Is the Spin-Orbit Interaction Changing with Neutron Excess?

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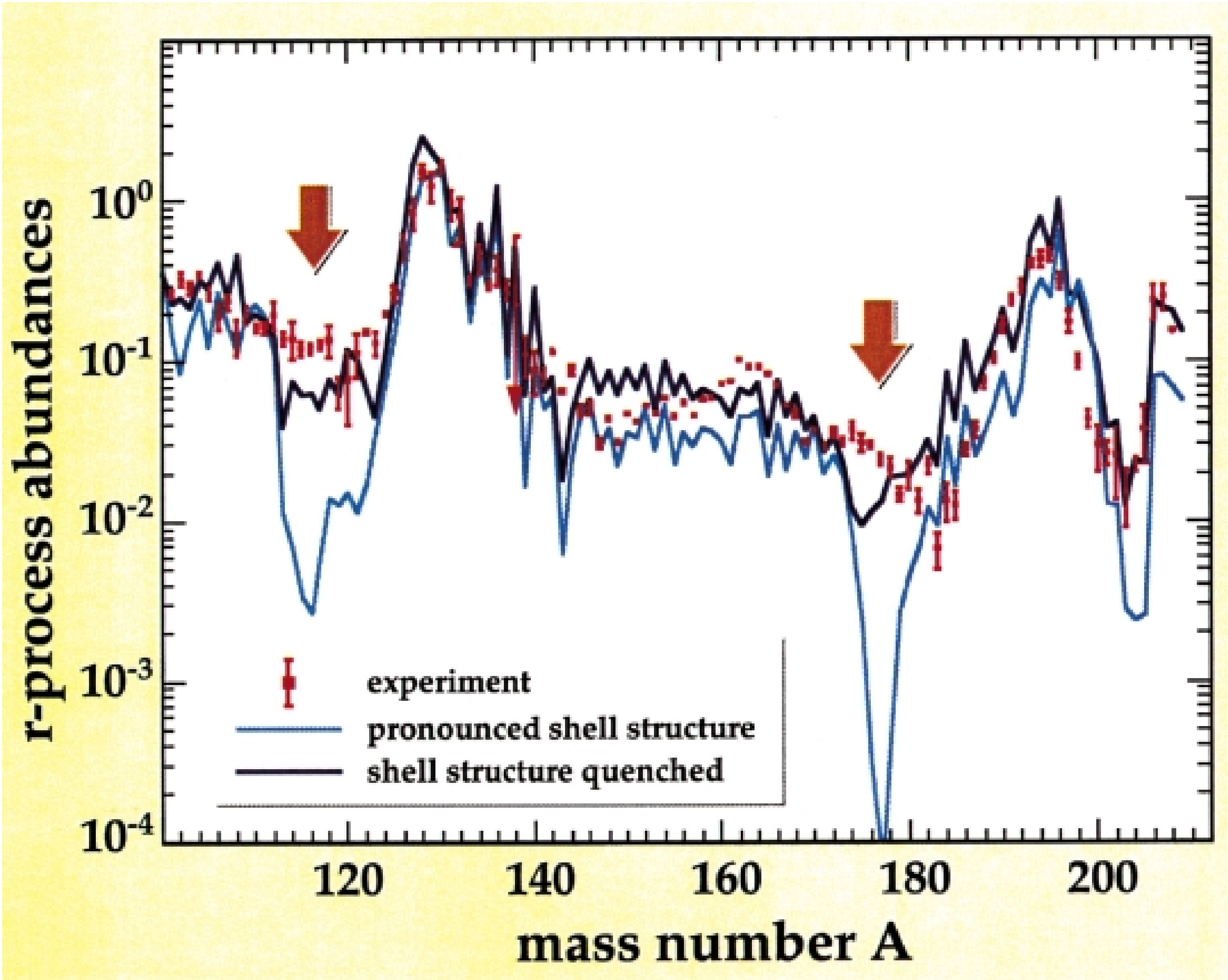
Motivation

- The origin of the nuclear shells or ‘magic numbers’ was a mystery until Maria Mayer and H. Jensen et al. noted that the spin-orbit force with j-j coupling could account for them.
- There has recently been talk of ‘shell quenching’, possibly from a change in the spin-orbit interaction, in neutron-rich nuclei, and there is some indication for this in r-process abundance data.



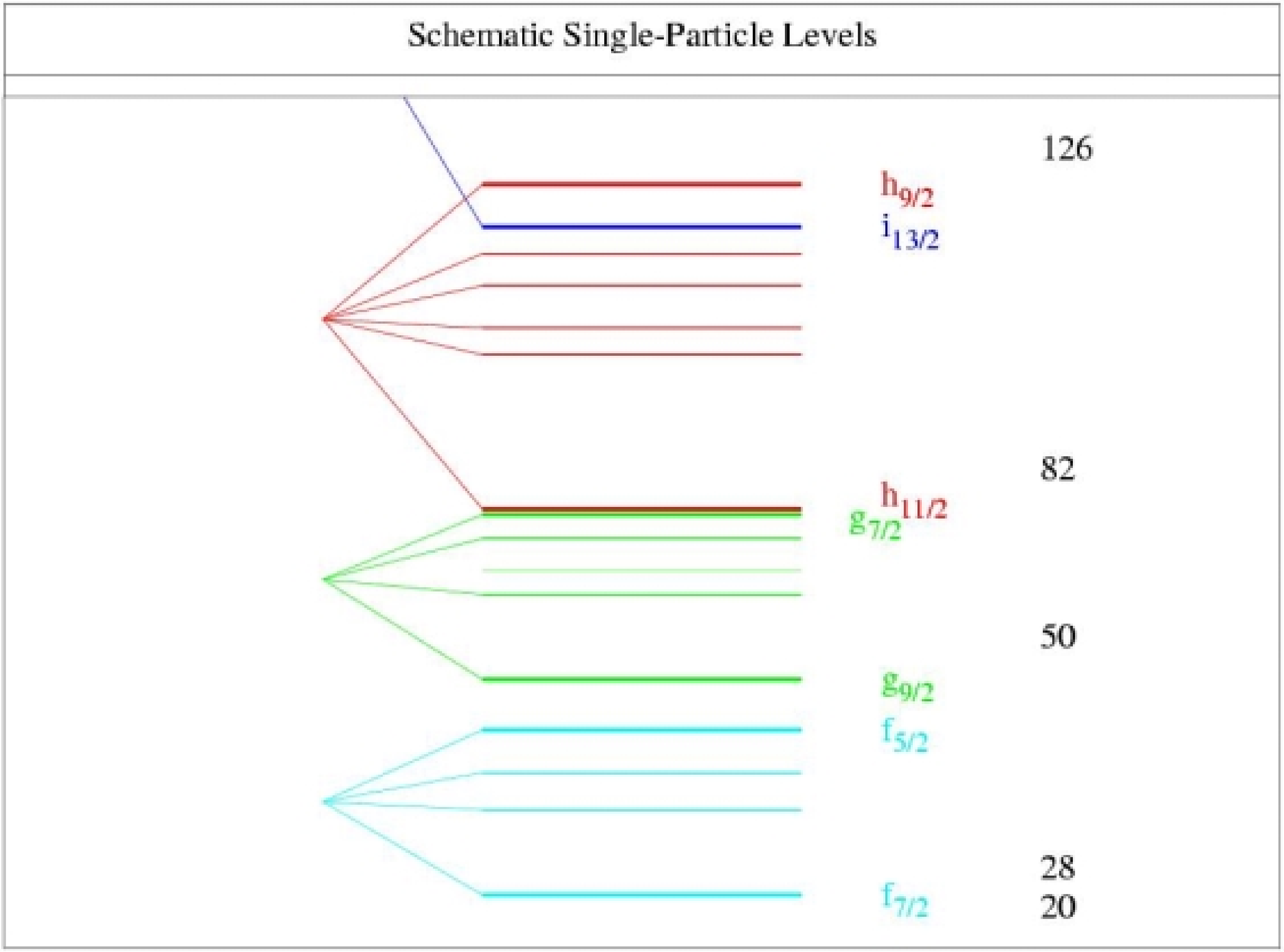
r-process abundances
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
120
140
160
180
200
mass number A
experiment
pronounced shell structure
shell structure quenched

