One- and two-particle spectroscopy : What should we expect for the suppression of one- and two-particle shell-model strength?

Coupling Nuclear Structure with Reaction Theory

"Nuclear Structure Near the Limits of Stability"
INT-05-3 Workshop, 31st October 2005

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Outline of topics covered – analyses of

- One- and two-nucleon knockout [sudden 2N removal] from nuclei at fragmentation energies – here 60 ~ 90 MeV/u on light nuclear targets – using eikonal/Glauber methodology. What has been/is being done – and the results to date. Can these be improved – structure and reaction-wise?

- Single-nucleon transfer reactions (d,p) and (p,d) – the sensitivities to 'standard' inputs (Betty Tsang+Jenny Lee) How can we constrain these better, theoretically?

- Must map many-body structure theory onto few-body reaction theory – should make use of 'generic' theoretical models which describe (A, Z, E) systematics (e.g. Hartree Fock, Microscopic NN effective interactions) when needed.

Direct (knockout, break-up, transfer) reactions – generics

1) Reactions in which there is a minimal rearrangement, or excitation involving a very small number of active (*effective*) degrees of freedom – remaining many-body coordinates are inert – 'spectators' –reactions are fast

2) Reaction energies are such that average, effective (complex) interactions can be used between the reacting constituents – regions of high level density

3) Because of complex effective interactions and short mean free paths, reactions are localised / dominated by interactions in the nuclear surfaces and hence by peripheral and grazing collisions – 'so fast'

What is the state of different reaction theories?

CDCC, time-dependent, TC, eikonal, sudden ...

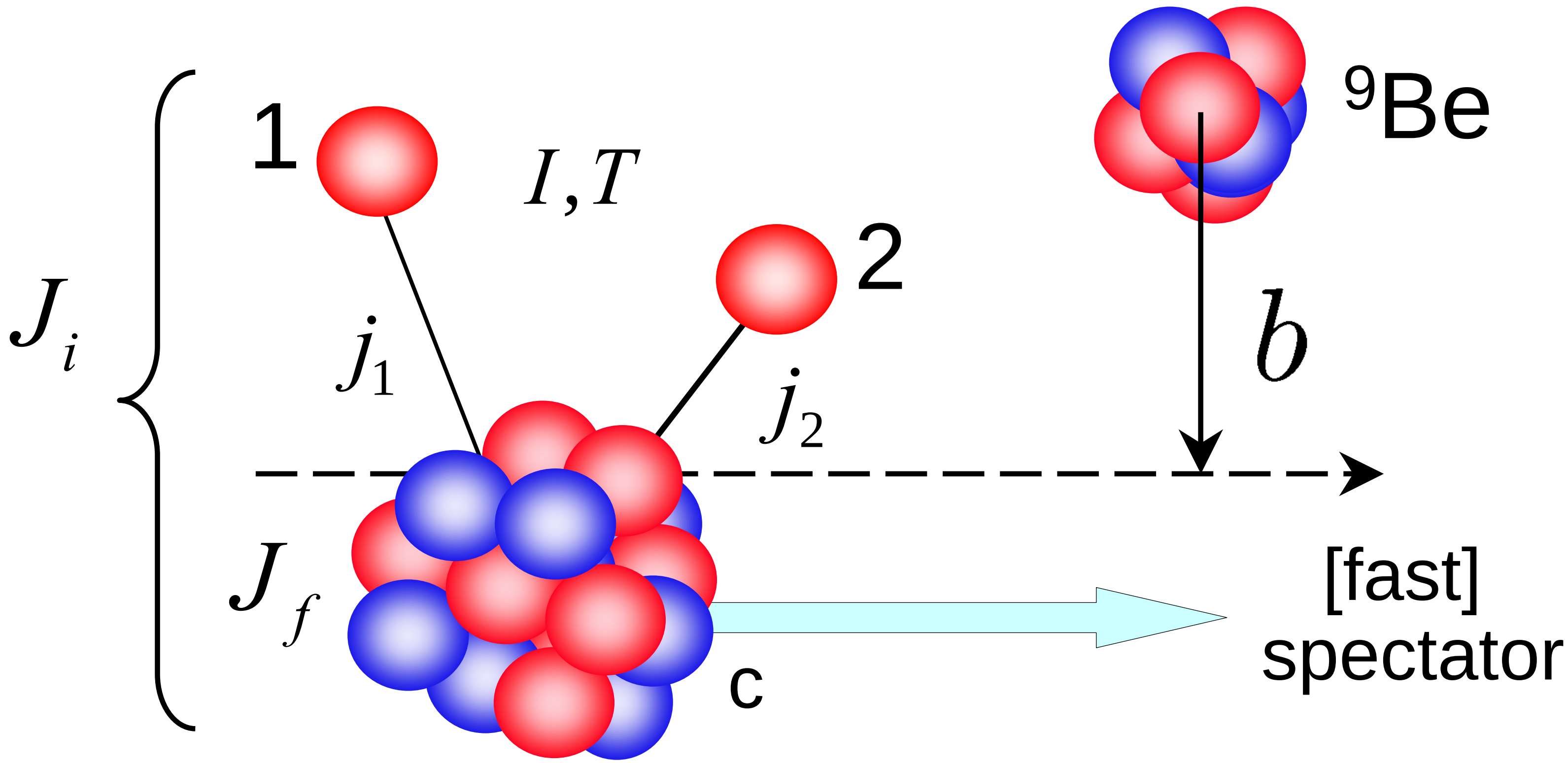
Do different reaction theories agree for the same structure and effective interaction inputs?

Theorists will (occasionally) argue the details but where fair tests and comparisons have been carried out - and domains of approximations overlap – answer is YES

Structure inputs – sp overlaps (potential models)

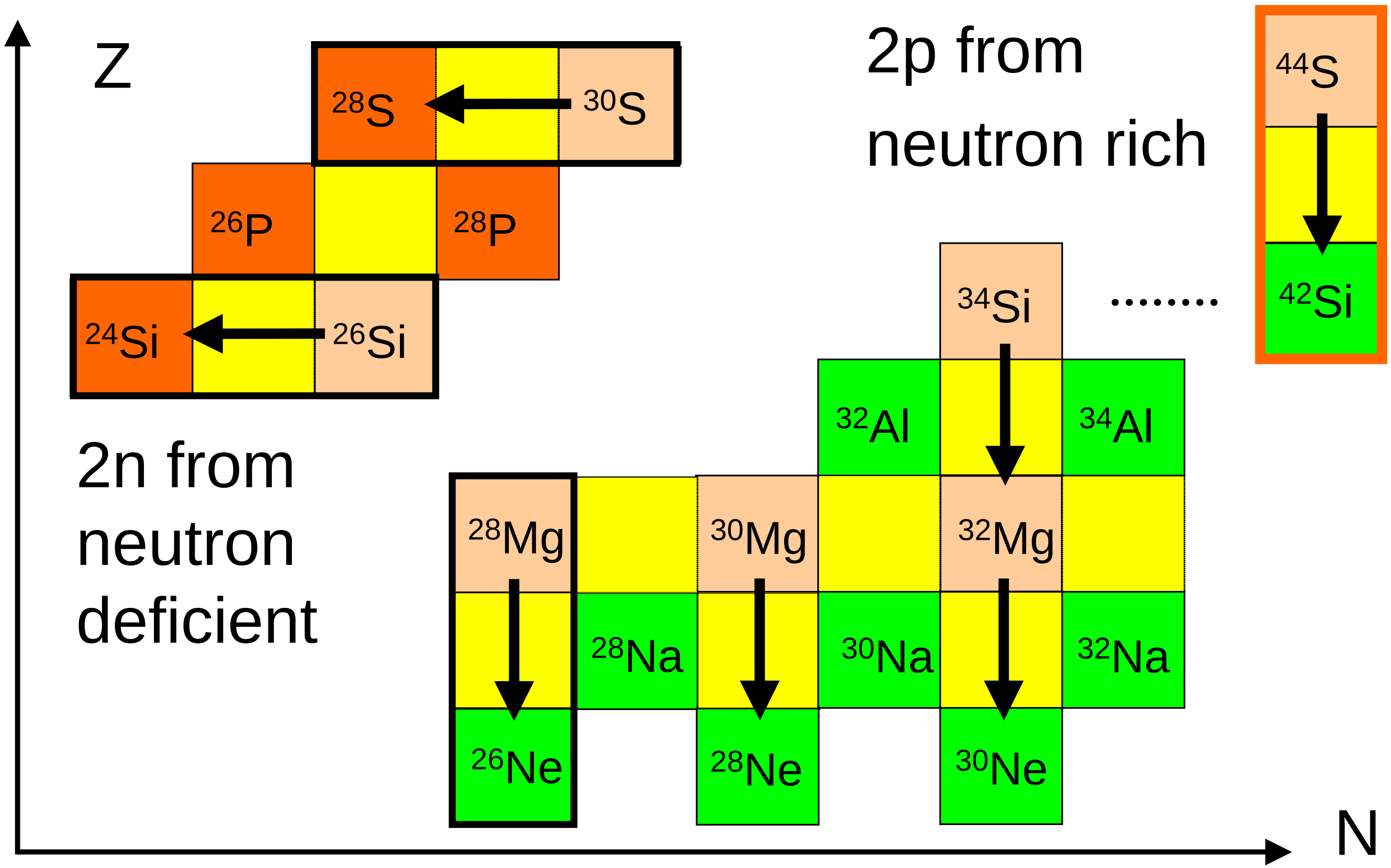
Dynamics – effective interactions

One and two-nucleon removal – 50~100 MeV/u

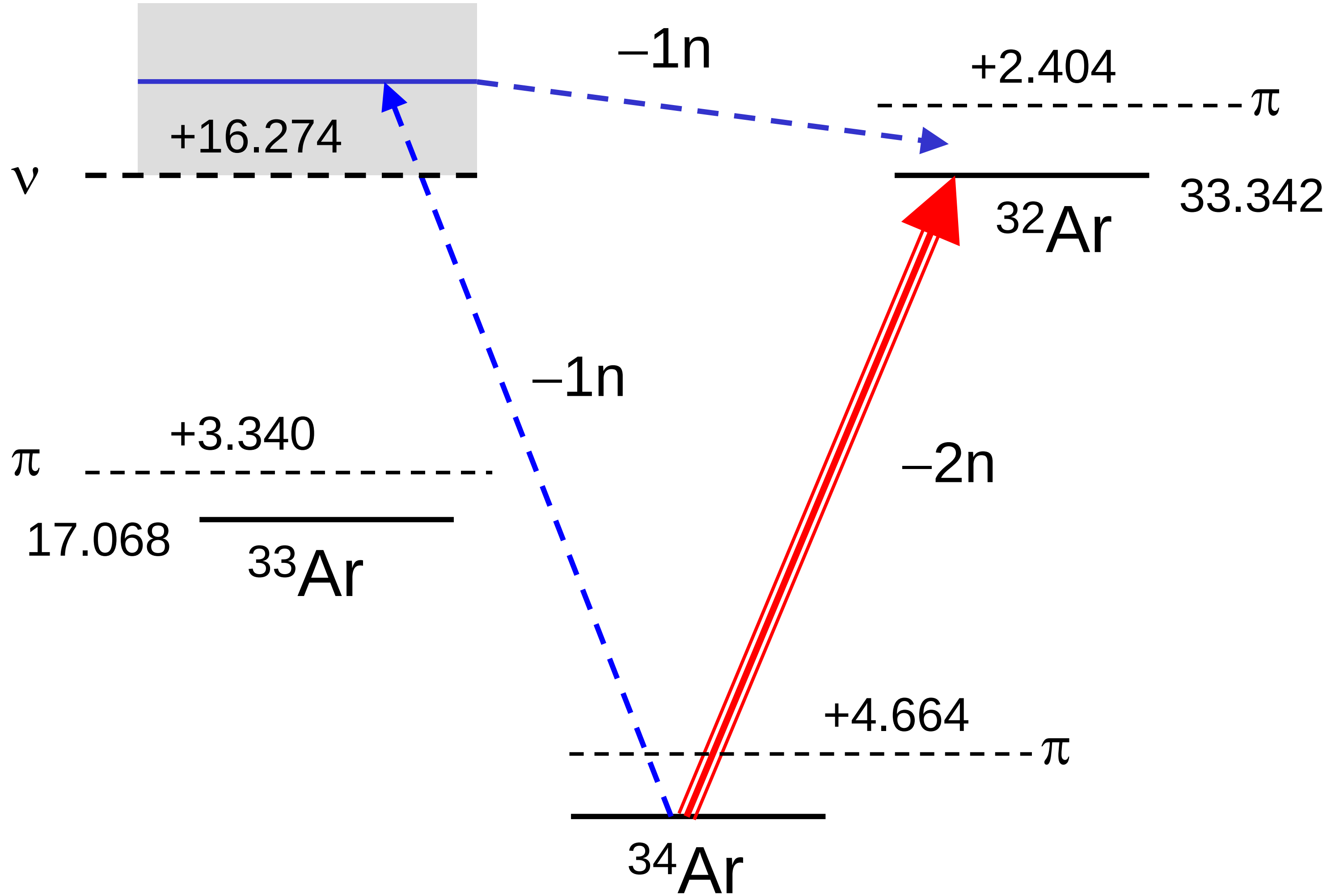


Experiments are generally inclusive (with respect to the target final states). Core final state sometimes measured – by gamma rays.

