Examining nuclei and nuclear models using fast two-nucleon removal

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Two-nucleon removal (knockout) reaction sensitivity

Probe of (spatial) two-nucleon correlations (g.s.)

angular ⟷ orbital angular momentum

Bottom line:

There us a need for data to benchmark and validate predictions for more <u>exclusive</u> final-state observables

Outline of this discussion

1. Removal (knockout) reactions – essentials:
   Spatial selectivity - near surface dominance
   Thresholds: direct vs indirect (two-step) pathways

2. 2N overlaps, two-particle density – angular correlations – value of the LS representation

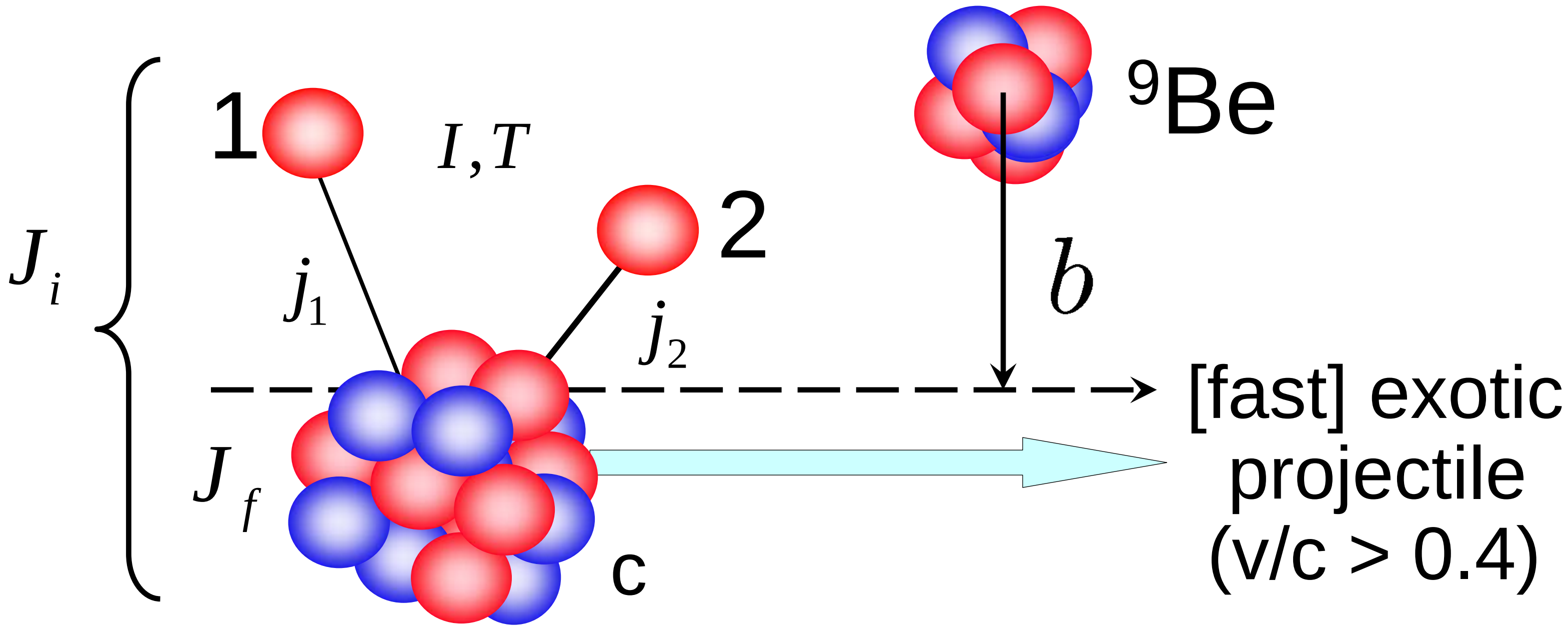
3. Limited data sets so far – status - tests

4. The case of ^{12}C(-2N) – asks several questions

5. Summary comments – further test cases?

Probing single particle (shell model) states

One such experimental option is one or two-nucleon removal – at ~100 MeV/nucleon

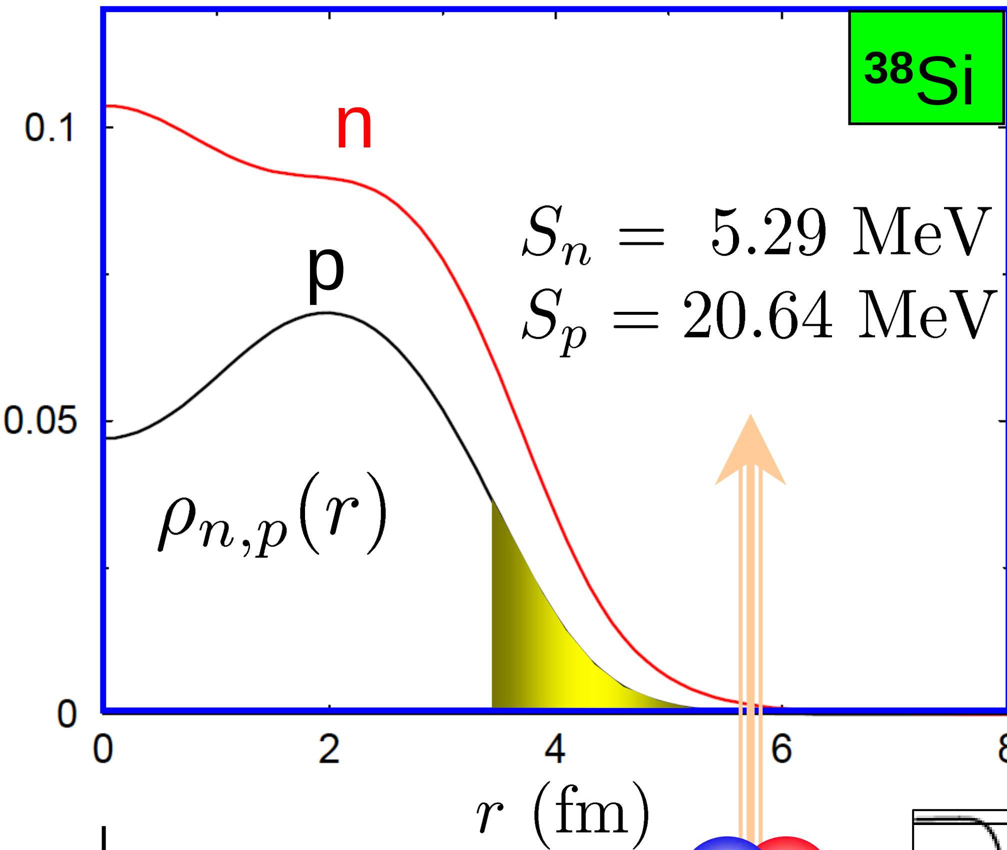


Experiments do not measure target final states. Final state of core c measured – using decay gamma rays.

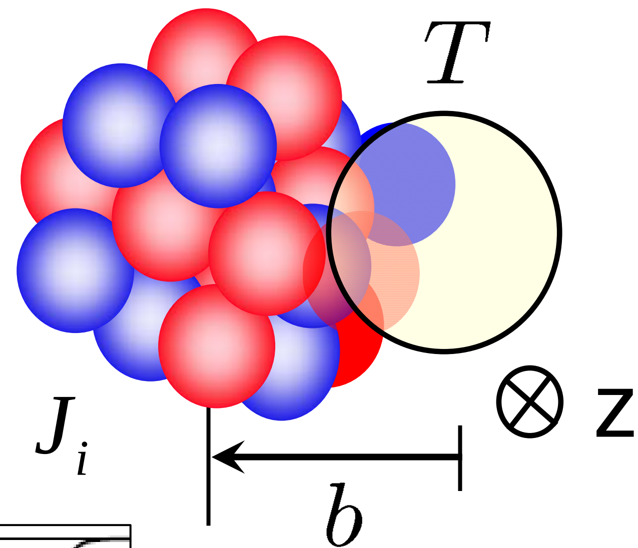
How can we describe and what can we learn from these?

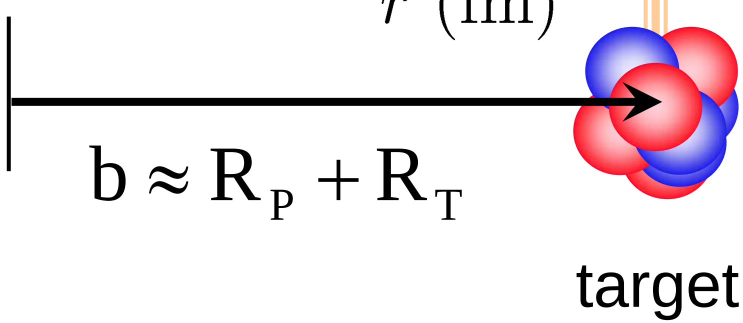
P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci **53** (2003) 219

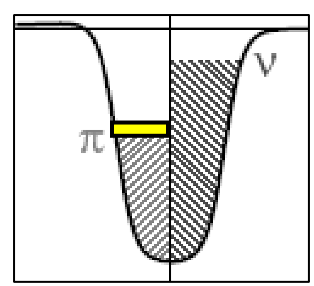
Removal probes single-nucleon wave functions



Interaction with the target probes wave functions at surface





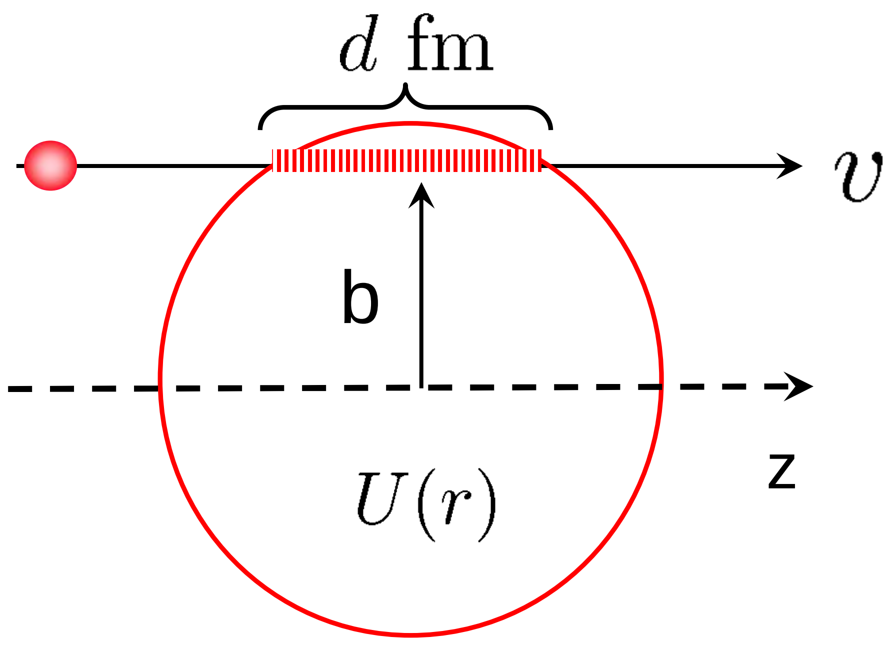


Reaction timescales – surface grazing collisions

For 100 and 250 MeV/u incident energy:

$$\gamma = 1.1, \quad v/c = 0.42, \qquad \gamma = 1.25, \quad v/c = 0.6,$$

$$\Delta t = 7.9 \times d \times 10^{-24} s, \qquad \Delta t = 5.6 \times d \times 10^{-24} s$$



Must include all 2 nucleon removal mechanisms

$$\sigma_{abs} \quad \rightarrow \quad 1 - |S_c|^2|S_1|^2|S_2|^2$$

$$\begin{aligned} 1 \quad &= \quad [\ \boxed{|S_c|^2} + \cancel{(1 - |S_c|^2)}] \\ &\times \quad [\ |S_1|^2 + (1 - |S_1|^2)] \\ &\times \quad [\ |S_2|^2 + (1 - |S_2|^2)] \end{aligned}$$

<u>core survival</u>
and nucleon
" removal "

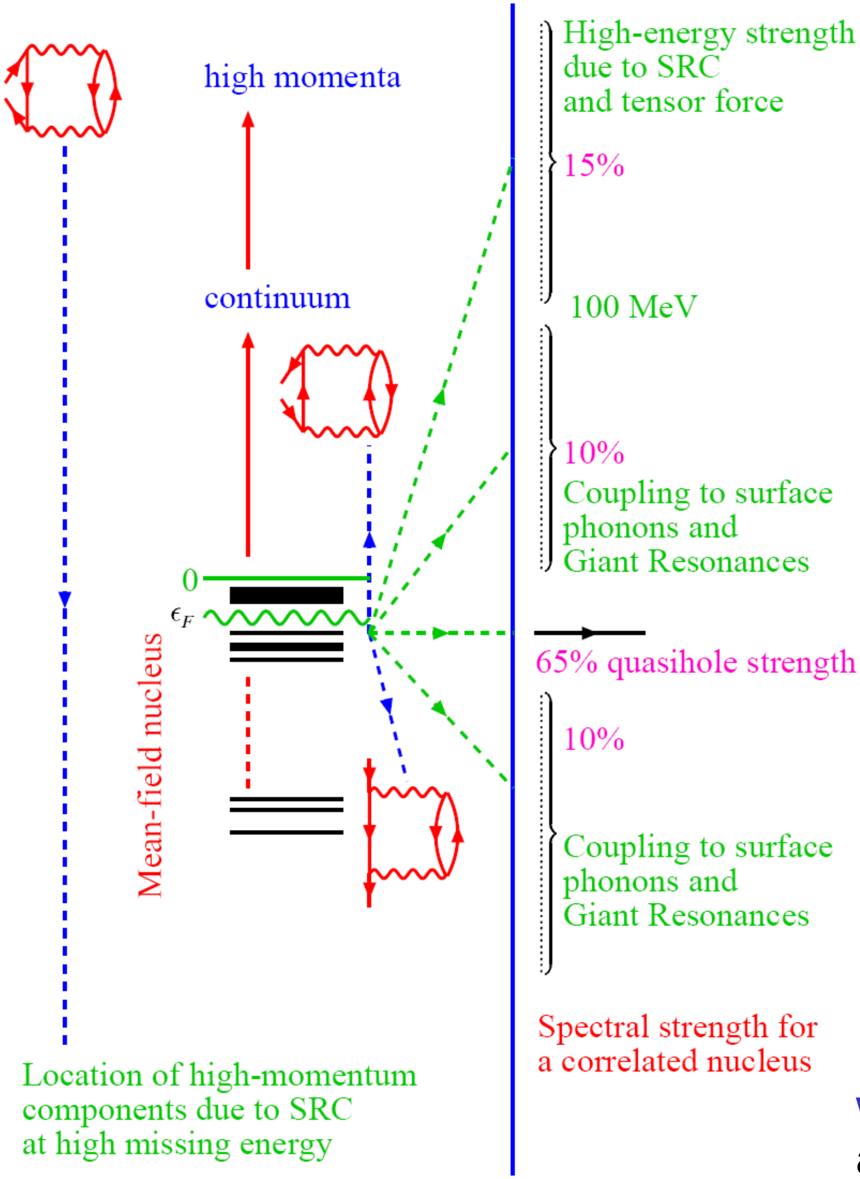
$$\begin{aligned} \sigma_{abs}^{\mathrm{KO}} \quad &\rightarrow \quad |S_c|^2 (1 - |S_1|^2)(1 - |S_2|^2) \\ &+ \quad |S_c|^2 |S_1|^2 (1 - |S_2|^2) \\ &+ \quad |S_c|^2 (1 - |S_1|^2)|S_2|^2 \end{aligned}$$

