Nuclear Spectroscopy with Knockout Reactions

Carlos Bertulani
University of Tennessee

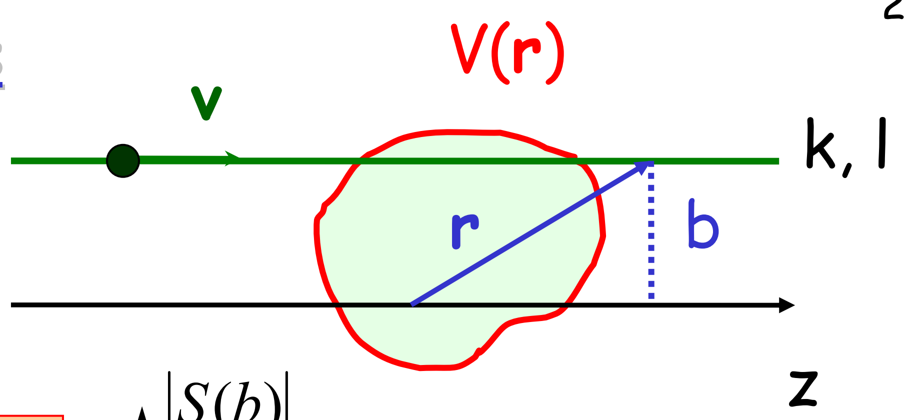
Alexandra Gade
Michigan State University

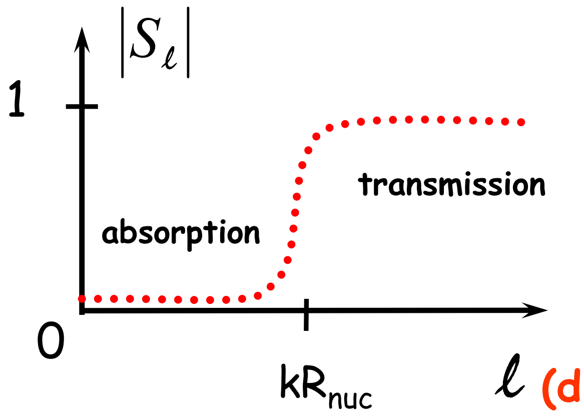
JUSTIPEN/LACM meeting

Oak Ridge, March 8, 2007

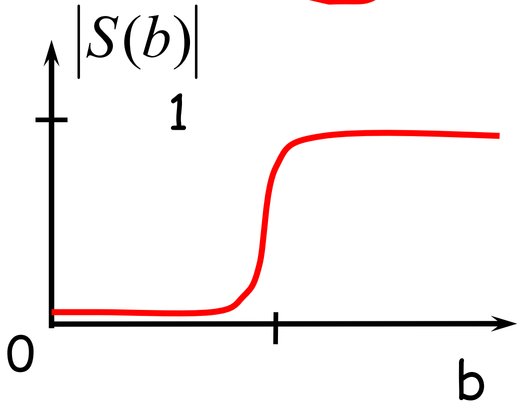
Basic Theory: Eikonal waves

$$\Psi^{(+)}(\mathbf{r})\Psi^{(-)*}(\mathbf{r}) = S(\mathbf{b})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$





$$S(\mathbf{b}) = e^{i\chi(\mathbf{b})}$$



"t-rho-rho" approximation

Ray, PRC 20 (1979) 1957

Hussein, Rego, C.B., Phys. Rep. 5 (1991) 279

$$\chi_{AB}^{(N)}(b) = \frac{1}{k_{nn}} \int_0^\infty dq\, q\, \widetilde{\rho}_A(q)\widetilde{\rho}_B(q)\, f_{nn}(q)\, J_0(qb)$$

$$f_{nn}(q) = \frac{k_{nn}}{4\pi}\sigma_{nn}\left(i + \alpha_{nn}\right)e^{-\beta_{nn} q^2}$$

(from nn scattering)

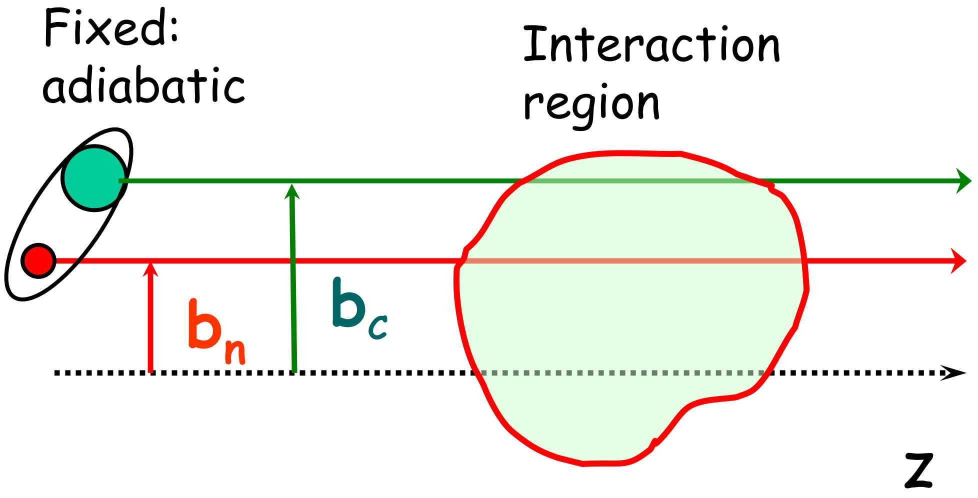
Glauber,

Nobel Prize

2006

Arizona
2006

Elastic scattering



Best possible wfs:

(Spectroscopy)

$$S_{elast}(\mathbf{b}) = \left\langle \phi_0 \middle| S_C(\mathbf{b}_C)\, S_n(\mathbf{b}_n) \middle| \phi_0 \right\rangle$$

Survival amplitude

for projectile at impact parameter b

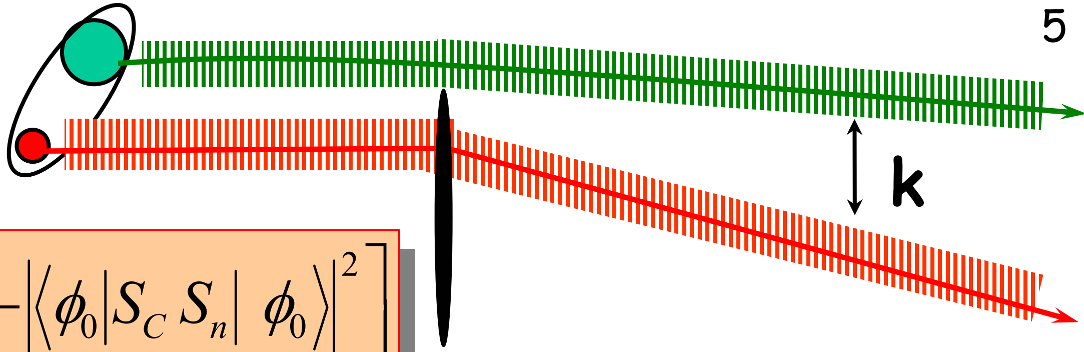
Survival amplitudes

for particles C and n at impact parameters b_C and b_n

(Dynamics)

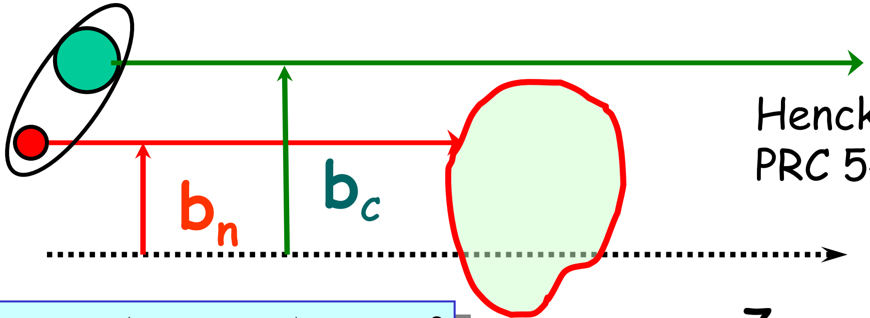
Hencken, Bertsch, Esbensen, PRC 54, 3043 (1996)

Diffraction Dissociation



$$\sigma_{dif.dis.}(\mathbf{b}) = \int d\mathbf{b}\left[\left\langle \phi_0 \left| |S_C\, S_n|^2 \right| \phi_0 \right\rangle - \left|\left\langle \phi_0 \right| S_C\, S_n \left| \phi_0 \right\rangle\right|^2\right]$$

Stripping

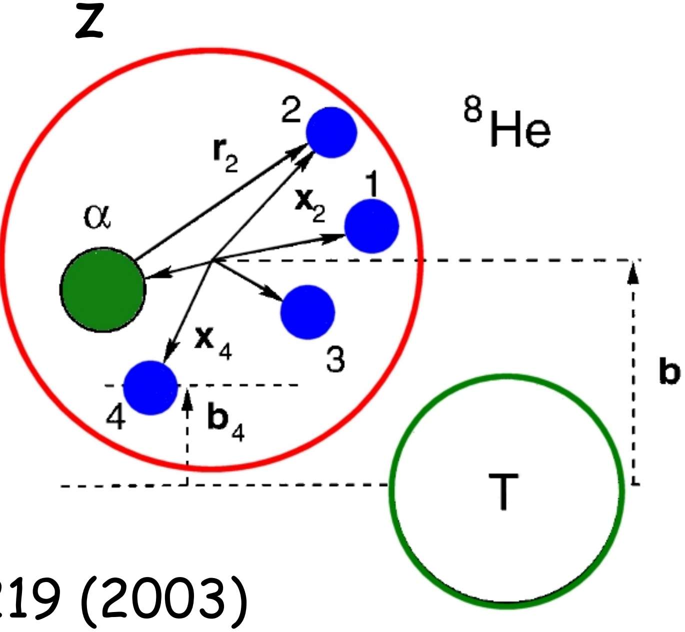


Hencken, Bertsch, Esbensen,
PRC 54, 3043 (1996)

$$\sigma_{strip} = \int d\mathbf{b}_n d\mathbf{b}_C \left\langle \phi_0 \right| |S_C|^2 \left(1-|S_n|^2\right) \left| \phi_0 \right\rangle^2$$

Composite particles

$$\sigma_{strip} = \int d\mathbf{b}_1 \ldots d\mathbf{b}_N \prod_{j\ survive} |S_j(\mathbf{b}_j)|^2 \prod_{k\ absorbed} \left(1-|S_k(\mathbf{b}_k)|^2\right)$$