Two nucleon knockout – a direct reaction

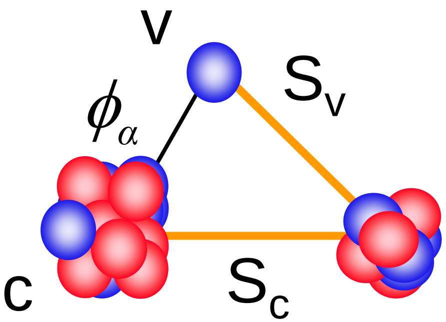


Two-neutron knockout - direct – e.g. $^{34}Ar \rightarrow ^{32}Ar$



Eikonal theory - dynamics and structure

Independent scattering information of c and v from target



dynamics

$$S_{\alpha\beta}(b) = \langle \phi_\beta \,|\, \overbrace{S_c(b_c)\, S_v(b_v)}\, |\, \phi_\alpha \rangle$$

structure

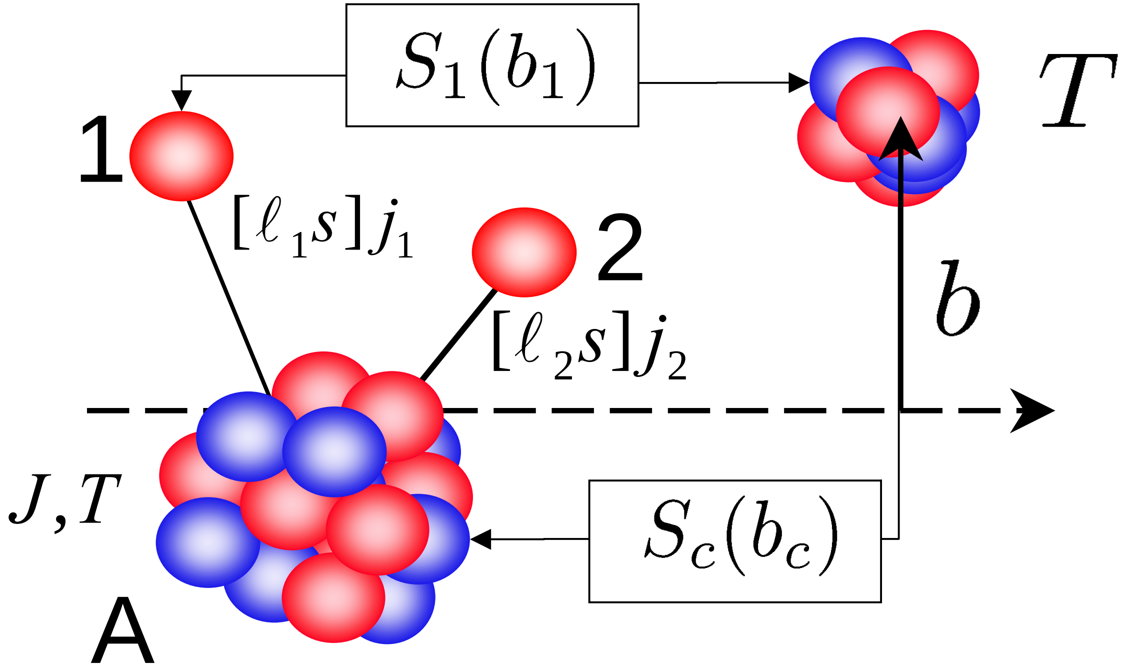
Use the <u>best available</u> few- or many-body wave functions

<u>More generally,</u>

$$S_{\alpha\beta}(b) = \langle \varphi_\beta \,|\, S_1(b_1)\, S_2(b_2) \ldots\ldots\; S_n(b_n) \,|\, \varphi_\alpha \rangle$$

for any choice of 1,2 ,3, ….. n clusters for which a most realistic wave function φ is available

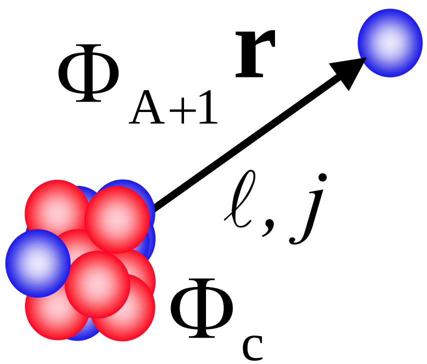
Sudden removal of correlated nucleons



$$\sigma = \frac{1}{2J+1} \sum_M \int d\vec{b} \langle \phi_{JM} | \text{Operator} | \phi_{JM} \rangle$$

$$\phi_{JM} = \sum C(j_1 j_2 J) [\overline{\phi_{j_1 m_1} \otimes \phi_{j_2 m_2}}]_{JM}$$

If core is spectator – One and two-nucleon overlaps



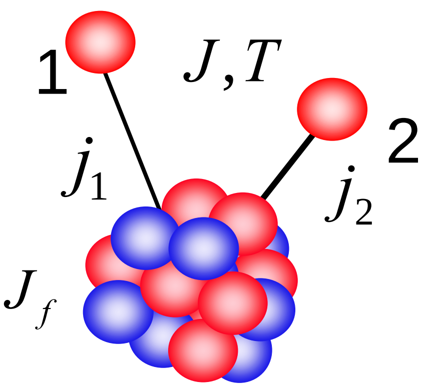
$$F_{jm}(\vec{r}) = \langle \vec{r}, \Phi_c | \Phi_{A+1} \rangle$$

$$S_N = E_{A+1} - E_c$$

$$F_{jm}(\vec{r}) = C(j)\phi_{jm}(\vec{r})$$

$$C^2 S(j) = |C_j|^2$$

Spectroscopic factor of this part of sp strength

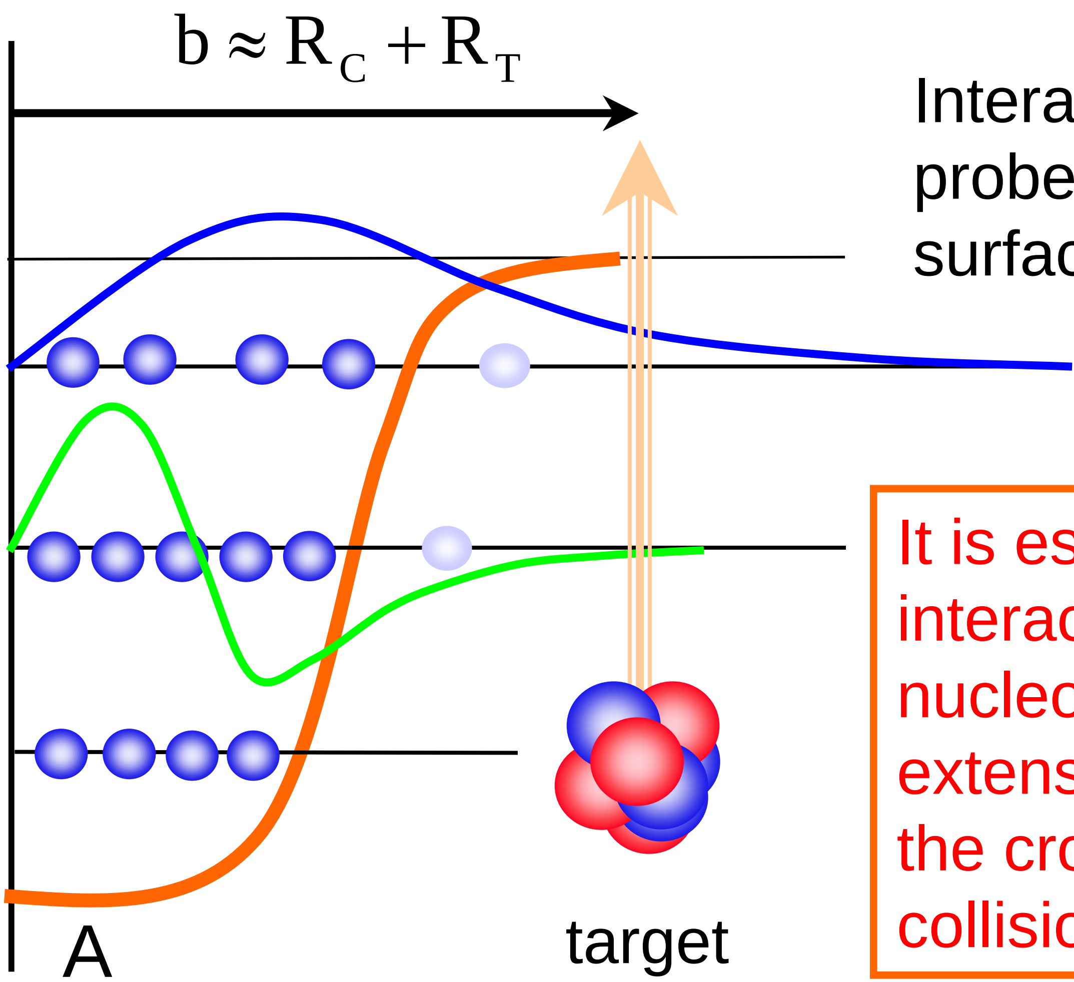


In two-nucleon case there are (in general) several (coherent) 2N configurations

$$\phi_{JM} = \sum C(j_1 j_2 J)[\overline{\phi_{j_1 m_1} \otimes \phi_{j_2 m_2}}]_{JM}$$

The ϕ are then calculated in a potential model (e.g. WS) !!

Viewed from the rest frame of the projectile



Interaction with the target probes wave functions at surface and beyond

$b \approx R_C + R_T$

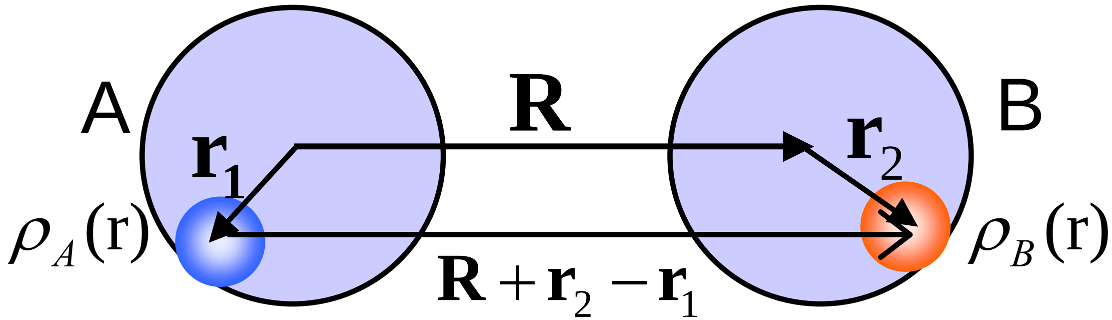
It is essential to define the interaction ranges and the nucleon formfactor spatial extensions to establish the cross sections in the collision quantitatively

Effective interactions – Folding models

Double folding

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

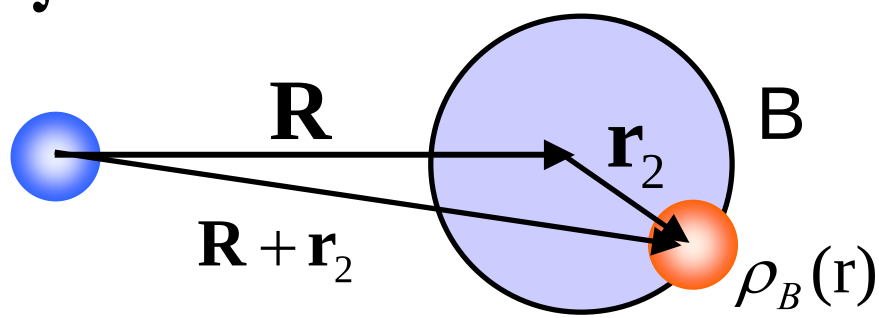
$$V_{cT}$$



Single folding

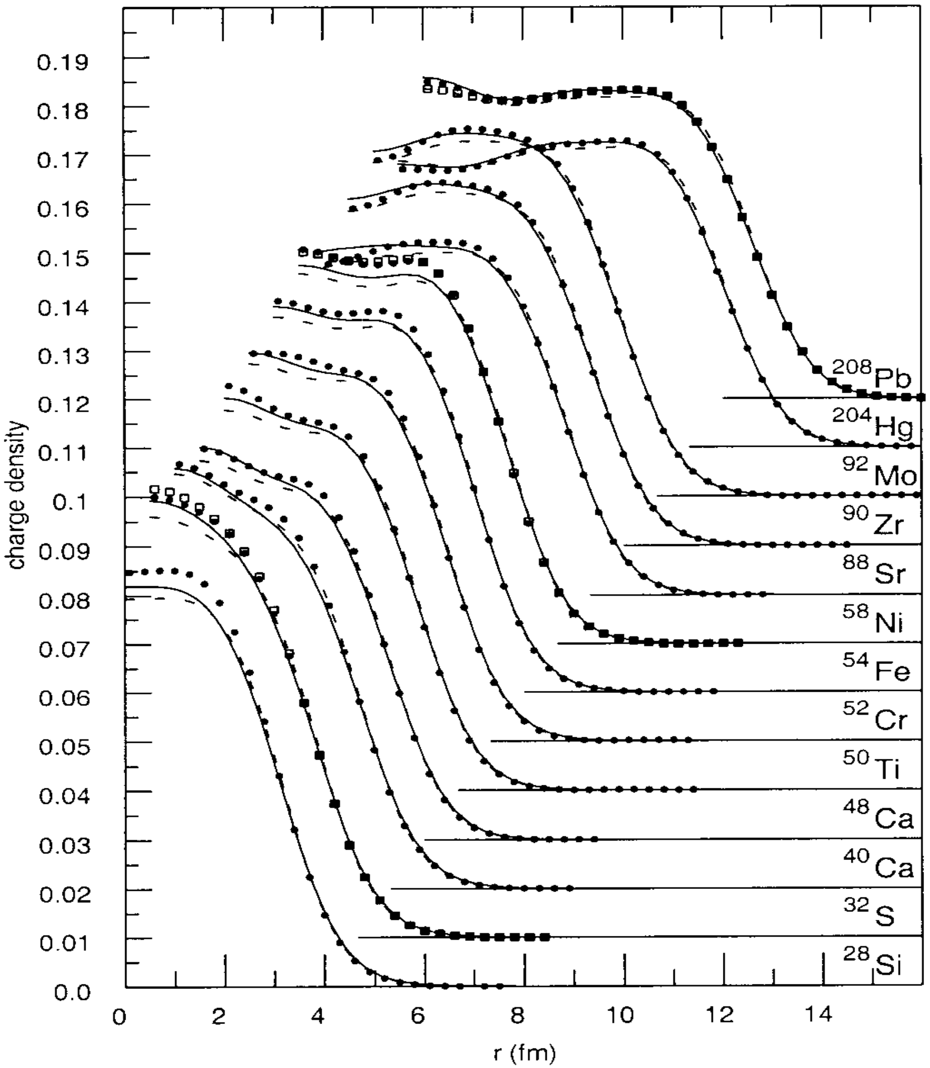
$$V_B(R) = \int d\mathbf{r}_2 \; \rho_B(r_2)\, t_{NN}(\mathbf{R} + \mathbf{r}_2)$$