Spin-Orbit Interaction

- Its microscopic origins are relatively poorly understood,
- It **must** be a surface effect,
- *Ab origine* calculations suggest that a good part of it may come from 3-body forces,
- Experimentally it is difficult to determine by direct measurement of the splitting because

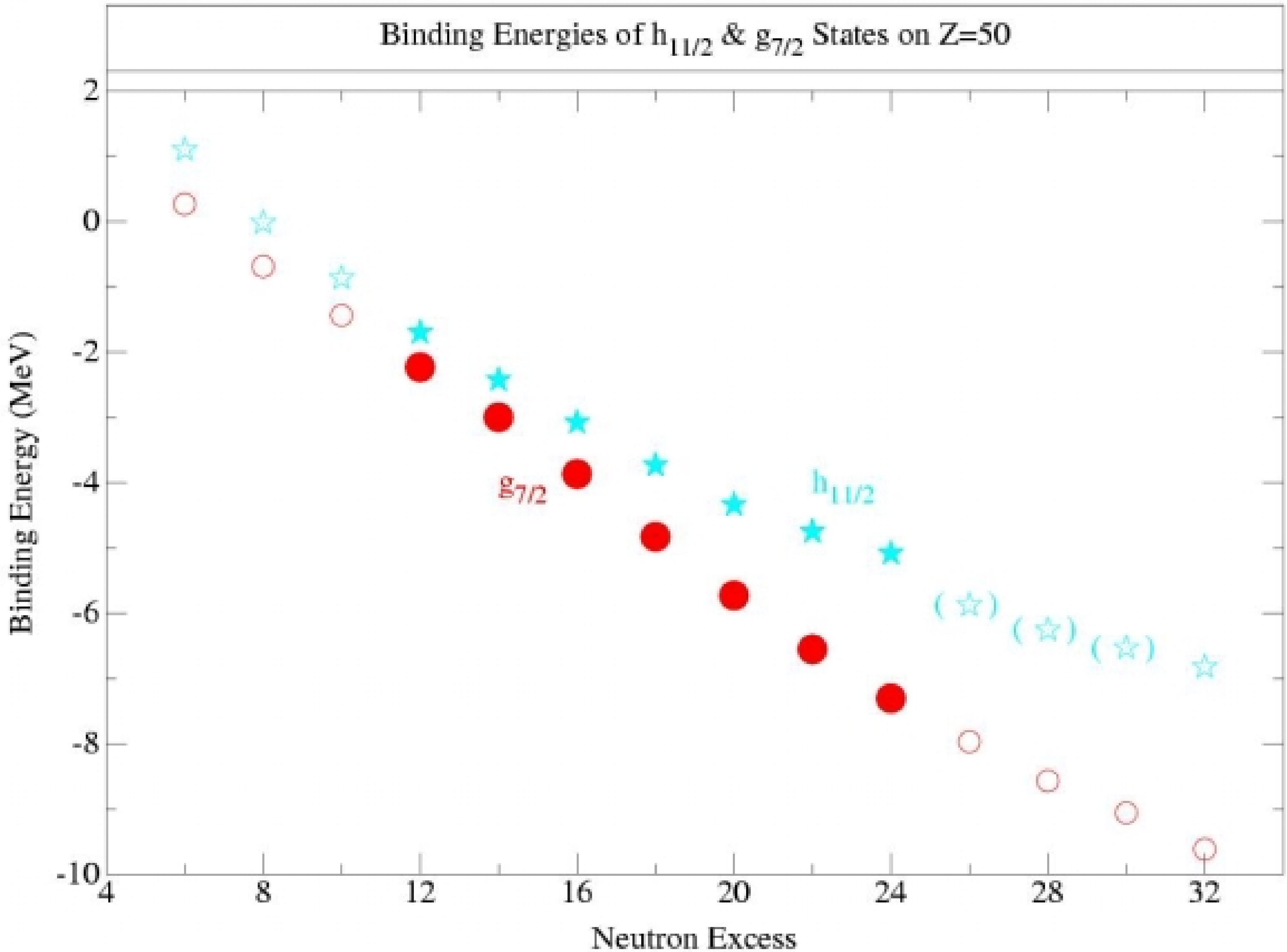
  a) for low l, the splitting is small, and even small admixtures make a difference,

  b) for large l, the upper member of a doublet is too high in excitation energy and badly fragmented.


Schematic Single-Particle Levels
126
h9/2
i13/2
82
h11/2
g7/2
50
g9/2
f5/2
28
20
f7/2

To track changes in spin-orbit structure use one-nucleon adding transfer reactions for the maximum l-states and the (relatively small) separation between the low-lying $j_<$ state from one shell and the $j_>$ (l+1 'intruder') state from the next shell.

e. g. $g_{7/2}$-$h_{11/2}$ or $h_{9/2}$-$i_{13/2}$



Binding Energies of h11/2 & g7/2 States on Z=50
Binding Energy (MeV)
Neutron Excess
g7/2
h11/2
2
0
-2
-4
-6
-8
-10
4
8
12
16
20
24
28
32

What is meant by 'single-particle states'?

A *single* state outside a closed shell, of a given (l, j) that has a 'large' spectroscopic factor in a nucleon adding reaction --

with no other state with significant strength and the same (l, j).

Or, if the strength is fragmented, then the centroid --

of the fragments weighted by their spectroscopic factors.

Absolute spectroscopic factors have to do with correlations in the many-body system and with reaction theory.

Comparing spectroscopic factors in the same vicinity of nuclei is an important tool for understanding nuclear structure.

Spectroscopic Factors -- History

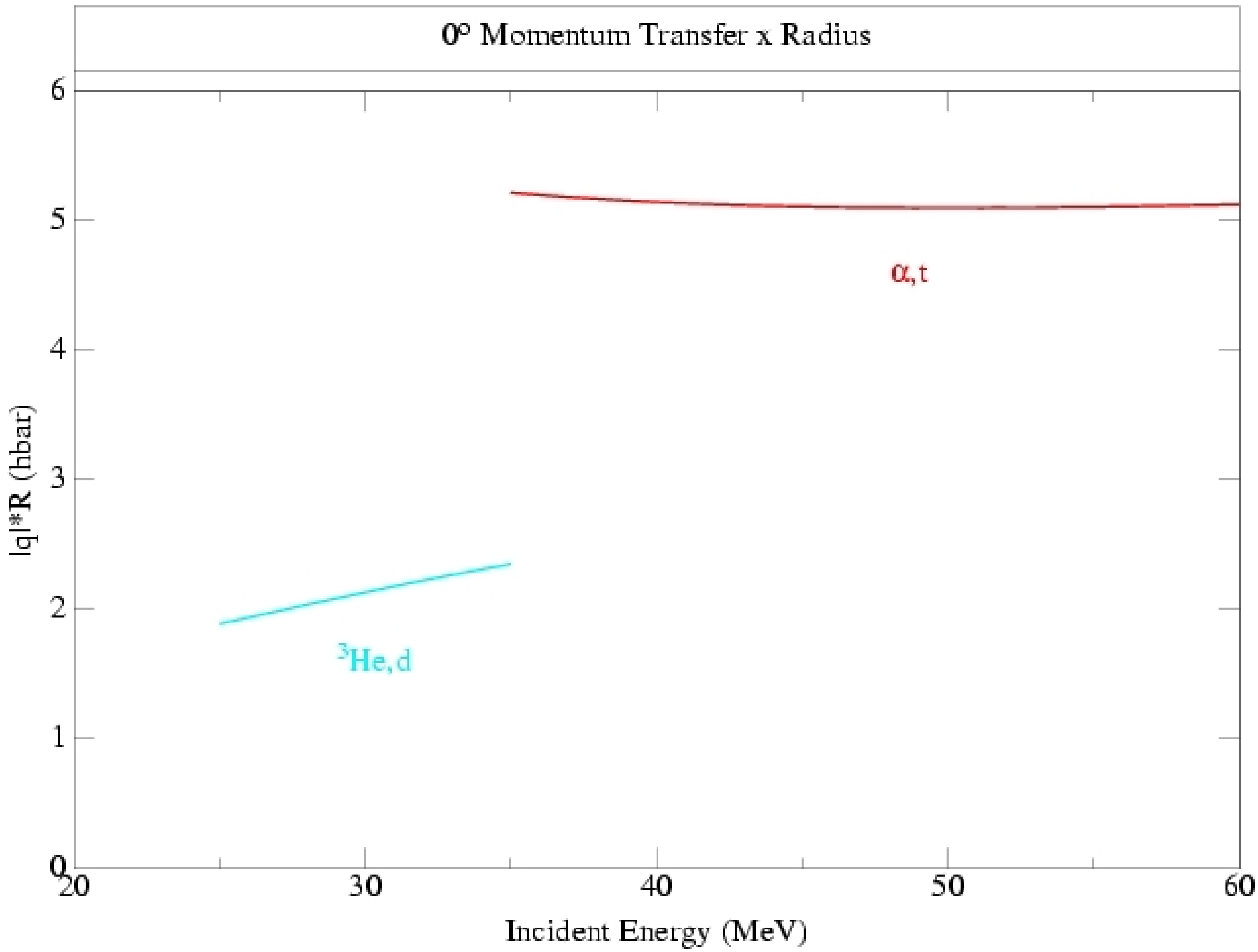
- To compare resonances with different widths in **R**-matrix theory (Wigner et al.) one defines a surface at radius R.
- Inside this surface things are black – unknown.
- Outside this surface is phase space, and one matches logarithmic derivatives on the surface.

