Perspectives and limitations of 2p and 2n knockout reactions

1st Int.Workshop on Quasi-free Scattering with Radioactive Ion Beams, ECT* Trento, 7-11 April 2008

Jeff Tostevin, Department of Physics
Faculty of Engineering and Physical Sciences
University of Surrey, United Kingdom

Acknowledge the ongoing (growing) collaboration

NSCL National Superconducting Cyclotron Laboratory at Michigan State University

P. Adrich
D. Bazin
B.A. Brown
C.M. Campbell
J.M. Cook
D.-C. Dinca
A. Gade
T. Glasmacher
P.G. Hansen
S. McDaniel
W.F. Mueller
A. Obertelli
K.P. Siwek
B.M. Sherrill
J.R. Terry
D. Weisshaar
K. Yoneda
H. Zwahlen

NSCL

University of Surrey

J.A. Tostevin
E.C. Simpson

東京大學

T. Otsuka

JAEA

Y. Utsuno

Towards 2N spectroscopy of rare isotope beams

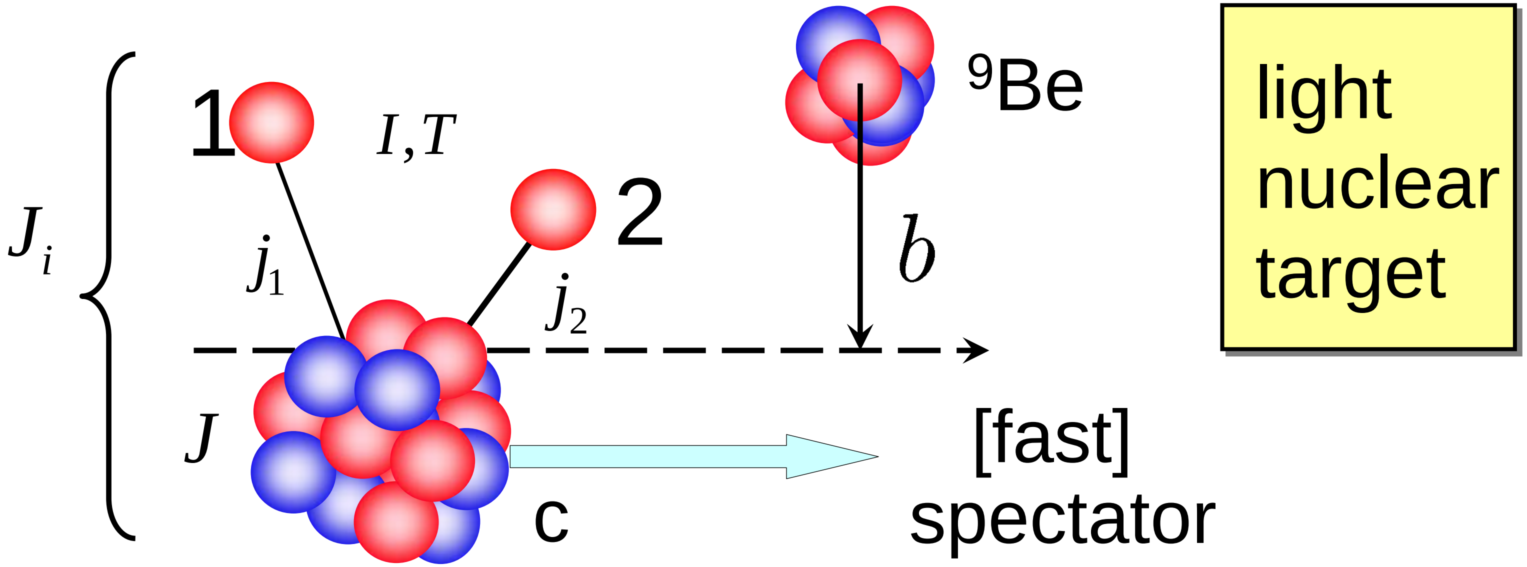
Outline

Knockout mechanism: (i) Sudden two nucleon (2N) removal from fast fragmentation beams, (ii) the ‘parameter selection’ scheme – where input as taken/guided by theory, (iii) recent results and status check, (iv) limitations – but still early days.

Interest: (i) assessing shell model wave functions and interactions, (ii) shell gaps & 2N correlations, as revealed by inclusive and partial cross sections, -2N momentum distributions

UNIVERSITY OF SURREY

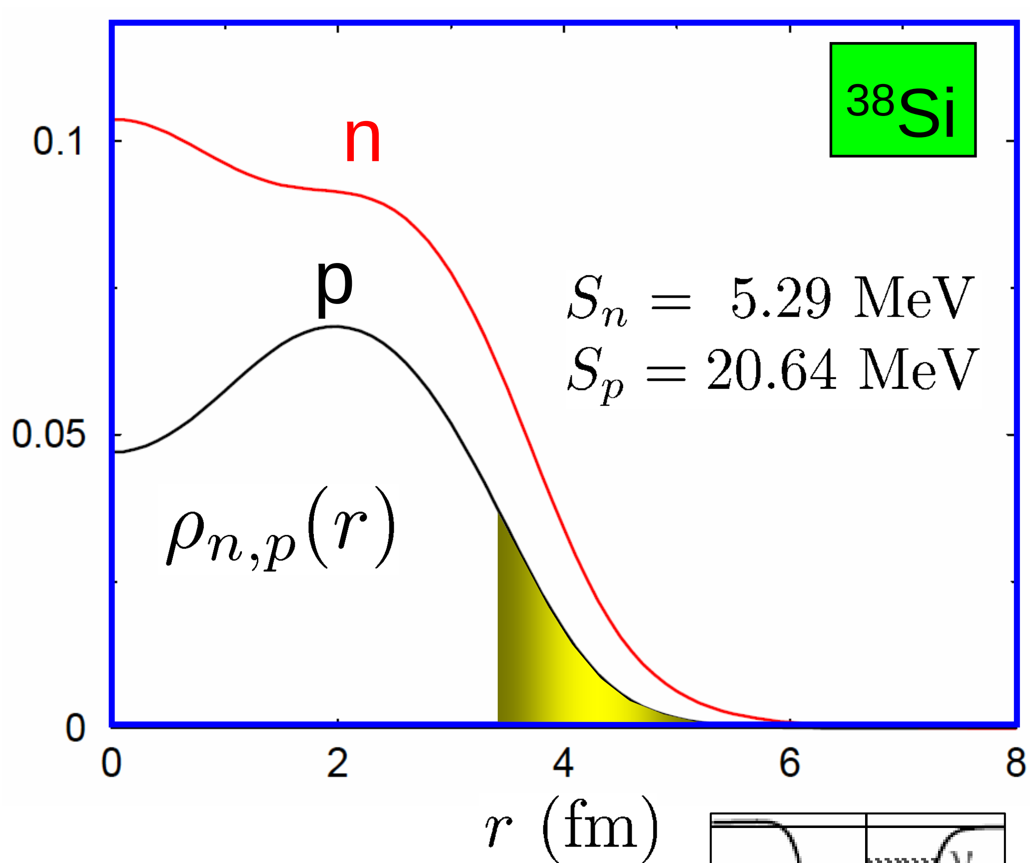
2N removal at beam energies > 100 MeV/nucleon



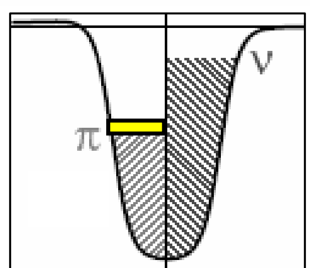
Experiments are inclusive (with respect to the target final states). Residue final state measured – using gamma rays, whenever possible – and momenta ($p_{//}$) of the residues.

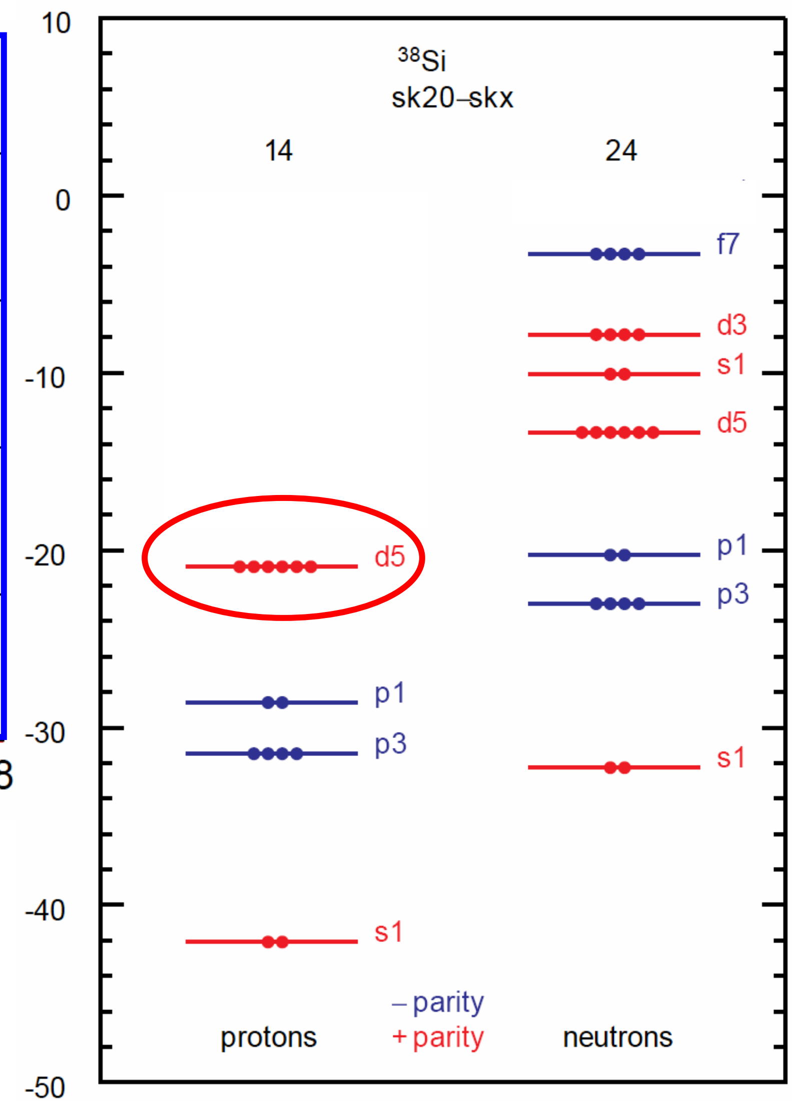
Cross sections are large and they include both:
Stripping (inelastic/absorptive) and diffractive (elastic) interactions of the removed nucleon(s) with the target

