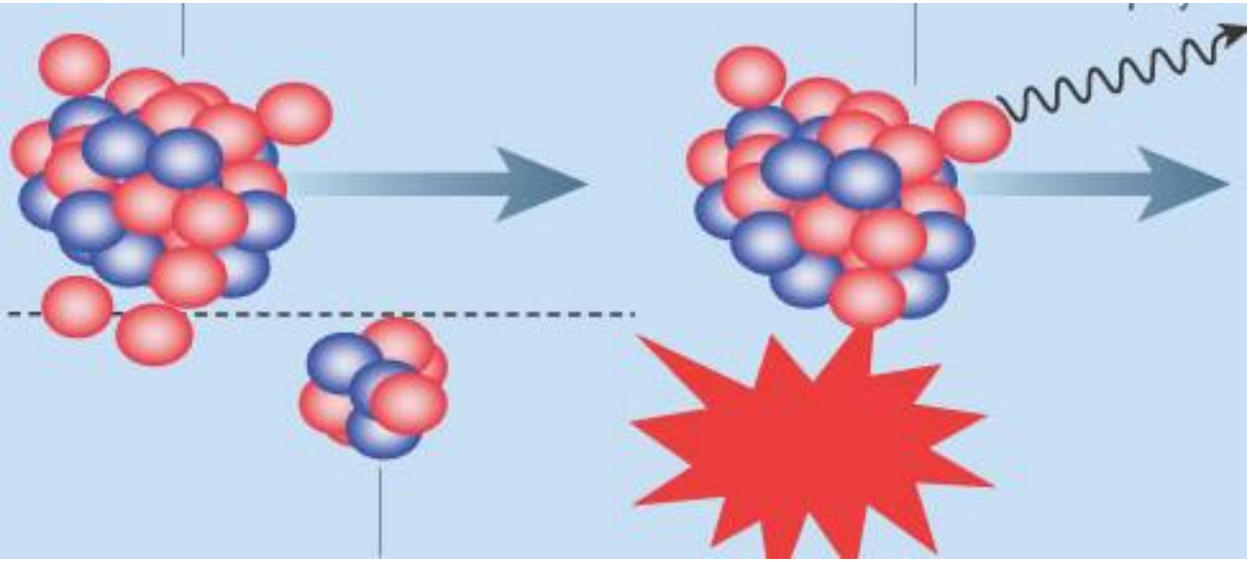
Nucleon knockout reactions – Status and open questions

Alexandra Gade

INT workshop, August 2011



National Superconducting Cyclotron Laboratory and
Department of Physics and Astronomy

Michigan State University, East Lansing, MI

Outline

- Status of one-nucleon knockout
- Reduction factors – who is to blame?
- Light nuclei – test of ab-initio structure theory
    - ^{10}Be-1n: probing the $\langle ^{10}\mathrm{Be}|^{9}\mathrm{Be}+n\rangle$ overlap
    - ^{10}C-1n : probing the $\langle ^{10}\mathrm{C}|^{9}\mathrm{C}+n\rangle$ overlap
- Sensitivity and precision test of reaction theory
- Status of two-nucleon knockout
- Reduction factors are back …
- Summary and outlook

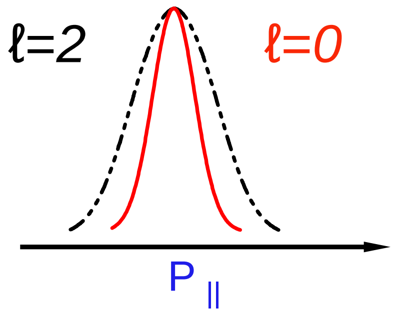
One-nucleon knockout

- More than 50MeV/nucleon:

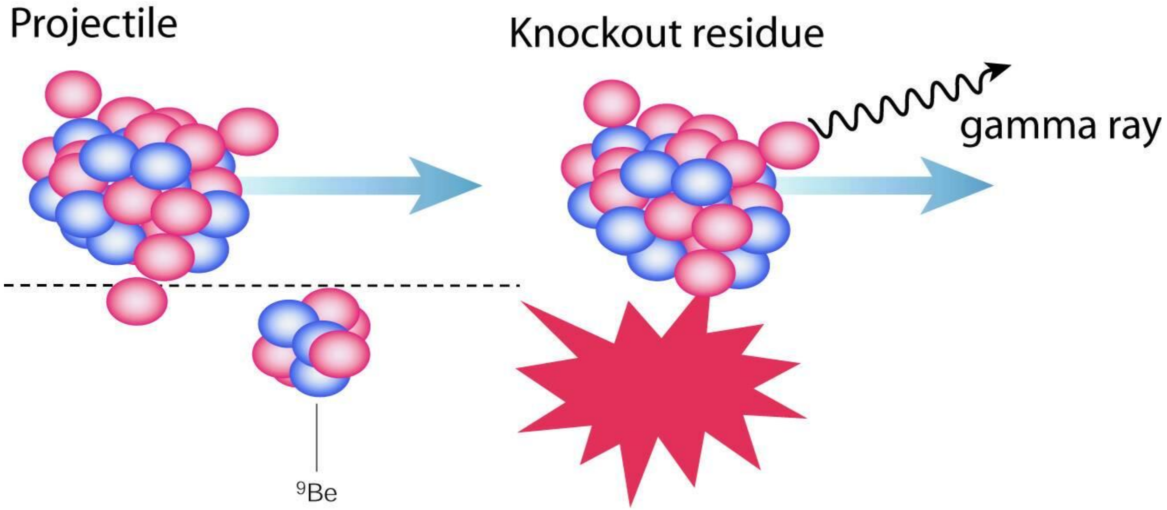
sudden approximation + eikonal approach (J.A. Tostevin, Surrey)

- Spectroscopic strengths

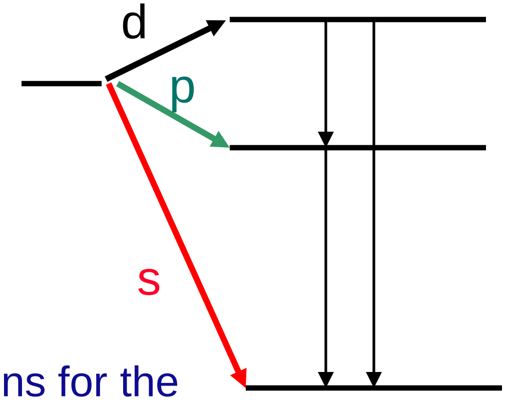
determined from the population of the residue with A-1



residue moment distribution
→ ℓ-value of knocked-out n



Compare measured to
calculated cross sections



Cross sections for the
population of final states
→ Spectroscopic strength

Theoretical cross section

Theoretical cross section:

$$\sigma(j^\pi) = \left(\frac{A}{A-1}\right)^N C^2 S(j^\pi)\sigma_{sp}(j, S_N + E_x[j^\pi])$$

Reaction theory

Structure theory

CoM correction – needed
for CI SM with HO basis

A. E. L. Dieperink and T. de Forest, PRC 10, 533 (1974)

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

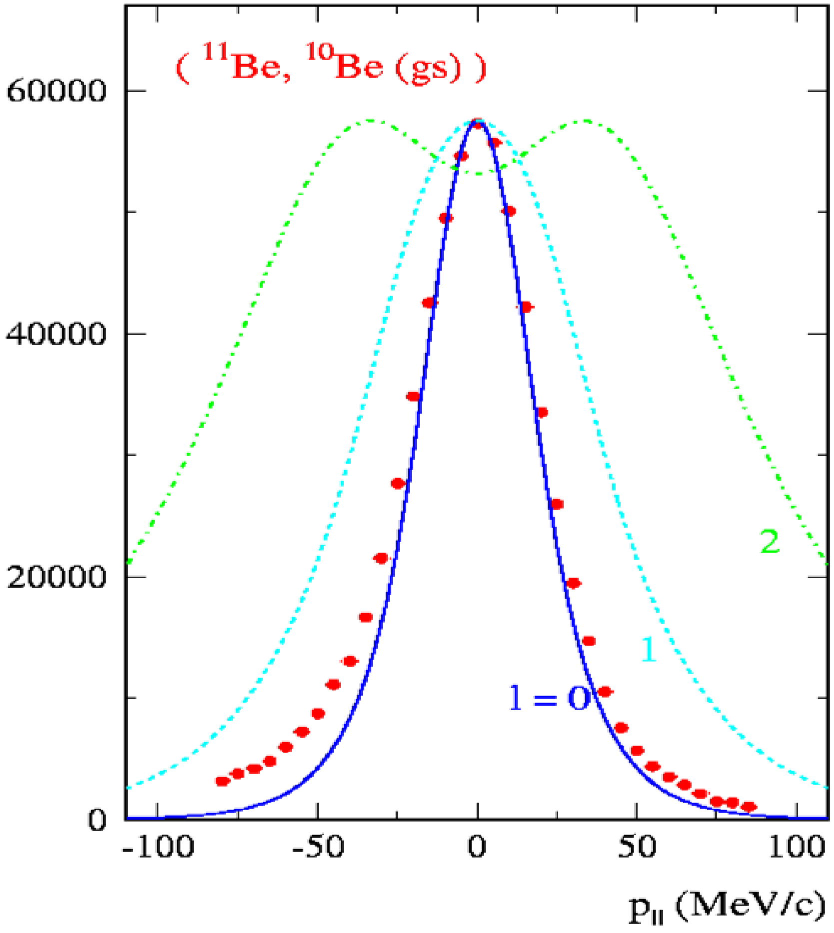
$$\sigma_{sp}(j,S_N) = \sigma_{sp}^{strip}(j,S_N) + \sigma_{sp}^{diffr}(j,S_N)$$

J. A. Tosetvin, J. Phys. G. 25, 735 (1999)

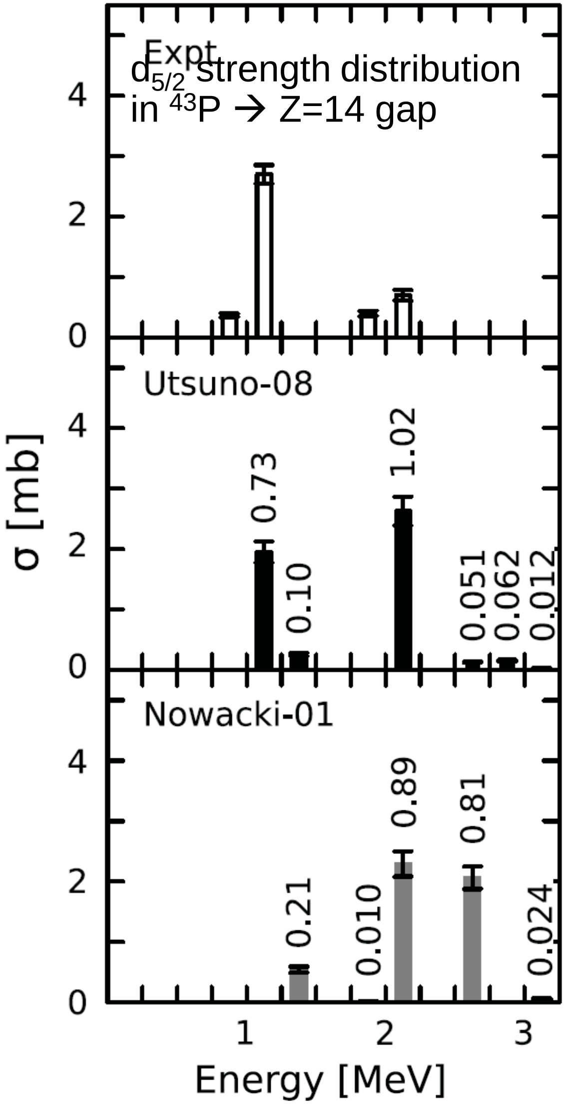
- spectator-core approximation to many-body eikonal theory
- (A-1) residue: at most elastically scattered
- S matrices as function of impact parameter from double-folding approach to Glauber multiple-scattering theory (free nn np cross sections with Gaussian range parameters $\beta_{nn}=\beta_{np}=0.5$ fm. Real-to-imaginary ratios interpolated from tables in *L. Ray, PRC 20, 1875 (1979)* .
- nucleon-residue relative wave functions: eigenfunctions of effective 2-body Hamiltonian containing a local potential with the depth adjusted to reproduce the separation energy

Knockout used so far

Halo states, T. Aumann et al., Phys. Rev. Lett. 84, 35 (2000)

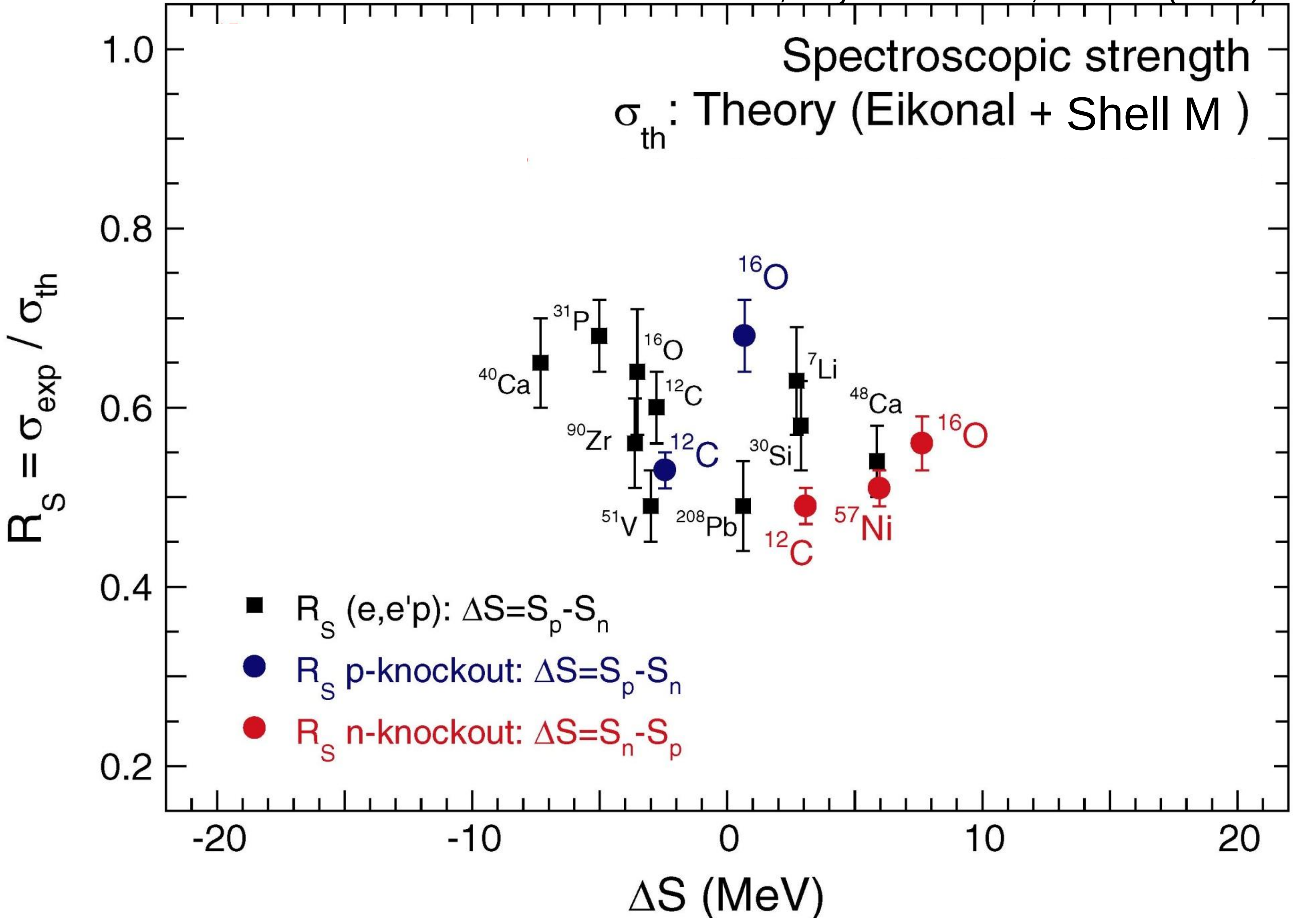


Tracking single particle strength . Example: ^{44}S-1p, L. A. Riley et al., Phys. Rev. C 78, 011303(R) (2008)



