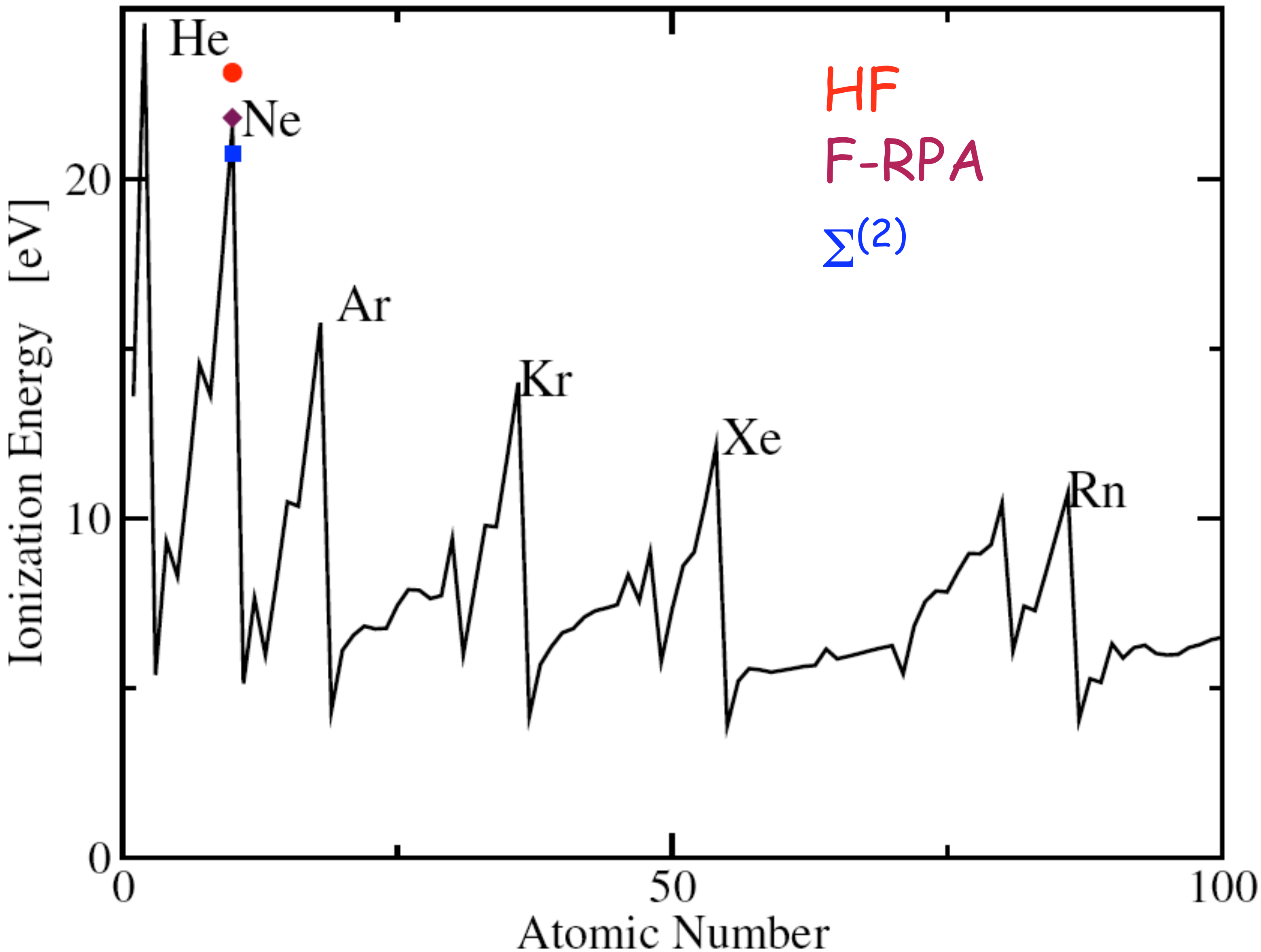
Periodic table



F-RPA, DOM and QP-DFT

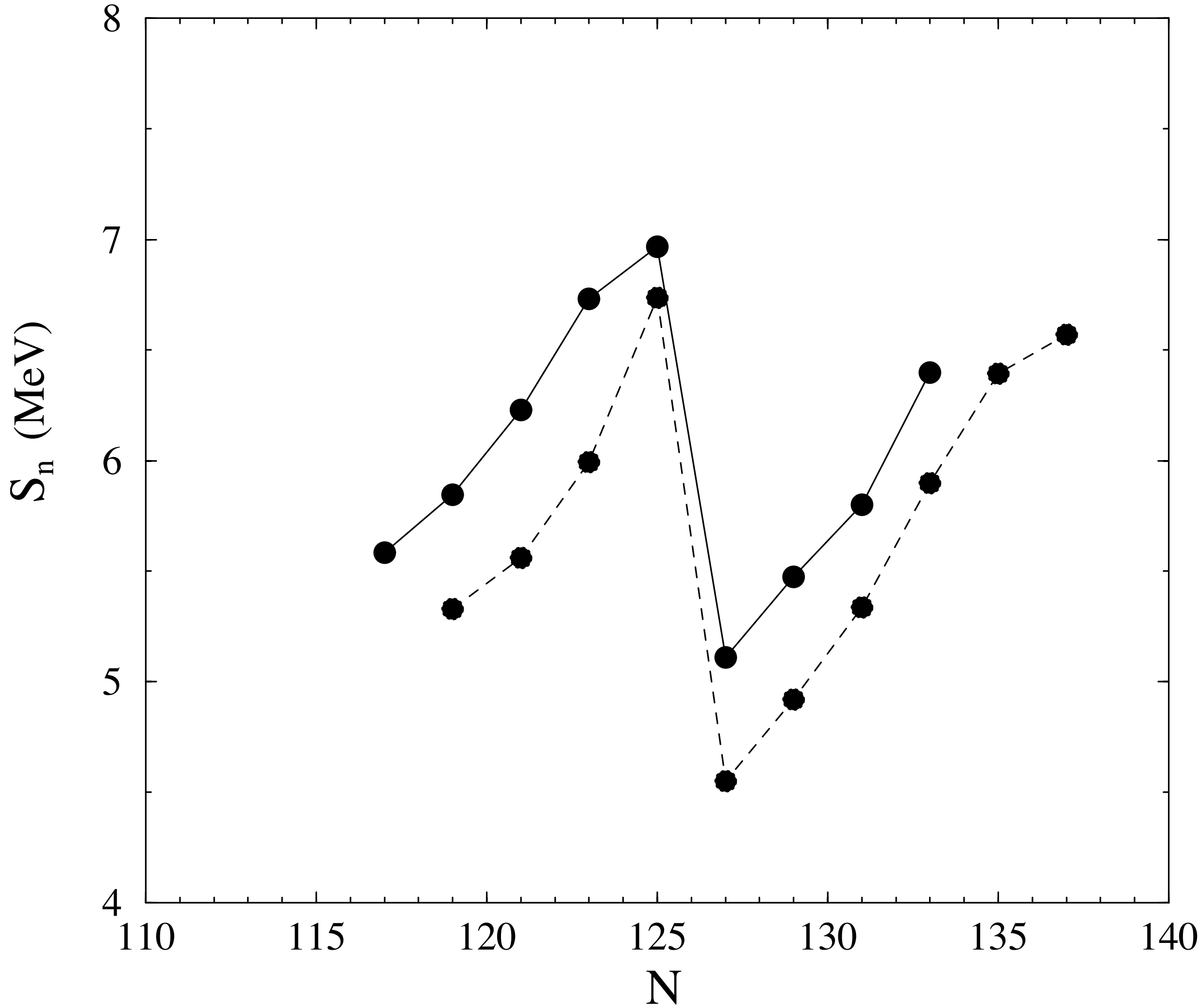
Nucleons in nuclei

- Atoms: shell closures at 2,10,18,36,54,86
- Similar features observed in nuclei
- Notation:
  - # of neutrons N
  - # of protons Z
  - # of nucleons $A = N + Z$
- Equivalent of ionization energy: separation energy
  - for protons $S_p(N,Z) = B(N,Z) - B(N,Z-1)$
  - for neutrons $S_n(N,Z) = B(N,Z) - B(N-1,Z)$
  - binding energy

$$M(N,Z) = \frac{E(N,Z)}{c^2} = N\, m_n \; + \; Z\, m_p \; - \; \frac{B(N,Z)}{c^2}$$

