Trento 3/4/04

Proton properties in the nucleus

\- *quantum physics at all energy scales* -

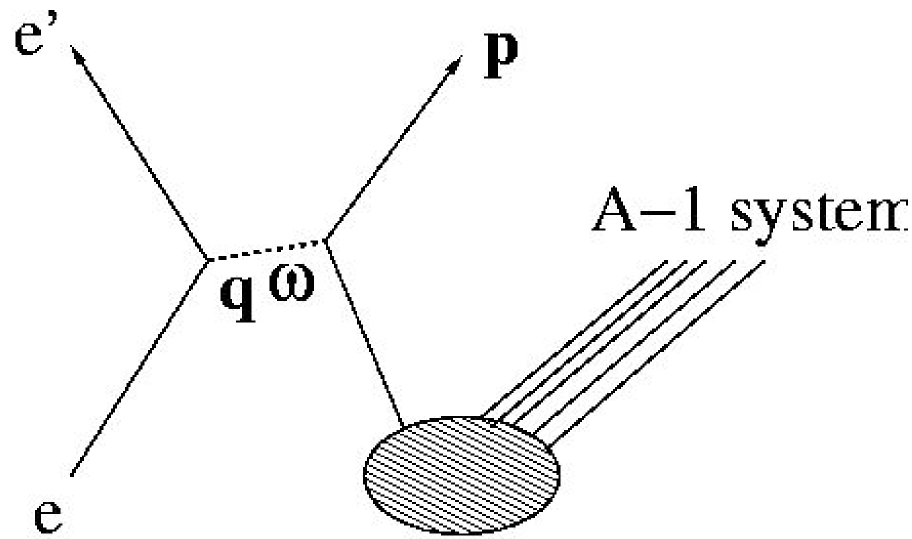
Wim Dickhoff
Washington University in St. Louis
(where the photon was discovered)

Outline

- Overview of theoretical understanding of proton properties in the nucleus
- Some well known results
- Overview of theoretical results
  - Consequences for excited states
  - Nuclei ⇨ recent developments
  - Nuclear matter
- Recent results from experiment
- What have we learned and what is unique?
- Conclusions

Review W.D. and C. Barbieri: arXiv:nucl-th/0402034

Basic idea of (e,2e) or (e,e´p)



$$\square_L \quad \left|\langle f|\square(q)|i\rangle\right|^2 \square(energy)$$

Simplest case: $\langle \vec{p}, n^{A\square 1}|\square(q)|0^A\rangle \;\square\; \langle n^{A\square 1}|a_{\vec{p}\square\vec{q}}|0^A\rangle$

$$\square \quad \square_L \quad \langle 0^A|a^{+}_{\vec{p}\square\vec{q}}|n^{A\square 1}\rangle\langle n^{A\square 1}|a_{\vec{p}\square\vec{q}}|0^A\rangle \square(energy)$$

Realistic case : distorted waves / more realistic description of knocked out particle

Theoretical Concepts

- Experimental data and spectral functions:

$$S_h(\alpha,\omega) = \sum_n \left| \langle \Psi_n^{A-1} | a_\alpha | \Psi_0^A \rangle \right|^2 \delta\left(\omega - \left(E_0^A - E_n^{A-1}\right)\right)$$

- Related to single-particle propagator:

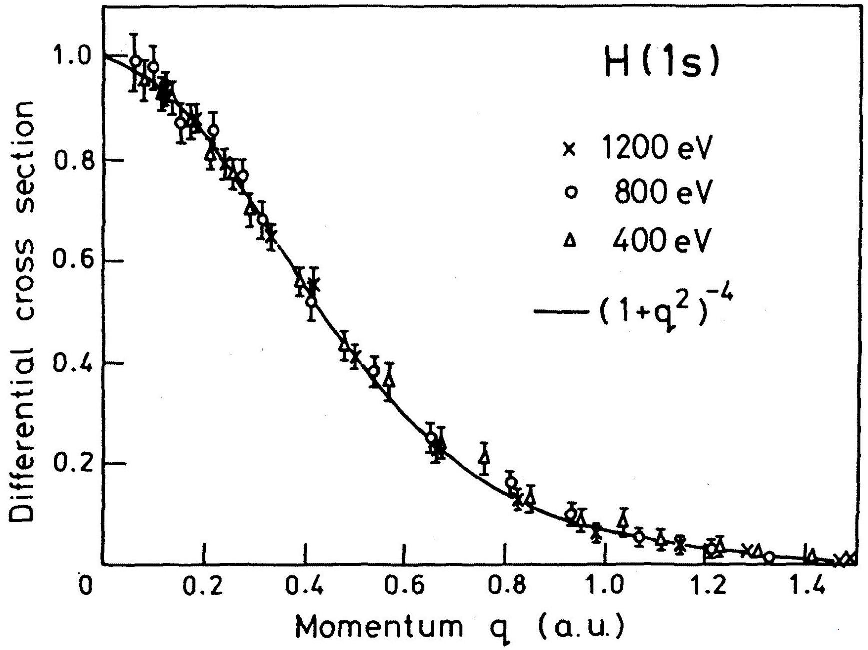
$$g(\alpha,\beta;\omega) = \sum_m \frac{\langle \Psi_0^A | a_\alpha | \Psi_m^{A+1} \rangle \langle \Psi_m^{A+1} | a_\beta^\dagger | \Psi_0^A \rangle}{\omega - \left(E_m^{A+1} - E_0^A\right) + i\eta} + \sum_n \frac{\langle \Psi_0^A | a_\beta^\dagger | \Psi_n^{A-1} \rangle \langle \Psi_n^{A-1} | a_\alpha | \Psi_0^A \rangle}{\omega - \left(E_0^A - E_n^{A-1}\right) - i\eta}$$

⟹ Particle part

⟹ Hole part

- Occupation Number: $n(\alpha) = \int_{-\infty}^{\varepsilon_F^-} S_h(\alpha,\omega)\, d\omega = \langle \Psi_0^A | a_\alpha^\dagger a_\alpha | \Psi_0^A \rangle$

- Also: $S_h(\alpha,\omega) = \frac{1}{\pi} \mathrm{Im}\, g(\alpha,\alpha;\omega)$ and $\varepsilon_F^- = E_0^A - E_0^{A-1}$

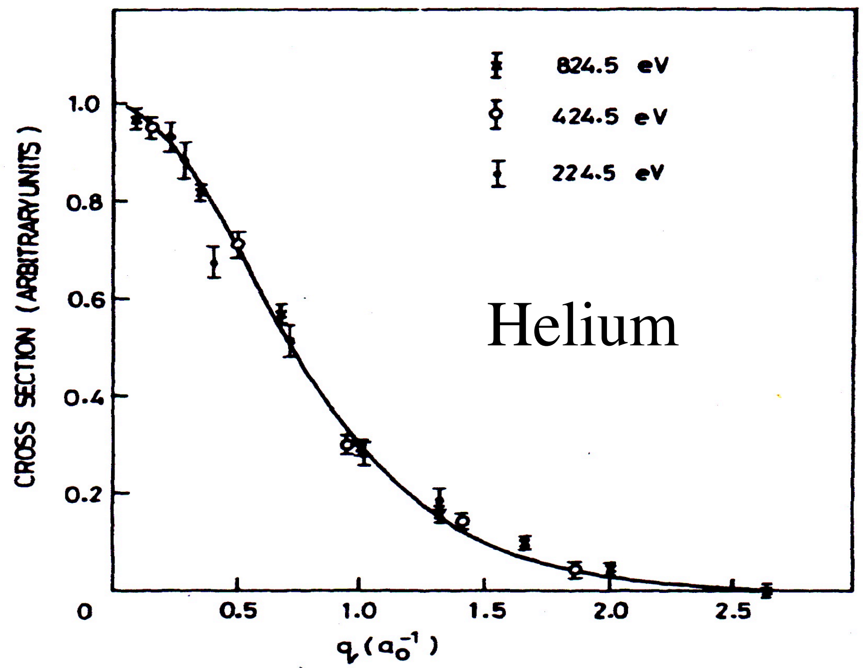


$$\Box_{1s}(q) = 2^{3/2}\,\Box\,\frac{1}{(1+q^2)^2}$$

Hydrogen 1s wave function
"seen" experimentally
Phys. Lett. 86A, 139 (1981)