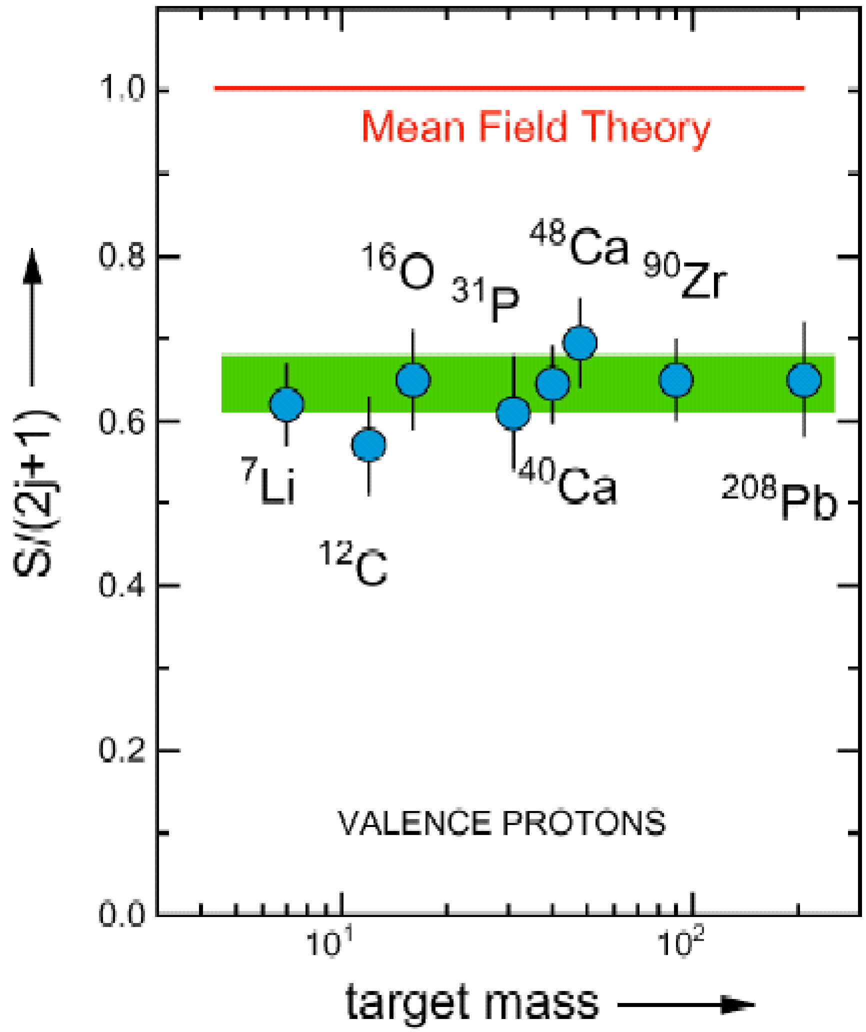
2N stripping

1N stripped
1N diffracted

$$+\ \text{2N diffraction contributions} \approx 6 - 8\%$$

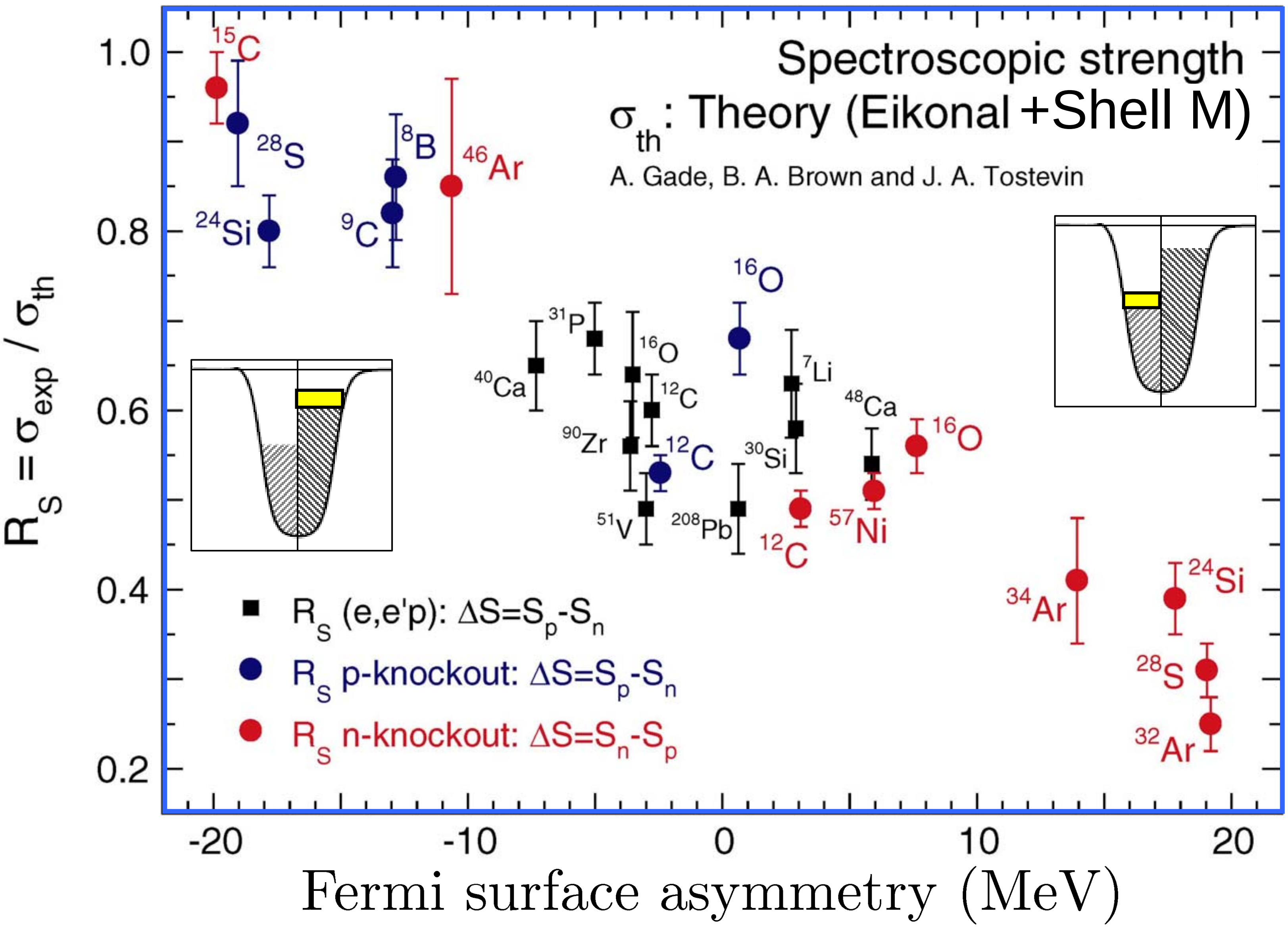
Strength from e-induced knockout – stable nuclei



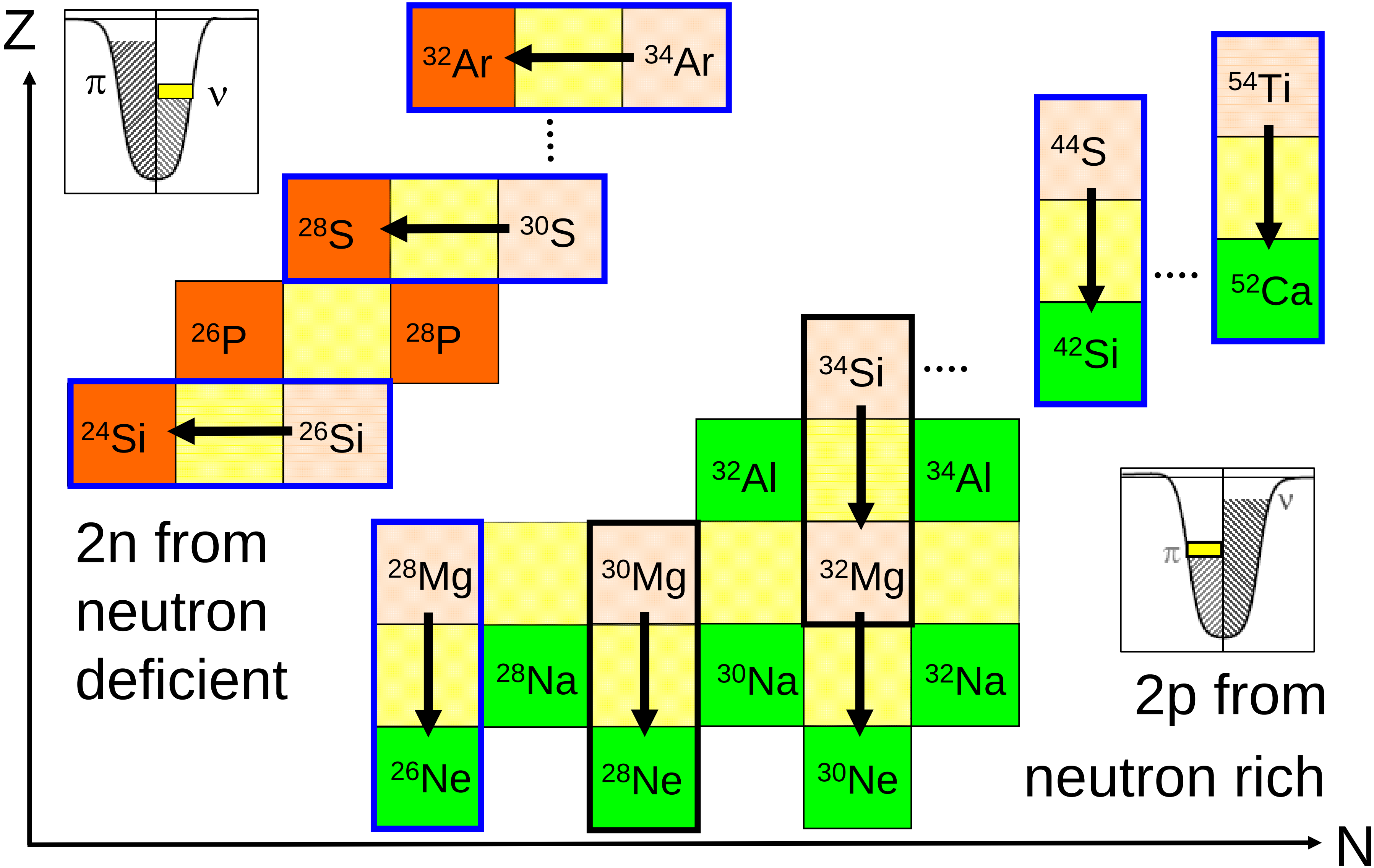


W. Dickhoff and C. Barbieri, Progress in Particle and Nuclear Physics **52** 377 (2004)

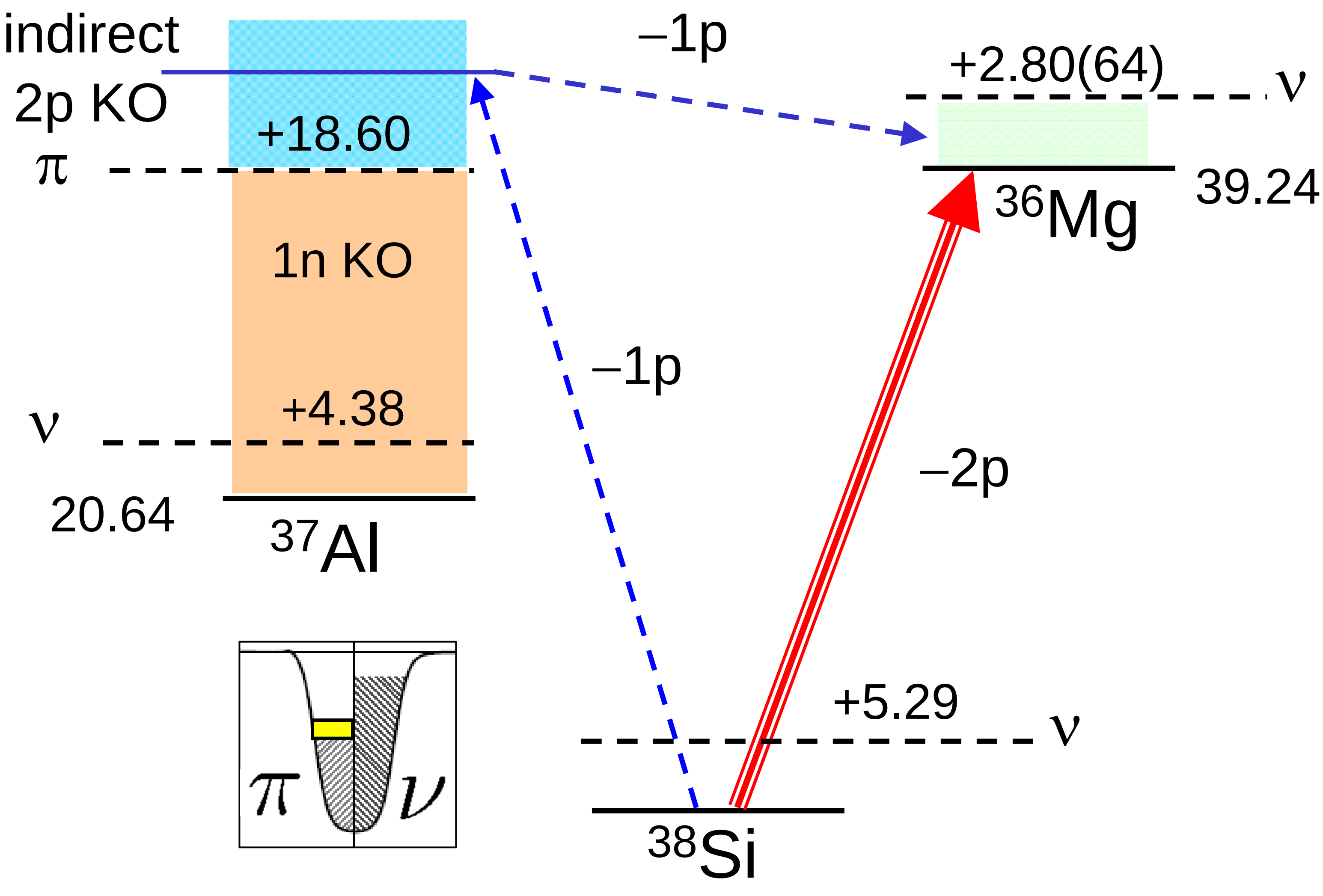
Removal strengths at the two Fermi surface(s)



