Knockout and breakup reactions

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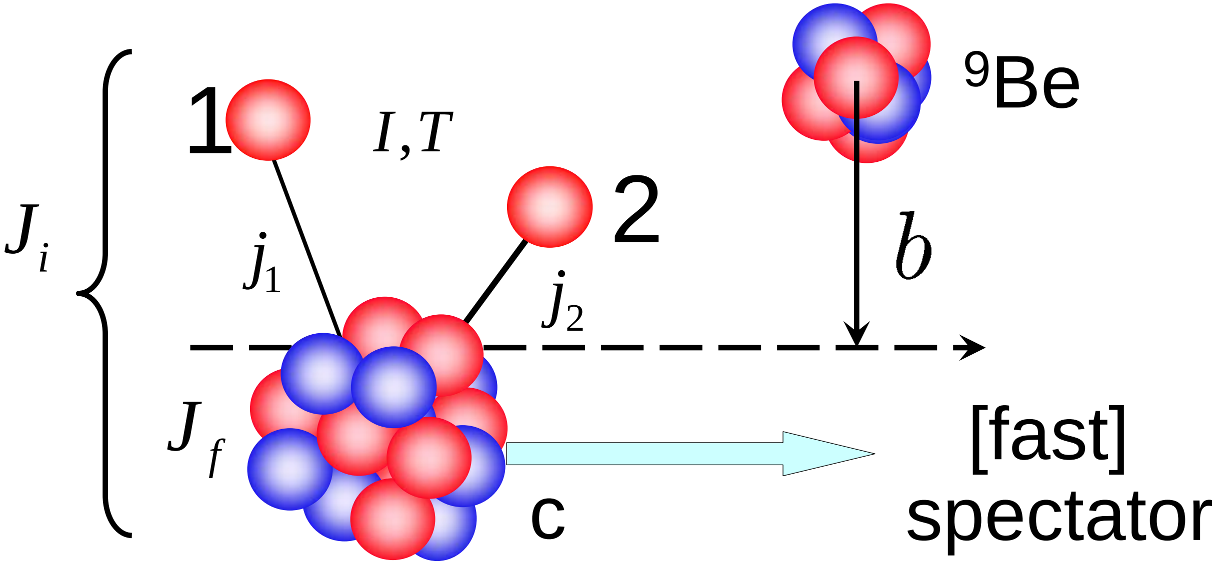
Motivation – ‘two-nucleon’ degrees of freedom

Can one observe experimentally the *correlations* of pairs of nucleons in exotic nuclei – by using suitable nuclear reactions (specifically, with fast secondary beams) ?

Will discuss the 2N knockout reaction mechanisms:
(i) specific first test cases and applications (ii) sensitivity to pair properties (iii) can these be exploited for spectroscopy of exotic systems and 2n correlations in n-rich systems?

Quenching of calculated single-particle strengths is a common feature in comparisons of structure calculations (e.g. the shell model) with experiment (an 0.7 factor in near-stable nuclei). What are the corresponding observations for 2N removal?

Nucleon removal (one and two): 70 ~ 120 A MeV



light nuclear target

Experiments are inclusive (with respect to the target final states). Core final state measured – using gamma rays – whenever possible – and also momenta of the residues c.

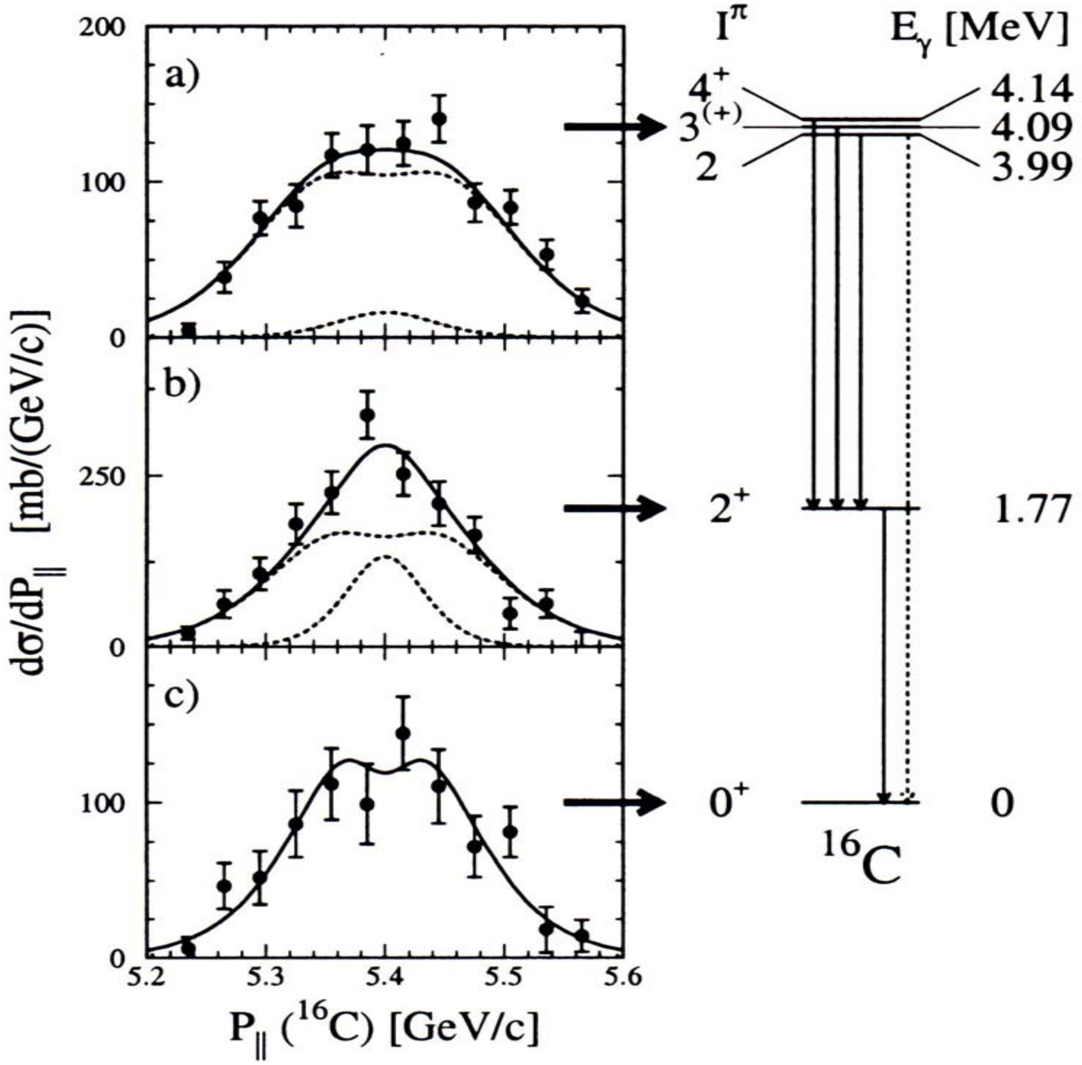
Cross sections can be large and they include both: Break-up (elastic) and stripping (inelastic/absorptive) interactions of the removed nucleon(s) with the target

