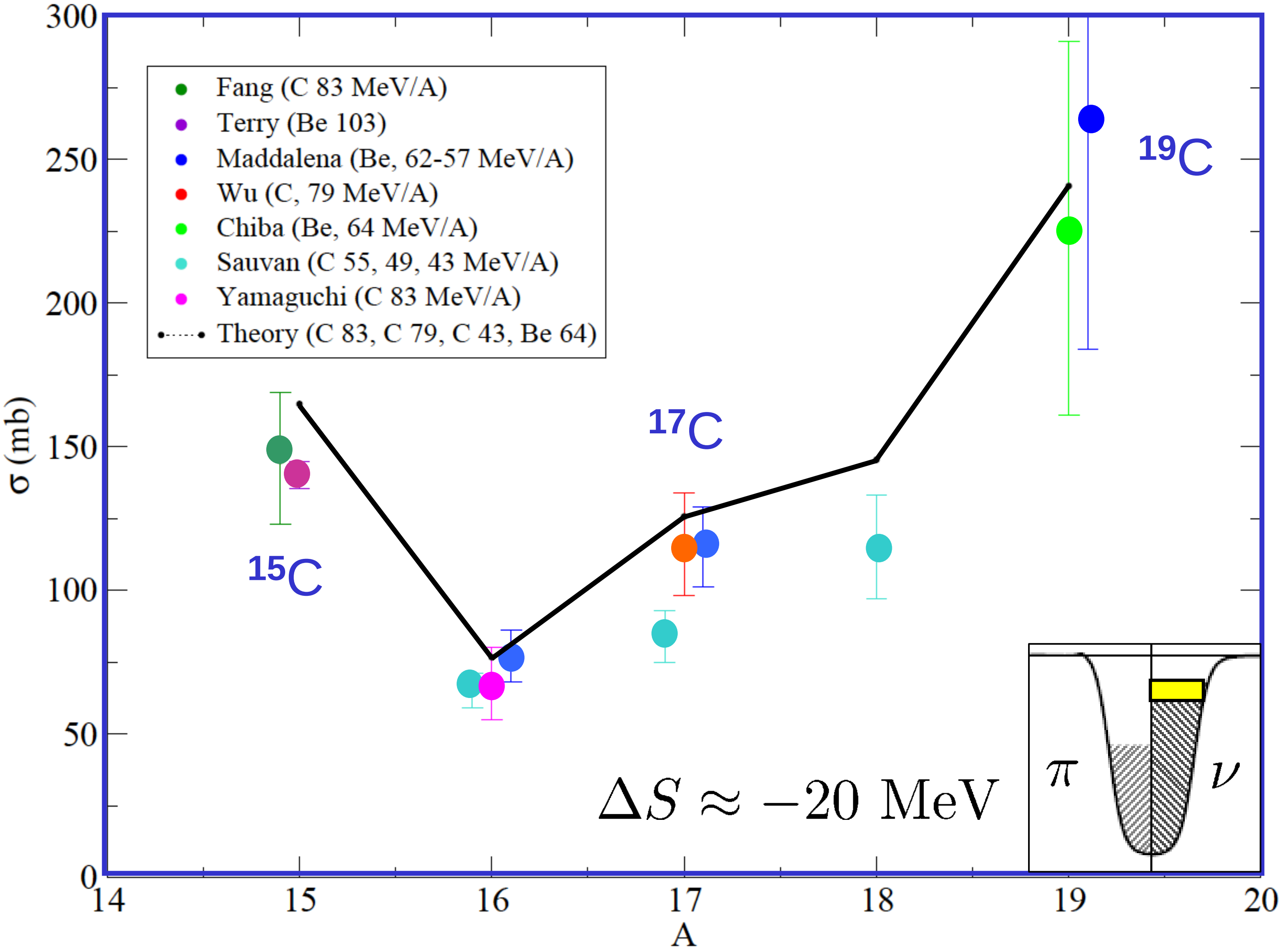
$$F_{JM}(\vec{r}) = \langle \vec{r}, \Phi_c | \Phi_{A+1} \rangle$$

$$F_{JM}(\vec{r}) = C(J)\phi_{JM}(\vec{r})$$

$$\boxed{C^2S(J) = |C_J|^2}$$

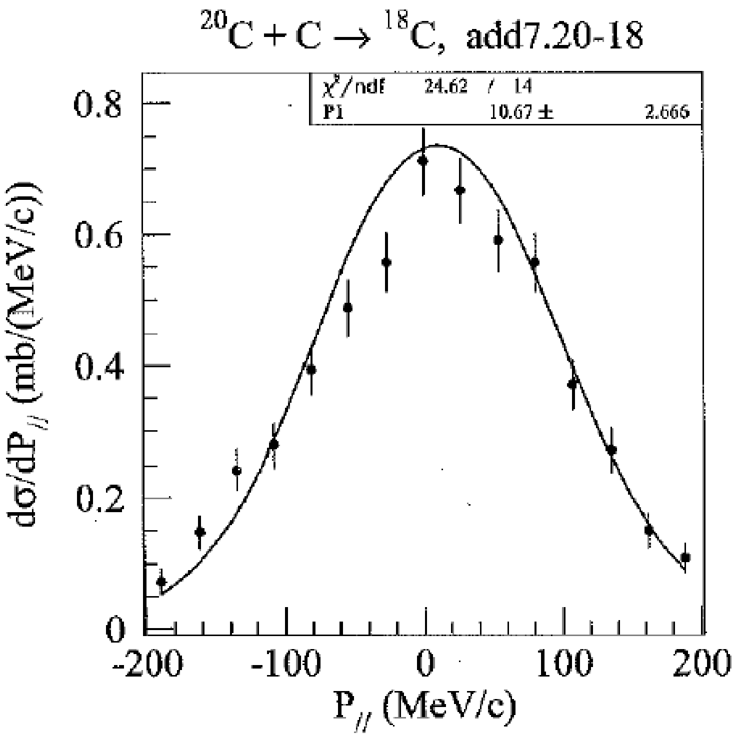
Spectroscopic factor/strength

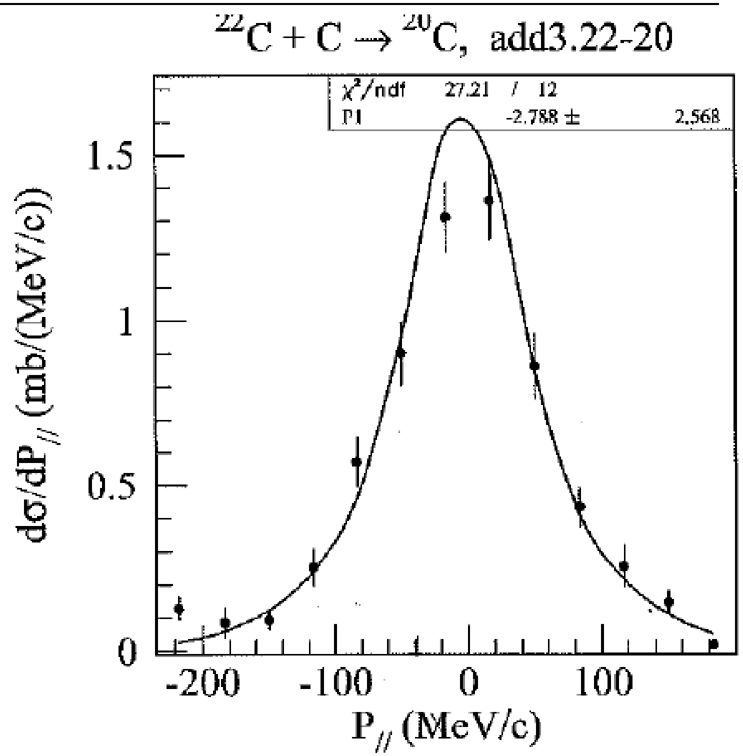
Inclusive neutron removal – $^{15\text{-}19}$C isotopes



E.C. Simpson and J.A. Tostevin, PRC 79 024616 (2009)