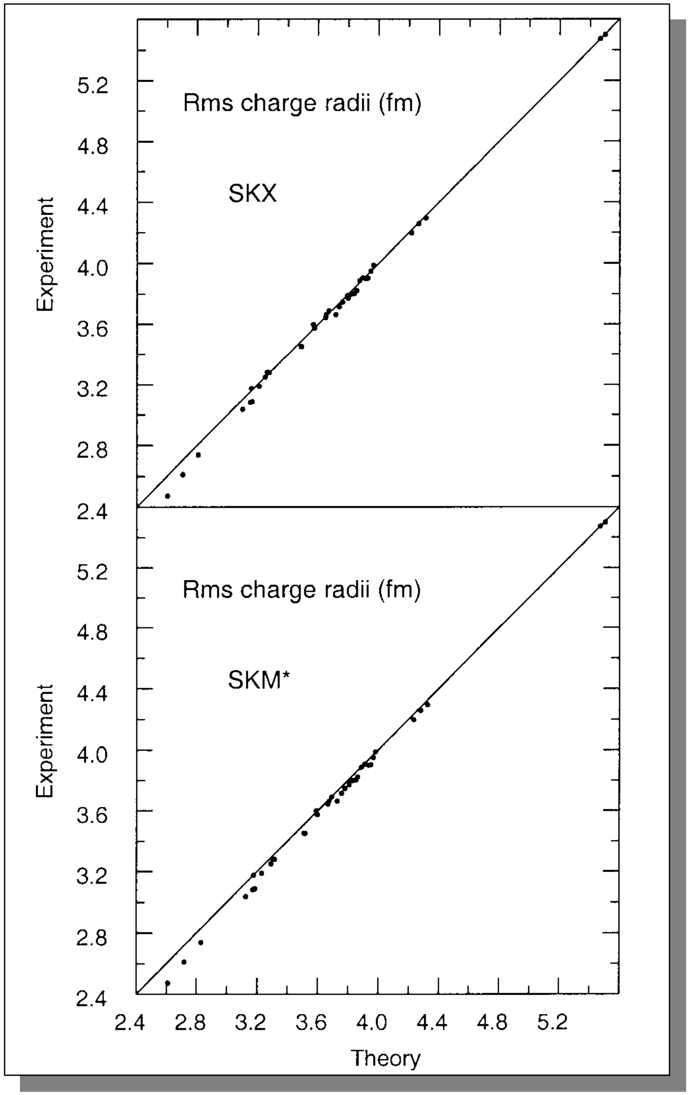
$$V_{vT}$$



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

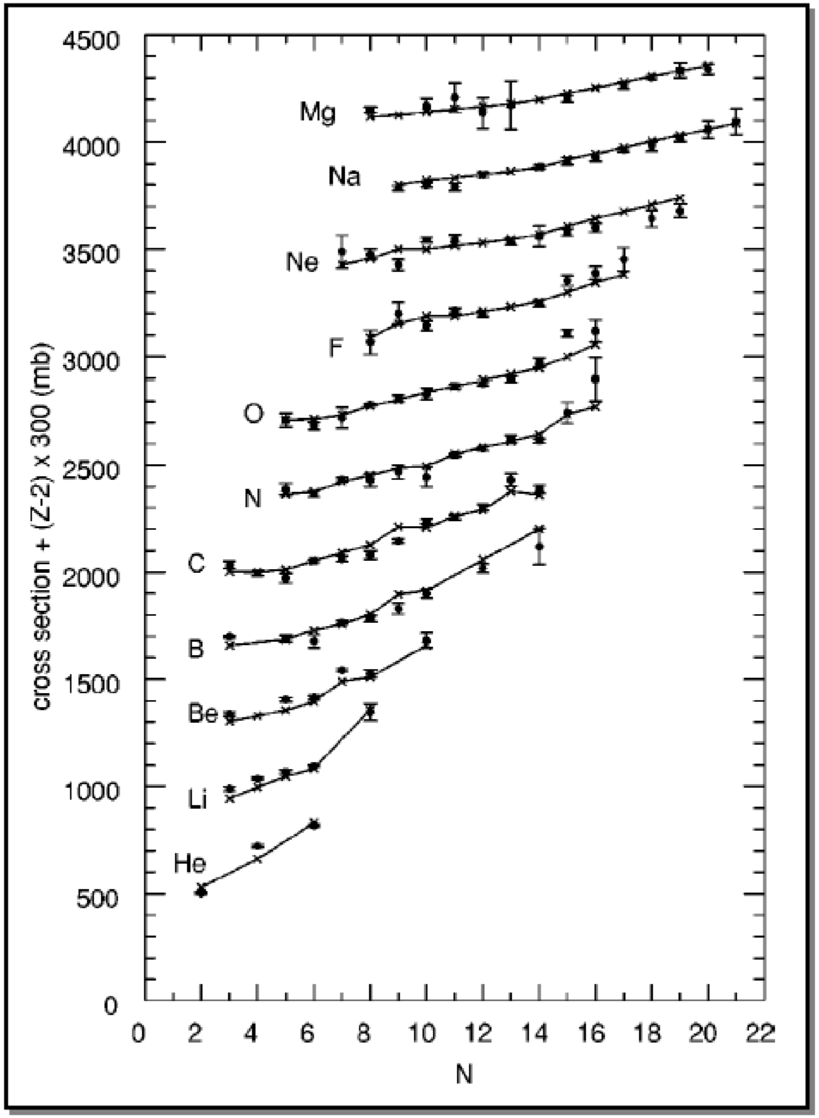
Skyrme Hartree-Fock (SkX) radii and densities

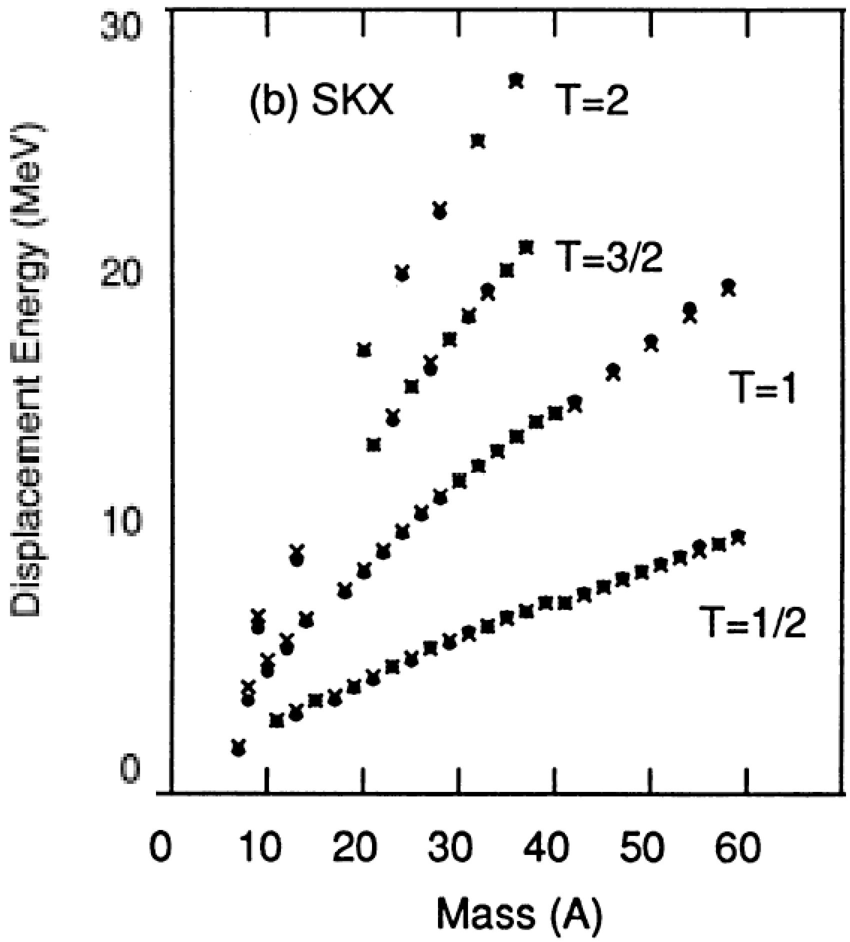




W.A. Richter and B.A. Brown, Phys. Rev. **C67** (2003) 034317

SkX HF - size and geometrical observables

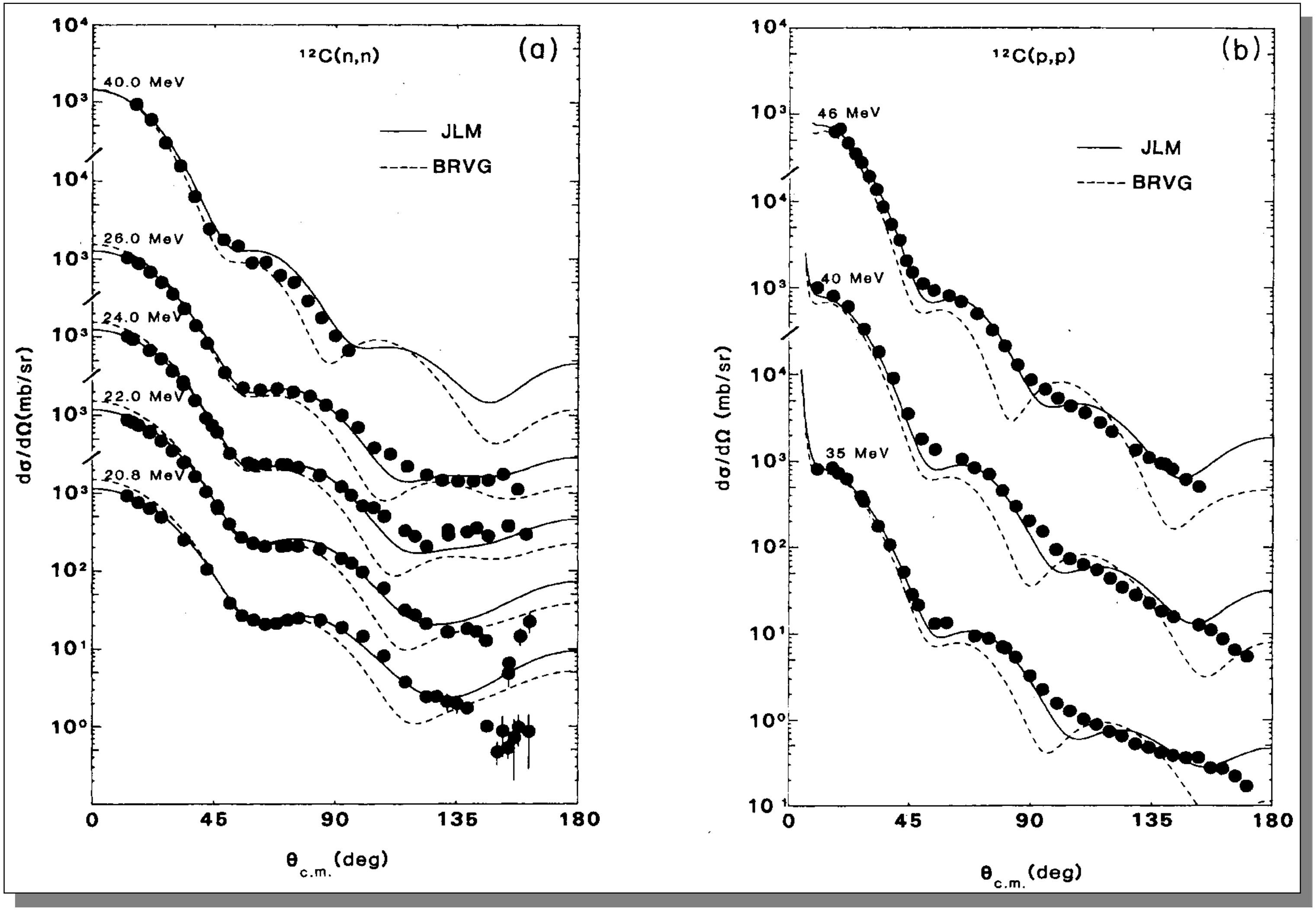




B.A. Brown et al., Phys. Lett. **B483** (2000) 49

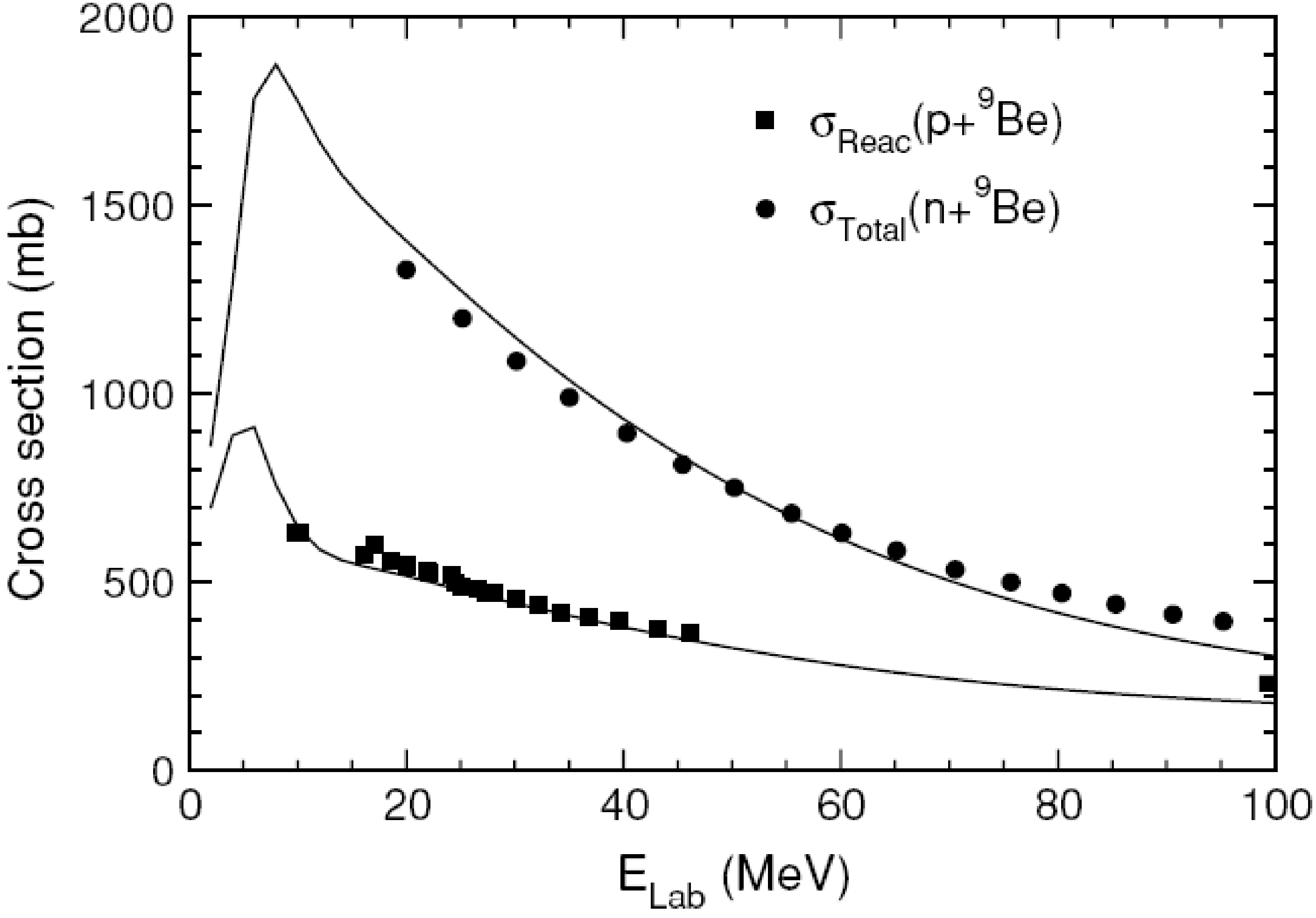
B.A. Brown et al., Phys. Rev. **C65** (2001) 014612