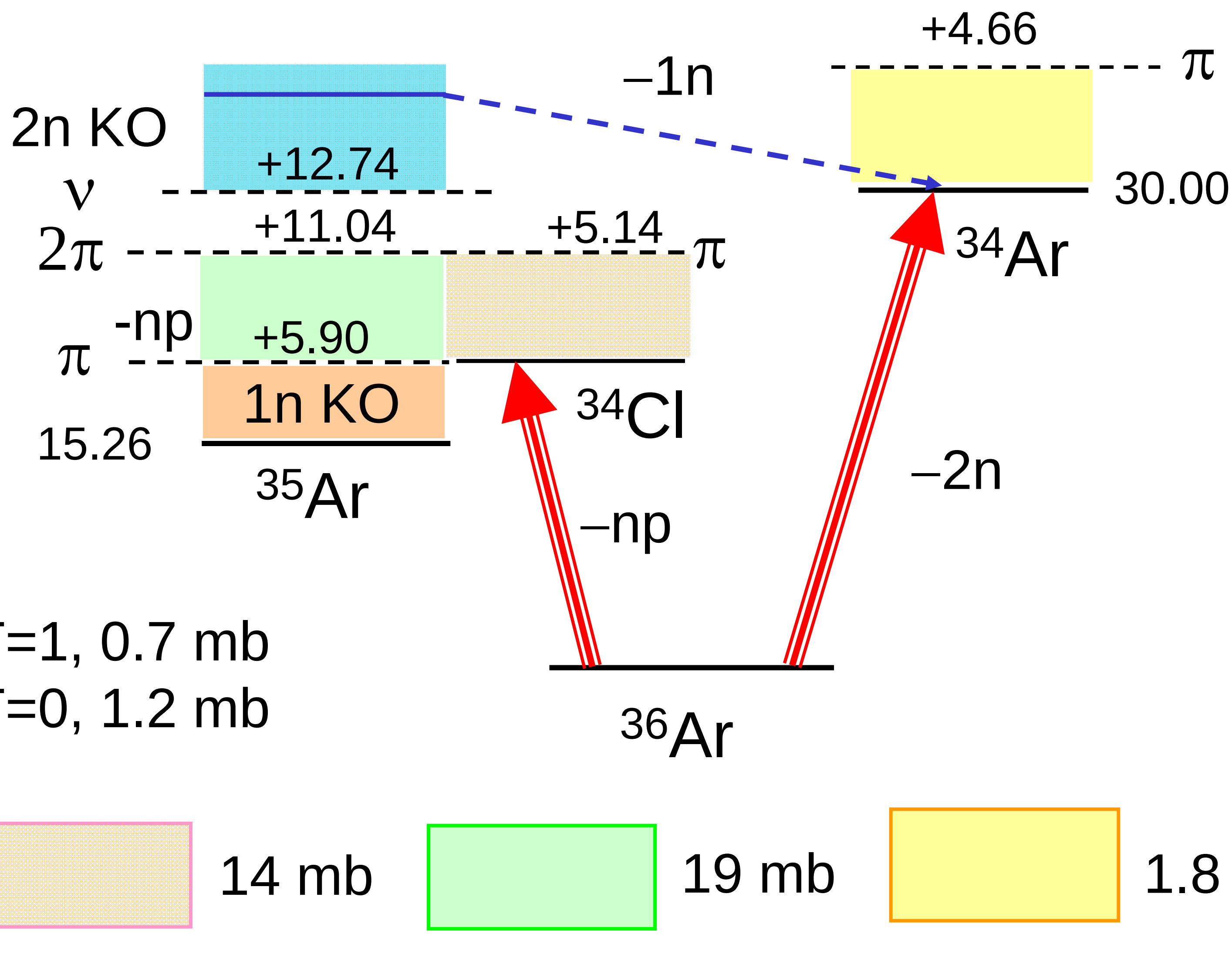
Two nucleon knockout – direct reaction set



Direct two-proton removal reaction mechanism



-np: direct and indirect – really hard



0^+,T=1, 0.7 mb

1^+,T=0, 1.2 mb

Structure interface – via the two-nucleon overlaps

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

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

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

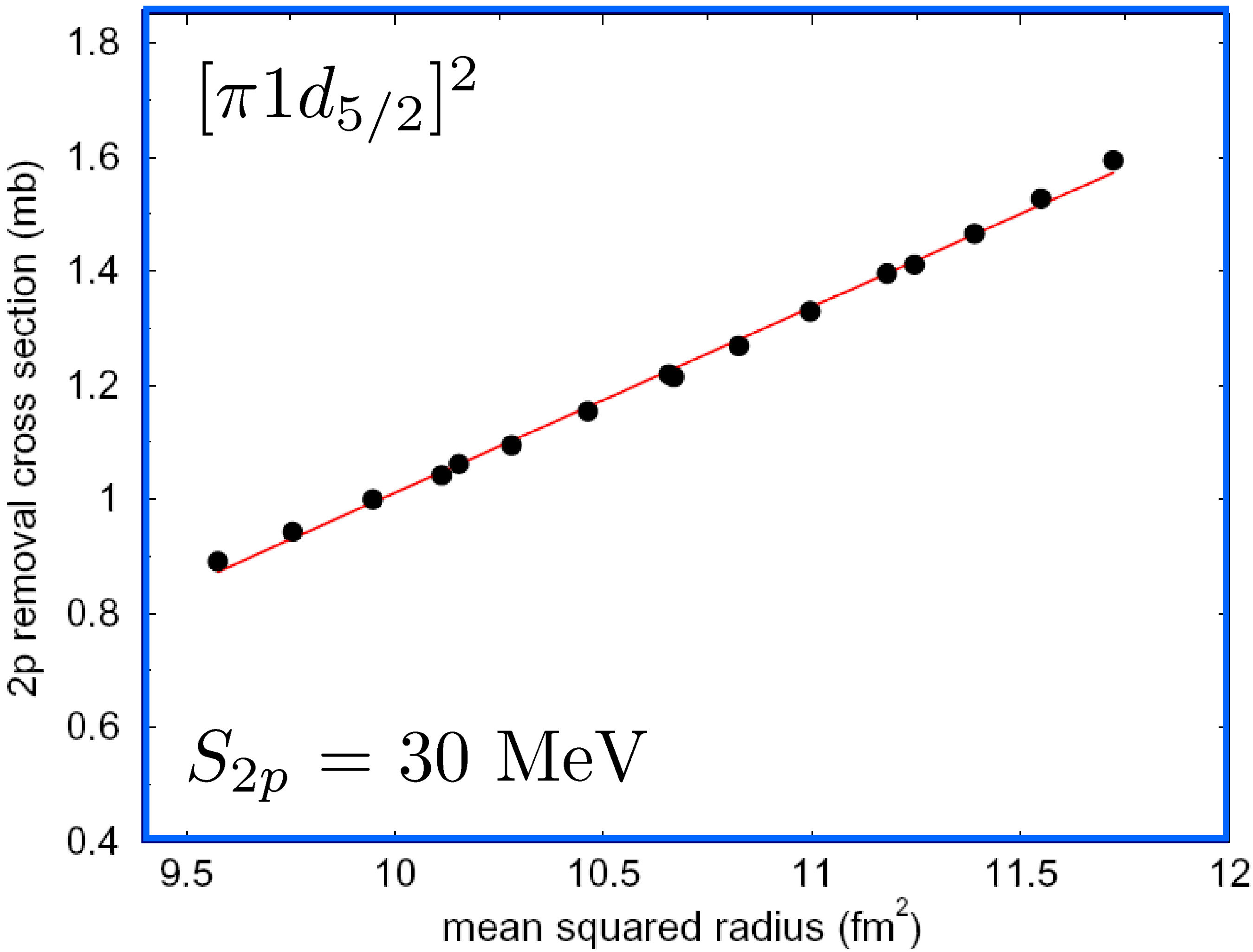
We use this <u>AS IS</u> – no Moshinsky, NN relative s-states projection … no light-ion vertex restrictions

with $J_i = 0^+$ jj-two-nucleon amplitudes – TNA

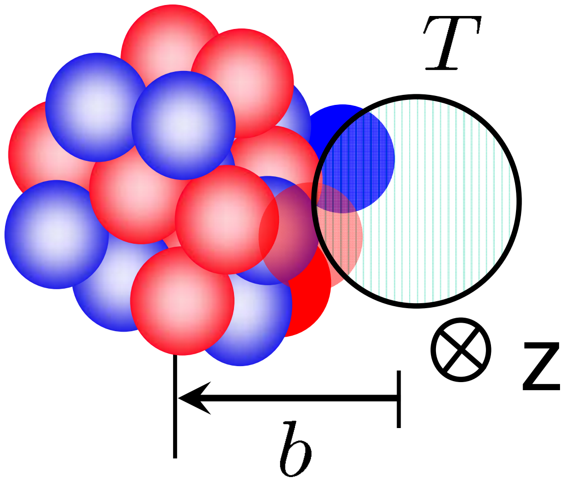
$$F_{IM}(1,2) = \sum_{j_1 j_2} (-)^{I+M} \, C(j_1 j_2 I) / \hat{I} \, \left[\overline{\phi_{j_1 m_1} \otimes \phi_{j_2 m_2}} \right]_{I-M}$$

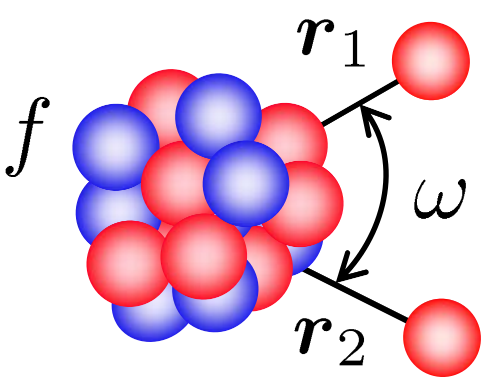
Sensitivity to s.p. orbitals – correlation with radii

$$^{28}\mathrm{Mg}+{}^{9}\mathrm{Be} \rightarrow {}^{26}\mathrm{Ne}(0^{+}) \quad 82.3\ \mathrm{MeV}$$



Target drills a cylindrical volume at projectile surface





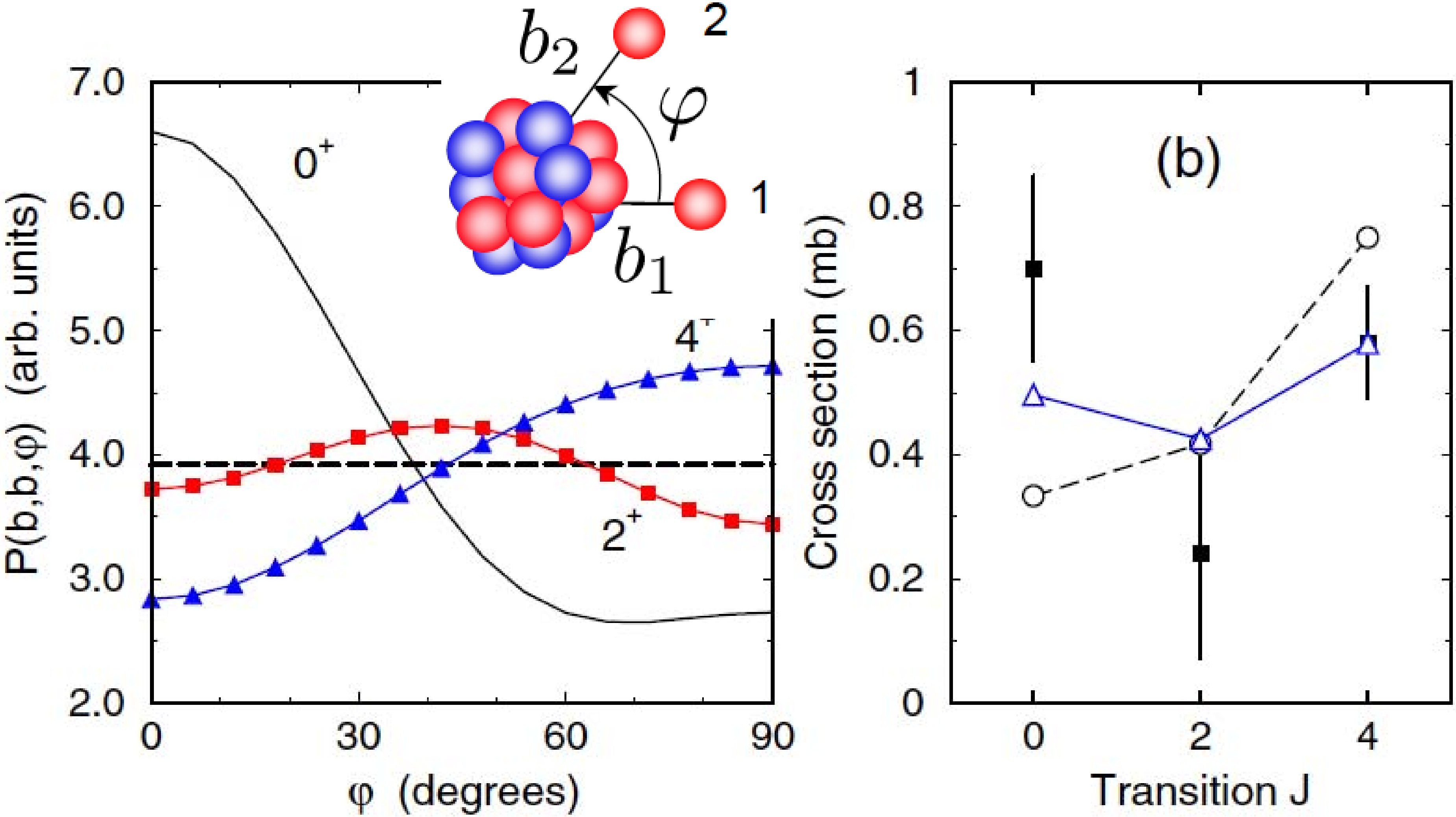
(i) 2N removal cross sections will be sensitive to the spatial correlations of pairs of nucleons near the surface

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

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

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

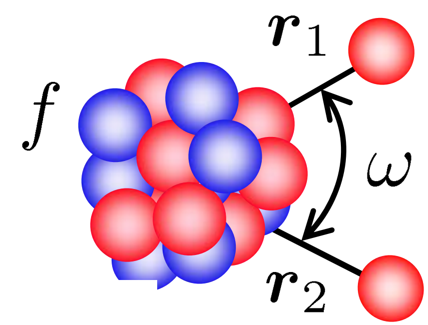
Correlations (cfp) of two d5/2 protons in ^{28}Mg



b=2.5 fm, for $[d_{5/2}]^2$ two-proton removal from ^{28}Mg

Two-nucleon position correlations

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



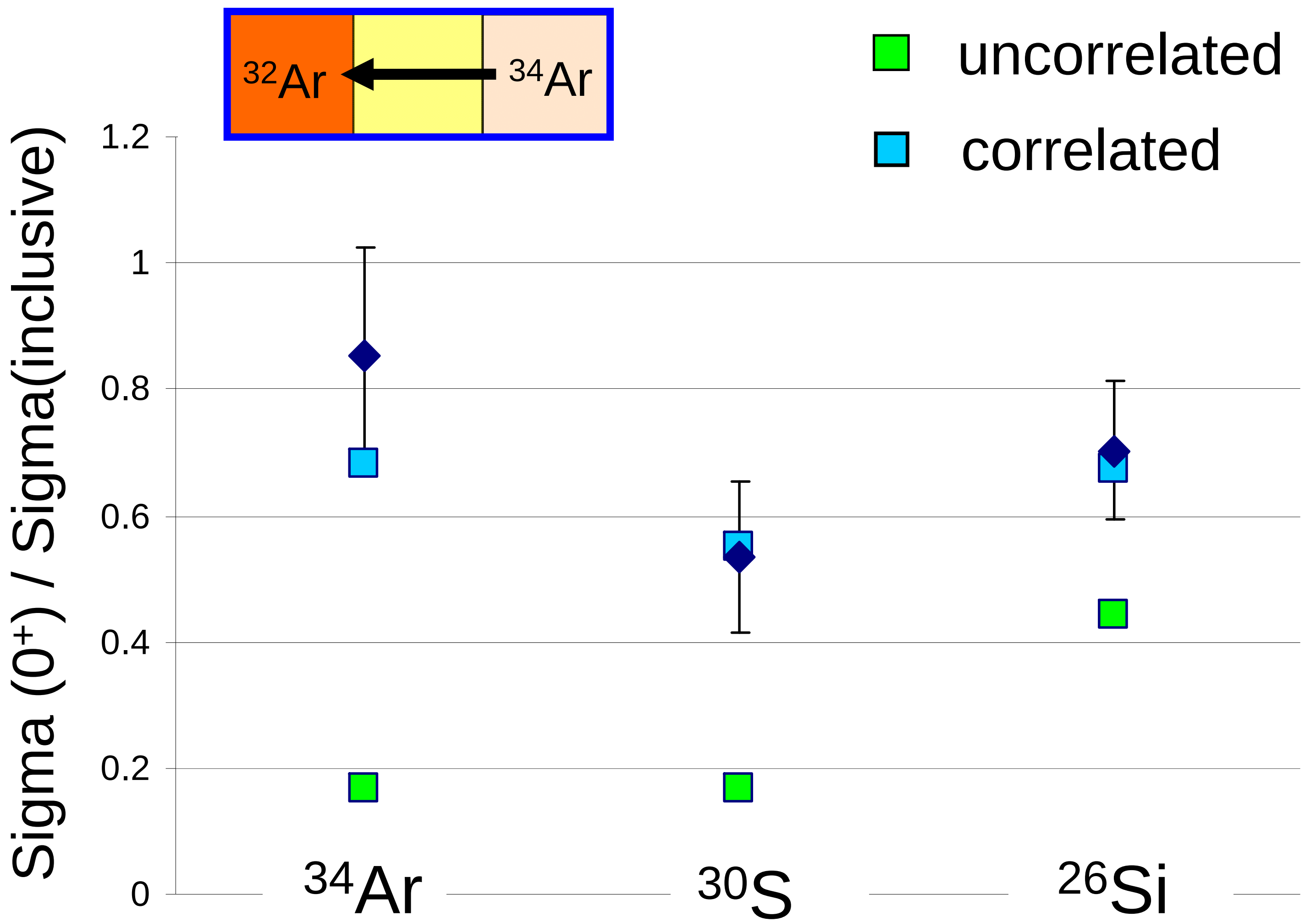
$$\rho_f(\boldsymbol{r}_1,\boldsymbol{r}_2) = \frac{1}{\hat{J}_i^2}\sum_{M_i M_f}\langle\Psi_i^{(F)}|\Psi_i^{(F)}\rangle_{sp}$$