2N removal – removal of deficient species - direct

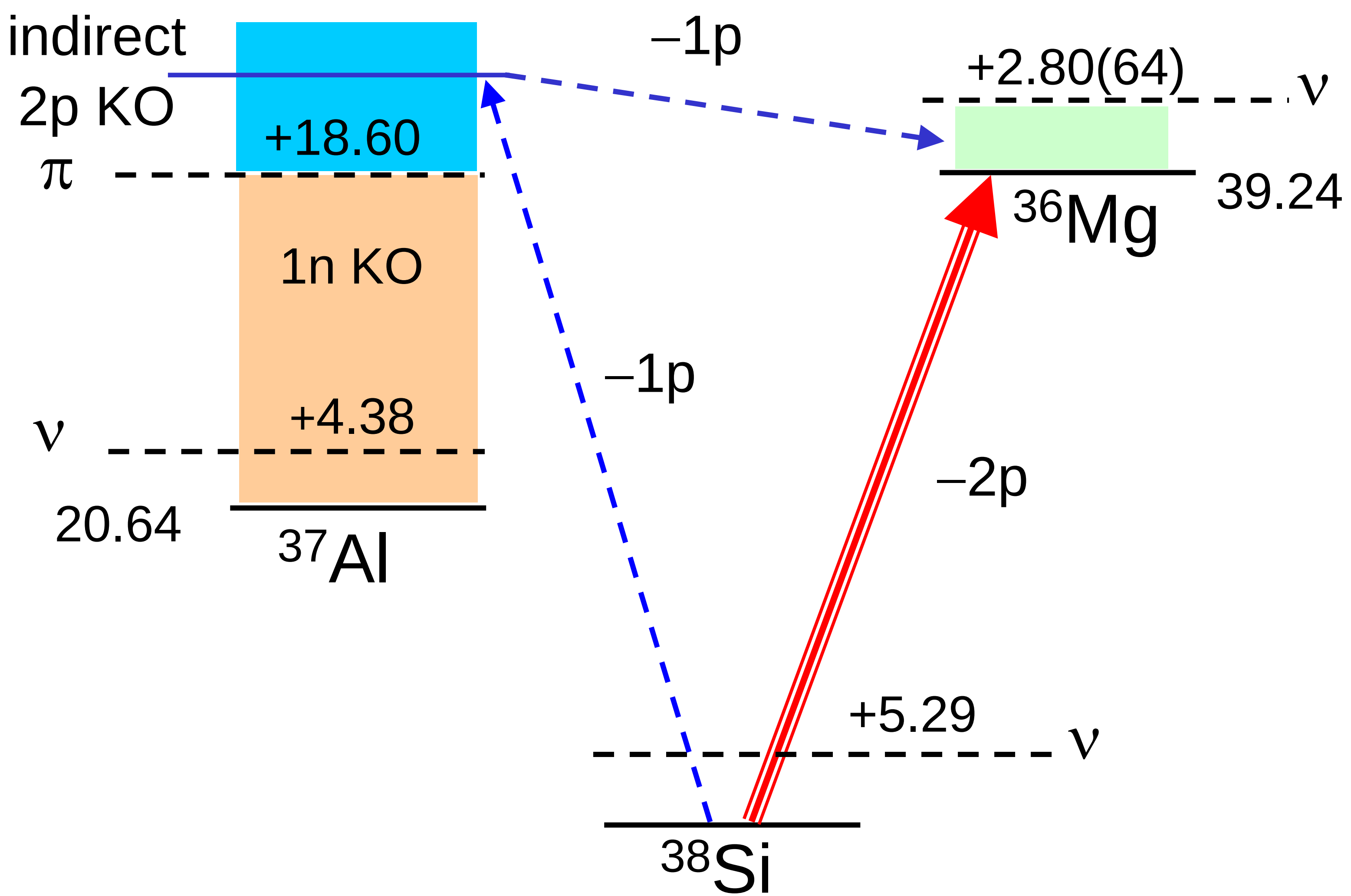


Spherical Hartree
Fock density (SkX)

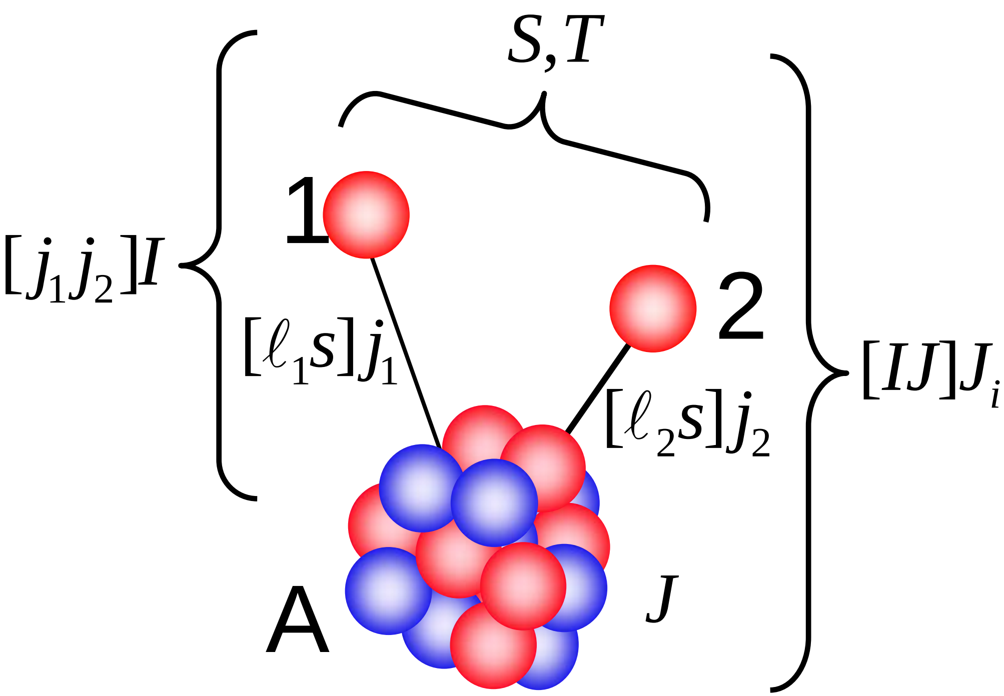




Energetics: 2p knockout: $^{38}Si \rightarrow {}^{36}Mg$



Sudden removal from the residue as a spectator

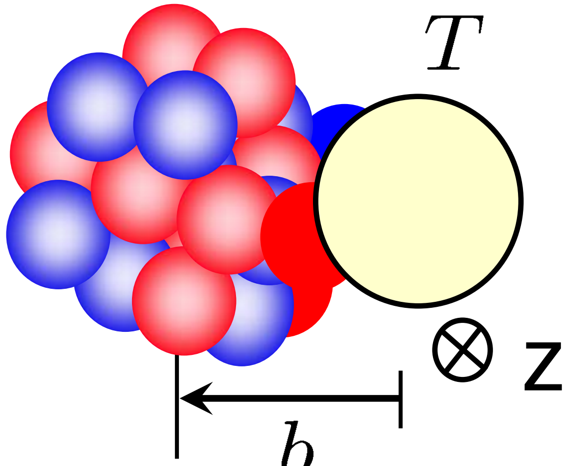


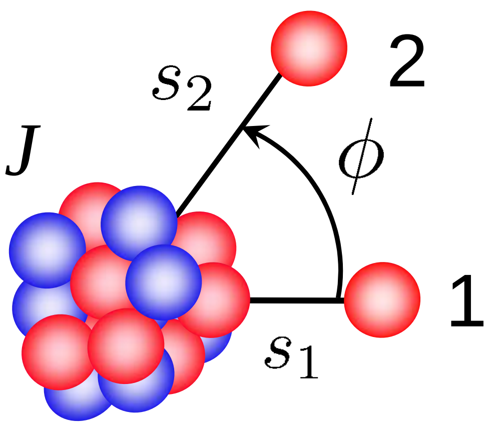
Core/residue state is assumed a spectator – so reaction probes the two nucleon overlap and (in general) there are several coherent active 2N configurations – overlap determined by the two nucleon amplitudes (TNA)

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

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

Target drills out a cylindrical volume at the surface





(i) Cross section will be sensitive to the spatial correlations of pairs of nucleons near surface

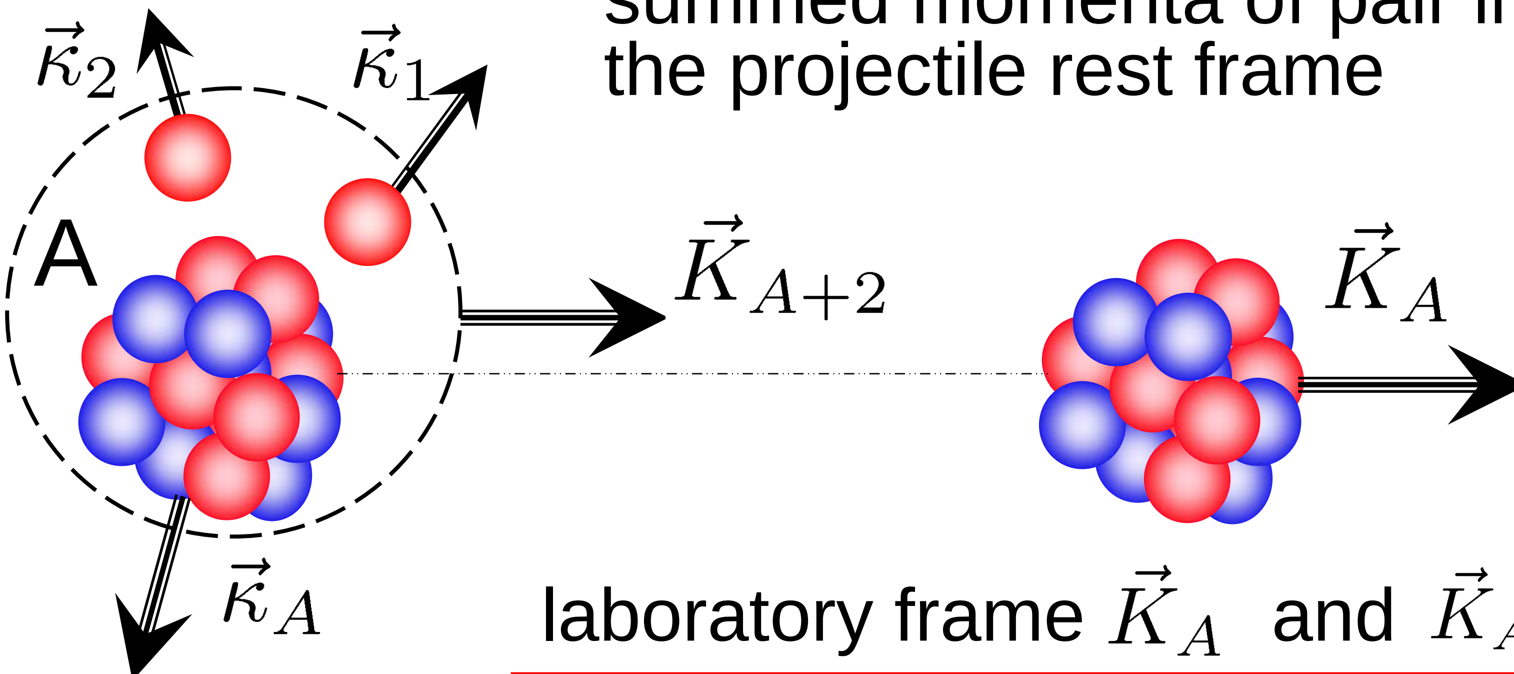
(ii) No spin selection rule (for S=0 versus S=1 pairs). Reaction mechanism

(iii) We can gain first expectation of the extent to which we are sensitive to correlations by looking at the 2N overlaps in this sampled volume

$$P_J(\vec{s}_1,\vec{s}_2) = \sum_M \int dz_1 \int dz_2 \langle F_{JM}(1,2)|F_{JM}(1,2)\rangle_{sp}$$