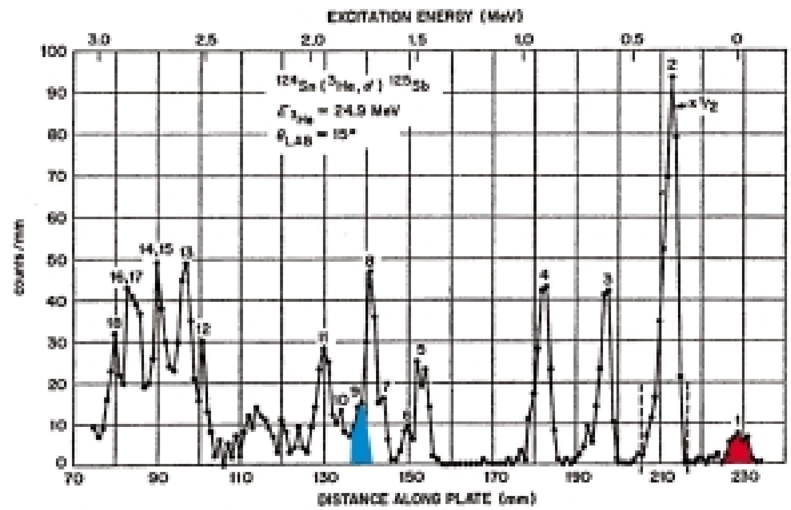
- The widths are defined by $\mathbf{\Gamma} \equiv P_l \gamma^2$, where γ^2 characterizes the interior and P_l the outside.
- The γ^2 obey the Wigner-Teichman sum rule which states that they can be no bigger than h-bar^2/(MR^2), the limit coming from purely dimensional arguments,
- When Macfarlane & French defined spectroscopic factors, **S** corresponded to γ^2, divided by this limit. Thus spectroscopic factors from the beginning refer to the **asymptotic tails** of the wave functions.
- The beautiful spectral functions from (e,e'p) are related, but **not** the same.

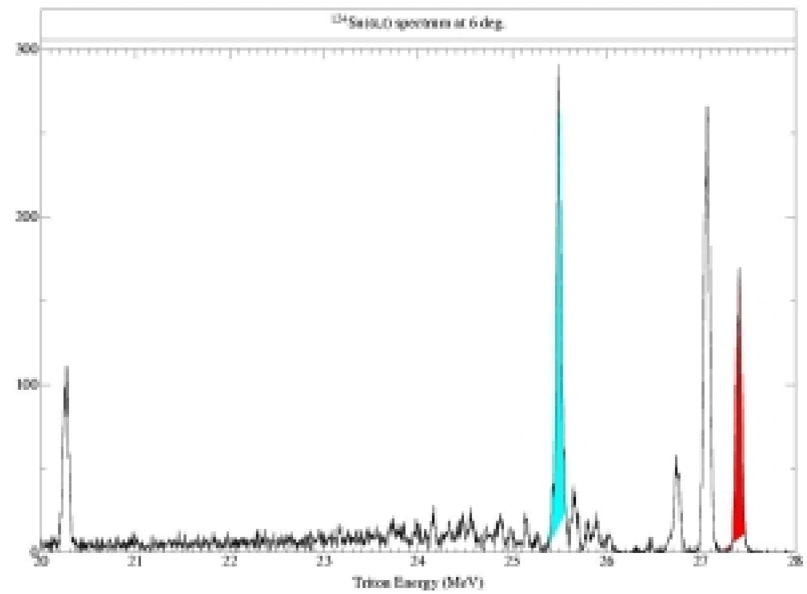
To obtain reliable information on spectroscopic factors, ***momentum matching*** is important: $|\boldsymbol{q}R| \approx l$.

Good matching is required for the validity of the approximations in the reaction models.

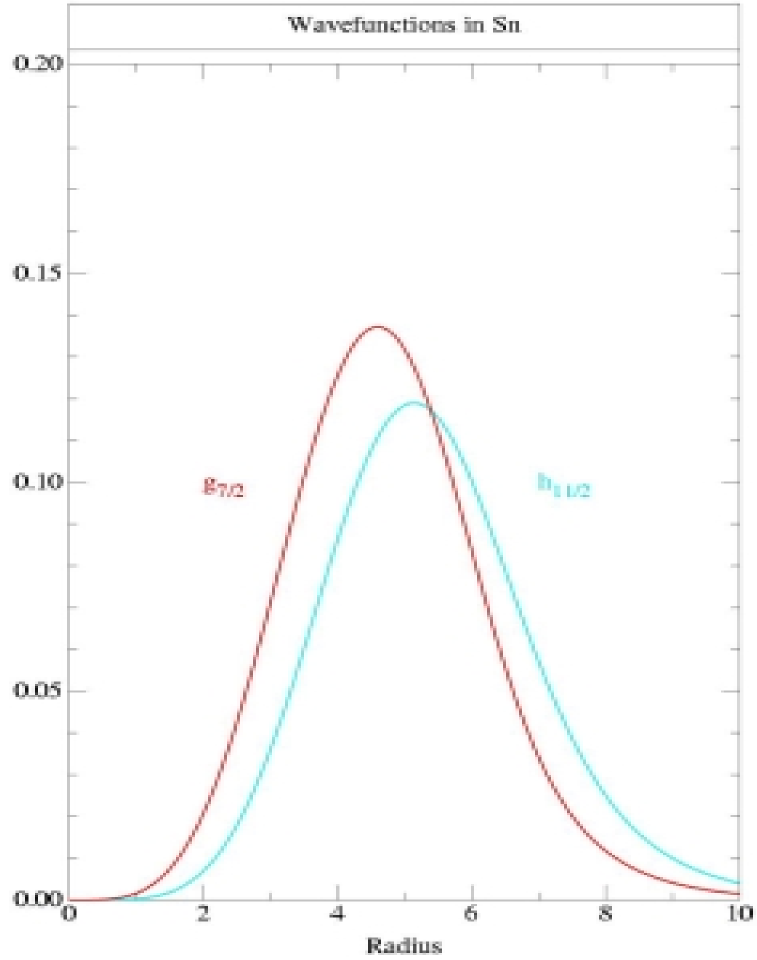
If momentum matching is poor, then more complicated higher-order process become significant and spectroscopic factors are less meaningful.