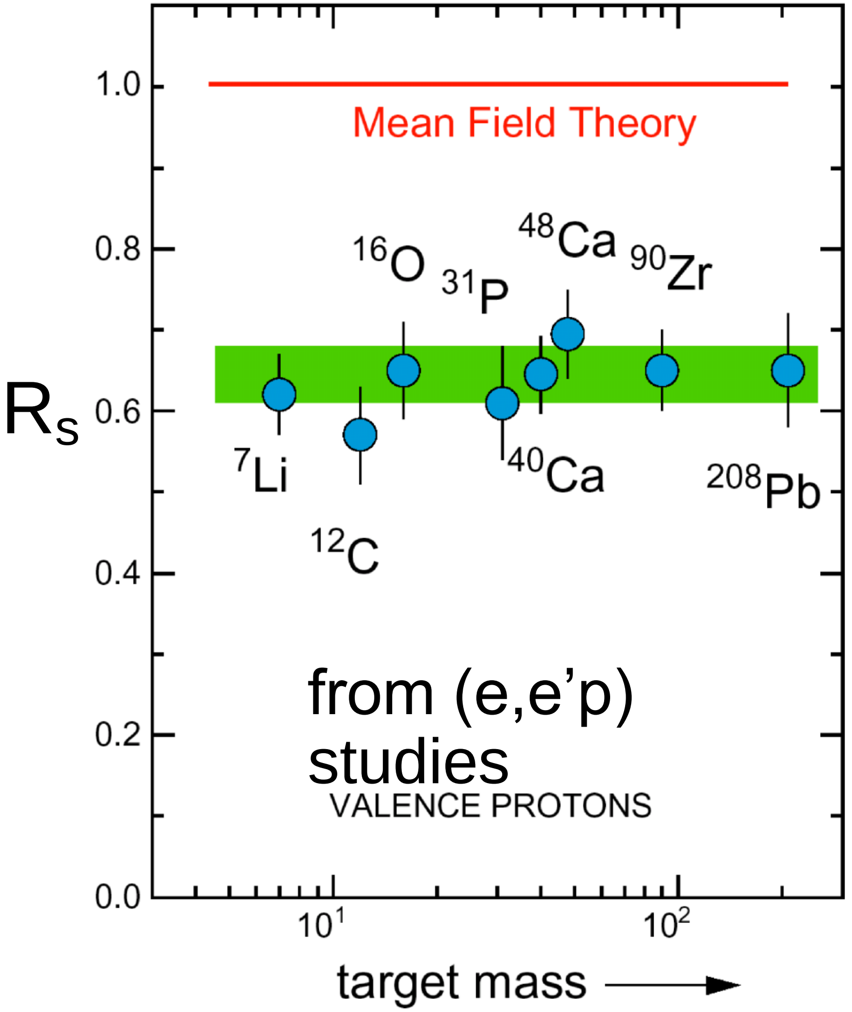
Reduction close to stability

A. Gade et al., Phys. Rev. C 77, 044306 (2008)



Correlation effects beyond effective-interaction theory

Figure from W. Dickhoff



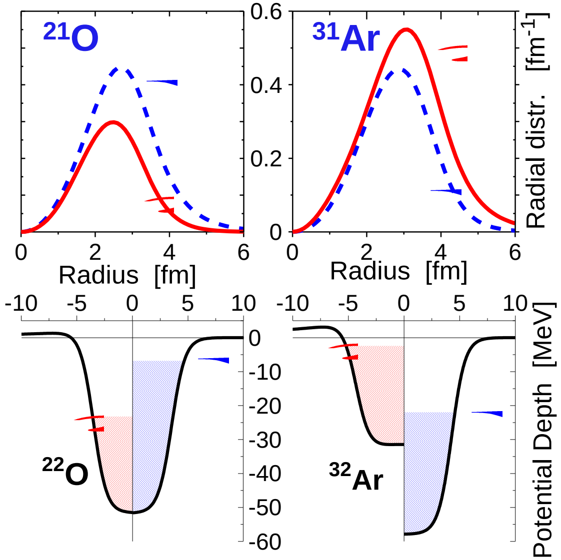
Reduction factor with respect to the IPM $R_s = C^2S_{exp} / C^2S_{IPM}$

The nuclear shell model pictures deeply-bound states as fully occupied by nucleons. At and above the Fermi sea, configuration mixing leads to occupancies that gradually decrease to zero.

Correlation effects (short-range, soft-core, long-range and coupling to vibrational excitations) are beyond the effective interactions employed in the shell model and mean-field approaches. The picture given above will be modified depending on the strength of the correlation.

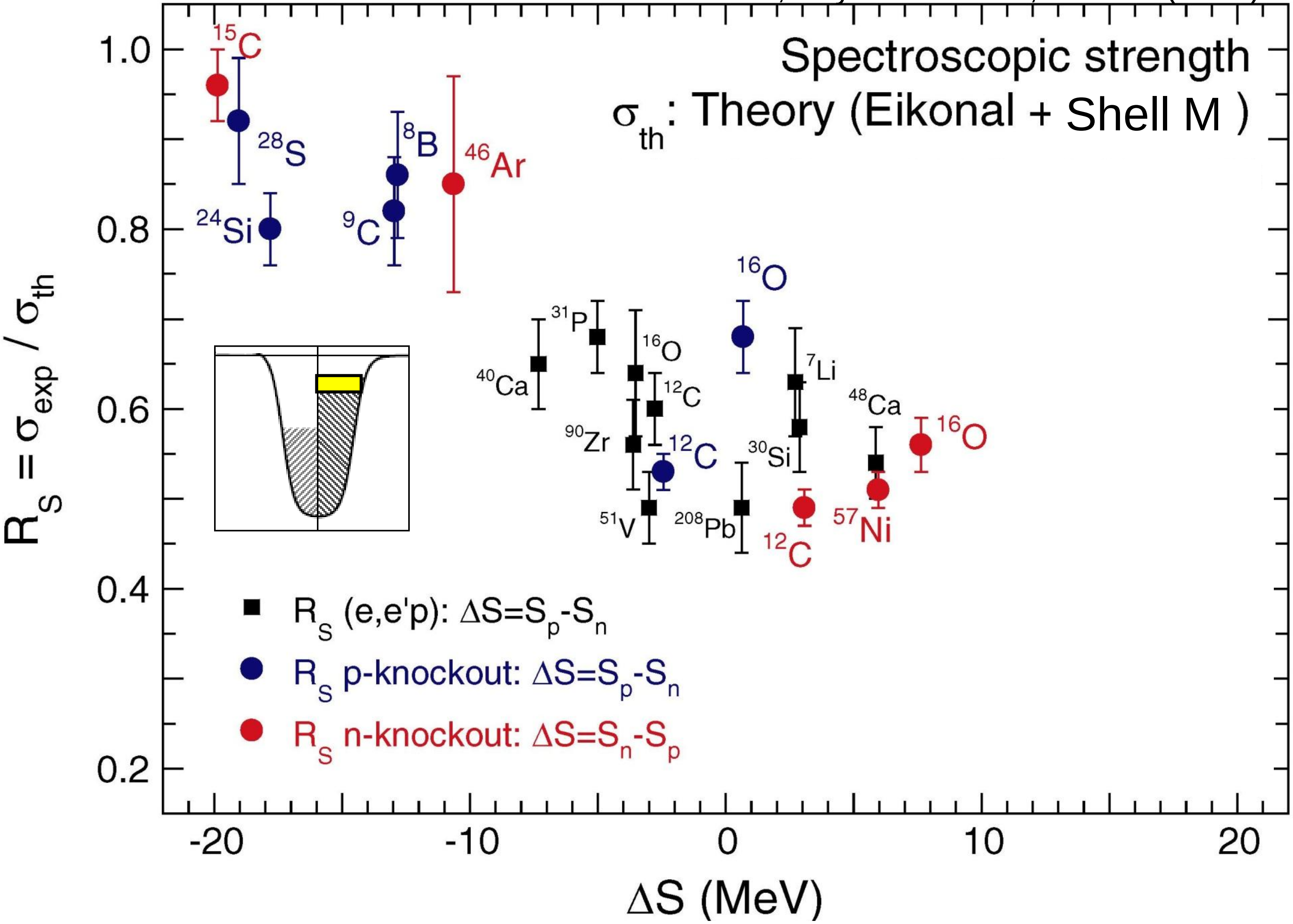
W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci. 52, 377 (2004).

What is the situation in weakly and deeply bound systems?