Reaction	E_x(MeV)	J$^\pi$	ℓ	$\sigma_{\rm sp}$ (mb)	C^2S	$\sigma_{-1n(e)}$ (mb)
$(^{20}\mathrm{C}(0^+),^{19}\mathrm{C}(\mathrm{J}^\pi))$	0.190^a	5/2$^+$	2	27.50	3.649	111.17
$S_{1n}(20)$=2.90 MeV	0.624	3/2$^+$	2	26.34	0.247	7.20
	0.927	1/2$^-$	1	26.46	1.426	41.79
	1.541	5/2$^+$	2	24.31	0.282	7.59
	2.417	3/2$^-$	1	22.27	0.689	17.00
	3.284	3/2$^+$	2	21.50	0.191	4.56
	3.717	1/2$^+$	0	30.53	0.055	1.86
		Inclusive				191.2
$(^{22}\mathrm{C}(0^+),^{21}\mathrm{C}(\mathrm{J}^\pi))$	0.000	1/2$^+$	0	89.35	1.403	137.55
$S_{1n}(22)$=0.70 MeV	1.109	5/2$^+$	2	29.39	4.212	135.87
	2.191	3/2$^+$	2	25.44	0.342	9.55
		Inclusive				283.0





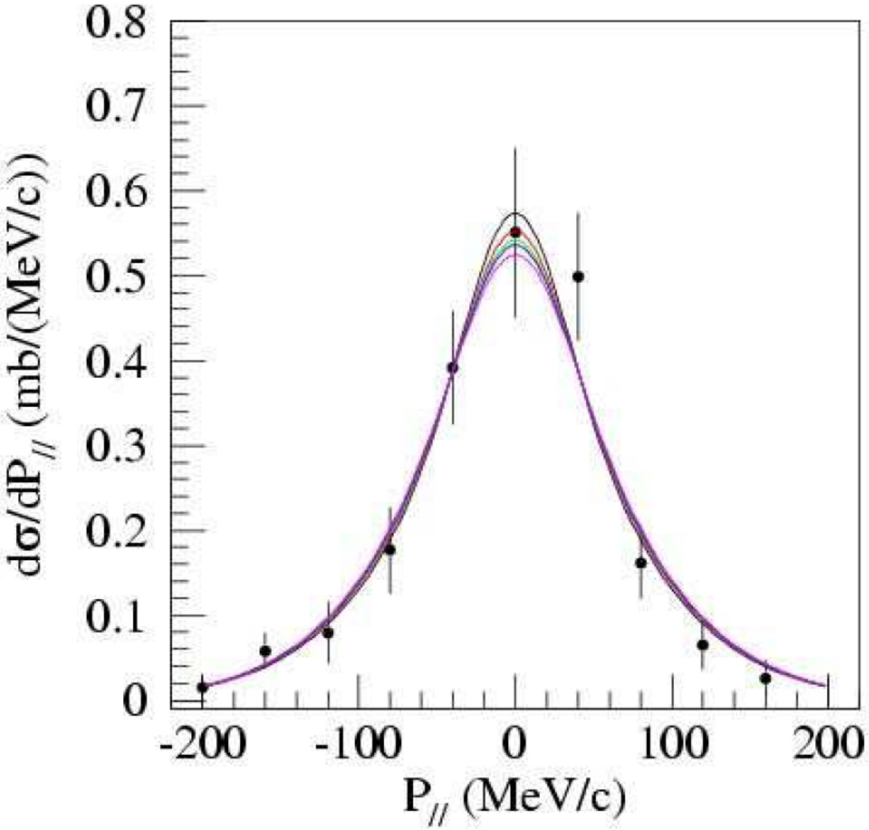
Shell-model: spdf-m predictions for ^{31}Ne → ^{30}Ne

$$^{31}\mathrm{Ne}(3/2^-) \rightarrow {}^{30}\mathrm{Ne}(J^\pi)$$

$$3p-2h(96\%) \quad 2p-2h(74\%)$$

$$[2p_{3/2}\otimes 0^+],\ C^2S=0.12$$
$$[2p_{3/2}\otimes 2^+],\ C^2S=0.27$$
$$[1f_{7/2}\otimes 2^+],\ C^2S=0.25$$
$$[1f_{7/2}\otimes 4^+],\ C^2S=0.72$$

$$E(2_1^+)=0.80\ \mathrm{MeV}$$
$$E(4_1^+)=2.35\ \mathrm{MeV}$$



$$\sigma_{incl}=79(7)\ \mathrm{mb}$$

Cross section predictions for ^{31}Ne → ^{30}Ne

$$^{31}\mathrm{Ne}(3/2^-, S_n = \boxed{20\ \mathrm{keV}}\ ) \rightarrow\ ^{30}\mathrm{Ne}(J^\pi)$$

$$3p-2h(96\%) \qquad\qquad 2p-2h(74\%)$$

$$\left.\begin{array}{l} [2p_{3/2}\otimes 0^+],\ C^2S = \boxed{0.12\times 2}\ \ 32.70\ \mathrm{mb} \\ [2p_{3/2}\otimes 2^+],\ C^2S = 0.27,\ 18.17\ \mathrm{mb} \\ [1f_{7/2}\otimes 2^+],\ C^2S = 0.25,\ \ 6.22\ \mathrm{mb} \\ [1f_{7/2}\otimes 4^+],\ C^2S = 0.72,\ 22.50\ \mathrm{mb} \end{array}\right\} 80\ \mathrm{mb}$$

