A secure path to the drip line based on theory and experiment

FRIB 11-20-08

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....

- Scientific question
- **Green's function method / framework**
- What we know about correlations
- How to proceed to the drip line?
- DOM: data ⇒ self-energy / propagator
  data-driven extrapolations ⇒ drip line
- (p,2p) & (p,pn) in inverse kinematics ⇔ (e,e′p)
- Outlook

Scientific Question

- How do the properties of protons and neutrons change as a function of nucleon asymmetry?

  Properties: elastic cross sections, bound single-particle properties, including removal energy, spectroscopic factors, strength distribution, one-body density matrix, E/A.

Program

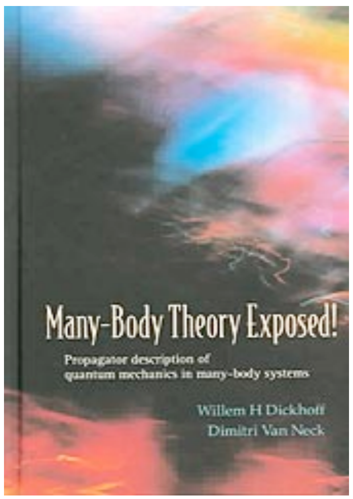
- Employ framework of Green's function method to link presently available data to be cast in the form of the complex potentials (including their asymmetry dependence) that govern the behavior of nucleons in a large energy window: $\varepsilon_F \pm 100$-200 MeV.
- Prediction of data for nuclei further along towards the dripline follows, allowing further improvements, etc.

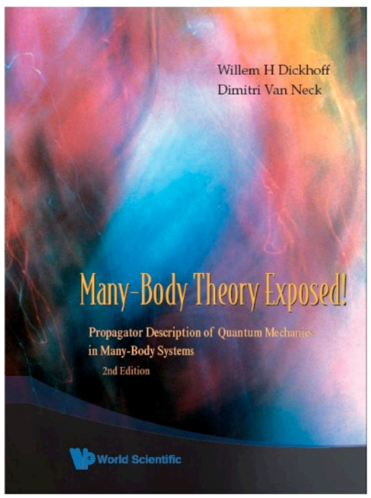
Description of the nuclear many-body problem

Ingredients: Nucleons interacting by "realistic interactions"
Nonrelativistic many-body problem

Method: Green's functions (Propagators)
⇨ amplitudes instead of wave functions (efficient)
keep track of all nucleons, including the high-momentum ones

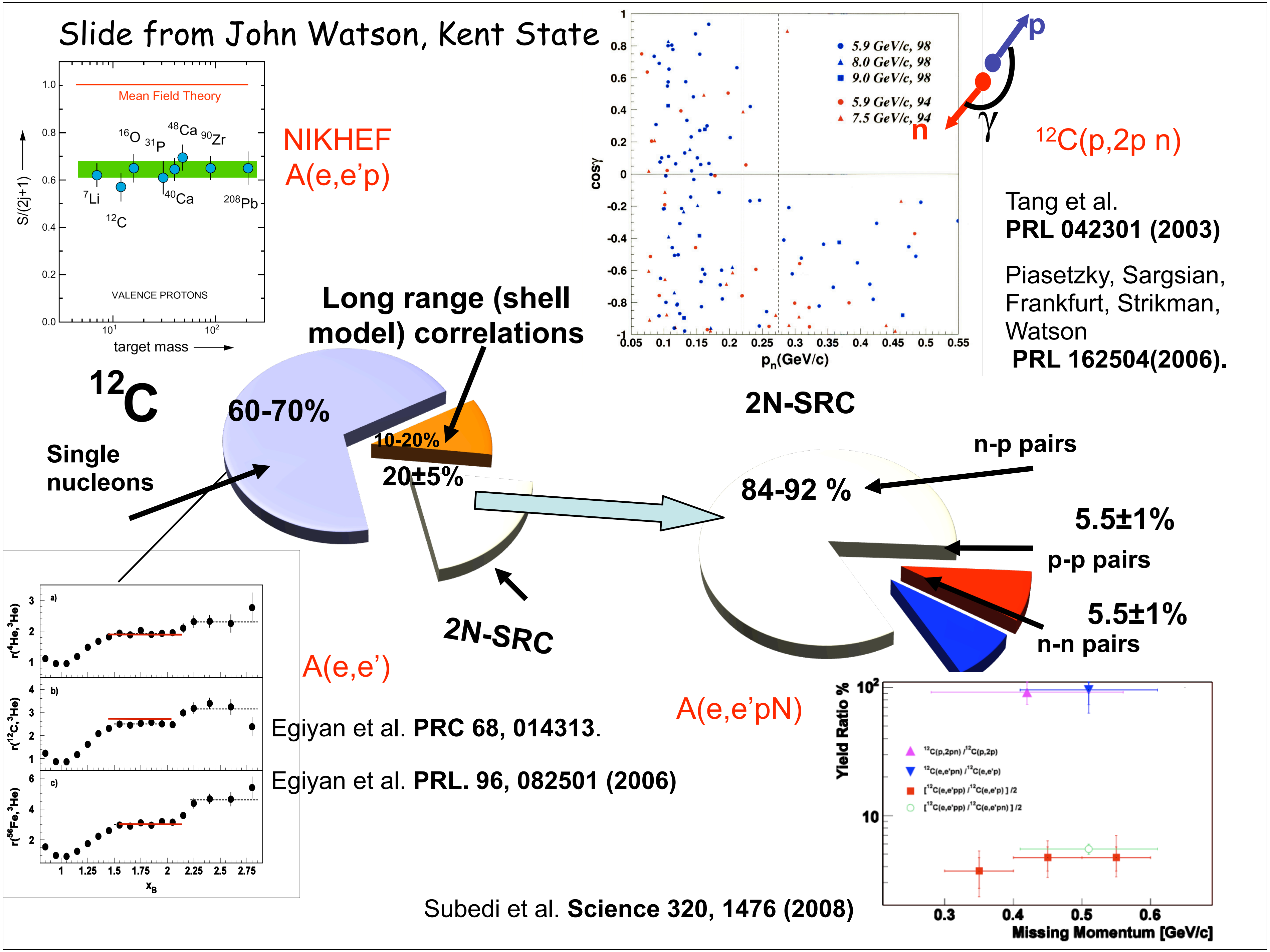
Book: Dimitri Van Neck & W.D. 2nd ed. 2008





Physical insight and useful for all many-body systems
Link between experiment and theory clear
Can include all energy scales
Also available as a framework to analyze and interpret experimental data

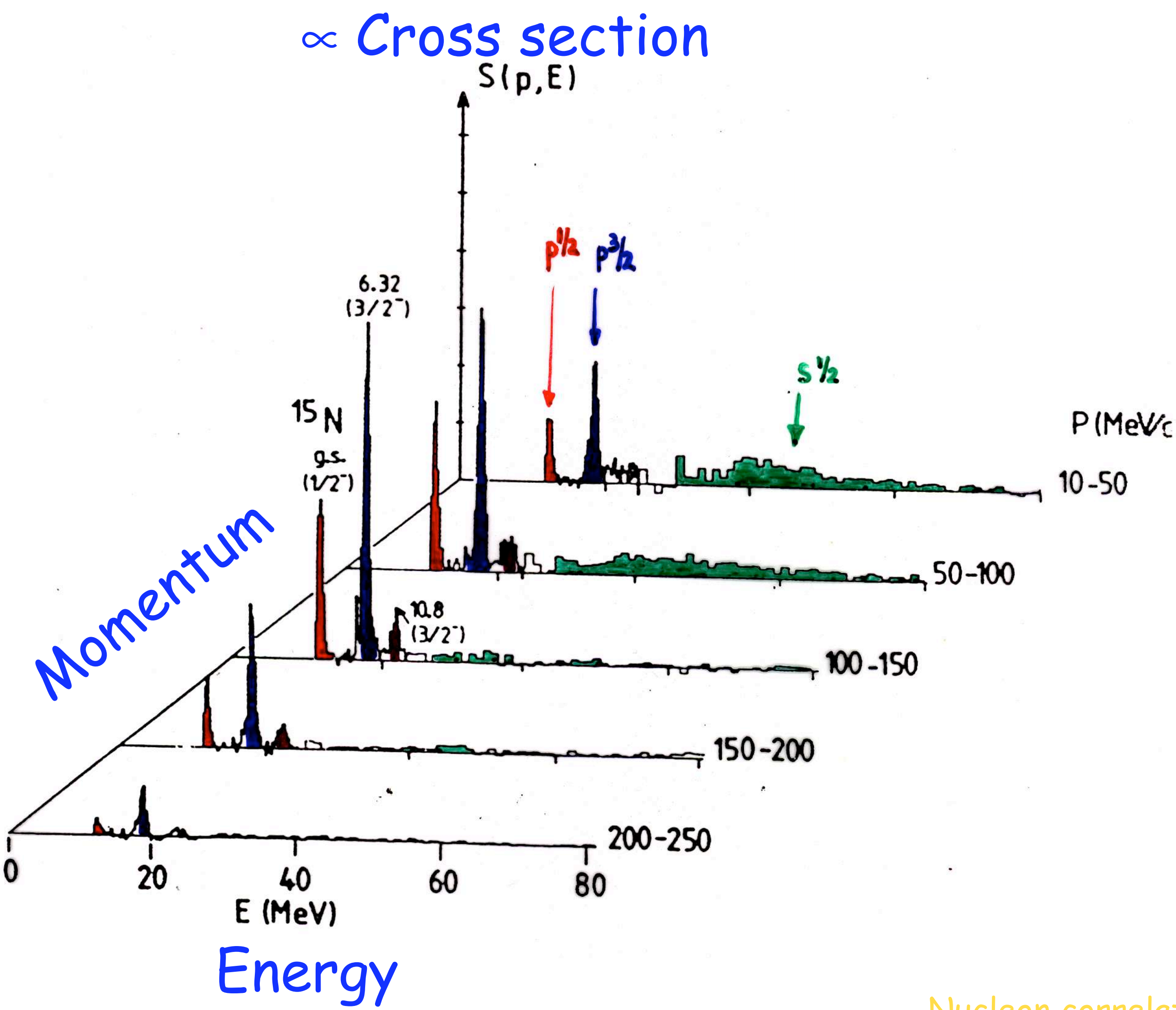
Review: W.H.D. & C. Barbieri, Prog. Part. Nucl. Phys. **52**, 377 (2004)