$$= \sum_{LST\,I}\sum_{\alpha\alpha'}\frac{\mathfrak{C}^{IT}_{\alpha LS}\mathfrak{C}^{IT}_{\alpha' LS}D_\alpha D_{\alpha'}}{\hat{L}^2}(T\tau T_f\tau_f|T_i\tau_i)^2$$
$$\times\left[U^D_{\alpha\alpha'}(r_1,r_2)\,\Gamma^{L,D}(\omega)\right.$$
$$\left. - (-)^{S+T}U^E_{\alpha\alpha'}(r_1,r_2)\,\Gamma^{L,E}(\omega)\right],$$

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

E.C. Simpson, JAT, PRC **82**, 044616 (2010)

Two-neutron removal – g.s. branching ratios

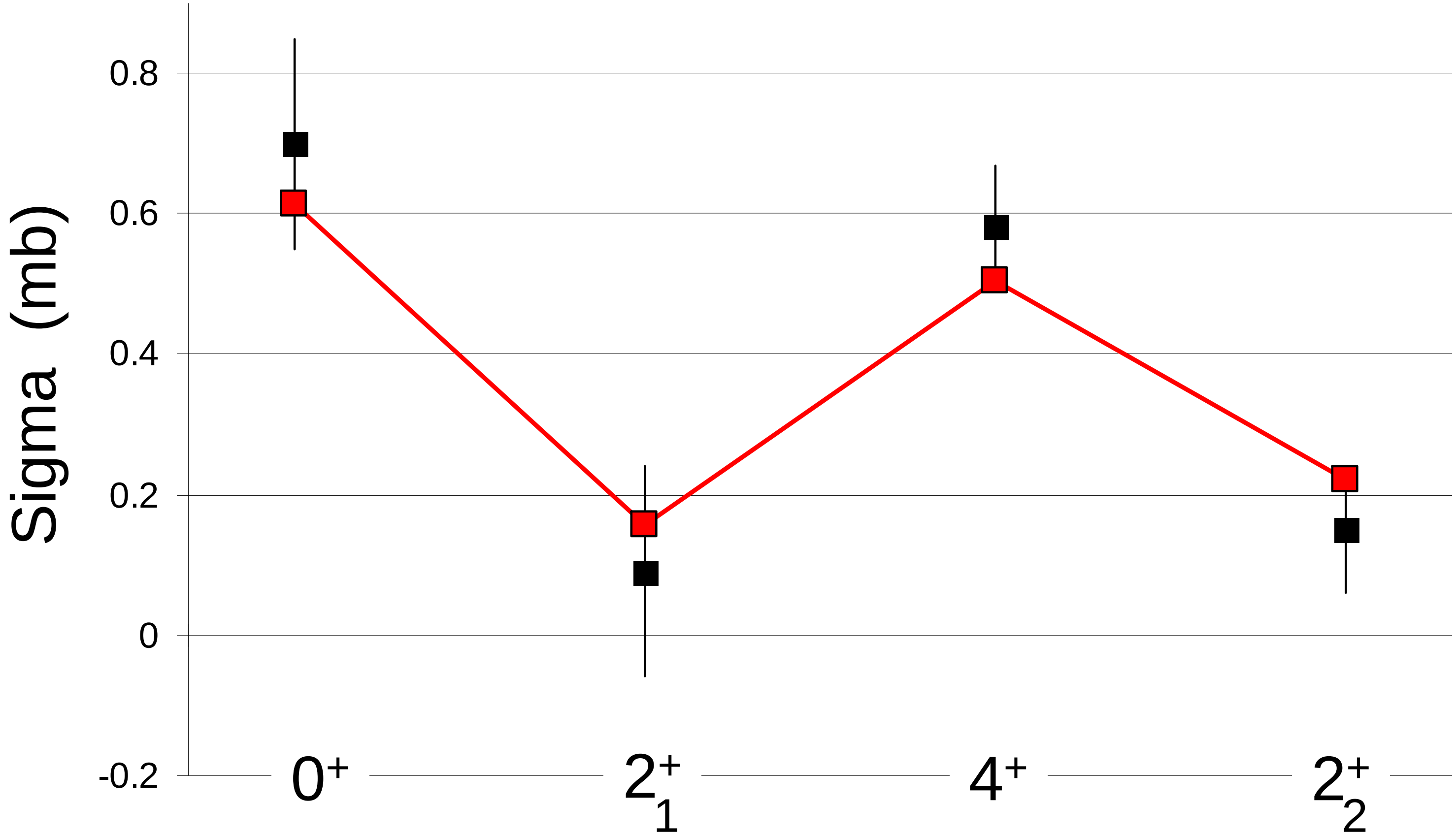


J.A. Tostevin et al., PRC **74** 064604 (2006

Knockout cross sections – correlated case

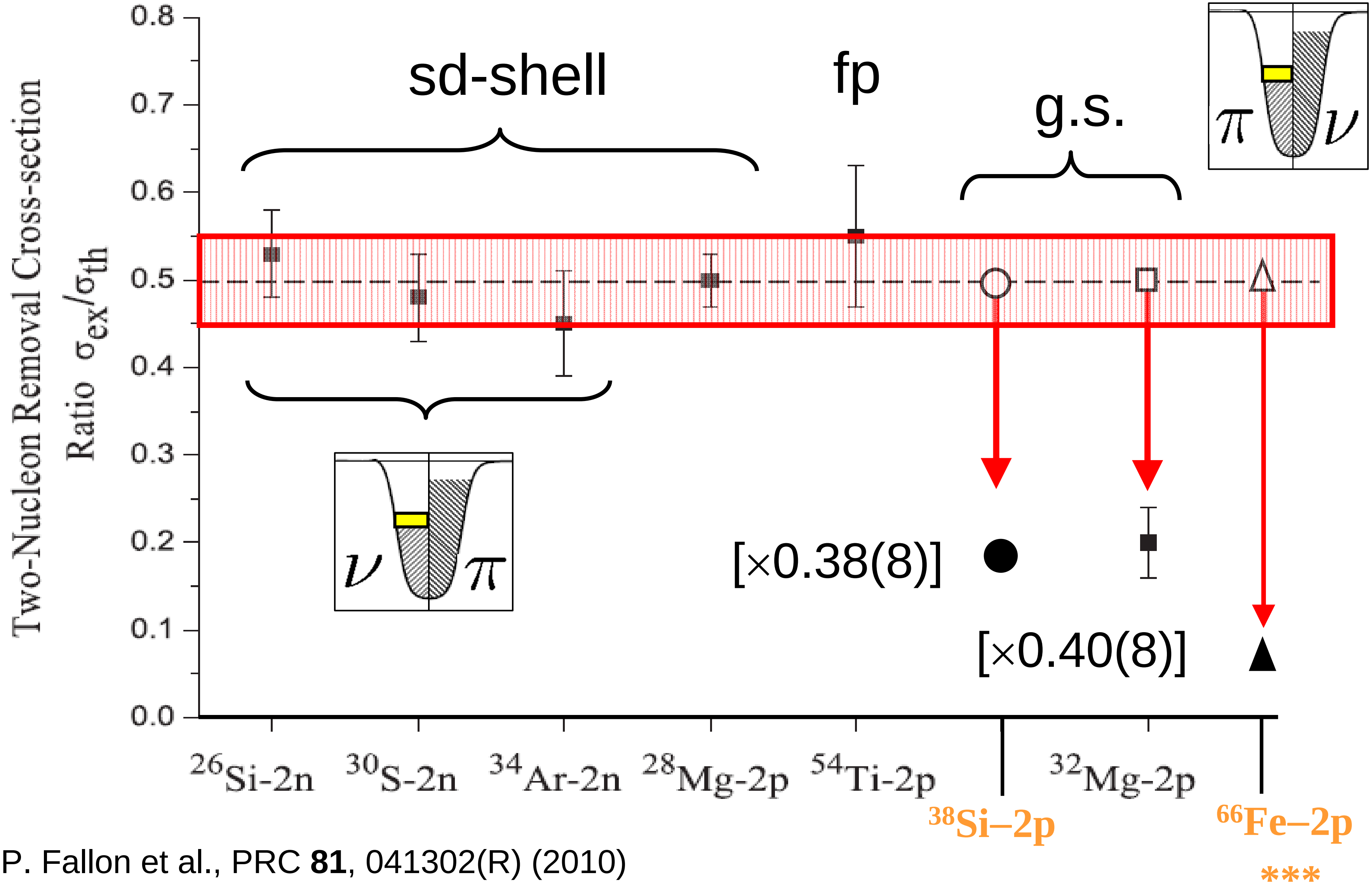
$^{28}Mg \rightarrow {}^{26}Ne(0^+, 2^+, 4^+, 2_2^+)$ 82.3 MeV/u

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



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

Mapping rapid changes of structure: a challenge

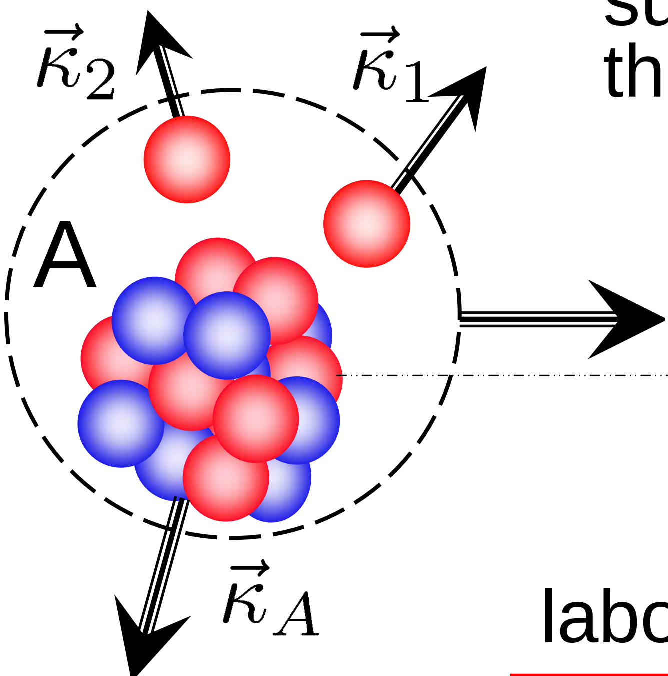


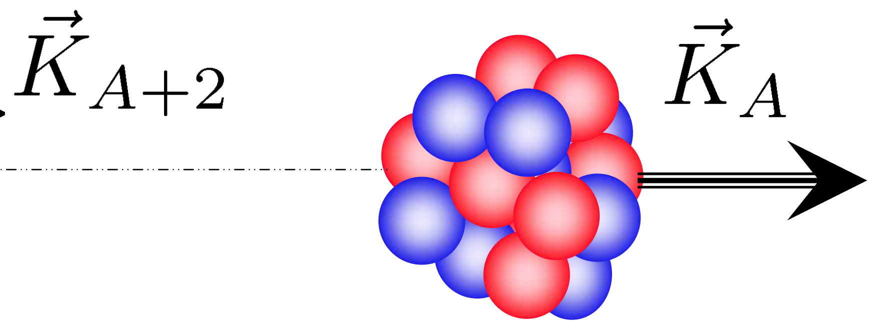
P. Fallon et al., PRC **81**, 041302(R) (2010)