0° Momentum Transfer x Radius
|q|*R (hbar)
6
5
4
3
2
1
0
20
30
40
50
60
Incident Energy (MeV)
α,t
3He,d

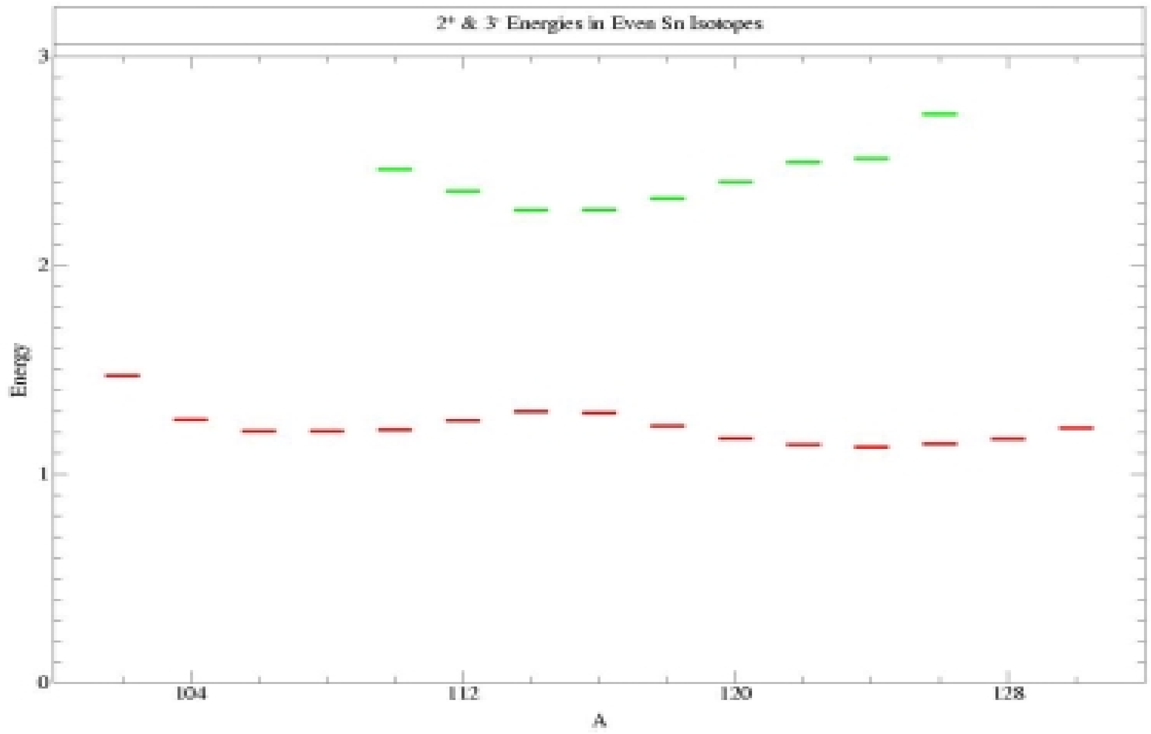

EXCITATION ENERGY (MeV)
124Sn (3He,d) 125Sb
E 3He = 24.9 MeV
θLAB = 15°
counts/mm
DISTANCE ALONG PLATE (mm)

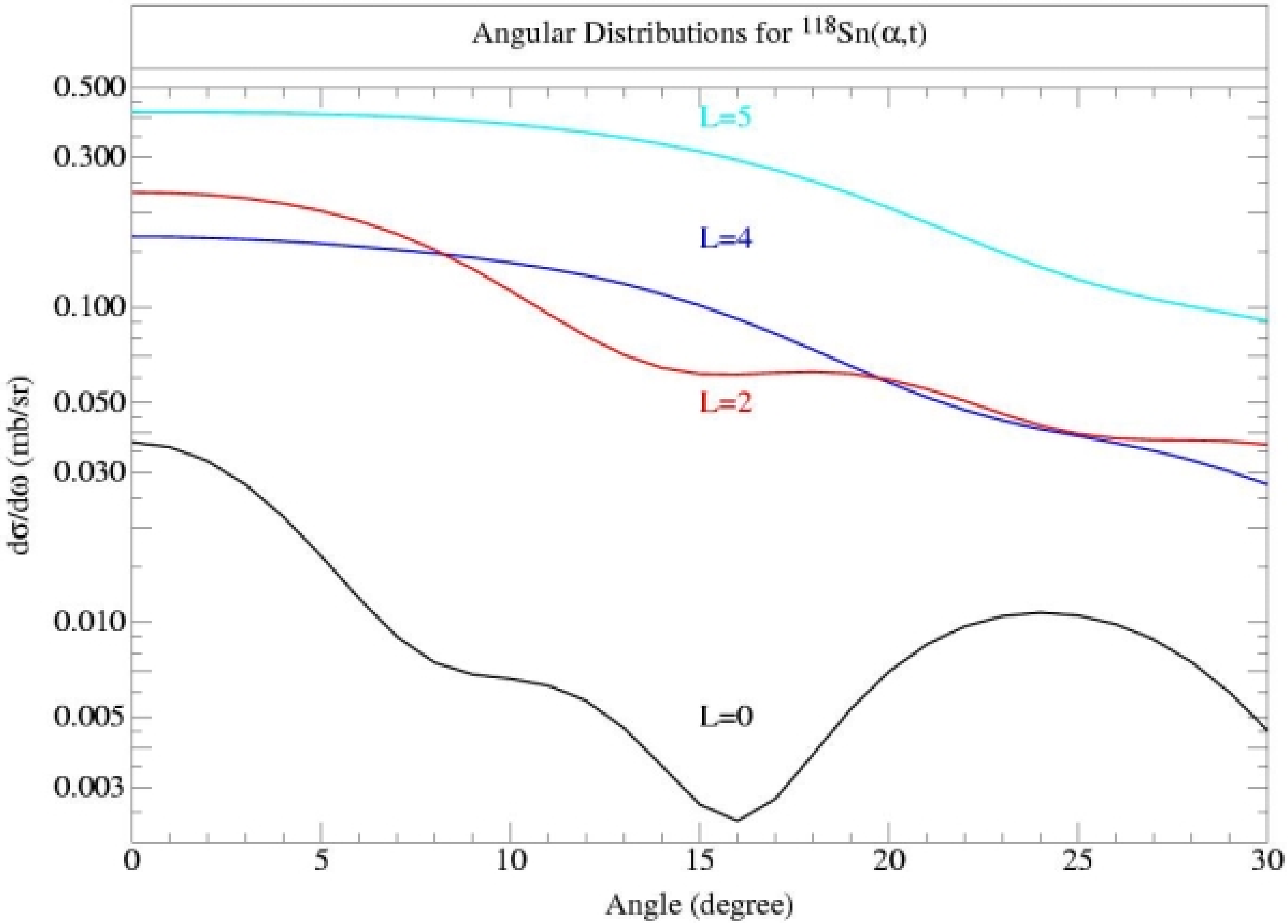

124Sn(α,t) spectrum at 6 deg.
Triton Energy (MeV)

Neither the $g_{7/2}$ nor the $h_{11/2}$ states have radial nodes -- so their radial structures are similar. Their sensitivity to changes in potential and their overlaps with changing neutron-orbit occupations are likely to be similar.