Sudden 2N removal from the mass A residue

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



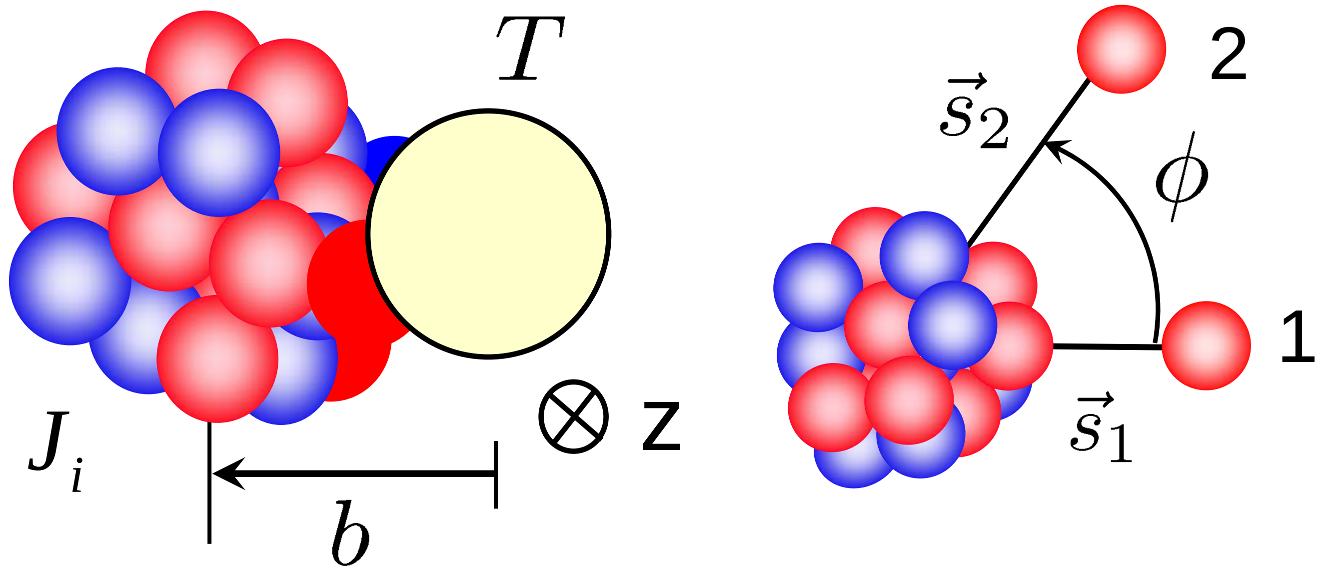
Projectile rest frame

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

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

and component equations

Look at momentum content of sampled volume



Probability of a residue with parallel momentum κ_A

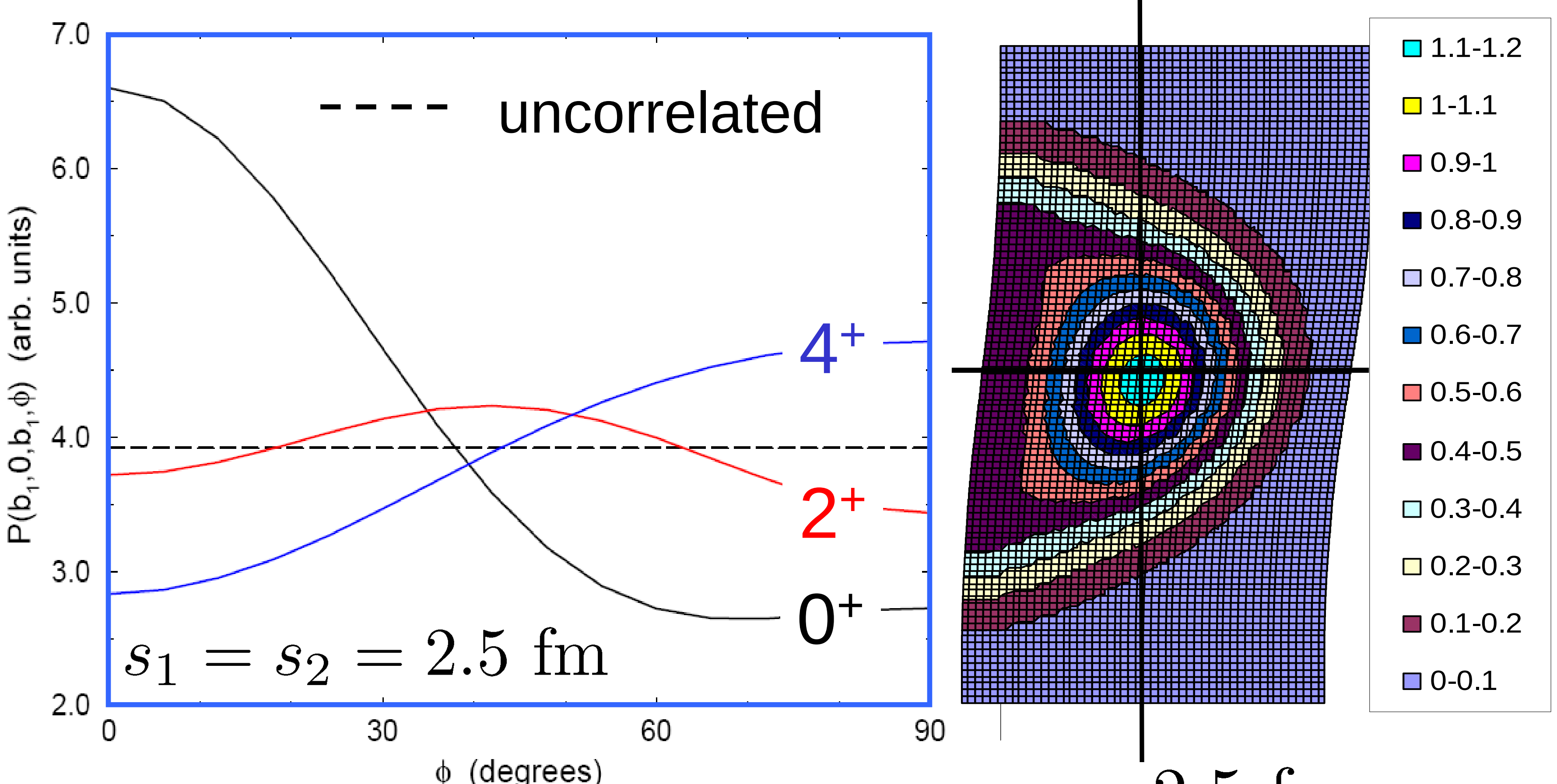
$$P(\kappa_A,\vec{s}_1,\vec{s}_2) = \sum_M \Big\langle \int d\kappa_1 \int d\kappa_2\ \delta(\kappa_A+\kappa_1+\kappa_2) \times \left| \int dz_1 \int dz_2\, e^{i\kappa_1 z_1} e^{i\kappa_2 z_2} F_{JM}(1,2) \right|^2 \Big\rangle_{sp}$$