Shell closure at N=126

- Odd-even effect: plot only even Z

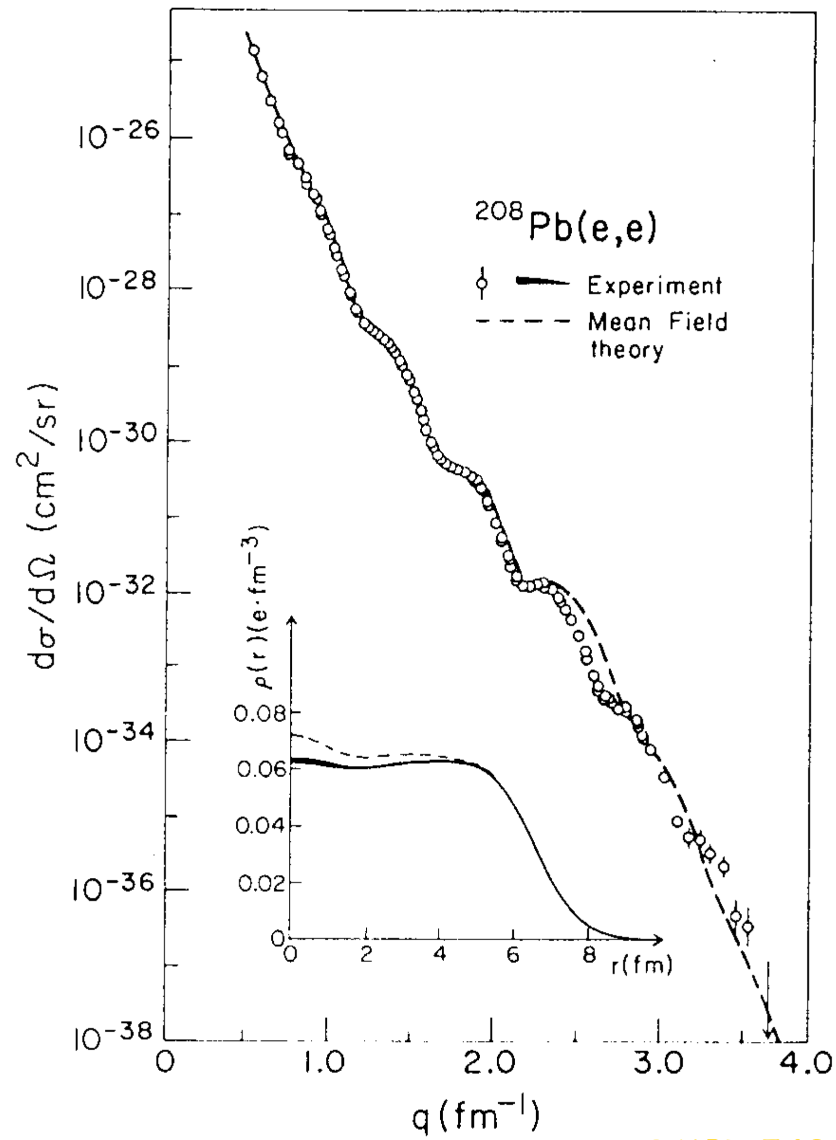


Solid: N-Z=41
Dashed: N-Z=43

- Also at other values N and Z: 2, 8, 20, 28, 50, and 82
- "Magic numbers"

Empirical potential

- Analogy to atoms suggests finding a sp potential ⇒ shells + IPM
- Difference(s) with atoms?
- Properties of empirical potential
  - overall?
  - size?
  - shape?
- Consider nuclear charge density



Frois & Papanicolas, Ann. Rev. Nucl. Part. Sci. **37**, 133 (1987)