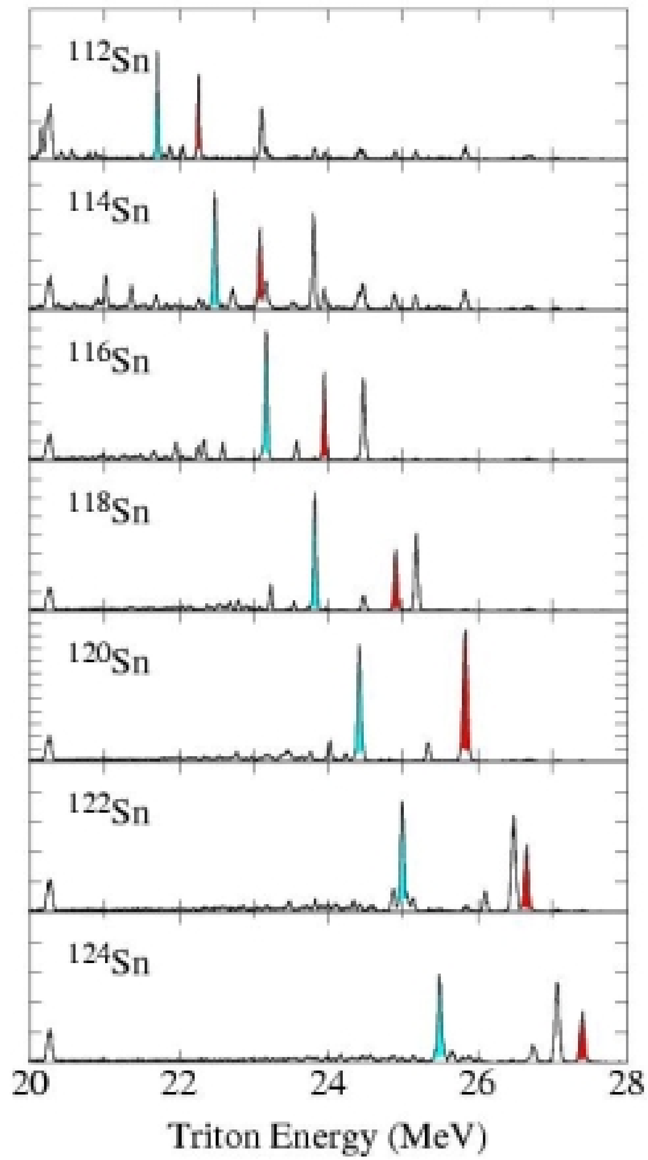
The Sn nuclei have a closed shell of 50 protons and their internal structure (low-lying 2^+ and 3^- states) is stable.

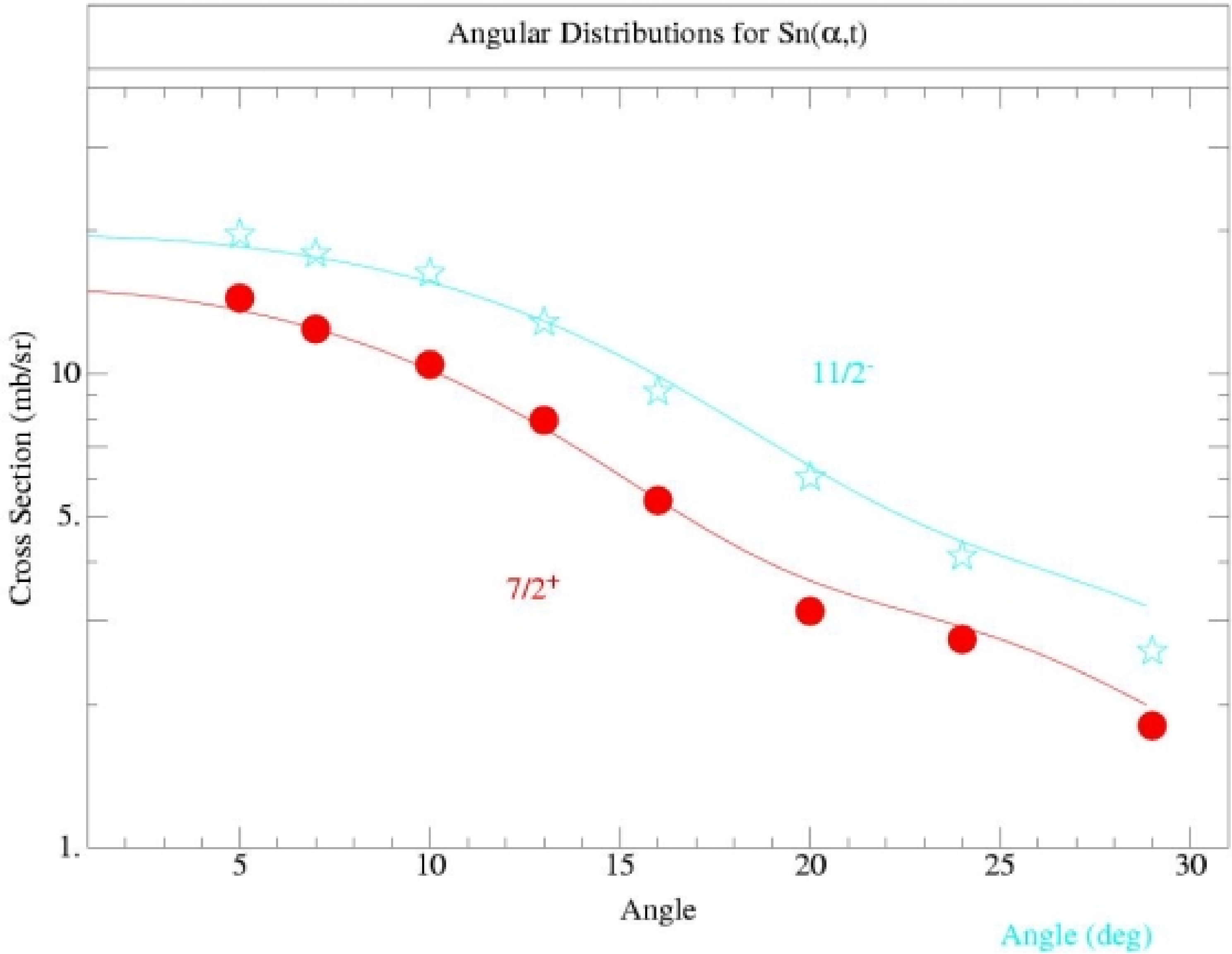



Angular Distributions for ^{118}Sn(α,t)
L=5
L=4
L=2
L=0
0.500
0.300
0.100
0.050
0.030
0.010
0.005
0.003
dσ/dω (mb/sr)
0
5
10
15
20
25
30
Angle (degree)