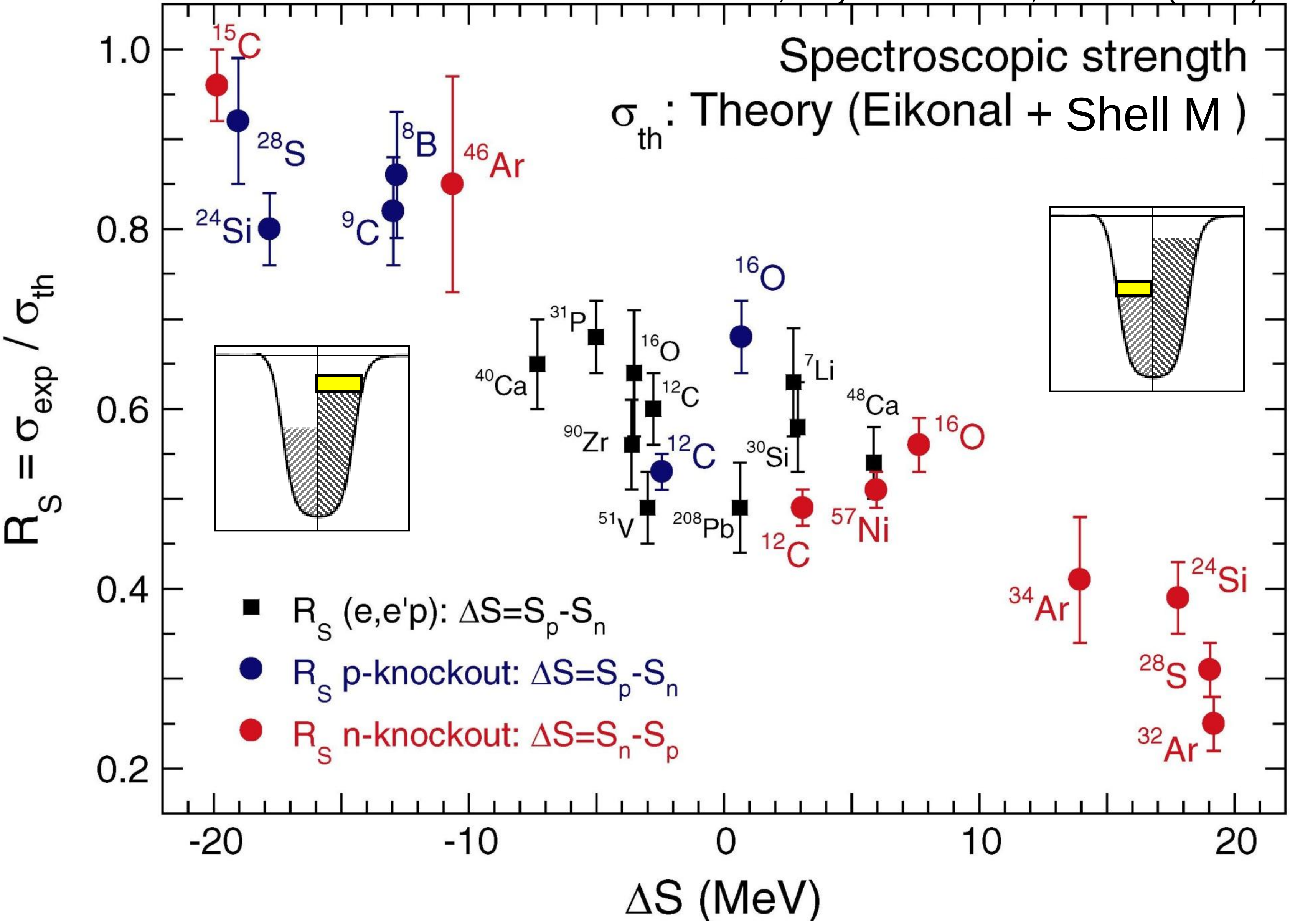
Weakly-bound systems

A. Gade et al., Phys. Rev. C 77, 044306 (2008)



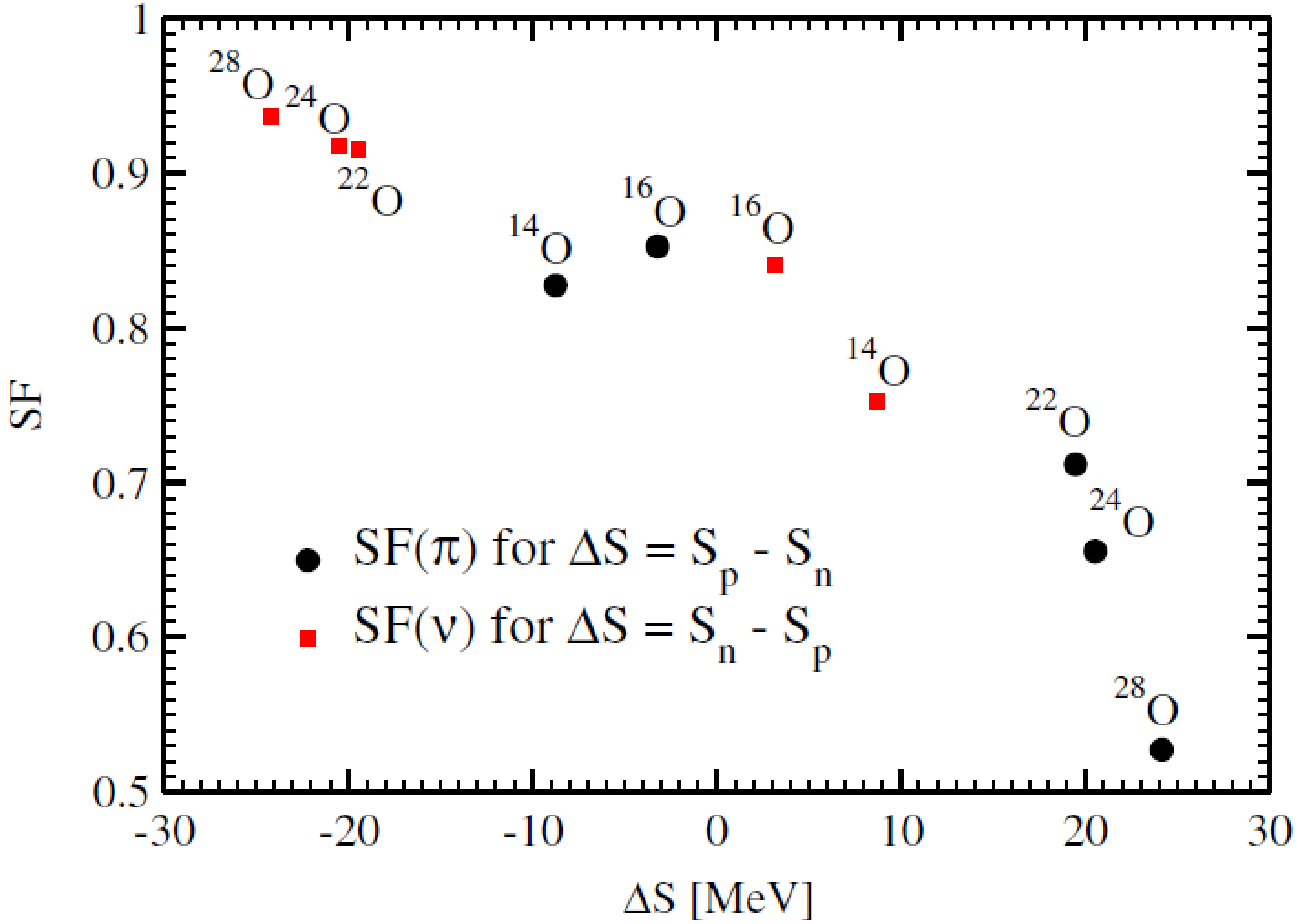
Strongly-bound systems

A. Gade et al., Phys. Rev. C 77, 044306 (2008)



One effect at the dripline … many-body correlations conspiring with the continuum

See Gaute's talk about Coupled-Cluster Calculations



O. Jensen, G. Hagen et al., Phys. Rev. Lett. 107, 032501 (2011)

Consistency with other probes?

For stable nuclei and near stability

- Consistent with (e,e’p)
- Consistent with transfer

  G. J. Kramer, H. P. Blok, and L. Lapikas, Nucl. Phys. A679, 267 (2001)
  Jenny Lee, J.A. Tostevin *et al.*, *Reduced neutron spectroscopic factors when using potential geometries constrained by Hartree-Fock calculations*, Phys. Rev. C 73, 044608 (2006).

In the regime of large asymmetry

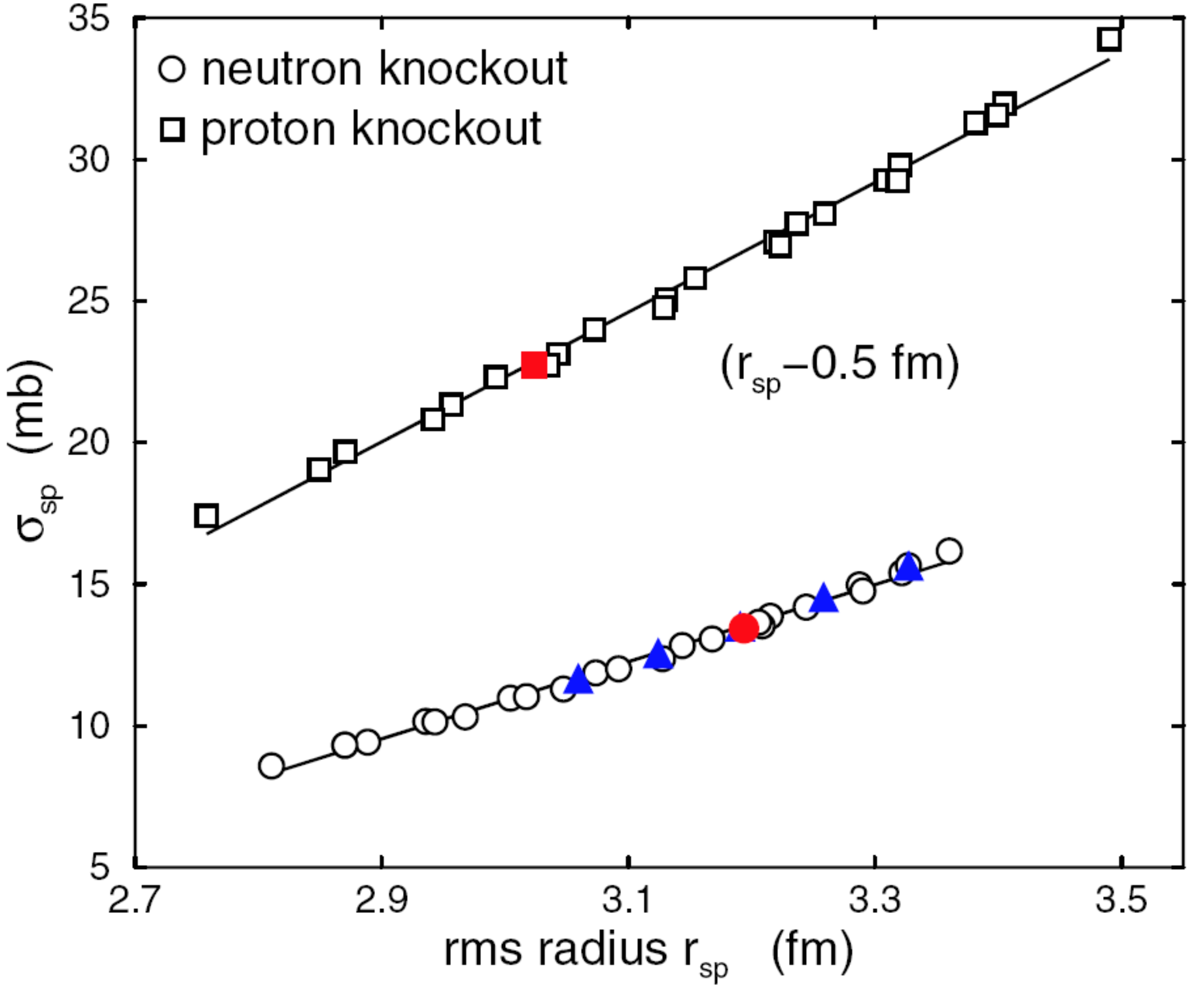
- Trend (not the magnitude) of increased reduction at larger asymmetry found consistent with conclusions from dispersive optical model analyses of elastic scattering data

  R. J. Charity *et al.*, Phys. Rev. C 76, 044314 (2007), Phys. Rev. Lett. 97, 162503 (2006).

Sensitivities: Single-particle cross sections vs. r_{sp}

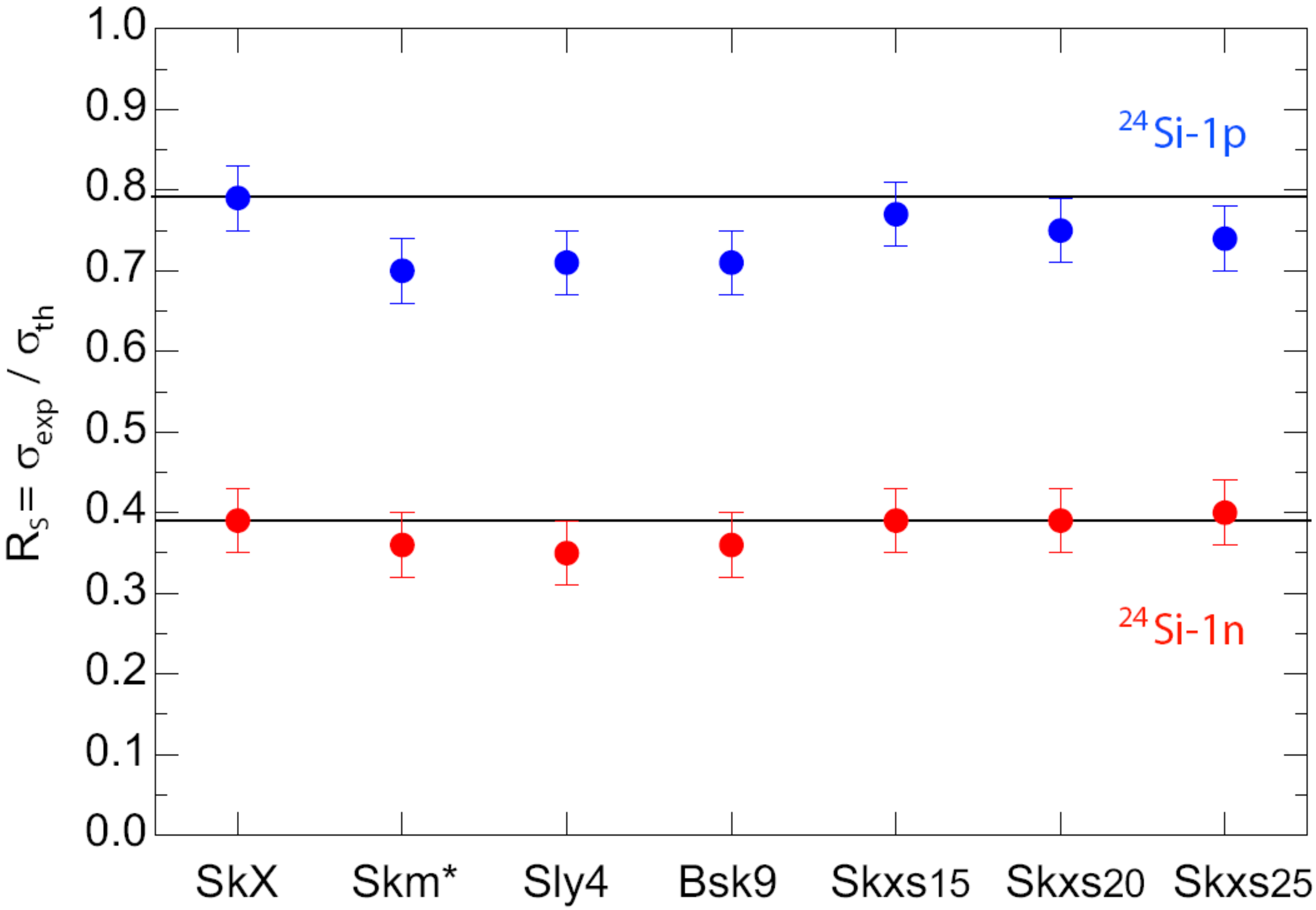
Weakly bound proton and deeply bound neutron from ^{24}Si

- Single-particle cross section calculated using various WS parameter combinations
- Cross section scales directly with single-particle rms radius, independent of shape of potential
- Red points show r_{sp} constrained by HF (SkX) rms radius



A. Gade et al., Phys. Rev. C 77, 044306 (2008)

Different Skyrmes



- SkX: shown to reproduce nuclear sizes will in Ca region
- Skm* gives better surface diffuseness for charge density
- Skxs15(20)(25) represent a reasonable variation in neutron skin thickness in ^{208}Pb
- Sly4 widely used

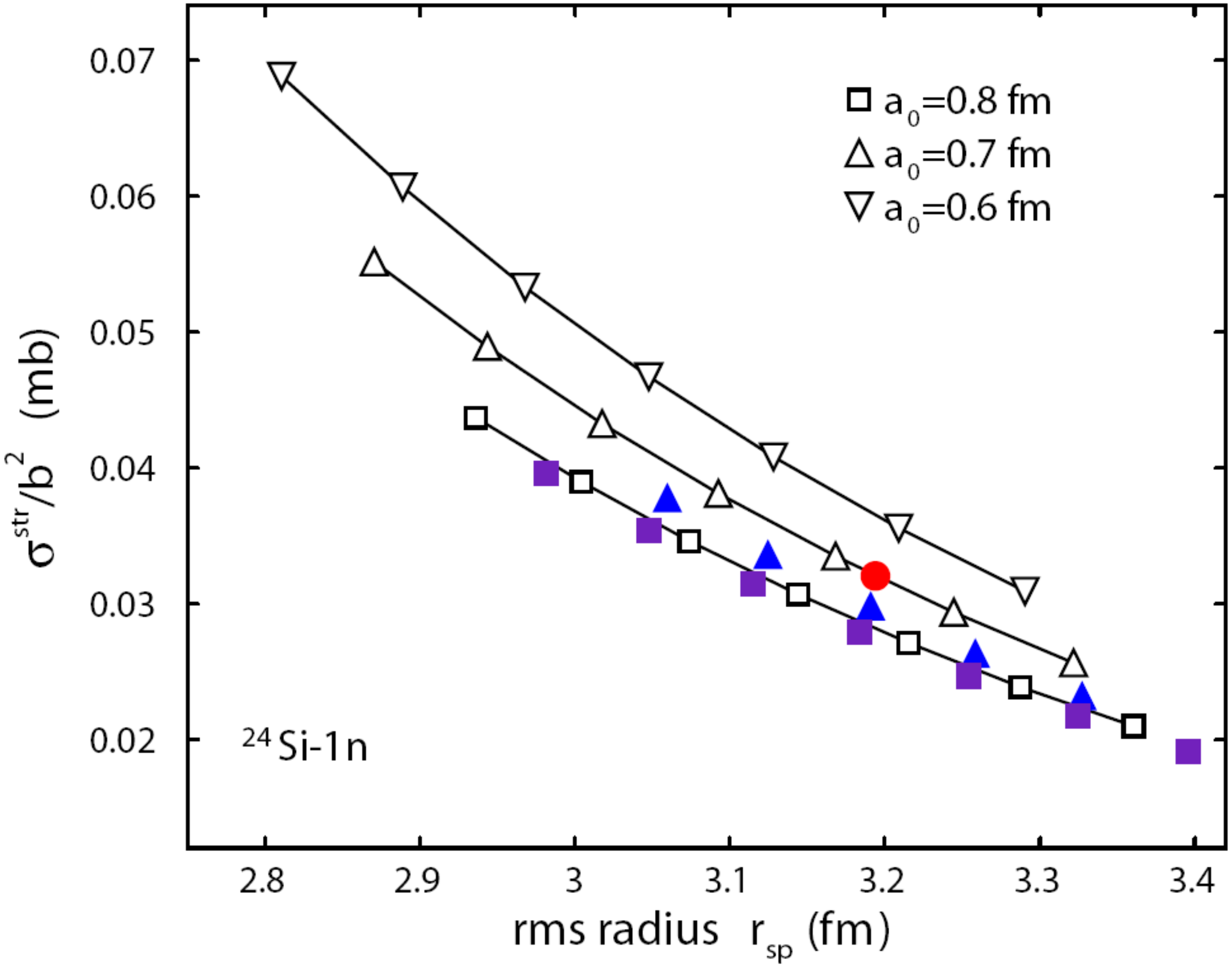
…

A. Gade et al., Phys. Rev. C 77, 044306 (2008)
SKX Skyrme: B. A. Brown, Phys. Rev. C 58, 220 (1998)

Single-particle stripping cross section/ANC^2 vs. r_{sp}

- Single-particle cross section divided by ANC^2
- Neutron removal from ^{24}Si

- Wide range of WS parameters and r_{sp}
- Knockout CS sensitive to more than tail of the WF
- Sensitivity encoded in the strict dependence with r_{sp}



A. Gade et al., Phys. Rev. C 77, 044306 (2008)

What if we go to light nuclei that can be described by ab-initio theory that contains more/most correlation effects?