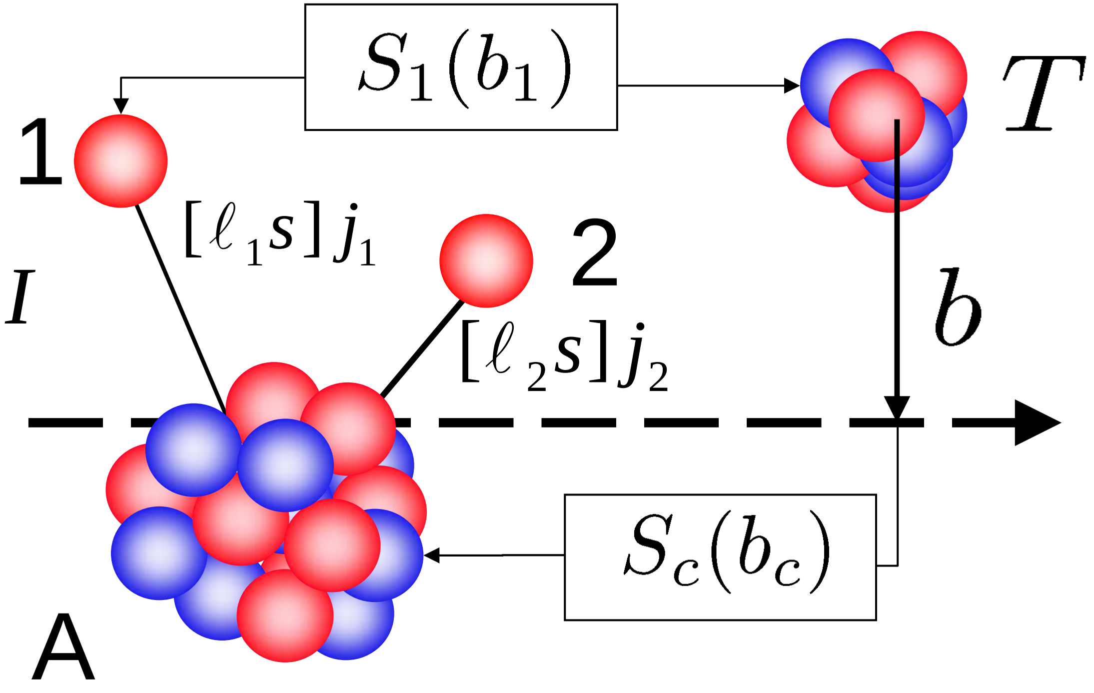
$$E(2_1^+) = 0.80\ \mathrm{MeV}$$

$$E(4_1^+) = 2.35\ \mathrm{MeV}$$

$$74\ \mathrm{mb\ if}\ S_n = 100\ \mathrm{keV}$$

$$\boxed{\sigma_{incl} = 79(7)\ \mathrm{mb}}$$

Sudden removal – eikonal reaction dynamics



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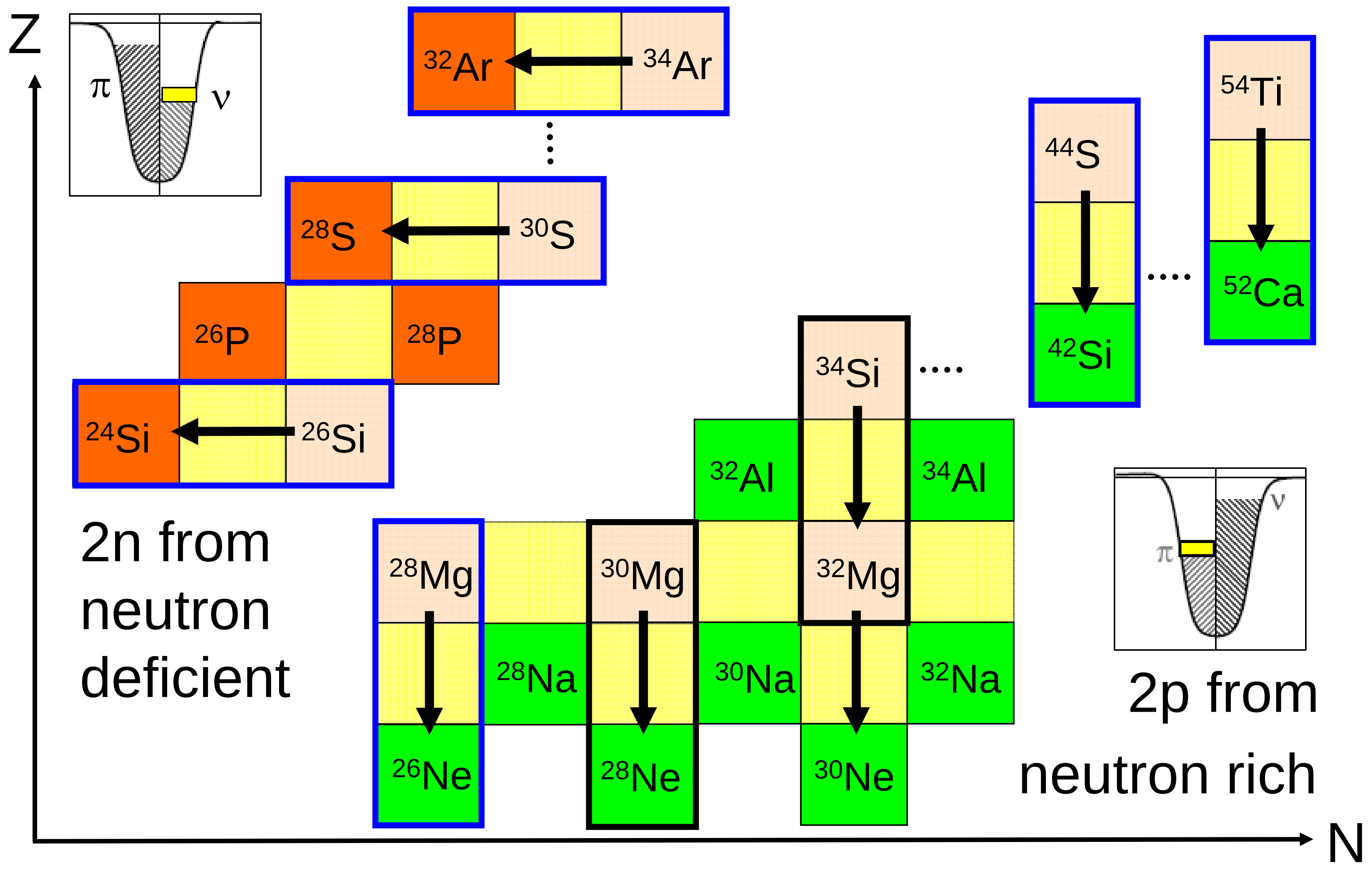
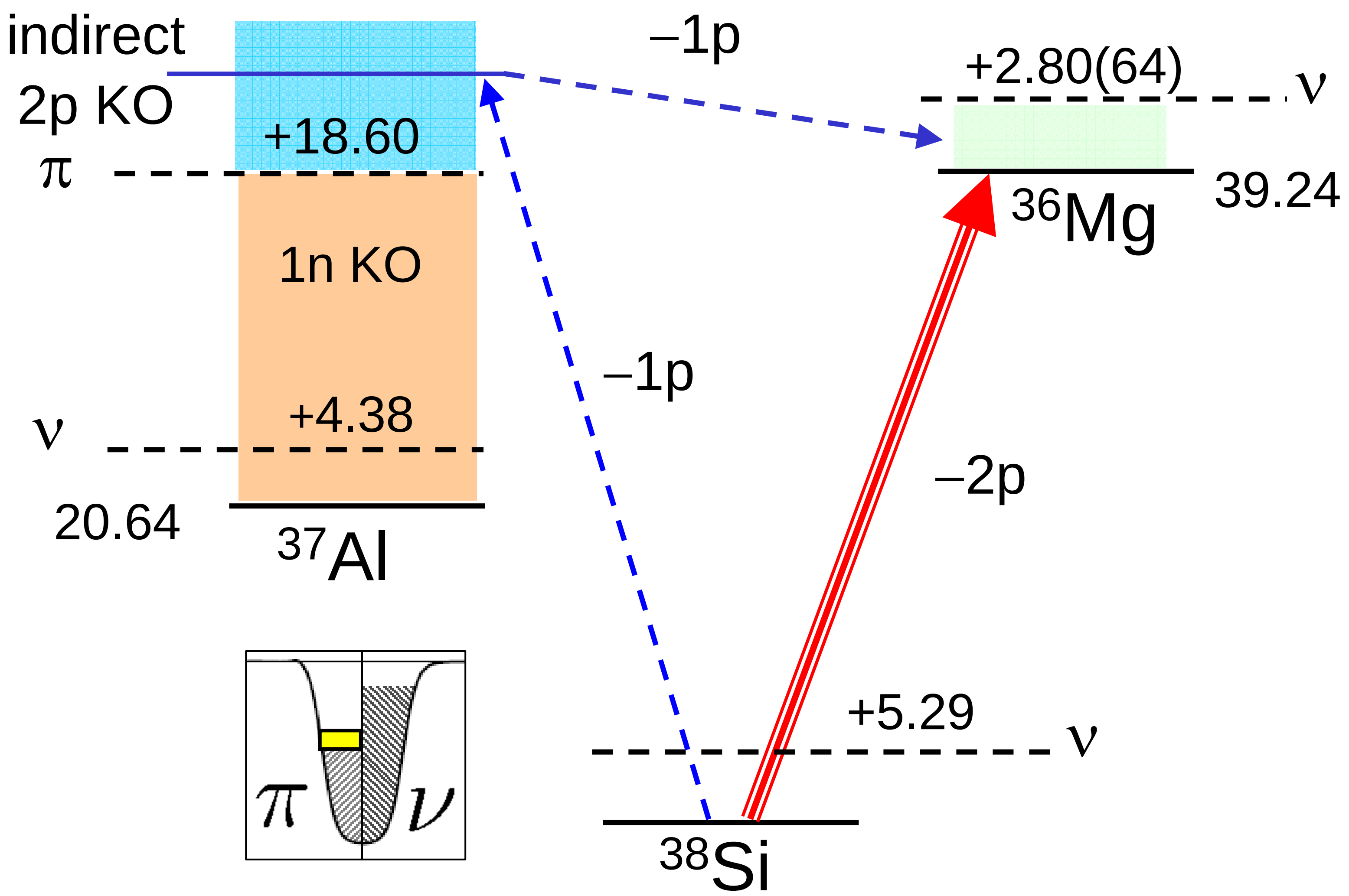
J.A. Tostevin *et al.*, PRC 70 (2004) 064602 and PRC 74 (2006) 064604
P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci **53** (2003) 219