Single-neutron knockout from ^{17}C

ℓ=0,2
admixture

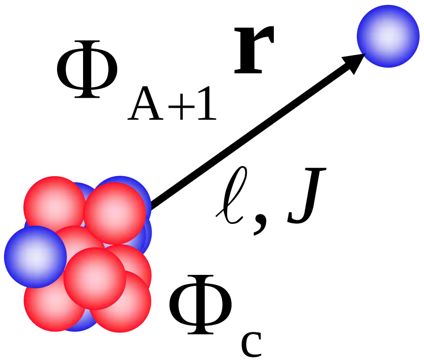
ℓ=0,2
admixture

ℓ=2
pure



V. Maddalena et al. PRC **63** (2001) 024613

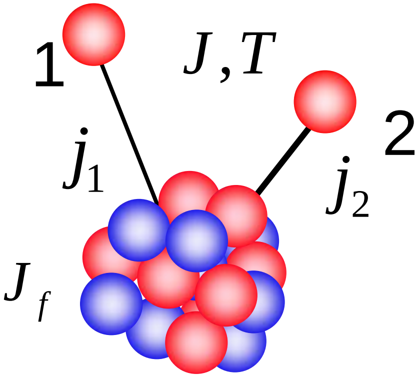
Spectroscopy: one- and two-nucleon overlaps



$$F_{JM}(\vec{r}) = \langle \vec{r}, \Phi_c | \Phi_{A+1} \rangle$$
$$S_N = E_{A+1} - E_c$$
$$F_{JM}(\vec{r}) = C(J)\phi_{JM}(\vec{r})$$

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

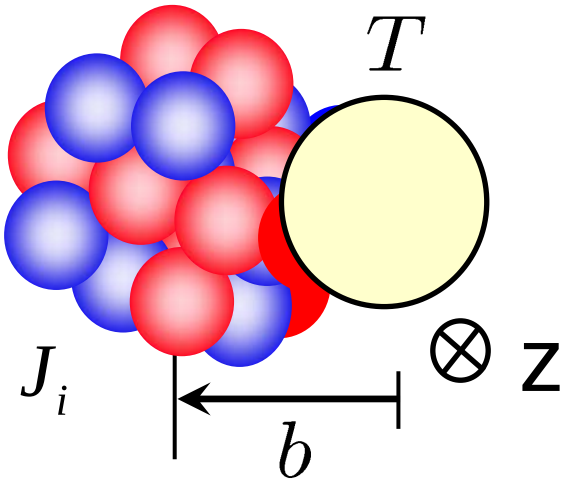
<u>Spectroscopic factor/strength</u>

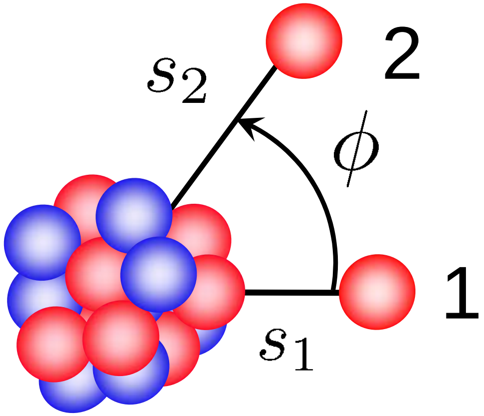


In <u>two-nucleon case</u> there are (in general) several <u>coherent</u> 2N configurations – the two-nucleon motions are <u>correlated</u>

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

Target drills out a cylindrical volume at the surface





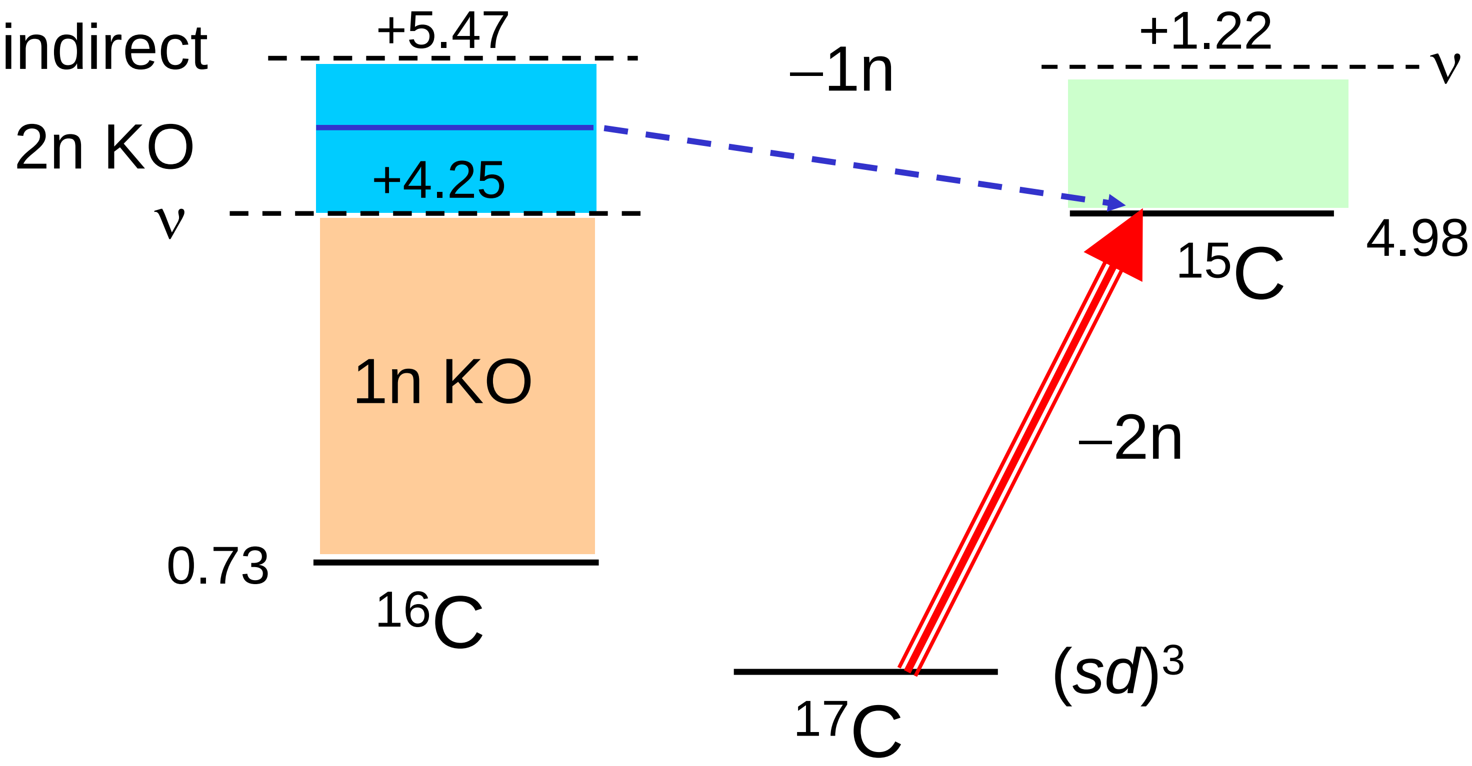
Cross section will be sensitive to the spatial correlations of pairs of nucleons near surface