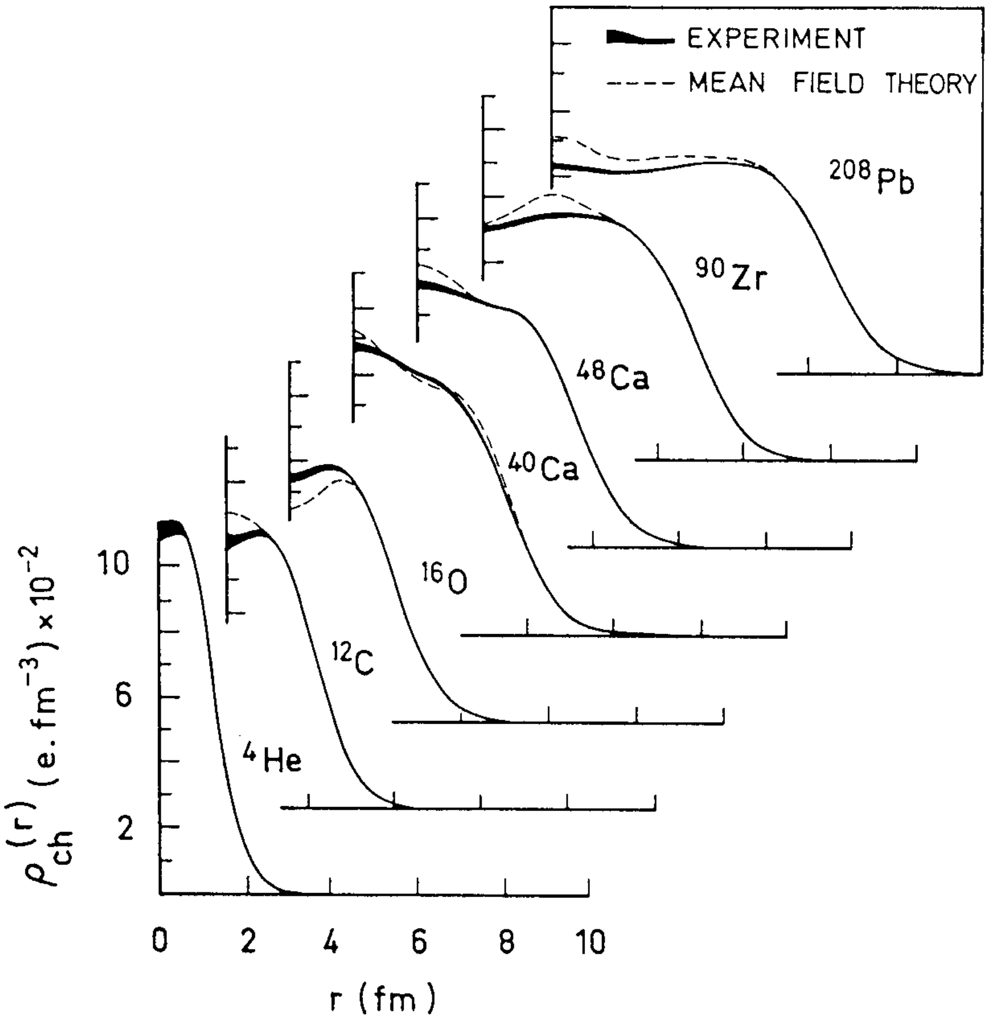
Nuclear density distribution

- Central density (A/Z* charge density) about the same for nuclei heavier than ^{16}O, corresponding to 0.16 nucleons/fm^3
- Important quantity
- Shape roughly represented by
- $$\rho_{ch}(r) = \frac{\rho_0}{1+\exp\left(\frac{r-c}{z}\right)}$$

$$c \approx 1.07 A^{\frac{1}{3}}\,\mathrm{fm}$$

$$z \approx 0.55\mathrm{fm}$$

- Potential similar shape



Empirical potential

- Bohr & Mottelson Vol.1

$$U = V f(r) + V_{\ell s} \left(\frac{\boldsymbol{\ell} \cdot \boldsymbol{s}}{\hbar^2} \right) r_0^2 \frac{1}{r} \frac{d}{dr} f(r)$$

- Central part roughly follows shape of density

$$f(r) = \left[1 + \exp\left(\frac{r - R}{a} \right) \right]^{-1}$$

- Woods-Saxon form
- Depth $V = \left[-51 \pm 33 \left(\frac{N - Z}{A} \right) \right] \text{ MeV}$

  + neutrons

  - protons

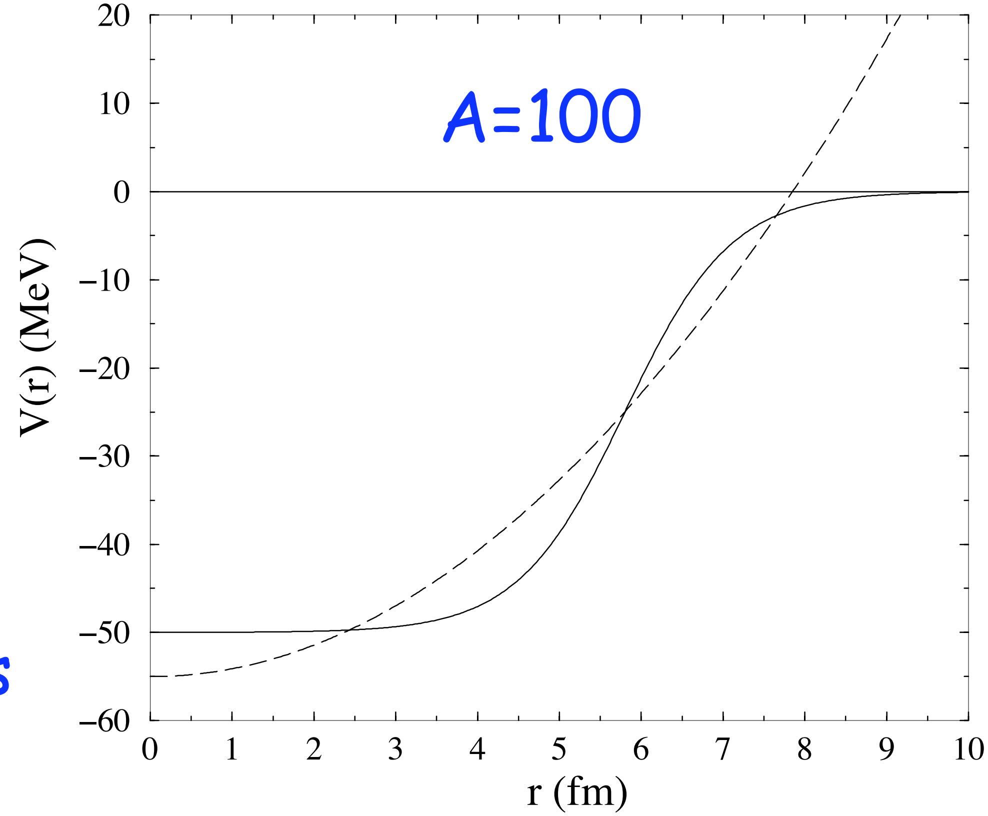
- radius $R = r_0 \, A^{1/3}$ with $r_0 = 1.27 \text{ fm}$
- diffuseness $a = 0.67 \text{ fm}$

Analytically solvable alternative

- Woods-Saxon (WS) generates finite number of bound states
- IPM: fill lowest levels ⇒ nuclear shells ⇒ magic numbers
- reasonably approximated by 3D harmonic oscillator

$$U_{HO}(r) = \frac{1}{2}m\omega^2 r^2 - V_0$$

$$H_0 = \frac{\boldsymbol{p}^2}{2m} + U_{HO}(r)$$



- Eigenstates in spherical basis

$$H_{HO}\left|n\ell m_\ell m_s\right\rangle = \left[\hbar\omega(2n+\ell+\tfrac{3}{2}) - V_0\right]\left|n\ell m_\ell m_s\right\rangle$$

Harmonic oscillator

- Filling of oscillator shells
- # of quanta $N = 2n + \ell$

N	n	ℓ	# of particles	"magic #"	parity
0	0	0	2	2	+
1	0	1	6	8	-
2	1	0	2		+
2	0	2	10	20	+
3	1	1	6		-
3	0	3	14	40	-
4	2	0	2		+
4	1	2	10		+
4	0	4	18	70	+

Need for another type of sp potential

- 1949 Mayer and Jensen suggest the need of a spin-orbit term
- Requires a coupled basis

$$|n(\ell s)jm_j\rangle = \sum_{m_\ell m_s} |n\ell m_\ell m_s\rangle\, (\ell\ m_\ell\ s\ m_s|\ j\ m_j)$$

- Use $\boldsymbol{\ell}\cdot\boldsymbol{s} = \frac{1}{2}(\boldsymbol{j}^2 - \boldsymbol{\ell}^2 - \boldsymbol{s}^2)$ to show that these are eigenstates

$$\frac{\boldsymbol{\ell}\cdot\boldsymbol{s}}{\hbar^2}|n(\ell s)jm_j\rangle = \tfrac{1}{2}\left(j(j+1) - \ell(\ell+1) - \tfrac{1}{2}(\tfrac{1}{2}+1)\right)|n(\ell s)jm_j\rangle$$

- For $j = \ell + \frac{1}{2}$ eigenvalue $\frac{1}{2}\ell$
- while for $j = \ell - \frac{1}{2}$ $-\frac{1}{2}(\ell + 1)$
- so SO splits these levels! and more so with larger ℓ

Inclusion of SO potential and magic numbers

- Sign of SO?