J. A. Tostevin, EPJ Special Topics **150**, 67 (2007) [RNB7 Proceedings]

Antisymmetrized ^{28}Mg → ^{26}Ne removal of $\pi[1d_{5/2}]^2$

$$F_{JM} \propto [\overline{\phi_j \otimes \phi_j}]_{J-M}$$

$$P(\vec{s}_1, \vec{s}_2) \quad 0^+$$

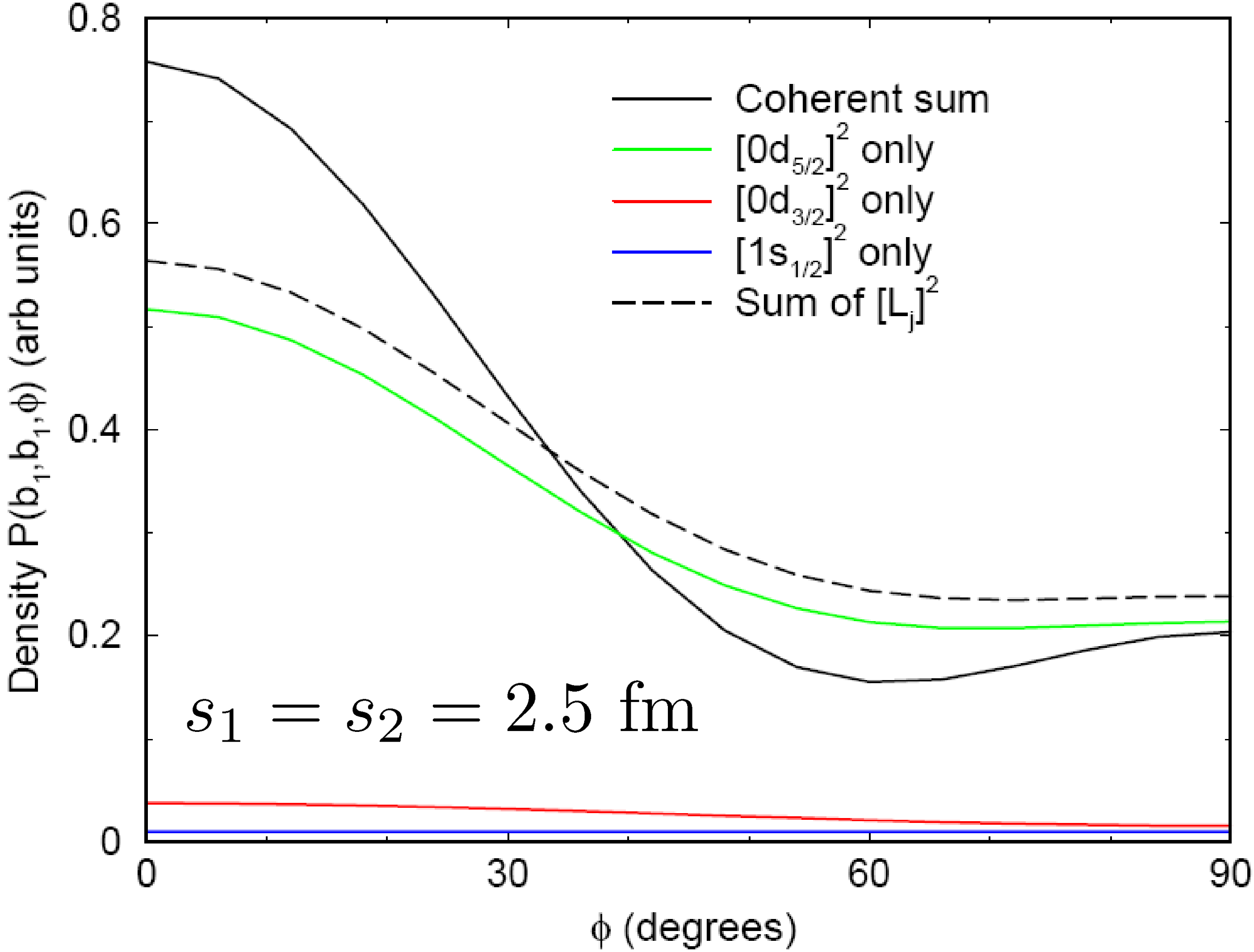


$$s_1 = 2.5 \text{ fm}$$

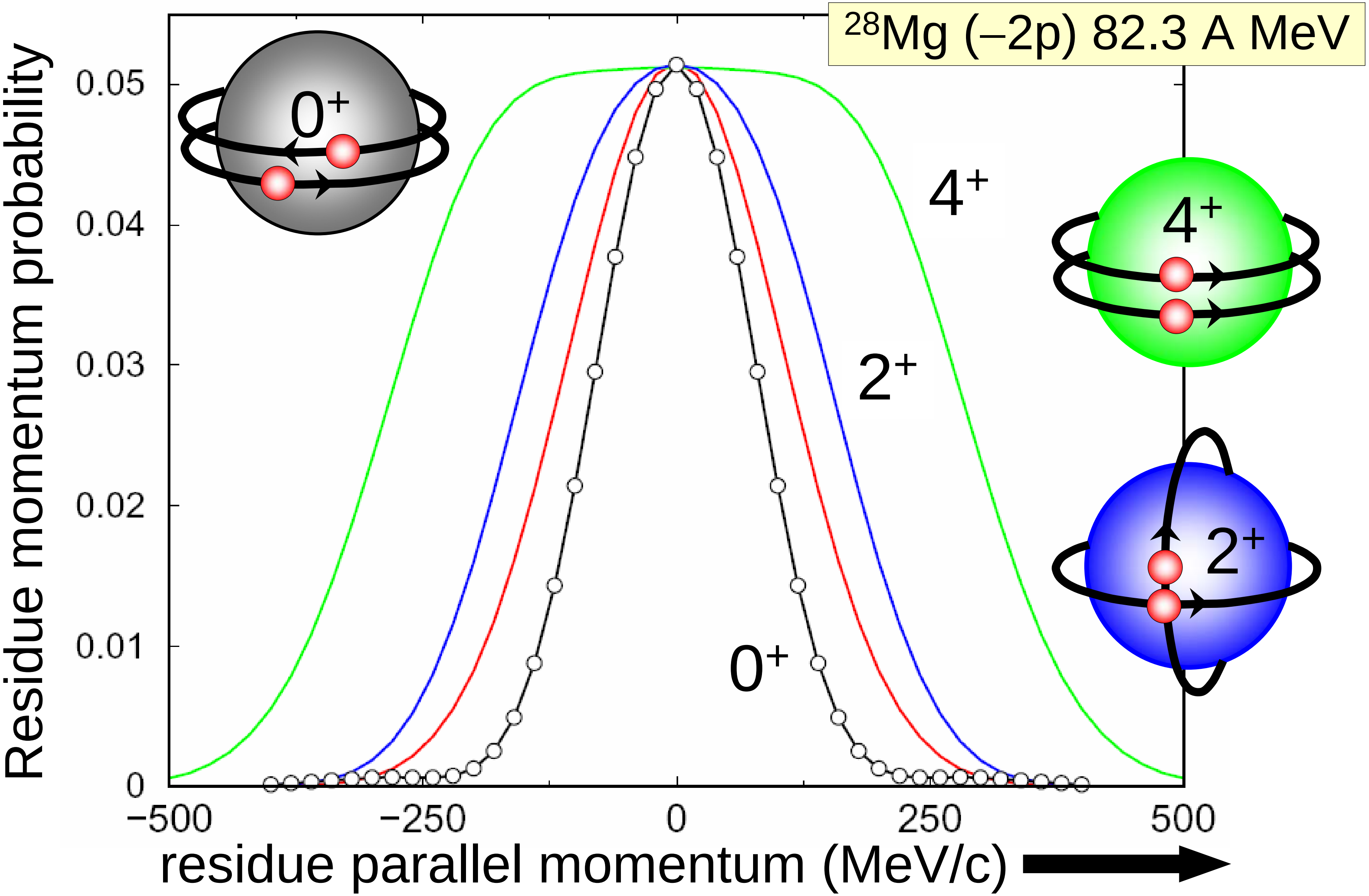
J.A. Tostevin, SENUF 06, JPG Conference series 2006

Coherence of shell model correlations

^{28}Mg (Z=12, N =16) → ^{26}Ne(0+)

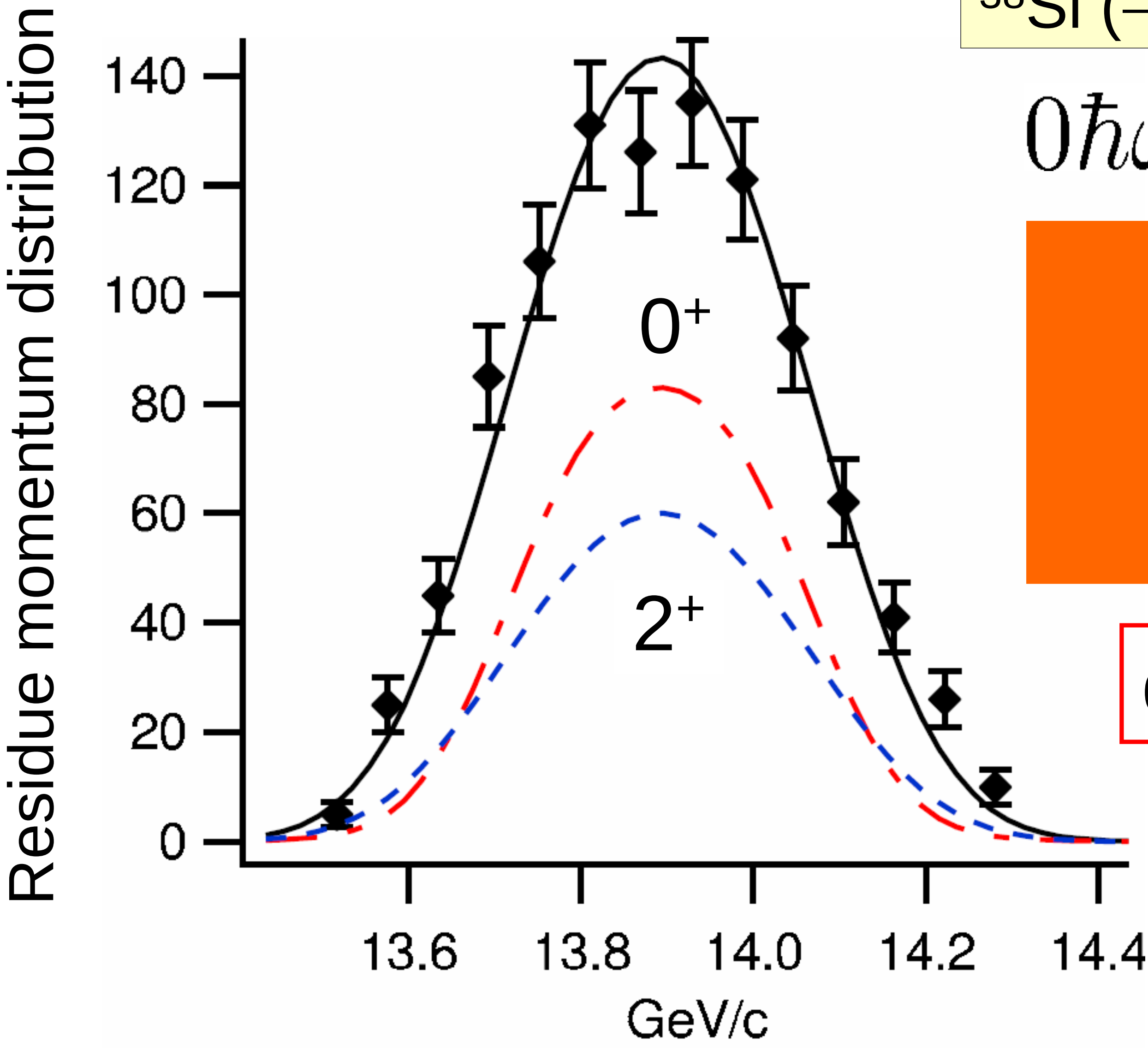


Two nucleon KO –J-dependence of $p_{//}$



Two proton knockout from $^{38}Si \rightarrow ^{36}Mg(0^+,2^+)$

^{38}Si (–2p) 83 A MeV

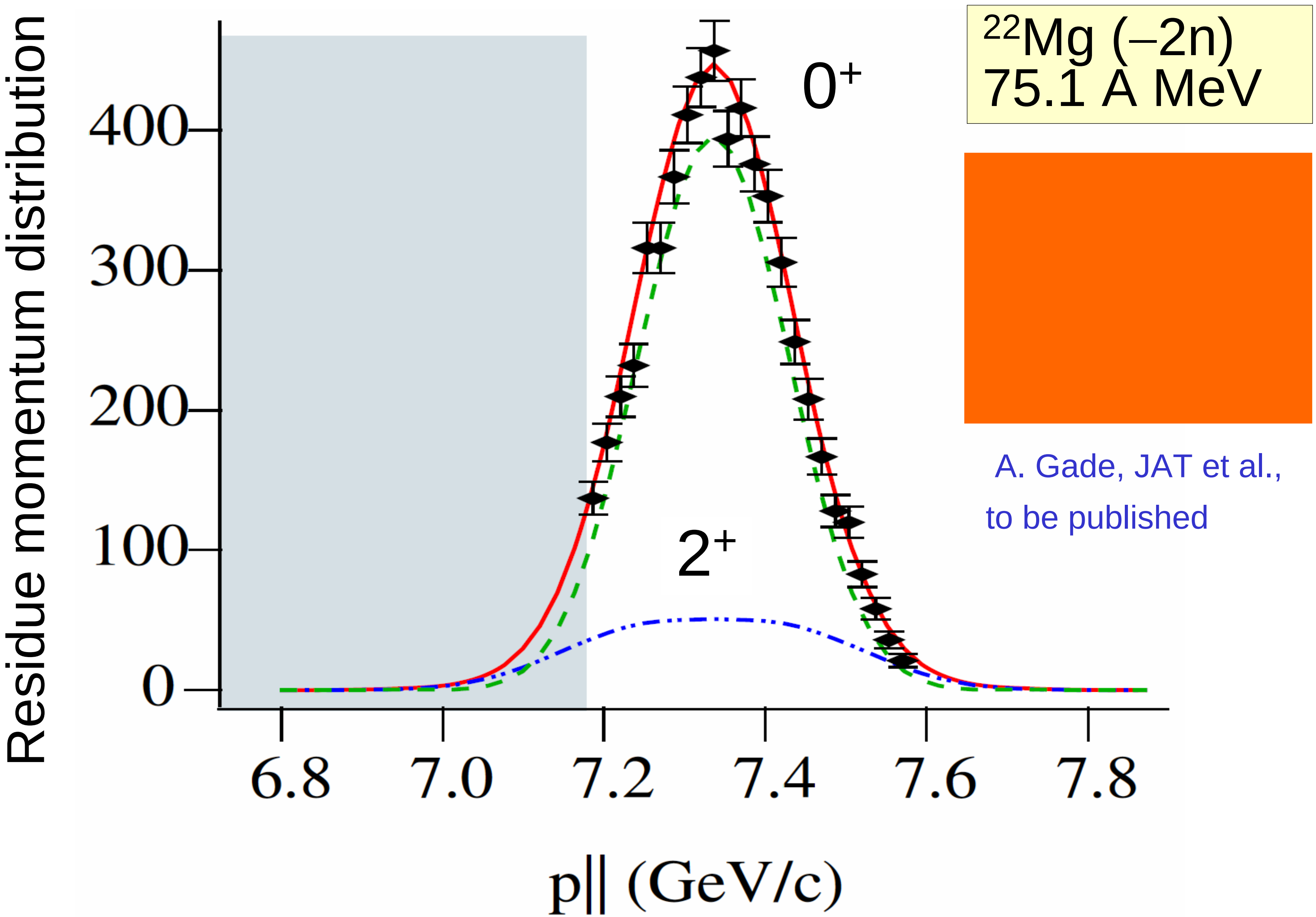


$0\hbar\omega$

dp/p=1.66%

A. Gade, JAT et al.,
to be published

Two neutron knockout from ^{22}Mg → ^{20}Mg(0^+,2^+)



A. Gade, JAT et al., to be published

Now include all 2N absorption mechanisms

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

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

<u>core survival</u>

and nucleon

" removal "

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

2N stripping

$$\left.\begin{aligned} &+ \quad |S_c|^2 |S_1|^2 (1 - |S_2|^2) \\ &+ \quad |S_c|^2 (1 - |S_1|^2) |S_2|^2 \end{aligned}\right\}$$