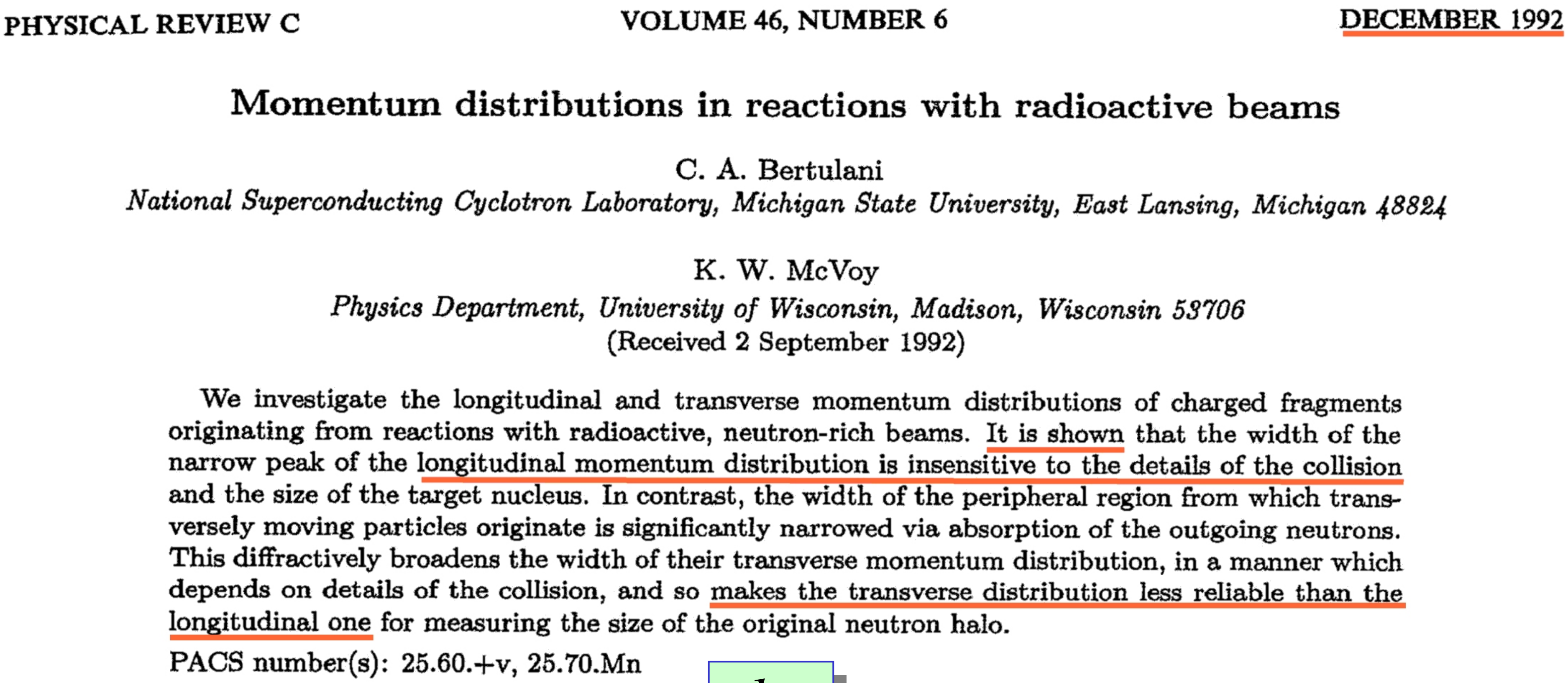
Applications: Hansen & Tostevin, ARNPS 53, 219 (2003)

Momentum Distributions

Serber model:
PR 72 (1947) 1008

$$\boxed{S_C(\mathbf{b}_C) \approx 1} \quad \longrightarrow \quad \boxed{\frac{d\sigma_{strip}}{d^3k_C} = C_{geometry} \left| \tilde{\psi}_{l_0 m_0}(\mathbf{k}_c) \right|^2}$$

Tanihata (1985): ^{11}Li



PHYSICAL REVIEW C VOLUME 46, NUMBER 6 DECEMBER 1992

Momentum distributions in reactions with radioactive beams

C. A. Bertulani
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

K. W. McVoy
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

(Received 2 September 1992)

We investigate the longitudinal and transverse momentum distributions of charged fragments originating from reactions with radioactive, neutron-rich beams. It is shown that the width of the narrow peak of the longitudinal momentum distribution is insensitive to the details of the collision and the size of the target nucleus. In contrast, the width of the peripheral region from which transversely moving particles originate is significantly narrowed via absorption of the outgoing neutrons. This diffractively broadens the width of their transverse momentum distribution, in a manner which depends on details of the collision, and so makes the transverse distribution less reliable than the longitudinal one for measuring the size of the original neutron halo.

PACS number(s): 25.60.+v, 25.70.Mn

$$\boxed{\frac{d\sigma}{dp_Z}}$$ better structure probe

Momentum Distributions: (a) Stripping

$$\frac{d\sigma_{strip}}{d^3k_C} = \frac{1}{(2\pi)^3}\frac{1}{(2l_0+1)}\sum_{m_0}\int d^2b_n\left[1-\left|S_n(\mathbf{b}_n)\right|^2\right]\left|\int d^3r\, e^{-i\mathbf{k}_C\cdot\mathbf{r}}\; S_C(\mathbf{b}_C)\,\psi_{l_0,m_0}(\mathbf{r})\right|^2$$

(b) Diffraction dissociation

$$\frac{d\sigma_{dif.dis.}}{d^2K_\perp\, d^3k} = \frac{1}{(2\pi)^5}\frac{1}{(2l_0+1)}\sum_{m_0}\left|\int d^3r\, d^2b\, e^{-i\mathbf{K}_\perp\cdot\mathbf{b}}\psi^*_{\mathbf{k}}(\mathbf{r})\, S_C(\mathbf{b}_C)\, S_n(\mathbf{b}_n)\,\psi_{l_0,m_0}(\mathbf{r})\right|^2$$

Open theoretical issues:

a) "In medium" modification of σ_{NN} .... C.B., JPG 27 (2001) L67

b) Final state interactions ...... Tostevin et al., PRC 66 (2002) 024607
C.B., Hansen, PRC 70 (2004) 034609

c) Diffraction dissociation .... C.B., NPA 767 (2006) 155

d) Connection with DWBA .... C.B., NPA 767 (2006) 155

Computer Code: MOMDIS

C.B., Gade, CPC 17 (2006) 372

Download from http://www.cpc.cs.qub.ac.uk/ Catalogue id: ADXZ

Calculates:

a) Total stripping + diff. dissociation X-sections
b) Momentum distributions
c) Elastic scattering
d) Coulomb effects

Based on: C.B., Hansen, PRC C70, 034609 (2004)

$$S(b)=\sum_{j=1}^{N}\alpha_j\, e^{-b^2/\beta_j^2}, \qquad \beta_j=\frac{R}{j}$$

$$\Longrightarrow$$

$$\underbrace{\iiint\cdots\iiint}_{\text{lots}}\cdots\Rightarrow\underbrace{\sum\cdots\sum}_{\text{few}}\cdots$$

S-matrices expanded on Gaussians

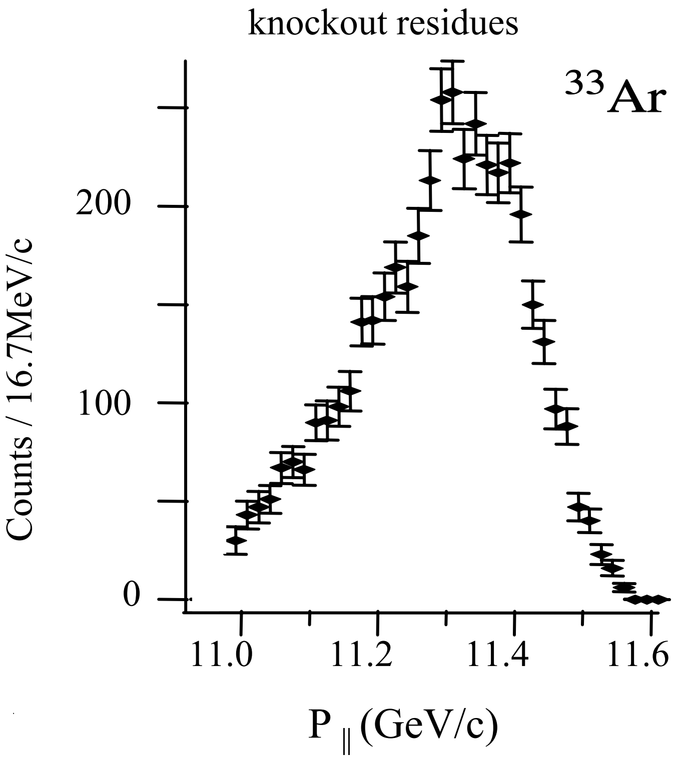
Nuclear spectroscopy

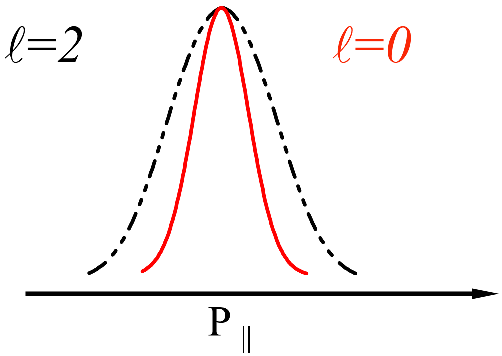
spectroscopic factor **single-particle cross section**

$$\sigma(nI^{\pi}) = \sum_{j} C^{2}S(j,nI^{\pi})\;\sigma_{sp}(j,S_{n})$$

nuclear structure information **reaction process**

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





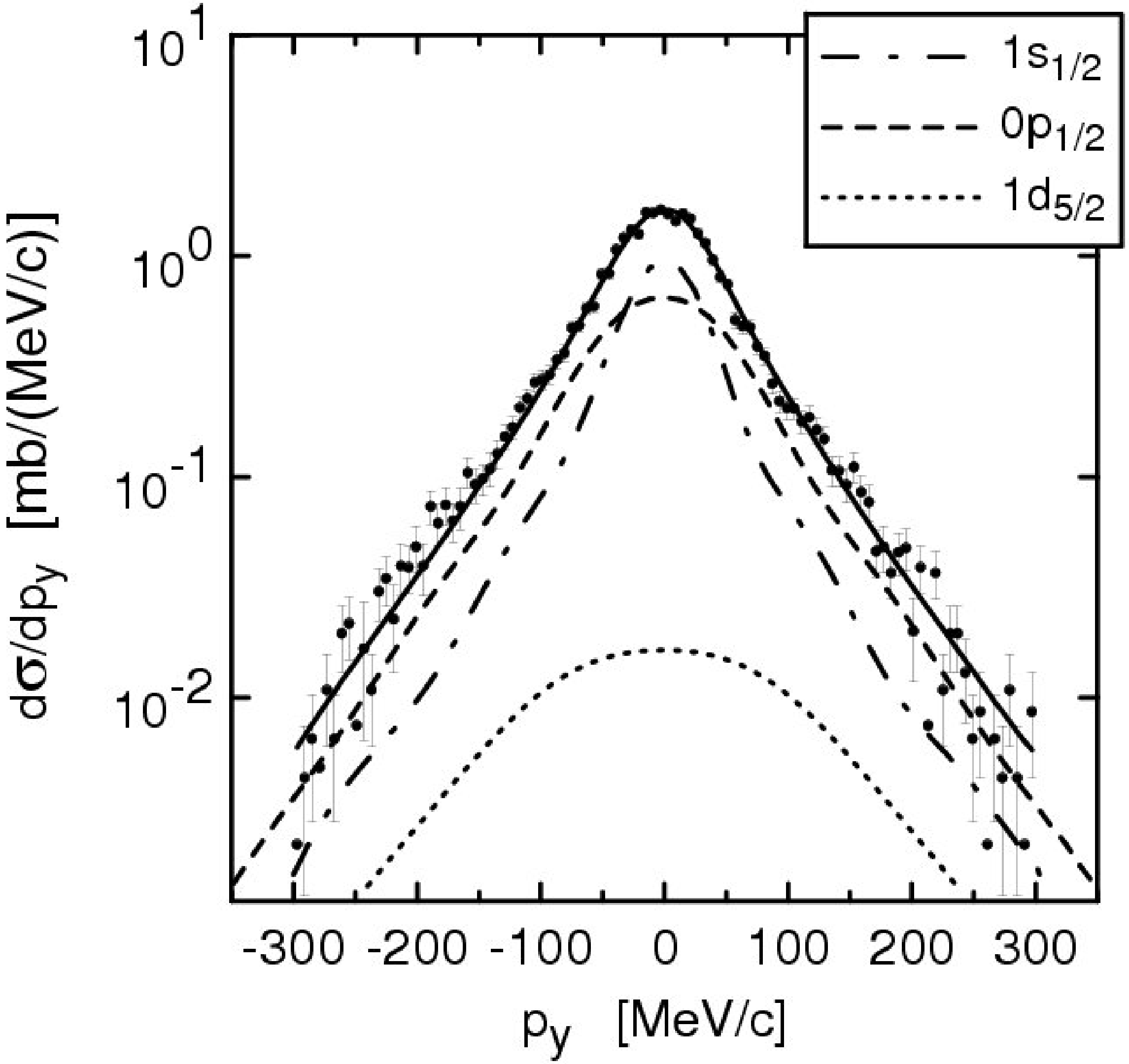
ℓ-value assigned in comparison to model calculations