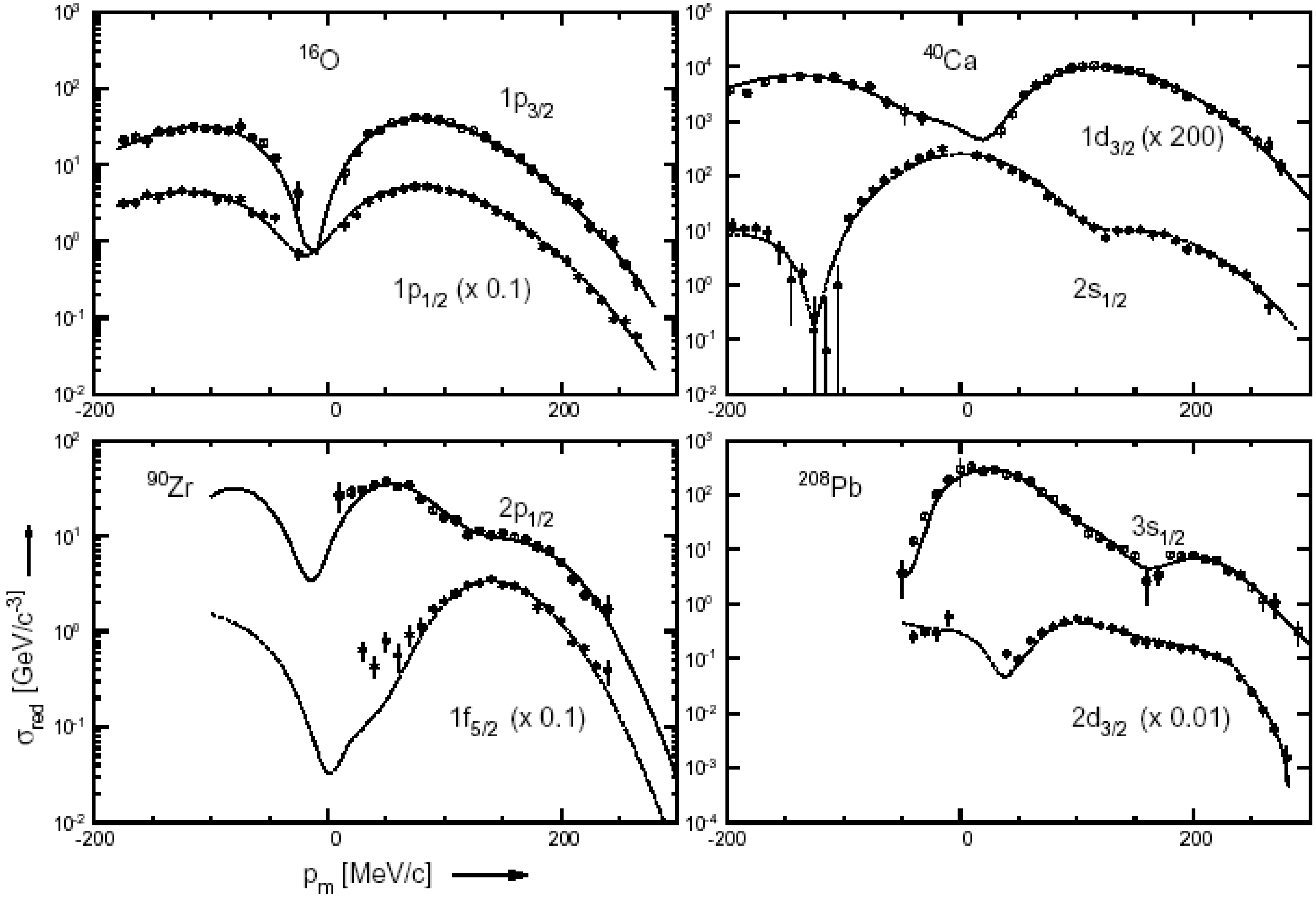
And so on for other atoms …

Helium
in Phys. Rev. A8, 2494 (1973)



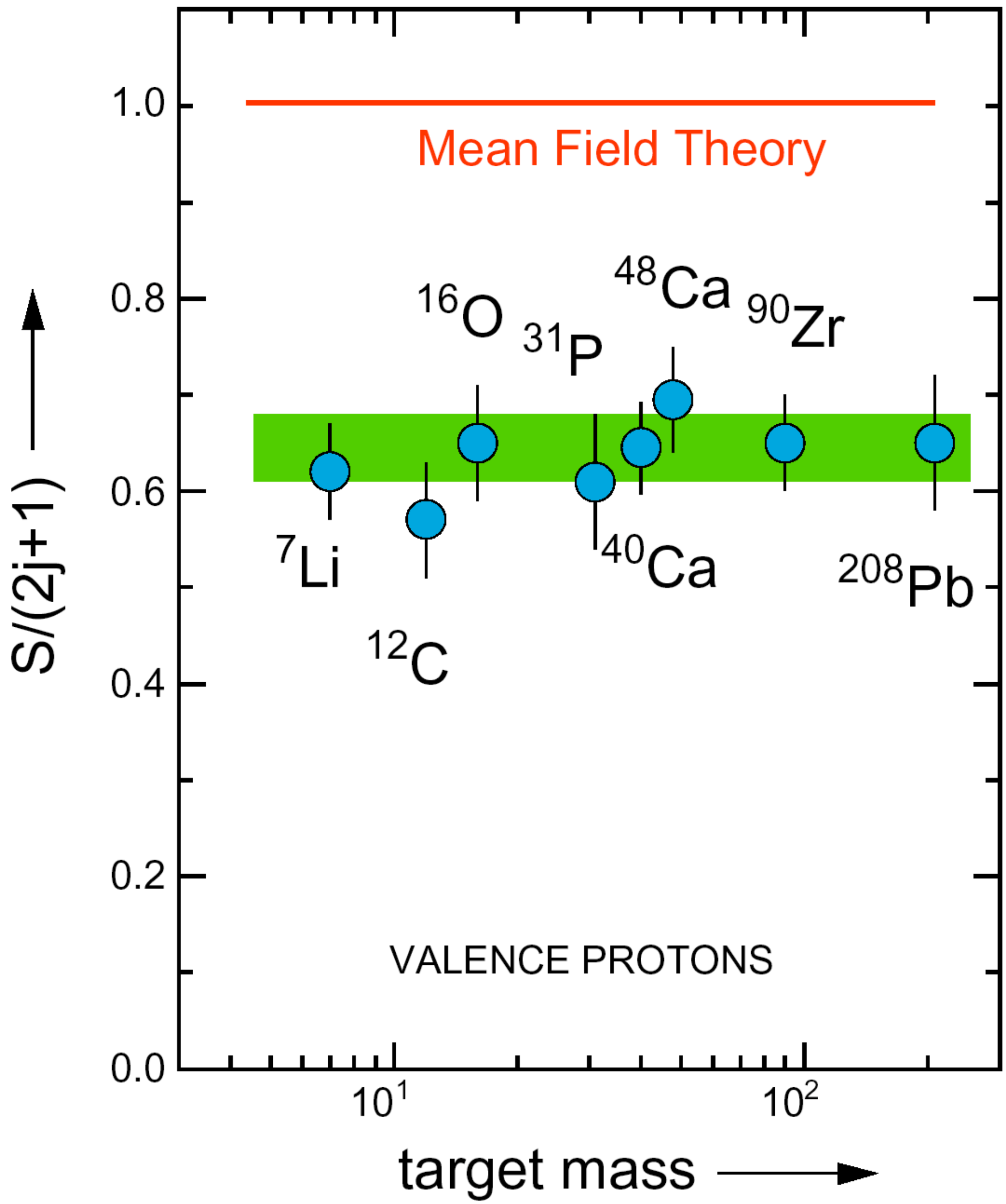
Works for nuclei too

NIKHEF data, L. Lapikás, Nucl. Phys. A553, 297c (1993)



Except ….

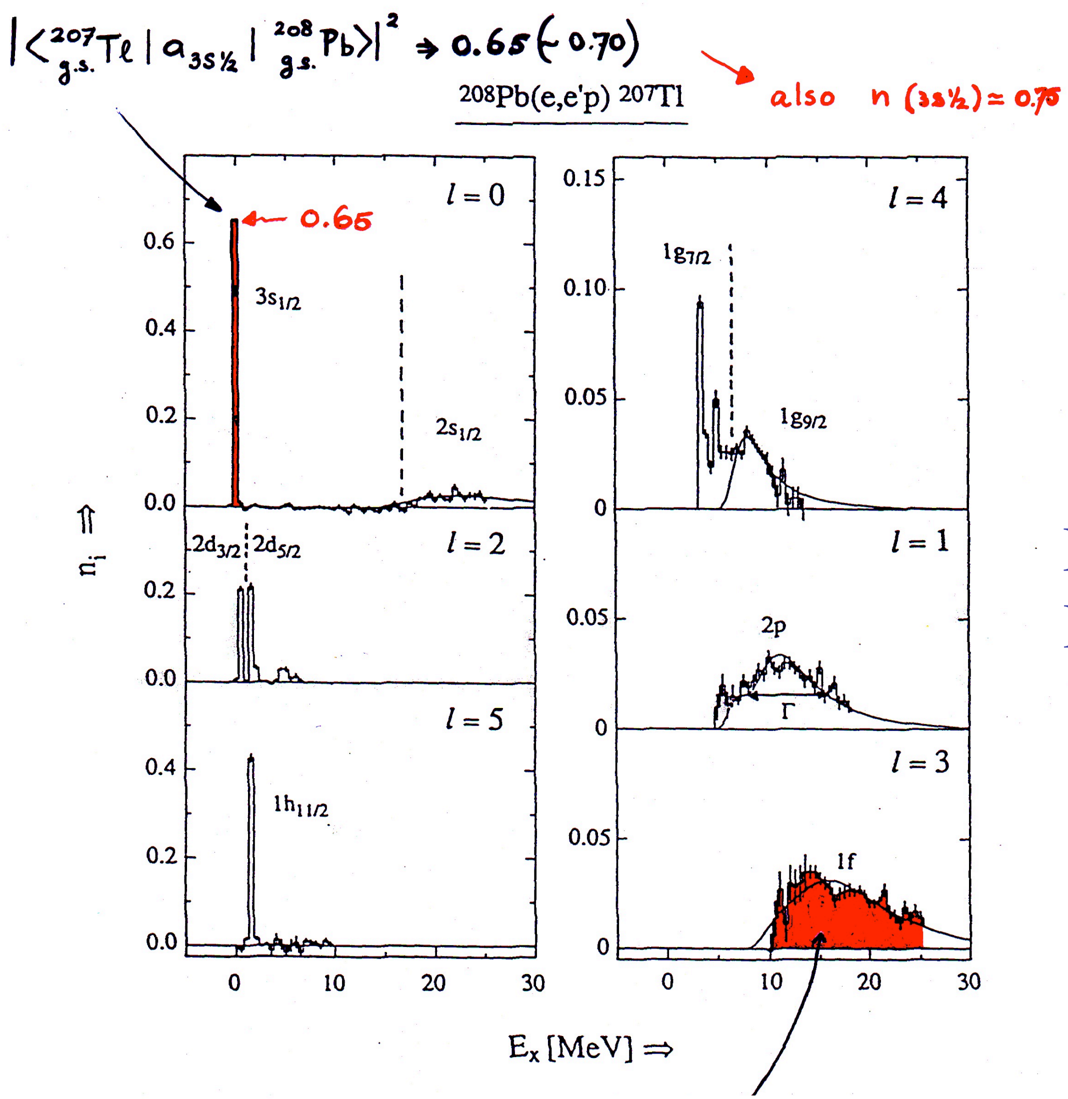
Removal probability for valence protons from NIKHEF data