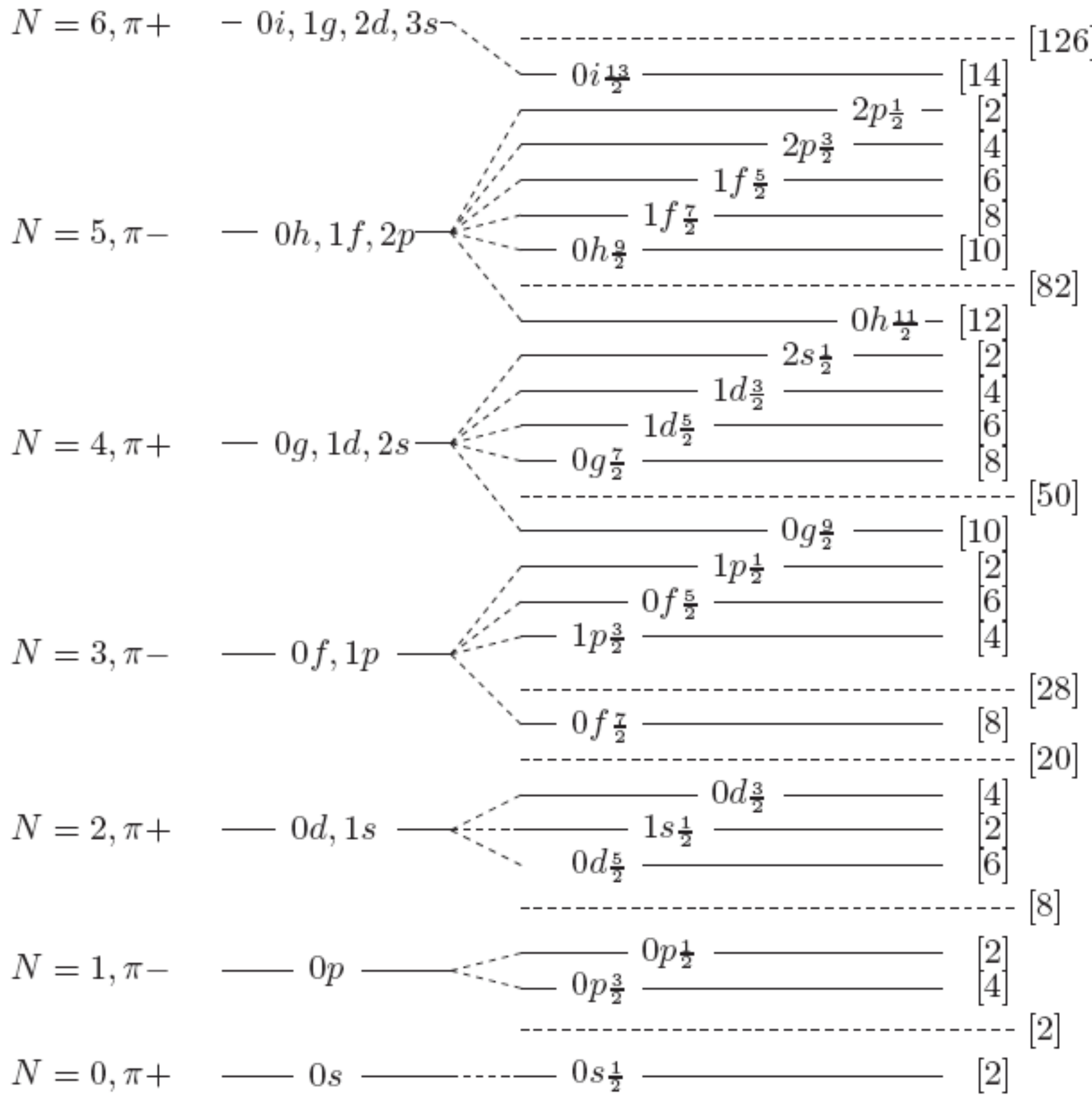
$$V_{\ell s}\left(\frac{\boldsymbol{\ell}\cdot\boldsymbol{s}}{\hbar^2}\right) r_0^2 \frac{1}{r}\frac{d}{dr} f(r)$$

$$V_{\ell s} = -0.44V$$

- Consequence for

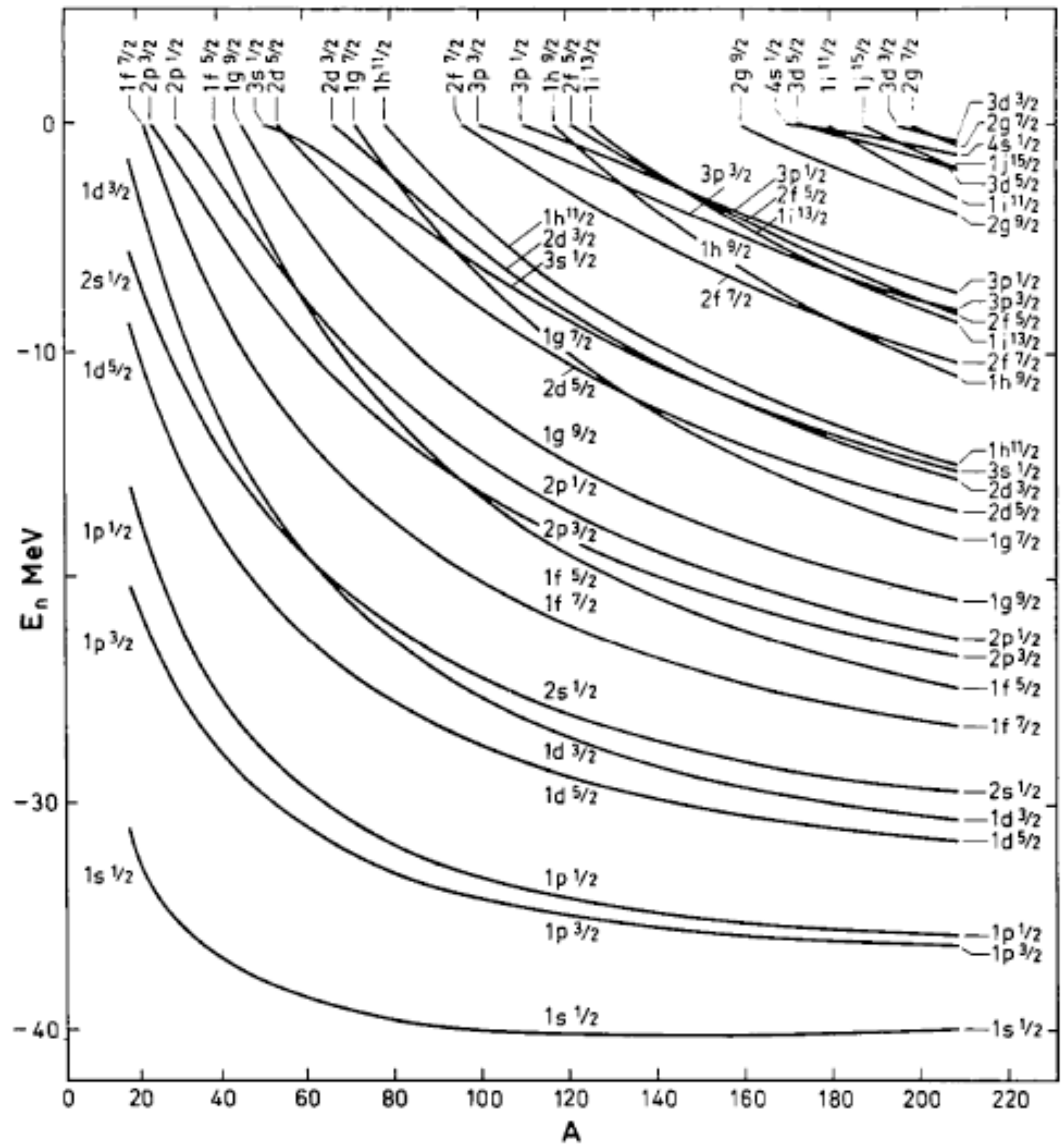
$$0f\tfrac{7}{2}$$
$$0g\tfrac{9}{2}$$
$$0h\tfrac{11}{2}$$
$$0i\tfrac{13}{2}$$