- Beyond the CI shell model: *ab-initio* approaches
- Solve many-body problem with fully correlated A-body wave functions
- Variational Monte Carlo (VMC) [Bob Wiringa]
- No-core shell model (NCSM) [Petr Navratil]
- Absolute cross sections from knockout reactions relate to overlap integrals
  - Try to probe wavefunction overlaps and point nucleon densities in the double-folding for core-target S-matrix from *ab-initio* models

Consistent calculation of the single-particle cross section

- In the past: Relative core-neutron wave function calculated in Woods-Saxon potential with a=0.7 fm and r_0 adjusted to reproduce the core-neutron rms separation from HF in the ground state. Here: probe overlaps from ab-initio models
- The depth of the potential is chosen to reproduce the effective binding of the initial state
- S-matrix from in double-folding optical limit of Glauber multiple scattering theory
  - Point nucleon densities taken from the ab-initio models were used to calculate the *A=9* core-target S-matrices

Our experiments: Choice of nuclei

Goals and challenges

- Achieve 5% precision on cross section measurement
- Light ions need large acceptances: corrections needed
- Consistent comparison

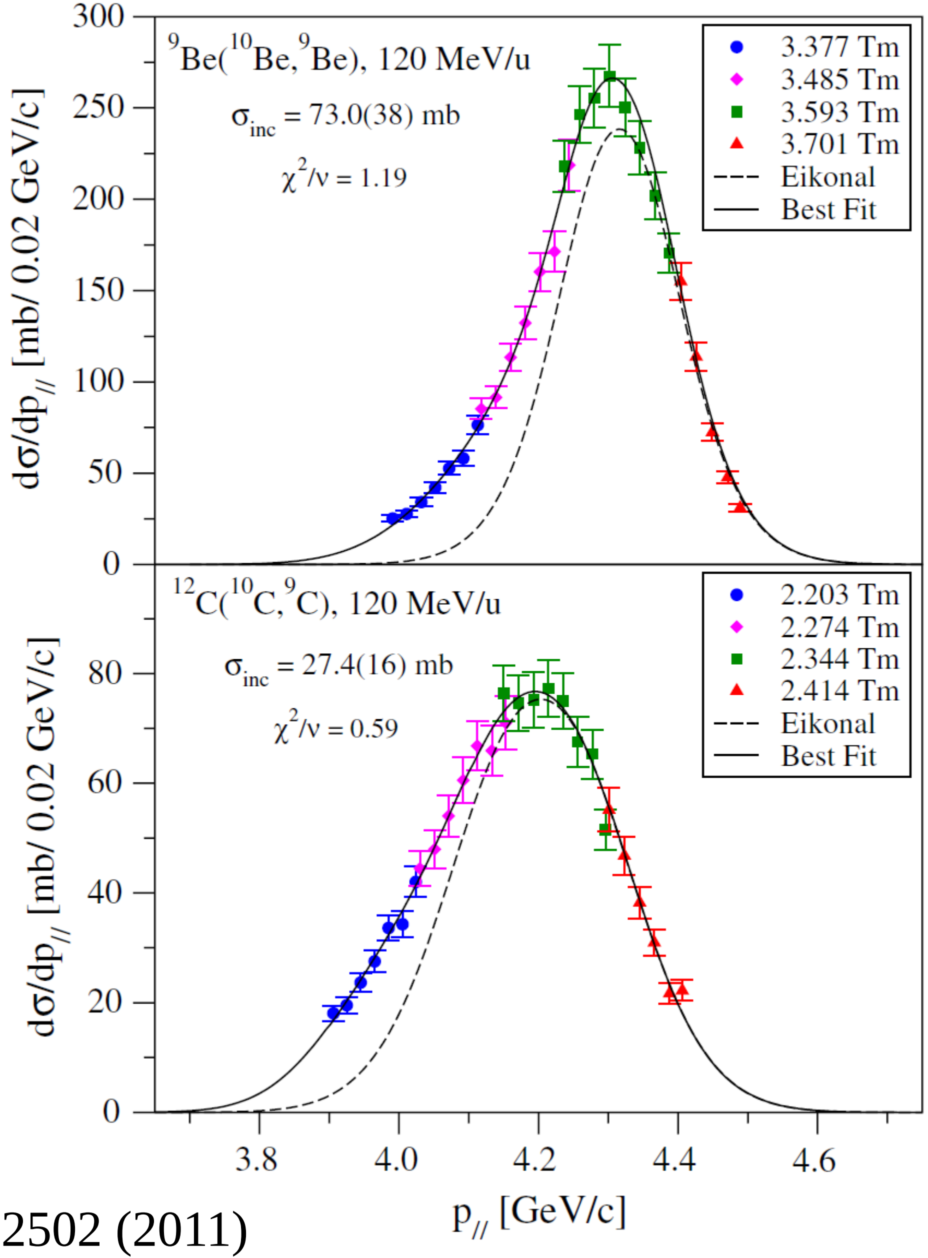
Chosen reactions: neutron knockout on ^{10}Be and ^{10}C

- No bound excited states in ^{9}Be and ^{9}C: one final state only – the ground state
- Different neutron binding energies: 6.8 MeV and 21.3 MeV
- Both VMC and NCSM densities and overlaps available
- Consistent comparison by using the densities and overlaps in reaction model

Longitudinal momentum distributions

Longitudinal momentum

- Required several rigidity settings of spectrometer
- Final distribution fitted with eikonal + Gaussian distributions
- Only ~ 7% of cross section from correction at low and high momentum



G. F. Grinyer et al., Phys. Rev. Lett. 106, 162502 (2011)

Cross sections

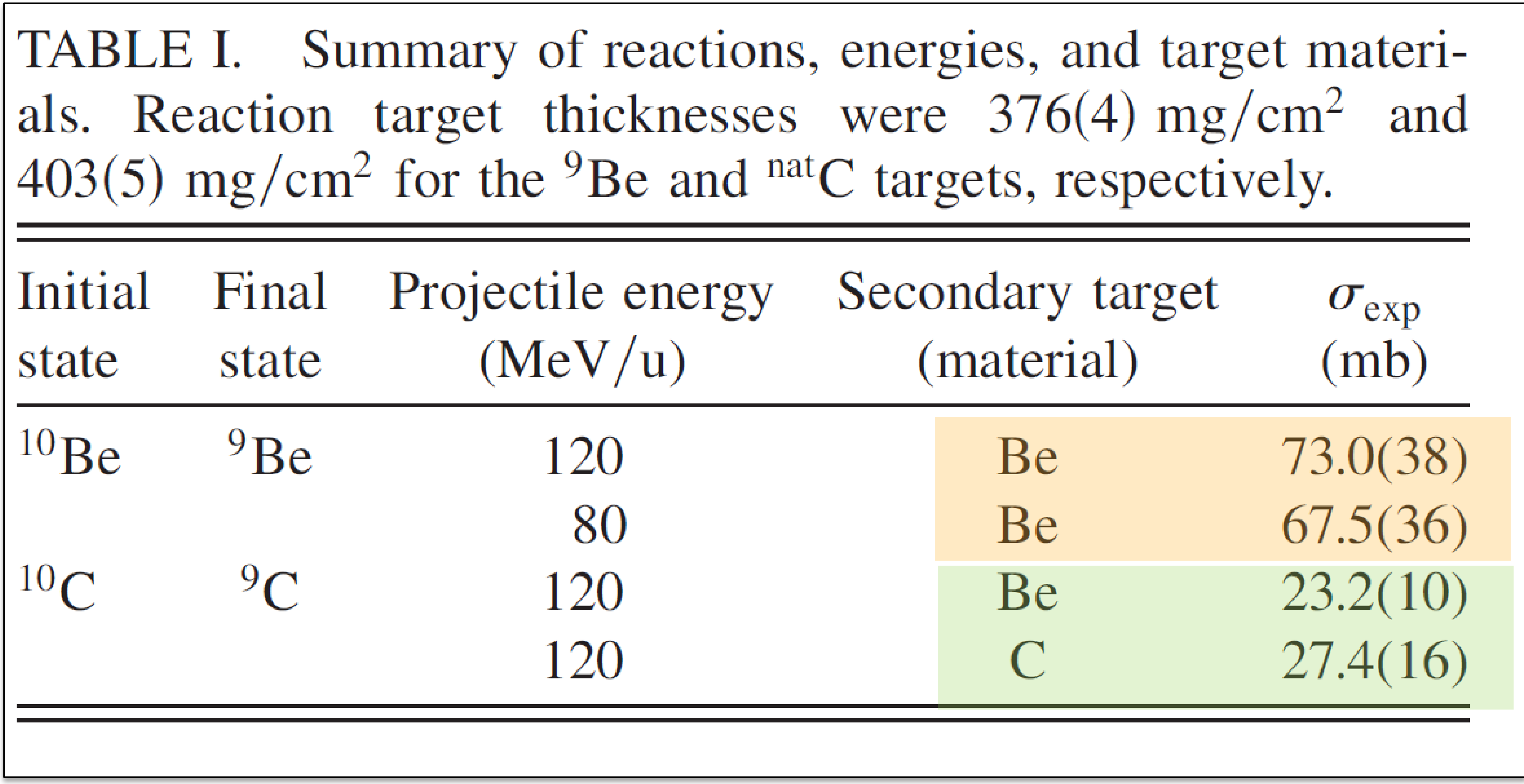


TABLE I. Summary of reactions, energies, and target materials. Reaction target thicknesses were 376(4) mg/cm^2 and 403(5) mg/cm^2 for the ^{9}Be and ^{nat}C targets, respectively.

Initial state	Final state	Projectile energy (MeV/u)	Secondary target (material)	σ_{exp} (mb)
^{10}Be	^{9}Be	120	Be	73.0(38)
		80	Be	67.5(36)
^{10}C	^{9}C	120	Be	23.2(10)
		120	C	27.4(16)

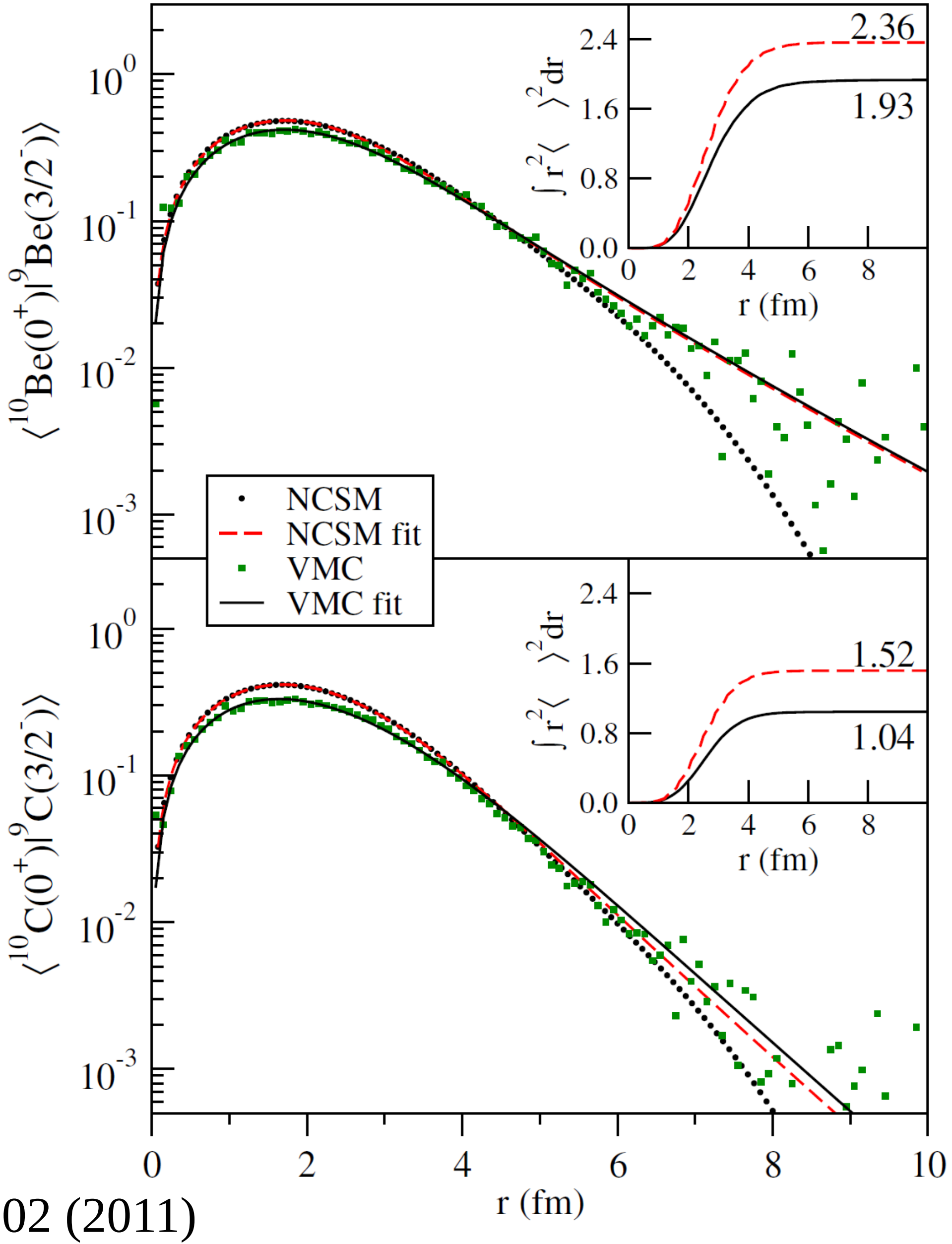
G. F. Grinyer et al., Phys. Rev. Lett. 106, 162502 (2011)