Note:

We have seen mostly data for removal of

valence protons

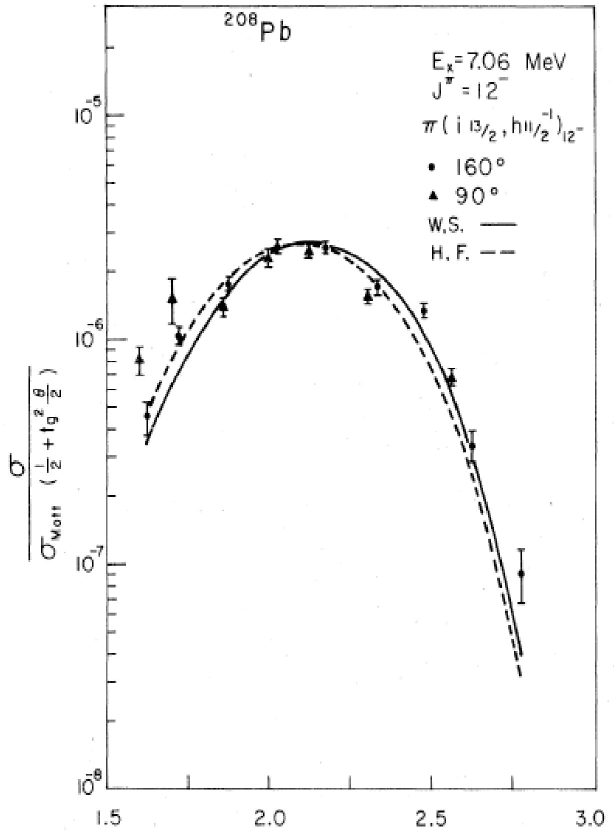


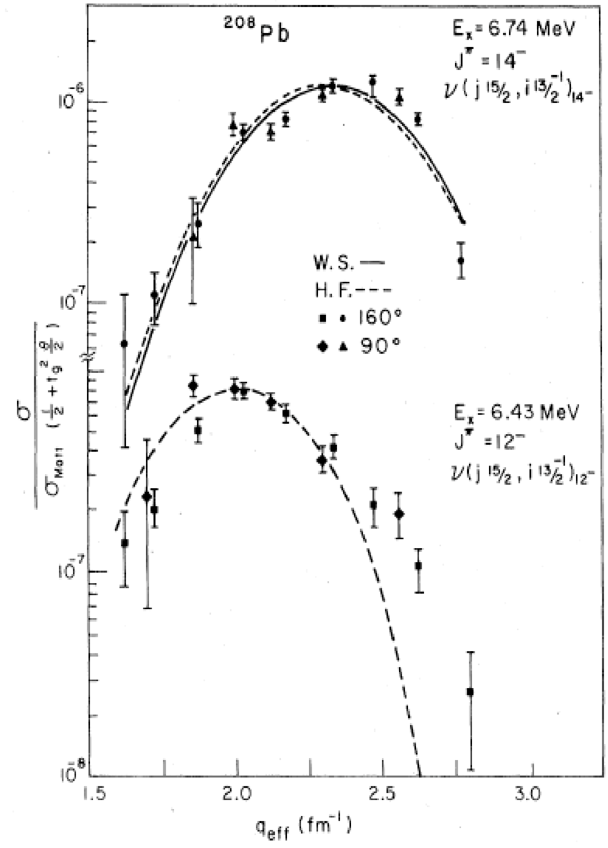
and …

E. Quint
Ph.D.thesis NIKHEF, 1988

Corresponding strong fragmentation of deeply-bound states

Consequences of correlated sp strength





M12 and M14 transitions in (e,e´) only 50% of ph estimate

⇒ $Z_h * Z_p$

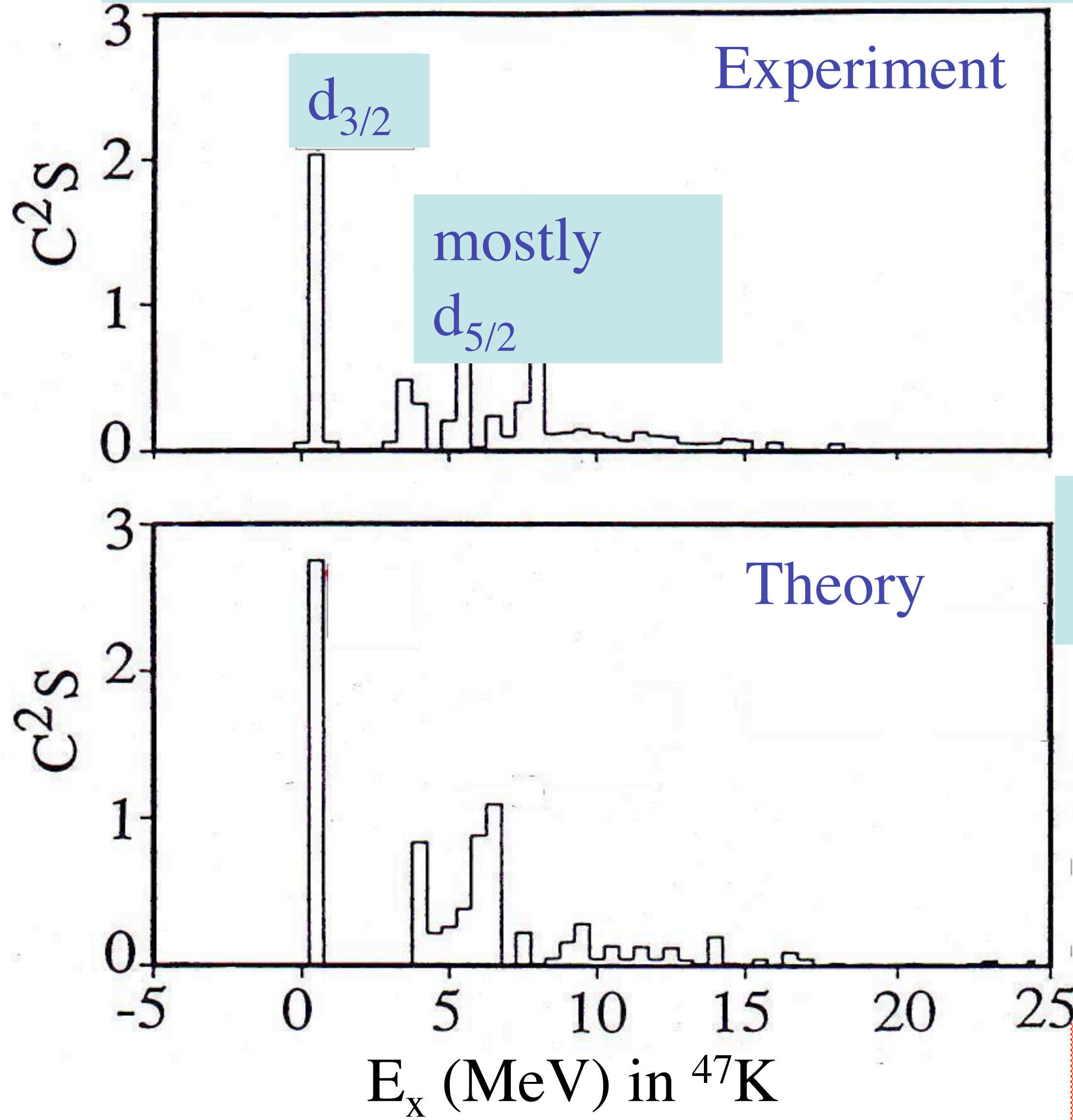
Data:

PRC20, 497(1979)

