Transfer Reactions:
Probing another Aspect of Nuclear Structure

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Outline:

- Brief History
- Nature of one-nucleon transfer reactions
- l-values, spectroscopic factors, sum rules
- Case-studies in applications (even some unfinished business on stable nuclei)
- The importance of momentum transfer
- Some common fallacies in using DWBA
- Sub-Coulomb Reactions
- Conclusions

Brief History:

1950-s Much of the information in nuclear structure at this time has come from beta and gamma spectroscopy with relatively crude detectors.

Two developments:

- The recognition of the importance of **collective** modes (rotational, vibrational, and giant resonances), and
- the discovery that transfer reactions probe **single-particle** excitations.

S. Butler points out the validity of the Born approximation in interpreting (d,p) '**stripping**' reactions from Liverpool and extracting **l-values**. Many others follow. Also, **Optical Model** clarifies single-nucleon excitation in the continuum.

1960-s There is an explosion of accelerators, spectrographs, data and improved theory (e.g. *Austern, Satchler*, etc.), adapting the optical model to more quantitative models '**DWBA**'.

The importance of '**spectroscopic factors**' (or reduced widths) is emphasized by *French* and *Macfarlane*. The validity and consistency of DWBA is explored.

Other transfer, inelastic and charge-exchange reactions are also used with great success.

1970-s This effort continues and then fades gradually as the single-particle structure is mapped out and all the 'easy' experiments are done.

> *Considerable pressure from funding agencies (in these pre-NSAC days) to shift focus of accelerator-based research to the 'modern' field of heavy ion physics.*

1980-s Transfer studies go out of fashion.

γ-ray studies find a new base with heavy ions, but not for transfer.

The possibility of extending transfer studies to unstable nuclei is recognized in conjunction with the new GSI storage ring and the Isospin report. LOI is written for d(^{132}Sn,p) at GSI.

1990-s Prototype (d,p) experiment in inverse kinematics done at GSI with a (stable) Xe beam. 'First' (d,p) experiment on a short-lived beam is done in inverse kinematics on d(^{56}Ni,p) and ^{3}He(^{56}Ni,d and single-particle structure is confirmed.

Features of Transfer Reactions.