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

Sudden nucleon removal from the mass A residue

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





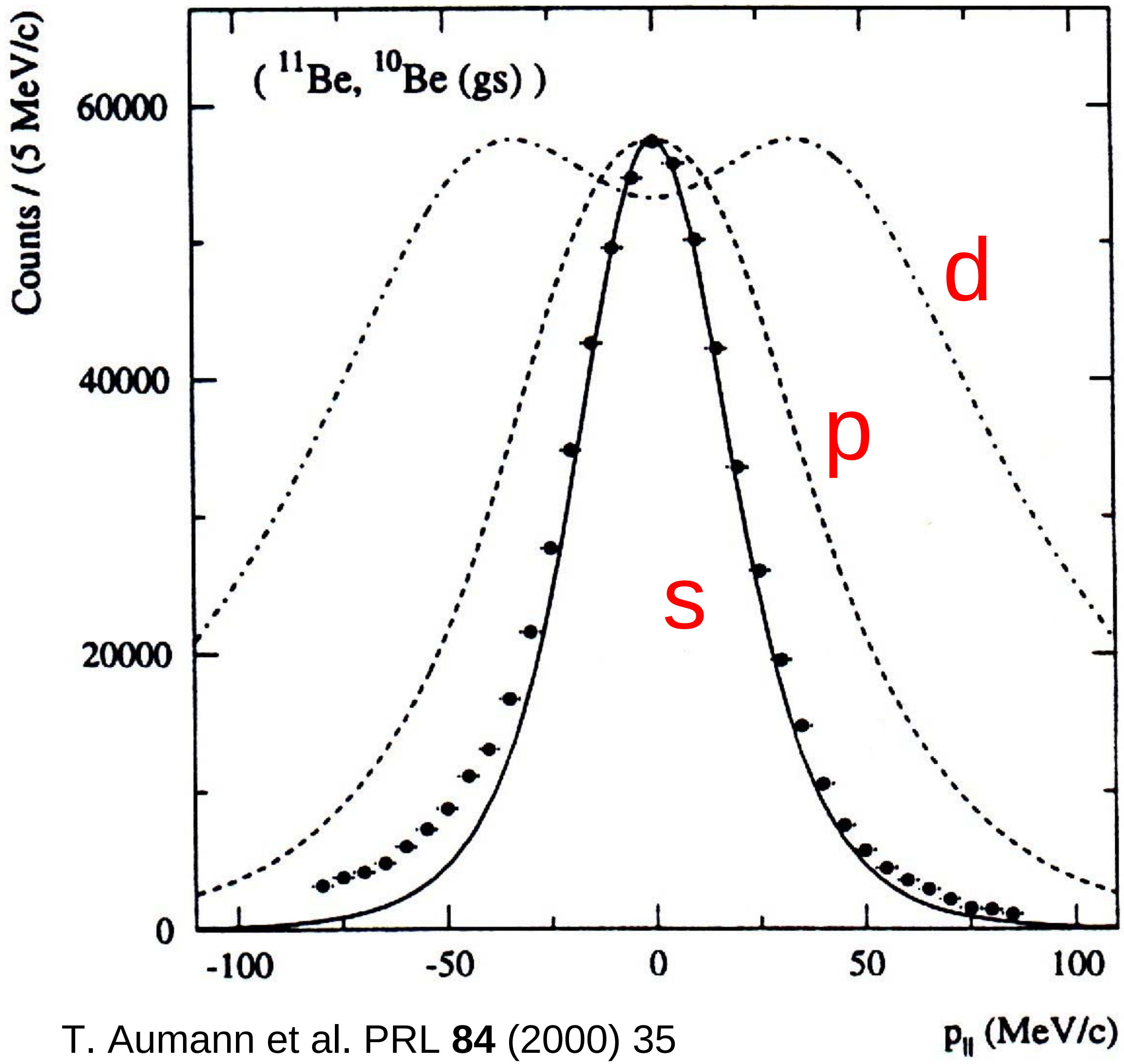
Projectile rest frame

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

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

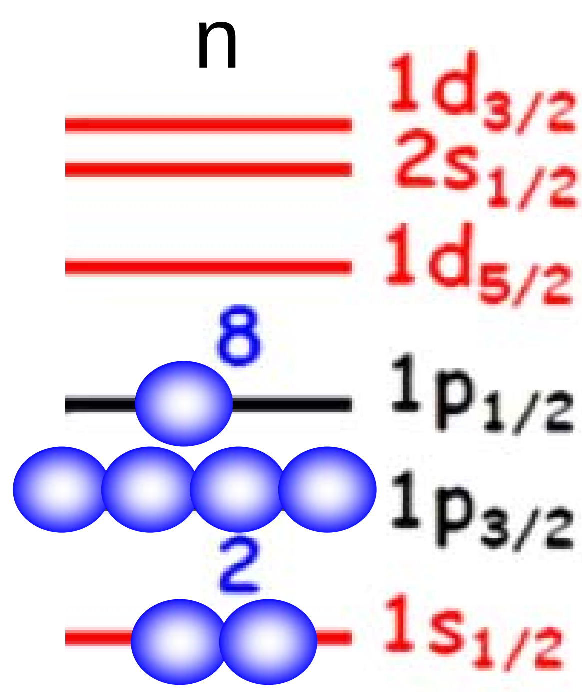
and component equations

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



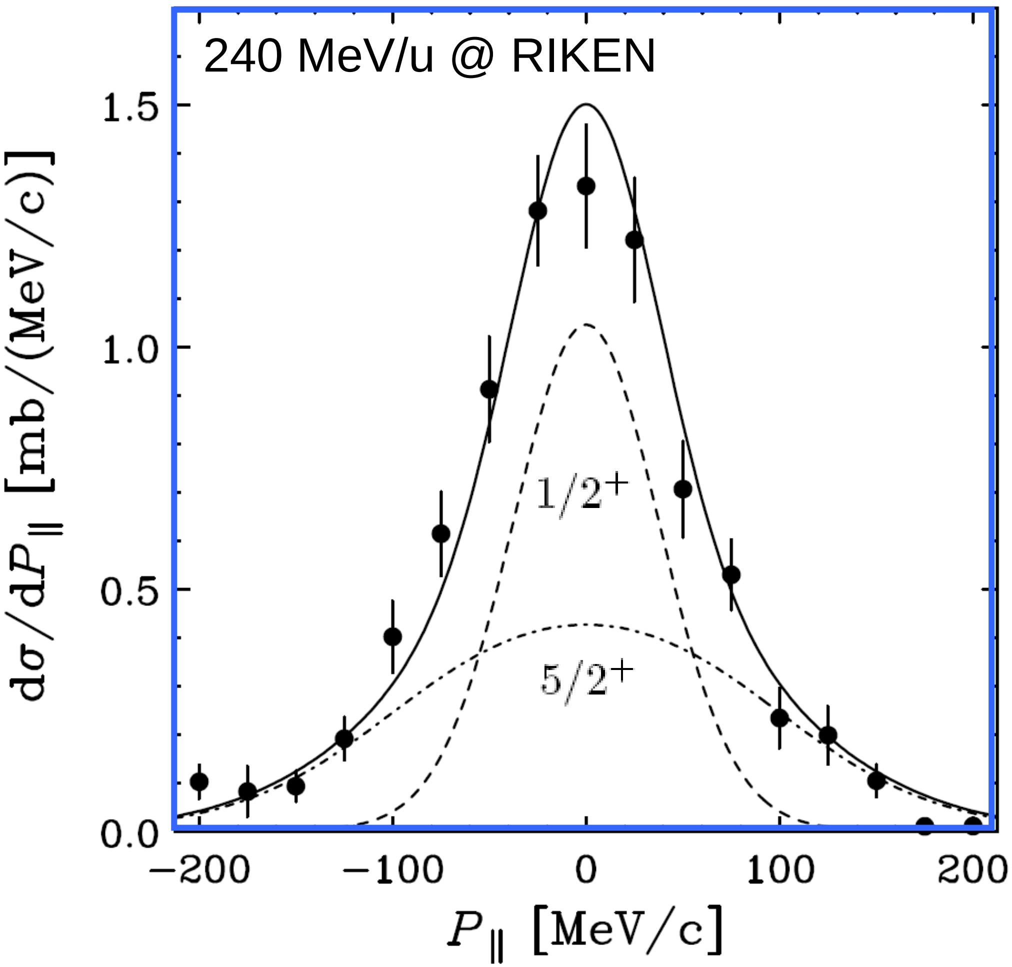
T. Aumann et al. PRL **84** (2000) 35

Z = 4, N = 7



^{11}Be

Single-neutron knockout to the continuum: ^{22}C



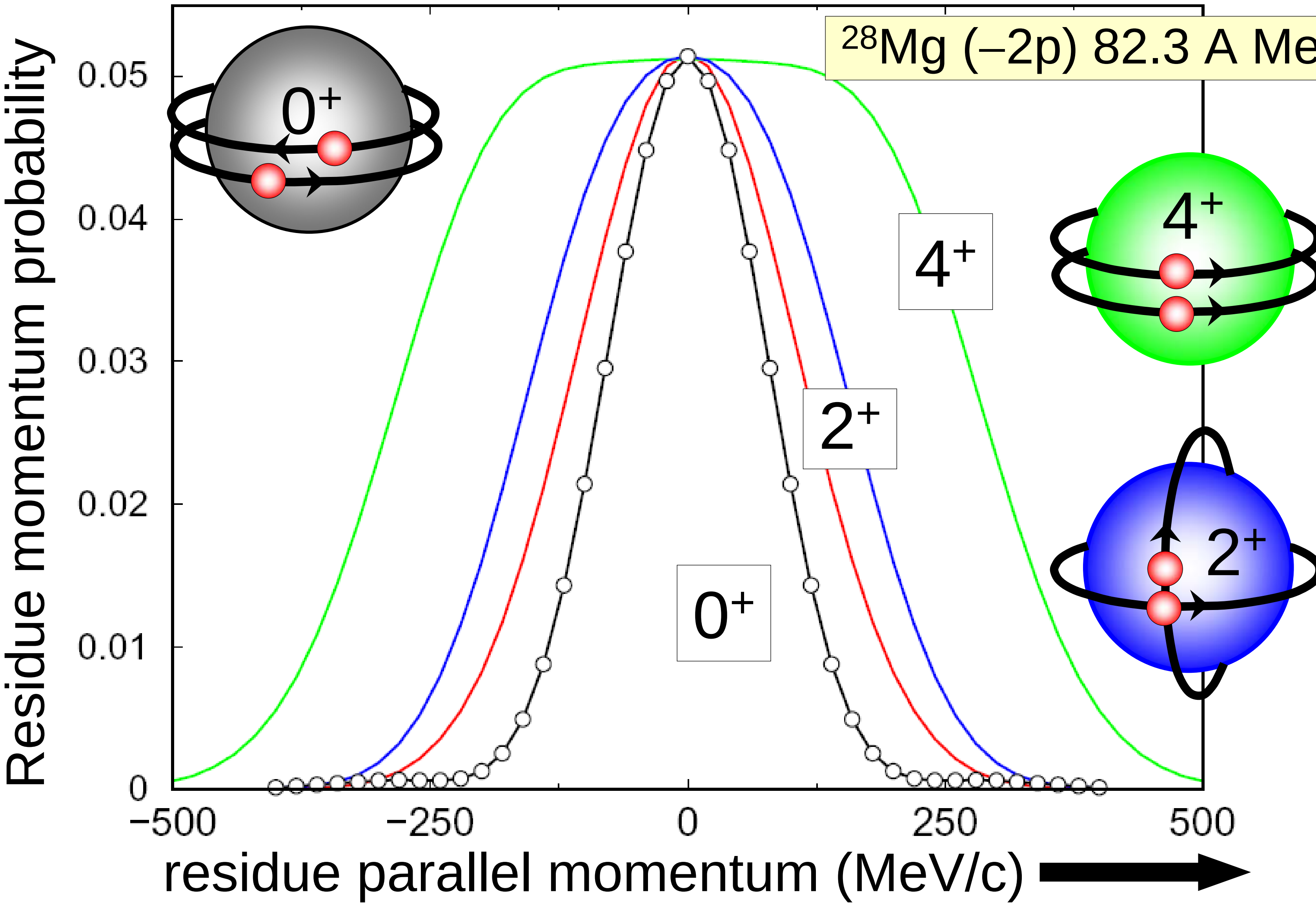
Shell model (WBP)

$(^{22}\mathrm{C}(0^+), ^{21}\mathrm{C}(J^\pi))$	0.000	$1/2^+$
$S_{1n}(22)$=0.70 MeV	1.109	$5/2^+$
	2.191	$3/2^+$

	SF	sigma (mb)
$1/2^+$	1.403	137.55
$5/2^+$	4.212	135.87
$3/2^+$	0.342	9.55
		283.0
	Expt.	208(14)

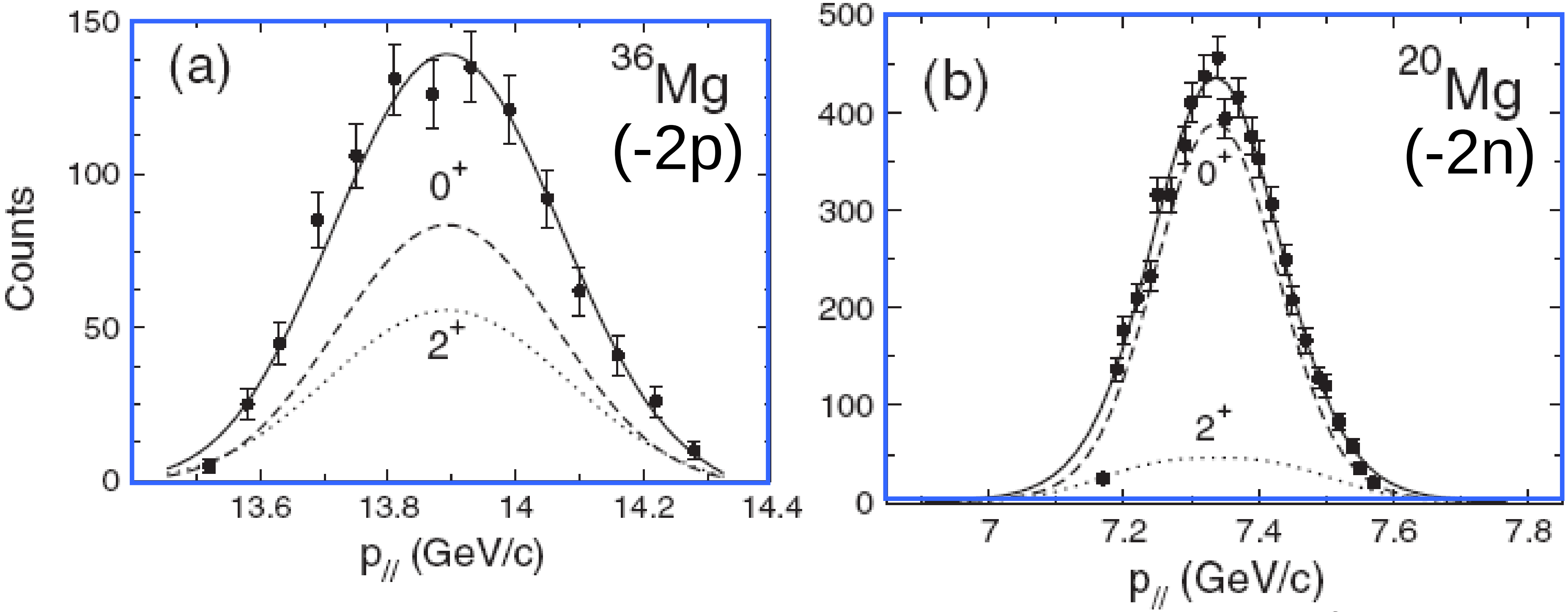
N. Kobayashi, T. Nakamura, JAT et al., (in preparation, 2011)