- Noticeably shifted
- Correct magic numbers!



Neutron levels as a function of A

- Phenomenological!
- Calculated from Woods-Saxon plus spin-orbit



(e,e'p) data for nuclei

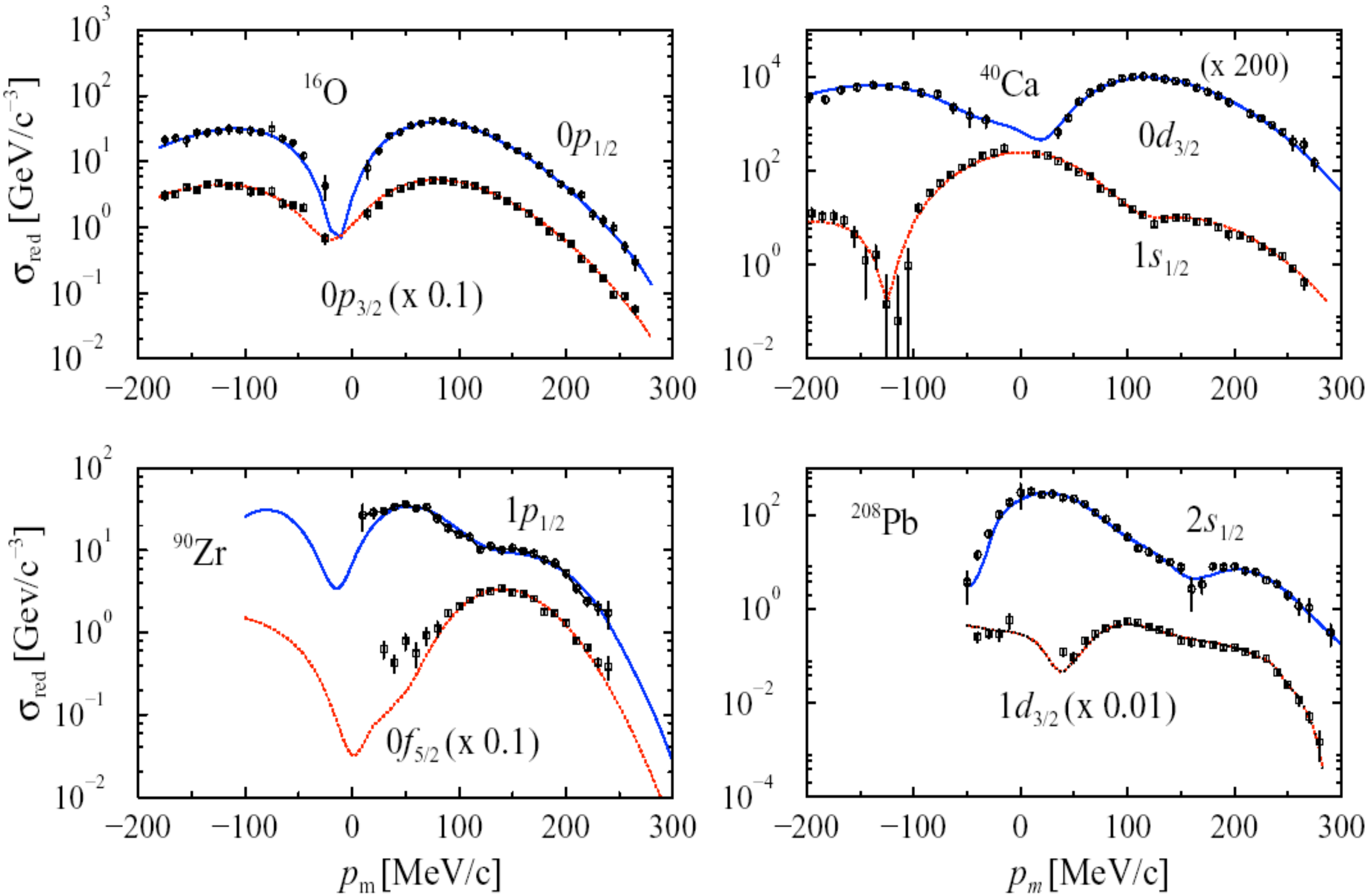
- Requires DWIA
- Distorted waves required to describe elastic proton scattering at the energy of the ejected proton
- Consistent description requires that cross section at different energy for the outgoing proton is changed accordingly
- Requires substantial beam energy and momentum transfer
- Initiated at Saclay and perfected at NIKHEF, Amsterdam
- Also done at Mainz and currently at Jefferson Lab, VA
- Momentum dependence of cross section dominated by the corresponding sp wave function of the nucleon before it is removed

(e,e'p) data for nuclei

- Requires DWIA
- Distorted waves required to describe elastic proton scattering at the energy of the ejected proton
- Consistent description requires that cross section at different energy for the outgoing proton is changed accordingly
- Requires substantial beam energy and momentum transfer
- Initiated at Saclay and perfected at NIKHEF, Amsterdam
- Also done at Mainz and currently at Jefferson Lab, VA
- Momentum dependence of cross section dominated by the corresponding sp wave function of the nucleon before it is removed