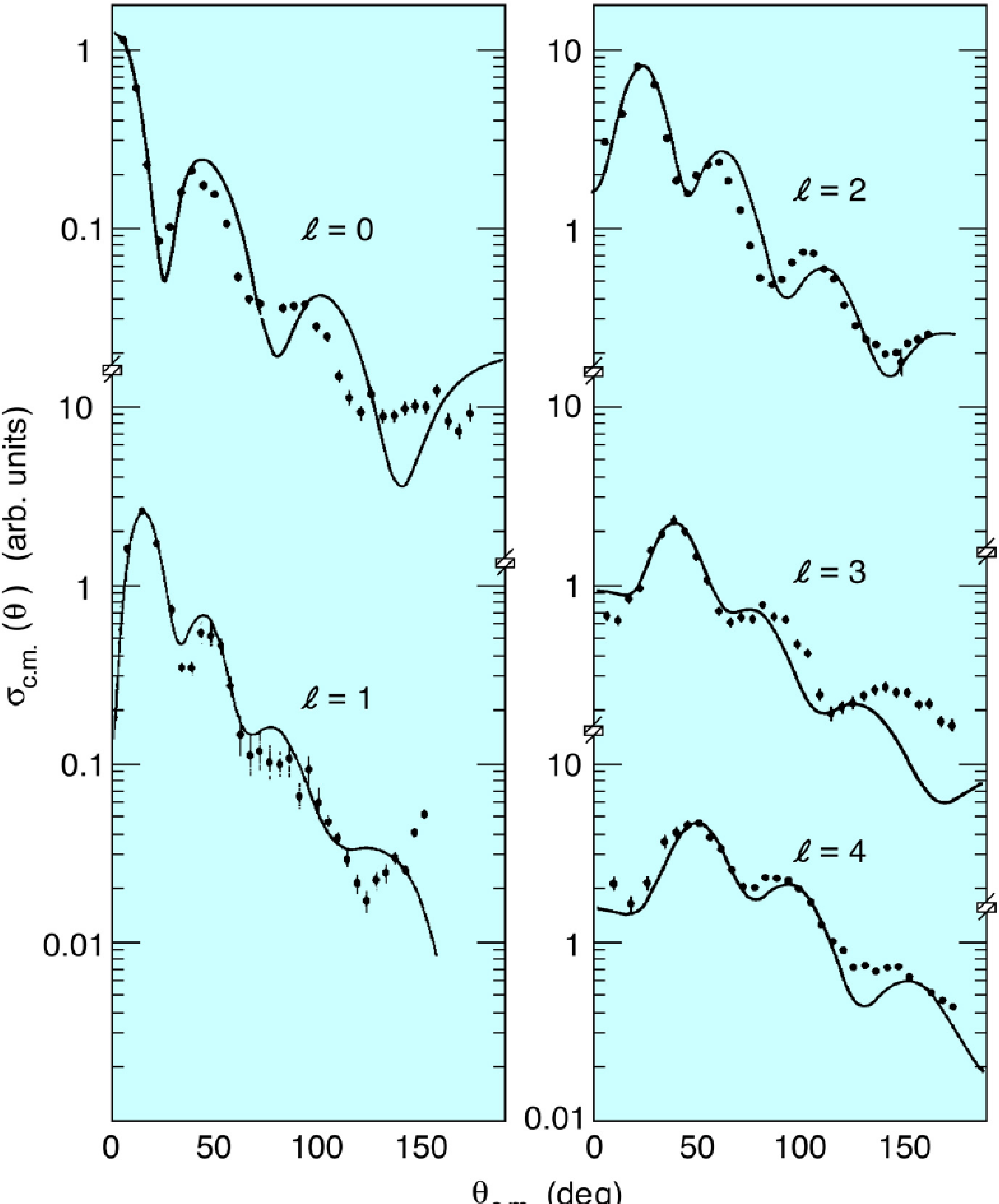
The most striking initial feature of direct reactions was the fact that the angular distribution of the outgoing particles reflect the transferred angular momentum, and the **l-value** can be extracted easily.

(j-values can also be obtained from polarization measurements and from detailed features of the unpolarized angular distributions.)