Two nucleon KO – predicted $p_{//}$ J-dependence

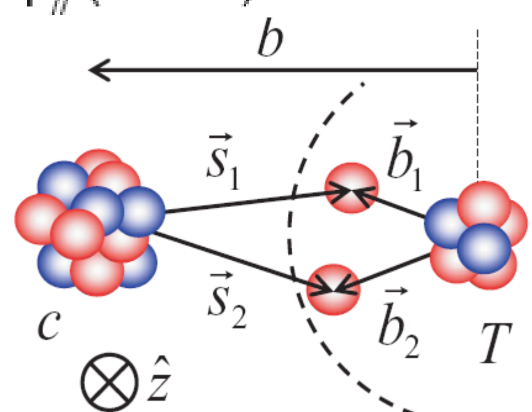


J. A. Tostevin, EPJ Special Topics **150**, 67 (2007)

Two-nucleon removal p// distributions

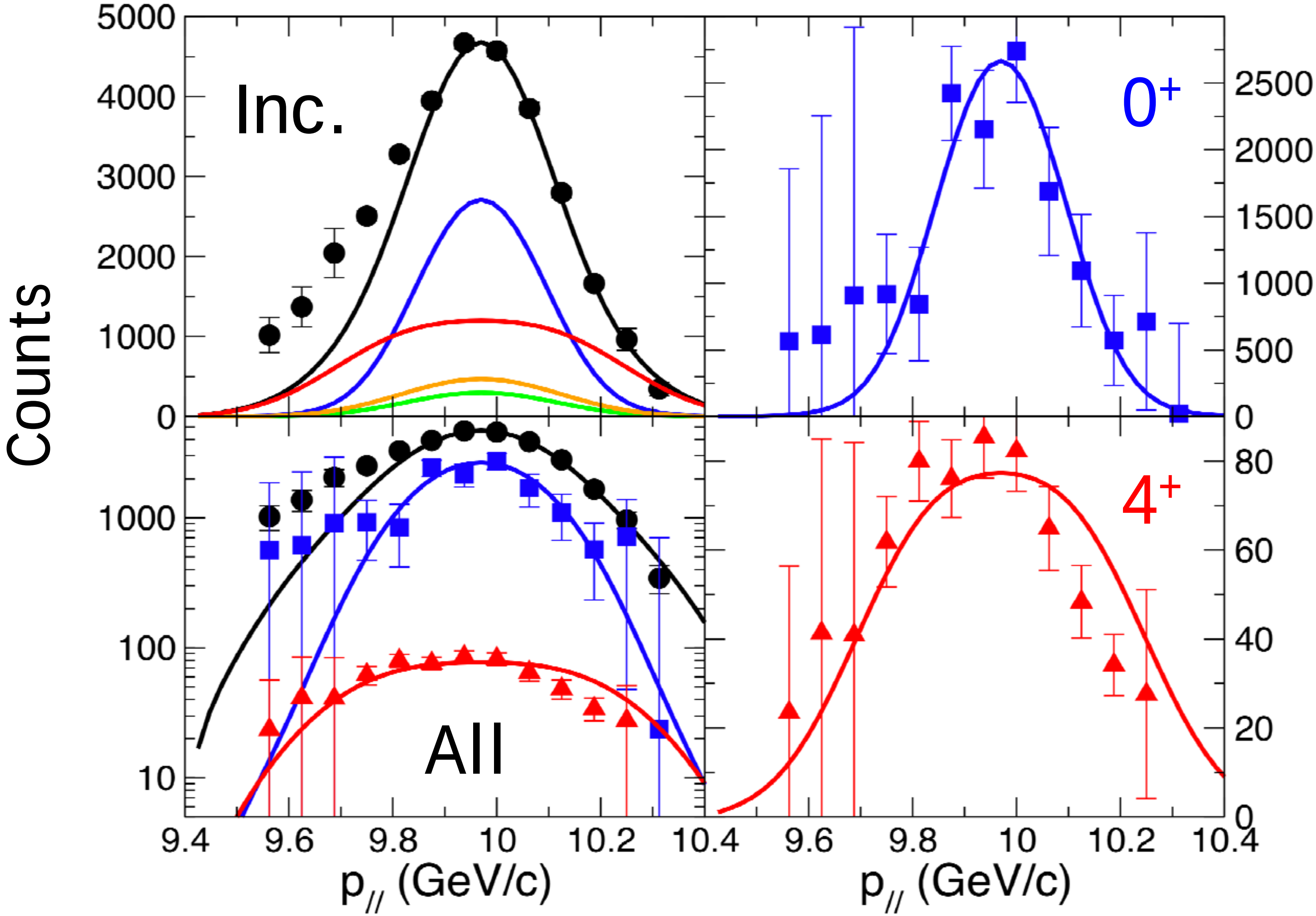


$$\bar{\mathcal{P}}_f(\vec{s}_1,\vec{s}_2,\kappa_c) = \frac{1}{\hat{J}_i^{\,2}} \sum_{M_i M_f} \int d\kappa_1 \int d\kappa_2 \frac{\delta(\kappa_c+\kappa_1+\kappa_2)}{(2\pi)^2} \times \left\langle \left| \int dz_1 \int dz_2 e^{i\kappa_1 z_1} e^{i\kappa_2 z_2} \Psi^{(F)}_{J_i M_i} \right|^2 \right\rangle_{sp}$$



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

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



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

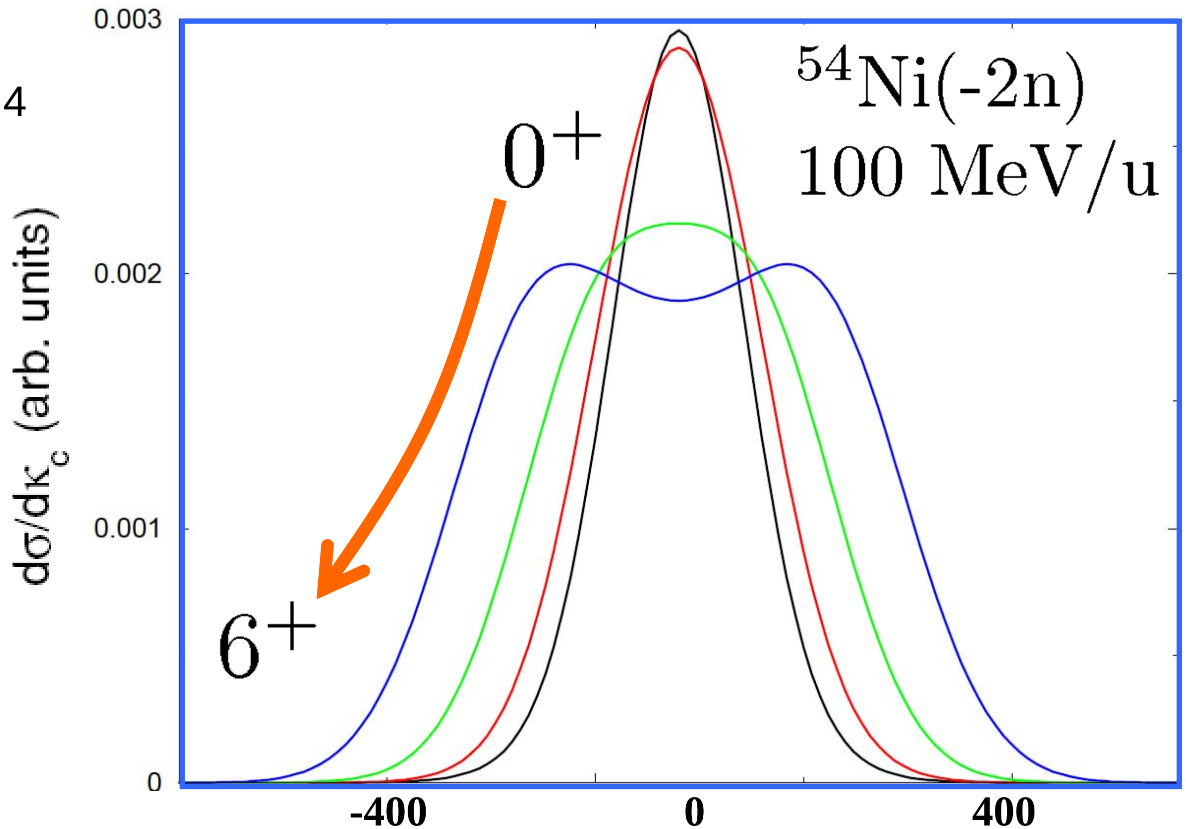
Final-state spin-value sensitivity: e.g. ^{54}Ni(-2n)

$\mathfrak{C}^{IT}_{\alpha L S}$

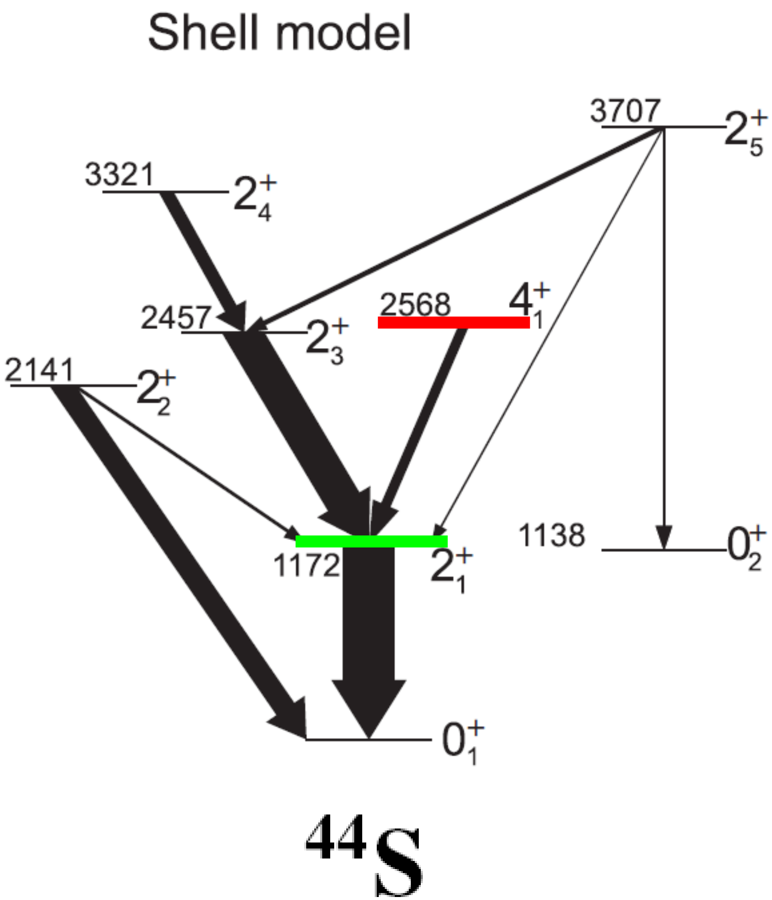
I	C(I=L)	C(L=I+1)	C(L=I-1)
0	**0.571**	**0.428**	0.0
2	**0.510**	0.122	**0.367**
4	**0.367**	0.034	**0.598**
6	0.142	0.0	**0.857**

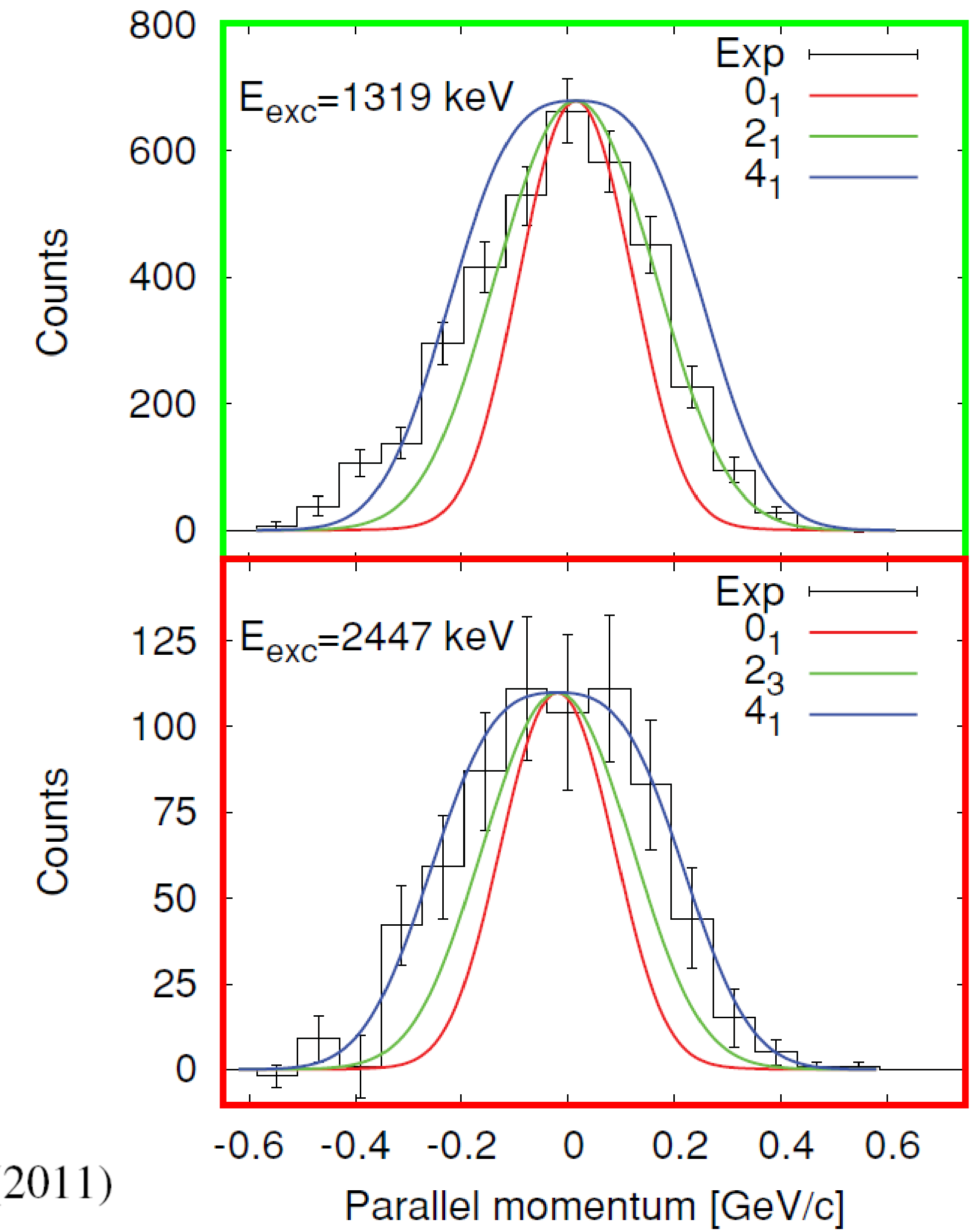
Relatively 'pure' 2N configurations give simple L (and I) – dependences – e.g. assuming $[f_{7/2}]^6 \rightarrow [f_{7/2}]^4$

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



Spectroscopy of ^{44}S at N=28 – using $^{46}Ar(-2p)$





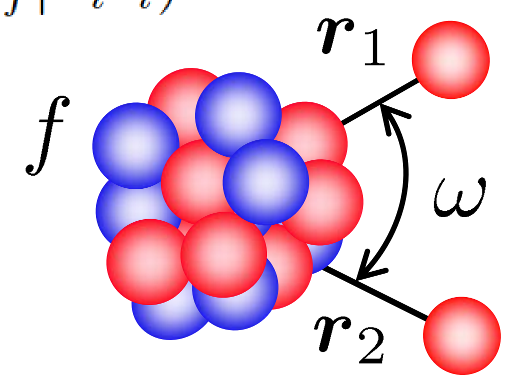
D. Santiago-Gonzalez, et al.,
PHYSICAL REVIEW C **83**, 061305(R) (2011)

Angular correlations – and L-transfer sensitivity

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

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

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



depends only on L (=$\lambda_1+\lambda_2$) of the two nucleons.