1N stripped

1N diffracted

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

The diffractive/stripping contributions

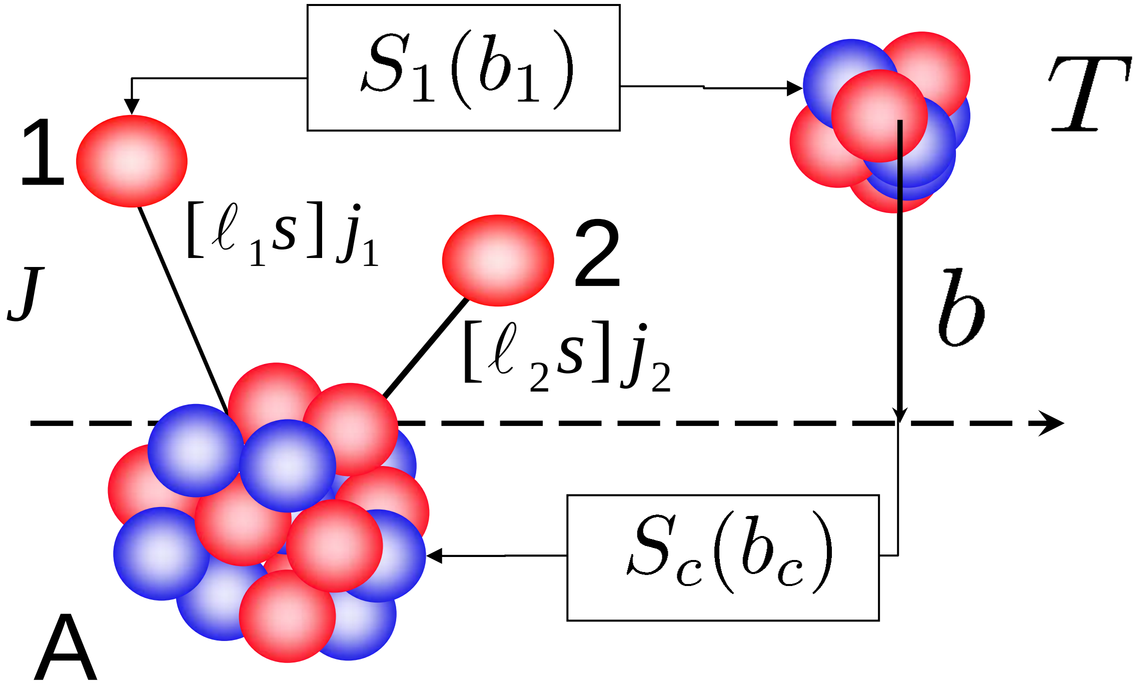
$$\sigma_2 \rightarrow |S_c|^2 |S_1|^2 \underbrace{(1 - |S_2|^2)}_{\text{nucleon 2 absorbed}}$$

nucleon 1 survives, but can be ~~bound~~ to c or unbound ✓

$$|S_1|^2 = S_1^* \left[\underbrace{\left(1 - \sum_{\text{bound}} |\alpha\rangle\langle\alpha|\right)}_{} + \underbrace{\cancel{\sum_{\text{bound}} |\alpha\rangle\langle\alpha|}}_{} \right] S_1$$

nucleon 1: (1+c) unbound (1+c) bound

Sudden removal – eikonal model cross sections

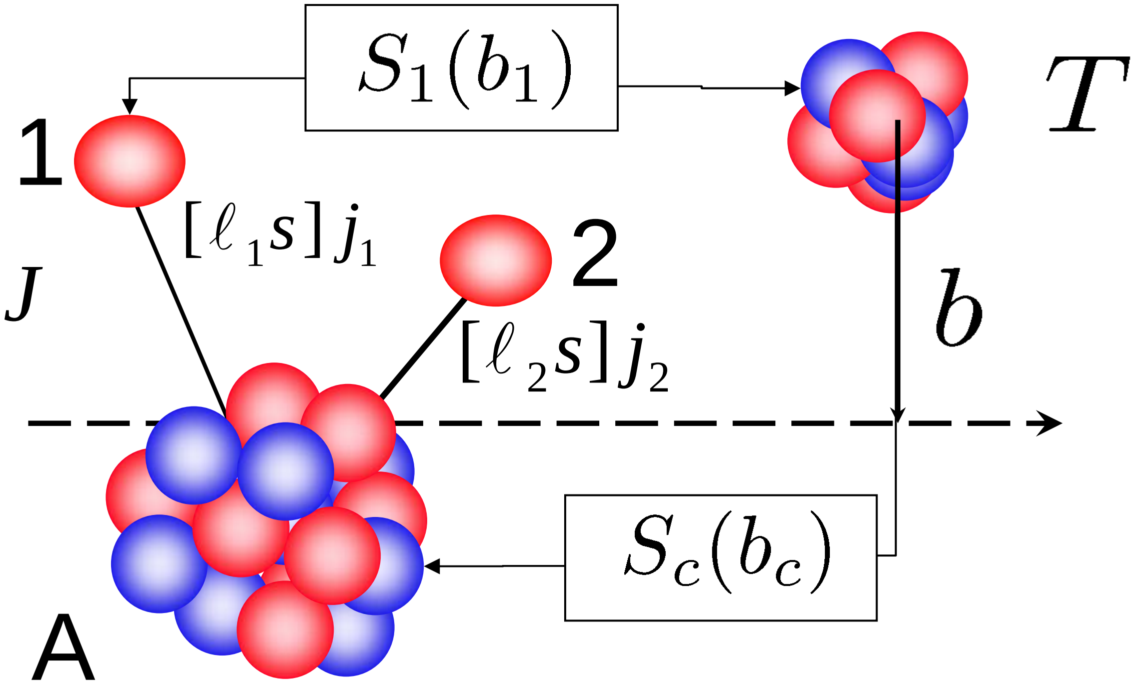


$$\sigma = \frac{1}{2J+1} \sum_M \int d\vec{b} \langle F_{JM} | \hat{O}(c,1,2) | F_{JM} \rangle$$

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

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

Sudden removal – eikonal model cross sections



At any given facility, and a programme of measurements (with essentially fixed energy per nucleon) and a given target then only two things change for different exotic beams (1) the core target interaction, (2) the nuclear structure ***

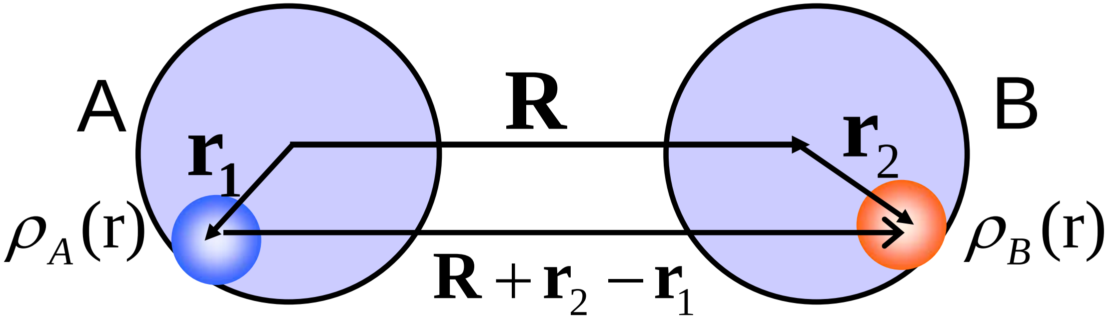
J.A. Tostevin, G. Podolyák *et al.*, PRC **70** (2004) 064602.

Effective interactions – Folding models

Double folding

V_{cT}

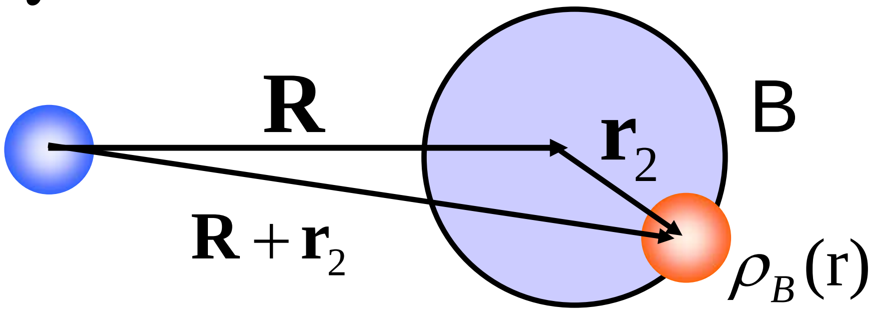
$$V_{AB}(R) = \int d\mathbf{r}_1 \int d\mathbf{r}_2\ \rho_A(r_1)\,\rho_B(r_2)\, t_{NN}(\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1)$$



Single folding

V_{vT}

$$V_B(R) = \int d\mathbf{r}_2\ \rho_B(r_2)\, t_{NN}(\mathbf{R}+\mathbf{r}_2)$$



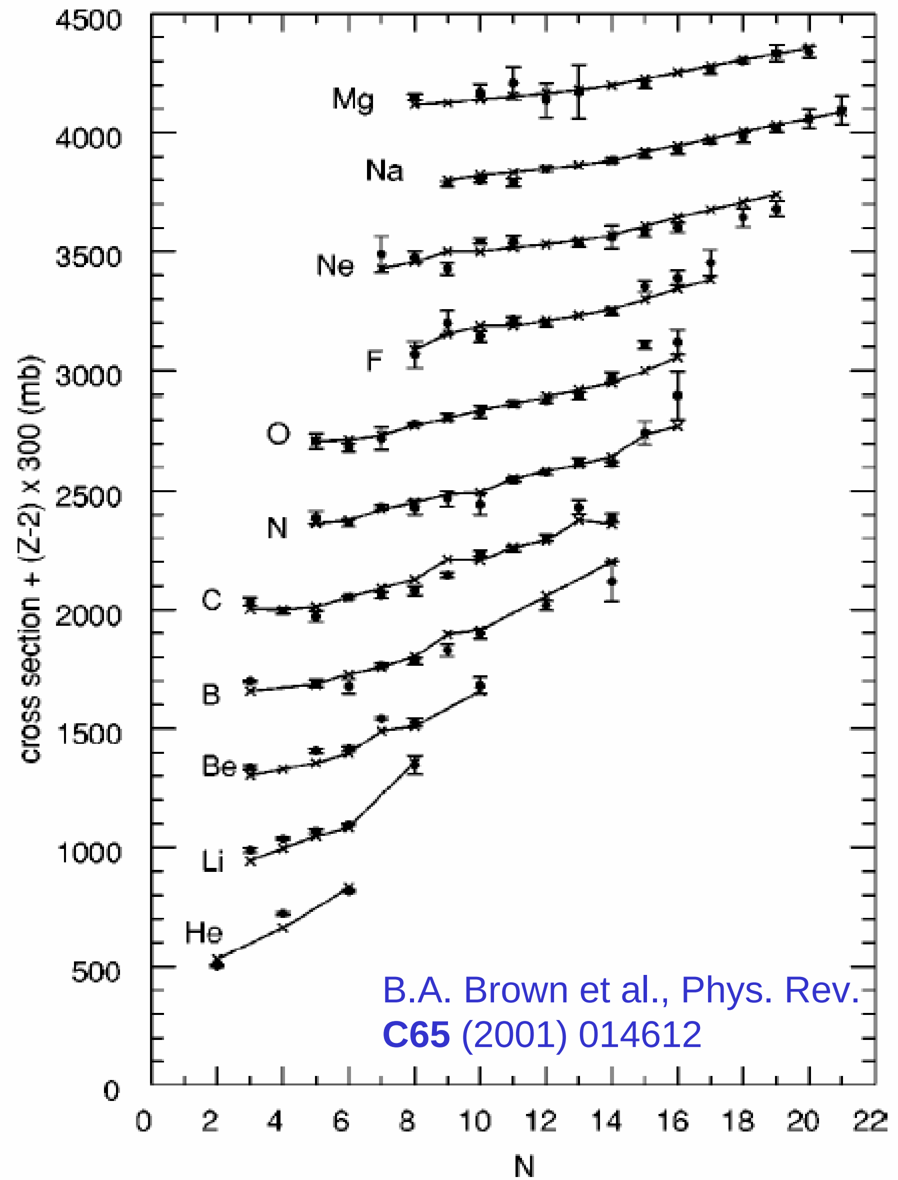
Glauber limit: $t_{np} = \sigma_{np}[i + \alpha_{np}] f_{np}(r)/2$, etc.