Overlaps from VMC and NCSM

- Theory overlaps were fit with Woods-Saxon parameterization
- VMC (AV18 + Urbana IX 2- and 3-body interactions)
- NCSM (CD-Bonn 2000 *NN* interaction)

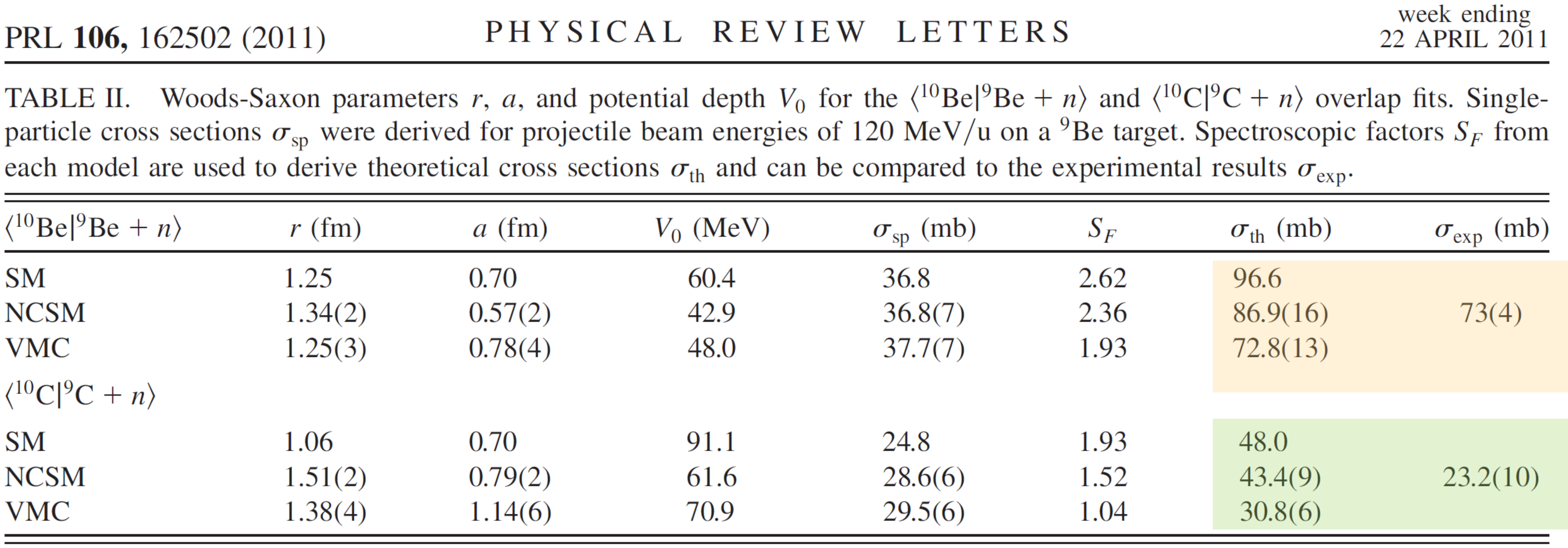
Observations:

- VMC and NCSM overlaps agree qualitatively out to 5 fm and are up to there well described by WS fit.
- They mainly differ by a scale factor (spectroscopic factor – see integration in inset)



G. F. Grinyer et al., Phys. Rev. Lett. 106, 162502 (2011)

Results



PRL **106,** 162502 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

TABLE II. Woods-Saxon parameters r, a, and potential depth V_0 for the $\langle {}^{10}\mathrm{Be}|{}^{9}\mathrm{Be} + n\rangle$ and $\langle {}^{10}\mathrm{C}|{}^{9}\mathrm{C} + n\rangle$ overlap fits. Single-particle cross sections σ_{sp} were derived for projectile beam energies of 120 MeV/u on a ${}^{9}\mathrm{Be}$ target. Spectroscopic factors S_F from each model are used to derive theoretical cross sections σ_{th} and can be compared to the experimental results σ_{exp}.

$\langle {}^{10}\mathrm{Be}\|{}^{9}\mathrm{Be} + n\rangle$	r (fm)	a (fm)	V_0 (MeV)	σ_{sp} (mb)	S_F	σ_{th} (mb)	σ_{exp} (mb)
SM	1.25	0.70	60.4	36.8	2.62	96.6	73(4)
NCSM	1.34(2)	0.57(2)	42.9	36.8(7)	2.36	86.9(16)	
VMC	1.25(3)	0.78(4)	48.0	37.7(7)	1.93	72.8(13)	
$\langle {}^{10}\mathrm{C}\|{}^{9}\mathrm{C} + n\rangle$							
SM	1.06	0.70	91.1	24.8	1.93	48.0	23.2(10)
NCSM	1.51(2)	0.79(2)	61.6	28.6(6)	1.52	43.4(9)	
VMC	1.38(4)	1.14(6)	70.9	29.5(6)	1.04	30.8(6)	

- Differences here originate from SF predictions
- Consistent approach of reaction model
- Experiment does differentiate between VMC and NCSM
- NCSM missing 3-body forces and continuum effects?
- ^{10}C discrepancy with VMC may be due to reaction model assumption (^{9}C spectator core when removing 21.3 MeV n)

Relies on reaction theory: Precision test of reaction theory

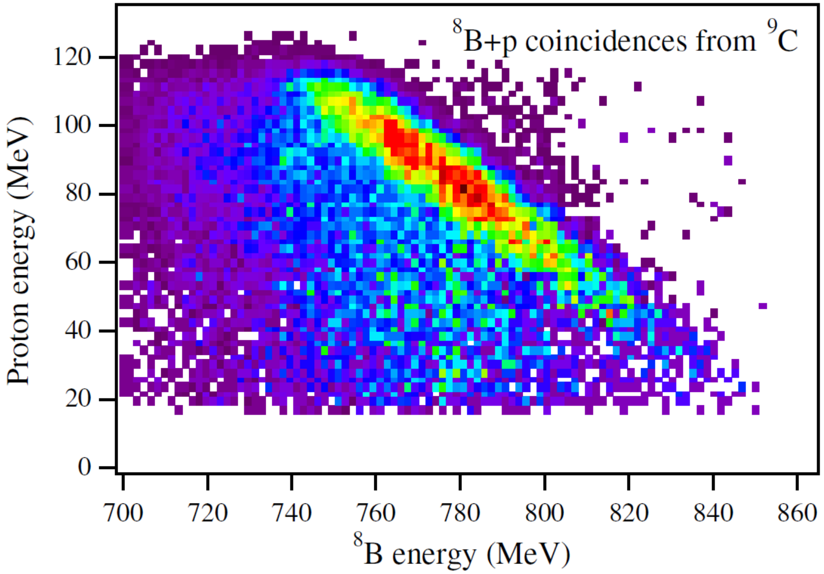
- Reaction model assumes two distinct reaction mechanisms
- Two separate single-particle cross sections for diffraction (elastic breakup) and stripping (inelastic breakup)
  - Elastic breakup: target stays in its ground state and removed nucleon is at most elastically scattered
- Exclusive experiment
  - Detect projectile residue AND knocked out nucleon in coincidence → elastic breakup
  - Reconstruct missing energy

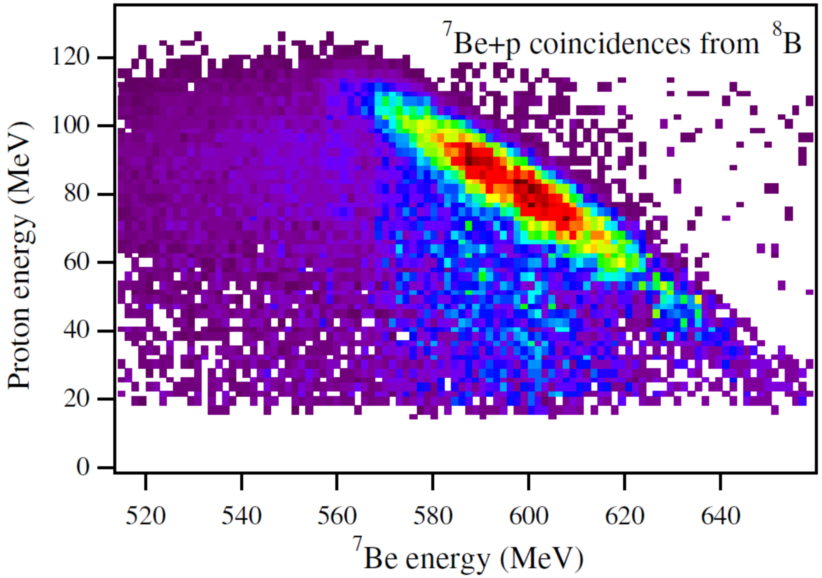
Proton detection: HiRA detector array

- 10 telescopes covering scattering angles between 10° and 60°
- Each telescope composed of 32×32 DSSD Silicon detectors, followed by 4 CsI crystals

Experimental evidence

- Clear kinematic difference between elastic and inelastic events
  - Spectra show proton energy vs residue energy
  - Diagonal bands correspond to energy conservation, hence elastic breakup



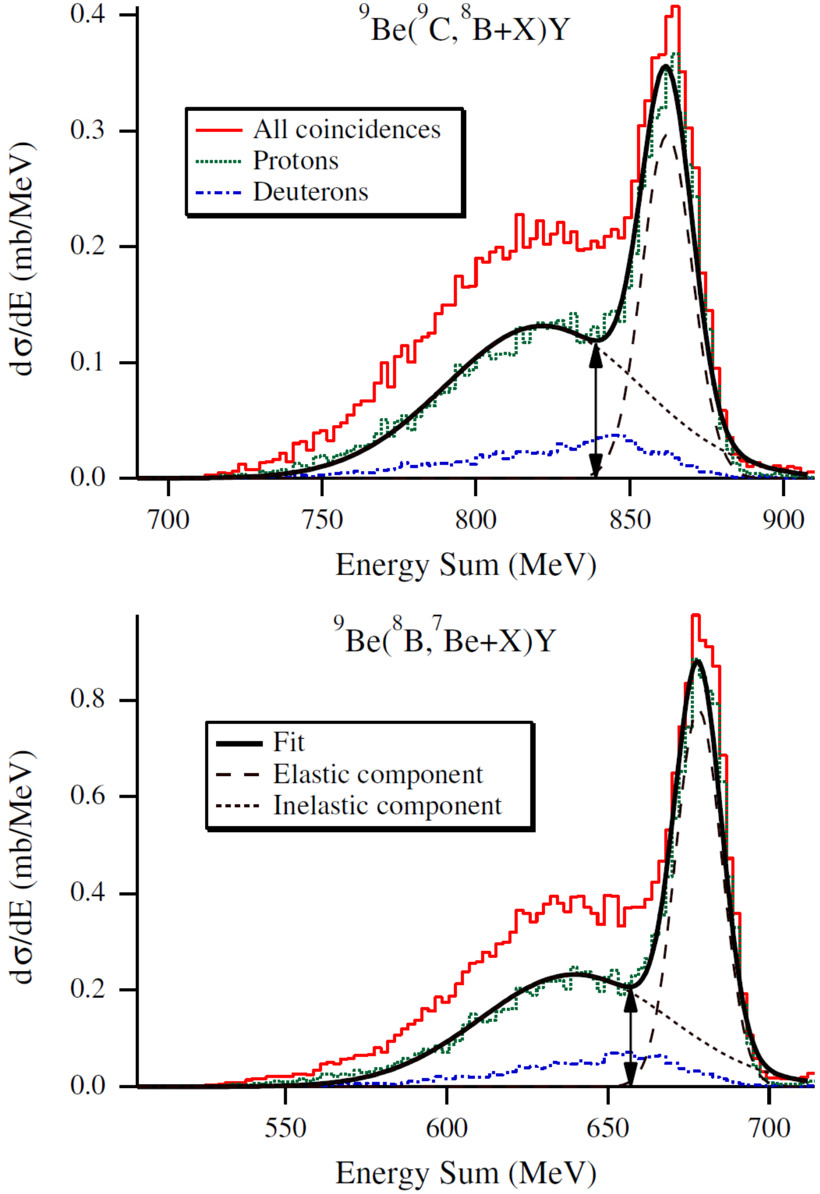


D. Bazin et al., Phys. Rev. Lett. 102, 232501 (2009)

Further evidence

- Elastic and inelastic components
  - Energy sum spectra
  - Sharp peak disappears with deuterons
- Extraction of elastic component
  - Double Gaussian fit
  - Subtract inelastic tail

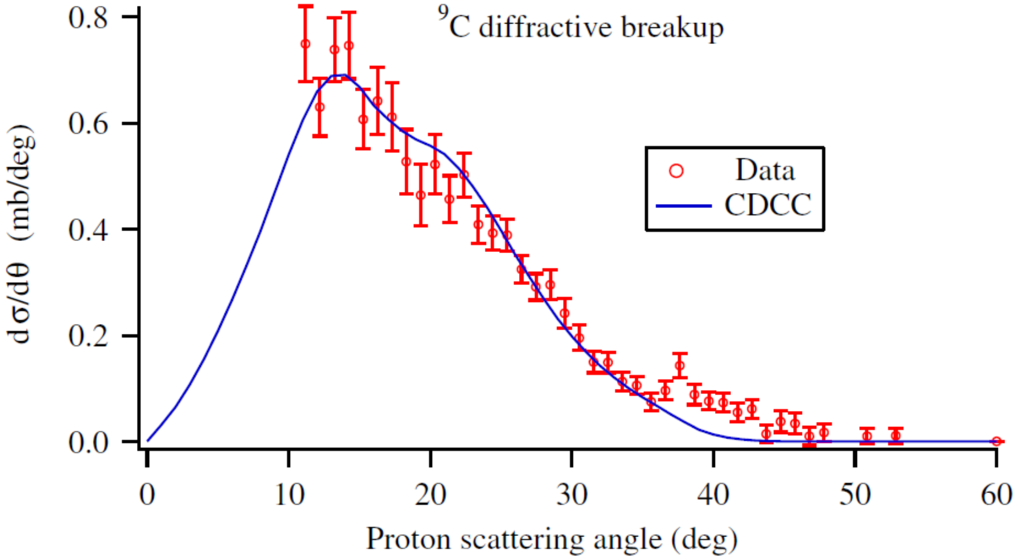
- Sharp peak corresponds to elastic breakup
- Double Gaussian fit to determine elastic cross section
- Deduce elastic breakup distributions by subtraction