Slide from John Watson, Kent State
Mean Field Theory
VALENCE PROTONS
S/(2j+1)
target mass
NIKHEF
A(e,e'p)
Long range (shell model) correlations
12C
60-70%
10-20%
20±5%
Single nucleons
2N-SRC
cosγ
p_n(GeV/c)
5.9 GeV/c, 98
8.0 GeV/c, 98
9.0 GeV/c, 98
5.9 GeV/c, 94
7.5 GeV/c, 94
p
n
γ
12C(p,2p n)
Tang et al.
PRL 042301 (2003)
Piasetzky, Sargsian, Frankfurt, Strikman, Watson
PRL 162504(2006).
2N-SRC
n-p pairs
84-92 %
5.5±1%
p-p pairs
5.5±1%
n-n pairs
A(e,e')
Egiyan et al. PRC 68, 014313.
Egiyan et al. PRL. 96, 082501 (2006)
A(e,e'pN)
Yield Ratio %
Missing Momentum [GeV/c]
Subedi et al. Science 320, 1476 (2008)

Mougey et al., Nucl. Phys. A335, 35 (1980)

$^{16}O(e,e'p)$

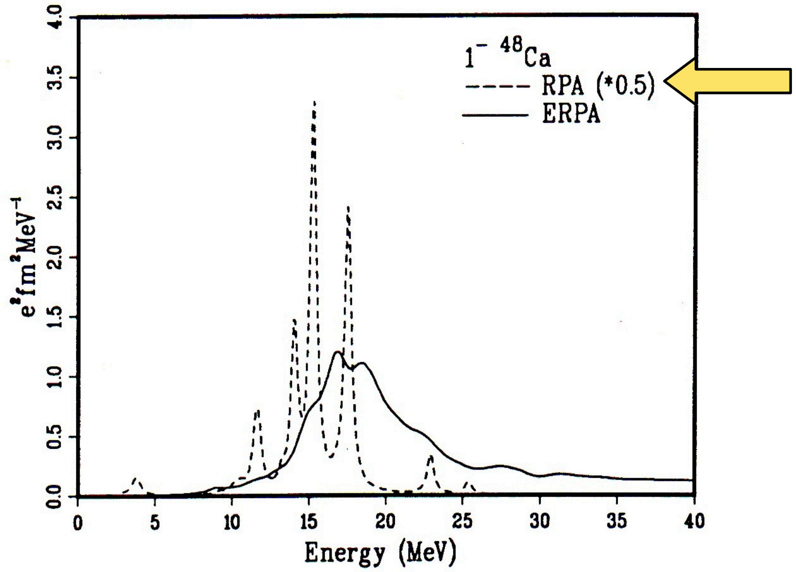


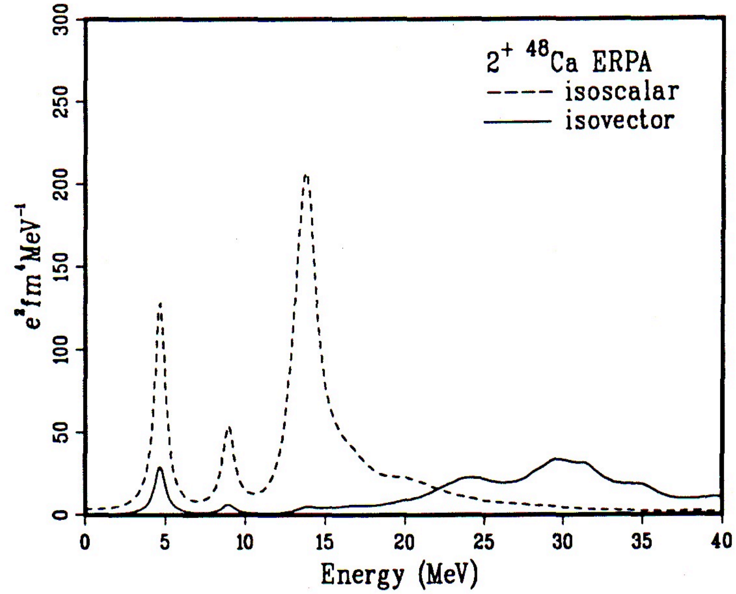
Nucleon correlations

RPA vs. E-RPA for Giant Resonances

includes sp fragmentation

Giant Dipole ${}^{48}Ca$ Giant Quadrupole





In turn: Excited states determine sp fragmentation

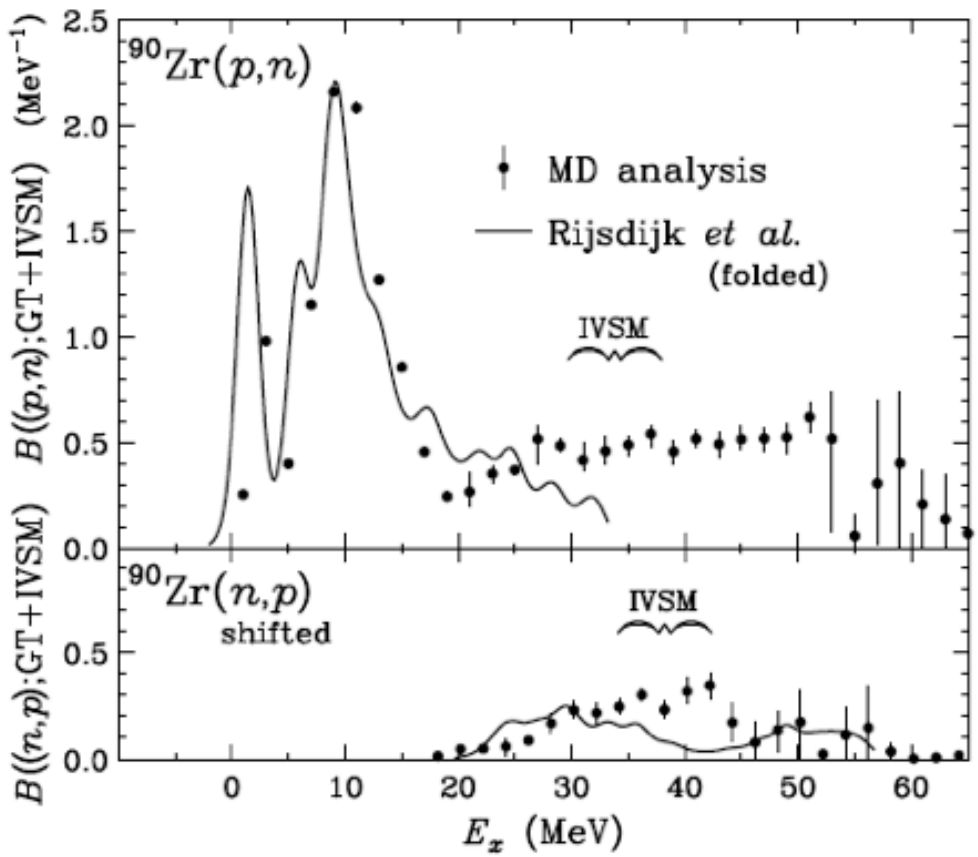
M. G. E. Brand, K. Allaart, and W. H. D.

Phys. Lett. **214B** , 483-489 (1988) & Nucl. Phys. **A509** , 1-38 (1990).

Still relevant …

Nucleon correlations

Gamow-Teller (p,n) / (n,p)



Yako et al. Phys. Lett. B

Fig. 3. GT plus IVSM strength distributions obtained by the MD analysis of the $^{90}Zr(p,n)$ and $^{90}Zr(n,p)$ reactions (in GT unit). The $^{90}Zr(n,p)$ spectrum is shifted by +18 MeV. The curves are taken from Ref. [30]. See text for details.