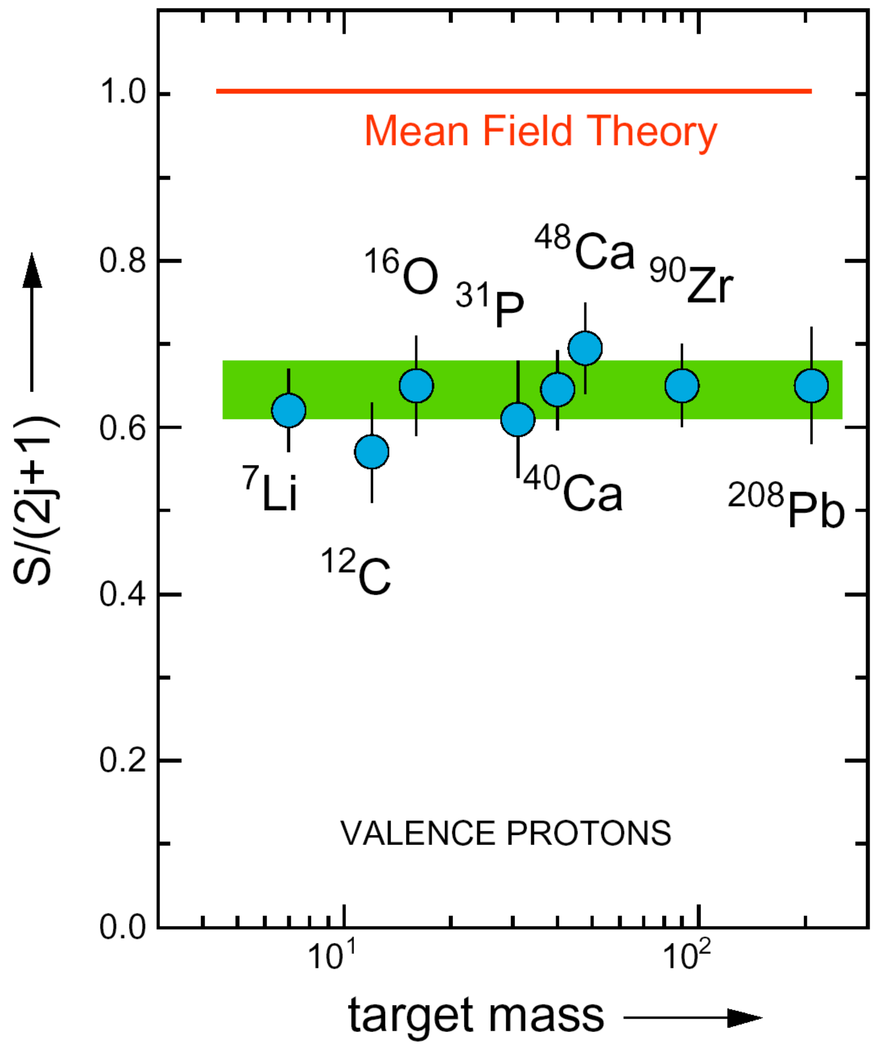
Momentum profiles for nucleon removal

- Closed-shell nuclei
- NIKHEF data, L. Lapikás, Nucl. Phys. A553, 297c (1993)



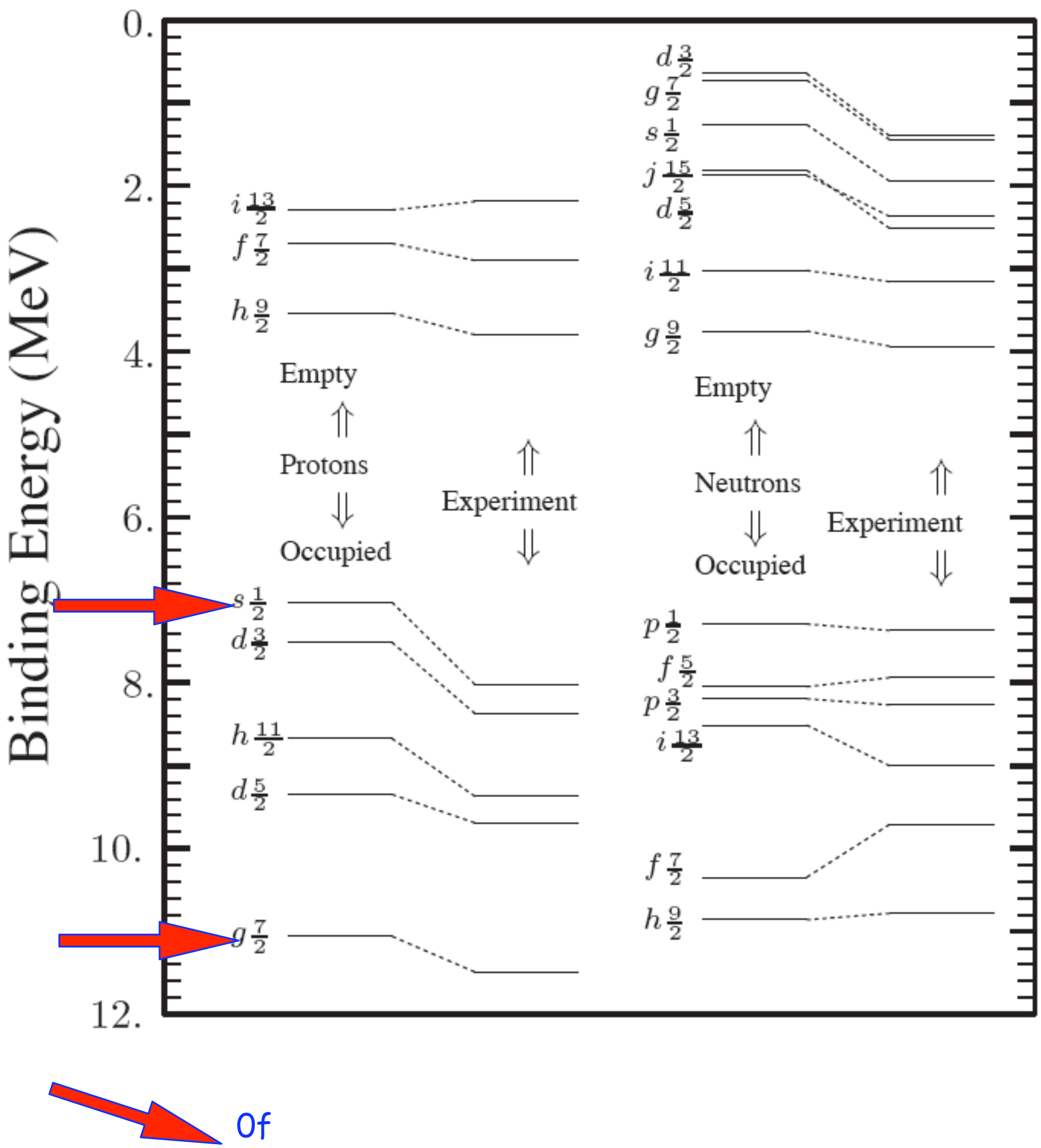
But...