Calculations of spectral functions in finite nuclei

- Qualitative features of experimental (e,e´p) data understood by coupling hole states to two-hole one-particle (2h1p) states
- Quantitative features can only be understood by including depletion effect due to SRC (10-15%) and the best possible description of low-energy collective correlations of 2h1p states including the giant resonance region (LRC)
- Current implementation works for nuclei like ^{48}Ca (see Nucl.Phys.A550, 1(1992))
- Depletion due to SRC is the same for mostly occupied levels (all calculations)
- Depletion due to LRC depends on nearness to Fermi energy
- ^{16}O is hard problem! Geurts et al. PRC53, 2207(96) include SRC and LRC and are still 15-20% above experimental *p*-hole spectroscopic factors.
- LRC in ^{16}O are very hard to calculate (see however Faddeev approach by C. Barbieri and WD, Phys Rev. C63,034313 (2001); C65,064313(2002))
- High-momentum components are at high missing energy as calculated for ^{16}O in Phys. Rev. C49,R17(94) and C51, 3040(95)
- Indeed high-momentum removal is not seen at small missing energy
- Can it reliably be identified at high missing energy? ⇨ Jlab E97-006
- No “quenching” of spectroscopic factors at large Q^2

Spectral function ^{48}Ca (e,e´p) ^{47}K $(l=2)$



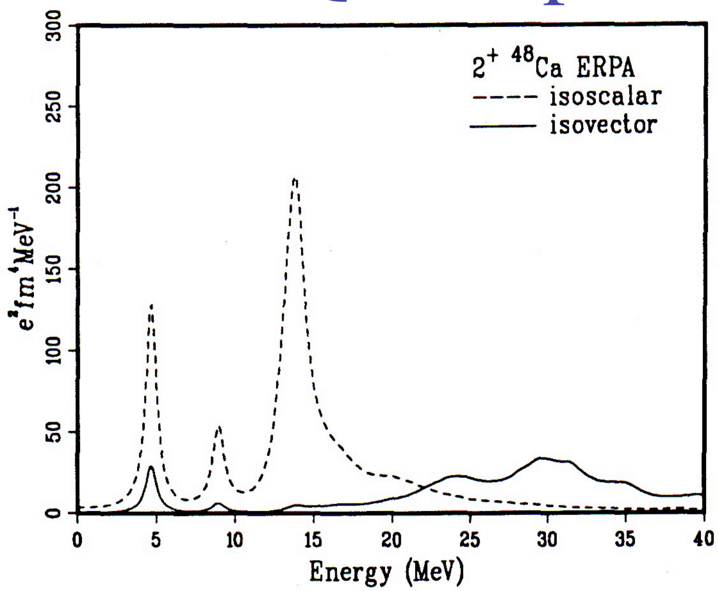
NIKHEF
G. Kramer, Thesis

G.Rijsdijk, K.Allaart, WD
Nucl.Phys.A550,159(1992)

Includes :
low-energy mixing
⇒ long-range correlations

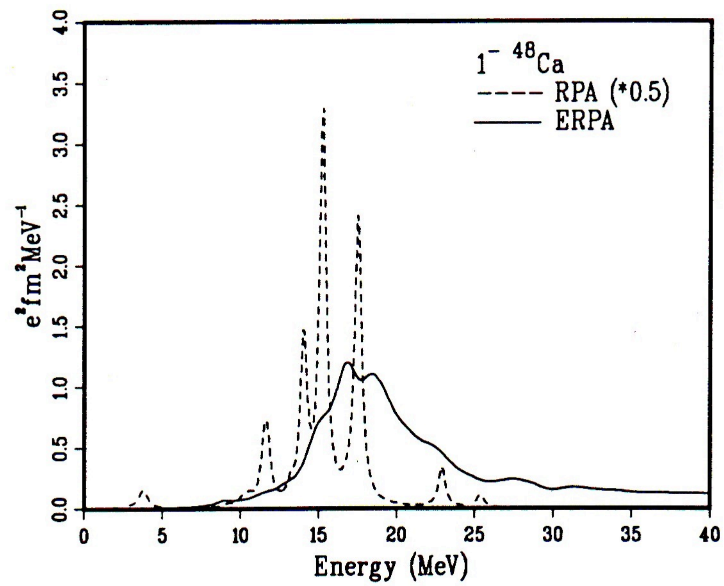
Excludes:
high-energy mixing
⇒ short-range correlations

Giant Quadrupole



Giant Resonances
only correct when
sp fragmentation is included

Giant Dipole



In turn:
Excited states
determine sp fragmentation

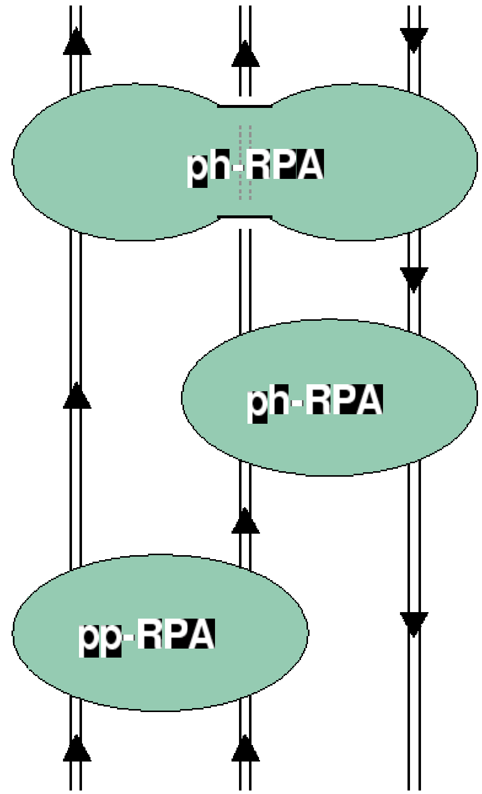
M. G. E. Brand, K. Allaart, and W. D.
Phys. Lett. **214B** , 483-489 (1988);
Nucl. Phys. **A509** , 1-38 (1990).

Faddeev technique and Long-Range Correlations

- Both pp (hh) and ph phonons are collective in nuclei using RPA
- Only Faddeev technique allows correct summation to all orders of these phonons
- Formalism:

  Phys. Rev. C**63**, 034313 (2001)
- Results: for ^{16}O

  Phys. Rev. C**65,** 064313 (2002)



Spectroscopic Strength in ^{16}O

Data: PRC49, 955 (94)

- Influence of SRC ✓✓
- Translational Invariance ✖
- Influence of LRC ✓

TDA from Geurts et al.

Phys. Rev. C53, 2207 (96)

- Influence of LRC ✓✓

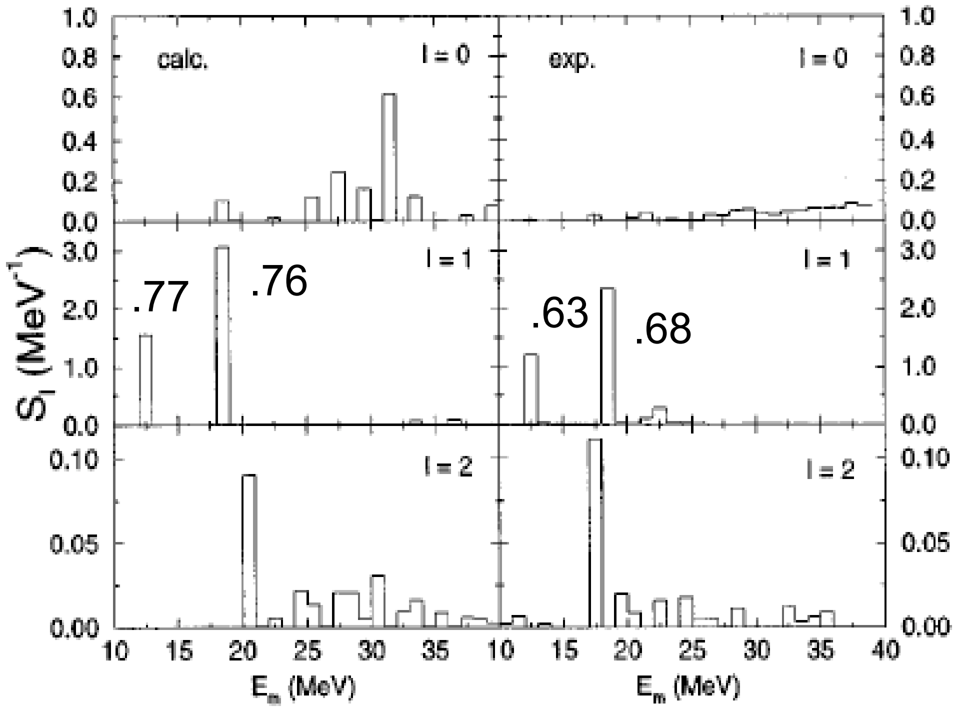
RPA + Faddeev

C. Barbieri and WHD,

Phys. Rev. C65, 064313 (2002)