Two nucleon knockout – direct reaction set



Direct two-proton removal reaction mechanism



Two-nucleon direct reactions overlaps

$$\Psi^{(f)}_{J_iM_i}(1,2) \equiv \langle \Phi_{J_fM_f}(A) | \Psi_{J_iM_i}(A,1,2)\rangle$$
$$= \sum_{I\mu\alpha} C^{J_iJ_fI}_{\alpha}(I\mu J_fM_f|J_iM_i)[\overline{\phi_{j_1}(1)\otimes\phi_{j_2}(2)}]_{I\mu}$$

$$[\overline{\phi_{j_1}(1)\otimes\phi_{j_2}(2)}]_{I\mu} = -N_{12}\langle 1,2|[a^{\dagger}_{j_1}\otimes a^{\dagger}_{j_2}]_{I\mu}|0\rangle$$

$$D_{\alpha} = N_{12}/\sqrt{2} = 1/\sqrt{2(1+\delta_{12})}$$

$$F_{IM}(1,2) = \langle 1,2,\Phi_{c,IM}(A)|\Phi_{A+2}\rangle \text{ and with } J_i = 0^+$$

Two-nucleon amplitudes – TNA

$$F_{IM}(1,2) = \sum_{j_1j_2}(-)^{I+M}\, C(j_1j_2I\ )/\hat{I}\,[\overline{\phi_{j_1m_1}\otimes\phi_{j_2m_2}}]_{I-M}$$

Stripping and diffraction-induced pair removal

$$\sigma_{ko} = \frac{1}{2J_i+1}\sum_{M_i}\int d\vec{b}\,|S_c|^2 \left\langle \Psi_{J_i M_i}\right| \boxed{\mathcal{K}_1(1,2)} + \boxed{\mathcal{K}_2(1,2) - \mathcal{K}_3(1,2)} \left|\Psi_{J_i M_i}\right\rangle$$

$$\mathcal{K}_1(1,2) = (1-|S_1|^2)(1+|S_2|^2)$$

$$\mathcal{K}_2(1,2) = |S_1|^2(1-|S_2|^2) + (1+|S_1|^2)|S_2|^2$$

$$\mathcal{K}_3(1,2) = \sum_{jm}\left[S_1^*\,|\phi_j^m)\,(\phi_j^m|\,S_1(1-|S_2|^2) + (1-|S_1|^2)S_2^*\,|\phi_j^m)\,(\phi_j^m|\,S_2\right]$$

Stripping component momentum distribution

$$\frac{d\sigma_{str}^{(f)}}{dK} = \int dk_1 \delta(K - k_1, k_2) \int_0^{2\pi} d\phi_c \int_0^{\infty} db_c b_c |S_c(b_c)|^2$$

$$\frac{1}{(2\pi)^2} \sum_{I\alpha\alpha'} \frac{C_{\alpha'}^{J_i J_f I} C_{\alpha}^{J_i J_f I} D_\alpha D_{\alpha'}}{\hat{I}^2}$$

$$\sum_{\lambda_1 \lambda_2 \lambda_1' \lambda_2'} \mathcal{C}_{l_1 \lambda_1} \mathcal{C}_{l_2 \lambda_2} \mathcal{C}_{l_1' \lambda_1'} \mathcal{C}_{l_2' \lambda_2'} \int_0^{\infty} ds_1 s_1 \int_0^{\infty} ds_2 s_2$$

$$\Big\{ \mathcal{G}^I_{j_1 j_2 j_1' j_2'} H_{\lambda_1 \lambda_1'}(s_1, \vec{b}_c)\ H_{\lambda_2 \lambda_2'}(s_2, \vec{b}_c)\ \ R^{j_1}_{l_1 \lambda_1}(s_1, k_1)$$

$$R^{j_1'}_{l_1' \lambda_1'}(s_1, k_1)^*\ R^{j_2}_{l_2 \lambda_2}(s_2, k_2)\ R^{j_2'}_{l_2' \lambda_2'}(s_2, k_2)^*$$

$$...\ +\ \text{terms from antisymmetrization} \Big\}$$

Momentum and impact parameter plane sampling

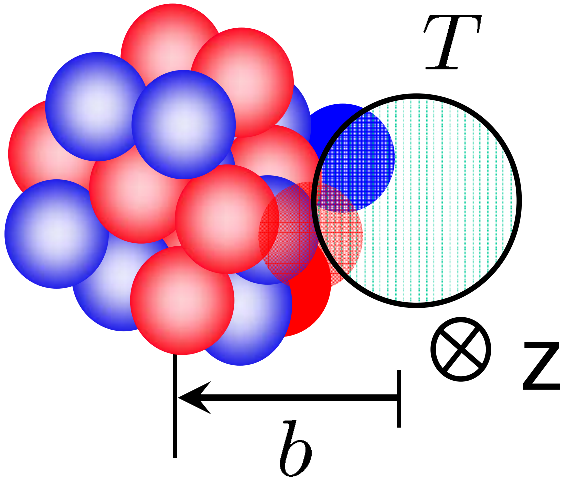
$$R^{j}_{l\lambda}(s,k) = \int_{-\infty}^{\infty} \mathrm{d}z\; u_{jl}((s^2+z^2)^{1/2})\; P_l^{\lambda}(\cos(\theta))\;\; \exp(-ikz)$$

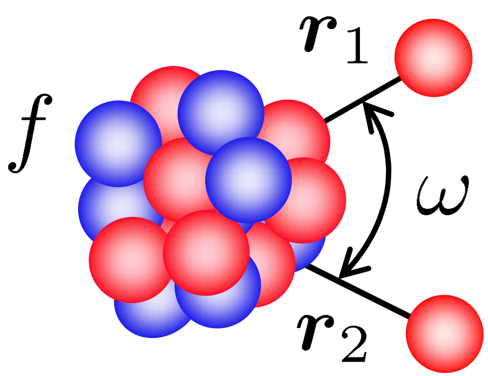
$$H_{\lambda\lambda'_{\prime}}(s_v,\vec{b}_c)\; = \int_0^{2\pi} d\phi_v\;\; \exp(i\phi_v(\lambda-\lambda'))\;(1-|S_v(|\vec{b}_c+\vec{s}_v|)|^2)$$

$$\begin{aligned}\mathcal{G}^{I}_{j_1 j_2 j'_1 j'_2} =& \hat{j}_1\hat{j}_2\hat{j}'_1\hat{j}'_2\hat{I}^2\;(-)^{j_2-j_1+l_1+l_2+l'_1+l'_2-\lambda_2-\lambda'_1} \\ &\times \sum_{kq} (-)^{-k}(l_2{-}\lambda_2 l'_2\lambda'_2|kq)\;(l_1{-}\lambda_1 l'_1\lambda'_1|k-q) \\ &\times W(j_1 l_1 j'_1 l'_1; sk)\; W(j_2 l_2 j'_2 l'_2; sk)\; W(j_2 I k j'_1; j_1 j'_2)\end{aligned}$$

Target drills a cylindrical volume at projectile surface

$$1\boxed{2}\mathrm{N}\ \text{stripping} : \hat{O}(c, 1, \boxed{2}) = |S_c|^2(1 - |S_1|^2)\boxed{(1 - |S_2|^2)}$$





(i) 2N removal cross sections will be sensitive to the <u>spatial correlations</u> of pairs of nucleons near the surface

(ii) <u>No spin selection</u> rule (for S=0 versus S=1 pairs) in this 2N removal reaction mechanism