Reaction description is rather robust - quantitative

Residue-target interaction is highly absorptive at >100 MeV/u with a range 'fixed' by the residue and target sizes. This is encoded within the double folding model and is cross referenced to

$$\sigma_R = 2\pi \int db[1 - |S_c(b)|^2]$$

These ion-ion interactions and their S-matrices are calculated reliably using Glauber methods – using Hartree-Fock densities.

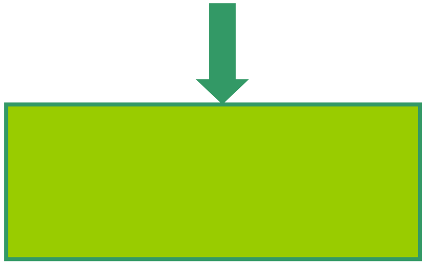


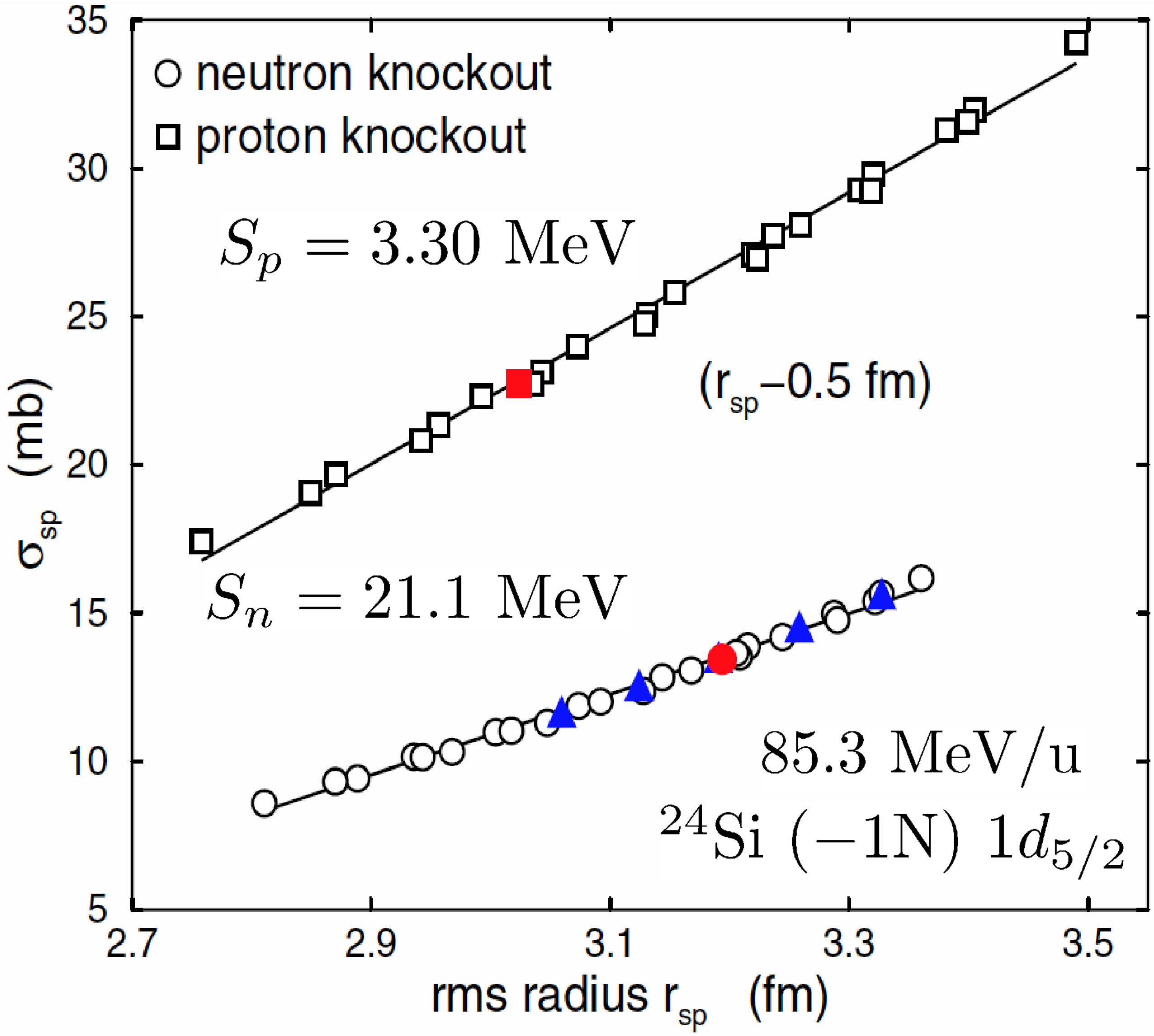
B.A. Brown et al., Phys. Rev. **C65** (2001) 014612

Overlap function sensitivity: Hartree Fock 'sizes'

Rms radii of sp formfactors are the requirement for determining the cross sections – to high precision
We constrain to Hartree-Fock values

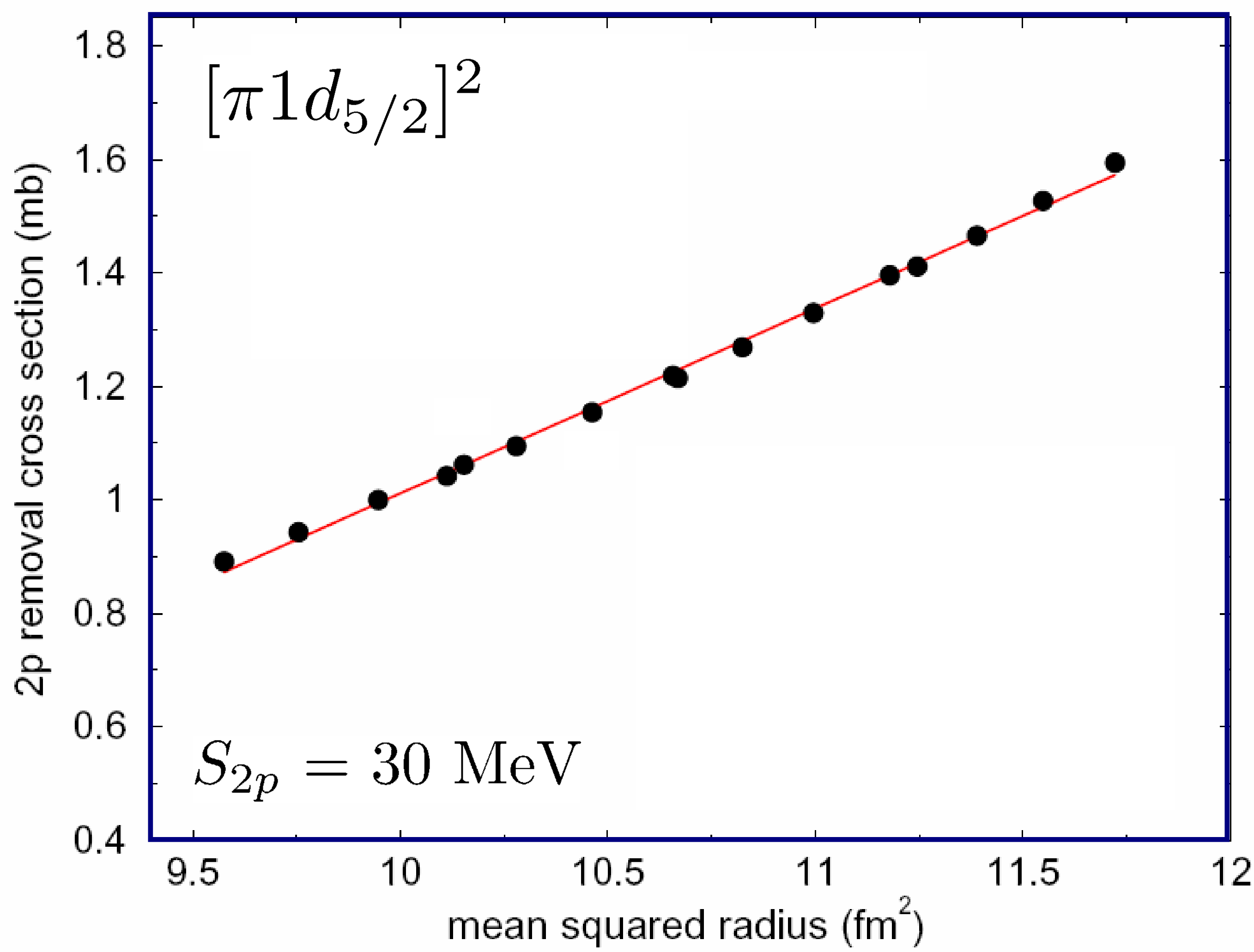
$$\sigma(r_0, a_0, V_{so}, \beta_{NL})$$





Sensitivity to s.p. orbitals – correlation with radii

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



Single particle radii – other benchmarks

Can compare sp rms radii in selected cases in the mass region under study with those used / deduced in electron scattering:
e.g. ** Kramer et al. NPA **679** 267 (2001)