- Spectroscopic factors substantially smaller than simple IPM



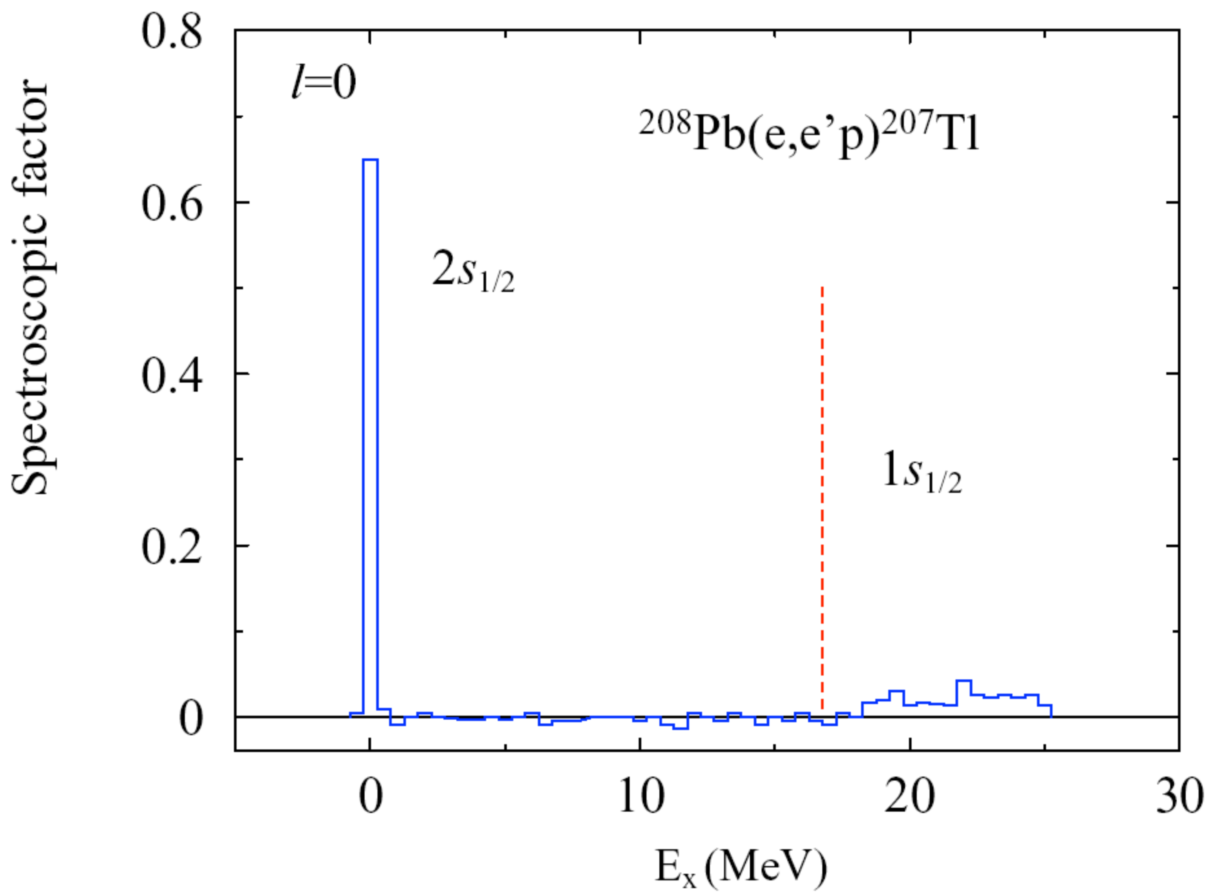
Consider

- ^{208}Pb sp levels



Fragmentation patterns

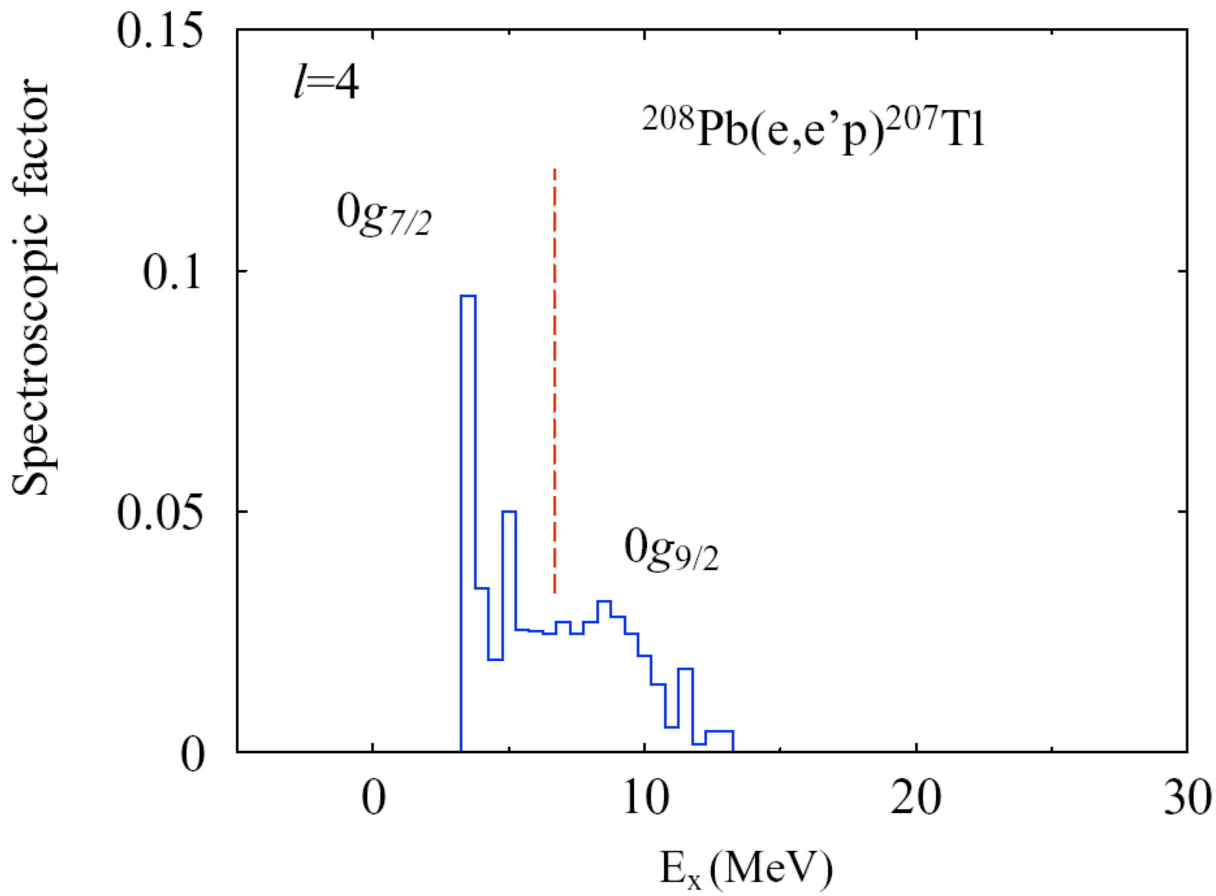
- ^{208}Pb(e,e'p) NIKHEF data: Quint thesis
- $S(2s_{1/2})=0.65$
- other data:
- $n(2s_{1/2})=0.75$