No spin selection rule (for S=0 versus S=1 pairs). Reaction mechanism removes anything that is in the way

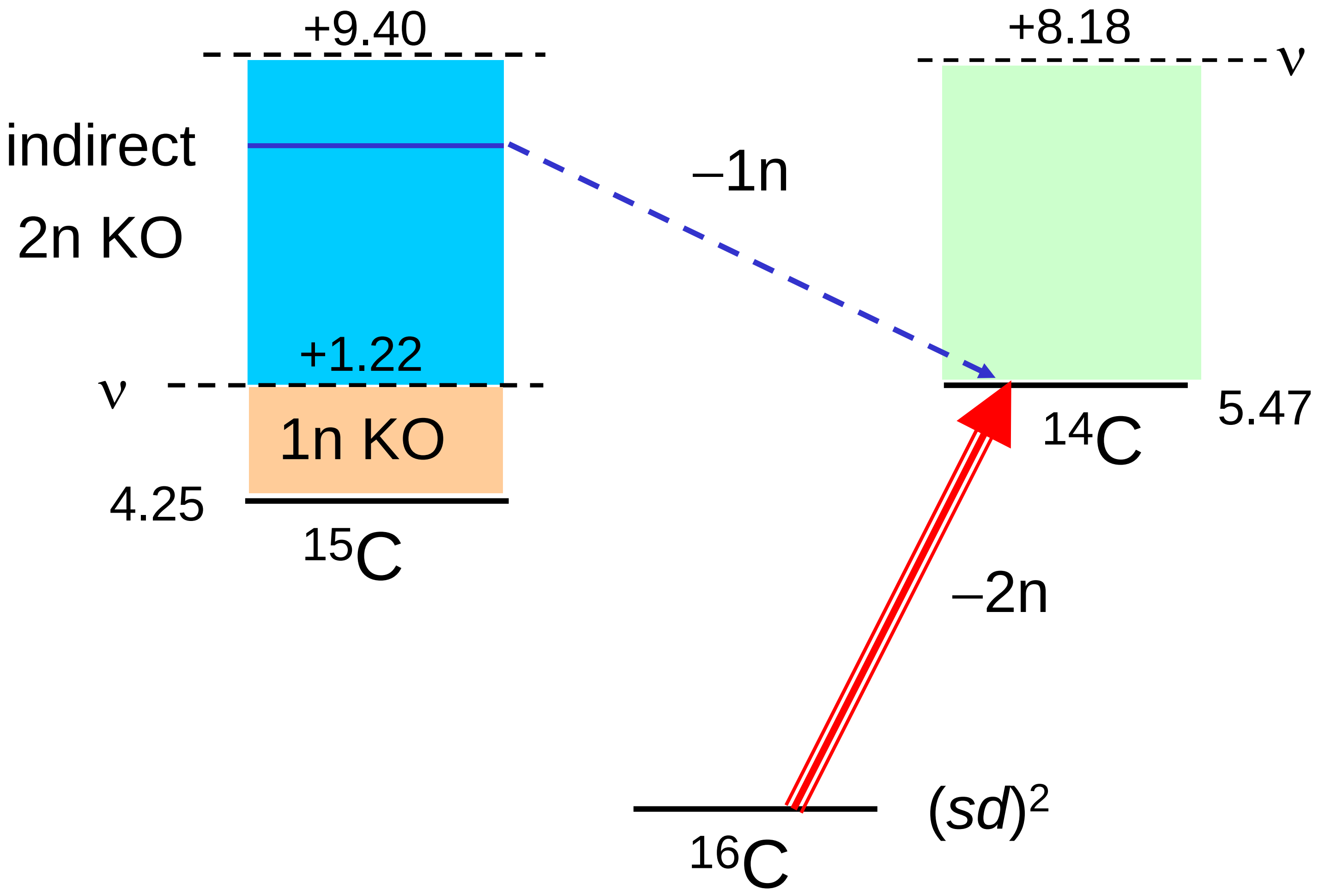
We can understand the important correlations by looking at the 2N wave function/probabilities in this sampled volume