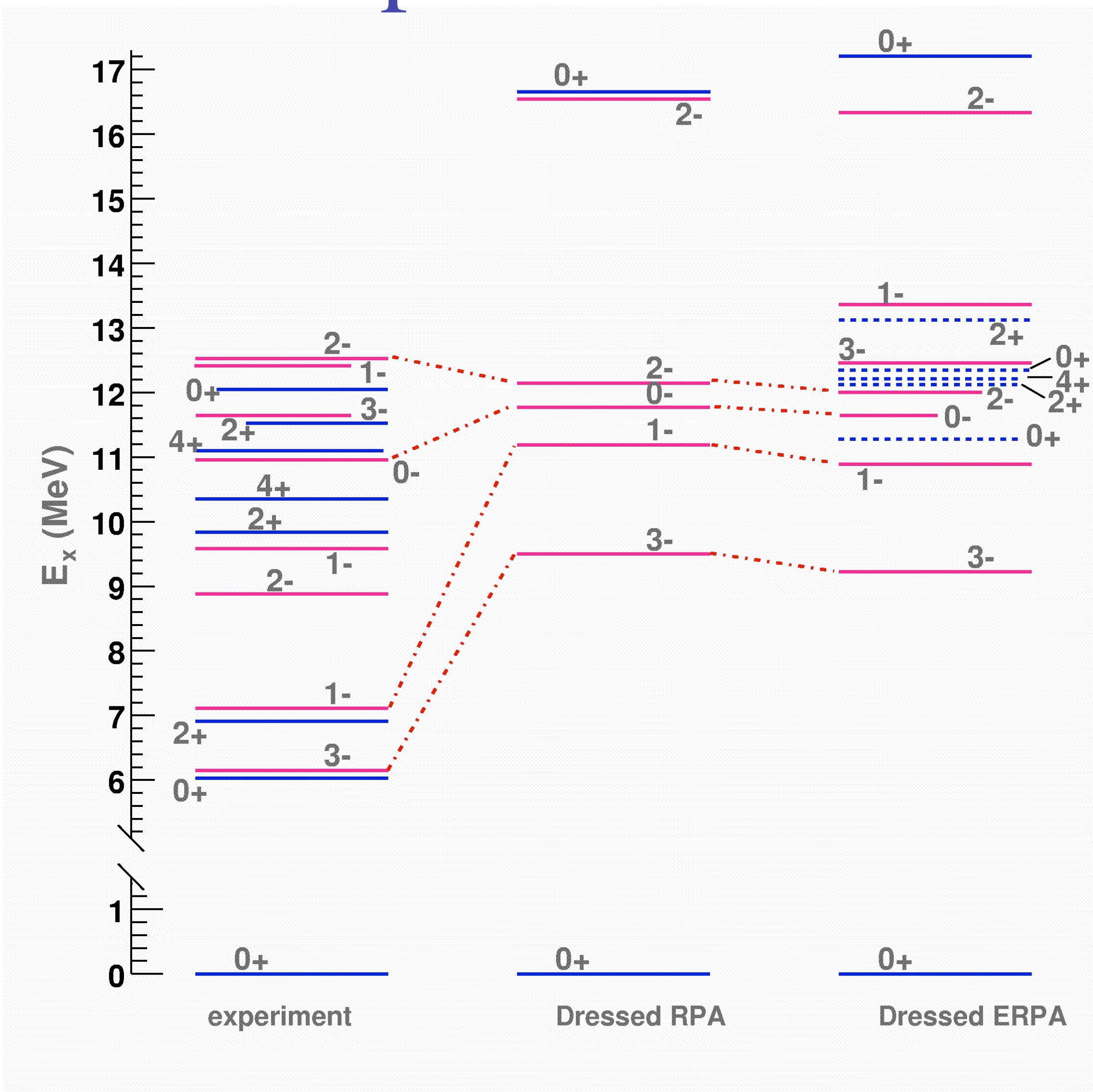
Still not solved!!

TDA



Shell	TDA	RPA
$d_{3/2}$	0.866	0.838
$s_{1/2}$	0.882	0.842
$d_{5/2}$	0.894	0.875
$p_{1/2}$	0.775	0.745
$p_{3/2}$	0.766	0.725

^{16}O spectrum



Long-range correlations in nuclei are HARD to calculate!!!

C. Barbieri & WHD

Phys. Rev. C68, 014311 (2003)

Need to do better!

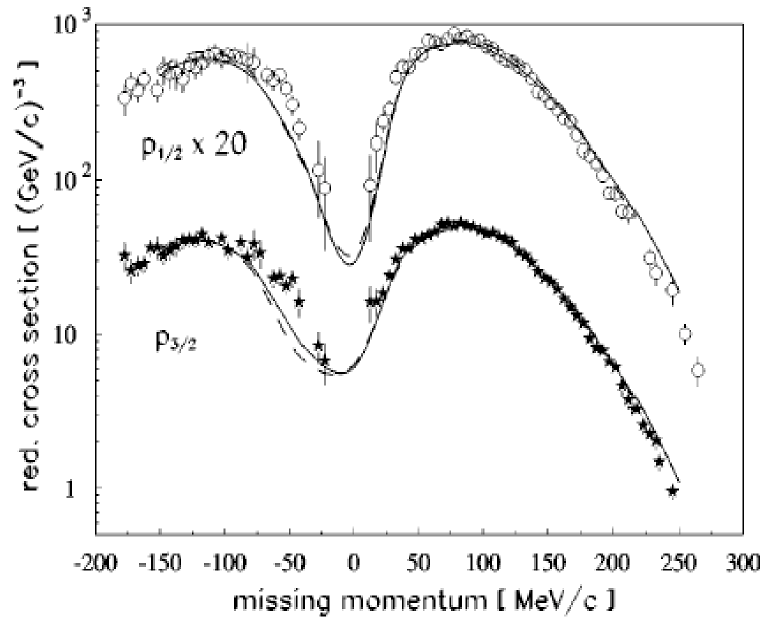
Relevant for (e,e´p) and (e,e´2N)

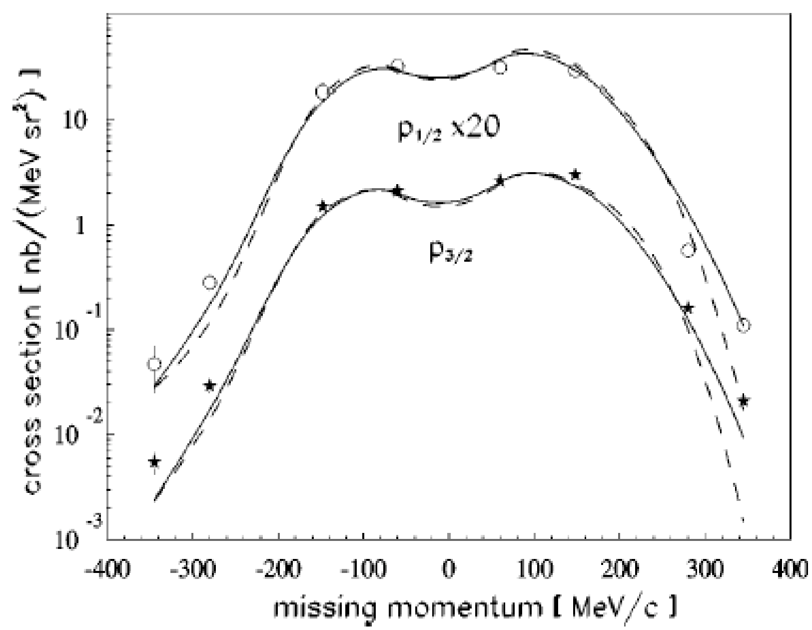
- Data from NIKHEF :
  Phys. Rev. C49, 955 (1994)

Calculation:
- quasihole wave function from microscopic calculation
- spectroscopic factors adjusted
- damping from standard optical potential

- Data from Jlab (Q^2=0.8):
  Phys. Rev. Lett. 84, 3265 (2000)