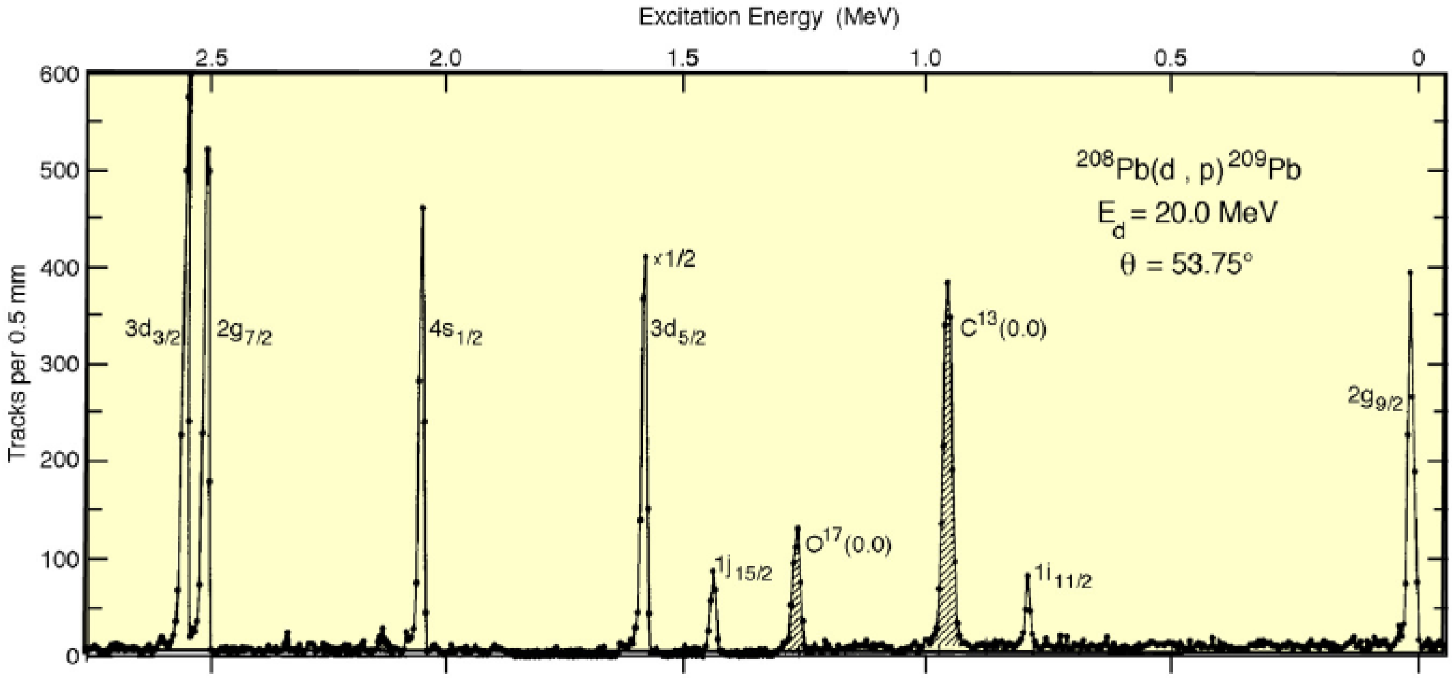
The **'spectroscopic factor'**, is proportional to the cross section; it is a measure of the overlap between the initial and final state (same as a 'reduced width' of a resonance) in the reaction channel (e.g. neutron width for d,p; pair-probability for p,t or t,p).

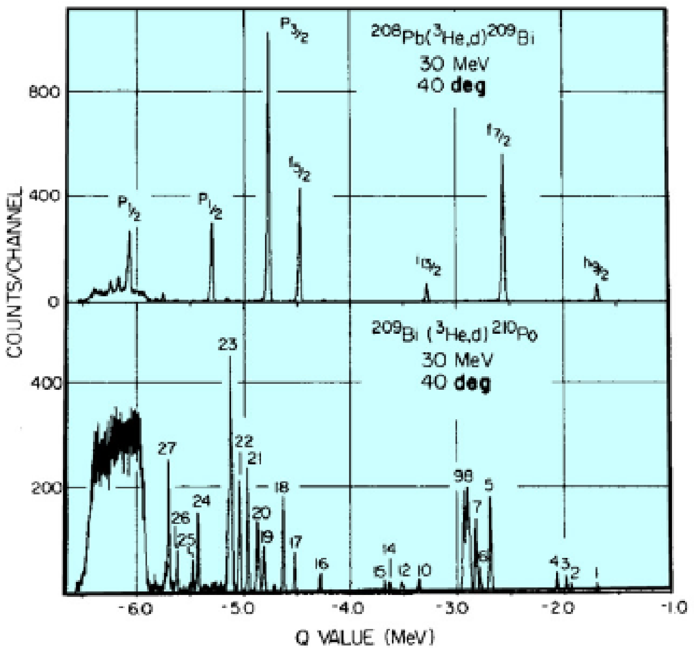
The selectivity of nucleon transfer makes it the ideal tool for mapping out ***the single-particle structure of nuclei***, it complements other process (e.g. electromagnetic) that probe ***collective*** aspects.