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

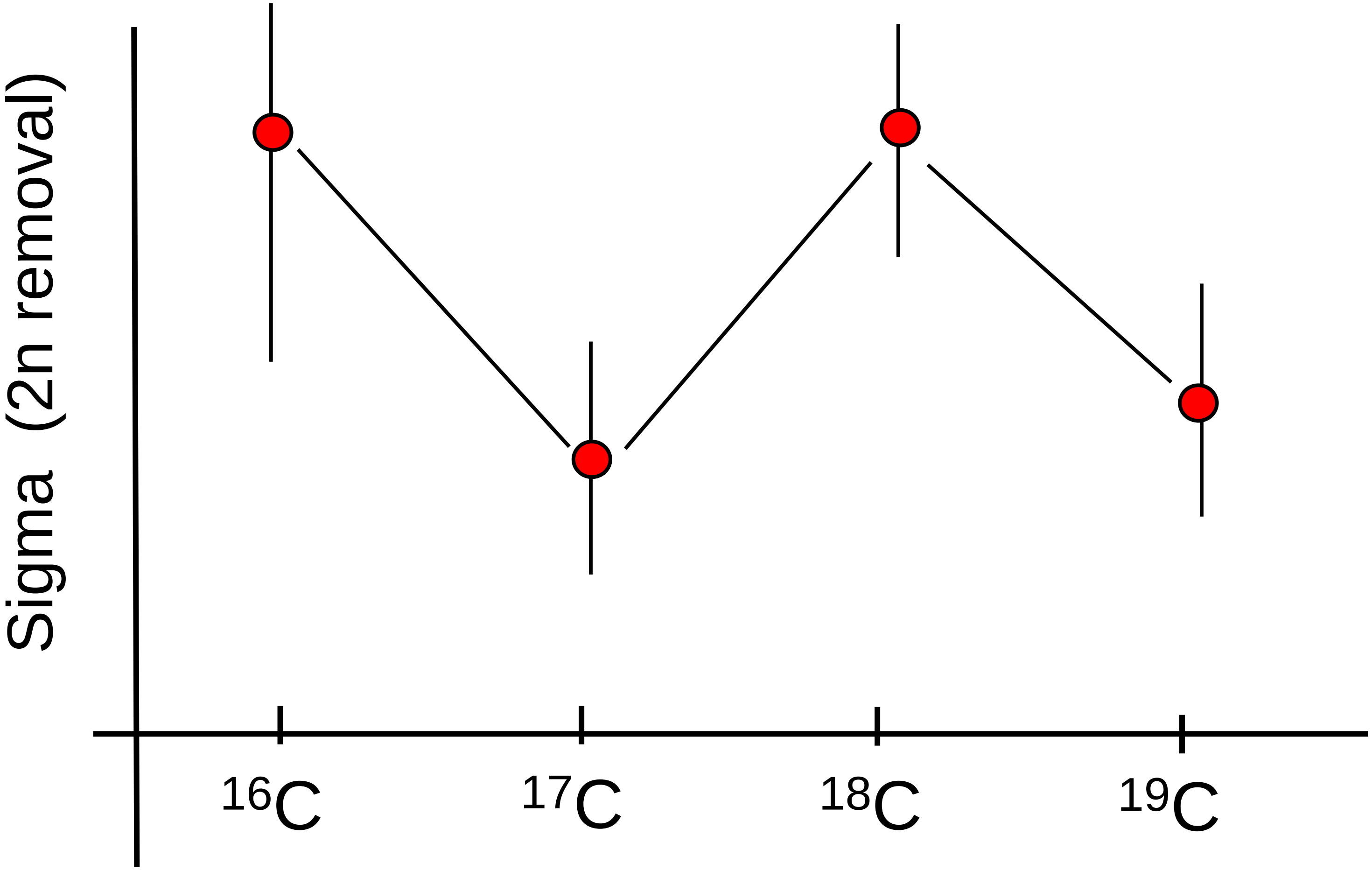
Two-neutron knockout: example $^{17}C \rightarrow ^{15}C$



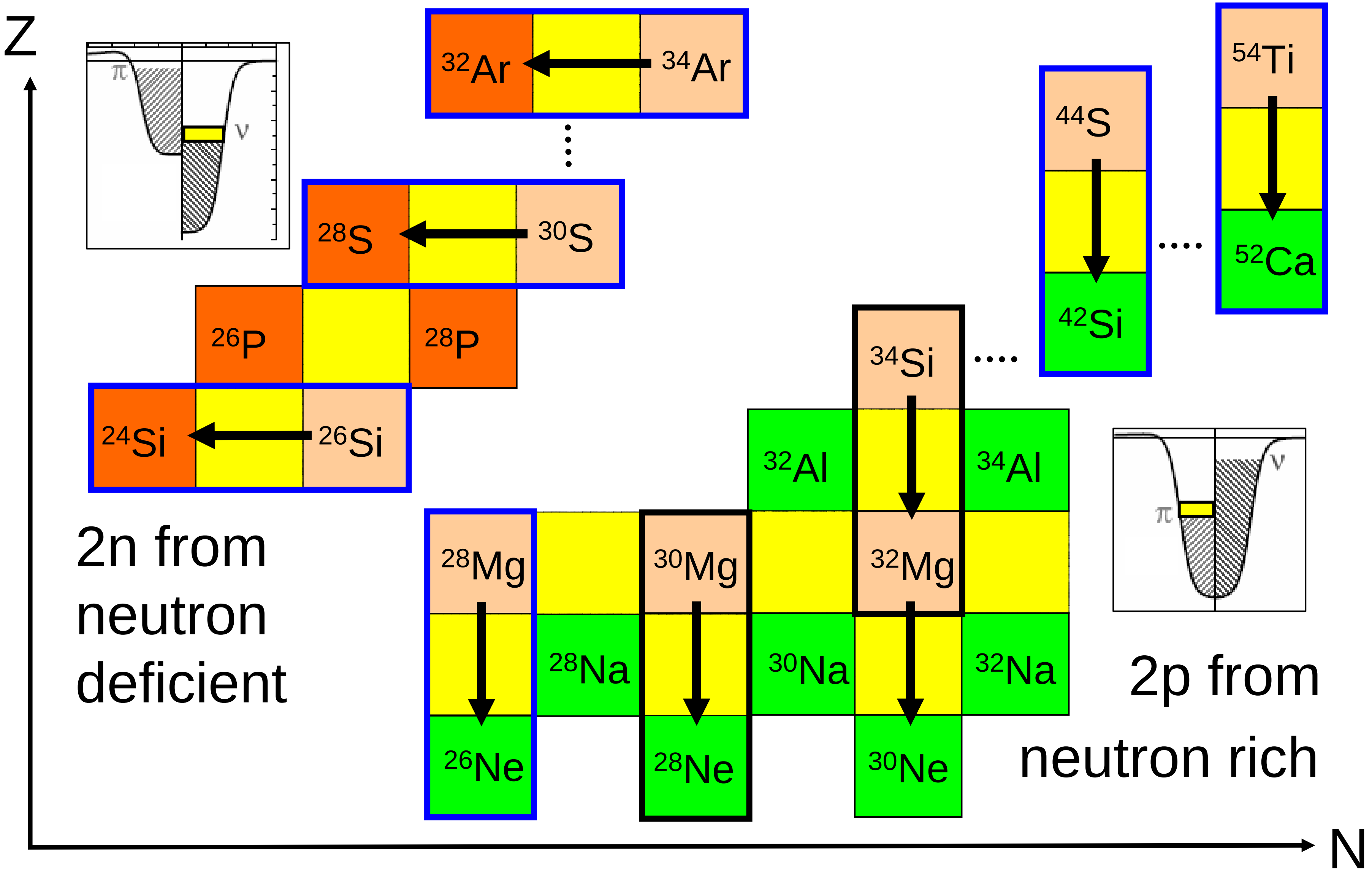
Two-neutron knockout: example $^{16}C \rightarrow {}^{14}C$



Inclusive 2n removal yields – staggering (is seen)