Hansen, PRL 77, 1016 (1996)

C.B., Hansen, PRC 70, 034609 (2004)

Applications: Testing nuclear models

(a) Three-body Model: C.B., Hansen, PRC C70, 034609 (2004)

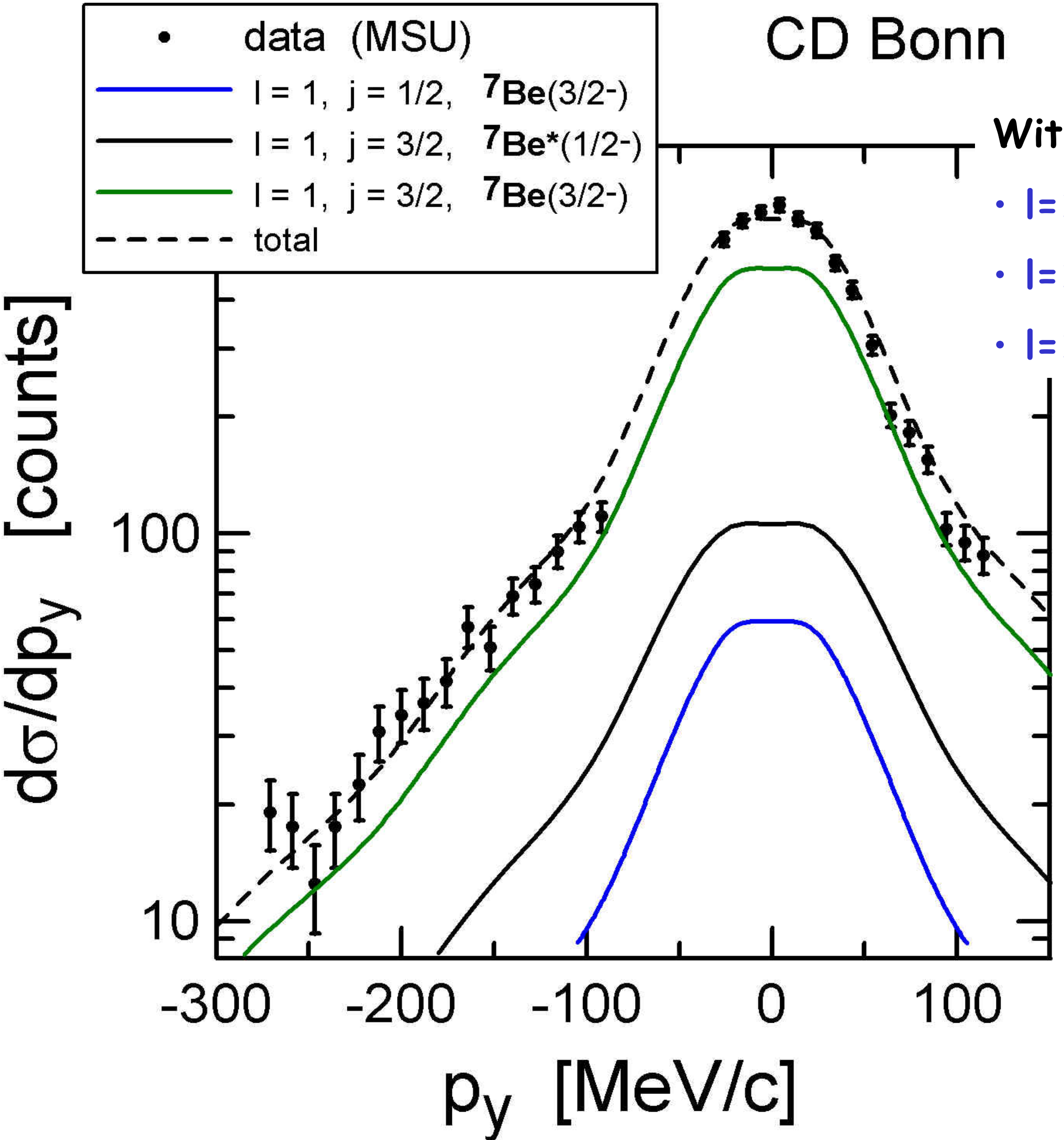


Data: **H.Simon et al.,PRL 83,496 (1999)**

(b) No-Core Shell Model

^{8}B (41 MeV/nucleon) + ^{9}Be → ^{7}Be + X

^{8}B (41 MeV/nucleon) + ^{9}Be → ^{7}Be + X

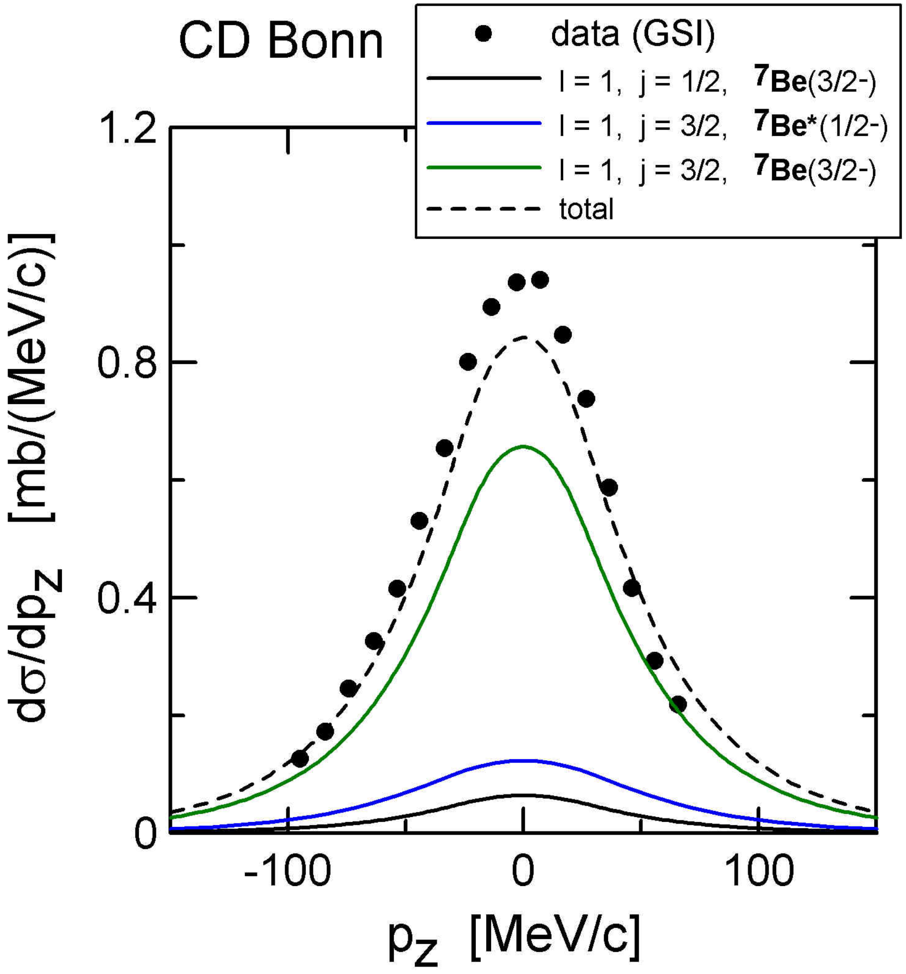


With NCSM wavefunctions (10 ħω)

- l=1, j=1/2, I_{7Be}=3/2: C^2S=0.085
- l=1, j=3/2, I_{7Be}=1/2: C^2S=0.280
- l=1, j=3/2, I_{7Be}=3/2: C^2S=0.958

Navratil, C.B., Caurier,
PLB 634 (2006) 191
PRC 73 (2006) 065801

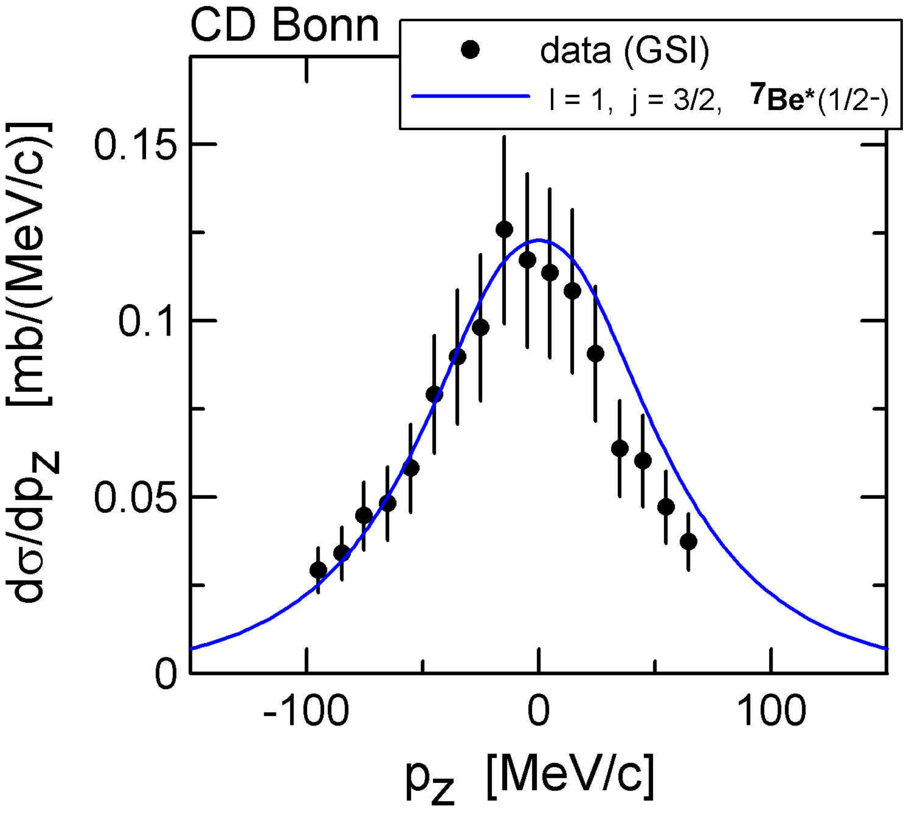
^{8}B (938 MeV/nucleon) + ^{12}C → ^{7}Be + X