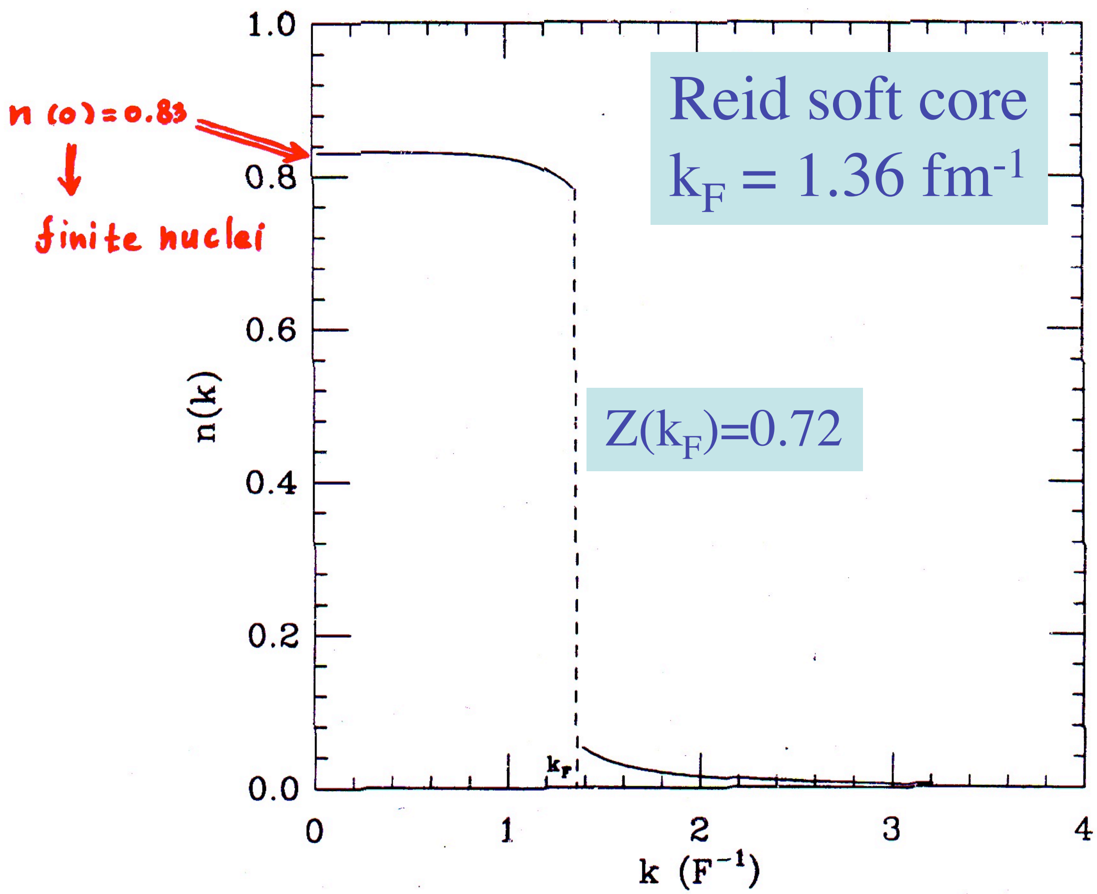
Calculation:
- spectroscopic factors from NIKHEF data
- same quasihole wave function
- damping from nuclear matter
  Radici, Dickhoff, Stoddard, PRC66,014613(2002)





⇨NO “QUENCHING”

Short-range correlations in nuclear matter



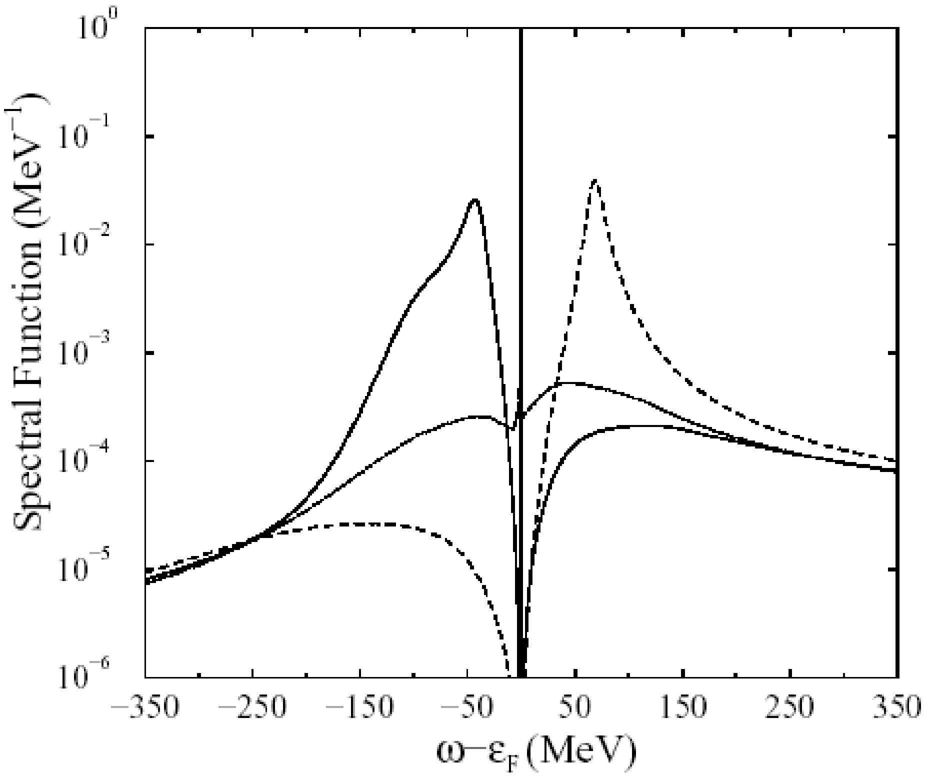
Old prediction!

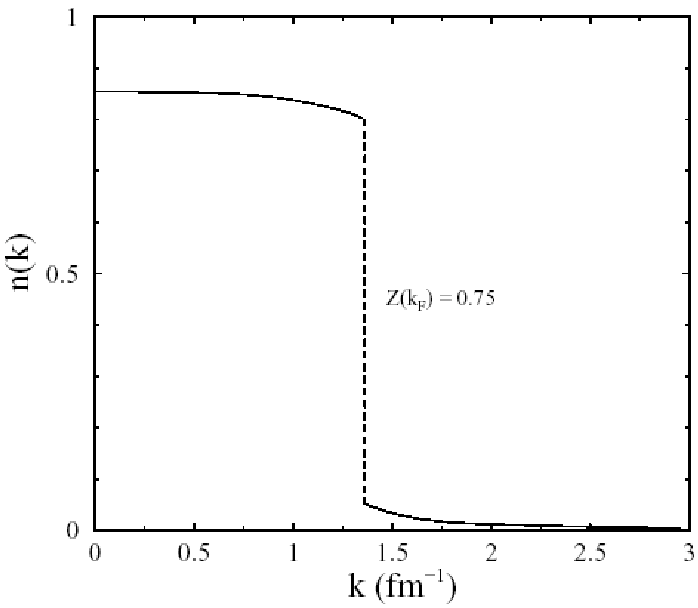
B.E.Vonderfecht et al. Nucl. Phys. A555, 1 (1993)

Results from Nuclear Matter

2nd generation (2000)

- Spectral functions for $k = 0, 1.36, \& \ 2.1 \text{ fm}^{-1}$
- Common tails on both sides of ε_F





Momentum distribution :

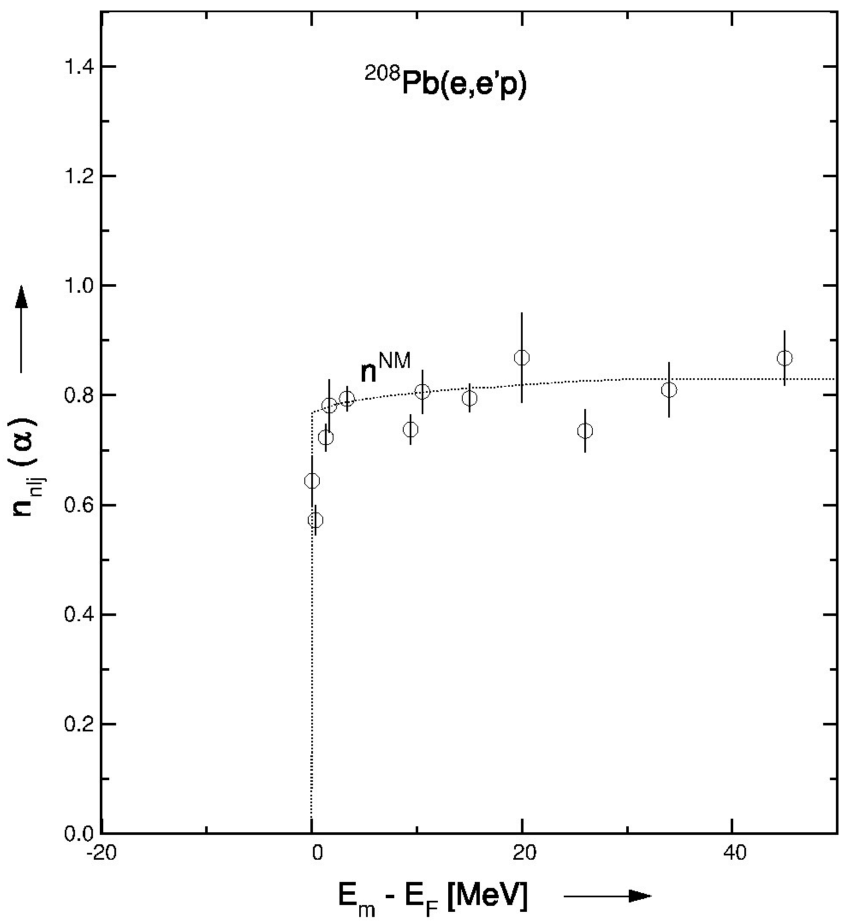
only minor changes

Occupation in nuclei

Depleted similarly!?!