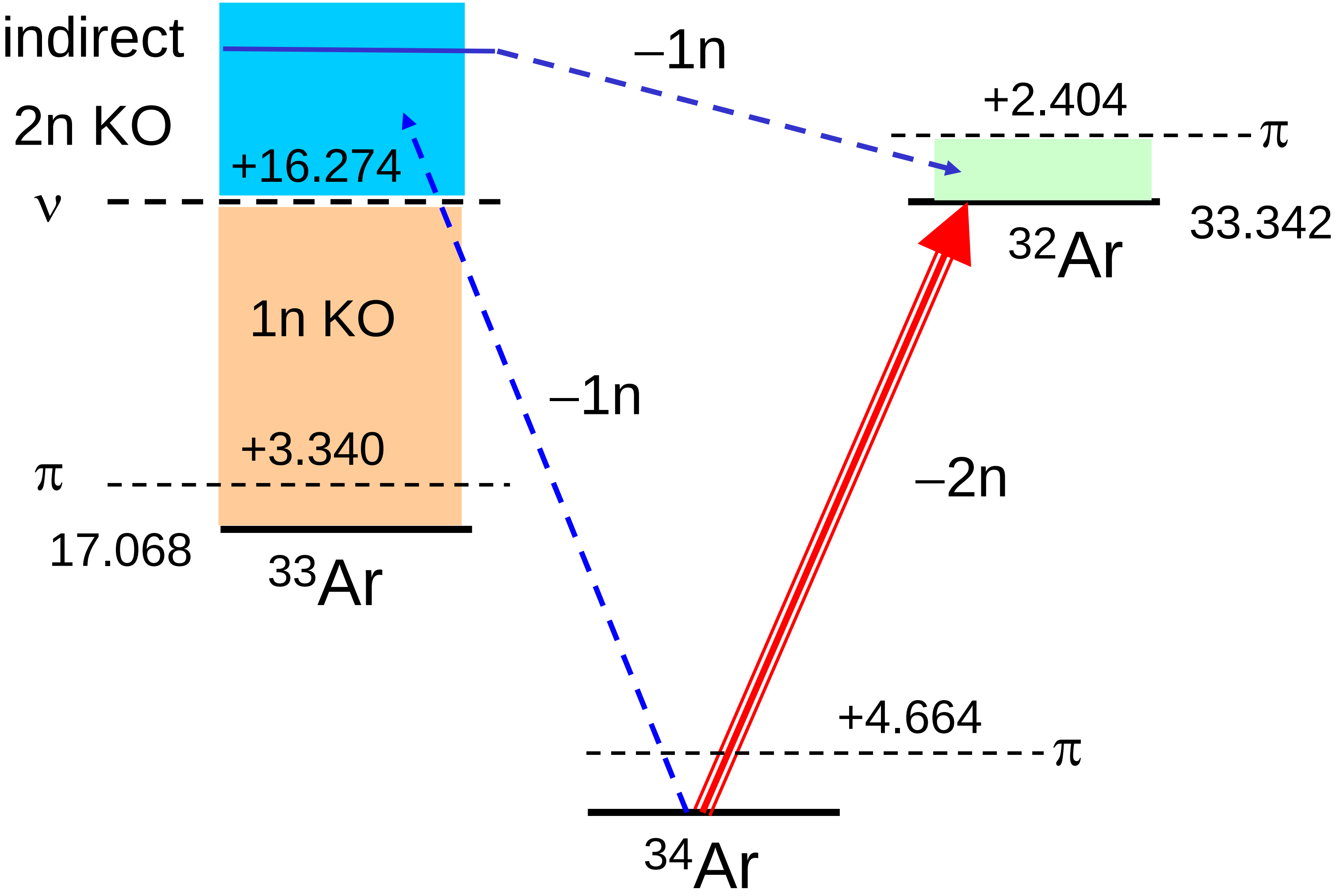
Two nucleon knockout – restricted direct reaction set



2n from neutron deficient

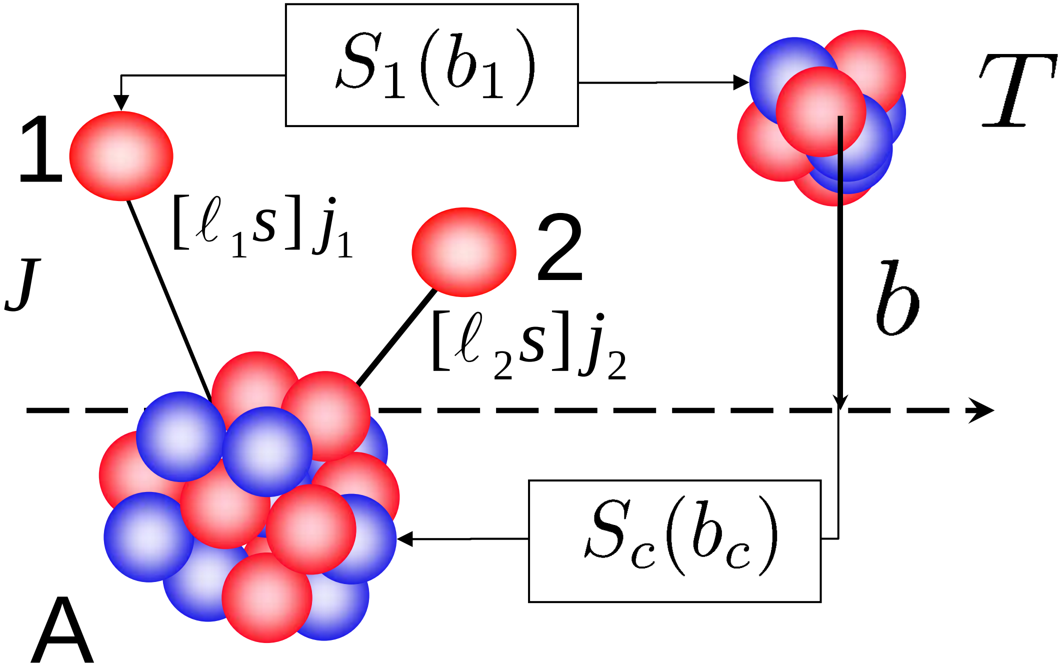
2p from neutron rich

Direct two-neutron knockout: example ^{34}Ar → ^{32}Ar



K. Yoneda *et al*., PRC **74** (2006) 021303(R)

Sudden removal – eikonal model cross sections



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

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

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

Must include all 2N removal mechanisms

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

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

core survival

and nucleon

“ removal ”

$$\sigma^{\mathrm{KO}}_{abs} \quad \rightarrow \quad \begin{array}{r} \\ + \\ + \end{array} \boxed{\begin{array}{c} |S_c|^2 \\ |S_c|^2 \\ |S_c|^2 \end{array}} \begin{array}{l} (1-|S_1|^2)(1-|S_2|^2) \\ |S_1|^2(1-|S_2|^2) \\ (1-|S_1|^2)|S_2|^2 \end{array}$$

2N absorption

1N absorption

1N diffracted

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

J.A. Tostevin *et al.*, PRC in press.