Triton spectra at 6^0

Colors: $g_{7/2}$ $h_{11/2}$

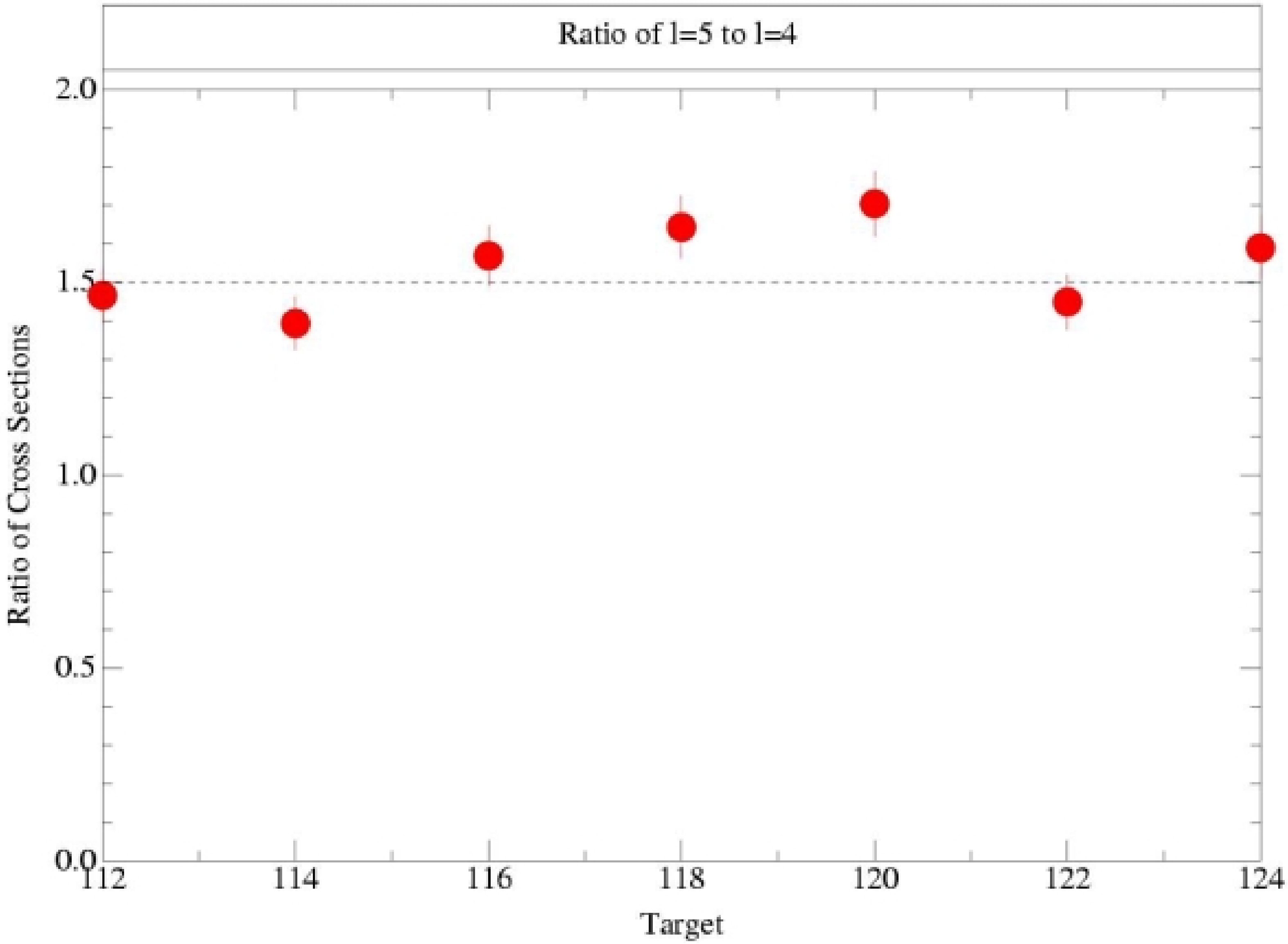


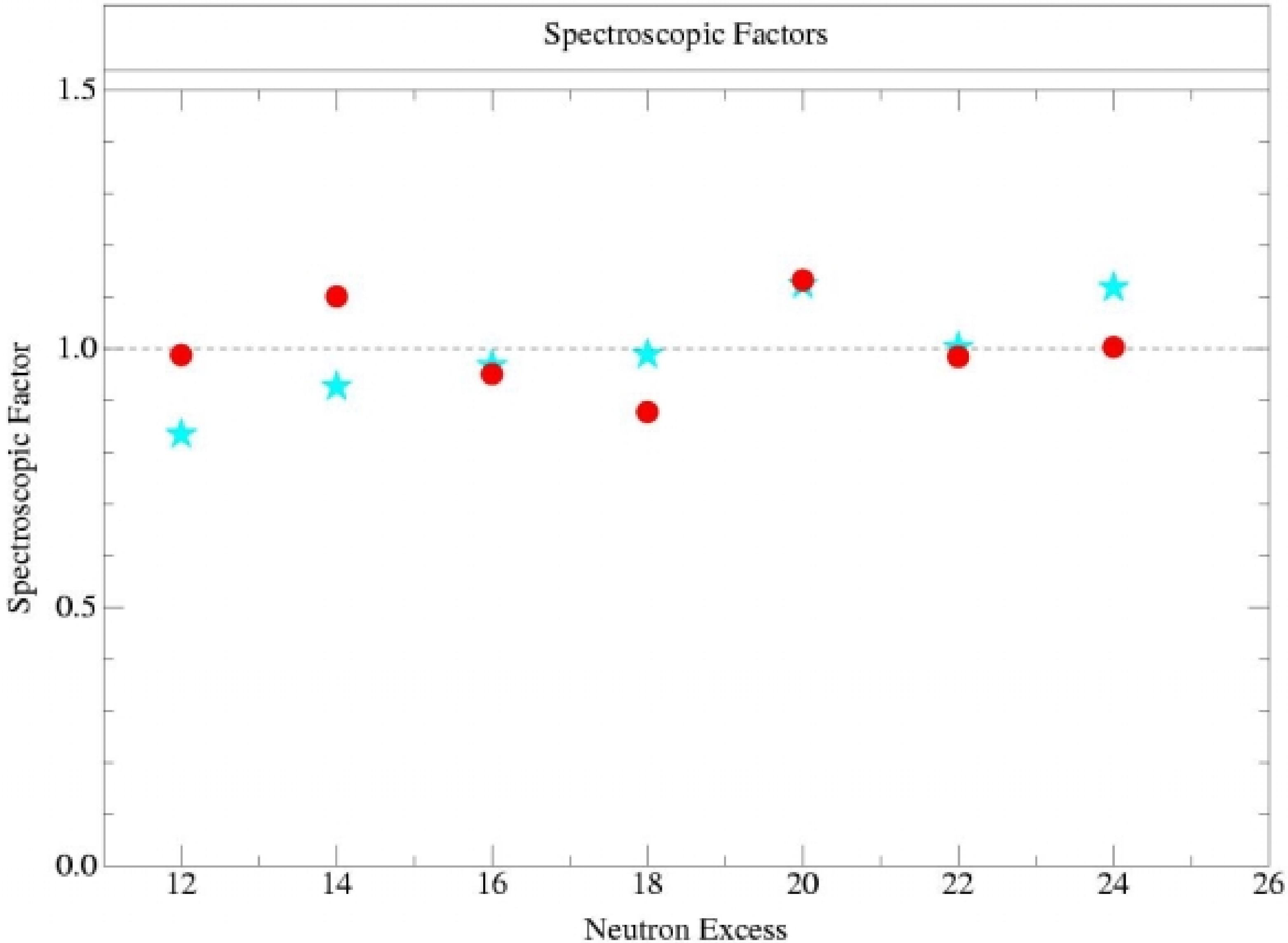

Angular Distributions for Sn(α,t)
Cross Section (mb/sr)
1.
5.
10
5
10
15
20
25
30
Angle
Angle (deg)
11/2⁻
7/2⁺