JLM microscopic nucleon optical potentials



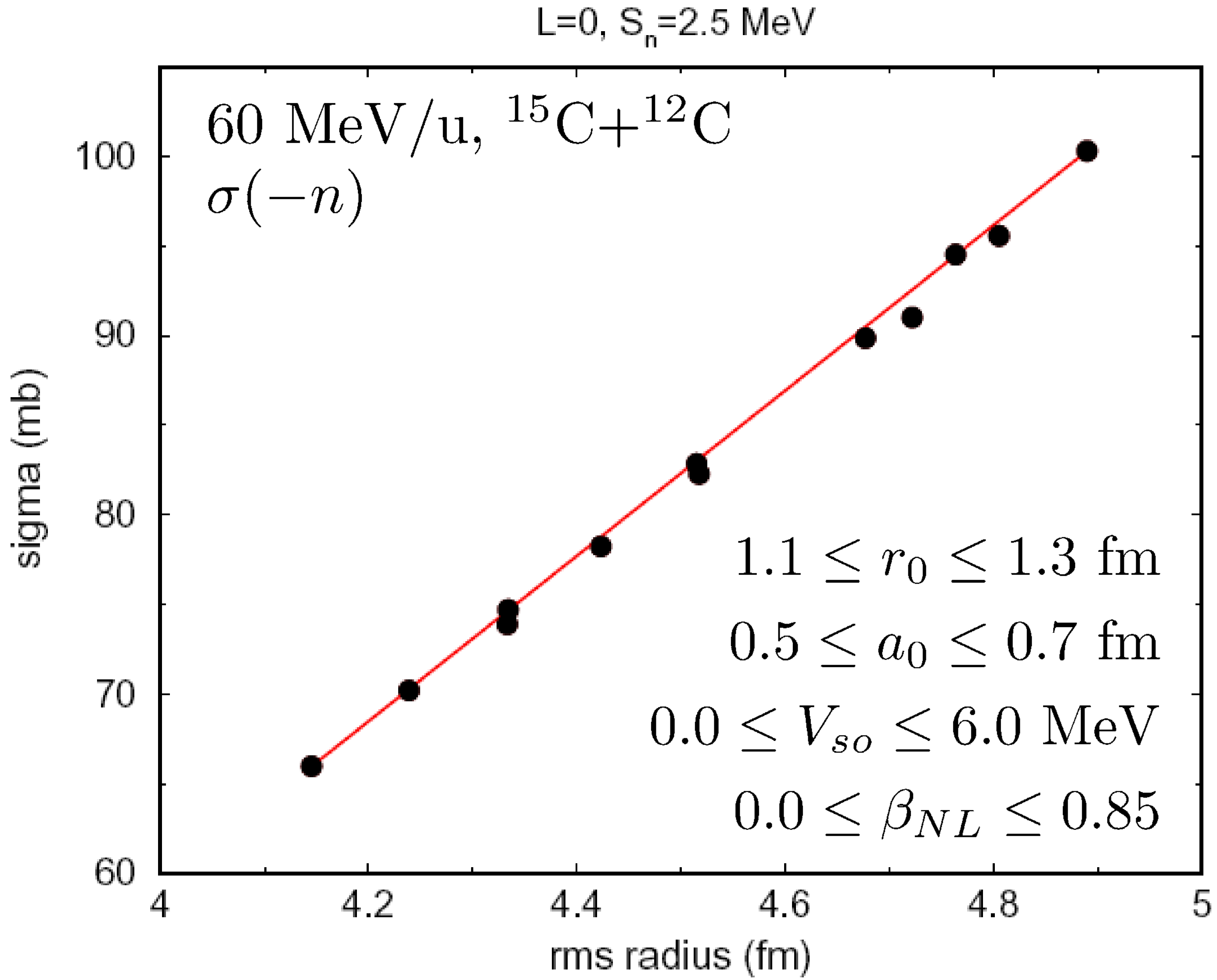
J.S. Petler et al. Phys. Rev. C **32** (1985), 673

JLM predictions for N+^{9}Be cross sections



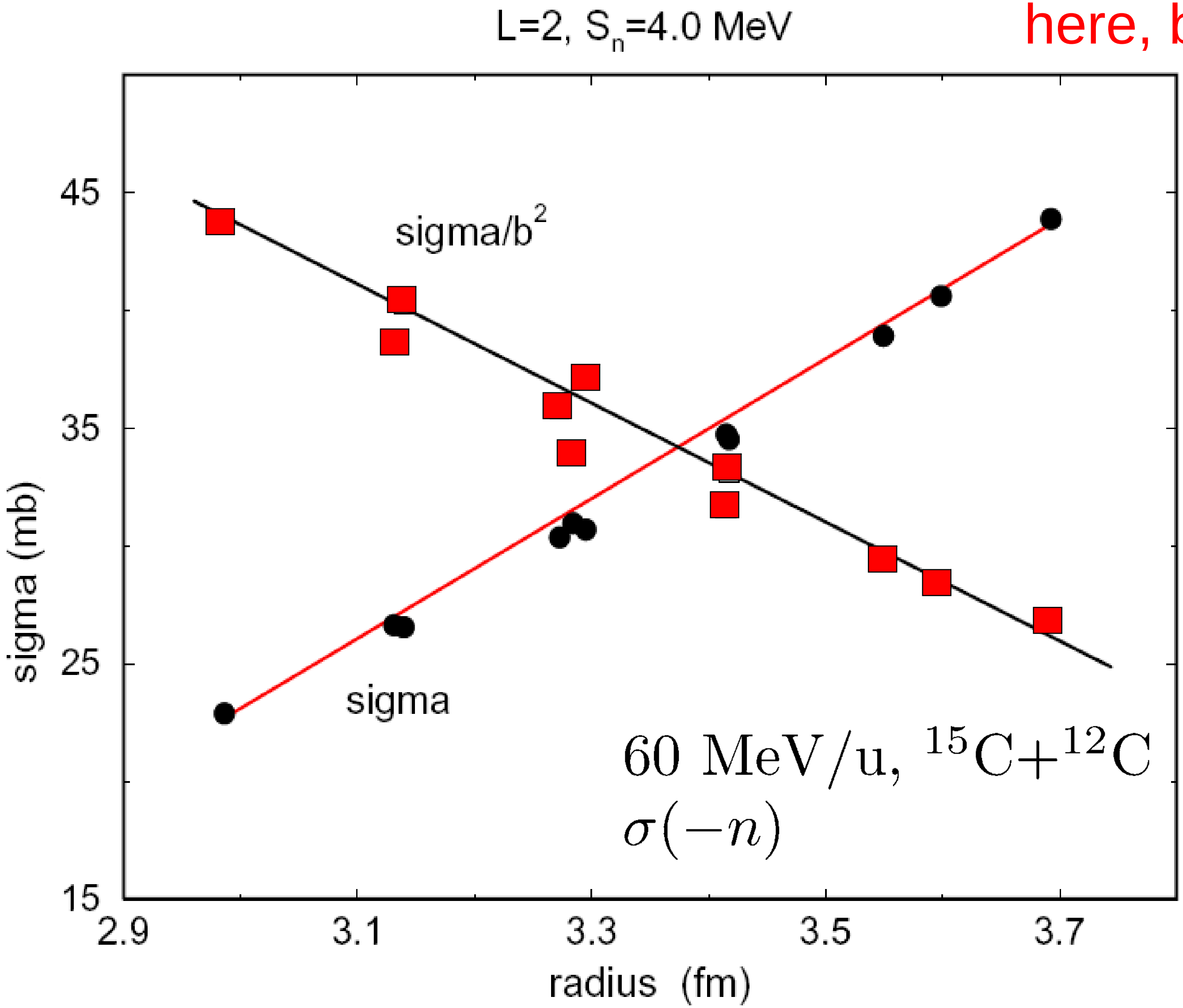
A. Garcıa-Camacho, et al. Phys. Rev. C **71**, 044606(2005)

Sensitivity to s.p. orbitals – correlation with size



Sensitivity is to more than the tail of the orbital

here, b=ANC



Sensitivity is to more than the tail of the orbital

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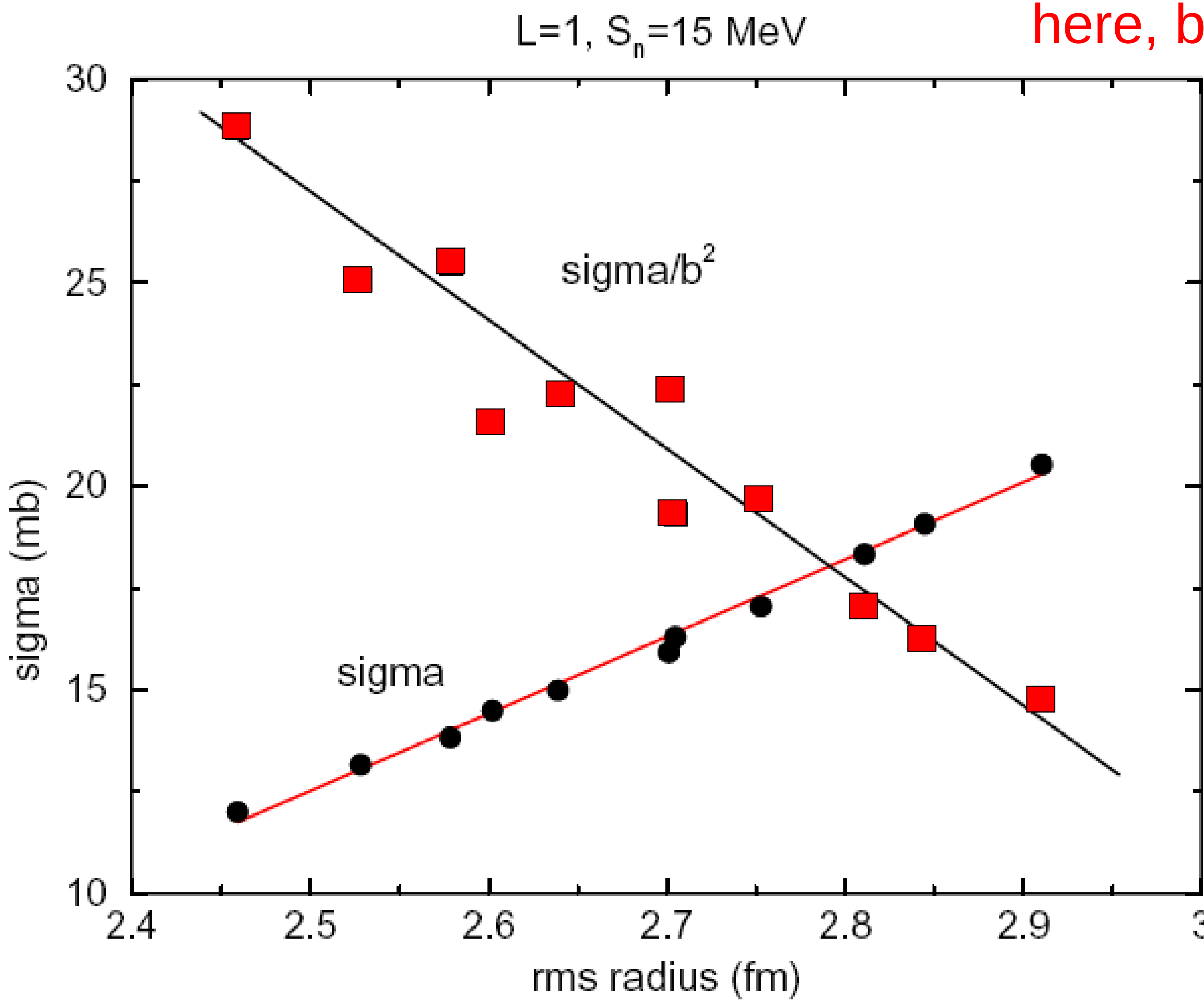
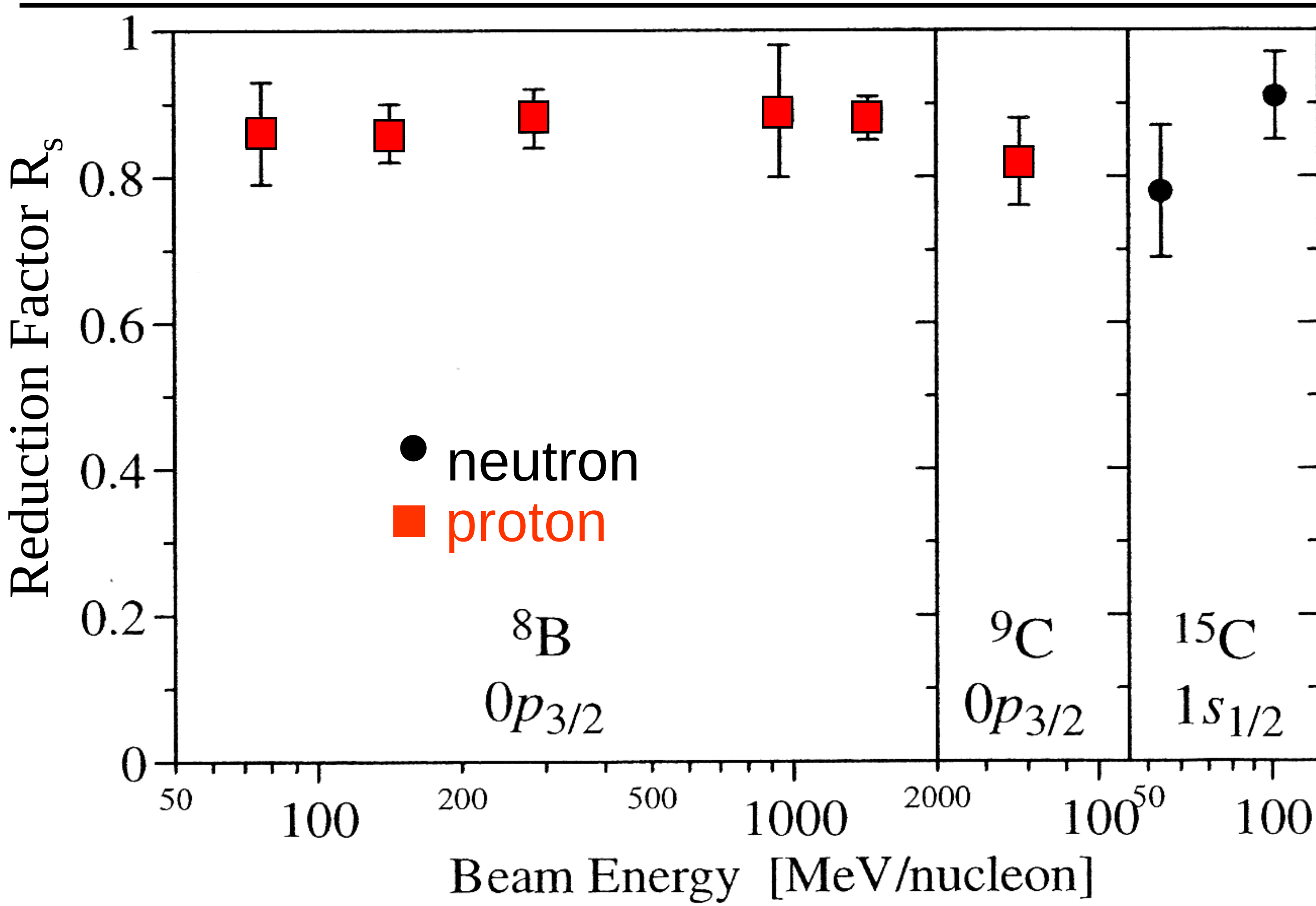
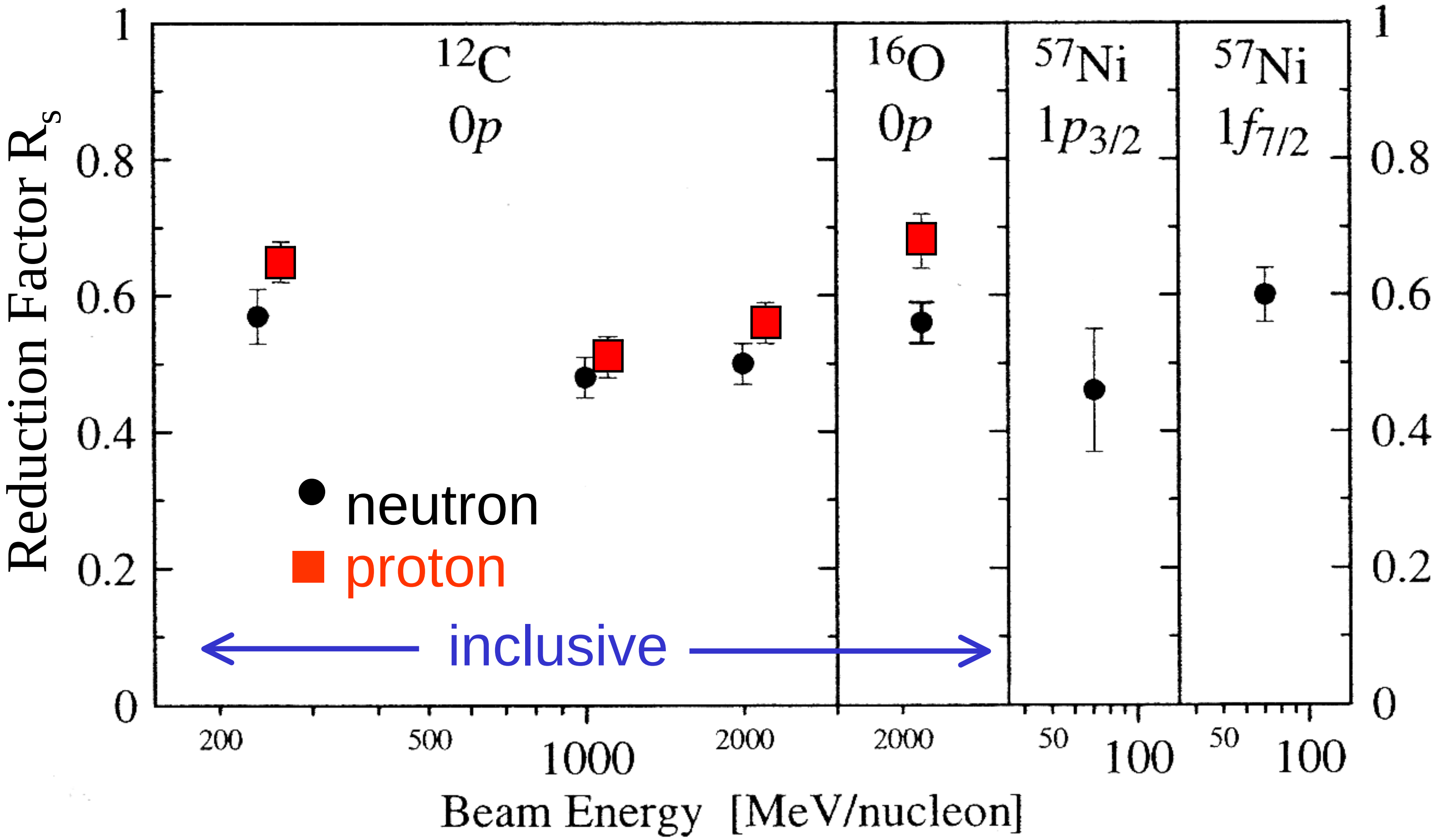