M. van Batenburg (thesis, 2001) & L. Lapikás from ^{208}Pb (e,e´p) ^{207}Tl

Occupation of deeply-bound proton levels

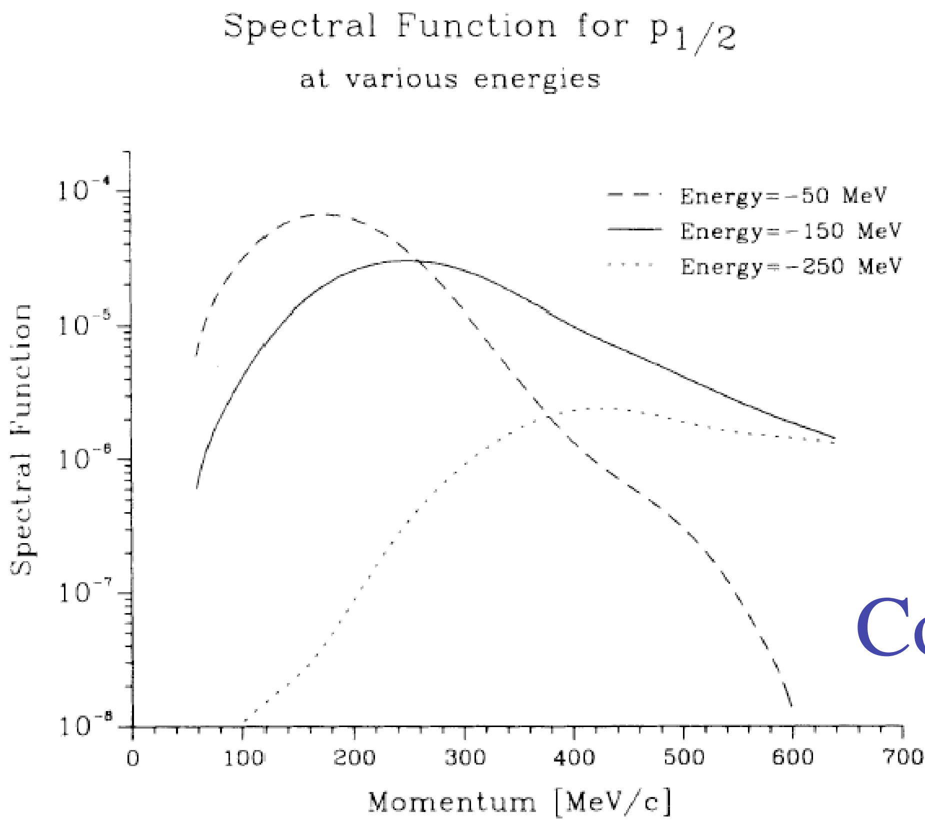


Up to 100 MeV
missing energy
and
270 MeV/c
missing momentum

Covers the whole
mean-field domain
for the FIRST time!!

Confirmation of theory

High-momentum components



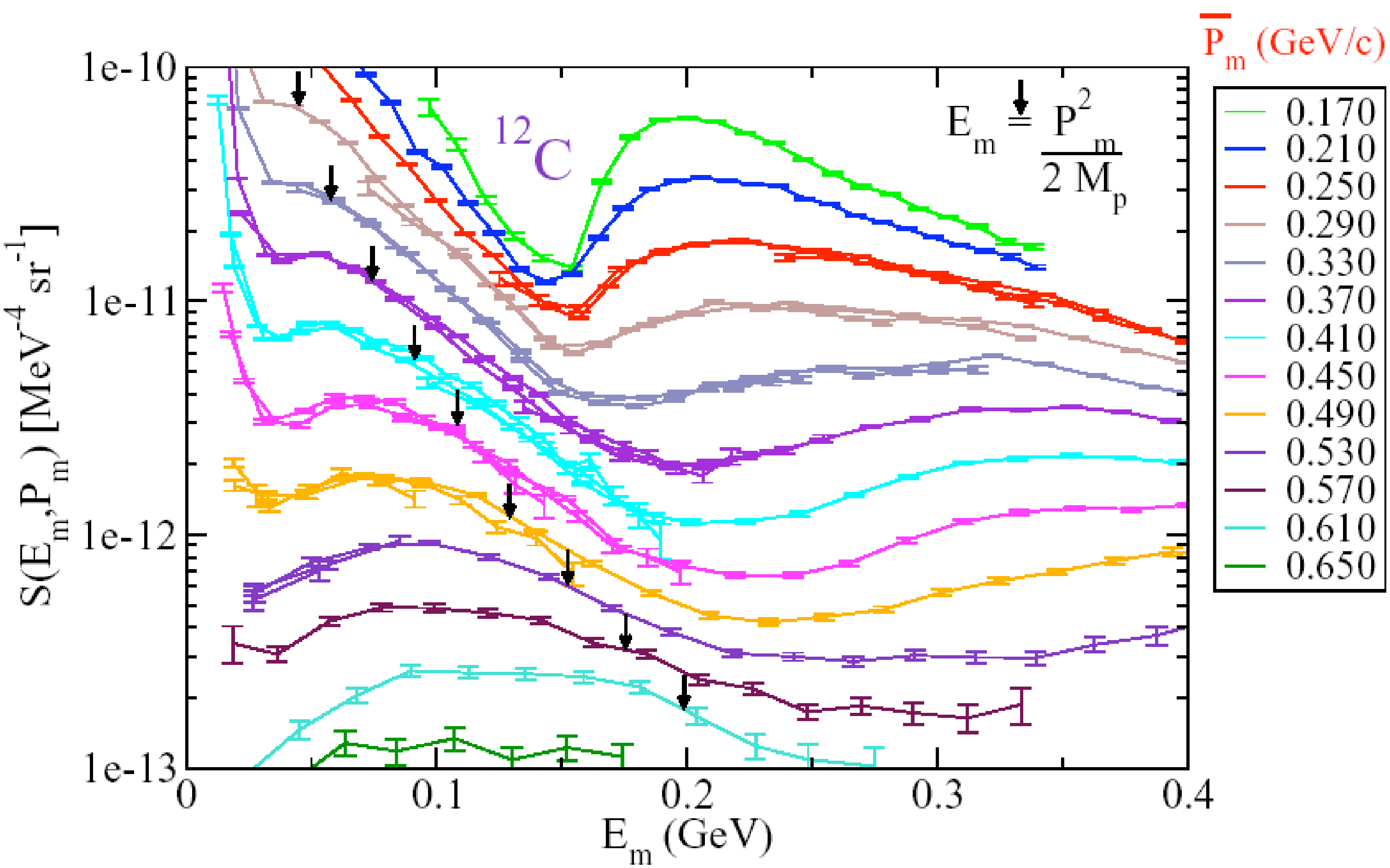
H. Müther and W.H.D

Phys. Rev.C 49, R17 (1994)

No high momenta
at low energy!
Confirmed by experiment

JLab Experiment 97-006 ⇨ Sick, Rohe et al.

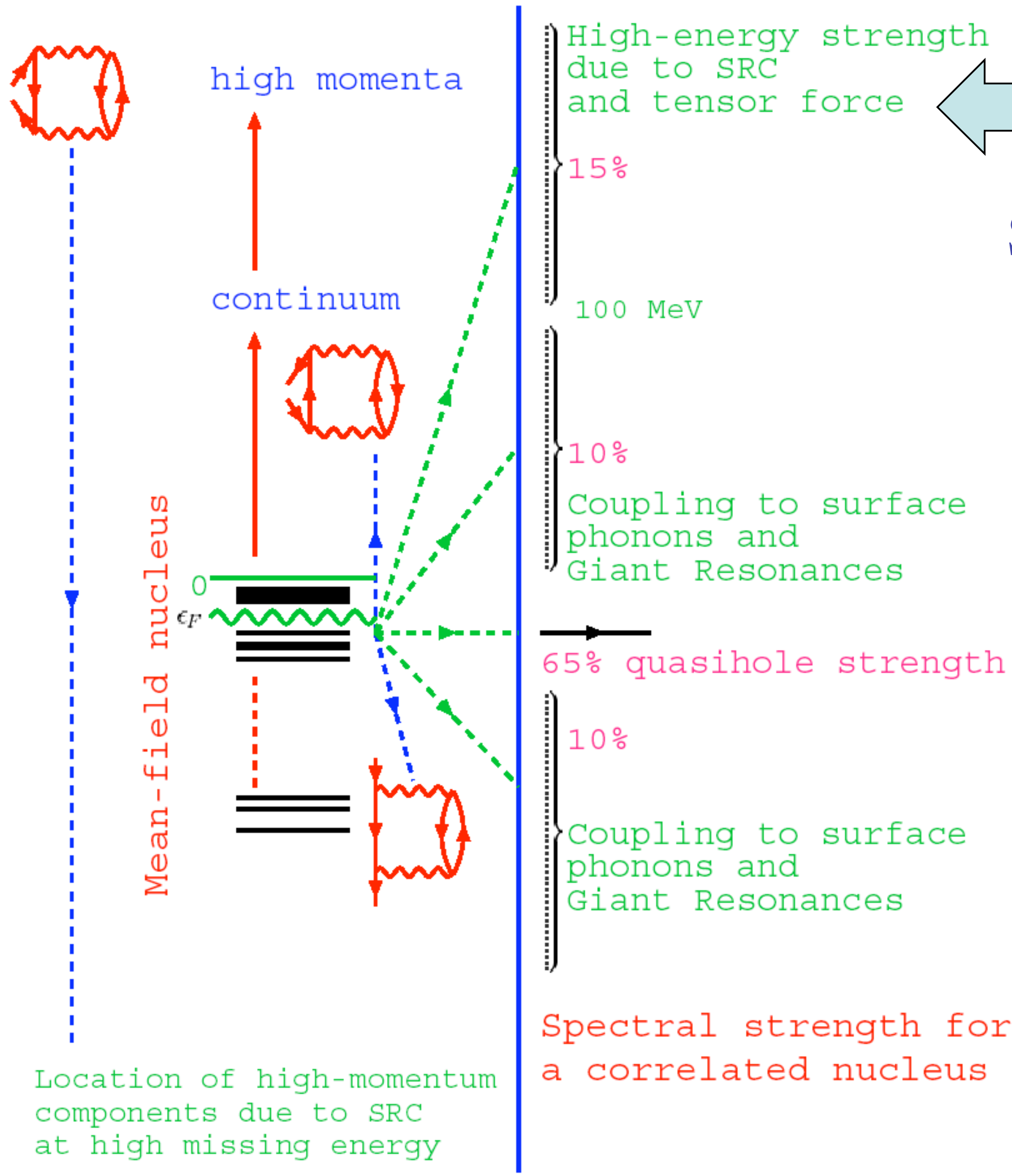
Location and number of high-momentum protons!