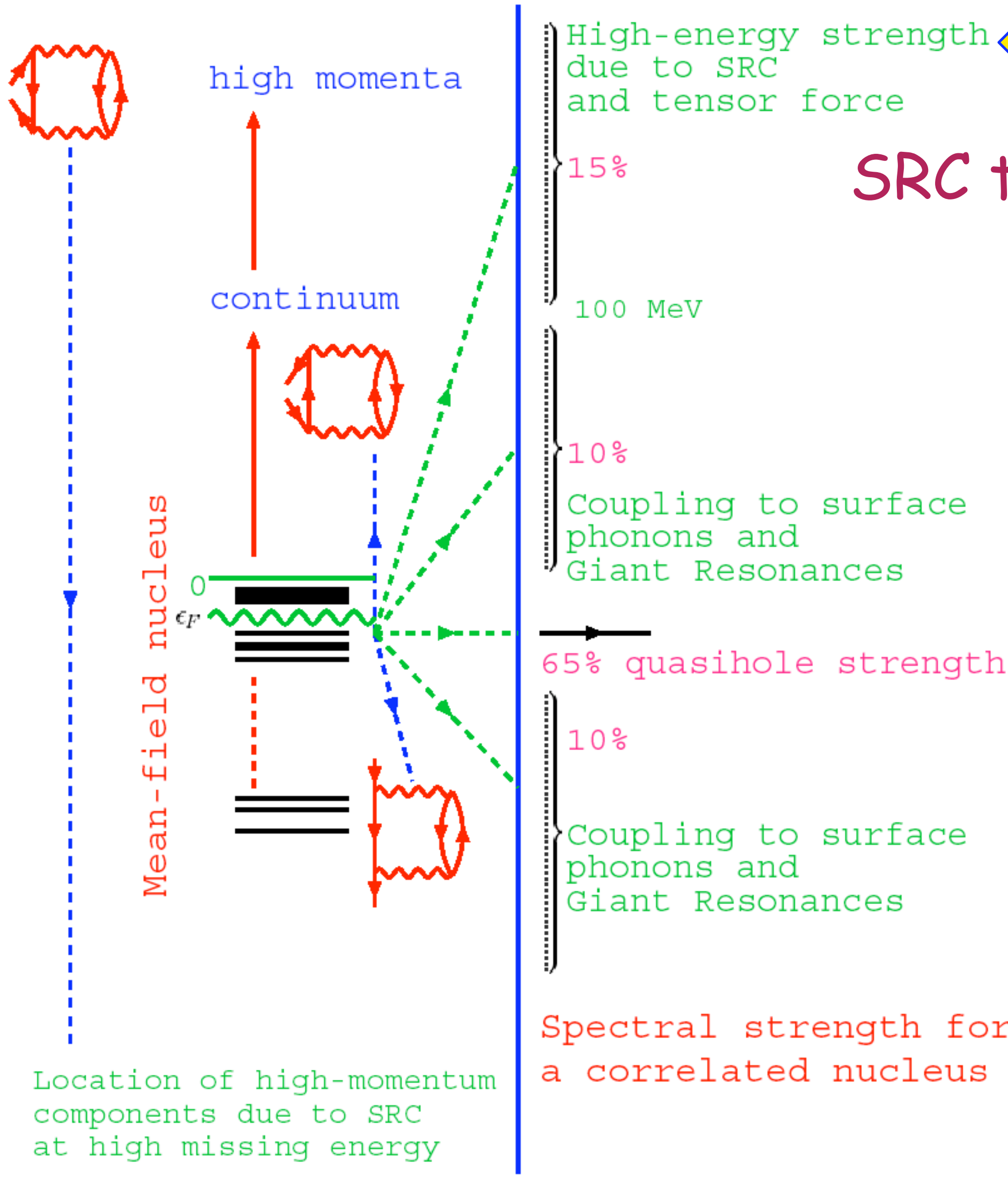
Location of single-particle strength in closed-shell (stable) nuclei

For example: protons in ^{208}Pb

SRC

JLab E97-006

Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



SRC theory

Elastic scattering

NIKHEF data

L. Lapikás

Nucl. Phys. A553,297c (1993)

Correlations for nuclei with N very different from Z?
⇒ Radioactive beam facilities

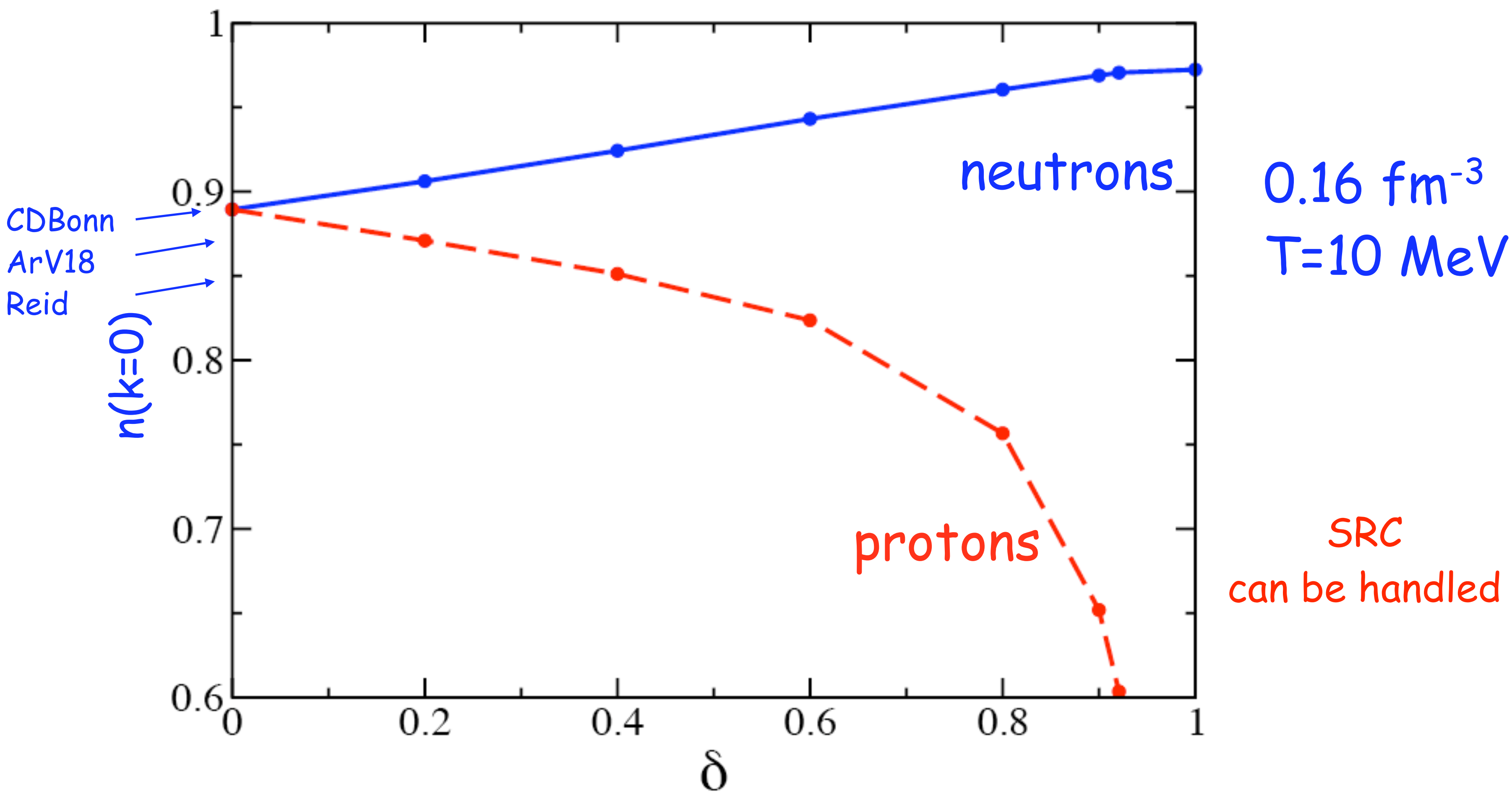
Nuclei are TWO-component Fermi liquids

- SRC about the same between pp, np, and nn
- Tensor force disappears for n when N >> Z (volume effect)
- Surface?
- Ideally: quantitative predictions based on solid foundation

Some pointers: from theory and experiment

SCGF for isospin-polarized nuclear matter including SRC ⇒ momentum distribution

Frick, Rios et al.
PRC71,014313(2005)

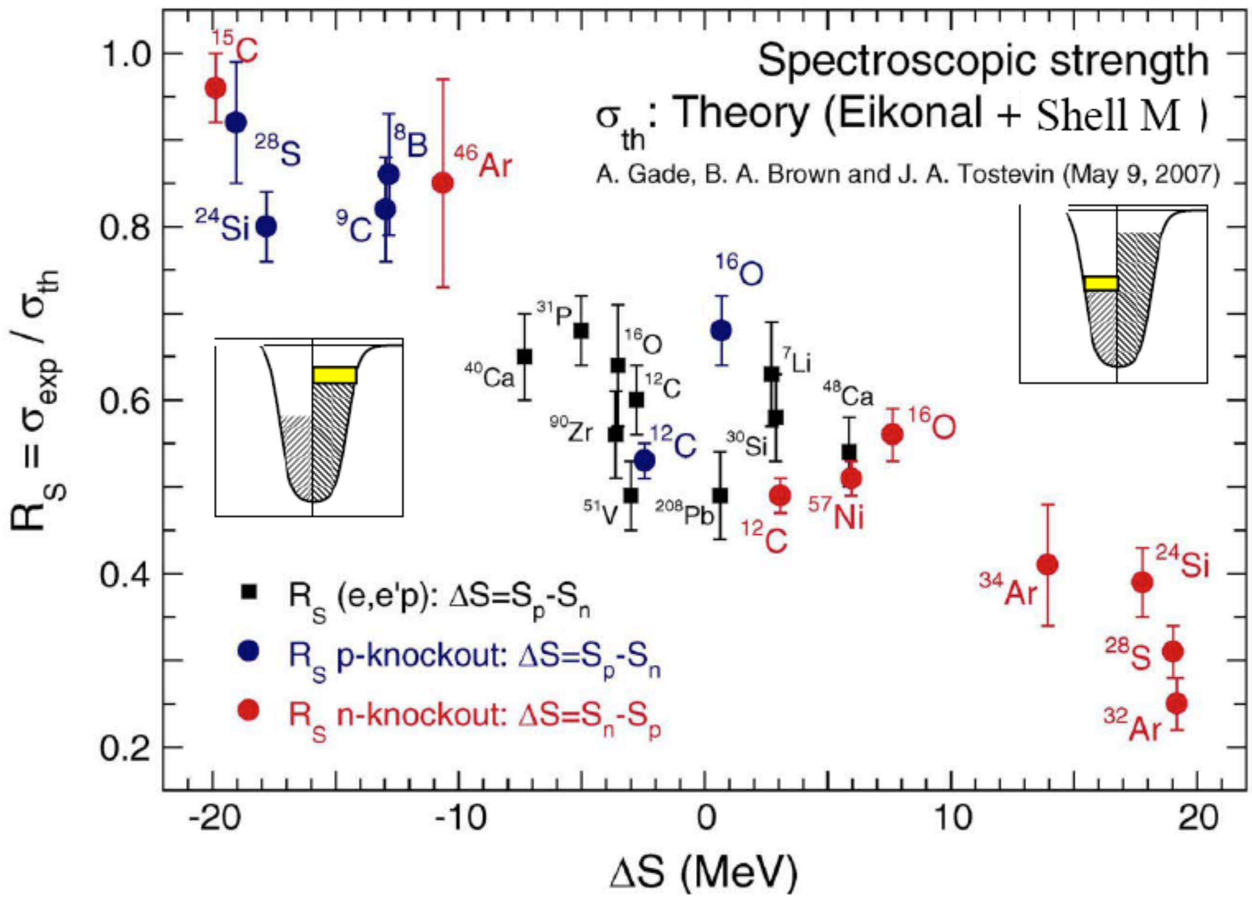


asymmetry = (N-Z)/A

Nucleon correlations

Gade et al. Phys Rev C77, 044396 (2008)

Deeply-bound systems



$R_S \neq$ not spectroscopic factor

Reduction w.r.t. shell model

neutrons more correlated with increasing proton number and accompanying increasing separation energy & vice versa

⇒ Spectroscopic factors become very small; too small?