Weakly bound states – with good statistics



P.G. Hansen and J.A.Tostevin, ARNPS **53** (2003), 219

More strongly bound states – n and p knockout



P.G. Hansen and J.A.Tostevin, ARNPS **53** (2003), 219

Results from e-induced knockout – stable nuclei

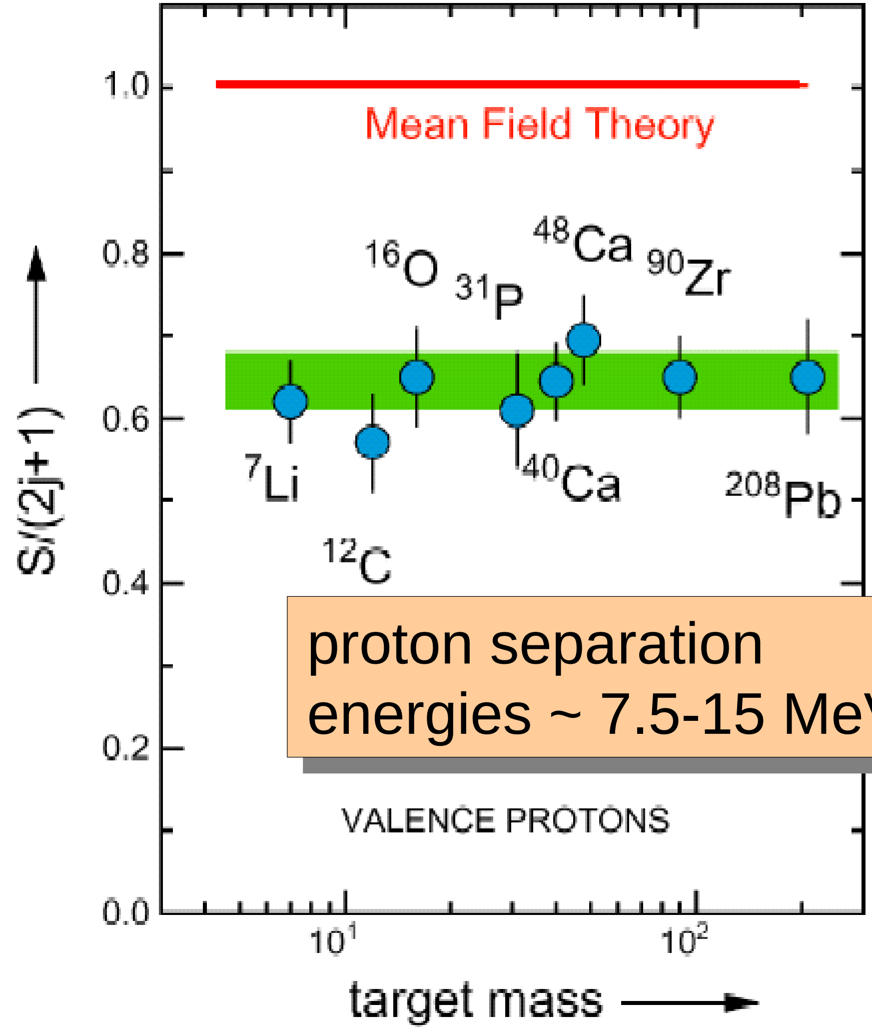
Departures of measured spectroscopic factors from the <u>independent single-particle model</u> predictions

Electron induced proton knockout reactions:

[A,Z] (e,e′p) [A-1,Z-1]

See only 60-70% of strength expected!

W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci., in press

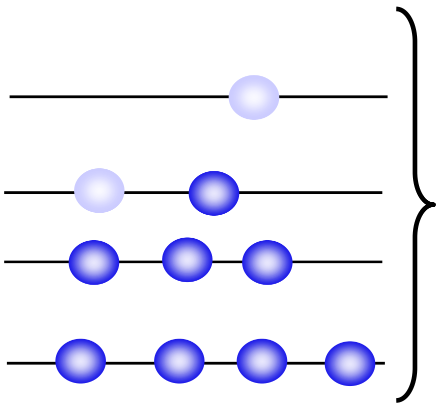


proton separation energies ~ 7.5-15 MeV

Correlations and truncated model spaces

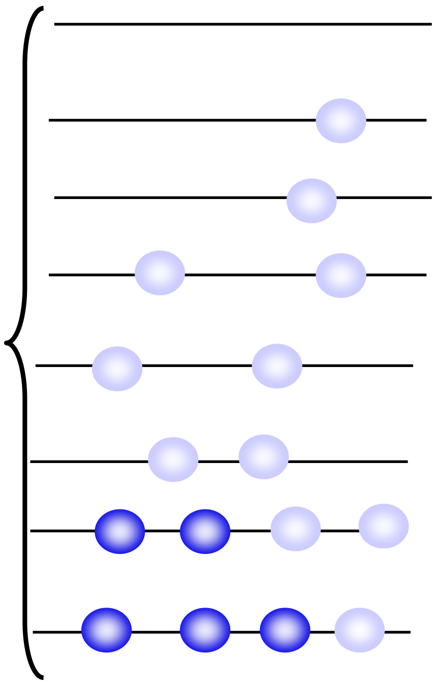
Truncated shell model space – with effective force

but reality is ? …



Few active orbitals, high ‘occupancy’

Greater distribution of nucleons to higher energy configurations - reduced occupancy of valence orbits



Filled core states

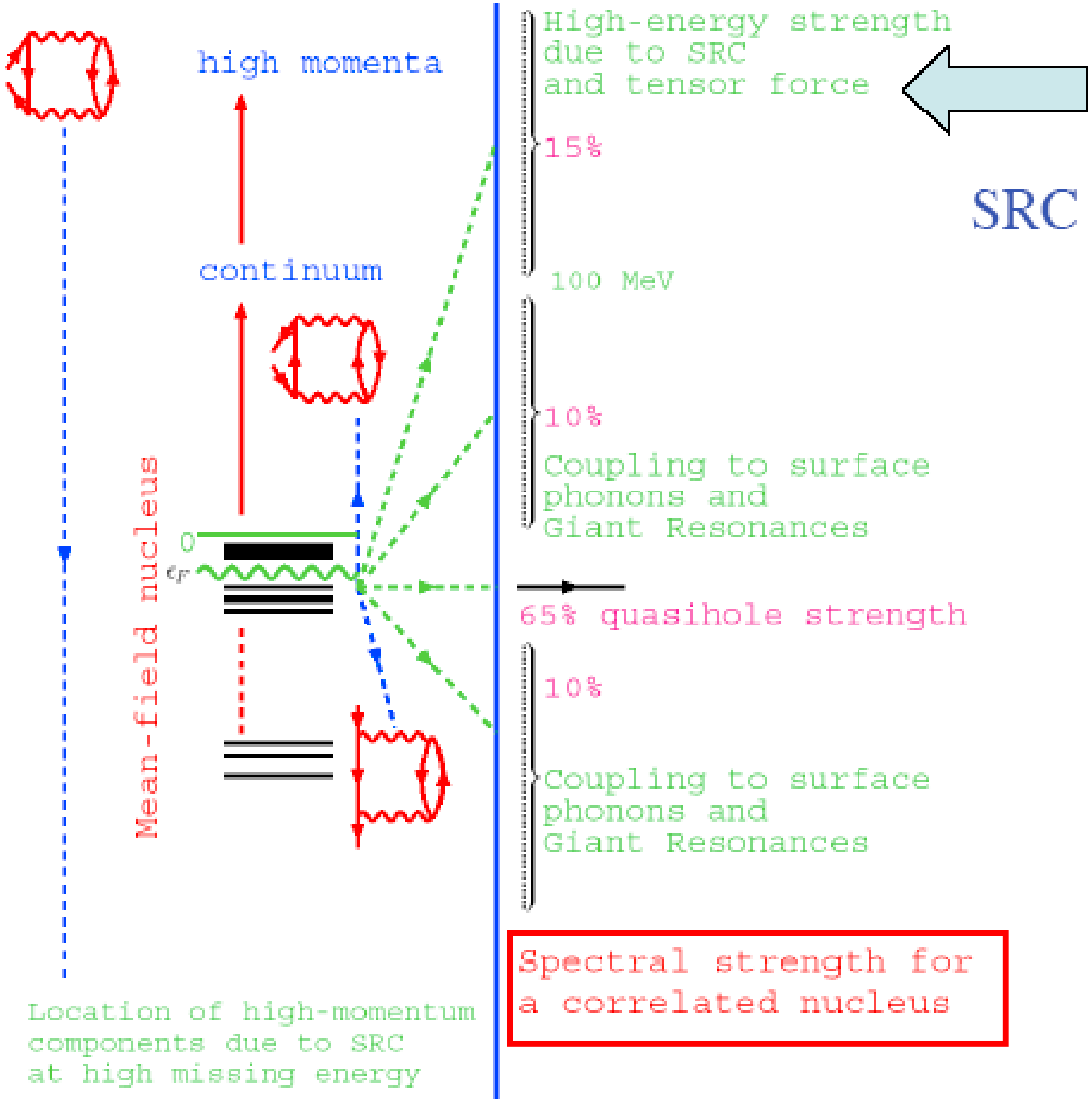
Short range, tensor force and collective correlations