- very different from atoms

Fragmentation patterns

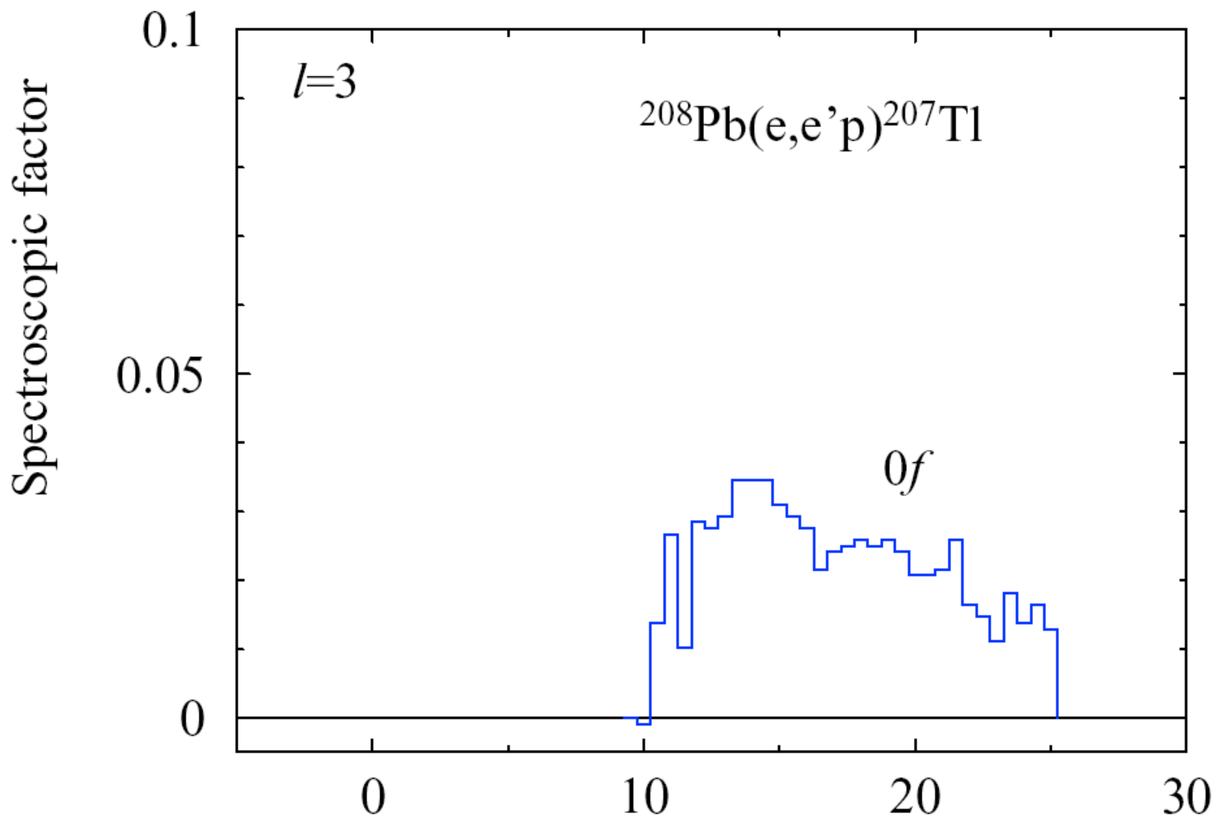
- ^{208}Pb(e,e'p) NIKHEF data: Quint thesis



- start of strong fragmentation
- also very different from atoms

Fragmentation patterns

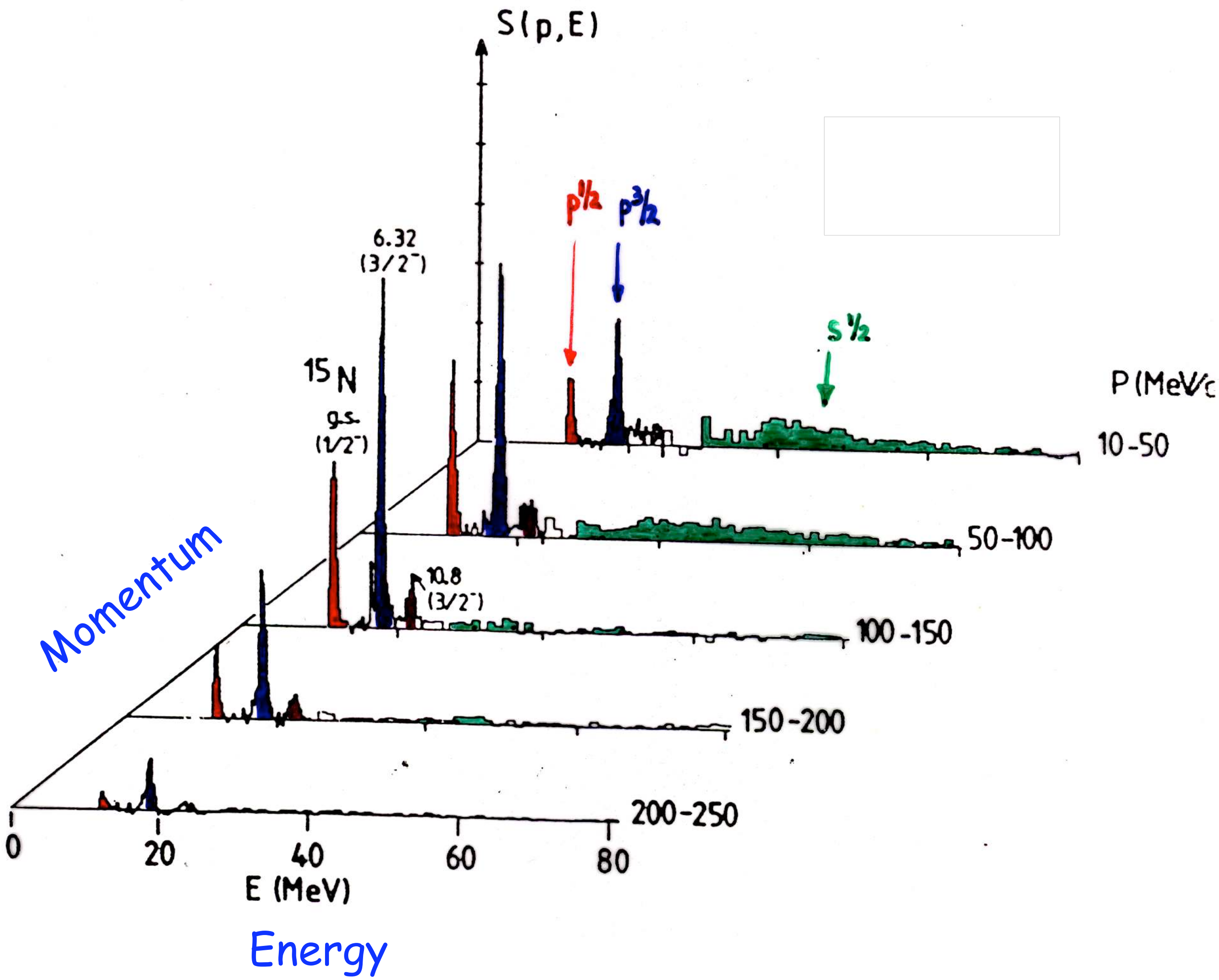
- ^{208}Pb(e,e′p) NIKHEF data: Quint thesis



- deeply bound states: strong fragmentation
- again different from atoms

^{16}O data from Saclay

- Simple interpretation!
- Mougey et al., Nucl. Phys. A335, 35 (1980)



Recent Pb experiment

- 100 MeV missing energy
- 270 MeV/c missing momentum
- complete IPM domain