σ_{str} = 99.39 mb

exp = 94 ± 9 mb

^{8}B (938 MeV/nucleon) + ^{12}C → ^{7}Be + γ + X

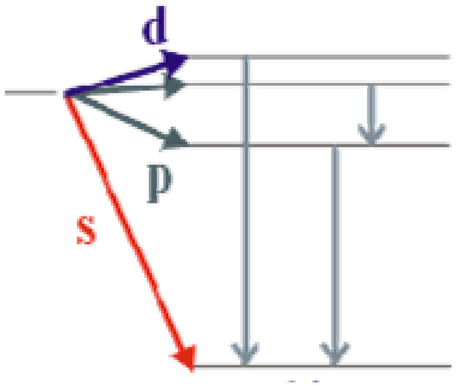


σ_{str} = 15.31 mb

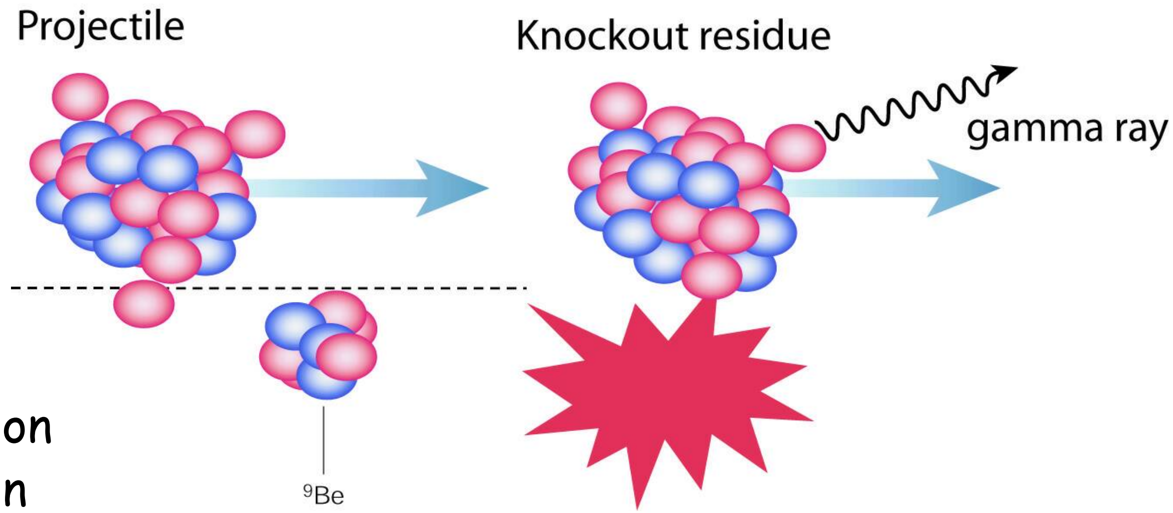
exp = 12 ± 3 mb

DATA: Cortina-Gil et al, 2002

MSU experiments Alexandra Gade



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



Spectroscopic Factors
determined from the population of the residue with A-1

- Fast exotic beams allow for
  - thick secondary targets (100-1000 thicker than at low energy)
  - event-by-event identification

- Example
  - $\sigma = 100$ mbarn
  - $N_T = 10^{22}$ cm^{-2}
  - $N_B = 30$ Hz
  - $N_R = 2600$/day

Applications: Detailed nuclear spectroscopy

Selected examples:

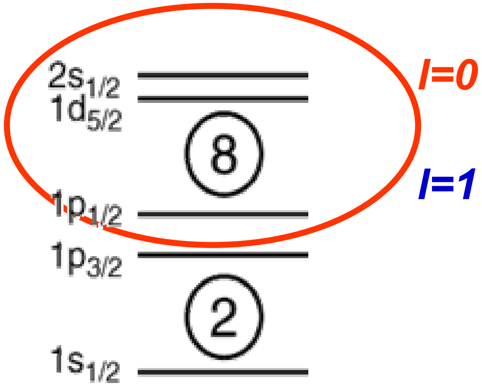
a) The breakdown and persistence of shell gaps

b) Evolution of nuclear structure approaching the "Island of Inversion"

c) Reduced spectroscopic strength and proton neutron asymmetry at the Fermi surface

A classic example: N=8 in ^{12}Be

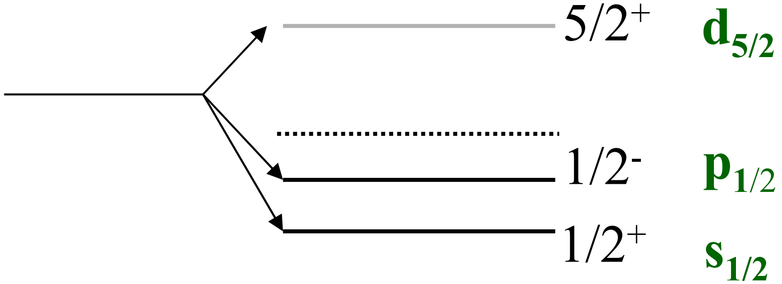
Single particle states in normal order:

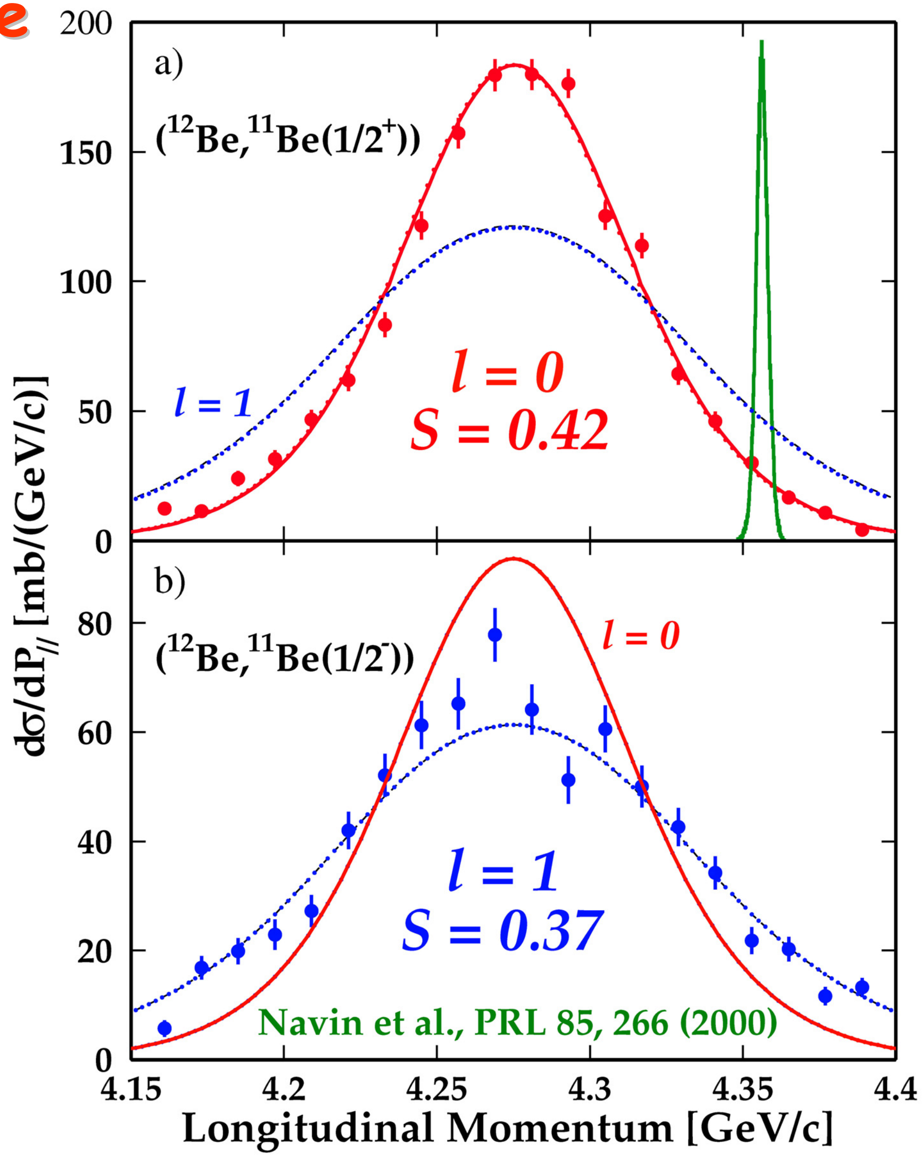


But there is a strong l=0 contribution

J^π	E_{ex} (MeV)	σ_{exp} (mb)
$1/2^+$	0	32.0(47)
$1/2^-$	0.32	17.5(26)

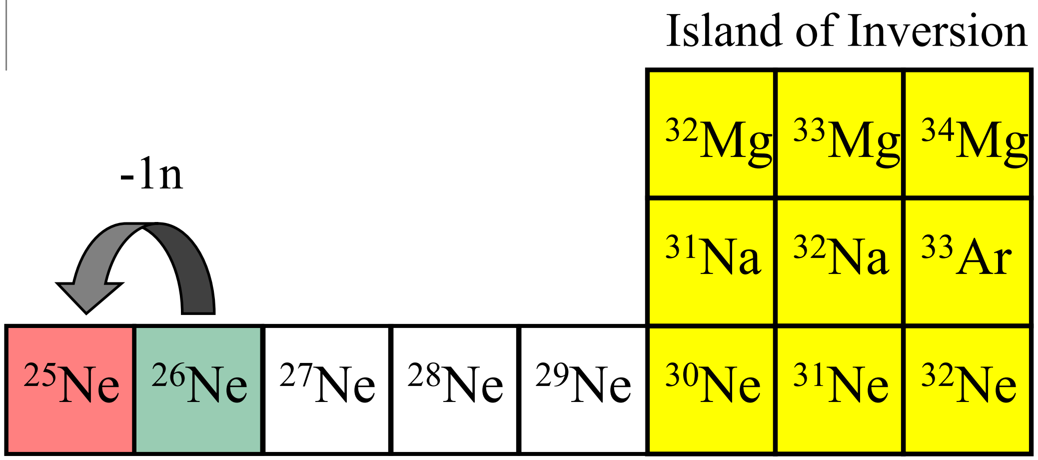
$$^{12}\mathrm{Be} \rightarrow {}^{11}\mathrm{Be}+n+\gamma$$





The $s_{1/2}$ orbit lowered below the N=8 gap and became an intruder

Approaching the island of inversion in the Ne chain I



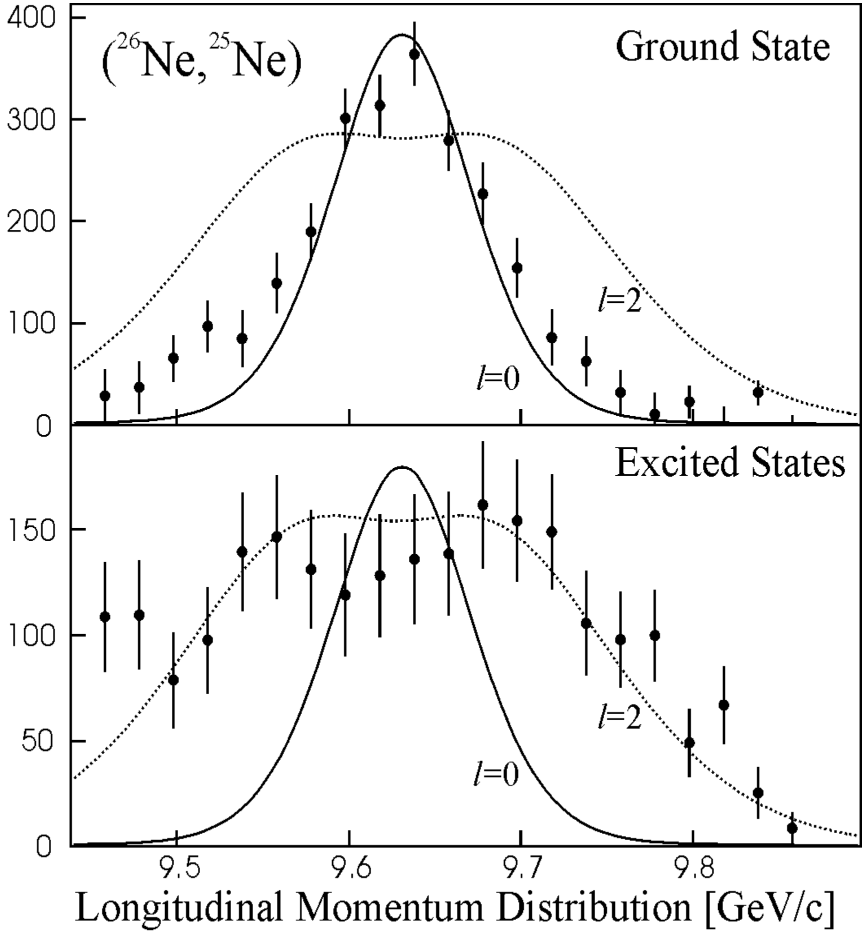
Island of Inversion

-1n

					^{32}Mg	^{33}Mg	^{34}Mg
					^{31}Na	^{32}Na	^{33}Ar
^{25}Ne	^{26}Ne	^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne