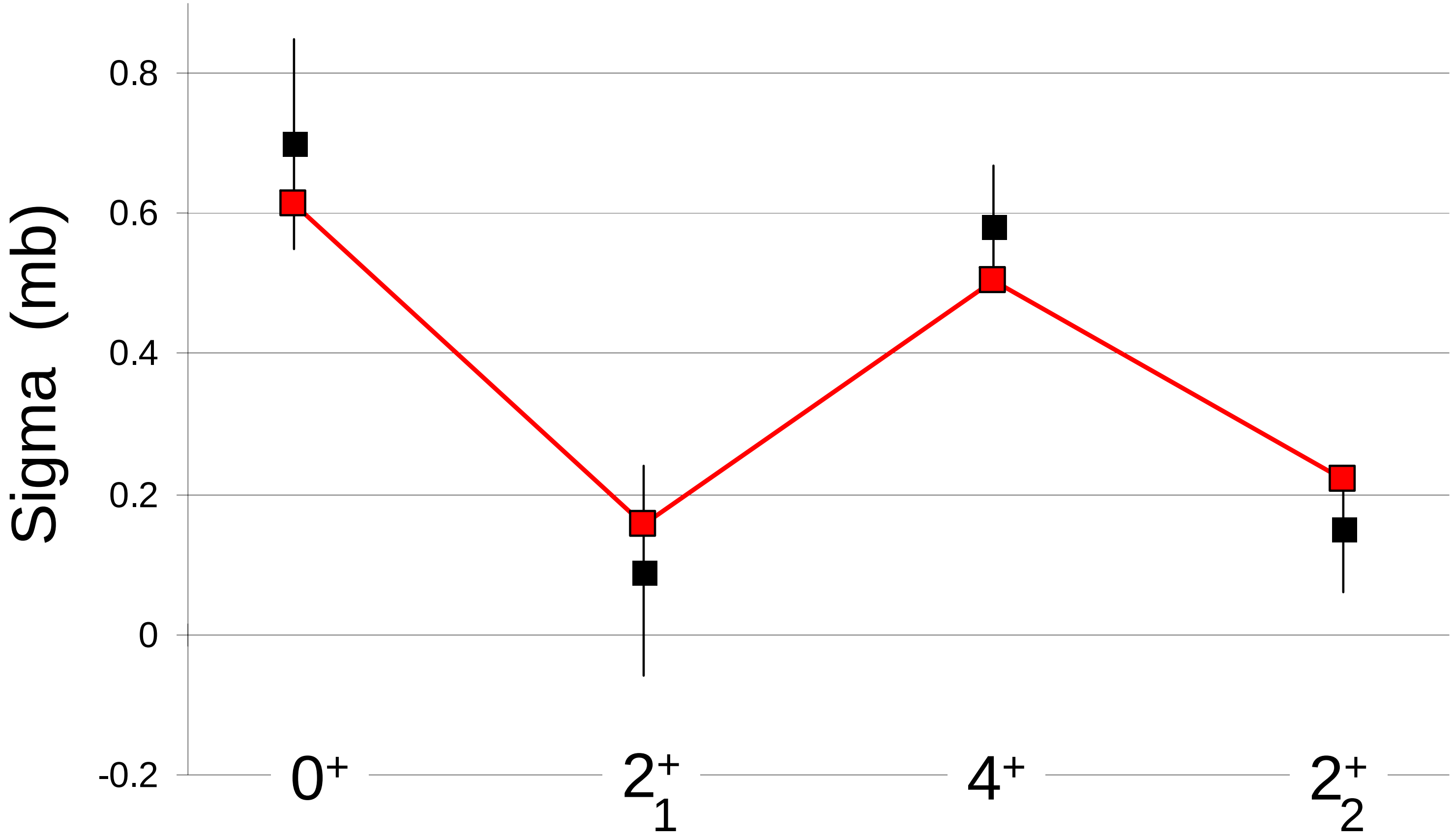
(iii) Expectation of the sensitivity to <u>correlations</u> can be predicted from 2N overlaps <u>in the sampled volume</u>

(iv) No linear or angular momentum mismatch – mechanism ‘sees’ ALL hole-like-state configurations

Knockout cross sections – correlated case

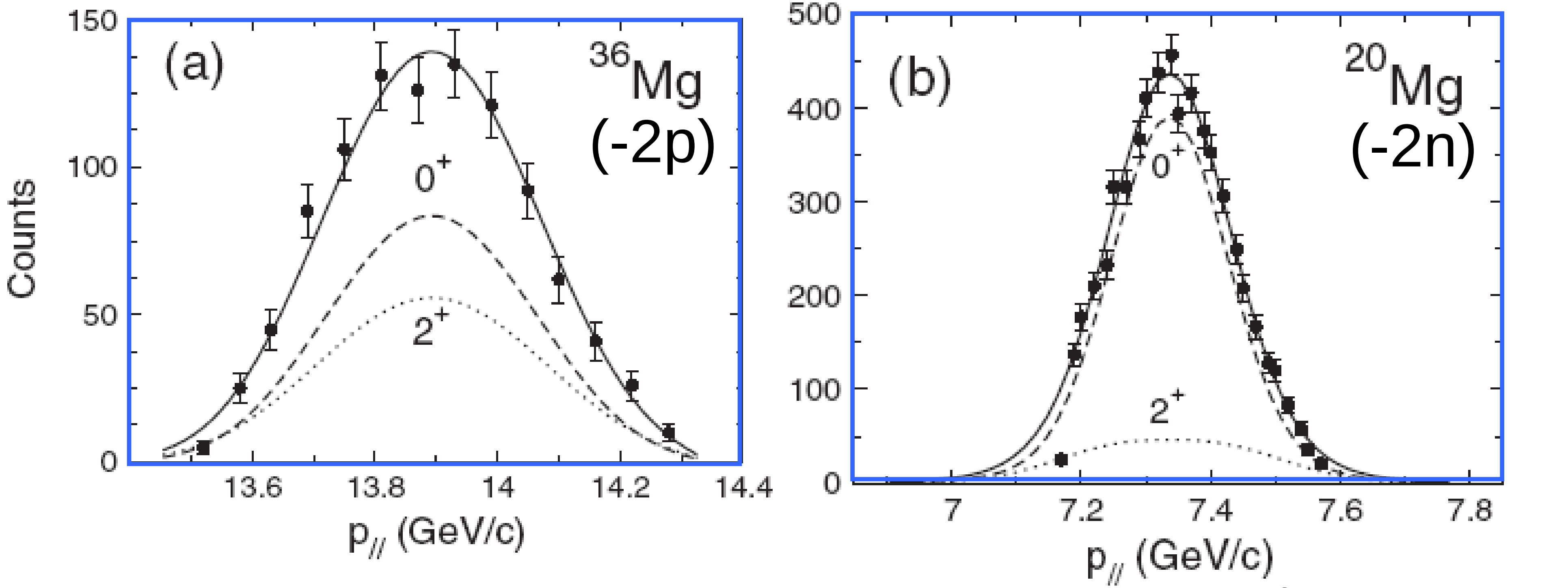
$^{28}Mg \rightarrow ^{26}Ne(0^+, 2^+, 4^+, 2_2^+)$ 82.3 MeV/u

$$\sigma_{inc}(-2p) = 1.50(10)\ \mathrm{mb},$$

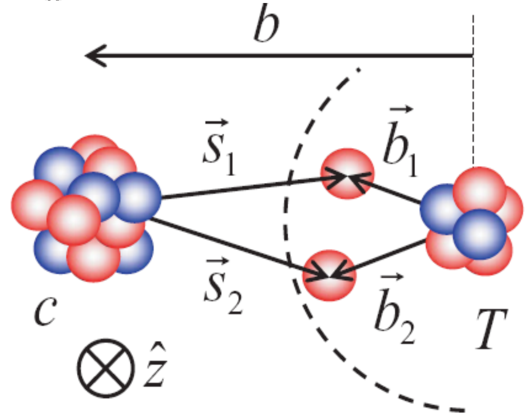


J.A. Tostevin et al., PRC **70** (2004) 064602, PRC **74** 064604 (2006)

“Inclusive” two-nucleon removal p// distributions



$$\bar{\mathcal{P}}_f(\vec{s}_1, \vec{s}_2, \kappa_c) = \frac{1}{\hat{J}_i^{\,2}} \sum_{M_i M_f} \int d\kappa_1 \int d\kappa_2 \frac{\delta(\kappa_c + \kappa_1 + \kappa_2)}{(2\pi)^2} \times \left\langle \left| \int dz_1 \int dz_2 e^{i\kappa_1 z_1} e^{i\kappa_2 z_2} \Psi_{J_i M_i}^{(F)} \right|^2 \right\rangle_{\mathrm{sp}}$$