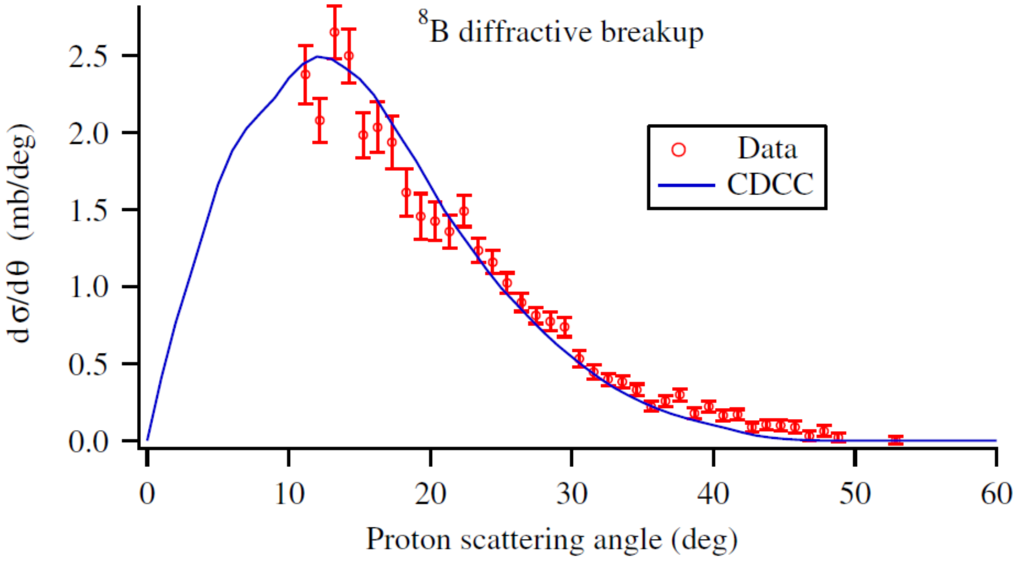


D. Bazin et al., Phys. Rev. Lett. 102, 232501 (2009)

Comparison to CDCC

- Elastic proton angular distributions
- Obtained by subtracting inelastic tail in the energy sum spectrum
- Compared to CDCC (Continuum Discretized Coupled Channels) calculation
- Used to estimate cross section below 10°



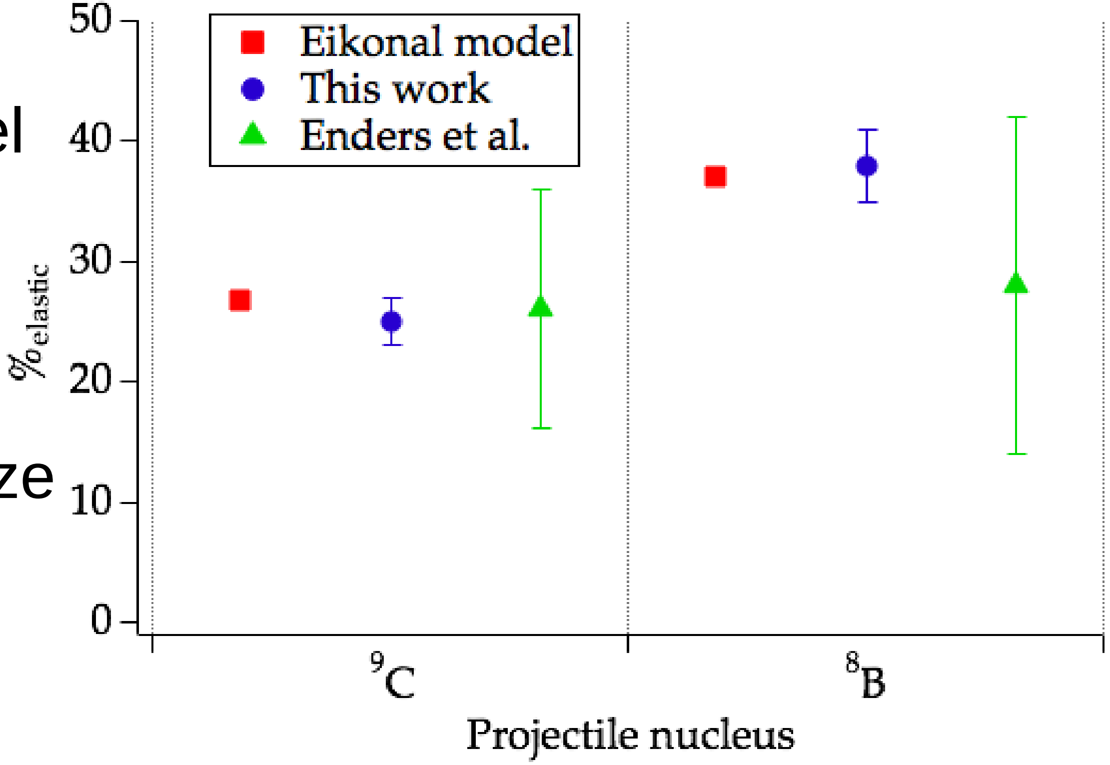


D. Bazin et al., Phys. Rev. Lett. 102, 232501 (2009)

Comparison with eikonal model

Proportions of elastic breakup:

- agrees with eikonal model predictions
- agrees with previous experiment
- Eikonal model:
- Quantitative tool to analyze and interpret knockout reactions



D. Bazin et al., Phys. Rev. Lett. 102, 232501 (2009)

Two-proton removal – Information on nuclear structure

D. Bazin et al., Phys. Rev. Lett. 91, 012501 (2003).

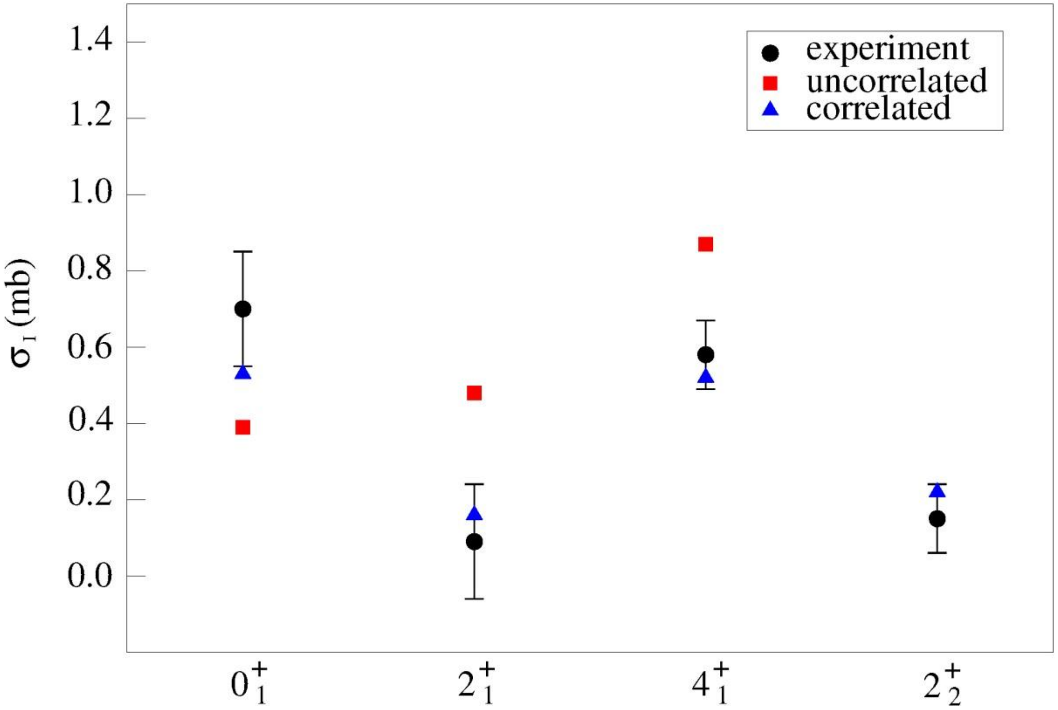
One-step process

- Competing two-step process involves proton evaporation
- Due to binding energies and Coulomb barrier, the neutron evaporation channel opens first

Two-proton knockout theory:

sd-many-body wave functions (B. A. Brown) with four-body eikonal reaction theory (J. A. Tostevin)

^{9}Be(^{28}Mg,^{26}Ne+γ)X: stripping cross section for the population of individual final states



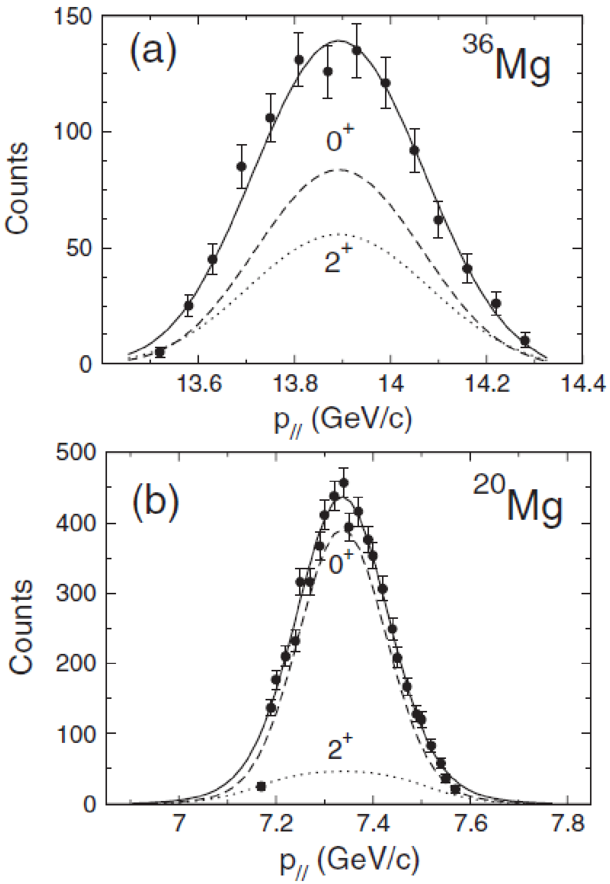
→ Information on nuclear structure

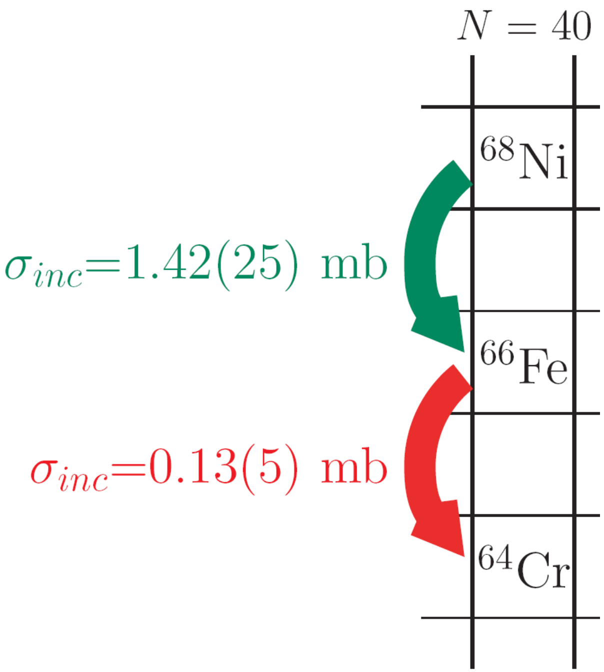
J. A. Tostevin et al., Phys. Rev. C 70, 064602 (2004).
J. A. Tostevin et al., Phys. Rev. C 74, 064604 (2006).

2N Knockout: Used for …

Spatial correlations: Final-state spin assignment from parallel momentum distributions E. C. Simpson et al., PRL 102, 132502 (2009) and PRC 79, 064621 (2009)

Changes in nuclear structure from reduced overlaps P. Adrich e al., Phys. Rev. C 77, 054306 (2008)

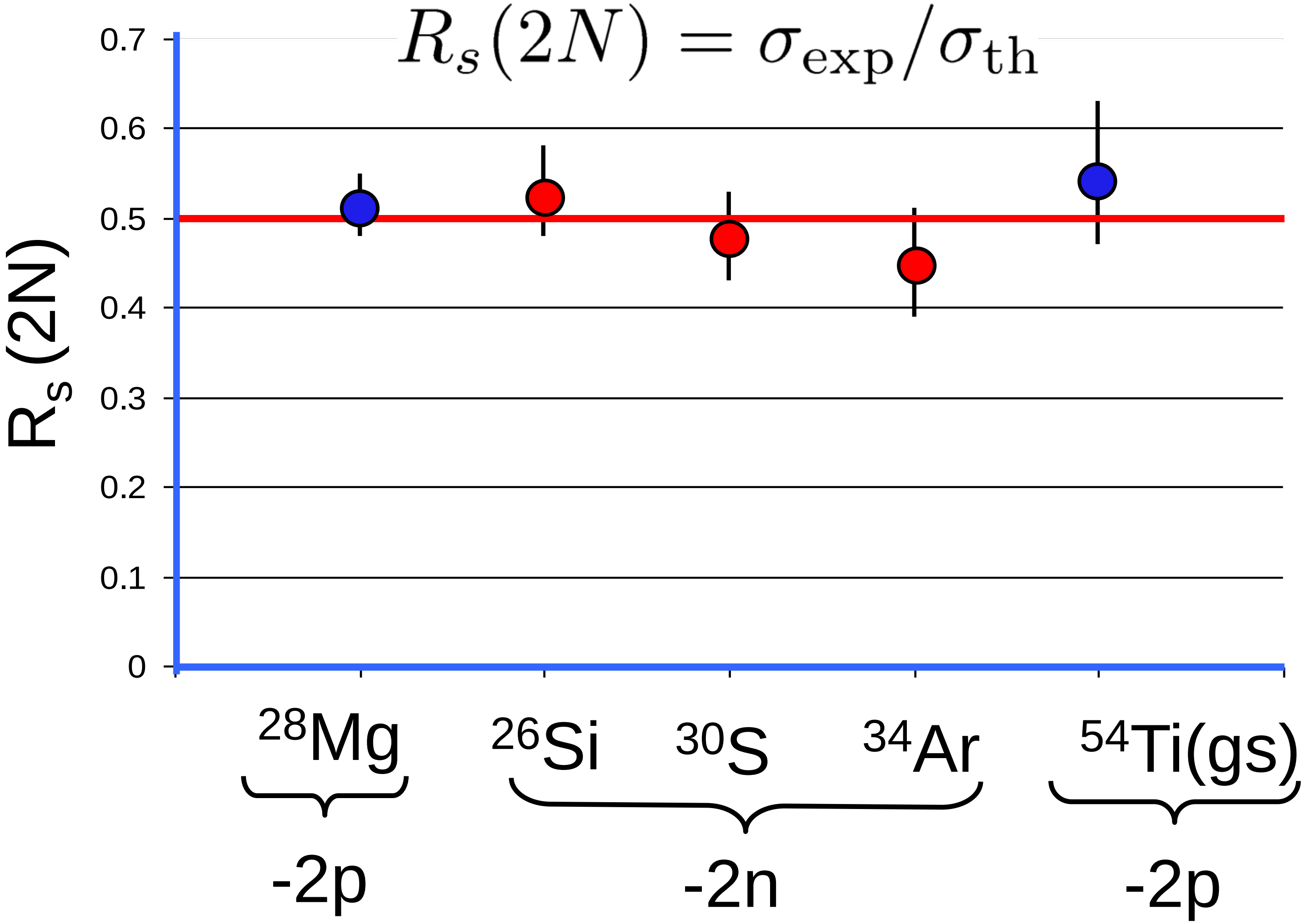




Similar studies in the Island of Inversion around N=20: A. Gade et al., Phys. Rev. Lett. 99, 072502 (2007) and P. Fallon et al.,Phys. Rev. C 81, 041302(R) (2010)