The diffractive/absorption contributions

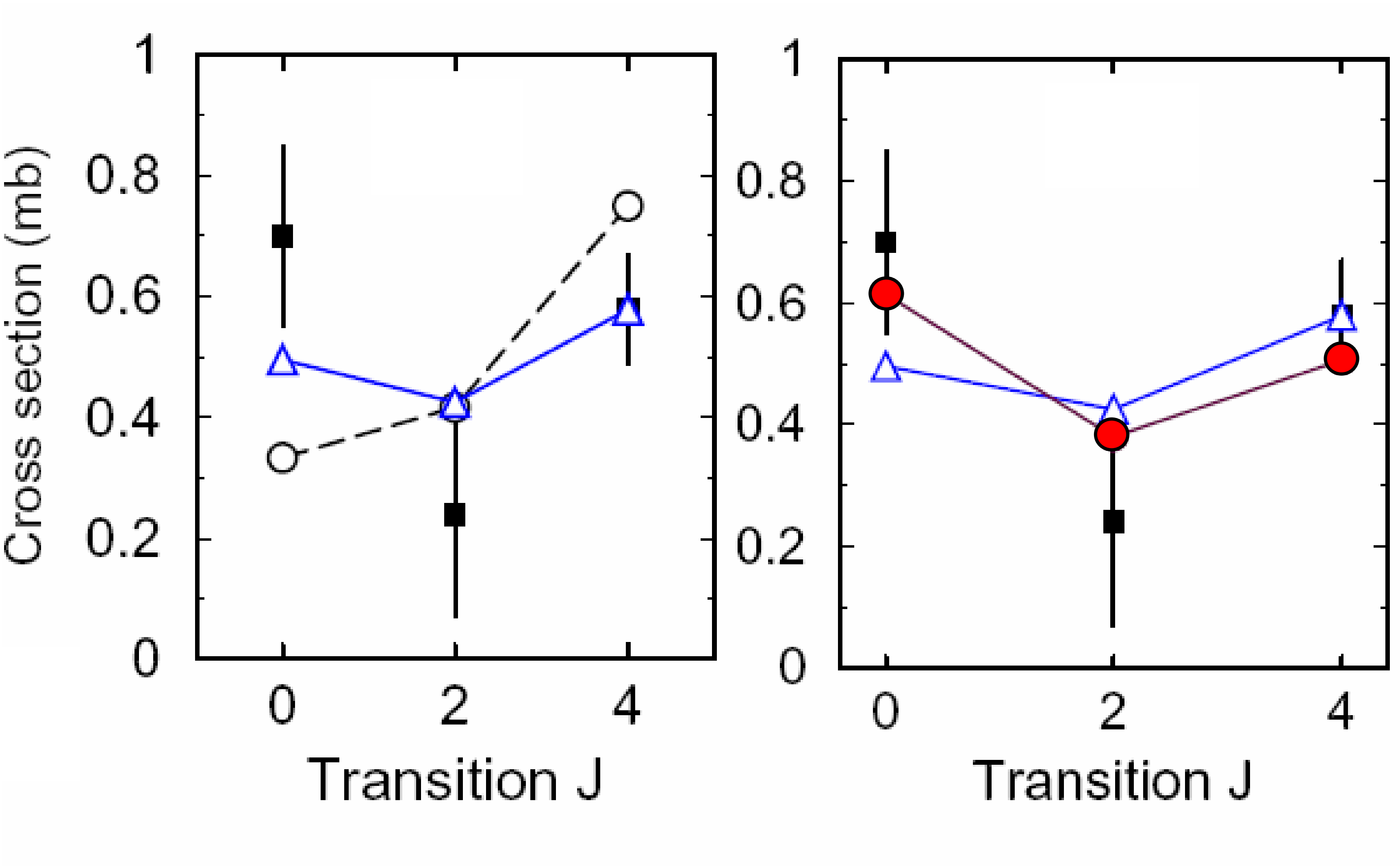
$$\sigma_2 \to |S_c|^2|S_1|^2\underbrace{(1-|S_2|^2)}_{\text{nucleon 2 absorbed}}$$