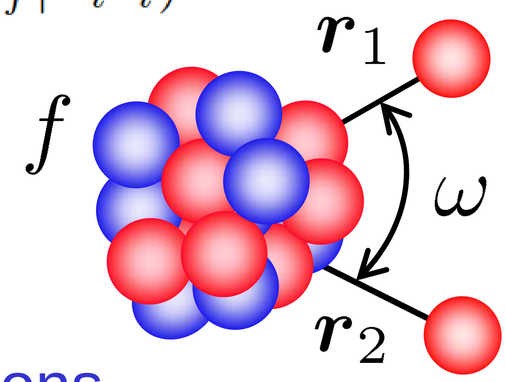
E.C. Simpson et al., PRL **102** 132502 (2009),; PRC **79**, 064621(2009)

Angular correlations – and L-transfer sensitivity

After summing over the nucleon spins (to which we are insensitive) the two nucleon joint-position probability is:

$$\rho_f(\boldsymbol{r}_1,\boldsymbol{r}_2)=\sum_{LST}\sum_{I\alpha\alpha'}\boxed{\frac{\mathfrak{C}^{IT}_{\alpha LS}\mathfrak{C}^{IT}_{\alpha' LS}D_\alpha D_{\alpha'}}{\hat{L}^2}}(T\tau T_f\tau_f|T_i\tau_i)^2$$

$$\boxed{\begin{aligned}&\times\left[U^D_{\alpha\alpha'}(r_1,r_2)\,\Gamma^{L,D}(\omega)\right.\\&\left.-(-)^{S+T}U^E_{\alpha\alpha'}(r_1,r_2)\,\Gamma^{L,E}(\omega)\right]\end{aligned}},$$



depends only on L ($=\ell_1+\ell_2$) of the two nucleons.

Structure calculation tells us strength of the <u>L-content</u> of the 2N overlap via the LS coupled two-nucleon amplitudes:

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

predict p// distribution

E.C. Simpson, JAT, PRC, submitted (2010)

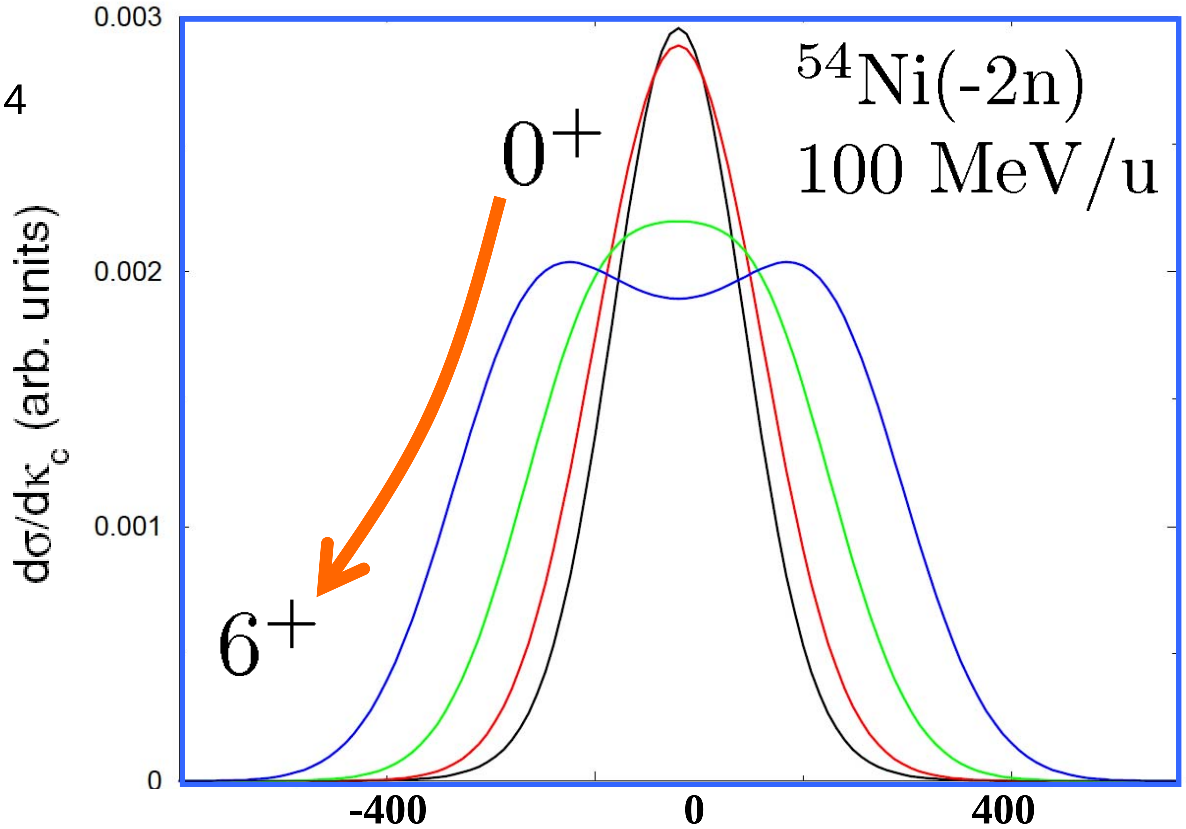
Final-state spin-value sensitivity: e.g. ^{54}Ni(-2n)

$$\mathfrak{C}^{IT}_{\alpha LS}$$

I	C(I=L)	C(L=I+1)	C(L=I-1)
0	**0.571**	**0.428**	0.0
2	**0.510**	0.122	**0.367**
4	**0.367**	0.034	**0.598**
6	0.142	0.0	**0.857**

Relatively 'pure' 2N configurations give simple L(and I) – dependences – e.g. assuming $[f_{7/2}]^6 \rightarrow [f_{7/2}]^4$

I	L-values
0	L= **0**, **1**
2	L= **1**, **2,** 3
4	L= **3**, **4**, 5
6	L= **5**, 6

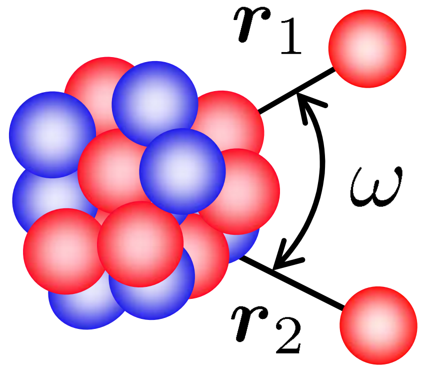


Two-nucleon position correlations

After summing over the nucleon spins (to which we are insensitive) the two nucleon joint-position probability is:

$$\rho_f(\boldsymbol{r}_1, \boldsymbol{r}_2) = \frac{1}{\hat{J}_i^2} \sum_{M_i M_f} \langle \Psi_i^{(F)} | \Psi_i^{(F)} \rangle_{sp}$$

$$\mathcal{P}_f(\boldsymbol{s}_1, \boldsymbol{s}_2) = \int dz_1 \int dz_2\, \rho_f(\boldsymbol{r}_1, \boldsymbol{r}_2)$$



J_f^π	$[1p_{3/2}]^2$	$[1p_{1/2}, 1p_{3/2}]$	$[1p_{1/2}]^2$
1_1^+	0.69899	0.97868	−0.01067
1_2^+	−1.13385	0.22886	0.36314

^{12}C(-np)→ ^{10}B(1^{+},T=0)

J_f^π	σ_{01}	σ_{10}	σ_{11}	σ_{21}	σ_{str}
1_1^+	2.41	0.00	0.00	0.06	2.47
1_2^+	0.60	0.59	0.00	0.63	1.81

σ_{LS} (mb)

E.C. Simpson, JAT, PRC, in press (2010)