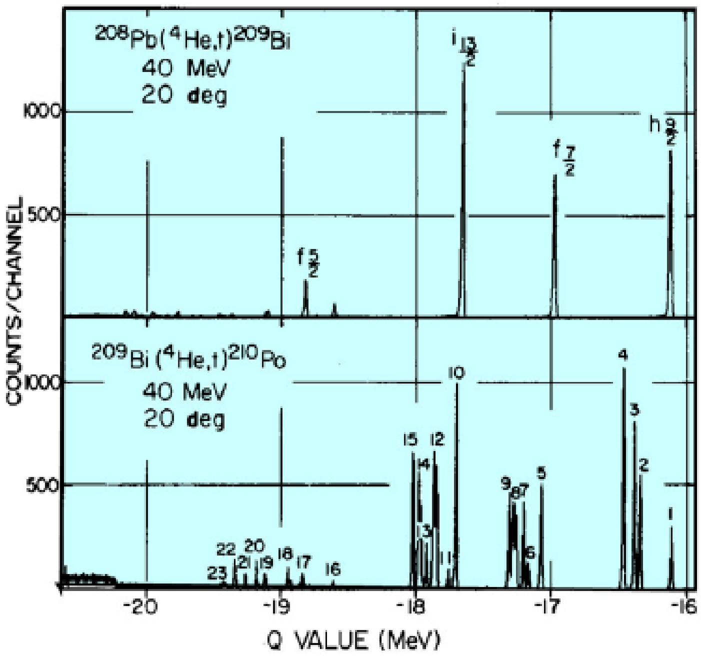
Zn (d , p) Reactions at E_d = 10 MeV