$^{16}\mathrm{O}$

$* \ 2.954 \quad 2.903 \ \mathrm{fm} \ (\mathrm{HF})$

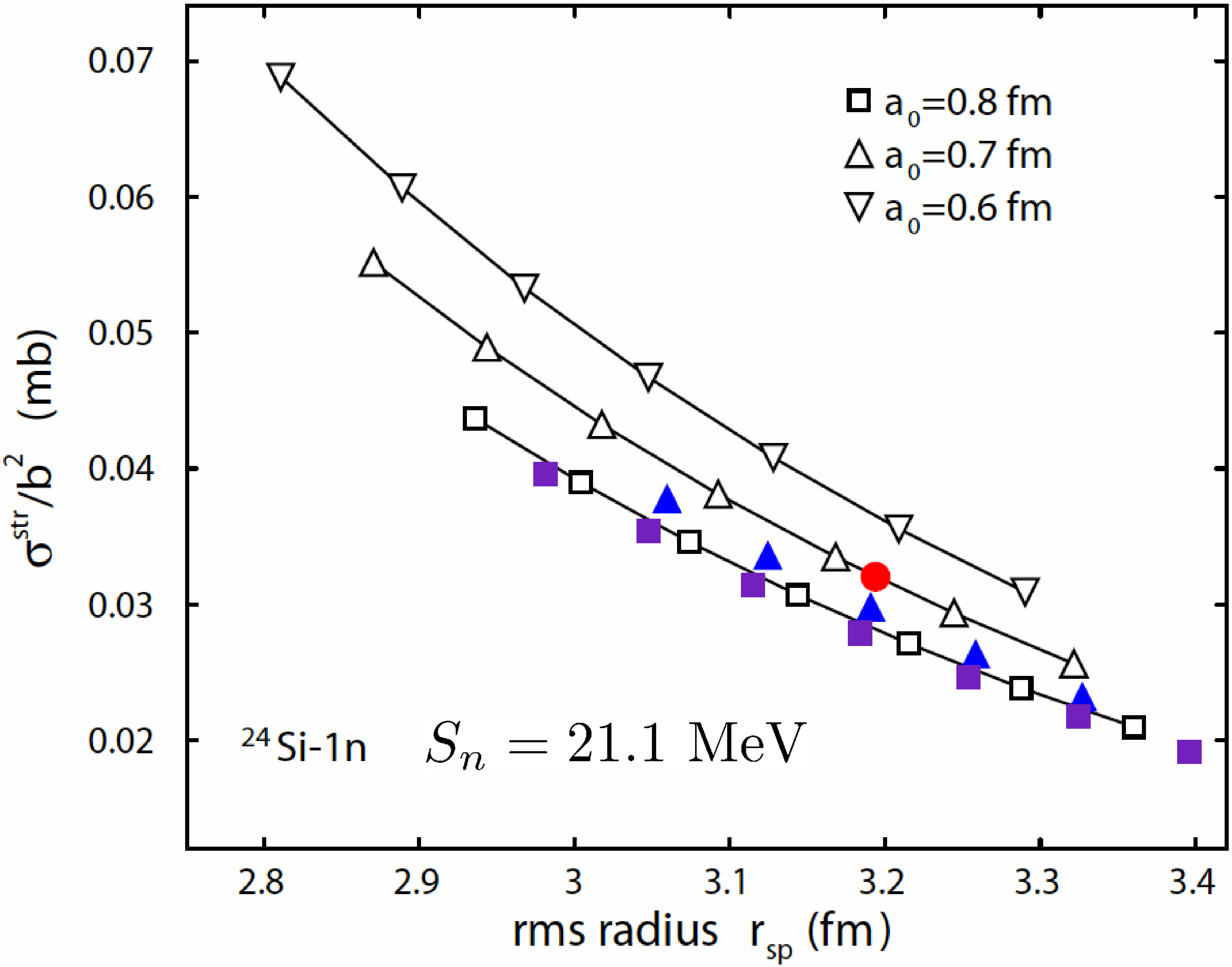
$^{40}\mathrm{Ca}$

$* \ 3.712 \quad 3.670 \ \mathrm{fm} \ (\mathrm{HF})$

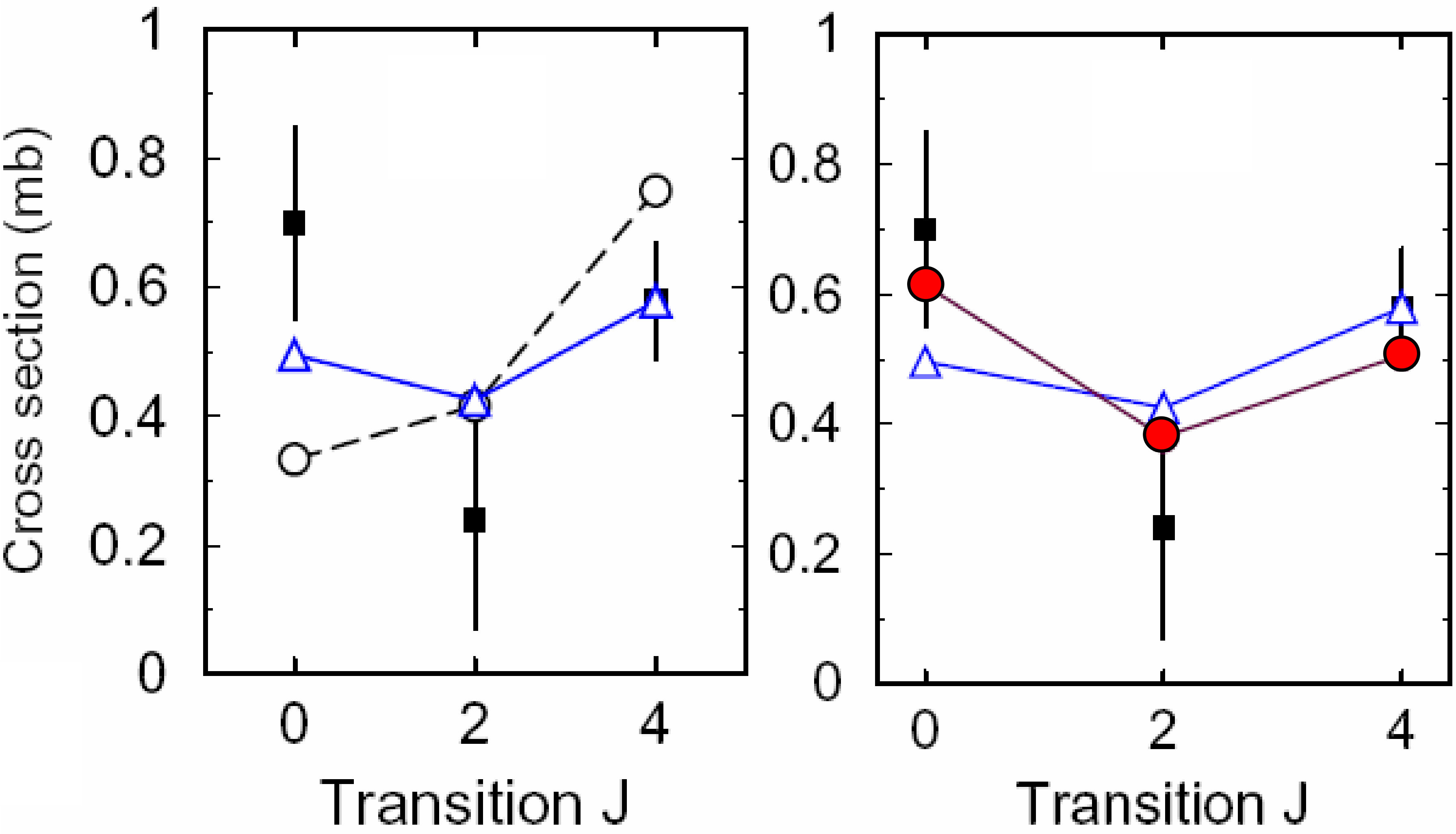
$^{48}\mathrm{Ca}$

$* \ 3.580 \quad 3.560 \ \mathrm{fm} \ (\mathrm{HF})$

Our sensitivity is not to to the ANC



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

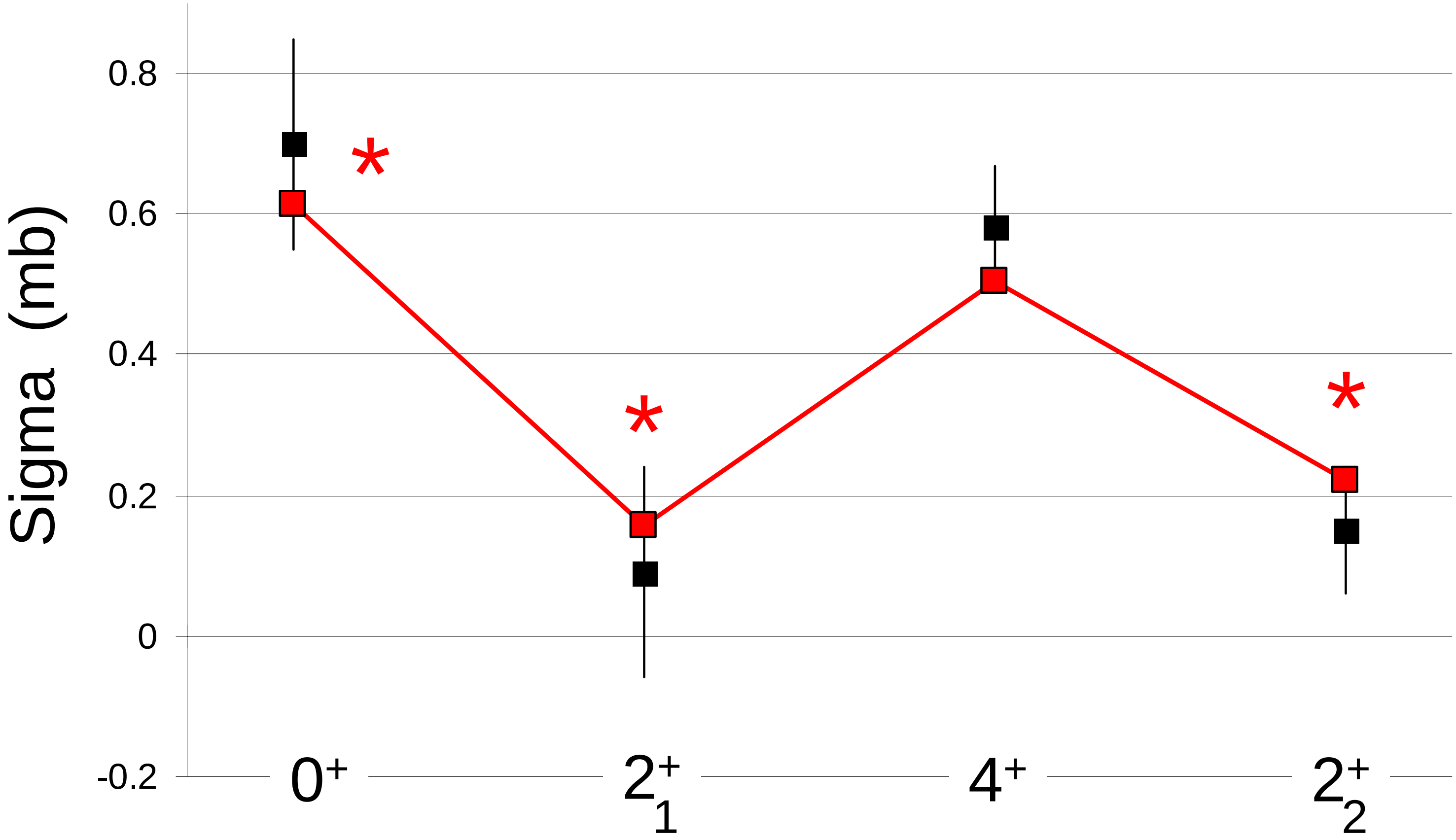


Data: D. Bazin et al., PRL **91** (2003) 012501

Knockout cross sections – correlated case

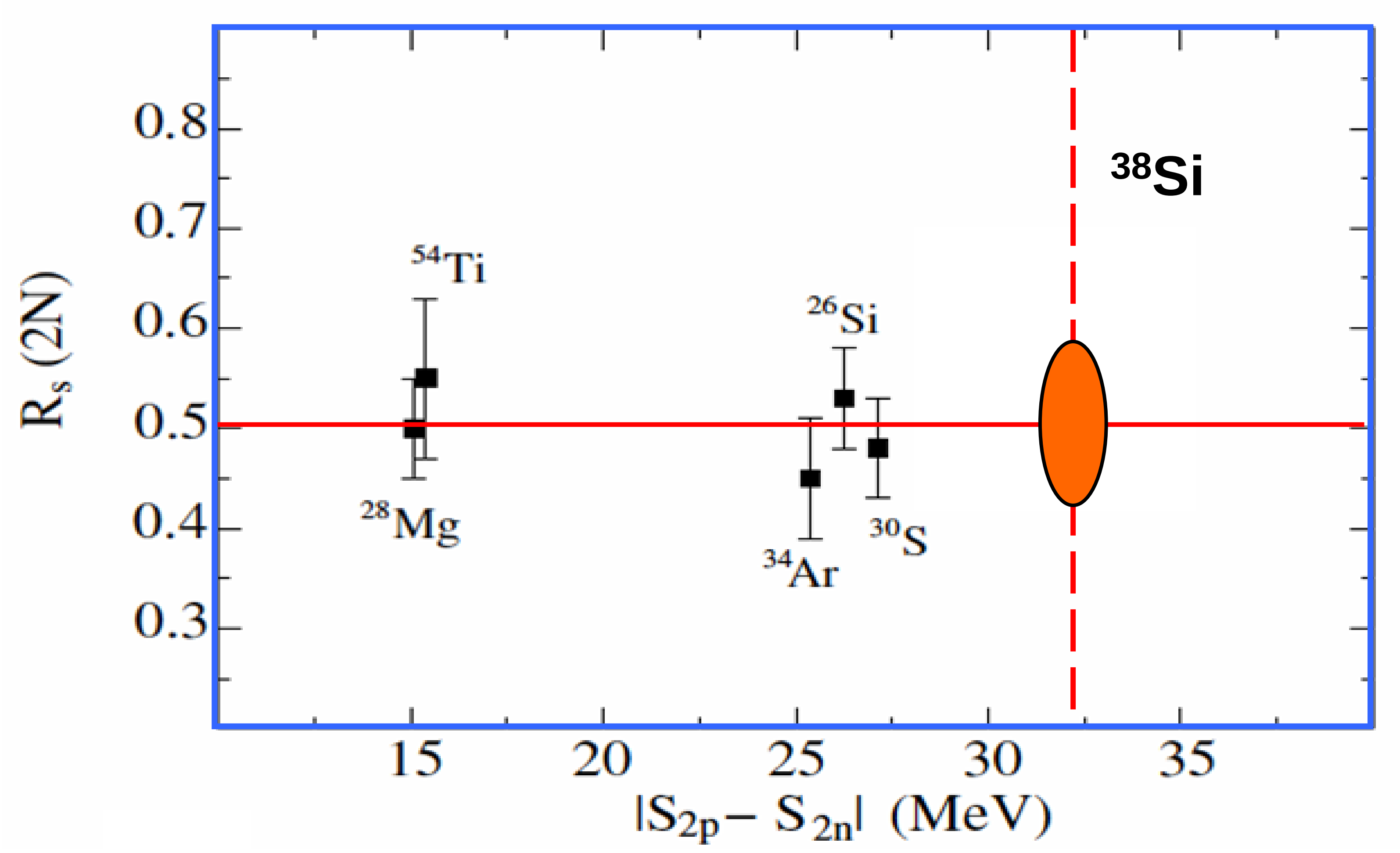
$^{28}Mg \rightarrow ^{26}Ne(0^+,\ 2^+,\ 4^+,\ 2_2^+)$ 82.3 MeV/u