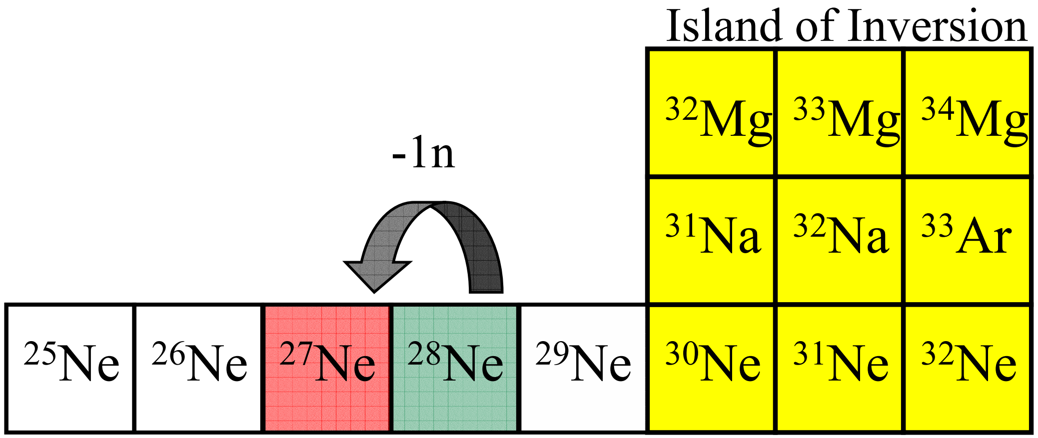
Consistent with enhanced N=16 sub-shell gap, no evidence for intruder states

- Strongest feeding to 1/2$^+$ ground state and to 5/2$^+$ states
- Weaker feeding to first 3/2$^+$ state



Terry et al., PLB 86 (2006).

Approaching the Island of Inversion in the Ne chain II



Island of Inversion

^{32}Mg ^{33}Mg ^{34}Mg

^{31}Na ^{32}Na ^{33}Ar

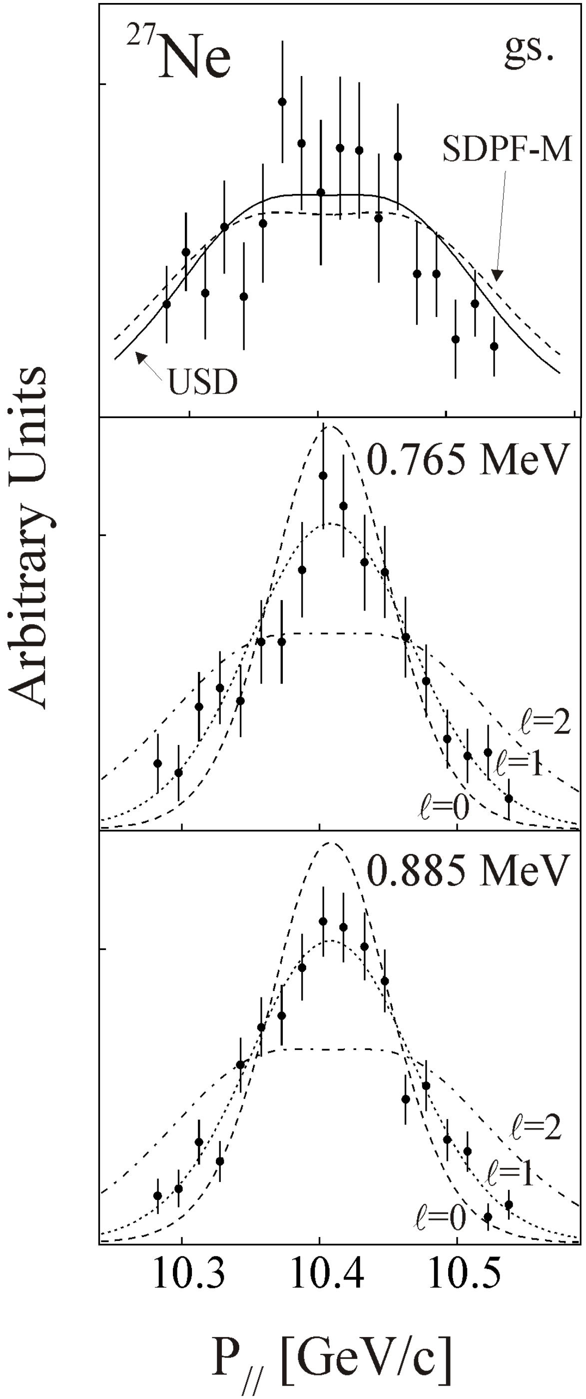
-1n

^{25}Ne ^{26}Ne ^{27}Ne ^{28}Ne ^{29}Ne ^{30}Ne ^{31}Ne ^{32}Ne

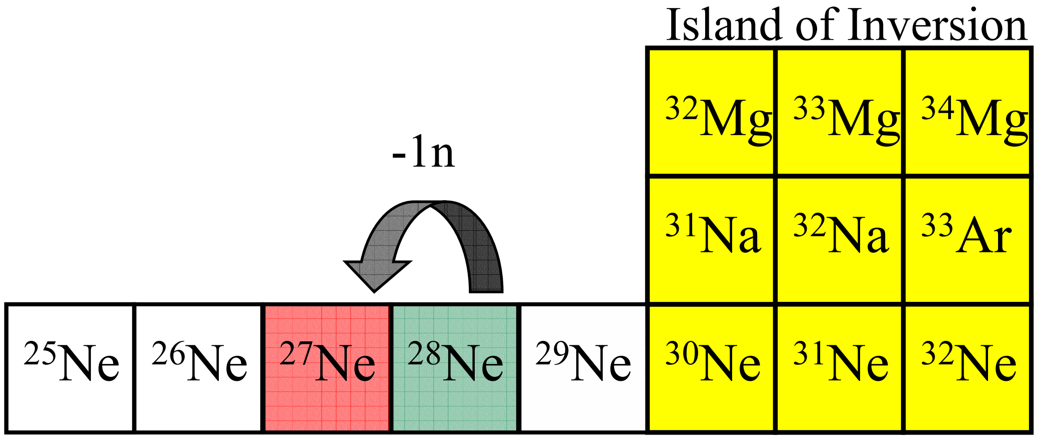
1- Observed three gamma-ray transitions; level scheme confirmed by γ-γ coincidences.

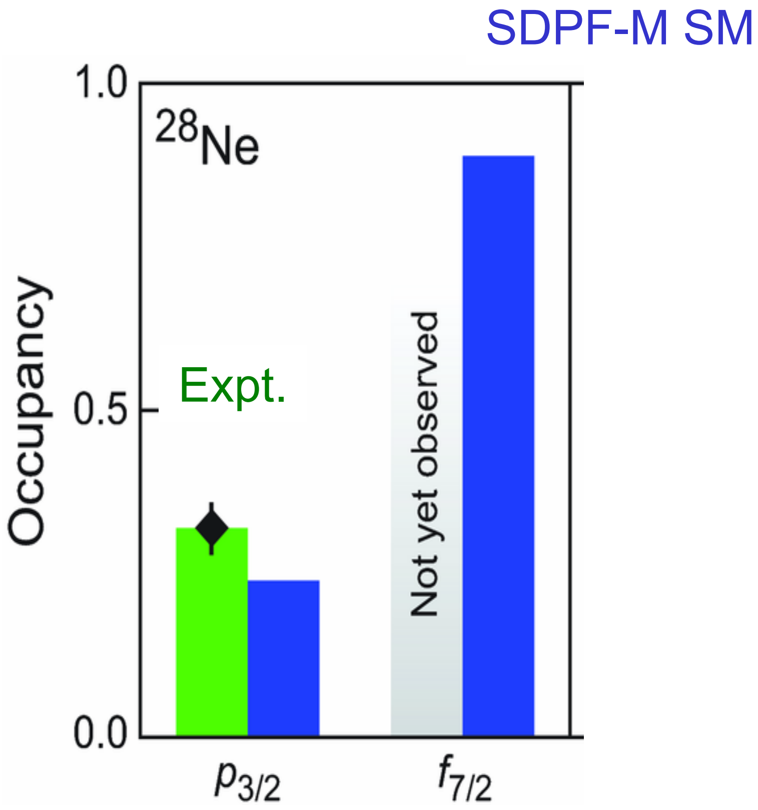
2- Momentum distributions extracted for 0.765- and 0.885-MeV transitions; both show ℓ<2, but low statistics make ℓ=0 and ℓ=1 difficult to distinguish

Terry et al., PLB 86 (2006).

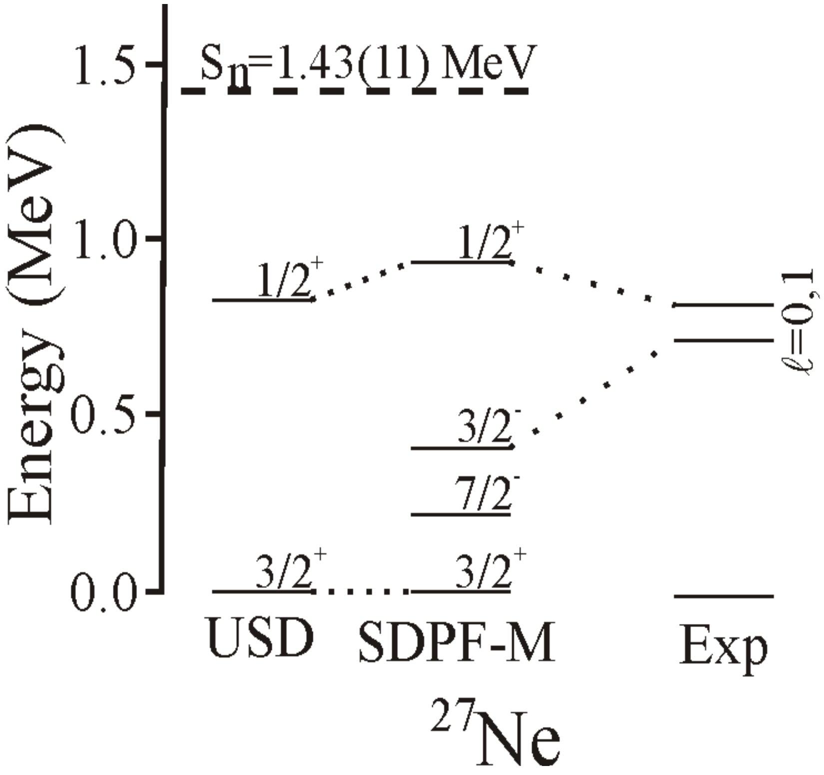


Approaching the Island of Inversion in the Ne chain II



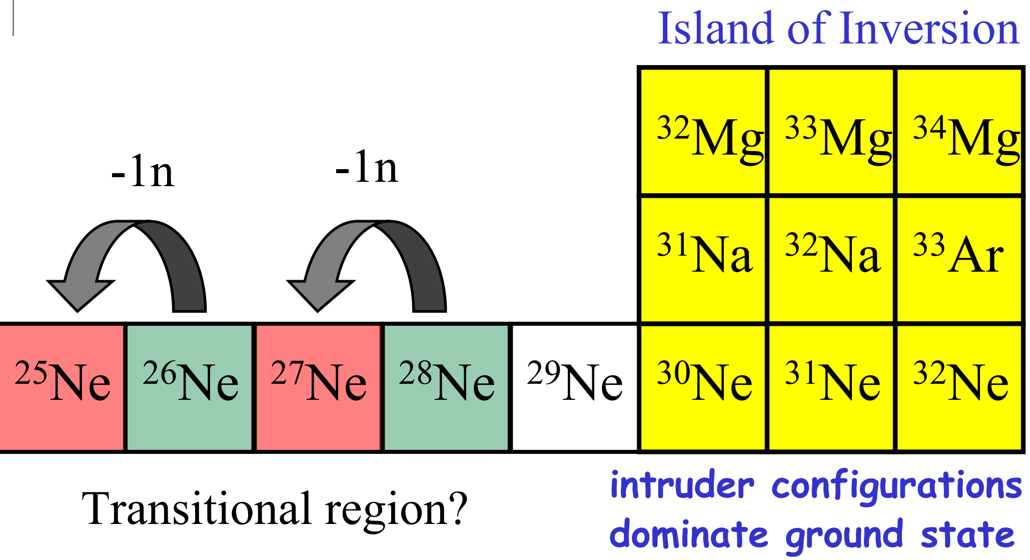


Terry et al., PLB 86 (2006).