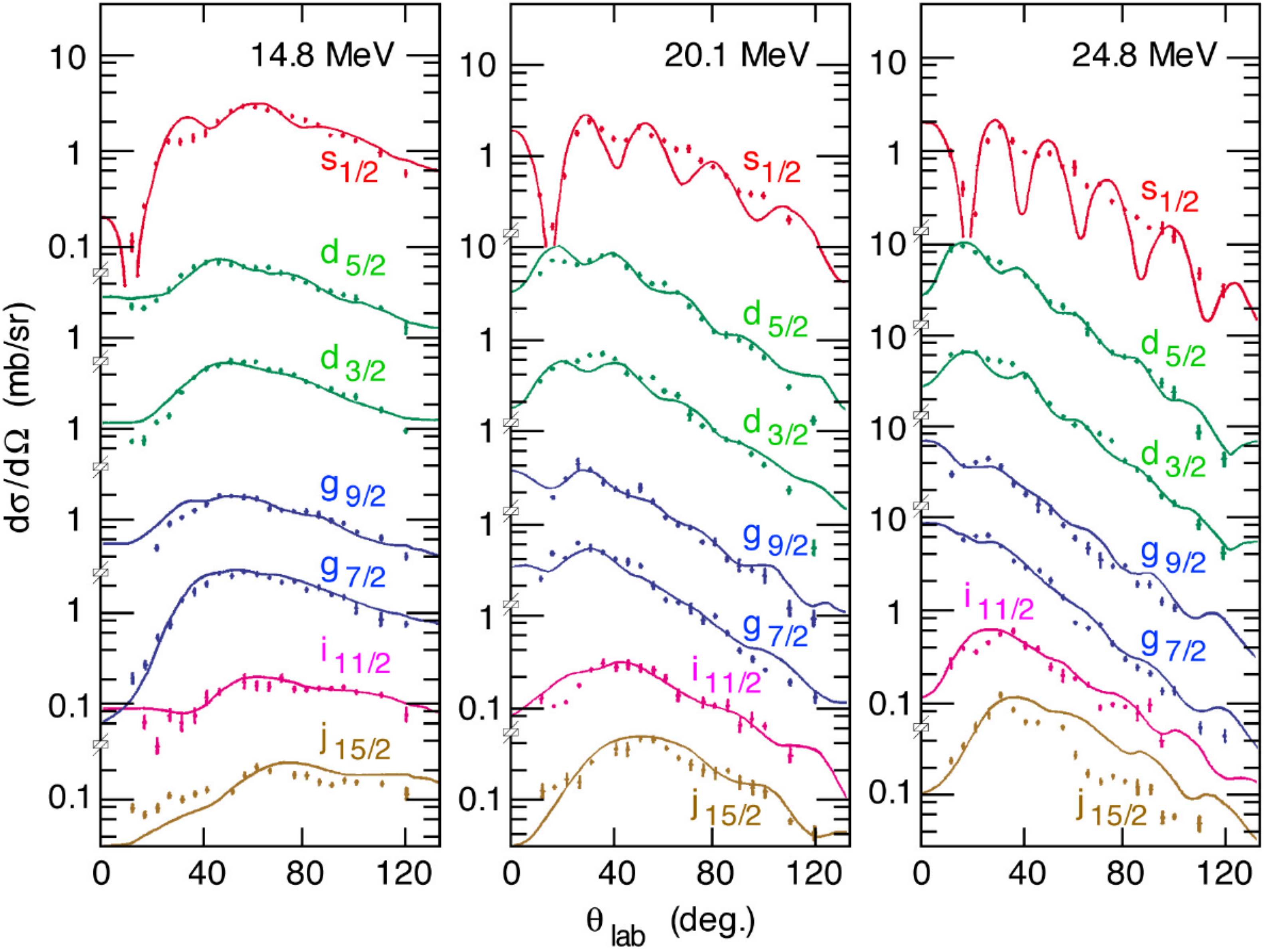
Neutron and Proton Single-Particle States Built on ^{208} Pb