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

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

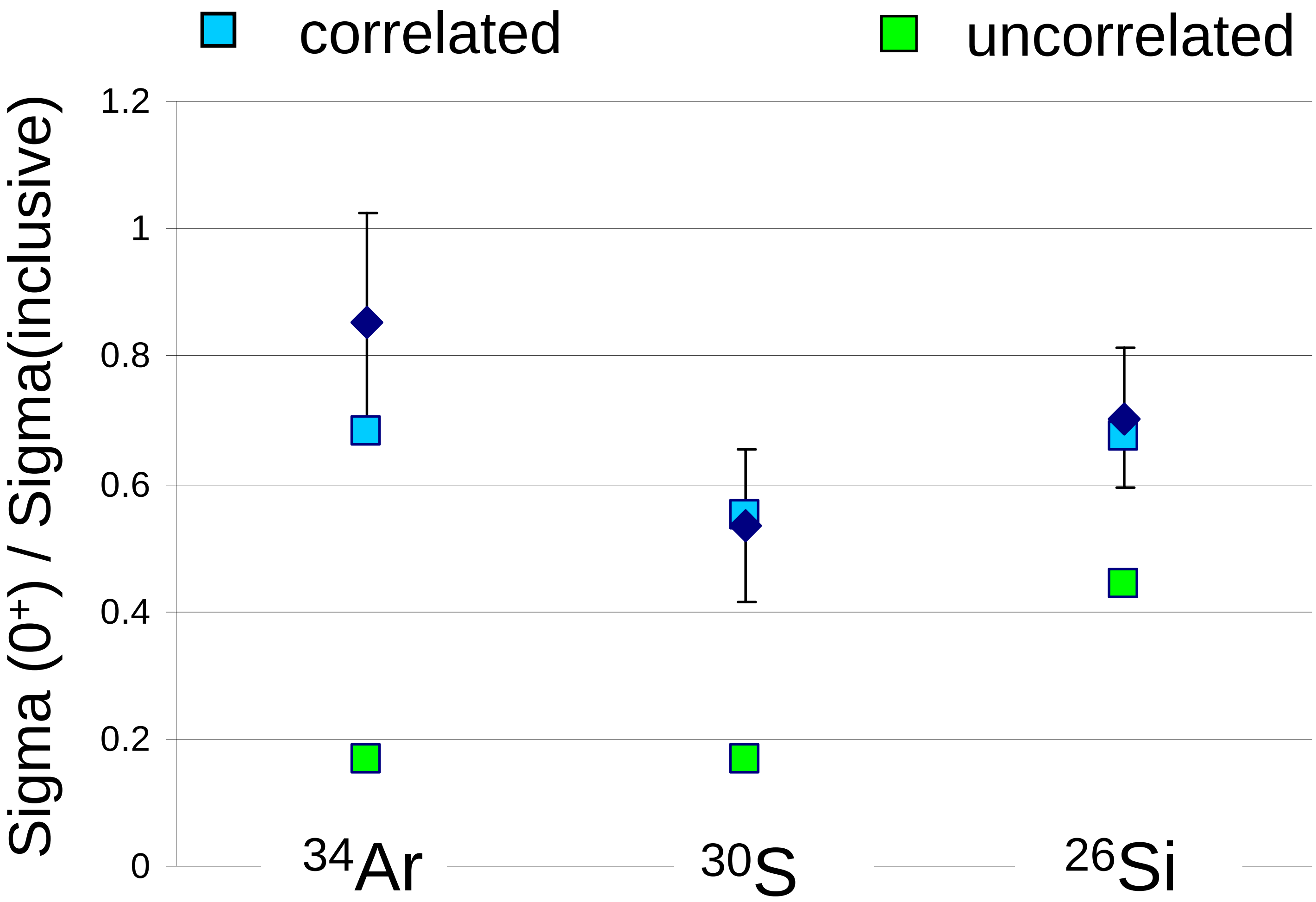
nucleon 1: (1+c) unbound (1+c) bound

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



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

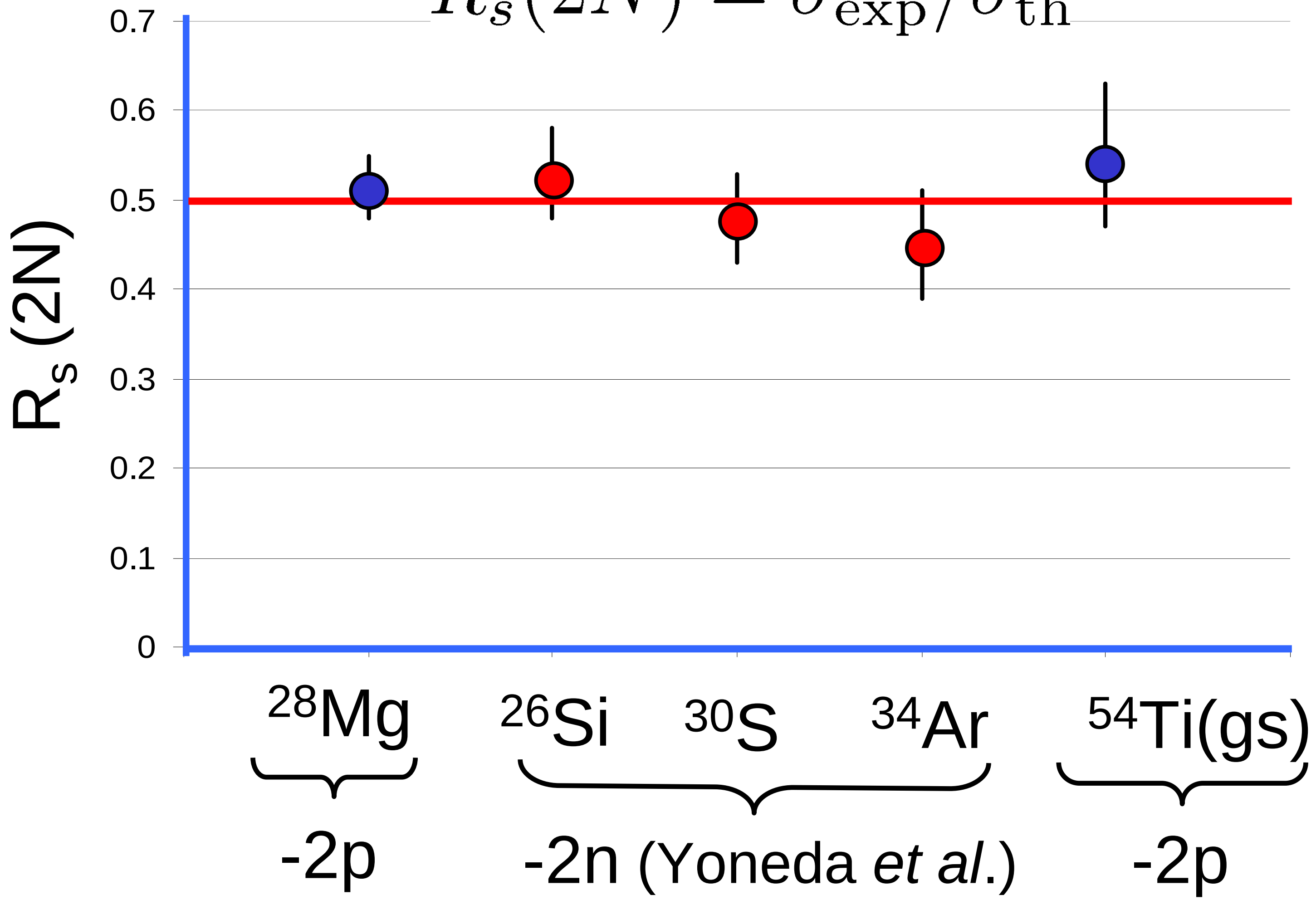
Two-neutron removal – g.s. branching ratios