- ▹ Additional excited state indicates intruder states at low excitation energy, likely $p_{3/2}$
- ▹ ℓ-value and spectroscopic strength inconsistent with SDPF-M prediction

A gradual transition into the “Island”



Island of Inversion

^{32}Mg ^{33}Mg ^{34}Mg

^{31}Na ^{32}Na ^{33}Ar

-1n -1n

^{25}Ne ^{26}Ne ^{27}Ne ^{28}Ne ^{29}Ne ^{30}Ne ^{31}Ne ^{32}Ne

Transitional region?

intruder configurations dominate ground state

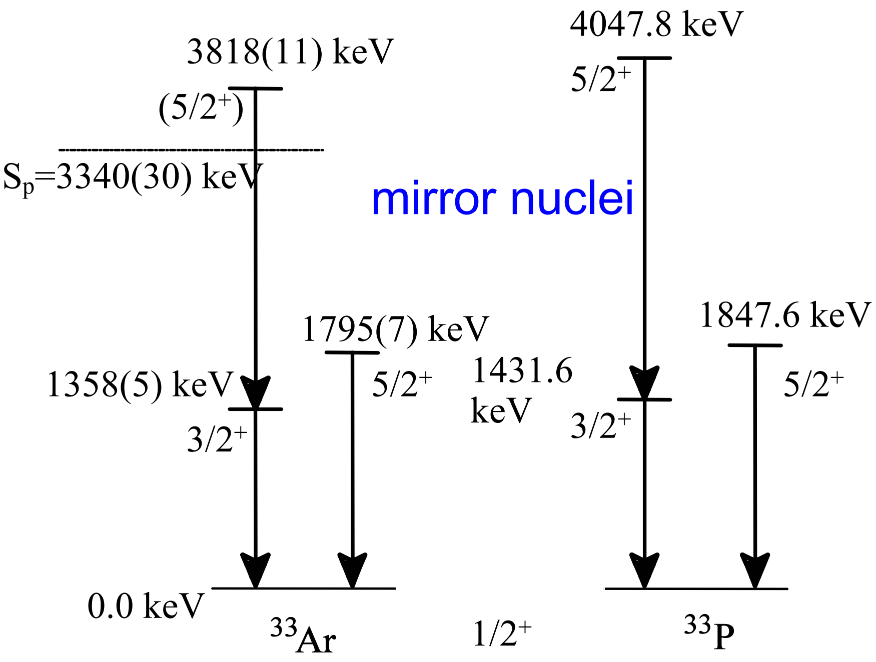
- γ-ray spectroscopy in coincidence with ^{25}Ne,^{27}Ne knockout residues → intruder state in ^{27}Ne but not in ^{25}Ne
- Parallel momentum distributions: intruder state in ^{27}Ne consistent with 3/2^{-} assignment as expected from theory **(SDPF-M shell model, Tokyo)**

→ Intruder states come down in energy

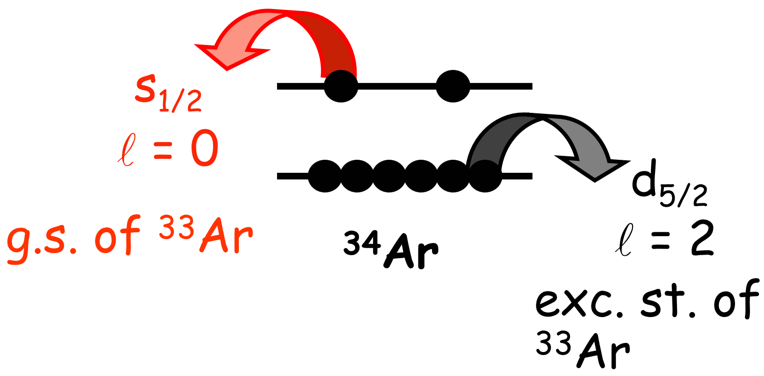
Terry et al., PLB 86 (2006)

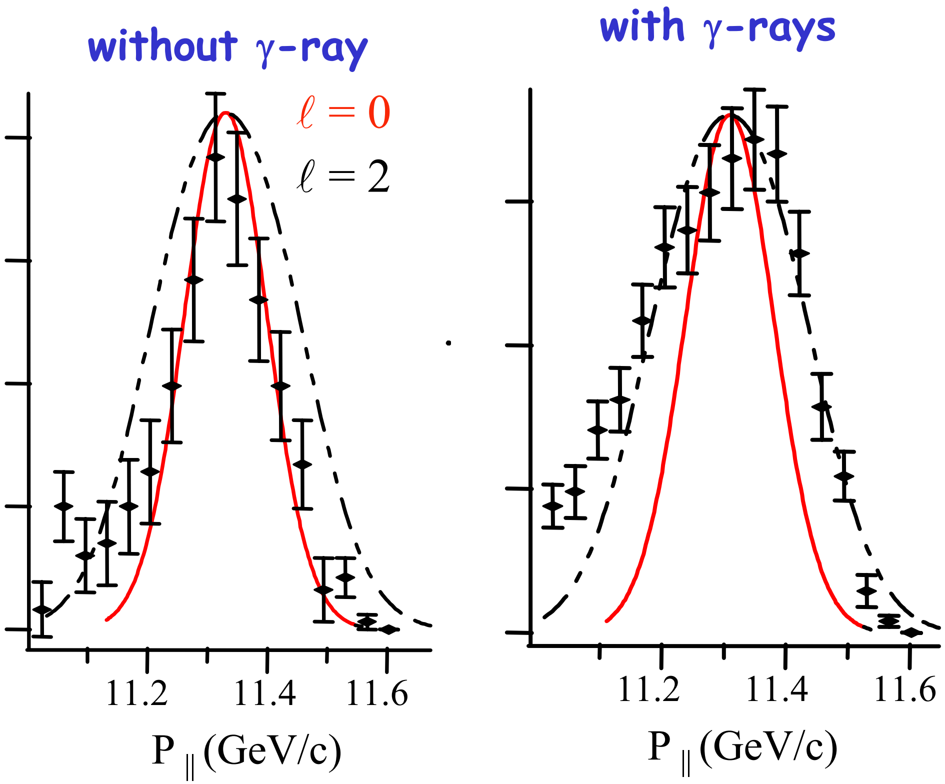
^{25}Ne	no low-lying intruder states
^{26}Ne	no intruder configurations in gs
^{27}Ne	low-lying intruder state (~800 keV)
^{28}Ne	$np_{3/2}$ intruder configuration in gs

^{9}Be(^{34}Ar, ^{33}Ar+γ)X



mirror nuclei



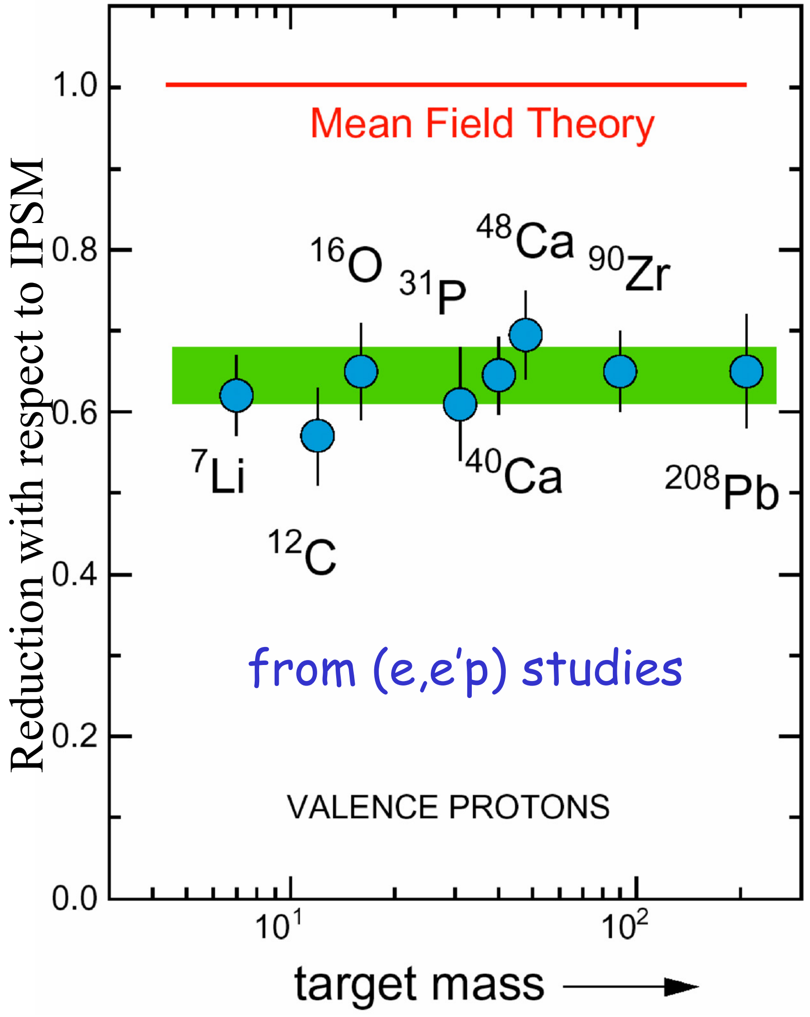


^{33}Ar level scheme confirmed in Clement et al, PRL 92, 172502 (2004)

Gade et al, PRC 69, 034311 (2004)

Correlation effects – stable nuclei

Figure from W. Dickhoff et al.