We now essentially know what all the protons are doing in the nucleus !!!

- Unique for a correlated many-body system
- Information available for electrons in atoms (Hartree-Fock)
- Not for electrons in solids
- Not for atoms in quantum liquids
- Not for quarks in nucleons

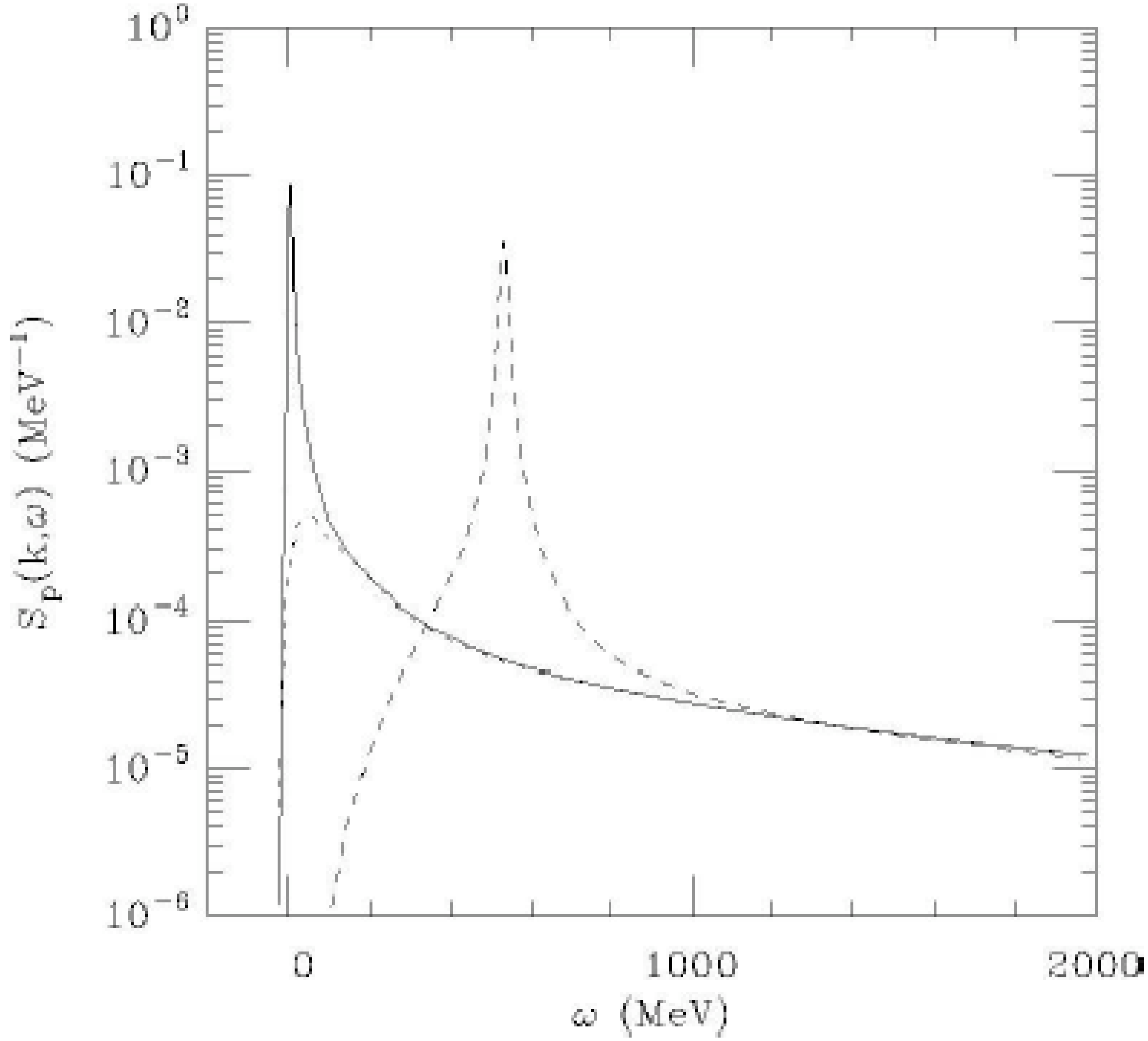
Location of single-particle strength in nuclei



SRC

SRC

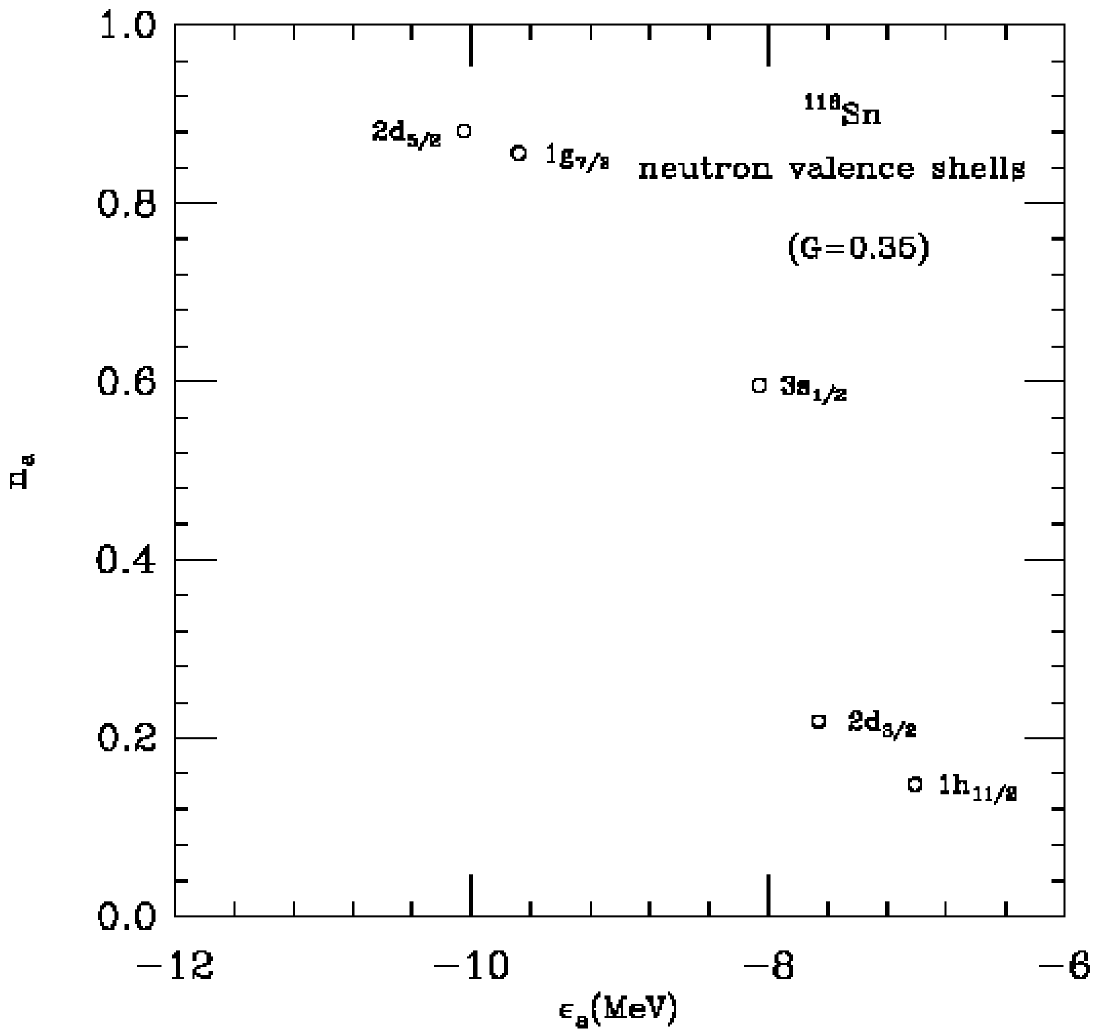
Where the depleted strength ends up …



Conclusions

- Good understanding of short-range correlations
  - Both in nuclear matter and nuclei
  - JLab data may show sensitivity
  - 2N knockout should be explored more fully
- Long-range correlations IMPORTANT
  - Link with realistic description of excited states
  - Needs more work
- We know what protons are up to in nuclei!!

What about open-shell systems?



SRC the same
GRs similar

only difference
near ϵ_F

Systems with N very different from Z?

- SRC still the same
- Less collective excited states
  - So less fragmentation
  - And removal of sp strength
  - More like mean-field (+ SRC)