Filled core states

Shifted (mean field) particle/hole strength

Location of single-particle strength in nuclei

Wim Dickhoff
Trento 2004

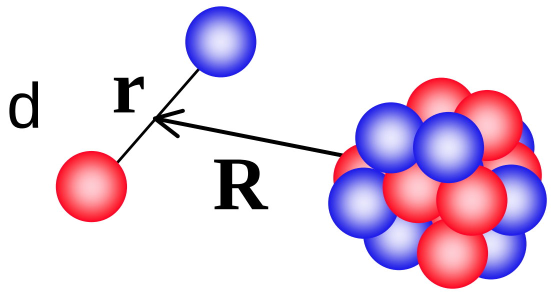


Adiabatic model of transfer reactions: e.g. (d,p)

$$T_{dp} = \left\langle \chi_p^{(-)}(\mathbf{r}_p)\phi_n(\mathbf{r}_n) \middle| V_{np} \middle| \Psi_{\mathbf{K}}^{(+)}(\mathbf{r},\mathbf{R}) \right\rangle$$

note $|\,\mathbf{r}\,| \leq$ range of V_{np}

$$[T_{\mathbf{R}} + U(\mathbf{r},\mathbf{R}) + H_d - E]\,\Psi_{\mathbf{K}}^{(+)} = 0$$



$$H_d \rightarrow -\varepsilon_0\,,\quad \Psi_{\mathbf{K}}^{(+)} \rightarrow \Psi_{\mathbf{K}}^{AD}$$

$$[T_{\mathbf{R}} + U(\mathbf{r},\mathbf{R}) - E_0]\,\Psi_{\mathbf{K}}^{AD} = 0$$

<u>ADIABATIC</u> $(|\,\mathbf{r}\,| \leq \text{range of } V_{np})$

$$\Psi_{\mathbf{K}}^{AD} \approx \phi_0(\mathbf{r})\,\tilde{\chi}_{\mathbf{K}}^{AD}(\mathbf{R})$$

$$[T_{\mathbf{R}} + \tilde{V}(\mathbf{R}) - E_0]\,\tilde{\chi}_{\mathbf{K}}^{AD} = 0$$

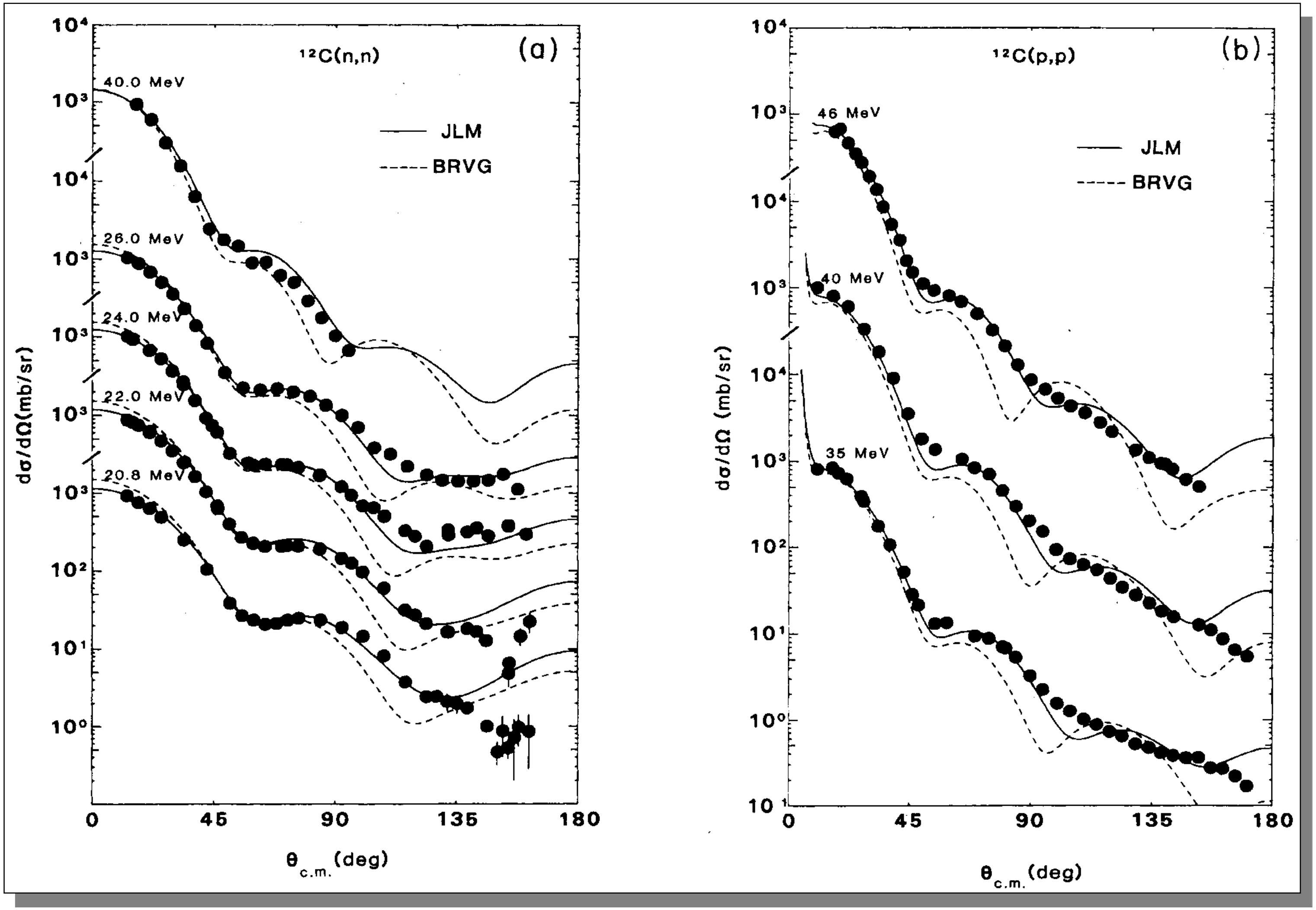
$$\tilde{V}(\mathbf{R}) = \frac{\langle \phi_0 \,|\, V_{np} U(\mathbf{r},\mathbf{R}) \,|\, \phi_0 \rangle}{\langle \phi_0 \,|\, V_{np} \,|\, \phi_0 \rangle} \approx U(\mathbf{r}=0,\mathbf{R})$$

<u>Three-body model</u>

Need to specify nucleon target optical potentials and the nucleon-core single-particle formfactor only – <u>must be consistent</u>

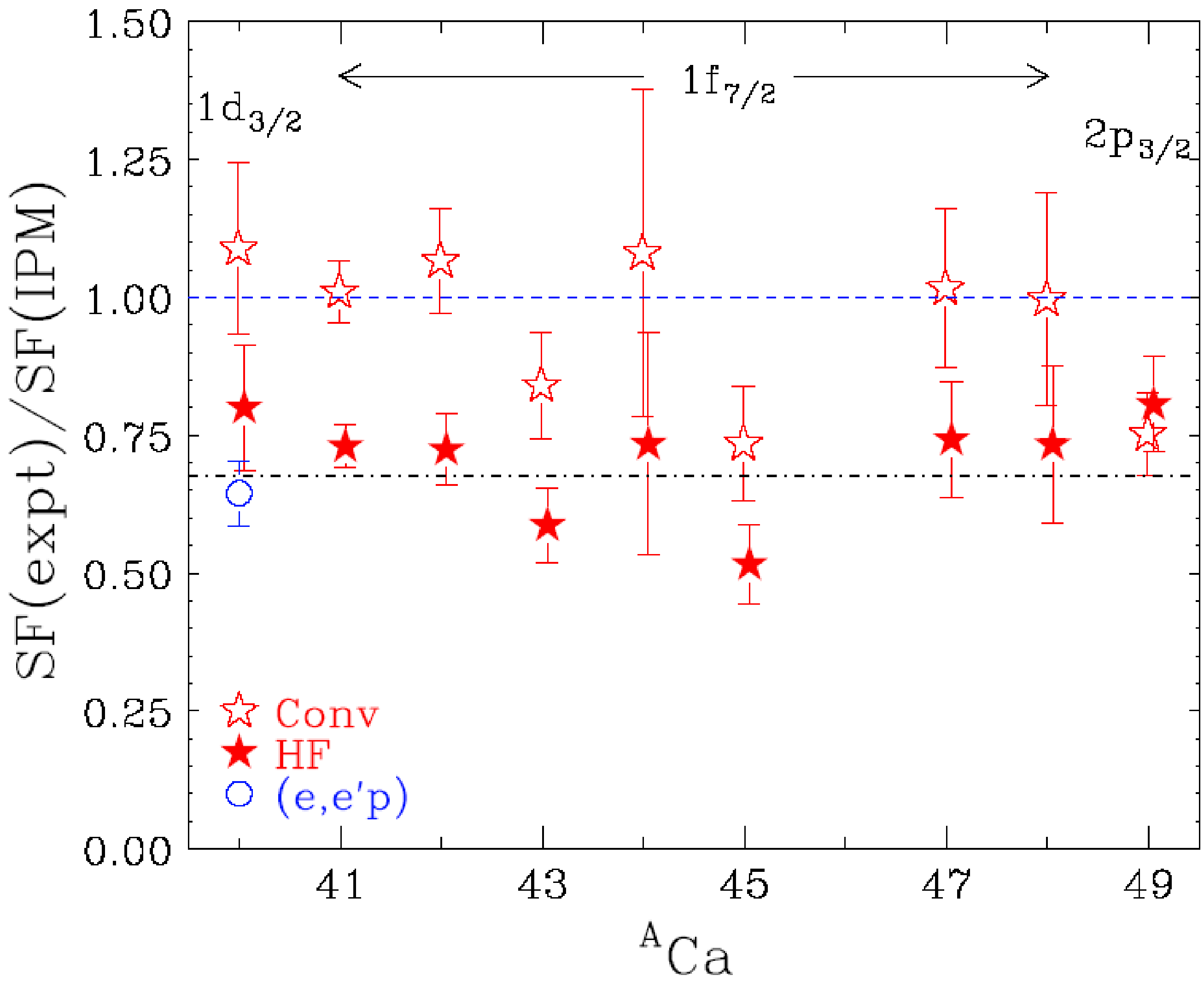
R.C. Johnson and P.J.R. Soper Phys. Rev. C **1** (1970), 976

JLM microscopic nucleon optical potentials



J.S. Petler et al. Phys. Rev. C **32** (1985), 673

Ca isotopic chain: from (d,p) and (p,d)

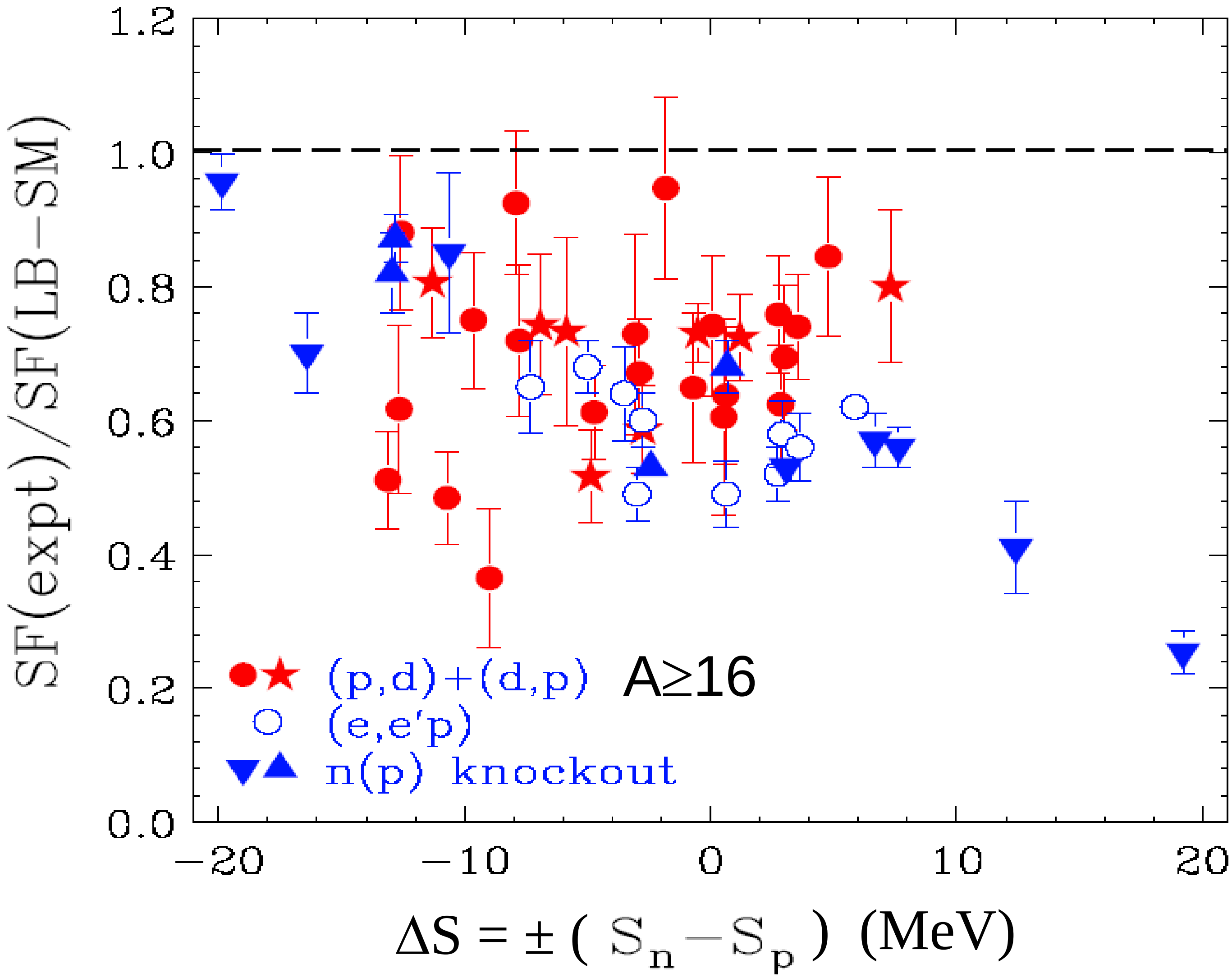


"Standard"

HF constrained

J.Lee, JAT, et al. in preparation

Correlation with the pn interaction?