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

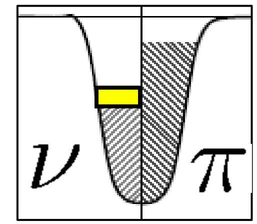
$$\mathfrak{C}^{IT}_{\alpha LS} = \hat{j}_1\,\hat{j}_2\,\hat{L}\,\hat{S} \begin{Bmatrix} \ell_1 & s & j_1 \\ \ell_2 & s & j_2 \\ L & S & I \end{Bmatrix} C^{IT}_{\alpha}$$

predict p// distribution

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

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



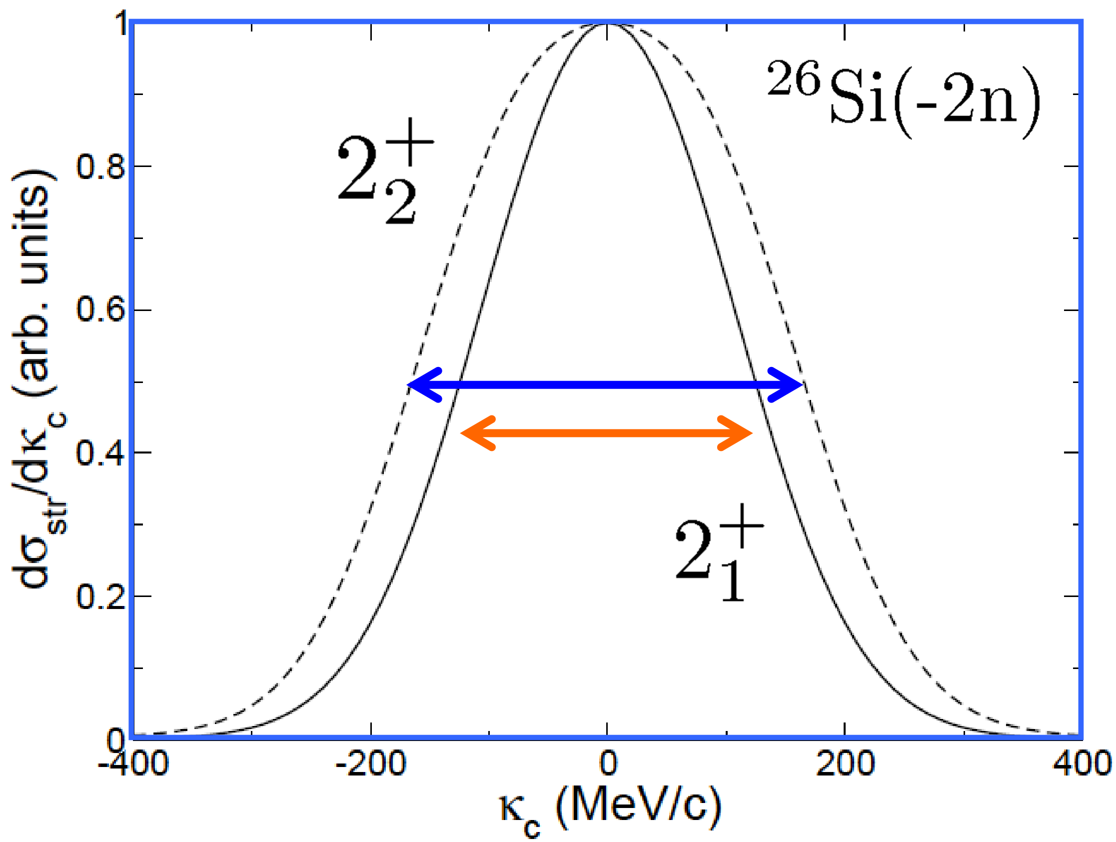
with cross sections:

σ_{LS} (mb)

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

$L = 1$
250 MeV/c

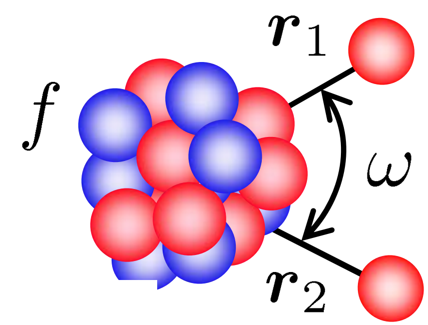
$L = 2$
330 MeV/c



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

Two-nucleon position correlations

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



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

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

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

$$\Gamma^L_{\ell_1 \ell_2 \ell'_1 \ell'_2}(\omega) = (-1)^L \frac{\hat{\ell}_1 \hat{\ell}'_1 \hat{\ell}_2 \hat{\ell}'_2 \hat{L}^2}{(4\pi)^2} \sum_k W(\ell_1 \ell_2 \ell'_1 \ell'_2; Lk)$$

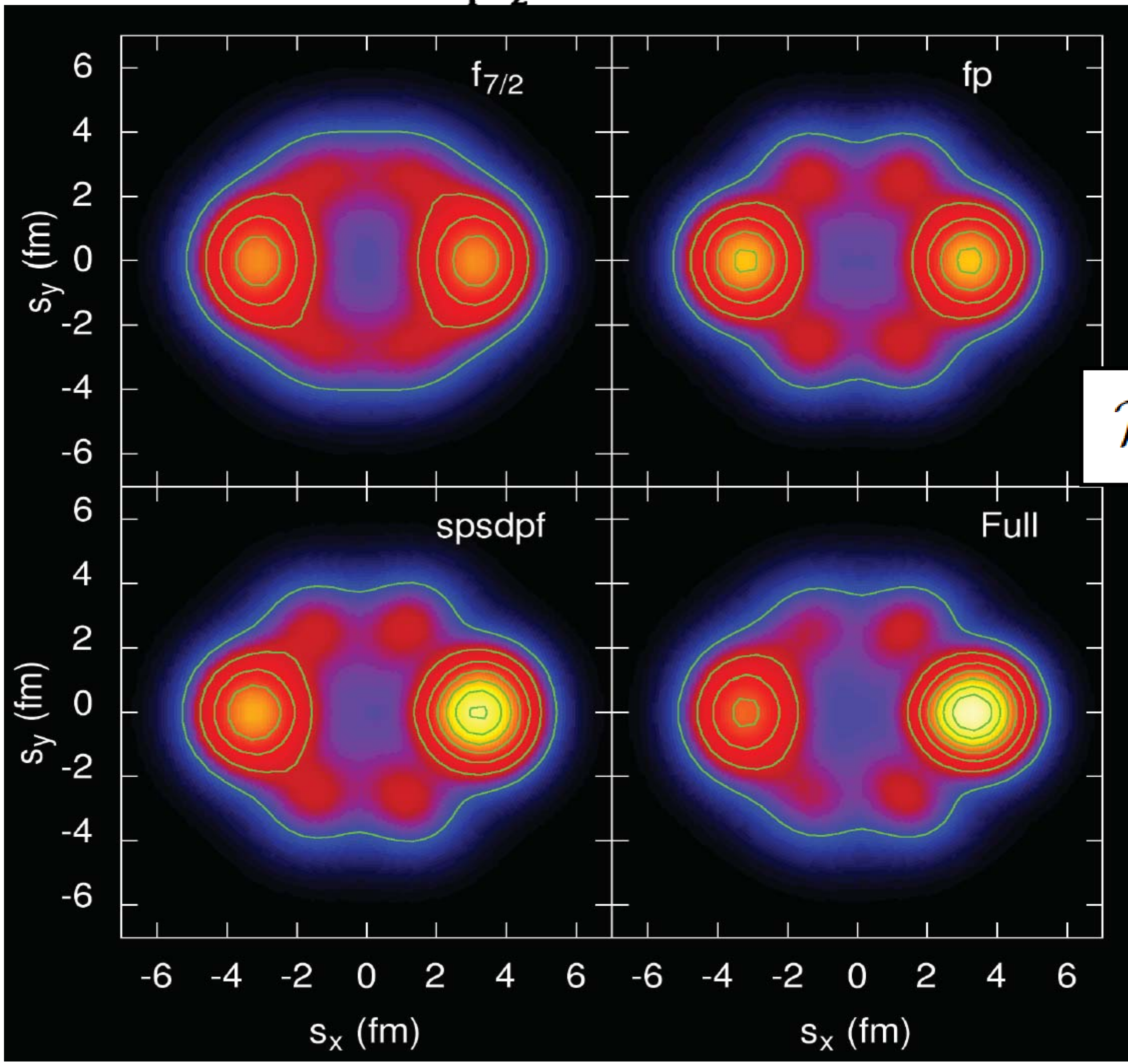
$$\times (-1)^k (\ell_1 0 \ell'_1 0 | k0)(\ell_2 0 \ell'_2 0 | k0) P_k(\cos\omega)$$

E.C. Simpson, JAT, PRC **82**, 044616 (2010)

Perturbative extended basis: 48Ca(-2n, gs)

$$\Psi = \psi((nlj)^2) + \sum_{n_1 n_2 l' j'} \psi(n_1 l' j', n_2 l' j') \frac{\langle n_1 l' j', n_2 l' j' | V | (nlj)^2 \rangle}{2\epsilon(nlj) - \epsilon(n_1 l' j') - \epsilon(n_2 l' j')}$$

$[f_{7/2}]^2$

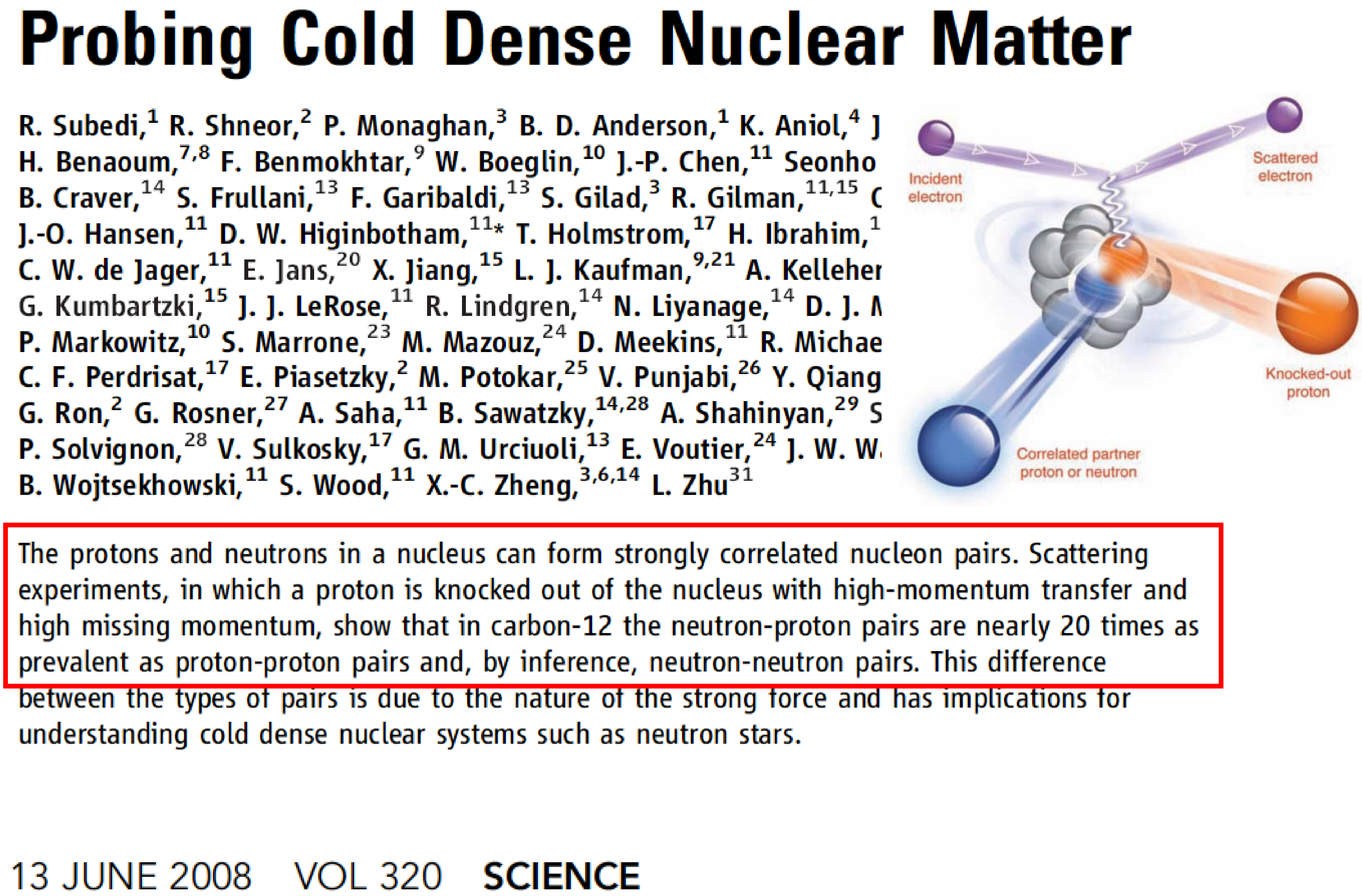


$$\mathcal{P}_f(\boldsymbol{s}_1, \boldsymbol{s}_2) = \int dz_1 \int dz_2\, \rho_f(\boldsymbol{r}_1, \boldsymbol{r}_2)$$

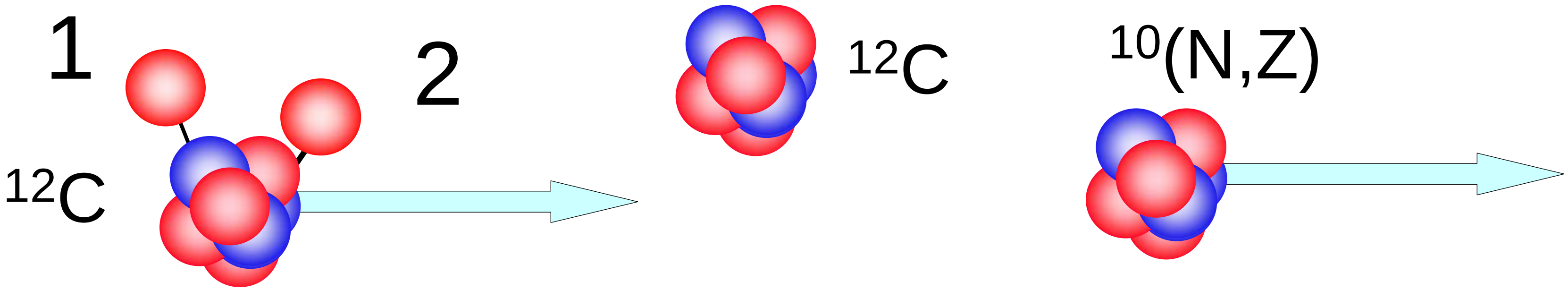
$$\vec{s}_1 = (3.8, 0.0)$$

$$\sigma \to \approx 2\sigma$$

np correlations - light nuclei – high thresholds



In two nucleon removal data - one sees



Energy/nucleon	250 MeV	1.05 GeV	2.1 GeV
10Be Experimental	5.88	5.30(30)	5.81(29)
10C Experimental	5.33(81)	4.44(24)	4.11(22)
10B Experimental	47.5(24)	27.9(22)	35.1(34)

Based simply on combinatorics - and removal of the (4) p3/2 nucleons we might expect scalings of:

sigma (pp or nn) [4 x 3]/2 = 6
sigma (np) 4 x 4 = 16

Cross sections: J.M. Kidd et al. PRC **37,** 2613 (1988)
Momentum distributions: D.E. Greiner et al., PRL **35**, 152 (1975)

Comparison to (inclusive) cross section data

Energy MeV/u	^{10}Be σ_{th}	σ_{exp}	σ_{exp}/σ_{th}	^{10}C σ_{th}	σ_{exp}	σ_{exp}/σ_{th}
250 [5]	7.25	5.88±9.70	0.81±1.34	5.80	5.33±0.81	0.92±0.14
1050 [13]	6.62	5.30±0.30	0.80±0.05	5.13	4.44±0.24	0.87±0.05
2100 [13]	6.52	5.81±0.29	0.89±0.04	5.04	4.11±0.22	0.82±0.04

^{10}B σ_{th}	σ_{exp}	σ_{exp}/σ_{th}
21.57	47.50±2.42	2.20±0.11
19.27	27.90±2.20	1.45±0.11
19.03	35.10±3.40	1.84±0.18