K. Yoneda *et al*., PRC **74** (2006) 021303(R)

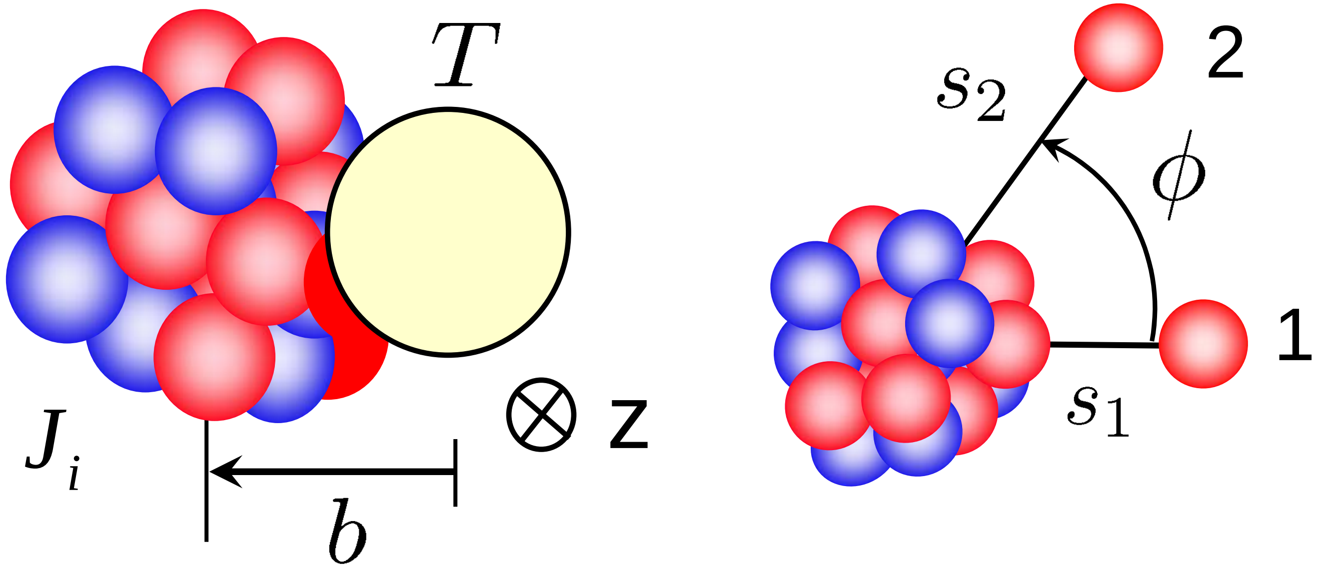
Two-nucleon removal – suppression - $R_s(2N)$

$$R_s(2N) = \sigma_{\rm exp}/\sigma_{\rm th}$$



J.A. Tostevin and B.A. Brown, PRC in press (2006).

Look at momentum content of sampled volume

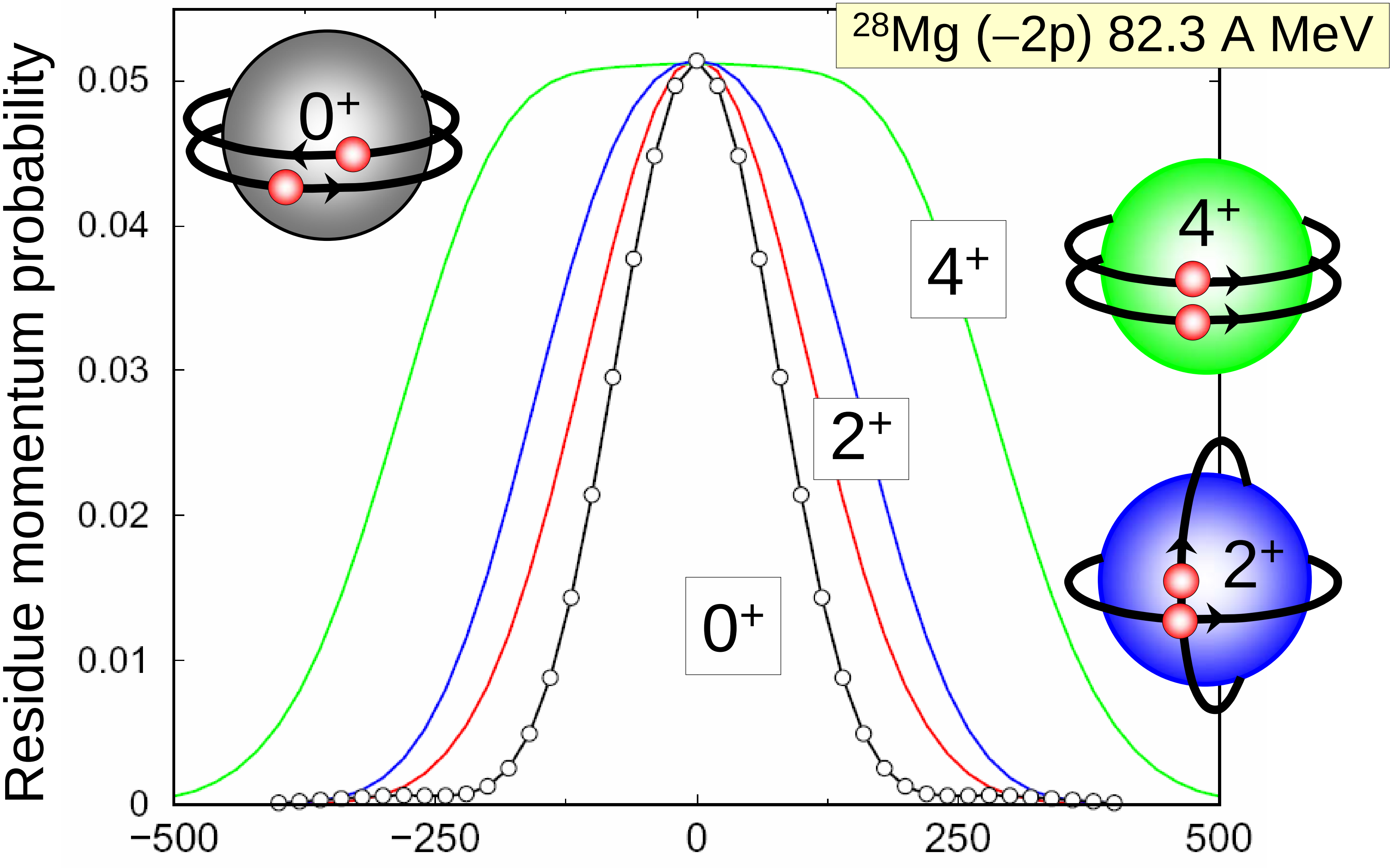


Probability of a residue with parallel momentum *K*

$$\begin{aligned} P(K,\vec{s}_1,\vec{s}_2) &= \sum_M \Big\langle \int dk_1 \int dk_2 \;\delta(K+k_1+k_2) \\ &\times \;\Big| \int dz_1 \int dz_2 \, e^{ik_1 z_1} e^{ik_2 z_2} F_{JM}(1,2) \Big|^2 \Big\rangle_{sp} \end{aligned}$$

J. A. Tostevin, RNB7, Eur. Phys. J. A, in press

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



residue parallel momentum (MeV/c)

Summary and lessons to date

At fragmentation energies (>50 MeV/u) reaction theory is rather accurate providing quantitative tests of structure model predictions.

Limited two neutron/proton knockout data – but already reveal sensitivity to (correlated) configurations in 2N wave functions.

Direct 2N knockout reaction mechanism can be very clean - the Combination of N and 2N removal reactions will help elucidate shell gaps, and structures around shell closures.

Five data sets are consistent with shell model spectroscopy and suppression [~0.50(5)] of 2N shell model strength – analog of 1N removal suppression (of 0.6 – 0.7) for well-bound nucleons.

It is predicted that there is valuable structure information to be gained from more final-state-exclusive residue momentum distribution measurements.