$$\sigma_{inc}(-2p)=1.50(10)\ \mathrm{mb},\ \ R_s(2N)=\sigma_{\rm exp}/\sigma_{\rm th}=0.52(4)$$



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

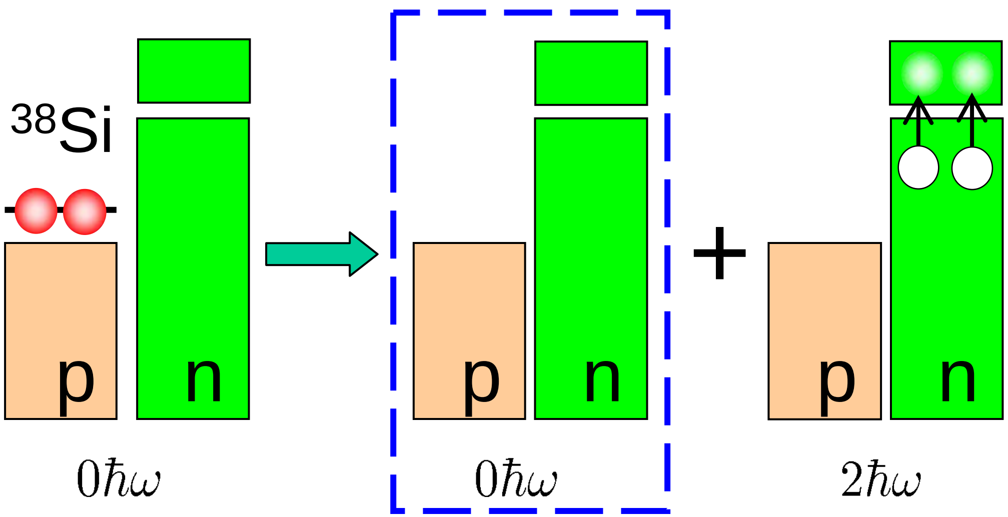
Ratio of measured to calculated cross sections

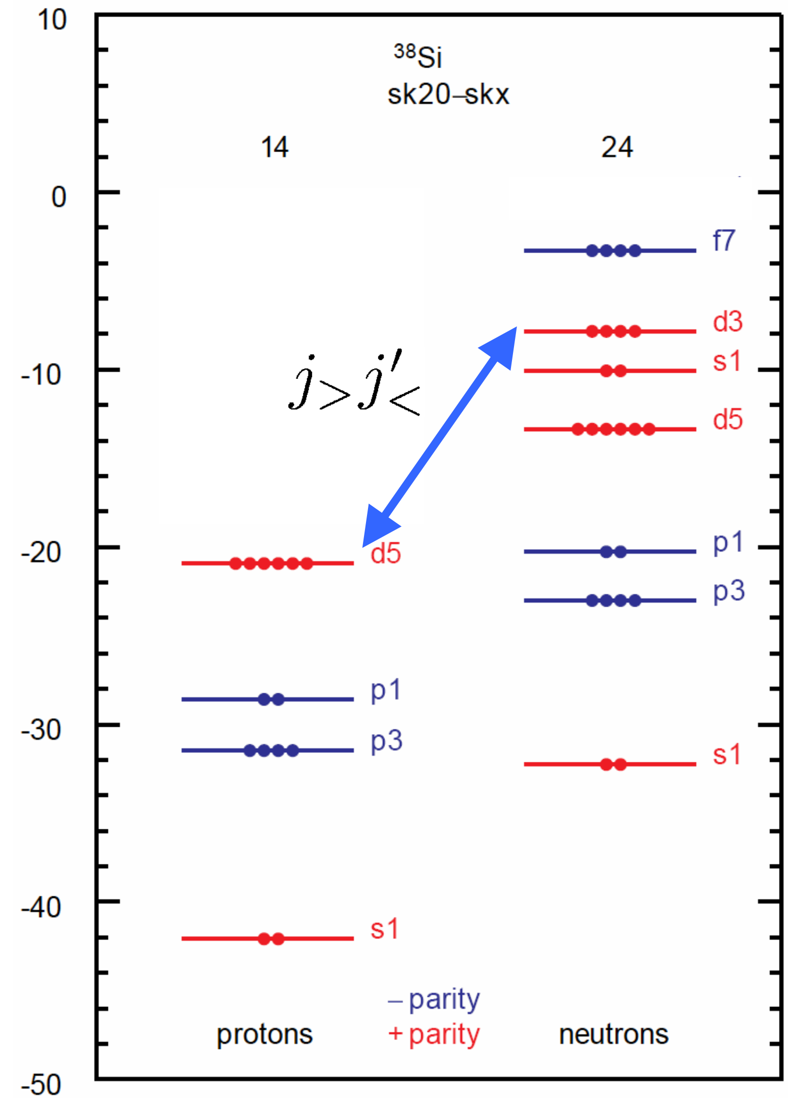


J.A. Tostevin and B.A. Brown, PRC **74** 064604 (2006), PRC **70** 064602 (2004)
Figure: A. Gade

Extent of the Island of Inversion: to ^{36}Mg?

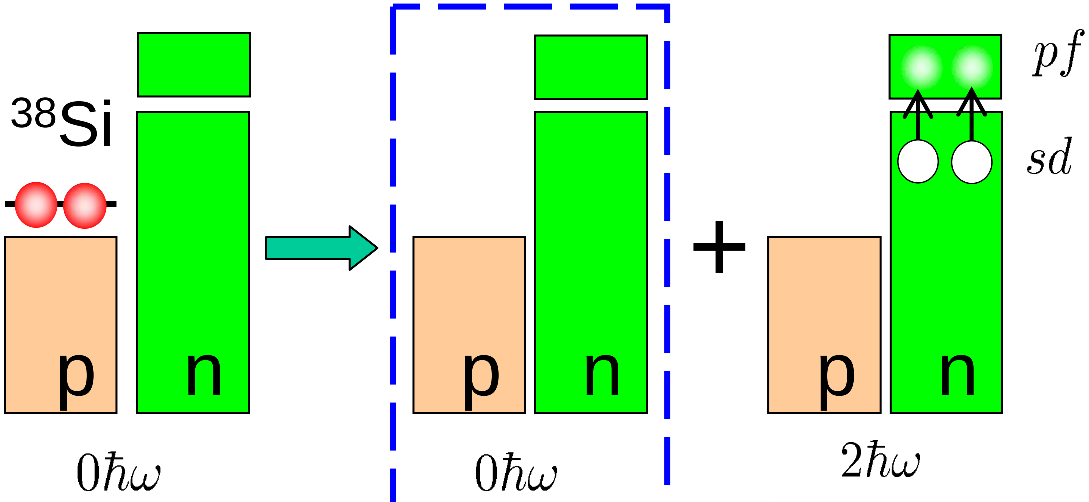
1) Insufficient yield for, e.g. secondary beam inelastic scattering
2) Parent for beta decay, ^{37}Na, is particle unbound
3) can use 2p removal from n-rich (sd-shell) parent, ^{38}Si





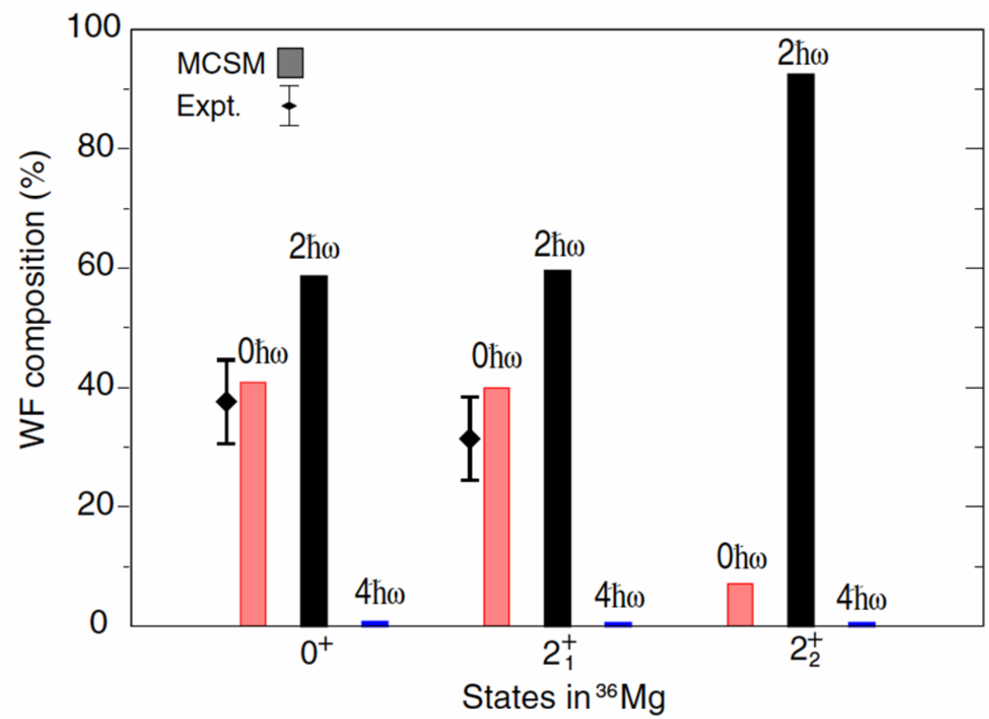
A. Gade et al, PRL **99**, 072502 (2007)

^{38}Si(-2p) to ^{36}Mg – shell model and interactions?



Monte-Carlo shell model calculations: SDPF-M interaction of Utsono, Otsuka *et al*.

Measured cross sections and those calculated assuming population of the 0hw components of the final states by the direct 2p knockout reaction mechanism



A. Gade et al, PRL **99**, 072502 (2007)

Status: we are able to

- calculate two-nucleon removal within a parameter free model – using specific shell model and systematic mean-field (spherical HF) structure information to set all important interaction and bound states ranges
- observe systematic renormalisation of (1N and) 2N strength –not yet understood quantitatively but already allows the identification of structure effects beyond these systematics
- have identified spectroscopic value of momentum distributions of -2N reactions and have a more complete calculation available