Nucleon correlations

DOM = Dispersive Optical Model

C. Mahaux and R. Sartor, Adv. Nucl. Phys. **20**, 1 (1991)

Green's function formulation $\Rightarrow$ "Mahaux analysis"

Goal: extract "propagator"/"self-energy" from data

Vehicle for data-driven extrapolations / predictions to the dripline

FRAMEWORK FOR EXTRAPOLATIONS BASED ON EXPERIMENTAL DATA

There is empirical information about the nucleon self-energy!!

Mahaux:

⇒ Optical potential to analyze elastic nucleon scattering data

⇒ Extend analysis from A+1 to include structure information in A-1 ⇒ (e,e'p) data

⇒ Employ dispersion relation between real and imaginary part of self-energy

Recent extension

Combined analysis of protons/neutrons in ^{40}Ca and ^{48}Ca

Charity, Sobotka, & WD, Phys. Rev. Lett. **97**, 162503 (2006)

Charity, Mueller, Sobotka, & WD, Phys. Rev. C**76**, 044314 (2007).

Large energy window (> 200 MeV)

Goal: Extract asymmetry dependence ⇒ $\delta = (N - Z)/A$

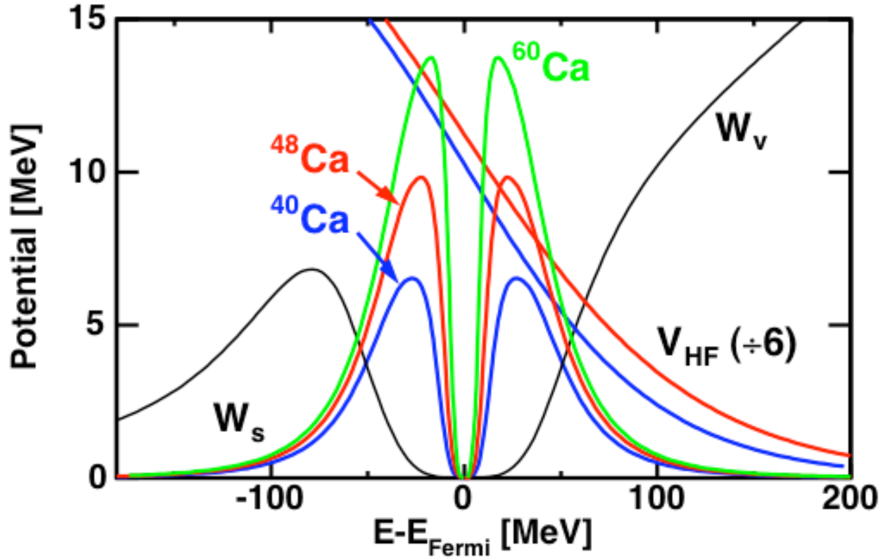
⇒ **Predict** proton properties at large asymmetry ⇒ ^{60}Ca

⇒ **Predict(?)** neutron properties … the dripline

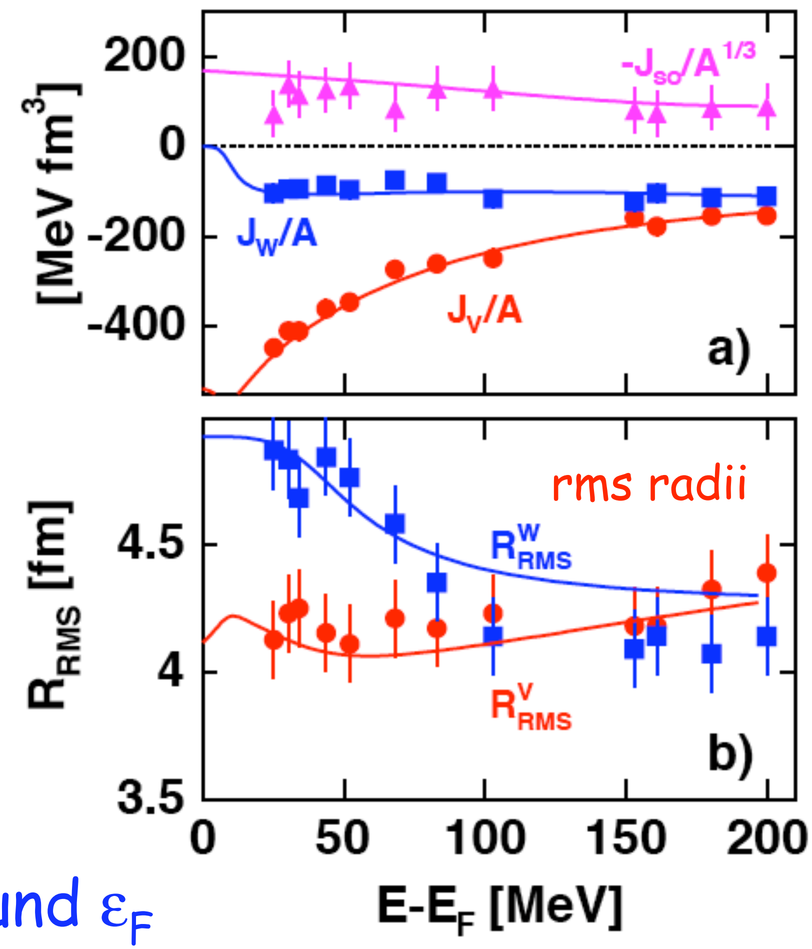
based on data!