J.Lee, JAT, et al. in preparation

Asymmetric nuclei – Fermi surfaces

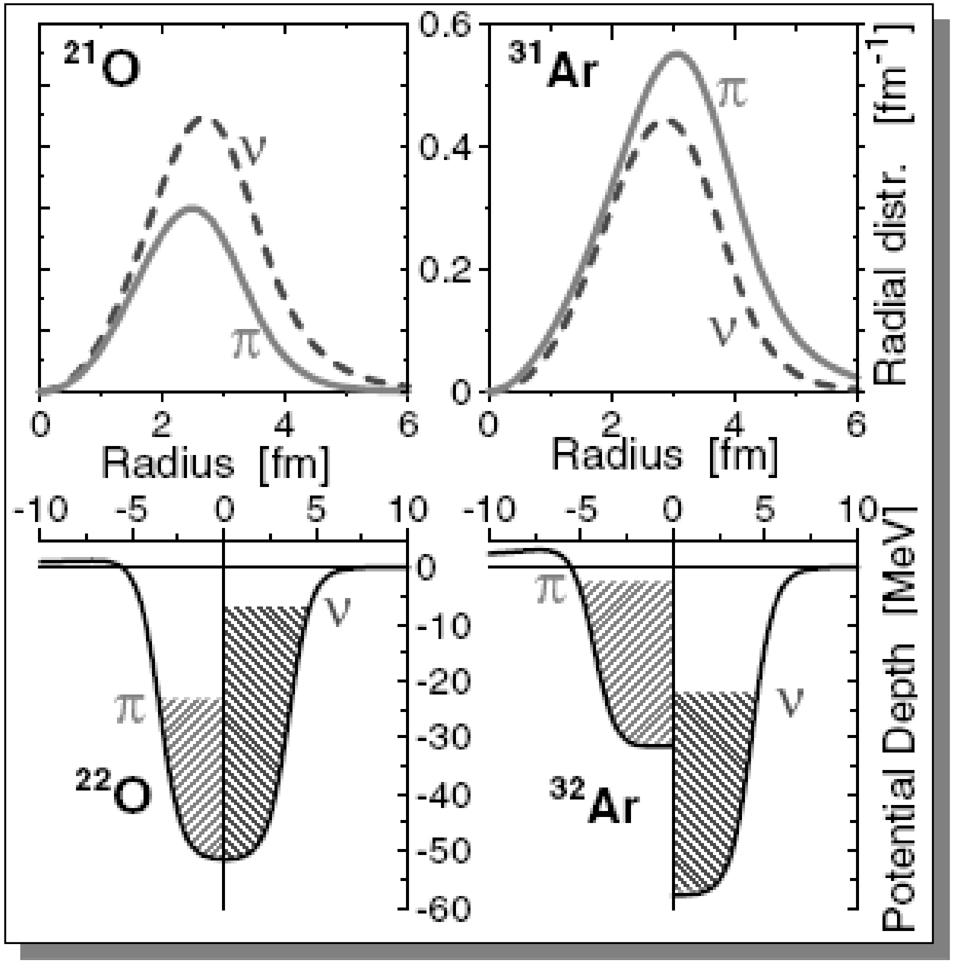
$^{22}O \rightarrow {}^{21}O$

Z=8

N=14

S_n=6.8 MeV

S_p=23 MeV



$^{32}Ar \rightarrow {}^{31}Ar$

Z=18

N=14

S_n=22 MeV

S_p=2.4 MeV

A.Gade et al., Phys. Rev. Lett. **93** (2004), 042501

Operators for the 2N absorption cross section

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

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

core survival

nucleon

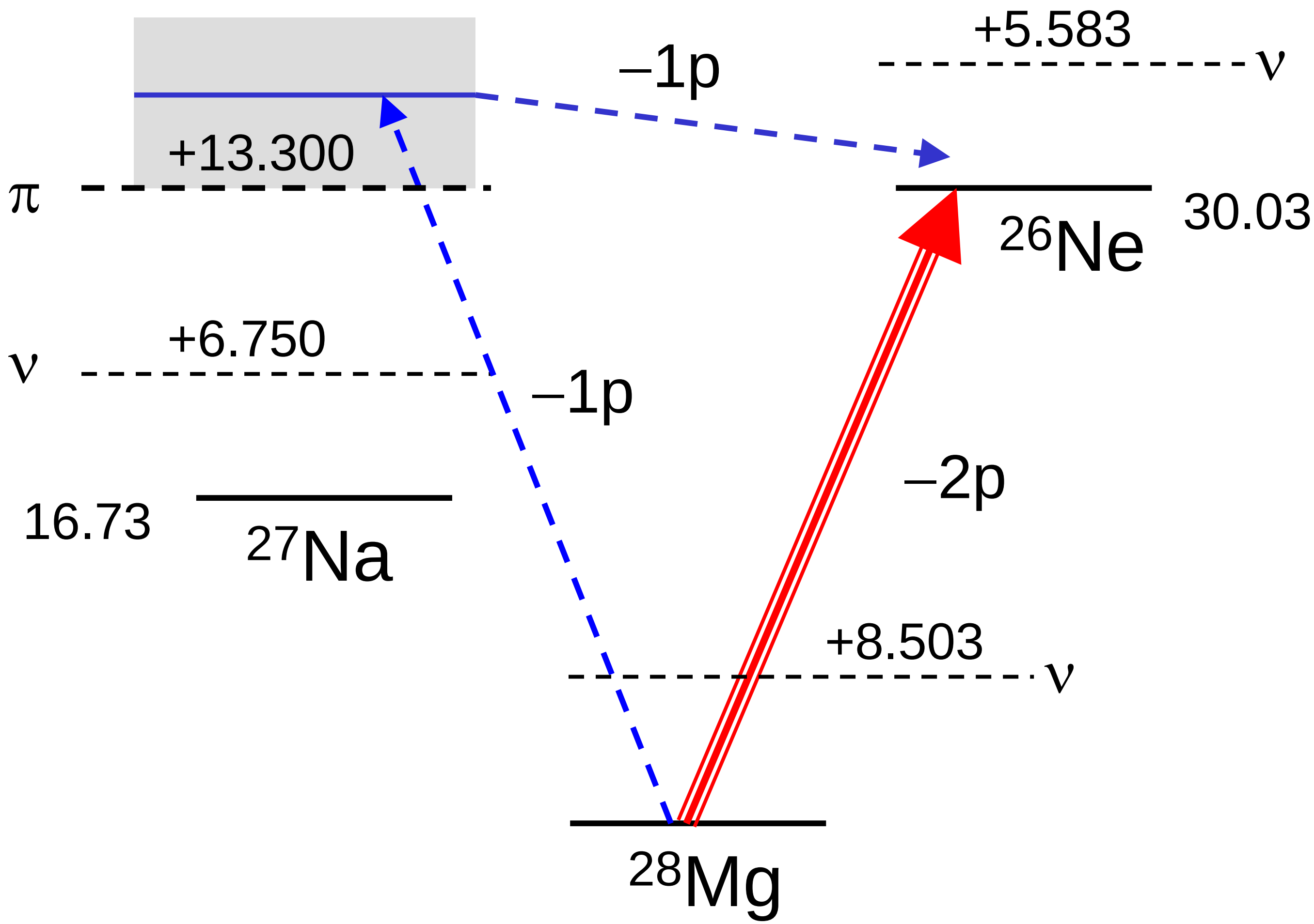
" knockout "

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

2N stripping

1N absorbed
1N surviving

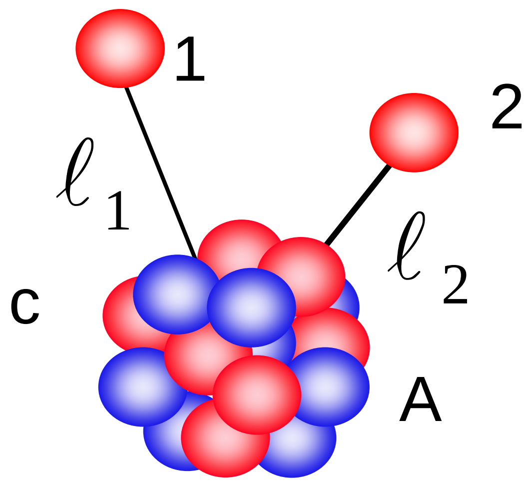
Direct two-proton knockout – ^{28}Mg → ^{26}Ne



Uncorrelated two-proton removal

$^{28}Mg \rightarrow {}^{26}Ne$(inclusive)

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



Assuming $(1d_{5/2})^4$ then

$$\sigma_{-2N} = \frac{4(4-1)}{2}\sigma_{strip}(22) \approx 1.8\,\text{mb}$$

Expt: 1.50(1) mb

$$\sigma_{strip}(22) = 0.29\text{ mb}$$

$$\sigma_{strip}(02) = 0.32\text{ mb}$$

$$\sigma_{strip}(00) = 0.35\text{ mb}$$

with weights to the ^{26}Ne final states from fractional parentage

0^+: 1.33
2^+: 1.67
4^+: 3.00

Cross sections – correlated (SM) stripping

^{28}Mg $\rightarrow$ ^{26}Ne(82.3 MeV/u) S = σ(in mb) / 0.29

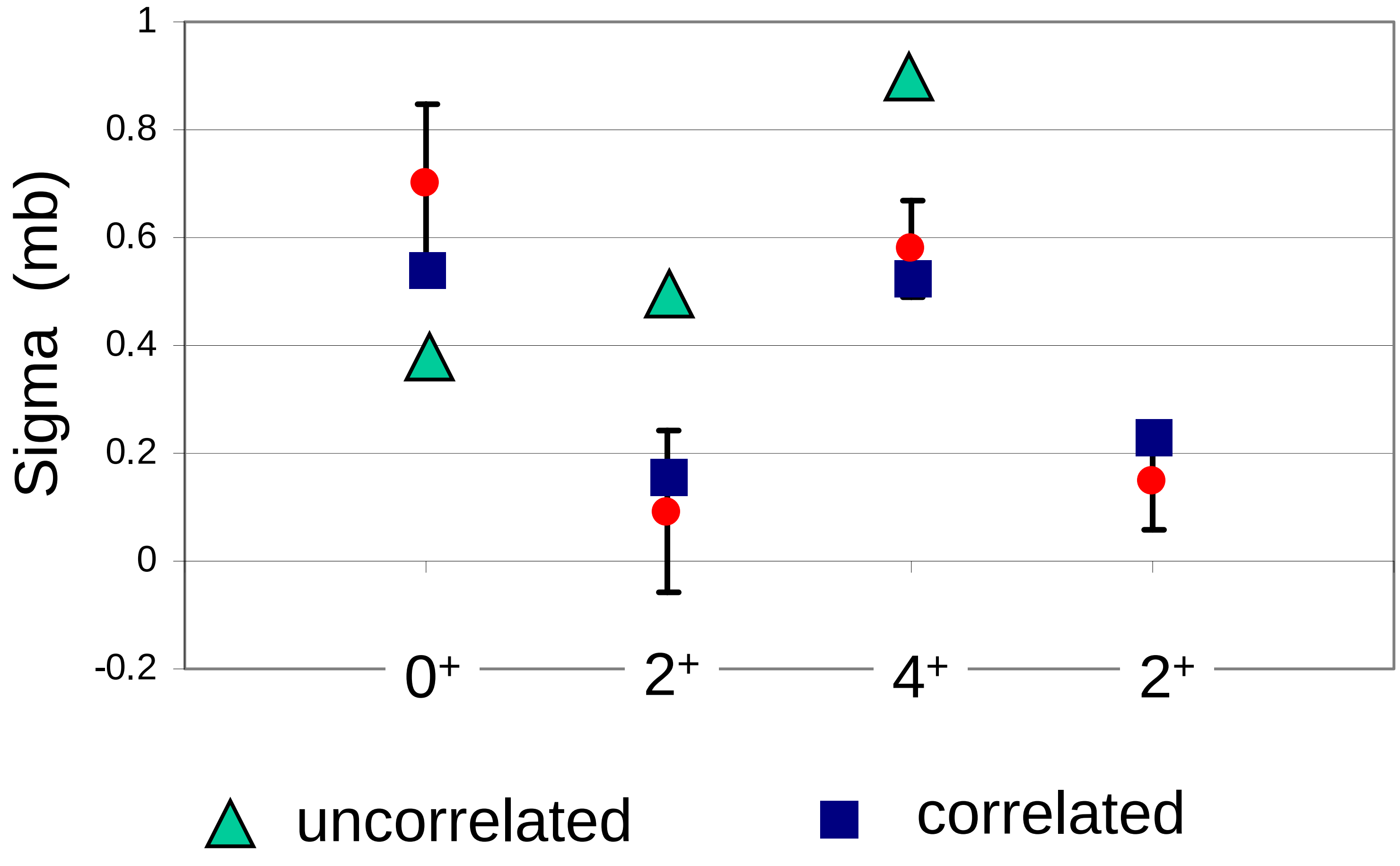
	S_{th} unc.	S_{exp}	S_{th} corr.	σ_{exp} (mb)	σ_{th} (mb)
0⁺	1.33	**2.4(5)**	**1.83**	0.70(15)	0.532
2⁺	1.67	**0.3(5)**	**0.54**	0.09(15)	0.157
4⁺	3.00	**2.0(3)**	**1.79**	0.58(9)	0.518
2⁺	-	**0.5(3)**	**0.78**	0.15(9)	0.225

Inclusive cross section (in mb) **1.50(10)** **1.43**

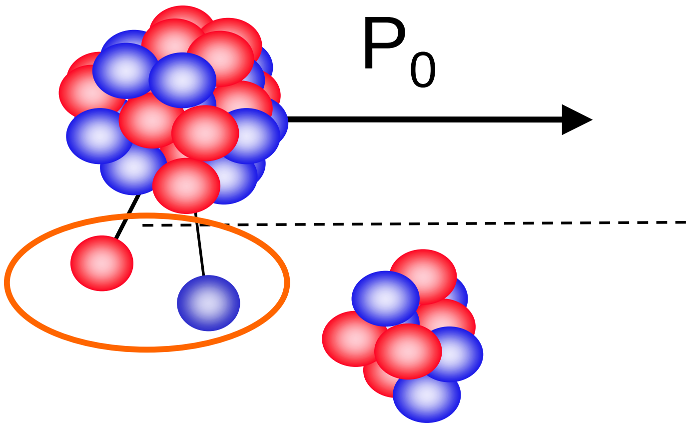
J.A. Tostevin, G. Podolyák, et al., PRC **70** (2004) 064602.