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

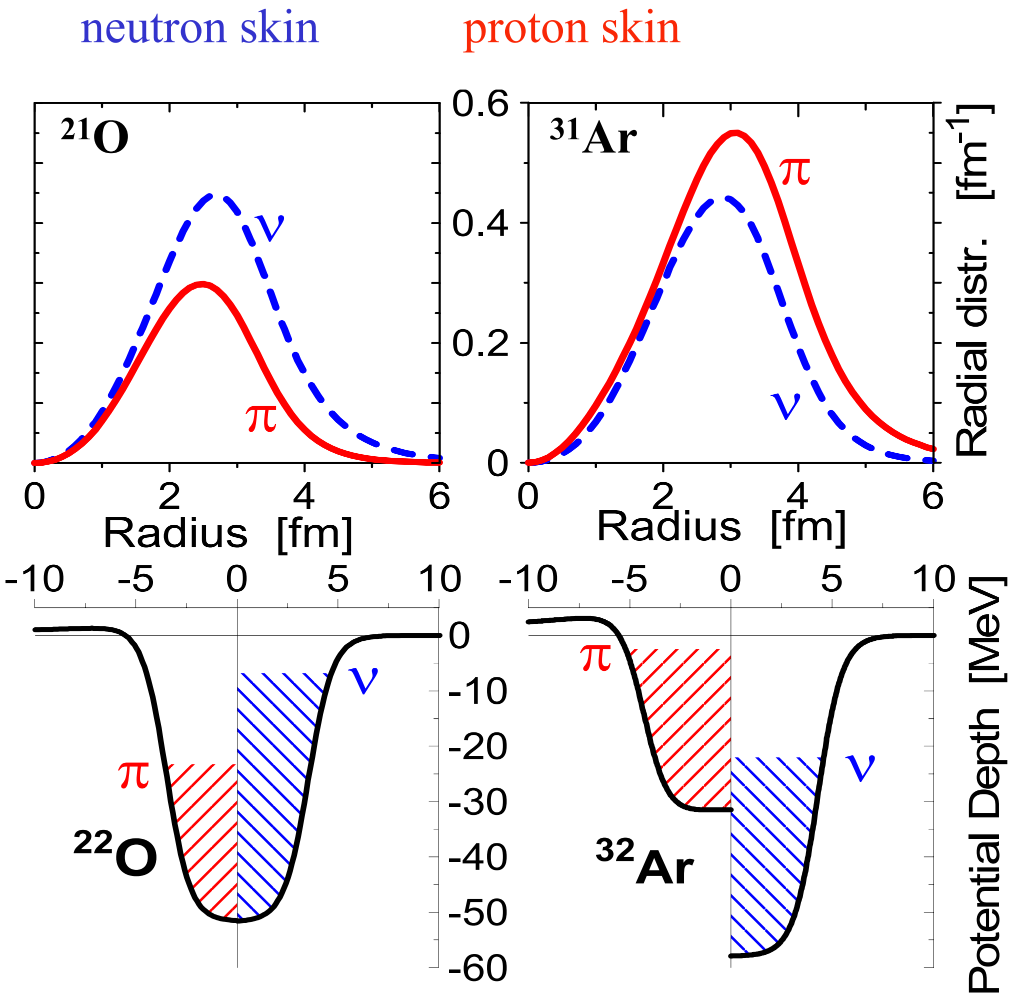
The nuclear shell model pictures deeply-bound states as fully occupied by nucleons. At and above the Fermi sea, configuration mixing leads to occupancies that gradually decrease to zero.

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 will be modified depending on the strength of the correlation.

Pandharipande *et al*, Rev. Mod. Phys. 69, 981 (1997)

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

Correlation effects - Weakly and deeply bound systems



What is the situation beyond the valley of β stability?

At rare-isotope accelerators:

Very deeply and weakly bound exotic nuclei become accessible

Experimental approach to assess the occupation of single-particle orbits in exotic nuclei: **1-nucleon removal reactions**

Measured spectroscopic factor C^2S relates to the occupation number of the orbit involved

Brown et al., PRC 65, 061601 (2002)

^{9}Be(^{15}C,^{14}C)X - A weakly-bound neutron system

Experiment:

- σ_{inc}= 140.2(46) mb

- b(g.s.) = 71.8(24) %

resulting partial cross section

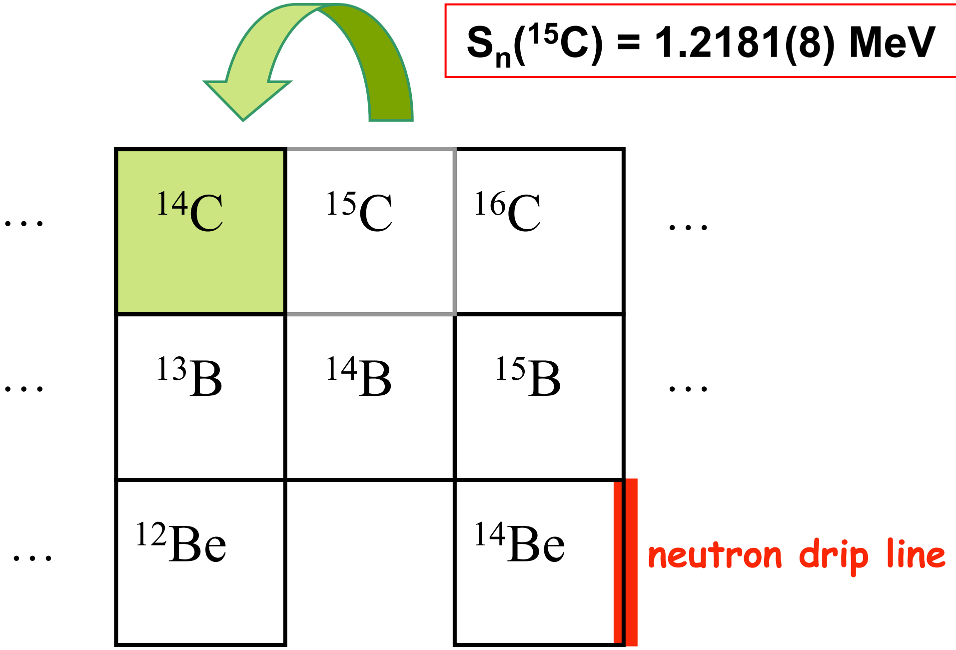
$\sigma(0^{+})$ = 100.8(44) mb

gives with

σ_{sp} = 99.4 mb

$C^{2}S$ = 1.01(4)(5)

S_n(^{15}C) = 1.2181(8) MeV



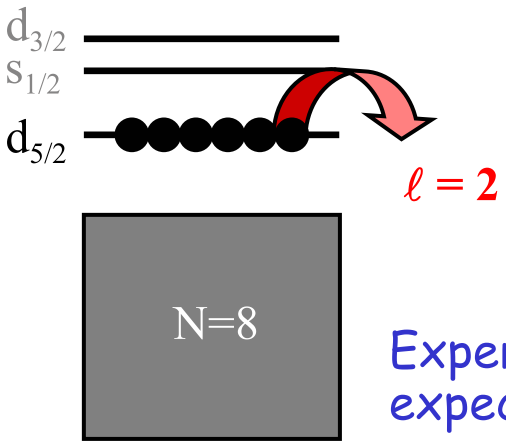
Terry et al., PRC 69, 054306 (2004).

USD shell model (B.A. Brown)

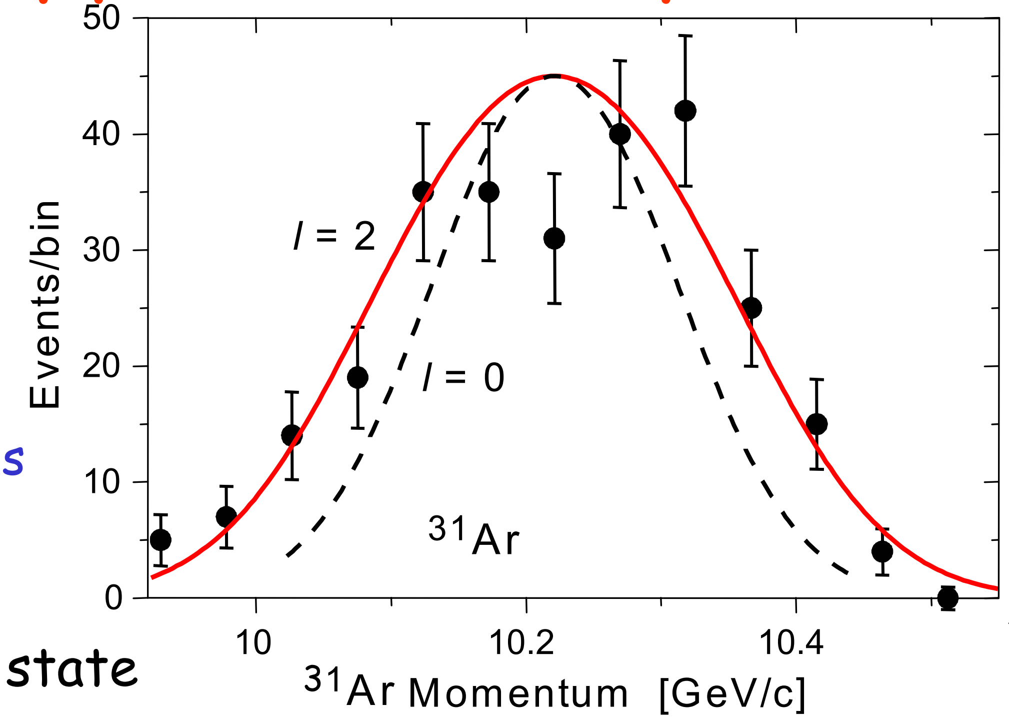
$C^{2}S$ = 1.128

Reduction of the experimental vs. theoretical spectroscopic factor: R_s = 0.90(4)(5)

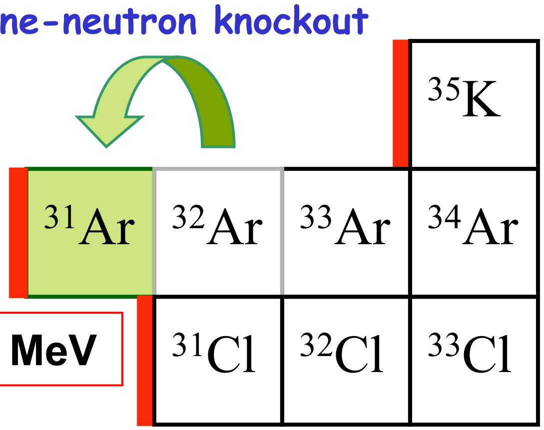
^{9}Be(^{32}Ar,^{31}Ar)X - A deeply-bound neutron system



Experiment confirms expected value ℓ=2



Only bound state in ^{31}Ar: ground state



one-neutron knockout

^{35}K

proton drip line

^{31}Ar ^{32}Ar ^{33}Ar ^{34}Ar

^{31}Cl ^{32}Cl ^{33}Cl

S_n = 21.99(5) MeV

$\sigma_{exp} = 10.4(13)$ mb

$\rightarrow C^2S = 1.00(13)$

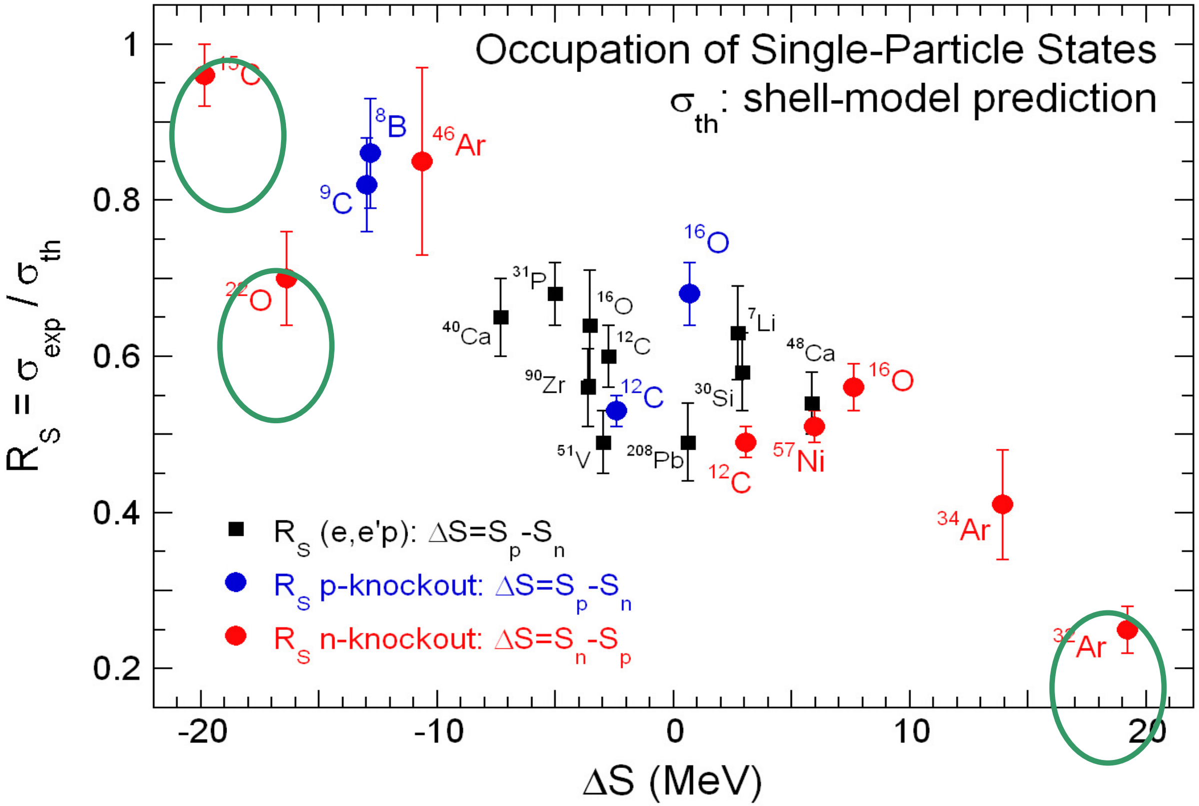
USD shell model:

$C^2S = 4.12$ (B.A. Brown)

Gade *et al.*, PRL **93** (2004) 042501

Reduction of the experimental vs. theoretical spectroscopic factor: R_s = 0.24(3)(4)

Reduction of spectrosopic strength



^{32}Ar and ^{22}O have the same neutron number but the reduction R_s is very different
Gade et al., PRL 93, 042501 (2004)

^{15}C-1n: precision measurement showing less reduction for weakly bound systems
Terry et al., PRC 69, 054306 (2004)

Determination of the occupancies provides information on the presence of correlation effects beyond effective-interaction theory

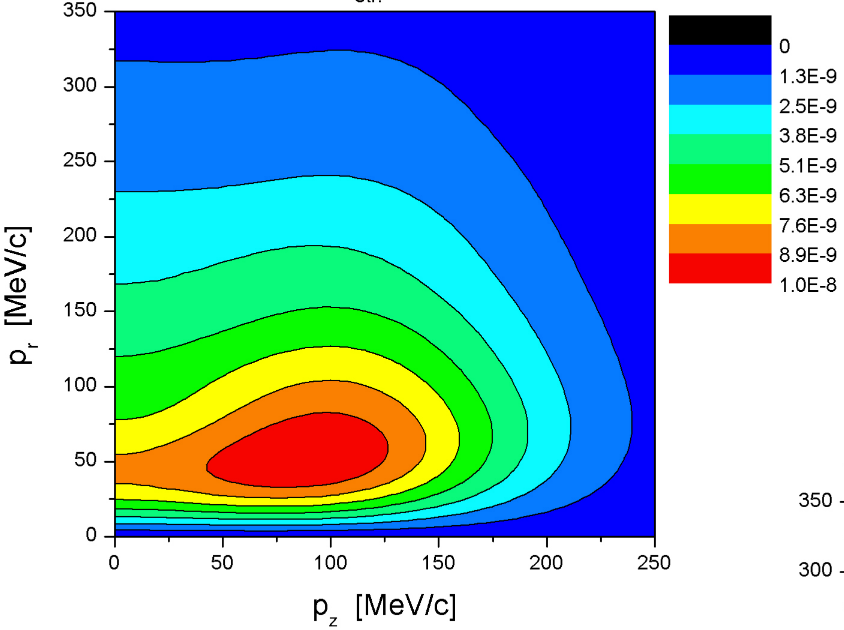
Consistent with a DOM study of elastic scattering:
Charity, Sobotka and Dickhoff, PRL 97 (2006) 162503

Consistent with transfer:
Lee, Tostevin et al., PRC **73** (2006) 044608

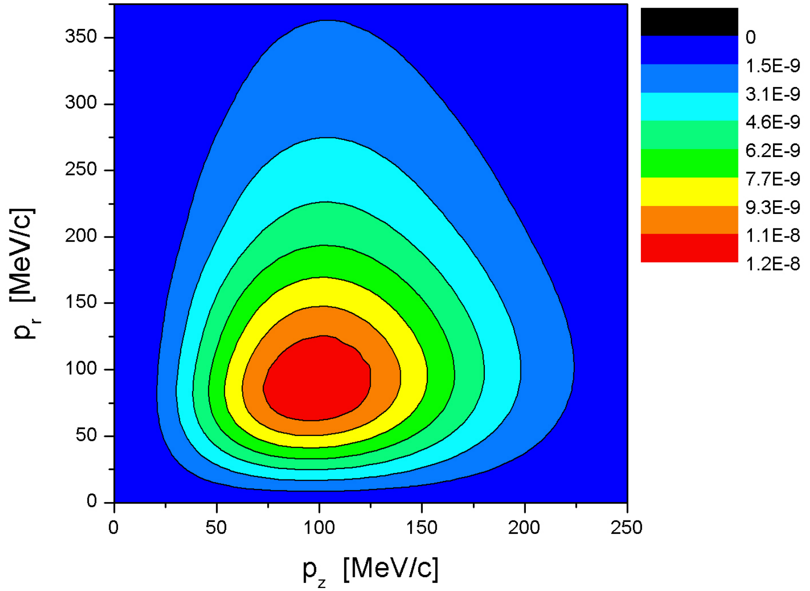
Future: Alignment experiments

C.B., Hansen, PRC C70, 034609 (2004)

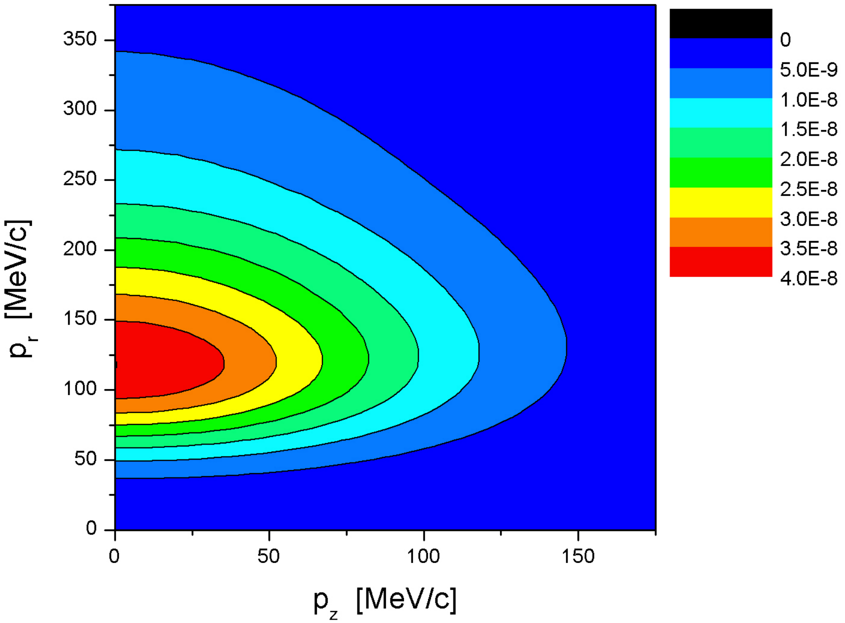
^{34}Ar (68.2 MeV/nucleon)
l=2, m=0, $\sigma_{Str.}$ = 1.175 mb



^{34}Ar (68.2 MeV/nucleon)
l=2, m=1, $\sigma_{Str.}$ = 2.296 mb



^{34}Ar (68.2 MeV/nucleon)
l=2, m=2, $\sigma_{Str.}$ = 4.715 mb



$$^{9}\mathrm{Be}\left(^{34}\mathrm{Ar},{}^{33}\mathrm{Ar}\right)\mathrm{X}$$

One neutron-removal

68.2 MeV/nucleon

0d5/2 neutron, S_n = 18.43 MeV

TMD x LMD: Alignment – γ-ray angular distribution

$$^{9}\mathrm{Be}\left(^{34}\mathrm{Ar},\ ^{33}\mathrm{Ar}+\gamma\right)\mathrm{X}$$

One neutron-removal

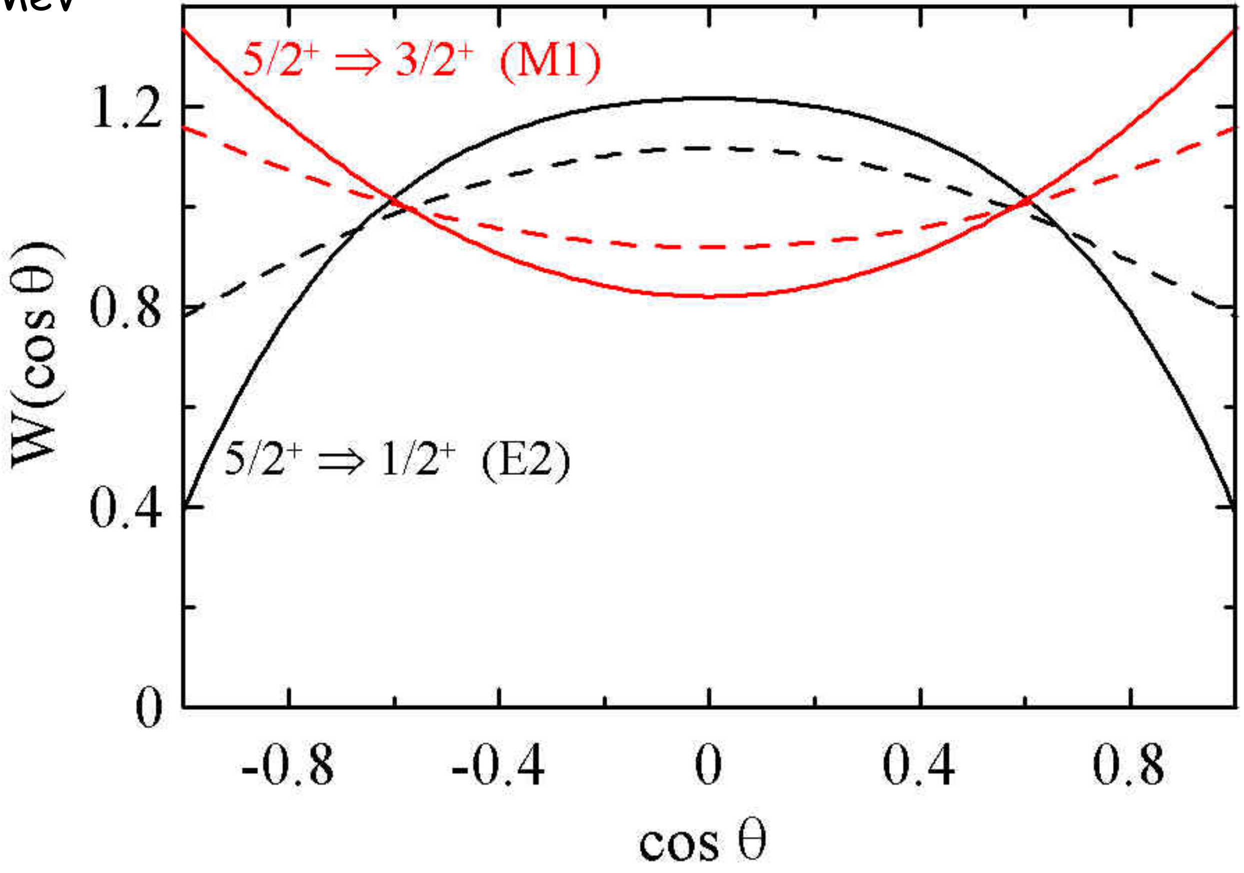
68.2 MeV/nucleon

0d5/2 neutron, S_n = 18.43 MeV

^{34}Ar

Angular distributions, center-of-mass system

dashed: all, full drawn: 13% cut around M=2



Brief summary and outlook

A few selected examples:

a) Track the evolution of nuclear structure in the vicinity of new and conventional magic numbers by wave-function spectroscopy with knockout reactions

b) Precision measurement of spectroscopic factors to compare to ab-initio calculations

c) Study the effect of the continuum (Gamov shell model)

d) Many more exciting opportunities lie ahead… too many to list