DOM Potentials

Surface potential strengthens with increasing asymmetry for protons



Volume integrals ^{40}Ca

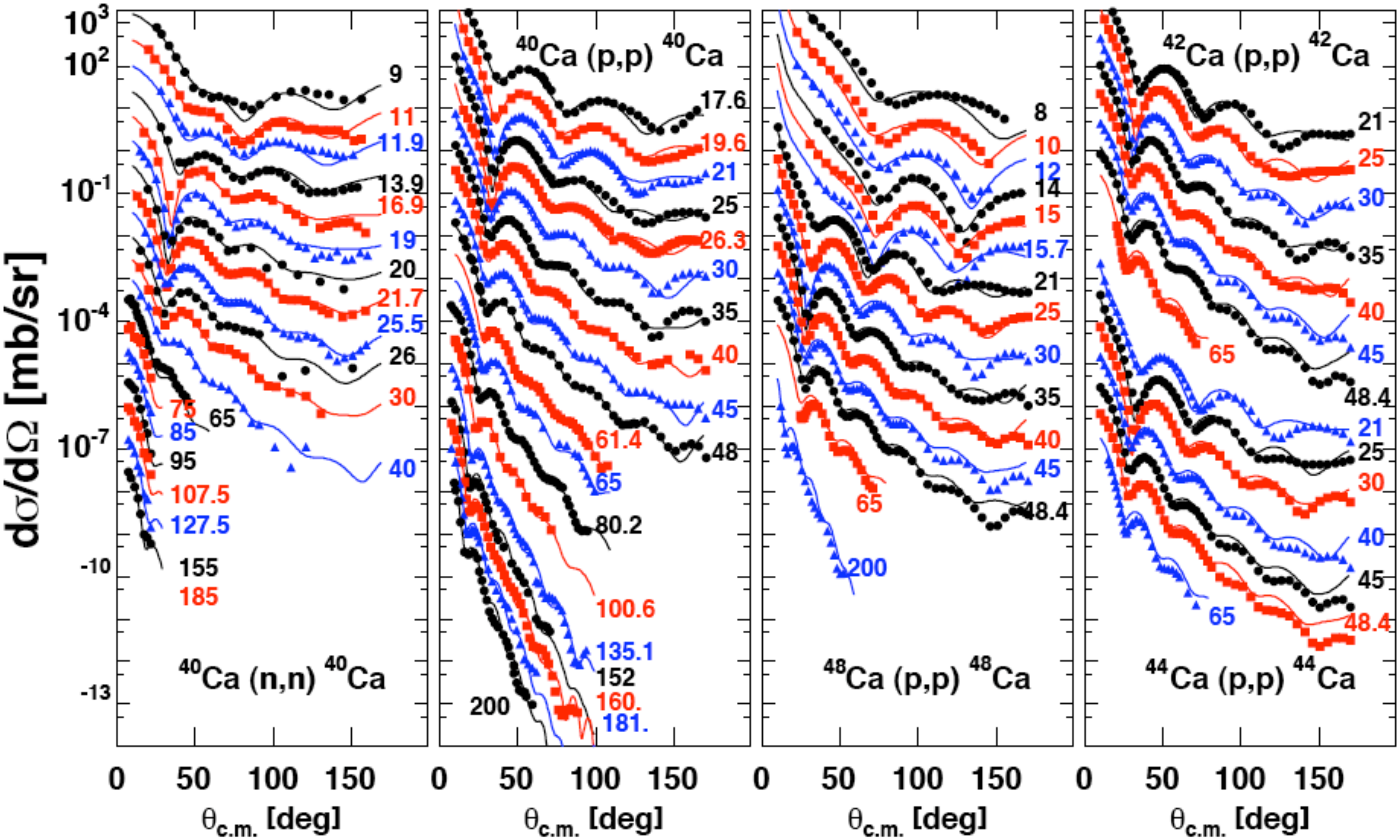


Surface potential symmetric around ε_F

Volume potential asymmetric around ε_F

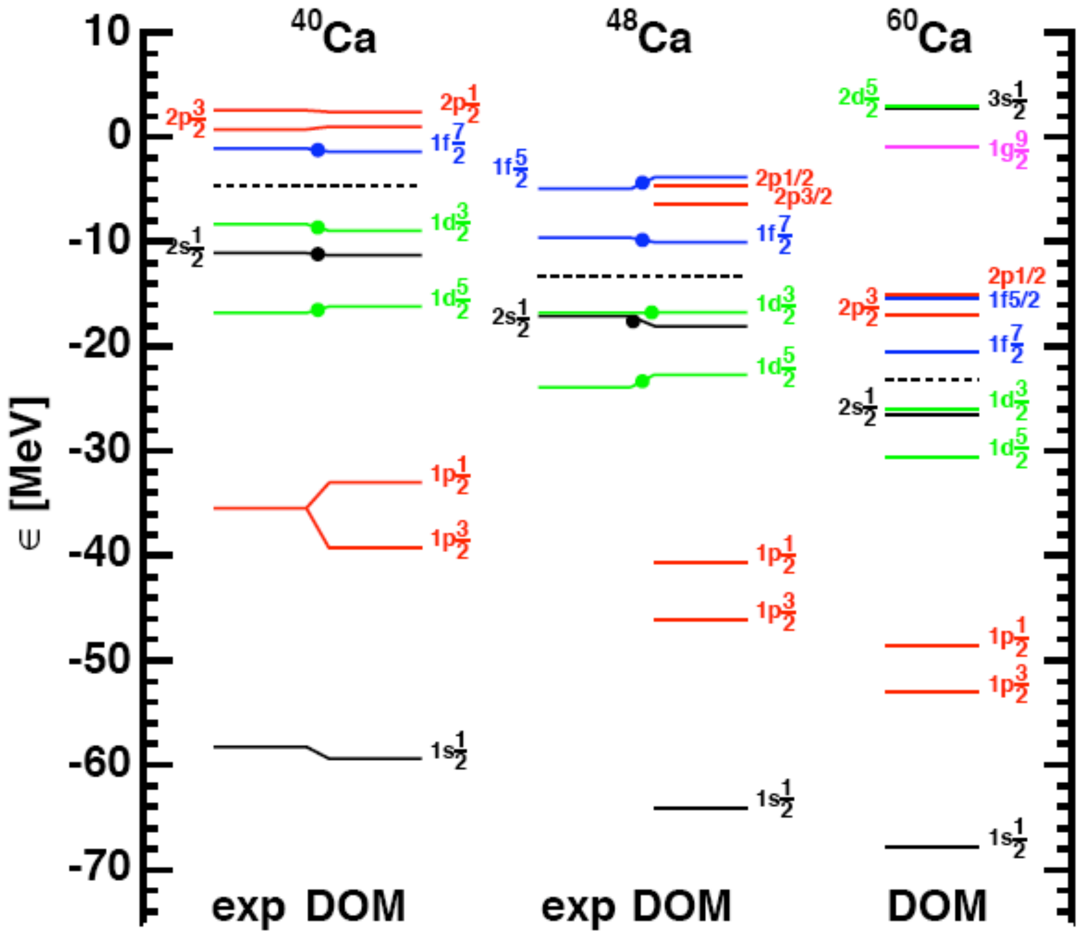
Nucleon correlations

Fit and predictions of n & p elastic scattering cross sections



Nucleon correlations

Proton single-particle structure ^{60}Ca prediction



Possible pairing of protons due to pn correlations?!

Increased correlations with increasing asymmetry!

Proton elastic scattering cross sections beyond ^{48}Ca predicted ⇒ experiments?

What about neutrons?

- Almost no elastic scattering data on ^{48}Ca until recently!
- Most pressing information
- Also very relevant for future applications of transfer reactions involving deuterons

Extrapolation in δ

Naïve: $p/n \Rightarrow D_1 \Rightarrow \pm (N-Z)/A$

Cannot be extrapolated for n

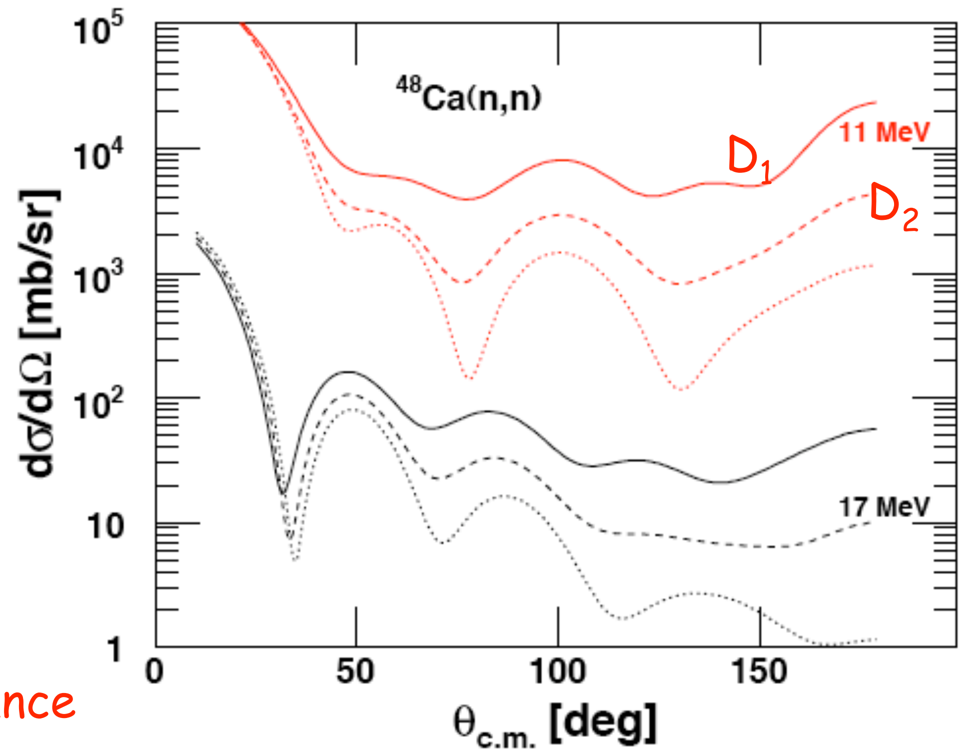
Less naïve:

$D_2 \Rightarrow p \Rightarrow +(N-Z)/A$

$D_2 \Rightarrow n \Rightarrow 0$

Emphasizes coupling to GT resonance

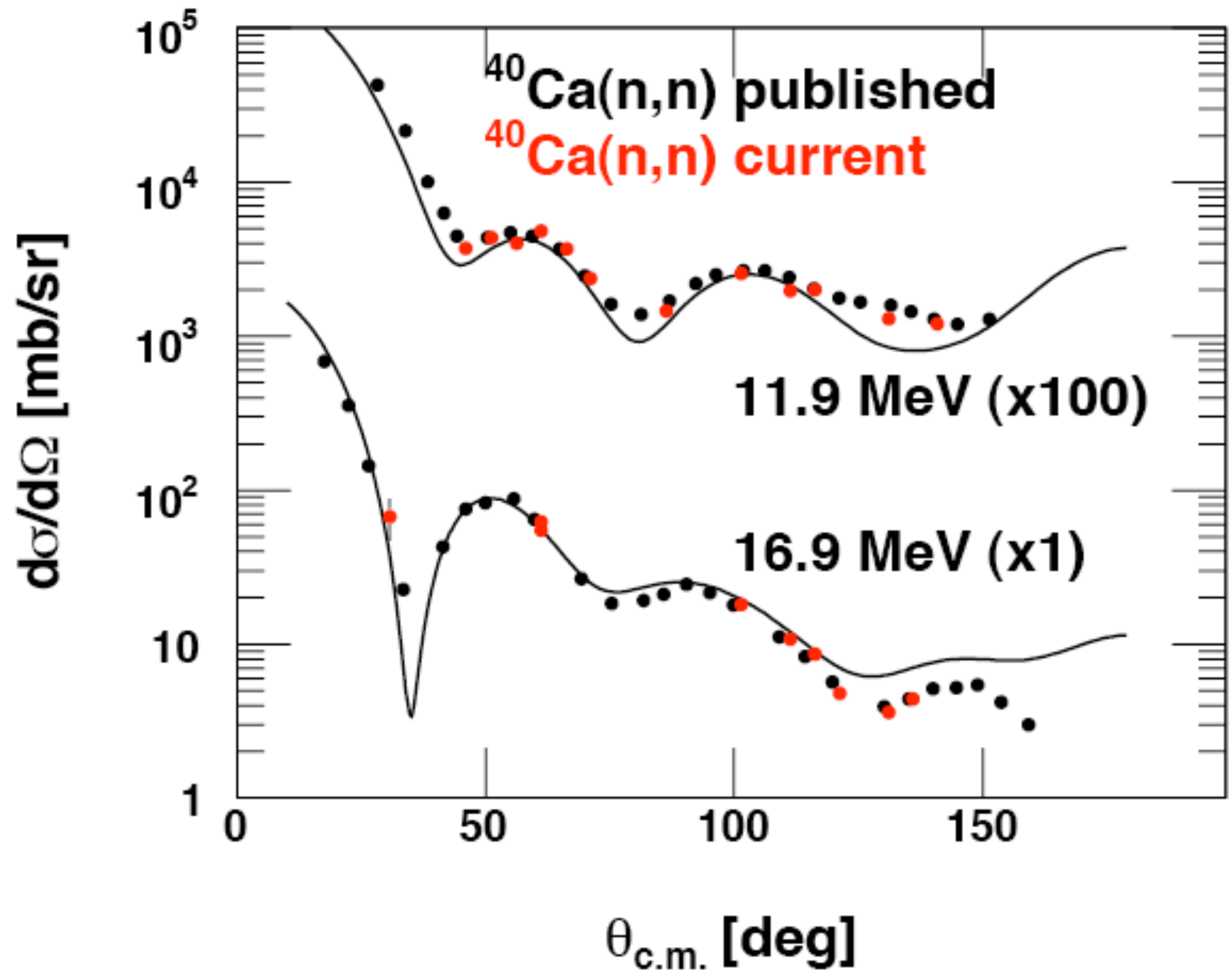
Consistent with n+^{A}Mo data



Need n+^{48}Ca elastic scattering data!!!