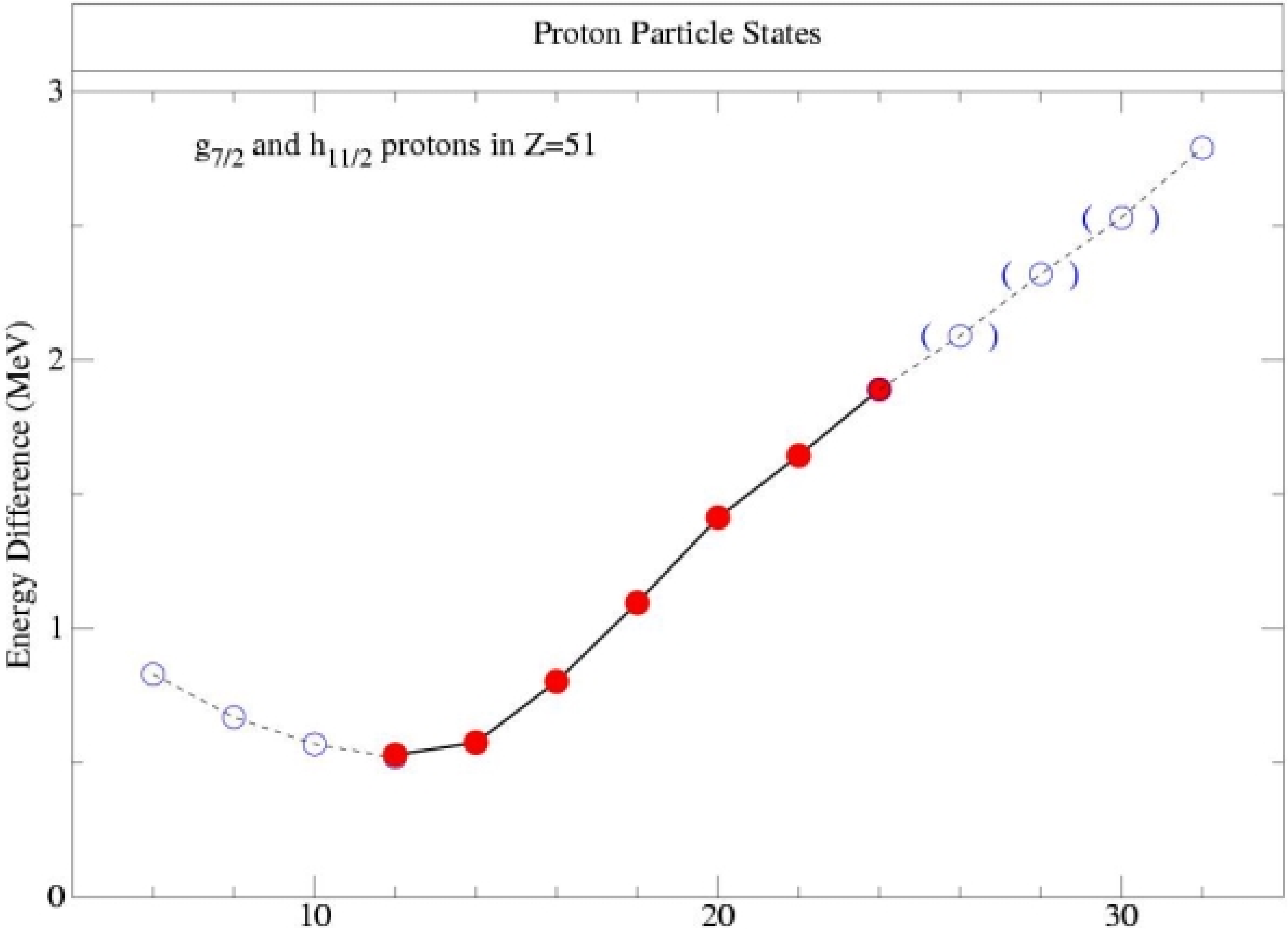
- Used 40 MeV α-s from Yale ESTU tandem with split-pole Enge spectrograph.
- To get accurate cross sections the elastic scattering at 9° was measured for each target and the right/left asymmetry monitored at +/- 30°.
- Cross sections for isolated states are believed to be accurate to <5%, with the major systematic uncertainty arising from possible contributions from other states.
- The total uncertainties in the cross sections are ~ ±10%.
- Parameters for DWBA calculations taken from the literature -- absolute spectroscopic factors vary by ±50% but relative values for a given parameter set are consistent at the 15% level.

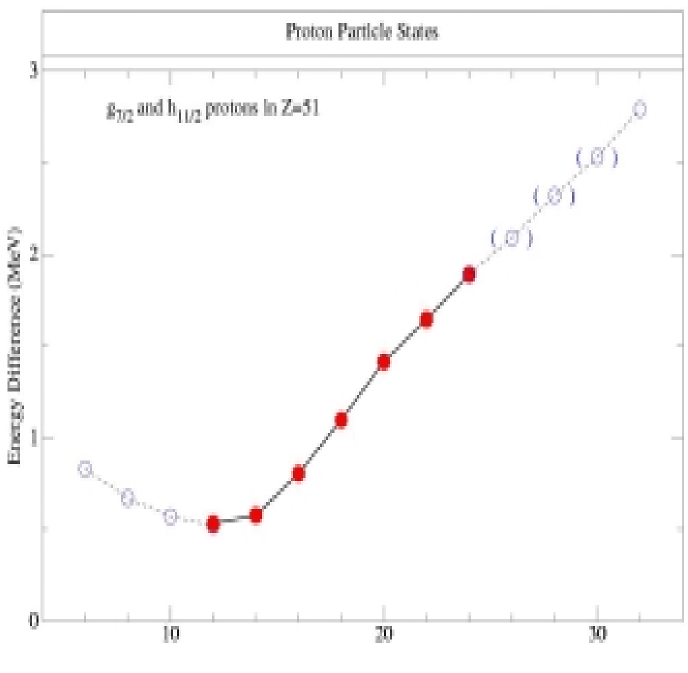
Target	Ratio ($\sigma_{6°}$)	$S_{7/2}$*	$S_{11/2}$*
^{112}Sn	1.47	0.99	0.84
^{114}Sn	1.39	1.10	0.93
^{116}Sn	1.57	0.95	0.97
^{118}Sn	1.64	0.88	0.99
^{120}Sn	1.41	1.13	1.12
^{122}Sn	1.45	0.98	1.00
^{124}Sn	1.59	1.00	1.12

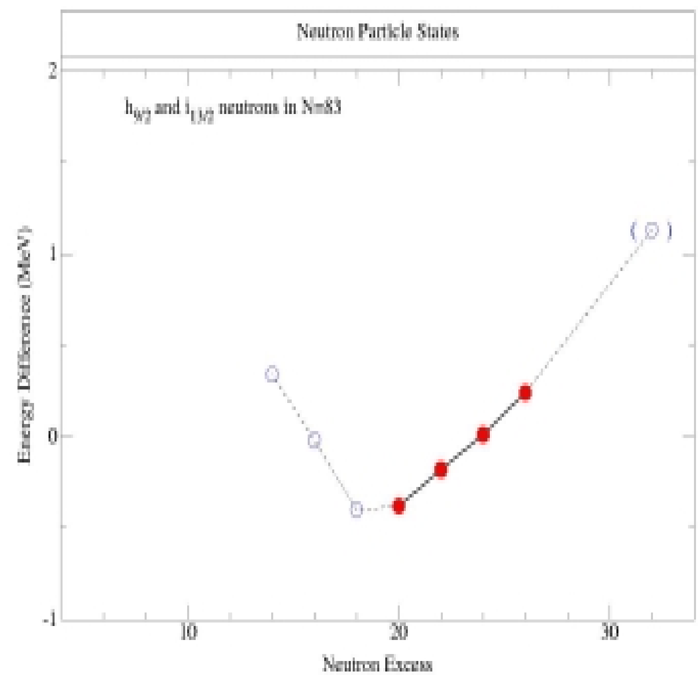
*Using a single normalization for all 14 transitions.


Ratio of l=5 to l=4
2.0
1.5
1.0
0.5
0.0
Ratio of Cross Sections
112
114
116
118
120
122
124
Target


Spectroscopic Factors
Spectroscopic Factor
1.5
1.0
0.5
0.0
12
14
16
18
20
22
24
26
Neutron Excess