$^{208}Pb(d, p)^{209}Pb$



Muehllener et al.
Phys. Rev. 159, 1043 (1967)

Momentum matching

The peaks in angular distributions occur roughly when the **momentum transfer**

$$q \equiv \left|\vec{k}_f - \vec{k}_i\right| \approx R/\ell$$

where R is the radius of the interaction region and ℓ is the transferred orbital angular momentum.

But momentum matching is important, more generally. Q-values in (α,^{3}He) reactions, for instance, are ~20 MeV more negative than in (d,p) reactions, and energies have to be higher because of Coulomb effects, the values of q will be larger and thus higher l-values favored and low ones are mismatched at all angles.

Comparisons to (α,^{3}He) (α,t) (^{3}He,α) are good ways to search for high-l states!

Momentum matching is also the reason transfer studies are not very practical at higher energies or with heavy ions – where Q-windows are much sharper.

SUM RULES FOR 1N TRANSFER

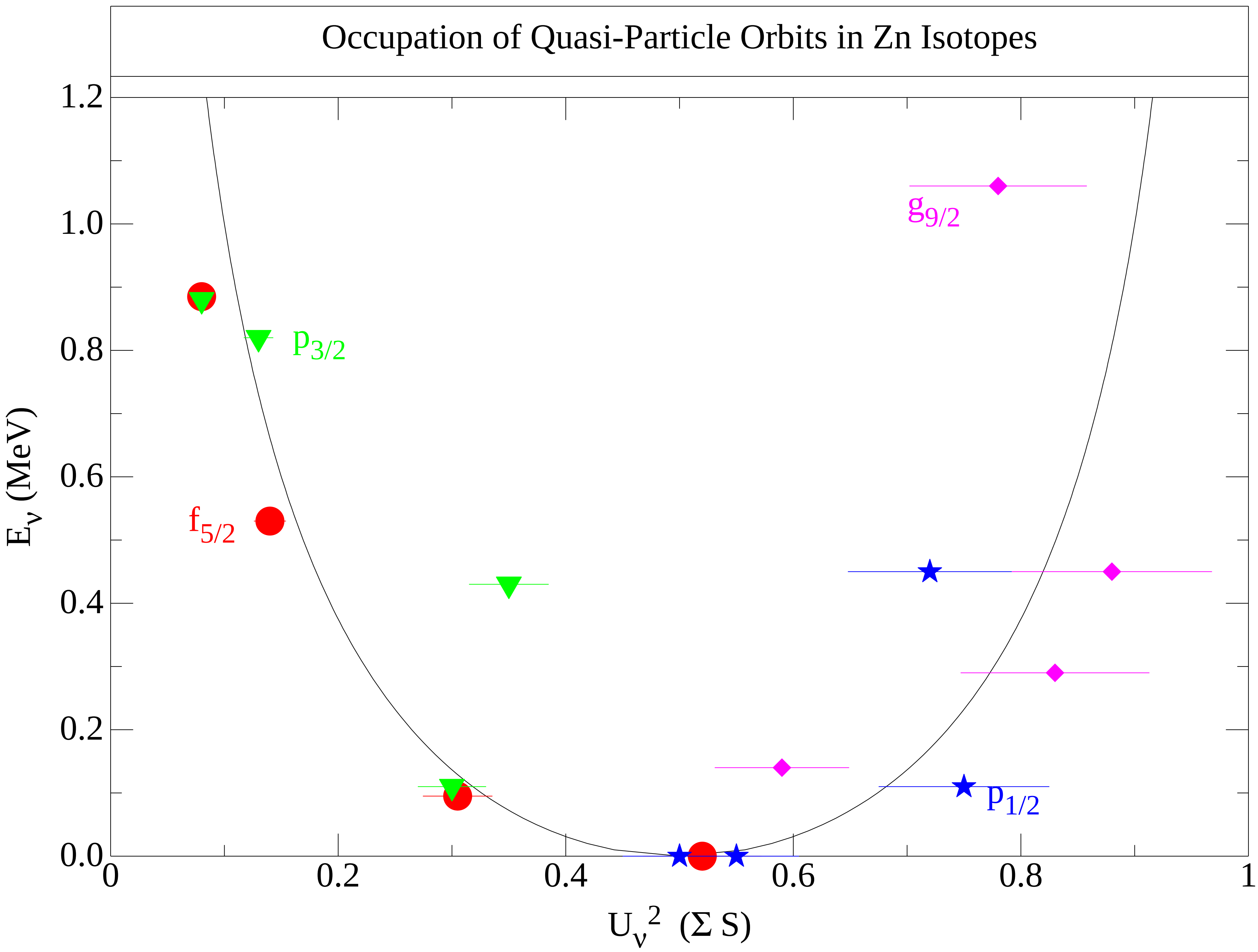
For adding a nucleon to a given j-shell the sum rule gives the vacancy in the shell

$$Number\,of\,Holes = \sum_i \left(\frac{2T_f^i+1}{2T_0+1}\right)\left(\frac{2J_f^i+1}{2J_0+1}\right)S_i$$

for removing a nucleon from a given j-shell it gives the occupancy of the shell, with the sum running over all final states *i*.

$$Number\,of\,Particles = \sum_i \left(\frac{2T_f^i+1}{2T_0+1}\right)S_i$$

Note that only one value of isospin $T_f(=T_0+1/2)$ is allowed for neutron adding or proton removing reactions, and two values $T_f(=T_0 \pm 1/2)$ for neutron removal or proton adding.