Performed at TUNL (Sobotka & Charity)

WashU exp: Sobotka, Shane, Mueller, Charity at TUNL



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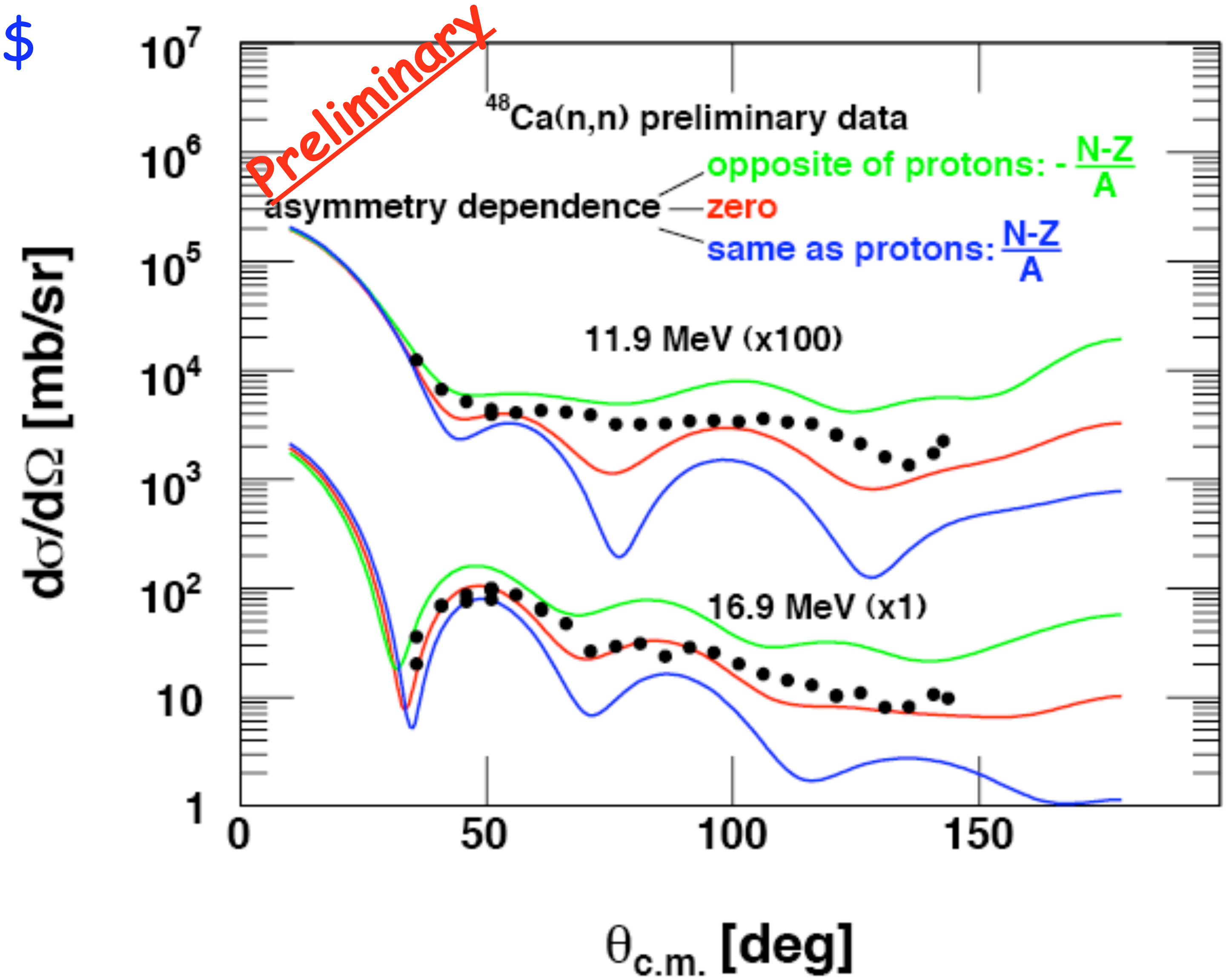
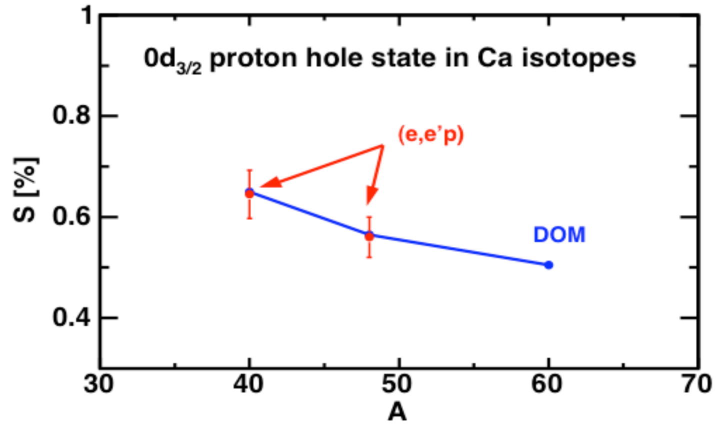
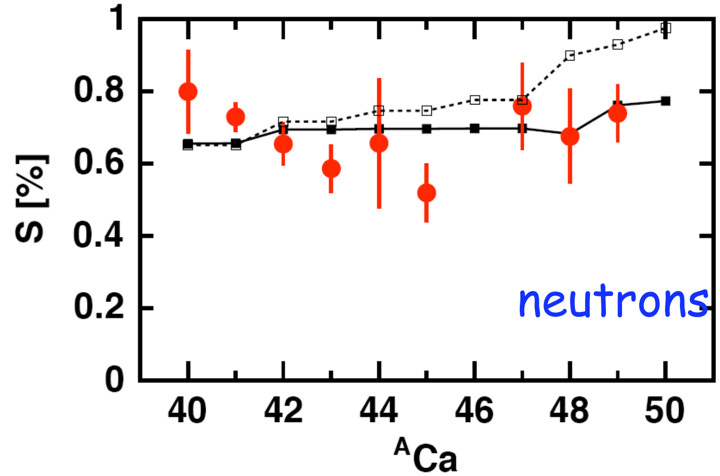


Preliminary
^{48}Ca(n,n) preliminary data
asymmetry dependence
opposite of protons: - $\frac{N-Z}{A}$
zero
same as protons: $\frac{N-Z}{A}$
11.9 MeV (x100)
16.9 MeV (x1)
$d\sigma/d\Omega$ [mb/sr]
$\theta_{c.m.}$ [deg]
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0
50
100
150

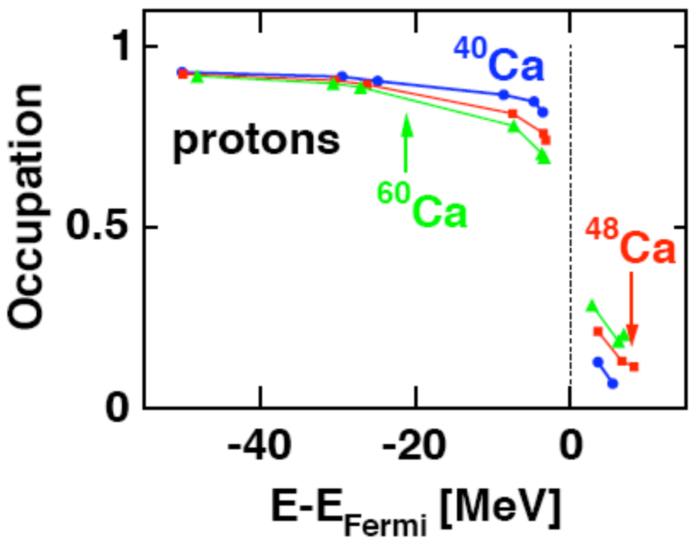
Spectroscopic factors as a function of δ