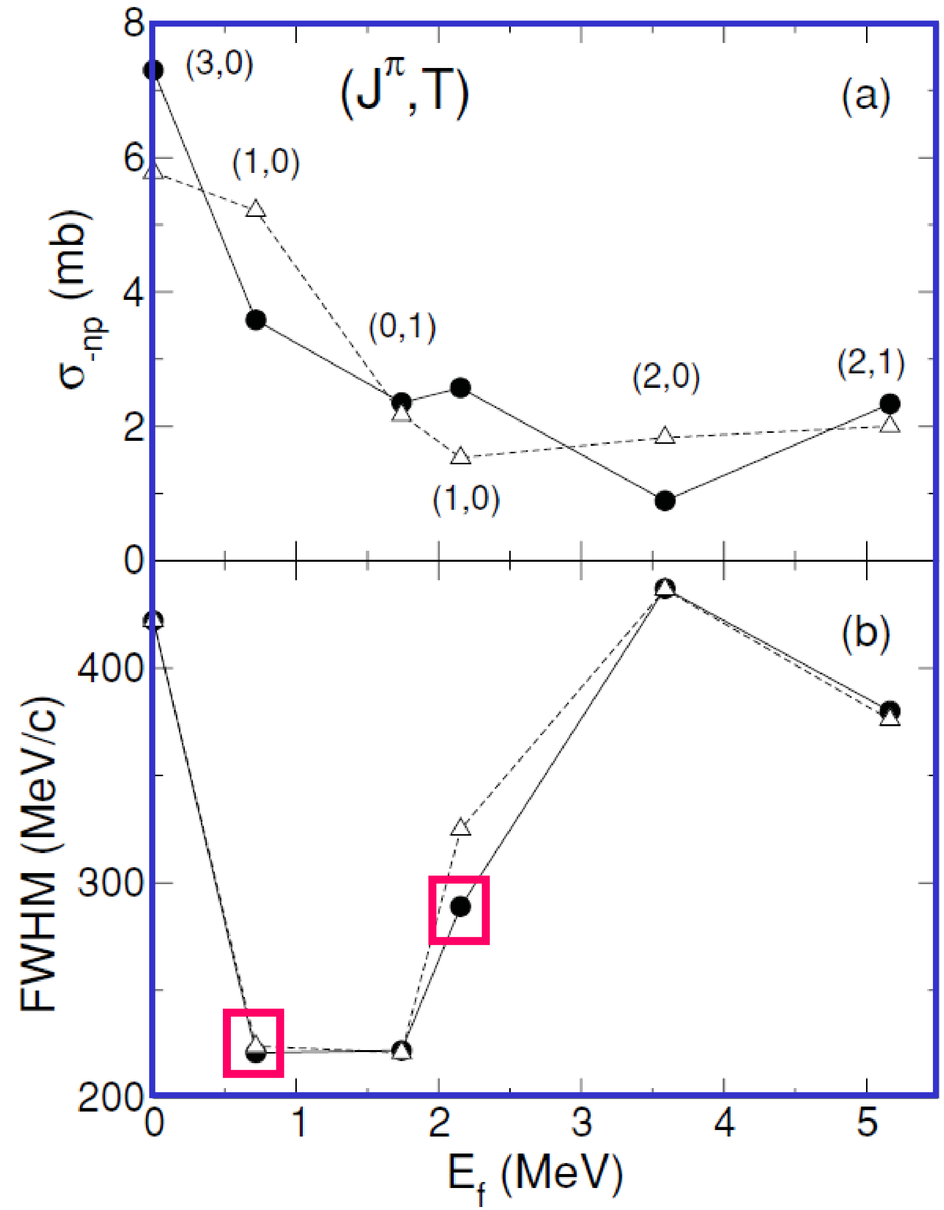
Cross sections: J.M. Kidd et al. PRC **37,** 2613 (1988)
Momentum distributions: D.E. Greiner et al., PRL **35**, 152 (1975)

Exclusive observables: 12C(-np) case at 2.1 GeV/u

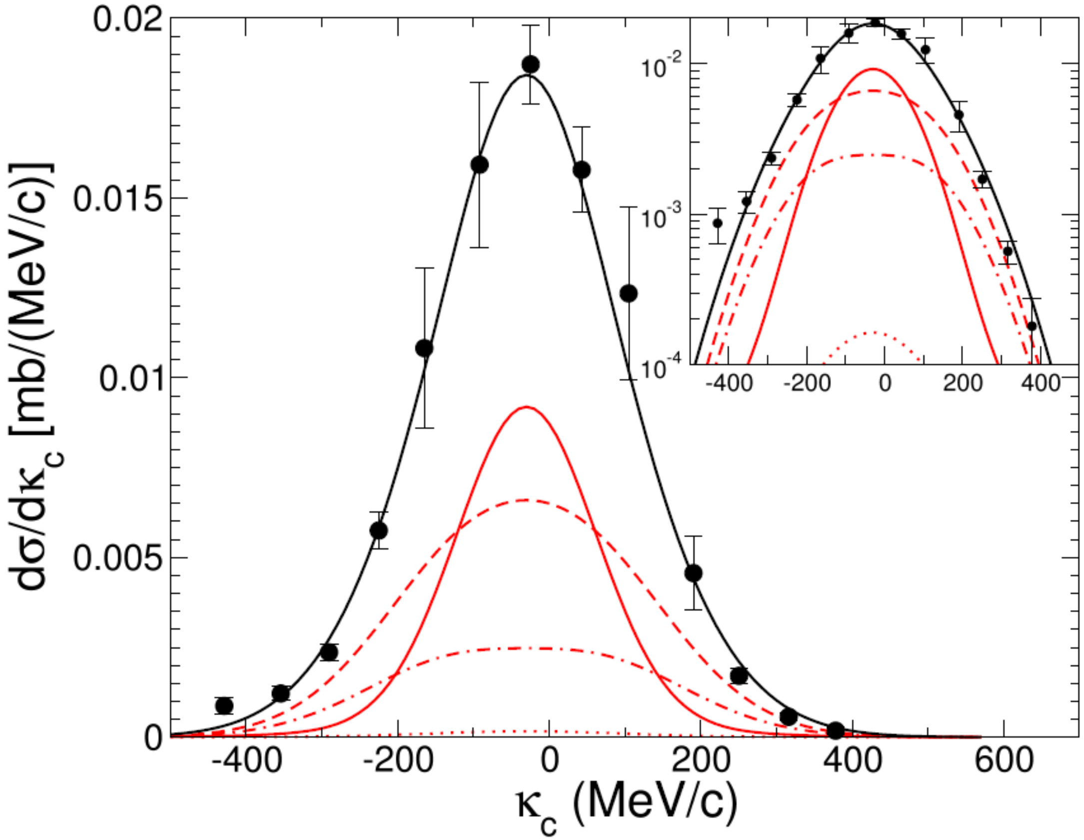
E.C. Simpson, JAT,
PRC **83**, 014605
(2011)

——————— WBP

- - - - - - - PJT



Inclusive 2p removal momentum distribution



E.C. Simpson, JAT, in preparation (2010)

FIG. 4: Comparison of ^{10}Be residue momentum distributions. Note the data is for a ^{9}Be target whereas the calculations use a ^{12}C target. The calculations have been offset by -30 MeV/c and the have been scaled to match the experimental two-proton removal cross section (^{9}Be target, 5.97 mb).

Momentum distributions: D.E. Greiner et al., PRL **35**, 152 (1975)

Existing (inclusive and averaged) p// distributions

TABLE V: Gaussian fits to experimental and theoretical momentum distributions. These results are shown for comparison only - the experimental results are averaged over a range of targets, whereas the theoretical results are for the carbon target only. This considered, there is good agreement between the measurements and calculations, both in terms of the relative widths of different distributions and the absolute widths of each distribution.

Residue	$\sigma_{exp}^{p_{\|\|}}$	σ_{th}^{κ}
^{11}B	106±4	99
^{11}C	103±4	100
^{10}Be	129±4	127
^{10}B	134±3	132
^{10}C	121±6	120

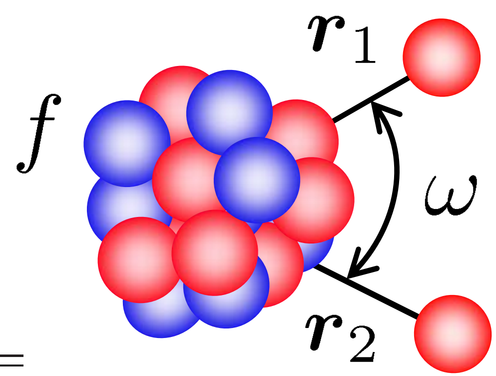
Momentum distributions: D.E. Greiner et al., PRL **35**, 152 (1975)

Two-nucleon position correlations

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 **82**, 044616 (2010)

Two-nucleon correlations

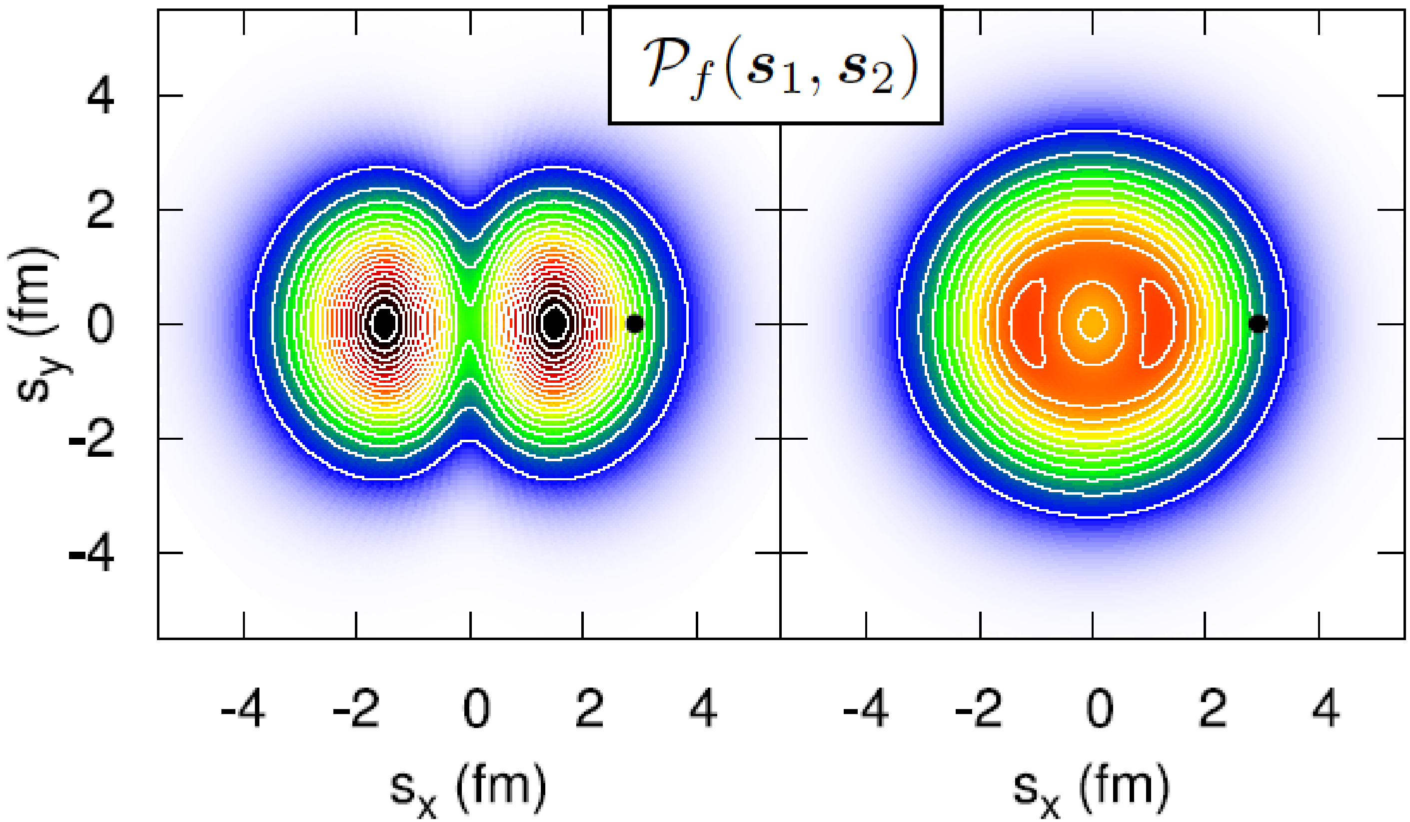


FIG. 4: Impact parameter plane-projected joint position probabilities for the first (left) and second (right) $T = 0$ $^{10}\text{B}(1^+)$ states populated via np knockout from ^{12}C.

E.C. Simpson, JAT, PRC **82**, 044616 (2010)

np-removal – specific predictions

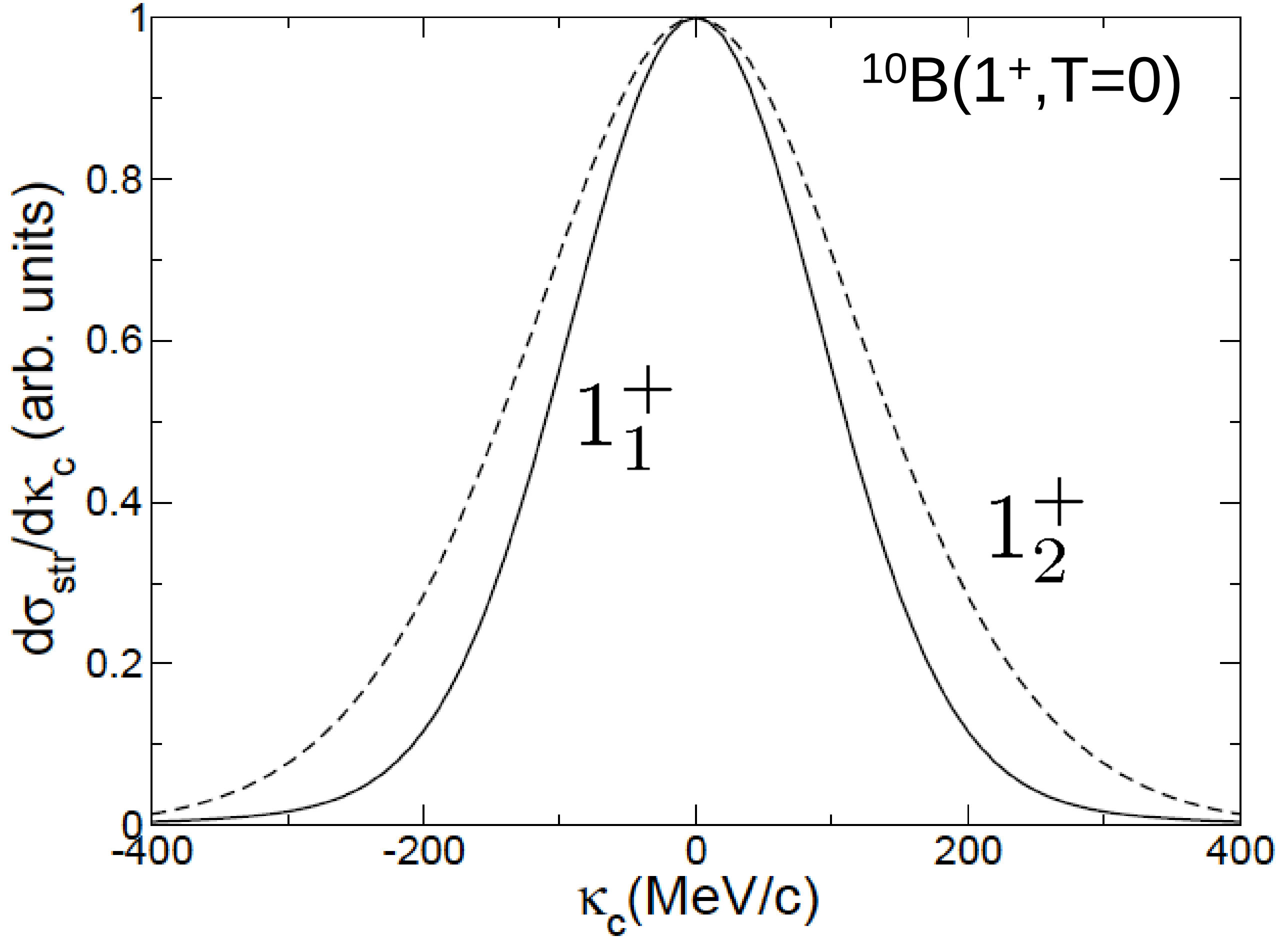


FIG. 3: Normalized residue momentum distributions for the first (solid) and second (dashed) ^{10}B(J_f=1$^+$) states populated in np knockout from ^{12}C at 2100 MeV per nucleon.

E.C. Simpson, JAT, PRC **82**, 044616 (2010)

Testing the T=0 wave function at A=12