Two-nucleon correlations

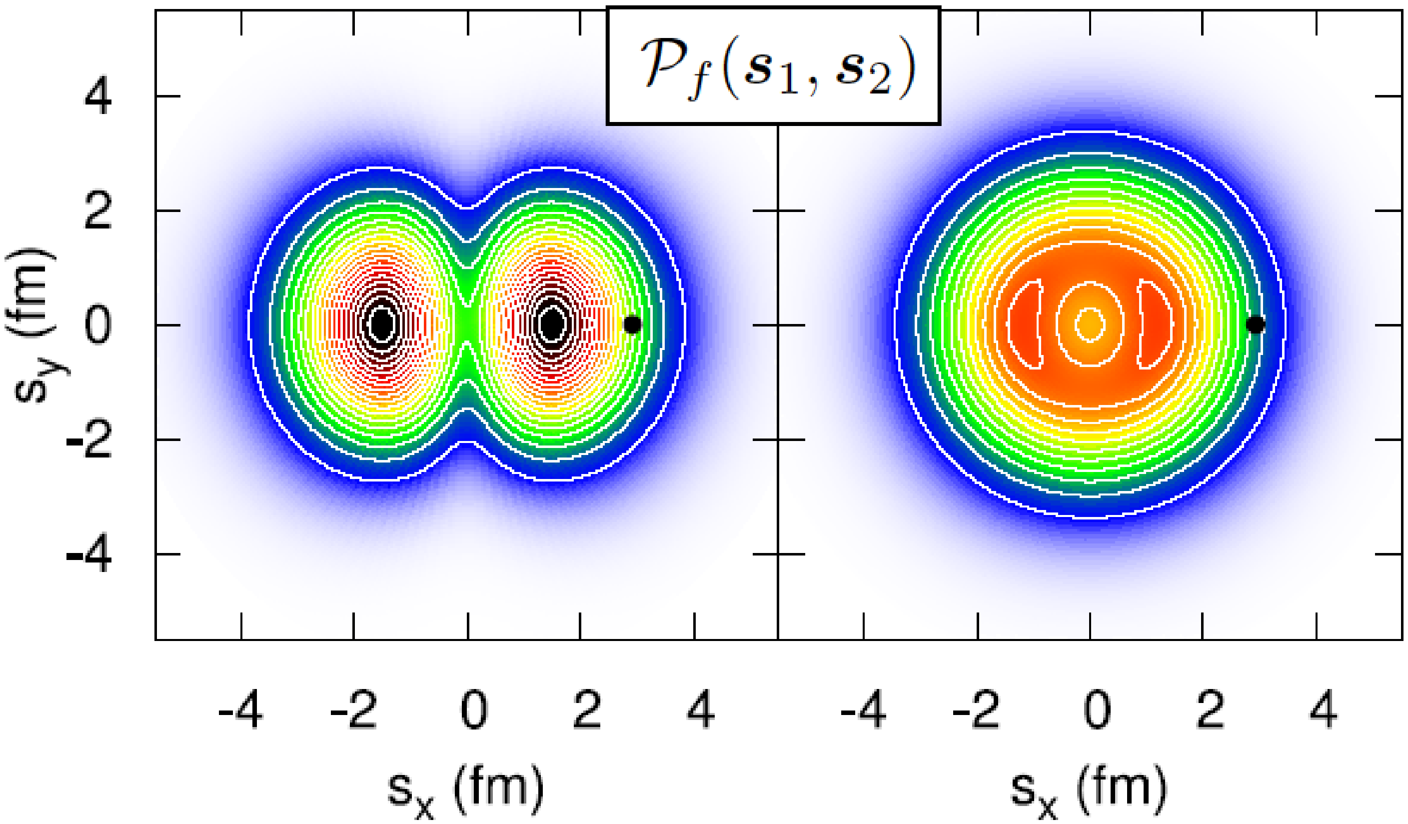


FIG. 4: Impact parameter plane-projected joint position probabilities for the first (left) and second (right) $T = 0$ ^{10}B(1^+) states populated via np knockout from ^{12}C.

E.C. Simpson, JAT, PRC, in press (2010)

Two-nucleon correlations

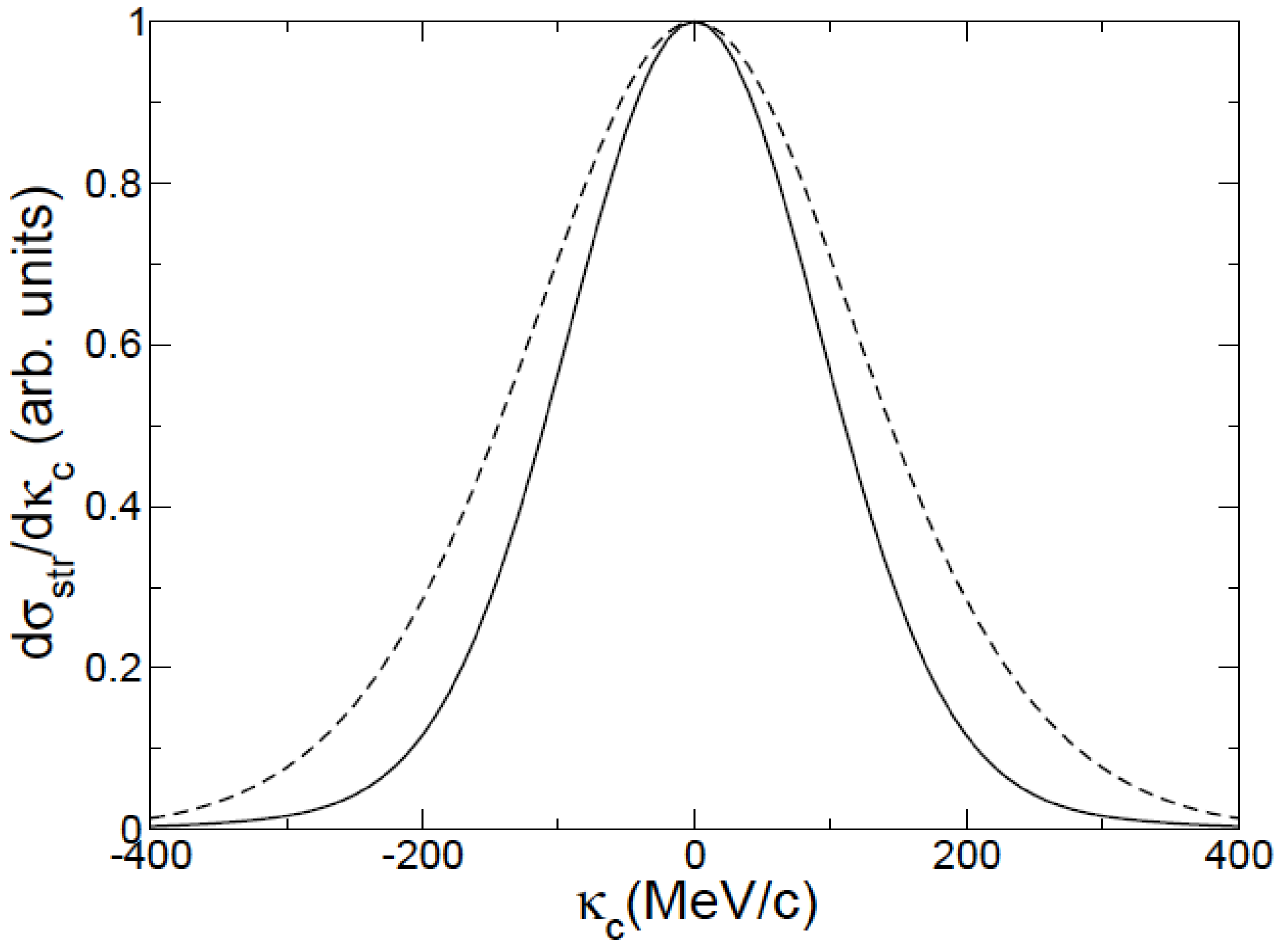
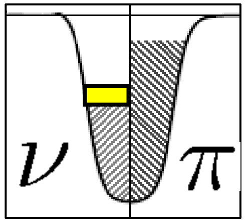


FIG. 3: Normalized residue momentum distributions for the first (solid) and second (dashed) $^{10}B(J_f=1^+)$ states populated in np knockout from ^{12}C at 2100 MeV per nucleon.