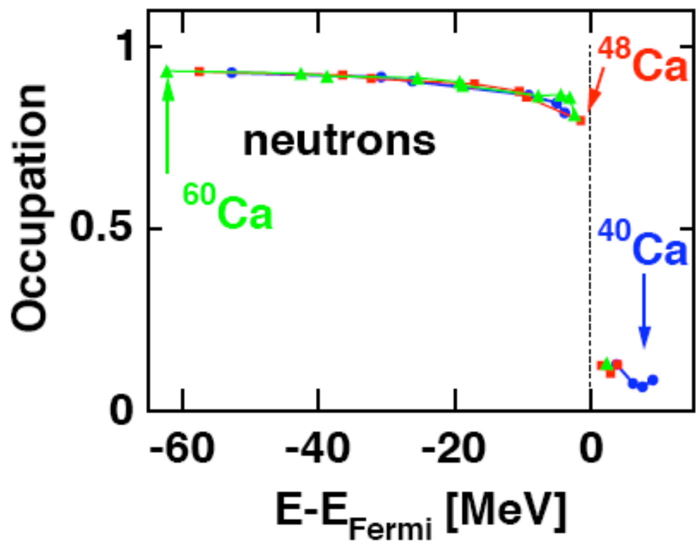




Data
MSU

Occupation numbers

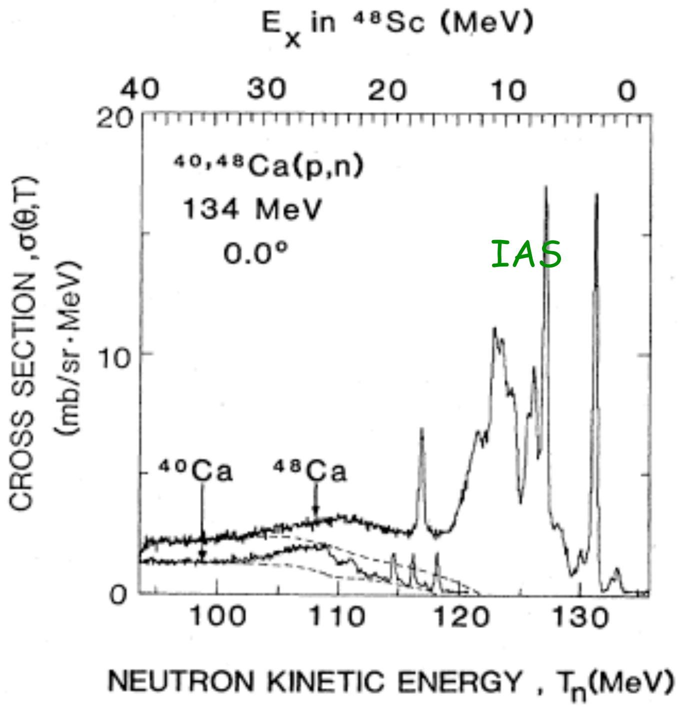


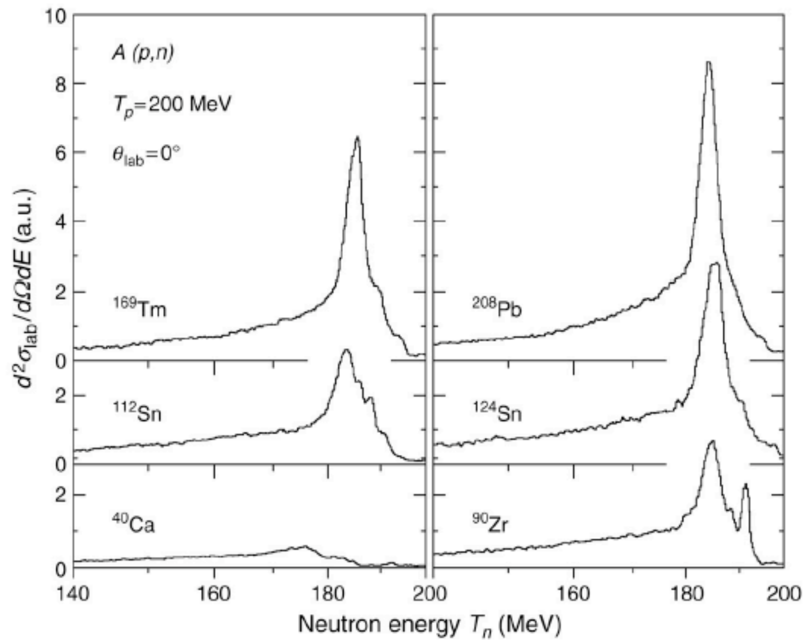


Protons more correlated with δ
Neutrons not much change

Nucleon correlations

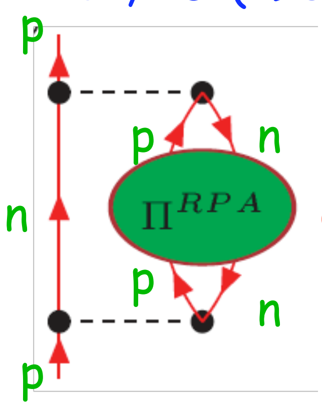
What's the physics? GT resonance?





PRC31,1161(1985)

NPA369,258(1981)



GT⁺ resonance

For N>Z only p affected

Nucleon correlations

Project DOM-DRIP How to do it:

Experiment

- ✦ Elastic scattering n+^{48}Ca (& other N $\neq$ Z nuclei)
- ✦ Elastic scattering of radioactive beams off p
- ✦ Heavy-on knock-out reactions (DOM + ...)
- ✦ **(p,2p & pn) inverse kinematics (DOM + NN T-matrix) to match (e,e'p)**
- ✦ Transfer reactions (DOM + Johnson, Tostevin, Nunes approach)

Extend DOM (⇒ more nuclei)

- ◉ Nonlocality (Van Neck)
- ◉ Isospin (Waldecker)
- ◉ Include charge density data
- ◉ Include (e,e'p) data including high-momentum JLab results
- ◉ Include higher energy data ⇒ relativity (Piekarewicz?)

Theory

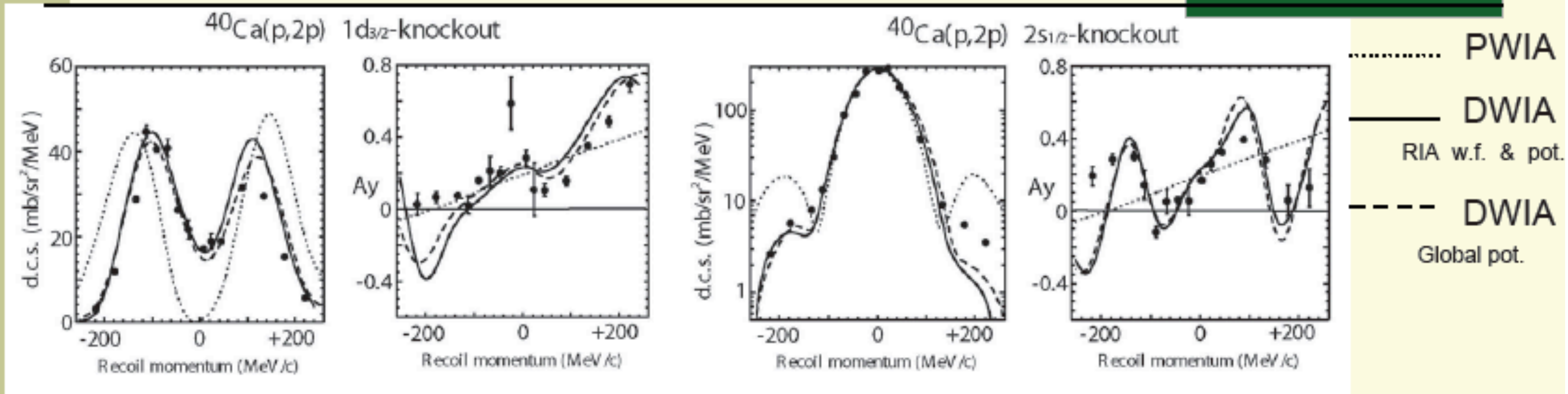
- ✳ Calculate self-energy microscopically including tensor force (Barbieri)
- ✳ Input for quasiparticle DFT (Burnett, Van Neck)

Nucleon correlations

(p,2p) stable targets (RCNP)

- Can emulate (e,e′p) results for orbits near the Fermi energy
- A_y puzzle
- (p,pn) experiments approved at RCNP
- Requires different NN interactions including pions that can carry energy! (Morris, WU) in progress

Typical data and spectroscopic factors



Spectroscopic factors (preliminary analysis)

(ZR analysis)
FR and NL effect is required.

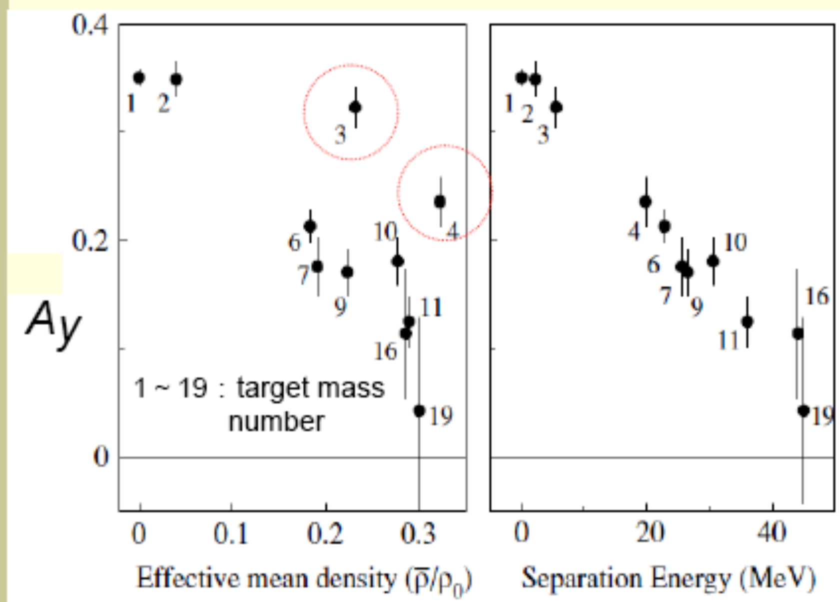
Target	State	RIA w.f. & pot.	Global pot.	(PWIA)	$(d,{}^{3}He)$ E_d=52MeV	$(e,e'p)$ E_e=280-500MeV
^{12}C	$1p_{3/2}$	1.4	1.3	(0.35)	2.98	1.72
^{12}C	$1p_{1/2}$	-	0.35	(0.09)	0.69	0.26
^{40}Ca	$1d_{3/2}$	1.8	2.1 (392MeV) 2.9 (200 MeV)	(0.3)	3.76	2.58
^{40}Ca	$2s_{1/2}$	0.71	0.91 (392 MeV) 1.0 (200 MeV)	(0.2)	1.65	1.02

Agree with $(e,e'p)$ results within ~20%.