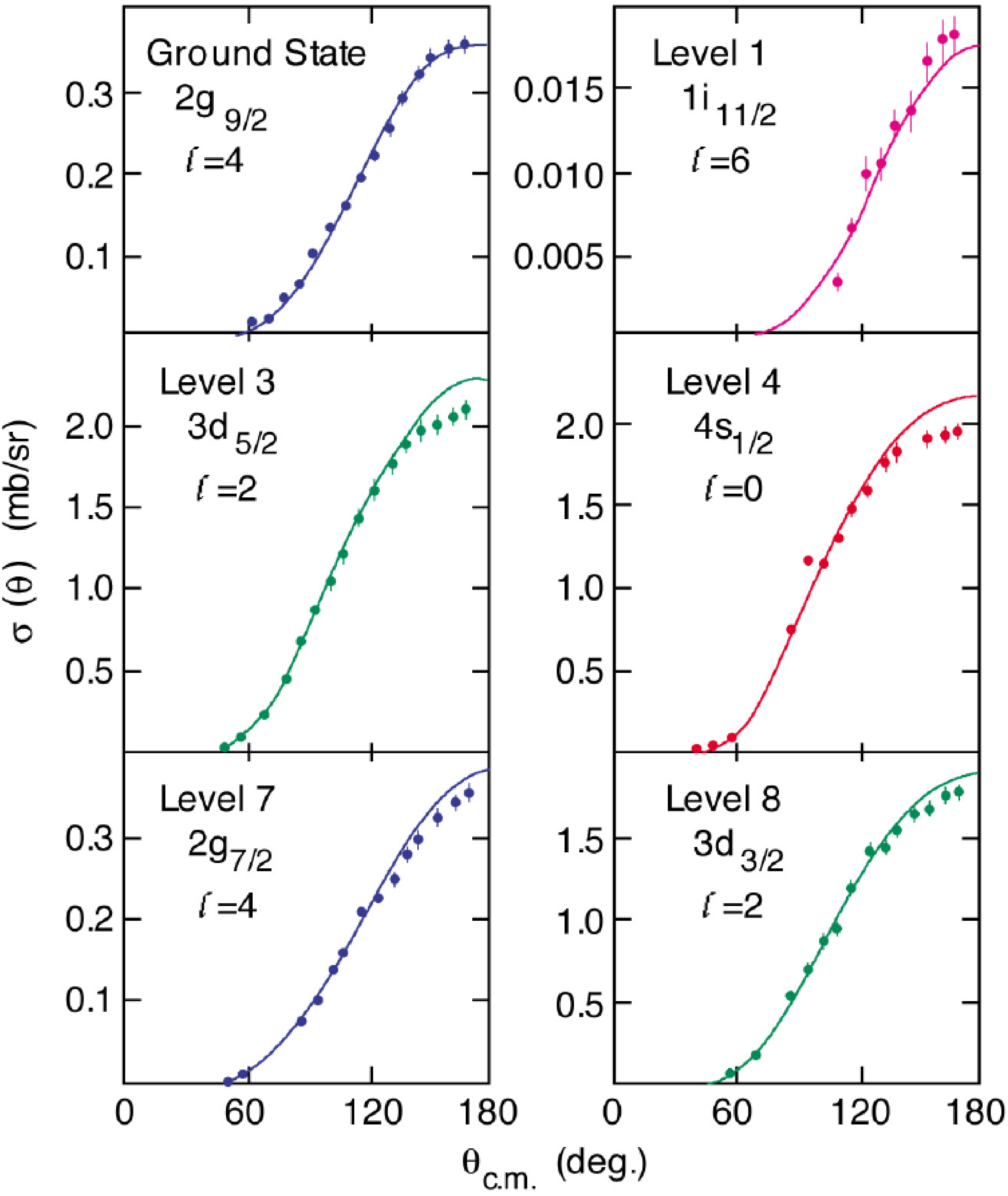

Occupation of Quasi-Particle Orbits in Zn Isotopes
E_ν (MeV)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
1
$U_\nu^{\,2}$ (Σ S)
$g_{9/2}$
$p_{3/2}$
$f_{5/2}$
$p_{1/2}$

Sub-Coulomb Reactions

- Reactions below the Coulomb barrier are particularly simple with backward-peaked trajectories.
- On the other hand, angular distributions are no longer sensitive to l-values
- Spectroscopic factors become sensitive to parameters: e.g. to the radius of the wavefunction of the bound state.
- Near ^{208}Pb $\frac{\Delta S}{S} \cong 12 \frac{\Delta \langle r^2 \rangle}{\langle r^2 \rangle}$
- This means that the bound state parameters have to be known extremely well to extract quantitative spectroscopic factors.
- But they are generally **not** so well known, because small differences in the geometry of the bound-state well (e.g. diffuseness, or spin-orbit geometry) can make a big difference. Thus, uncertainties in spectroscopic factors

will be considerably larger at sub-Coulomb energies than at 5-10 MeV/u.