Cross shell excitations, A. Gade et al., Phys. Rev. C, 021302(R) (2006): Selective population of a 3^- state in ^{52}Ca

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



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

Summary

- Knockout reactions – when analyzed in a consistent way with properly constrained reaction theory – offer a unique tool to probe densities and overlaps from structure theory
- Reduction of spectroscopic strength … keep on adding pieces to the puzzle
- Comparison to ab-initio models: Cross sections calculated with VMC input agree very well (^{10}Be,^{9}Be+n) and within 25% (^{10}C,^{9}C+n) with experiment, cross sections calculated with NCSM input are 20% and 50% higher than experiment for (^{10}Be,^{9}Be+n) and (^{10}C,^{9}C+n), respectively
- Details of the reaction theory – ratio of diffraction and stripping – were successfully benchmarked with experiment for *A=9* and *A=8* systems
- 2N removal – unique tool to study spatial correlations (New: Spin determination of residue final state)

Partners in Crime … or the knockout conspiracy

NSCL National Superconducting Cyclotron Laboratory at Michigan State University

Michigan State University

Advancing Knowledge. Transforming Lives.

Main exp. collaborators:

Daniel Bazin

Geoff Grinyer (now permanent staff at GANIL)

HiRA group (for proton detection):

Bill Lynch

Betty Tsang

Mike Famiano (WMU)

Reaction theory:
Jeff Tostevin (Surrey, UK)

VMC:
Bob Wiringa (ANL)

NCSM:
Petr Navratil (LLNL,Triumf)
Sofia Quaglioni (LLNL)

CI shell model:
B. A. Brown

Some ideas and future plans

- Limitations of reaction model for deeply bound cases (looking for a 10-20% effect, maybe)
  - How to improve reaction model to include core breakup?
- Extend comparison with *ab-initio* calculations
  - Several other *p*-shell cases including excited final states
  - Mirror removal reactions with same SFs
    Example: (^{10}Be, ^{9}Li) mirror of (^{10}C, ^{9}C)

Input and sensitivity

From SKX Skyrme Hartree Fock

B.A. Brown, Phys. Rev. C 58, 220 (1998)

- rms radius of knockout residue $R^{(r)}$
- neutron and proton density distributions
- root-mean-squared separation of the removed nucleon and the residue in the projectile R_{sp}

Sensitivity of the single-particle cross section to input parameters:

$$\delta\sigma_{sp}/\sigma_{sp}=1.1\delta R_{sp}+1.2\delta R^{(r)}$$

0.1 fm change in R_{sp} and $R^{(r)}$:
16% uncertainty for the single-particle cross section for the removal of a strongly bound nucleon

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

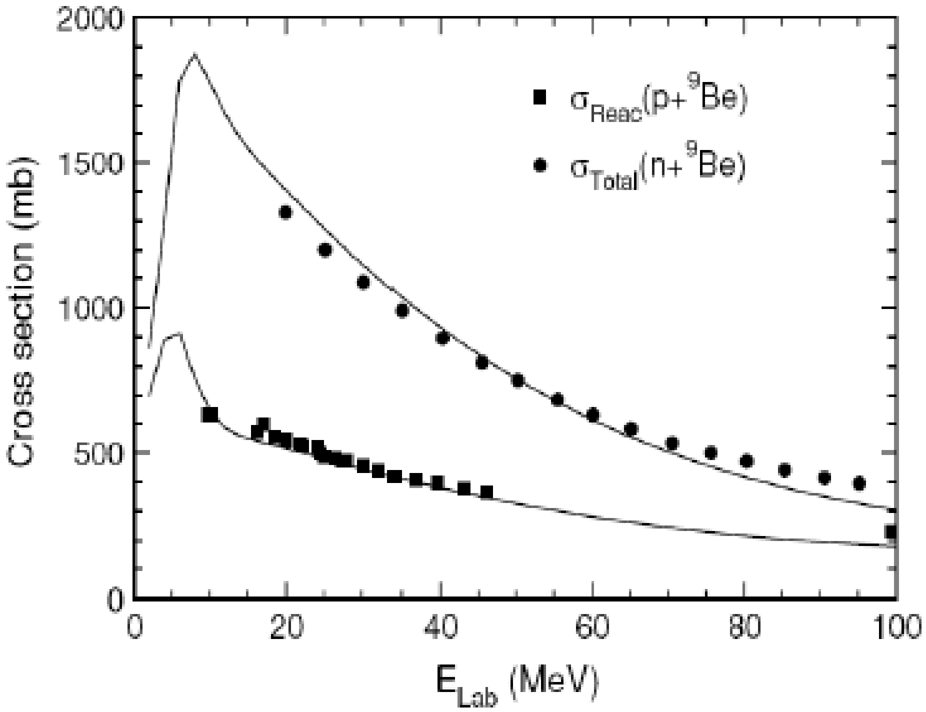
Spectroscopic factors

- The quantity *S* expresses the parentage of the initial state with respect to a specific final state coupled to a nucleon with given angular-momentum quantum numbers (*l j*).

Stripping

- Stripping mechanism depends only on the absorptive content of the interaction – $|S|^2$ and is highly constrained by the reaction cross section of the fragments and the nuclear sizes. These are calculated reliably using Glauber methods and by making use of Hartree-Fock for input that depends on nuclear sizes.

- The description of the nucleon's interaction with the target is common to all final states and different systems



Cross section

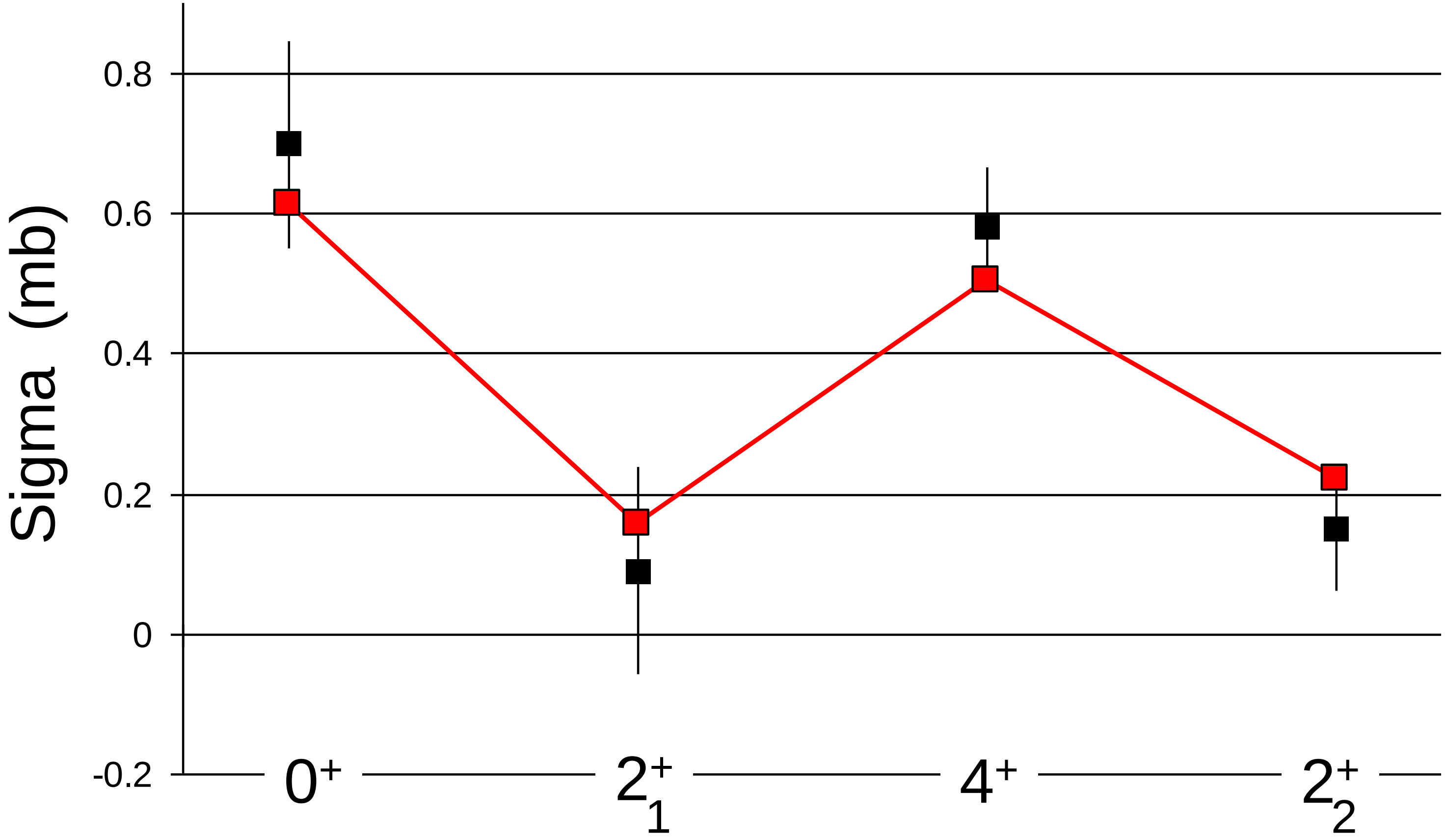
- spectator-core approximation to many-body eikonal theory
- (A-1) residue is at most elastically scattered
- S matrices as function of impact parameter from Glauber theory (free nn np cross sections with Gaussian range parameters $\beta_{nn} = \beta_{np} = 0.5$ fm. Real-to-imaginary ratios interpolated from tables in *L. Ray, PRC 20, 1875 (1979)*
- nucleon-residue relative wave function calculated as eigenfunction of effective 2-body Hamiltonian containing local potential with the depth adjusted to reproduce the separation energy

$$\sigma_{sp}(j, B_n) = \frac{1}{2j+1} \sum_m 2\pi \int b\,\mathrm{d}b \langle jm \,|(1-|S_N|^2)|S_C|^2|\, jm >$$

2p knockout in the neutron-rich sd shell

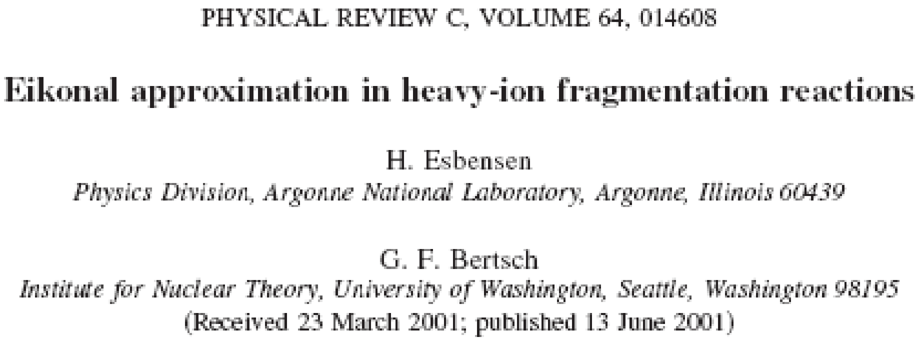
^{28}Mg $\rightarrow$ ^{26}Ne(0^+, 2^+, 4^+, 2_2^+) 82.3 MeV/u

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



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

Validity of the Eikonal approximation



PHYSICAL REVIEW C, VOLUME 64, 014608

Eikonal approximation in heavy-ion fragmentation reactions

H. Esbensen
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

G. F. Bertsch
Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195
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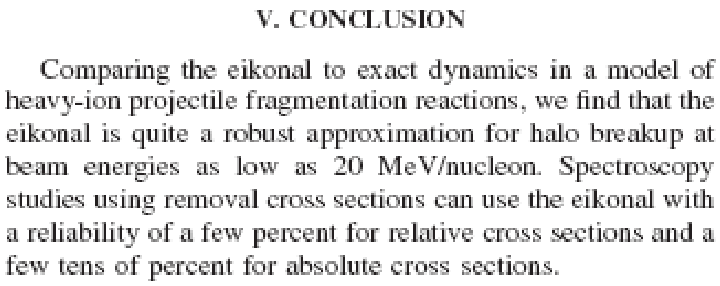


V. CONCLUSION

Comparing the eikonal to exact dynamics in a model of heavy-ion projectile fragmentation reactions, we find that the eikonal is quite a robust approximation for halo breakup at beam energies as low as 20 MeV/nucleon. Spectroscopy studies using removal cross sections can use the eikonal with a reliability of a few percent for relative cross sections and a few tens of percent for absolute cross sections.

Spectroscopic factor

Spectroscopic factor defined from the overlap of two many-body shell-model wave functions

$$\langle \vec{r}, \Psi_f^{A-1} | \Psi_i^A \rangle = \sum_j c_j^{if} \psi_j(\vec{r})$$

$$C^2 S_j^{if} = | c_j^{if} |^2 \leq (2j+1)$$

To what extent reflect the intensities of the core states Φ_{A-1}, measured following the reaction, a pre-existing component in the incident projectile wave function Φ_A.