E.C. Simpson, JAT, PRC, in press (2010)

Configuration-mixed, sd-shell example: ^{26}Si(-2n)

J_f^π	$[1d_{5/2}]^2$	$[1d_{5/2}, 1d_{3/2}]$	$[1d_{3/2}]^2$	$[2s_{1/2}, 1d_{3/2}]$	$[2s_{1/2}, 1d_{5/2}]$
2_1^+	-0.70074	0.43499	0.00594	-0.00188	-0.02781
2_2^+	-0.38021	-0.12354	-0.12945	-0.15876	-0.58292



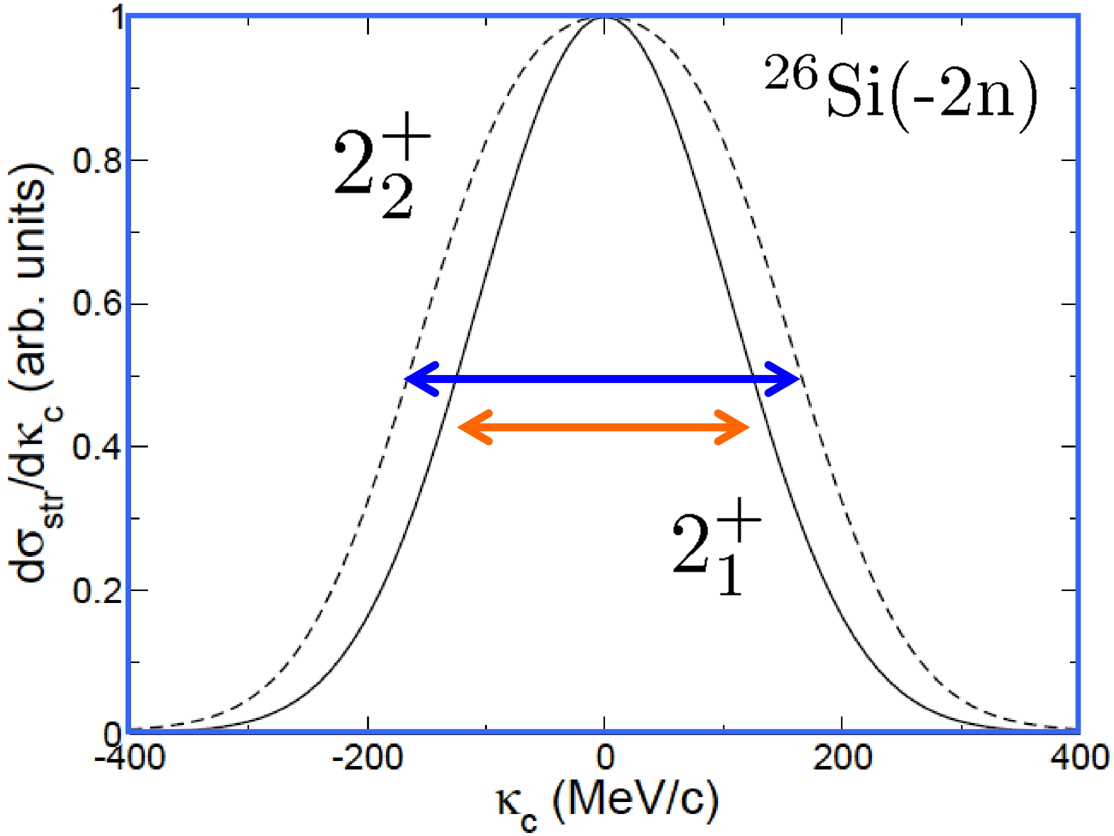
with cross sections:

σ_{LS} (mb)

J_f^π	σ_{11}	σ_{20}	σ_{21}
2_1^+	$\boxed{0.17}$	0.02	0.00
2_2^+	0.01	$\boxed{0.17}$	0.01

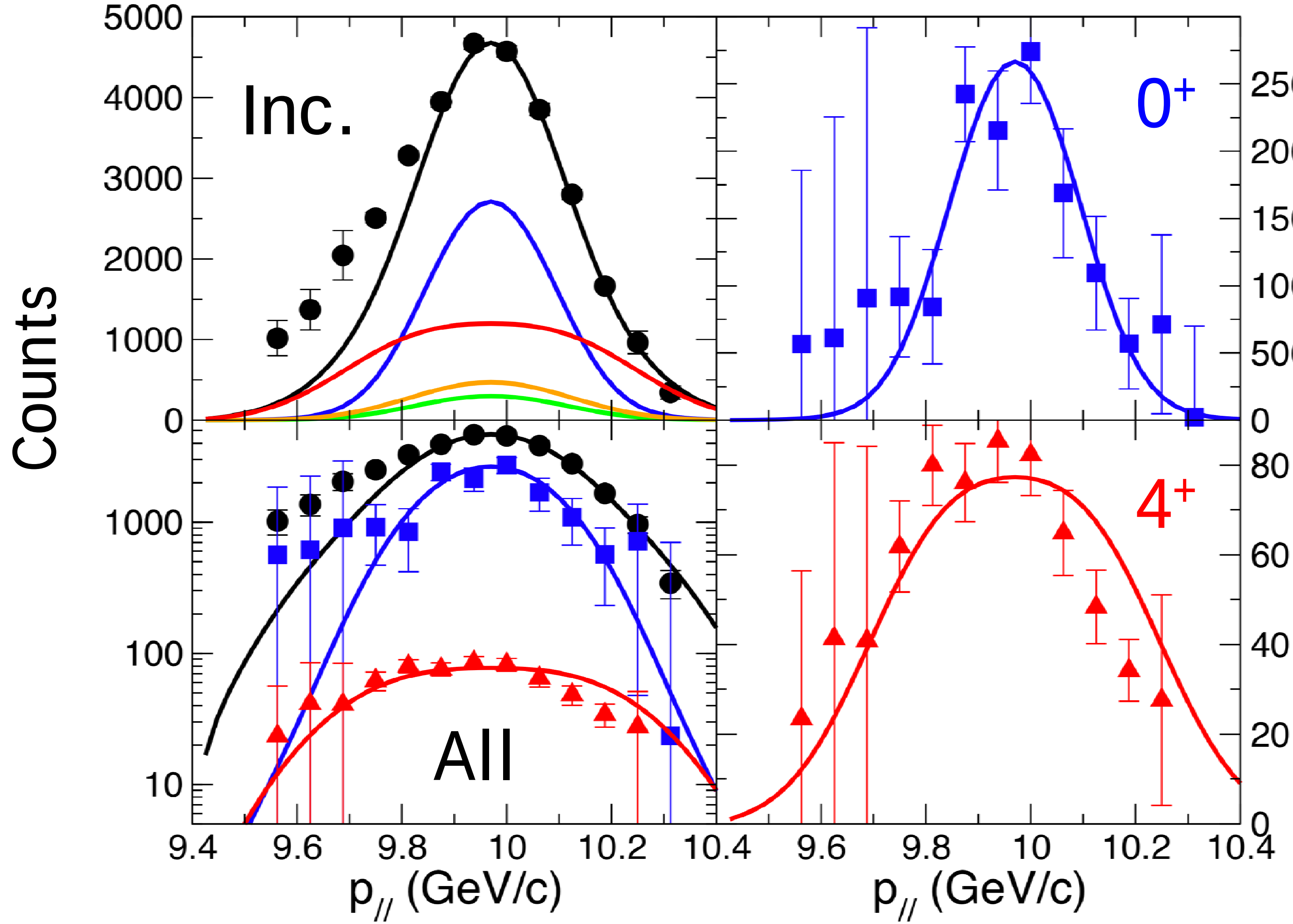
$L = 1$
250 MeV/c

$L = 2$
330 MeV/c



E.C. Simpson, JAT, PRC submitted (2010)

First final-state-exclusive p//: ^{28}Mg(-2p)



E.C. Simpson et al., PRL **102** 132502 (2009)

Summary comments

1. At the energies of fragmentation beams (100 MeV per nucleon and greater) reaction calculations are *robust* and can return *quantitative* information.
2. Heavier near-dripline systems will, for some time be measured with *inclusive* degrees of freedom. Both heavy and light target data are necessary to untangle the structures (plus *specific structure input*)
3. Final-state $p_{//}$ distributions after 2N removal can test the 2N correlations predicted by theoretical models
4. We can understand/predict that such exclusive residue momentum measurements have the potential to probe calculated wave functions at an increasingly detailed level.