Stripping cross sections – correlated (SM) case

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

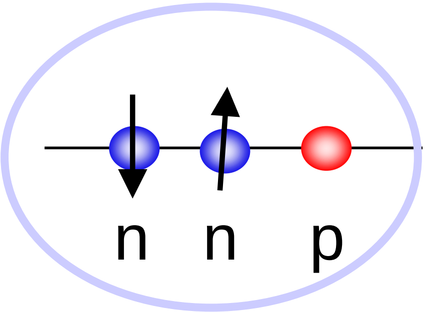


Nature of the (SM) NN-pair correlations probed ?



Removed nucleon pair are <u>spatially</u> correlated but no restriction on pair spin (S=0,1) or relative orbital angular momentum in formalism. All contributing pair wave functions are included.

Unlike, e.g. (p,t) reaction – ⟨p|t⟩ where structure selects nn pair with J=S=0 in relative ℓ =0



Can assess - by projecting S=0 component of knockout

Spin-correlations – not the same as in transfer

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

J_f^π	S_{unc}	S_{rel}	S'_{rel}	$S_{S=0}$	S_{exp}	S_{th}	σ_{th} (mb)	$\sigma_{S=0}$ (mb)
0^+	1.33	1.6	1.88	3.70	2.4(5)	1.83	0.532	0.484
2^+	1.67	0.14	0.15	0.26	0.3(5)	0.54	0.157	0.034
4^+	3.00	(2.0)	(2.0)	(2.0)	2.0(3)	1.79	0.518	0.259
2_2^+	-	0.46	0.43	0.95	0.5(3)	0.78	0.225	0.123

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

The diffractive/stripping contributions

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

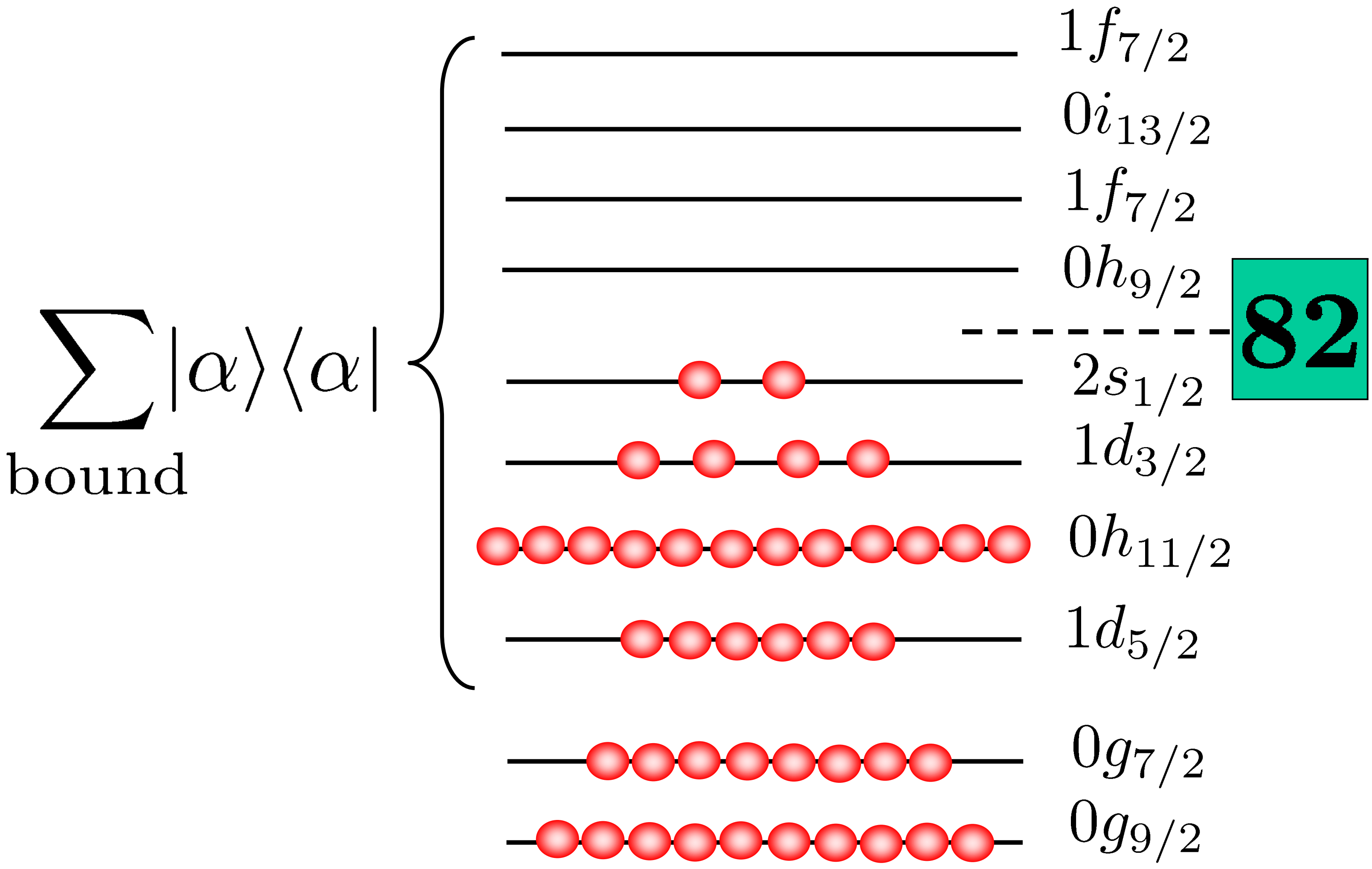
nucleon 2 absorbed

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

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

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

2p knockout from ^{208}Pb : excluded bound states



Importance of diffractive terms - correlated

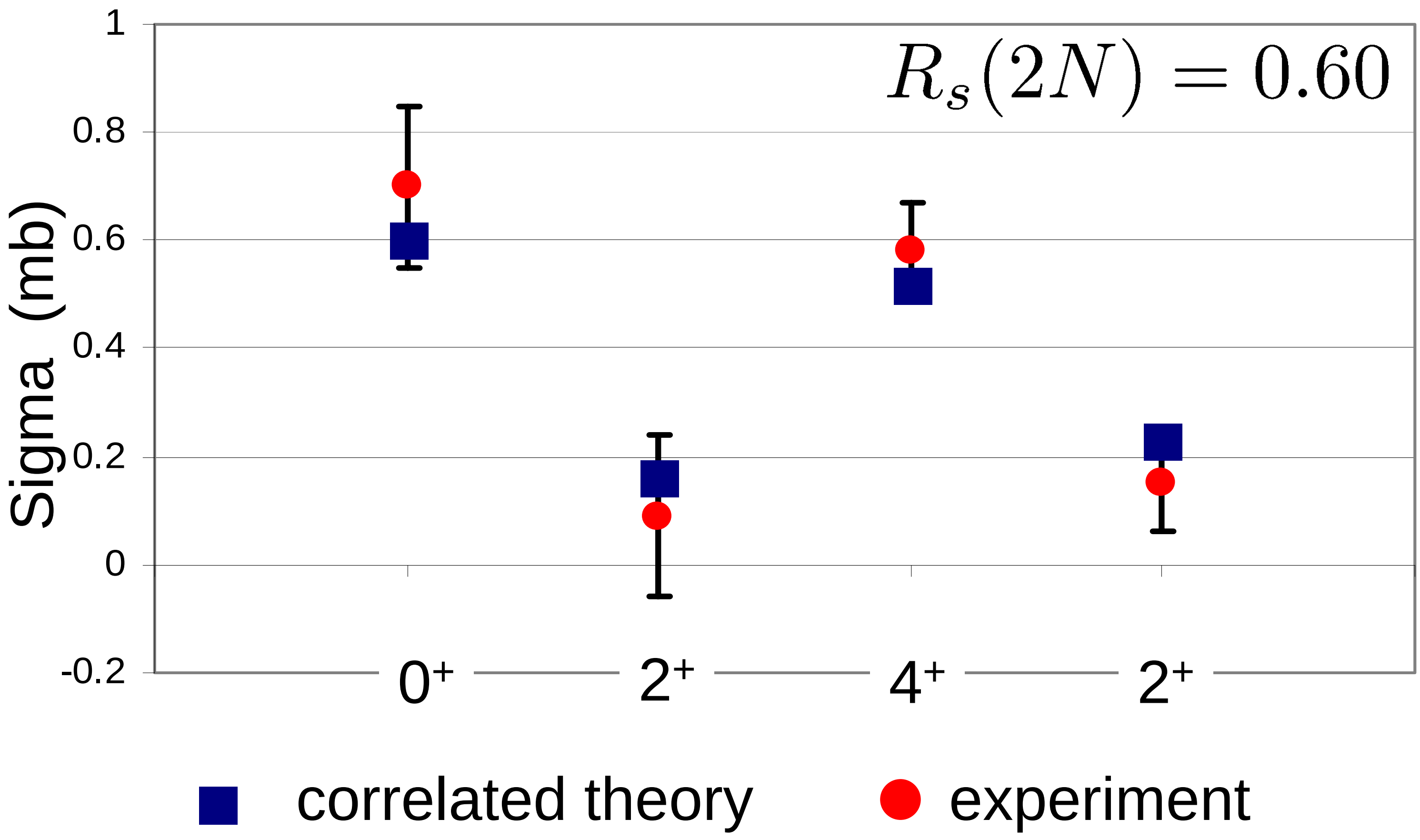
$^{28}Mg \rightarrow ^{26}Ne(0^+,\ 2^+,\ 4^+,\ 2_2^+)$ 82.3 MeV/u

J^π	stripping	diff/strip	diffraction*	$\sigma(J^\pi)$ (mb)
0^+	0.543	0.389	0.070	1.002
2^+	0.159	0.093	0.014	0.266
4^+	0.524	0.296	0.042	0.862
2_2^+	0.229	0.135	0.020	0.382
Incl.	1.455	0.913	0.145	2.514
Expt.				1.50(10)

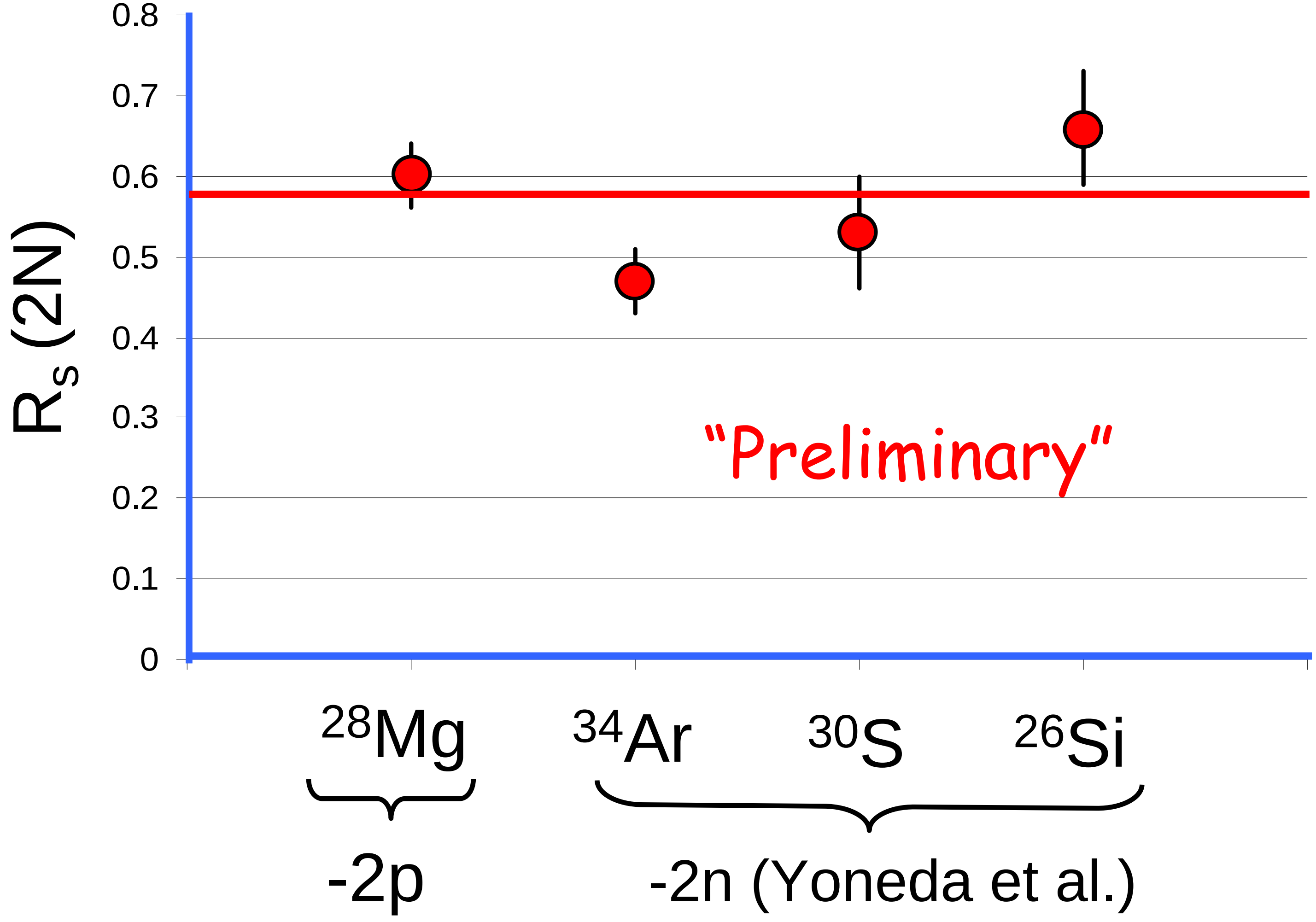
so suppression of $R_s(2N) = 1.50(10)/2.514 = 0.60(4)$

Stripping cross sections – correlated (SM) case

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



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



Conclusions

At fragmentation energies (>50 MeV/u) reaction theory is accurate, allowing the possibility to extract quantitative structure information

Deviations from (shell) model space spectroscopic strengths are being observed in one and two-nucleon knockout. This technique can access stable and unstable nuclei, as well as neutron sp states. Is this telling us about NN correlations? We rely on the use of simple radial overlaps but these are constrained by Hartree-Fock - systematics.

Only limited overlap with cases studied using (e,e′p). Agreement in cases of ^{12}C and ^{16}O (inclusive data). Transfer reactions are broadly consistent when theoretically constrained. Can accuracy of these be improved?

Still limited two neutron/proton knockout data, but they already reveal sensitivity to 2N wave function and both S=0,1 pair correlations. There is evidence of suppression of 2N strength relative to the shell model ~0.6

Direct 2N knockout reaction mechanism can be very clean and selective – scope for more test cases and applications. N and 2N, shell gaps, seniority-2 isomers, ..