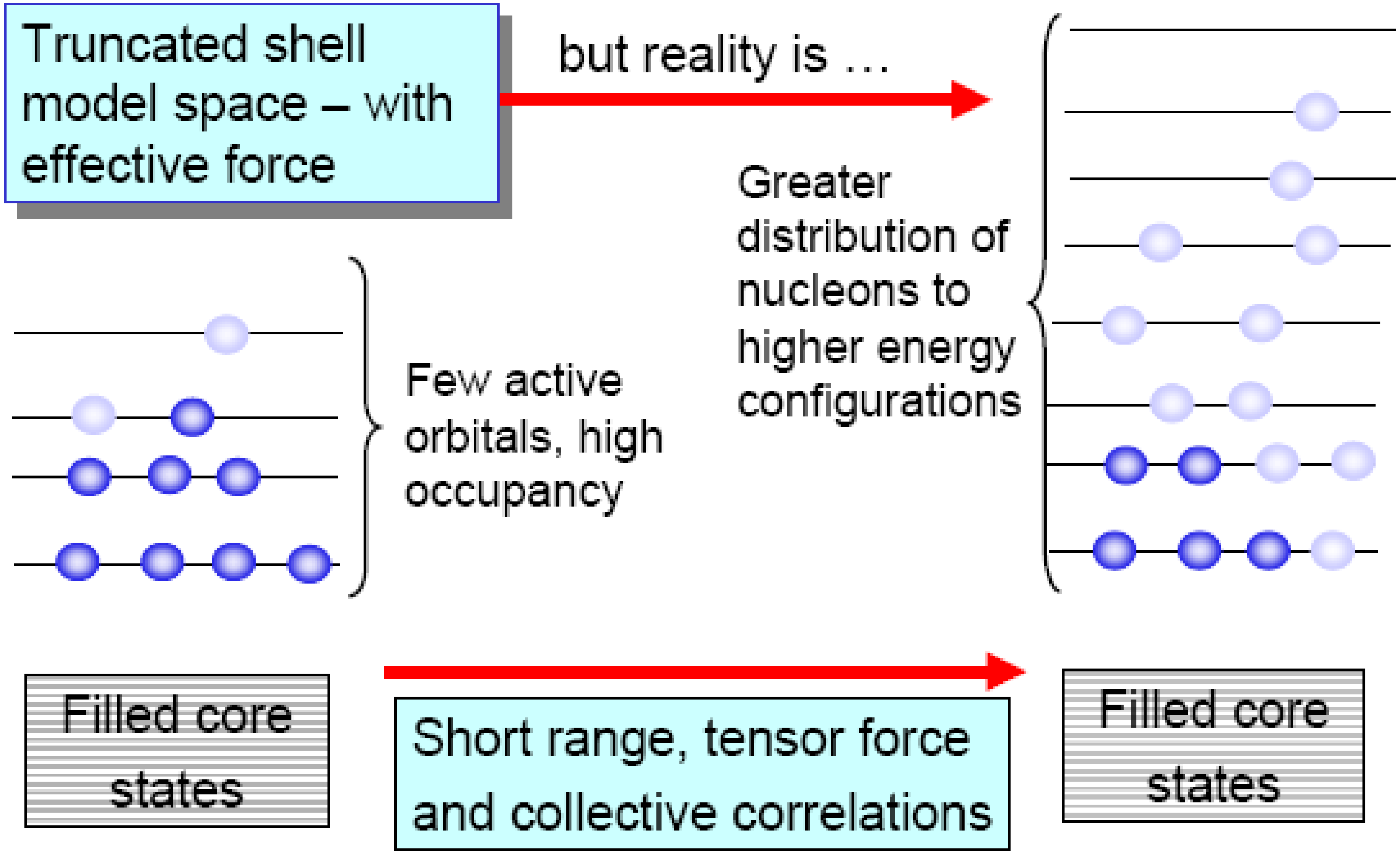
Cross section

- spectator-core approximation to many-body eikonal theory
- (A-1) residue is at most elastically scattered
- S matrices as function of impact parameter from Glauber theory (free nn np cross sections with Gaussian range parameters $\beta_{nn} = \beta_{np} = 0.5$ fm. Real-to-imaginary ratios interpolated from tables in *L. Ray, PRC 20, 1875 (1979)*
- nucleon-residue relative wave function calculated as eigenfunction of effective 2-body Hamiltonian containing local potential with the depth adjusted to reproduce the separation energy

$$\sigma_{sp}(j, B_n) = \frac{1}{2j+1} \sum_m 2\pi \int b \, \mathrm{d}b \, \langle jm | (1 - |S_N|^2) |S_C|^2 | jm >$$

Reduction of single-particle strength

Figure from J. A. Tostevin



Truncated shell model space – with effective force

but reality is …

Few active orbitals, high occupancy

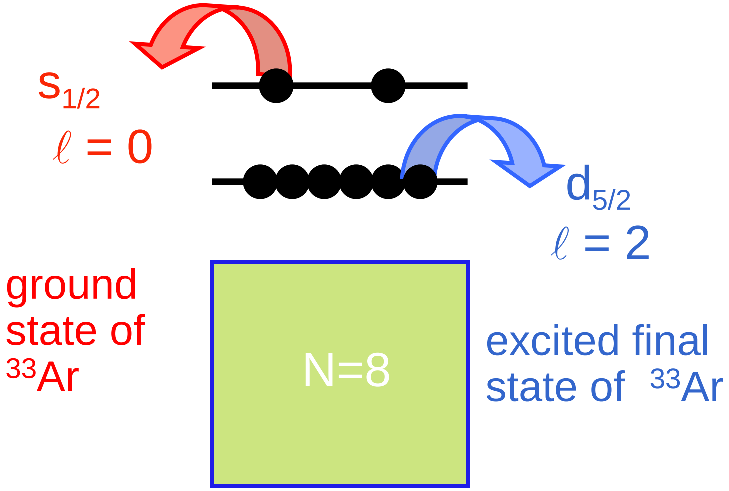
Greater distribution of nucleons to higher energy configurations

Filled core states

Short range, tensor force and collective correlations

Filled core states

Example: ^{9}Be(^{34}Ar,^{33}Ar)X – ℓ-values from $p_{||}$



$s_{1/2}$

$\ell = 0$

$d_{5/2}$

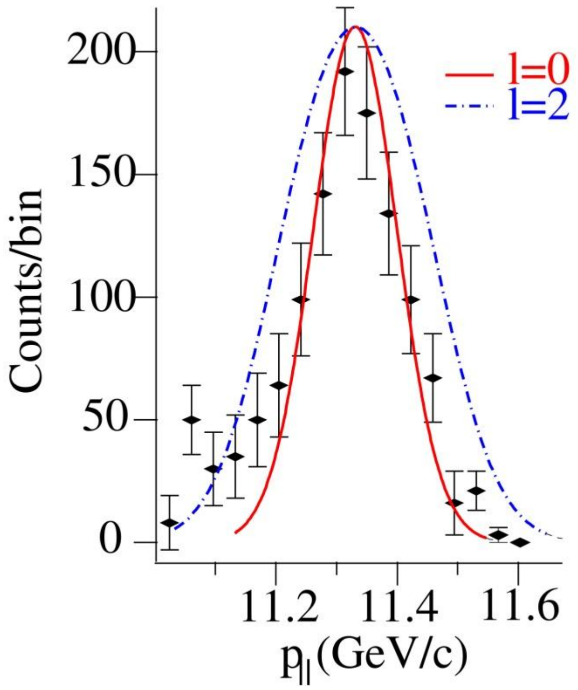
$\ell = 2$

ground state of ^{33}Ar

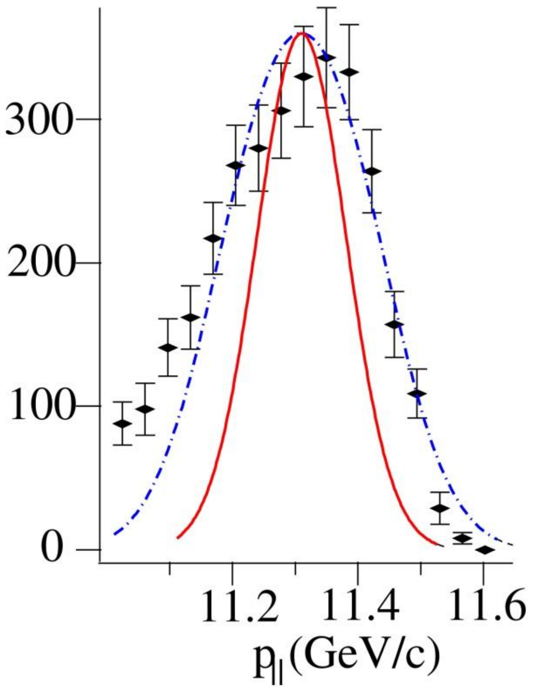
N=8

excited final state of ^{33}Ar

knockout residues without γ-ray



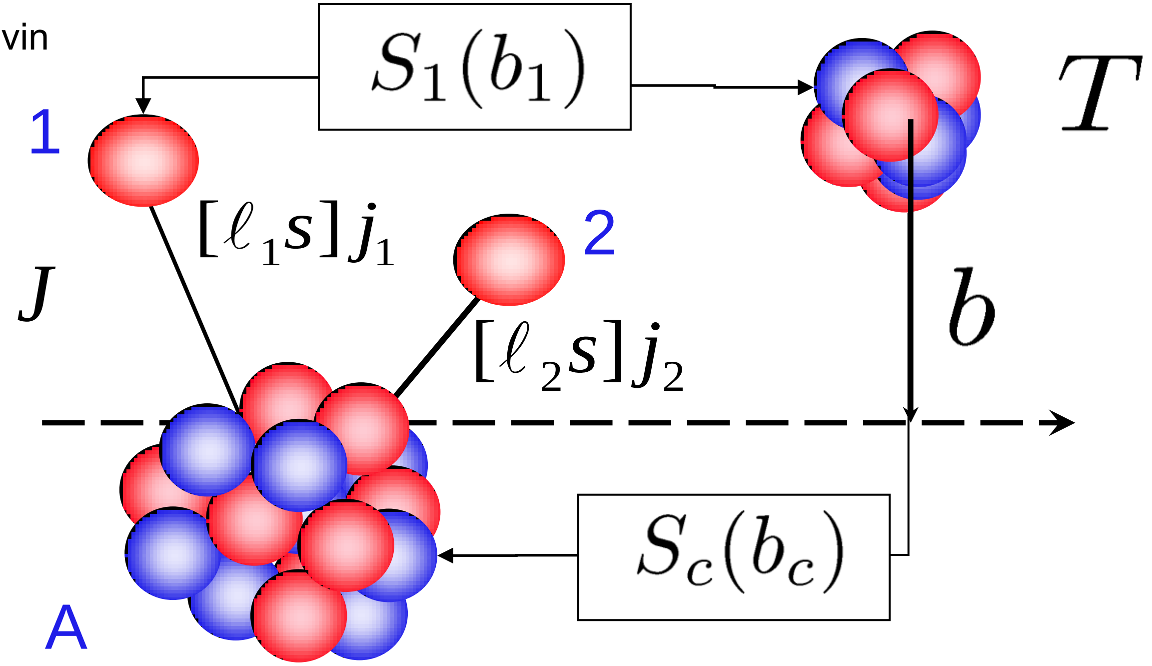
in coincidence with γ-rays



A. Gade *et al*., Phys. Rev. C 69, 034311 (2004).

Sudden removal – eikonal model cross sections

From from J. A. Tostevin



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

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

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

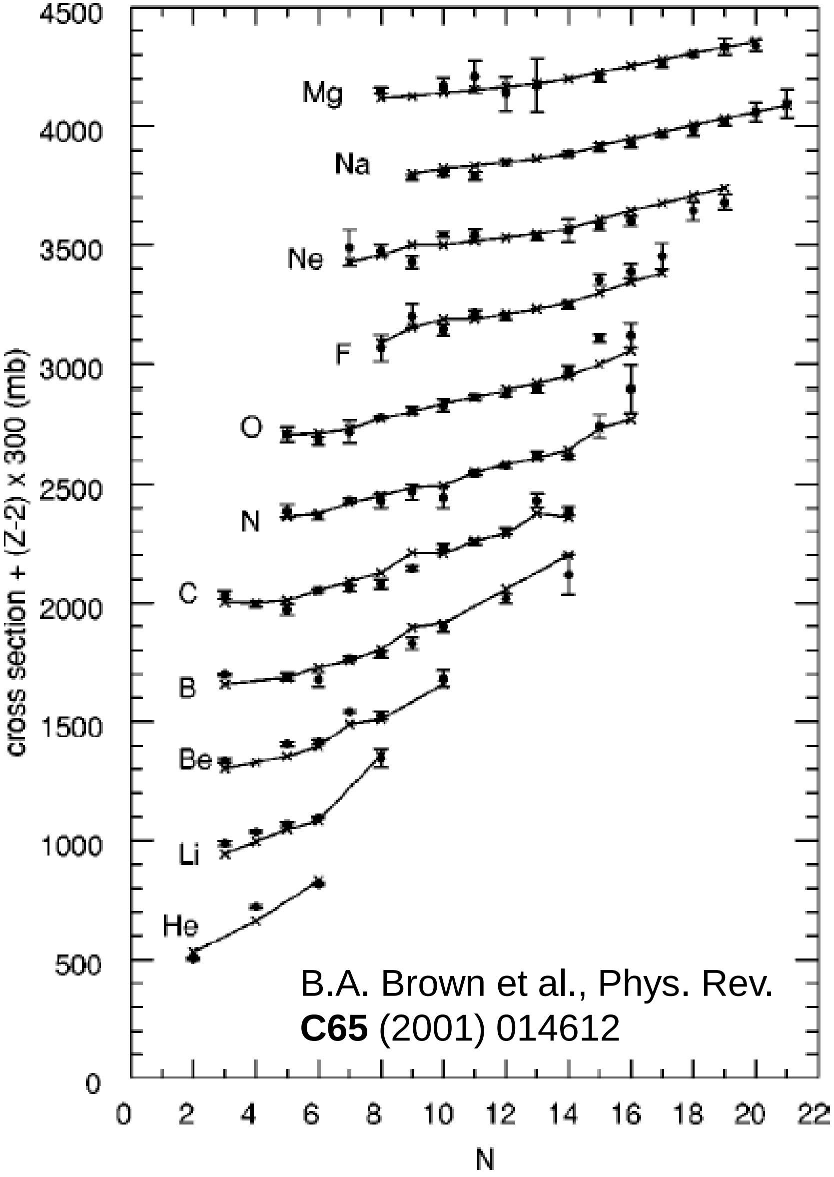
J.A. Tostevin *et al.*, PRC 70 (2004) 064602 and PRC 74 (2006) 064604.

Reaction description is very robust and quantitative

Core/residue-target interaction is highly absorptive at 100 MeV/u. The range of this absorption is determined by the core and target sizes which is encoded within the double folding model and can be cross referenced to

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

These interactions and the rquired S-matrices can be calculated reliably using Glauber methods – using, e.g. Hartree-Fock densities.



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