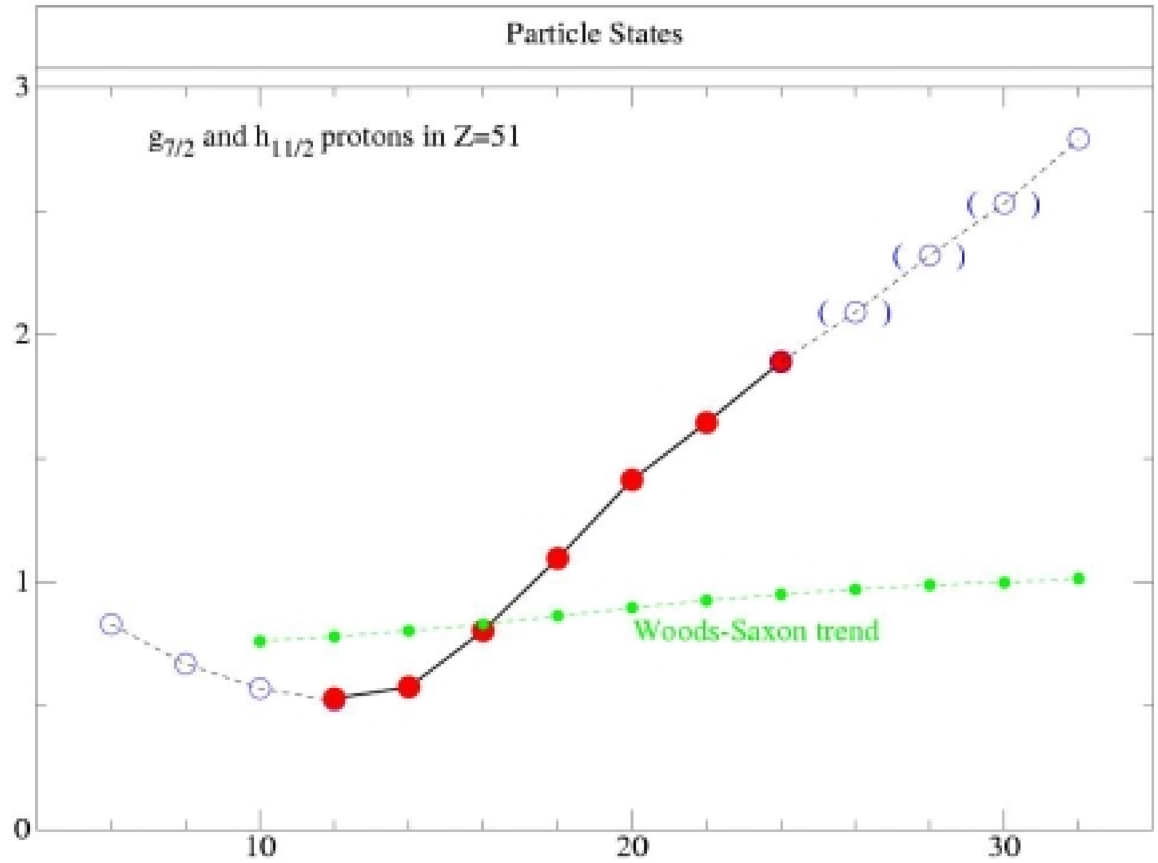

Proton Particle States
g7/2 and h11/2 protons in Z=51
Energy Difference (MeV)
0
1
2
3
10
20
30


Proton Particle States
g7/2 and h11/2 protons in Z=51
Energy Difference (MeV)
0
1
2
3
10
20
30

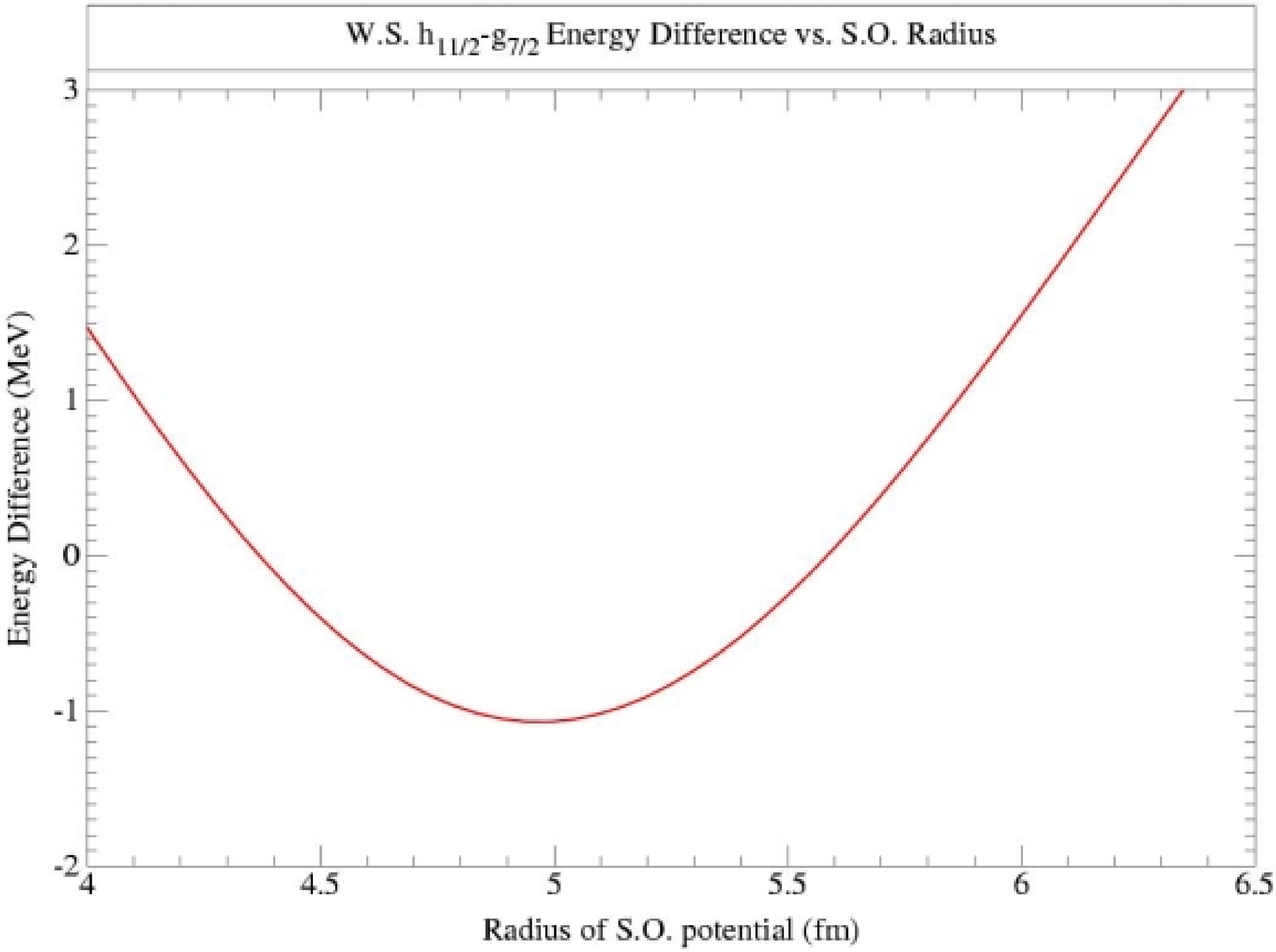

Neutron Particle States
h9/2 and i13/2 neutrons in N=83
Energy Difference (MeV)
-1
0
1
2
10
20
30
Neutron Excess

Conclusions (1)

- The observed spectroscopic factors are consistent with 'single-particle states' for the $g_{7/2}$ and $h_{11/2}$ for all seven even Sn targets.
- The relative energies are changing in a way that is consistent with decreasing s.o. strength with increasing N.
- Extrapolating with γ-decay data, the s.o. strength is reduced by ~ a factor of almost 2 by ^{132}Sn.
- The qualitative behavior is similar for the existing data for $h_{9/2}$-$i_{13/2}$ for one neutron outside N=82.
- The maximum s.o. splitting appears near the line of maximum β-stability (a little to the left) where proton and neutron radii are most nearly equal.
- Could it be changes in the radial structure of the s.o. potnl.?



Woods-Saxon parameters fixed, with $A^{1/3}$ dependence of radii and well-depth adjusted to fit binding of $g_{7/2}$ state.


W.S. h11/2-g7/2 Energy Difference vs. S.O. Radius
3
2
1
0
-1
-2
Energy Difference (MeV)
4
4.5
5
5.5
6
6.5
Radius of S.O. potential (fm)

Conclusions (2)

- The change in s.o. radius needed to explain the effect seems too large -- but perhaps it provides a hint?
- There is no sign of such behavior in H.F.B calculations, for instance of Dugue, Bonche, et al.
- The most promising other regions with stable targets are the $g_{9/2}$-$f_{5/2}$ proton-holes in Z=50 and the $h_{11/2}$-$g_{7/2}$ neutron-holes in N=82. There is evidence that the single-hole strength is much more fragmented than that of the states studied here. No other promising regions are apparent until radioactive beams become available.