Noro, Kyushu (ECT* workshop, April 2008)

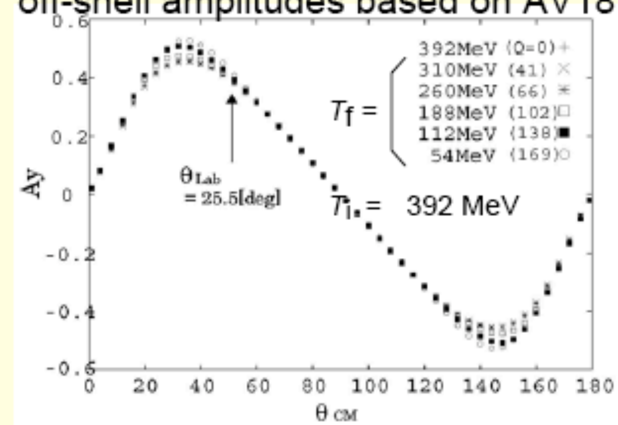
Ay for various light target nuclei

Noro
Kyushu



- Data are better correlated with E_s
- In particular, ^{3}He and ^{4}He data deviate from others in the ρ-plot.

Analyzing power calculated using half off-shell amplitudes based on AV18



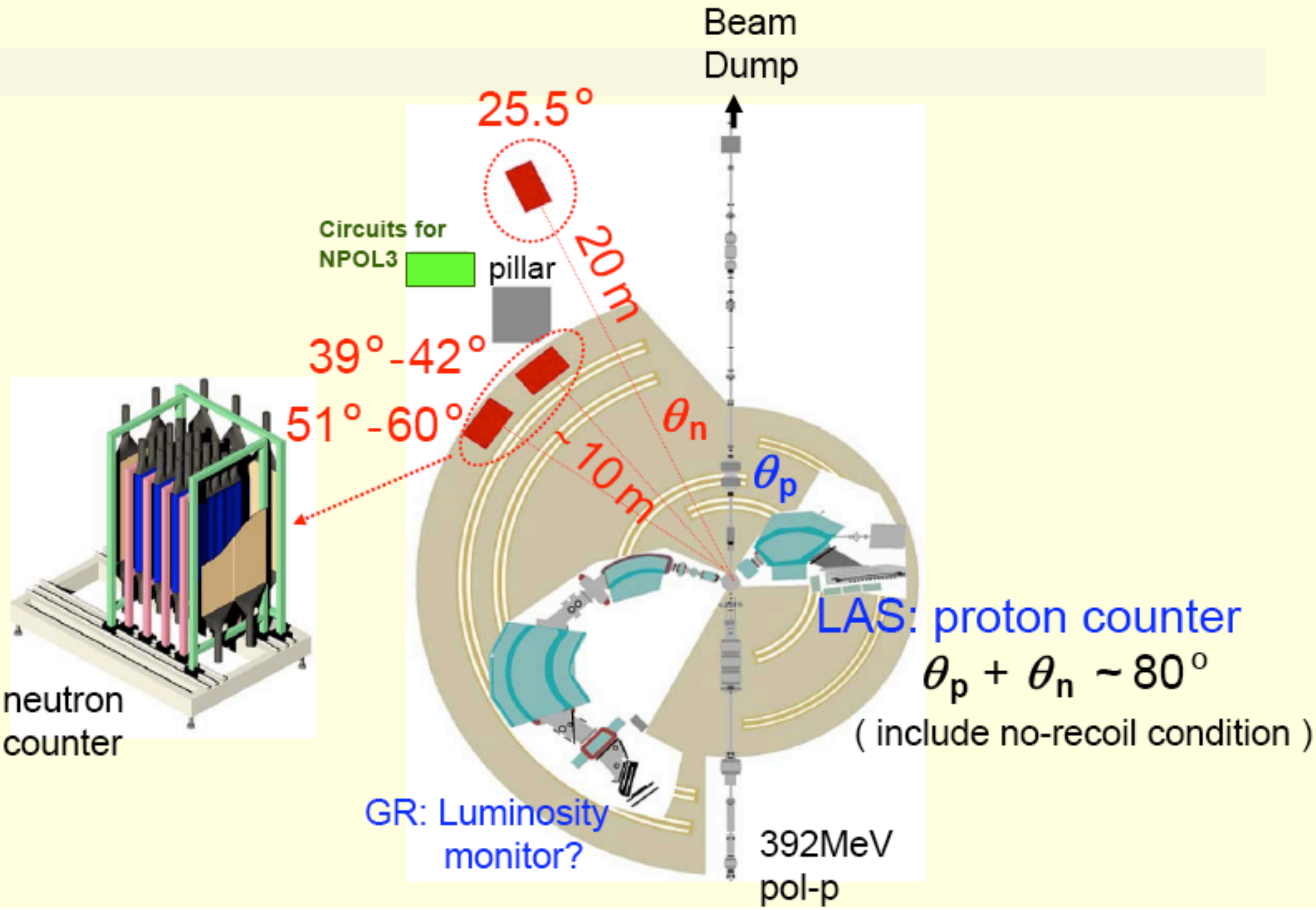
Off-shell effect ?

But, non-relativistic off-shell amplitude causes almost no change of Ay.

or

Is ‘ the mean-density’ not applicable to lightest nuclei as ^{3}He and ^{4}He?

Approved experiment : (*p,pn*)



at RCNP

(p,2p) inverse kinematics

HIMAC ✓

RIKEN ☺

GSI/FAIR ☺

US ☹ or ☺ ?

HIMAC data (Kobayashi et al.) for C isotopes!

Conclusion

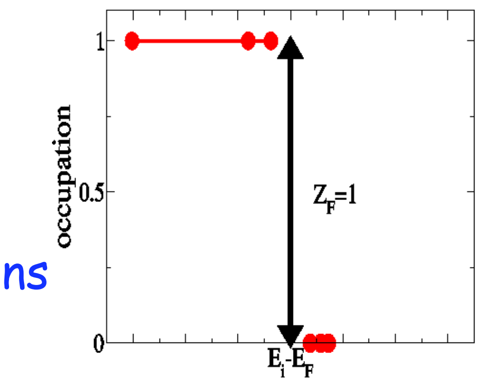
Project DOM-DRIP

- suggests many new experiments (some in the pipeline)
- allows data-driven extrapolation to the drip line
- room for lots of theoretical input
- room for lots of improvements

Correlations

in ... Atoms

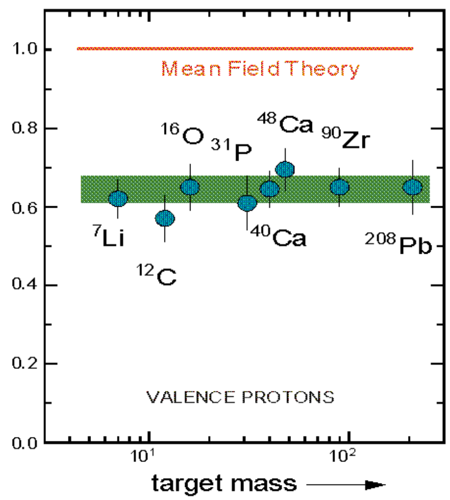
weak correlations



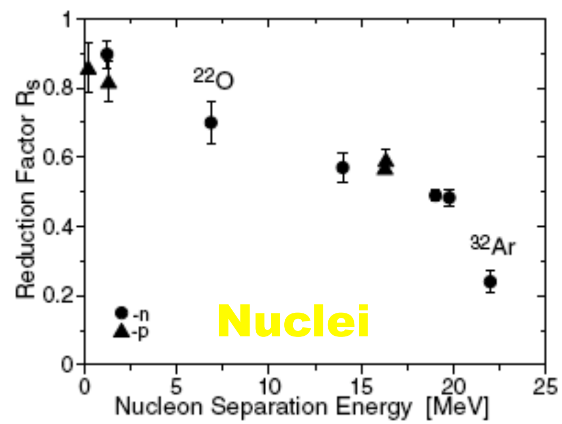
electrons in Ne
Data from (e,2e)

(e,e'p)

Z_F

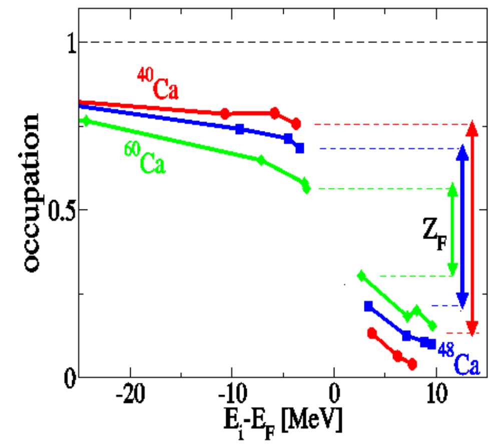


Z_F



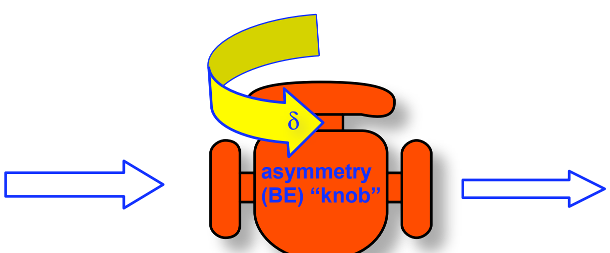
Neutron-proton asymmetry

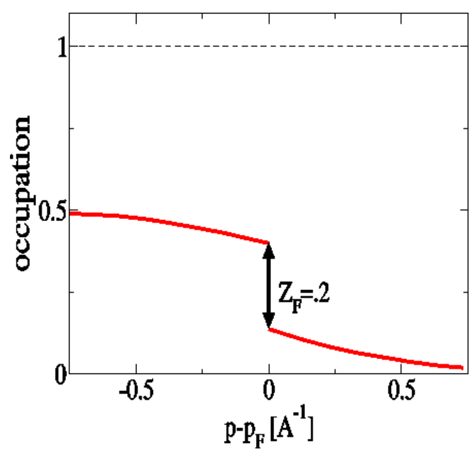
DOM



protons in stable
closed-shell nuclei

protons in Ca





Liquid 3He

very strong correlations
Data from (n,n')

Nucleon correlations