$^{208}Pb(d,p)^{209}Pb$ $E_d = 8$ MeV



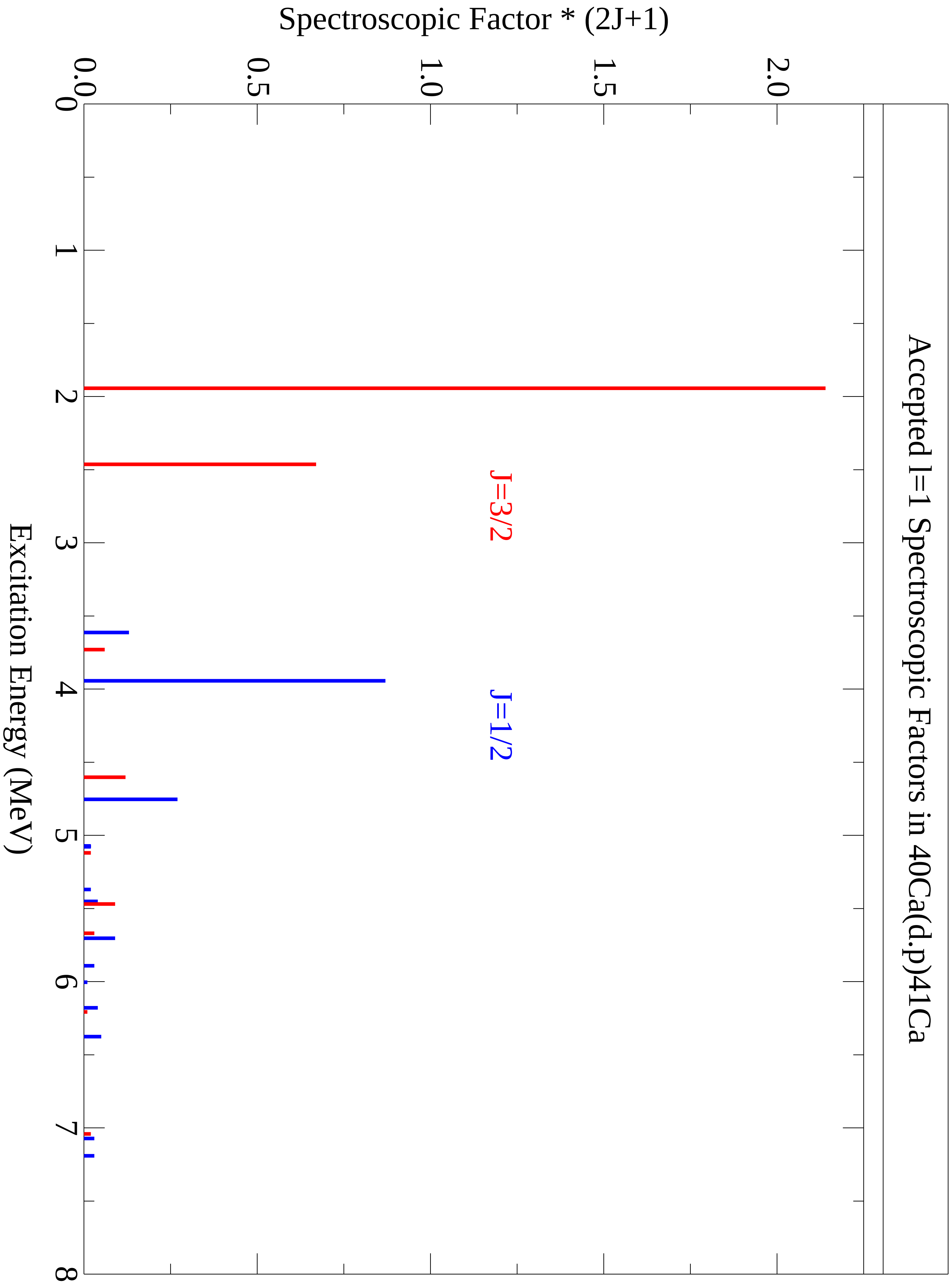
Jeans et al.
NP A128, 230 (1969)

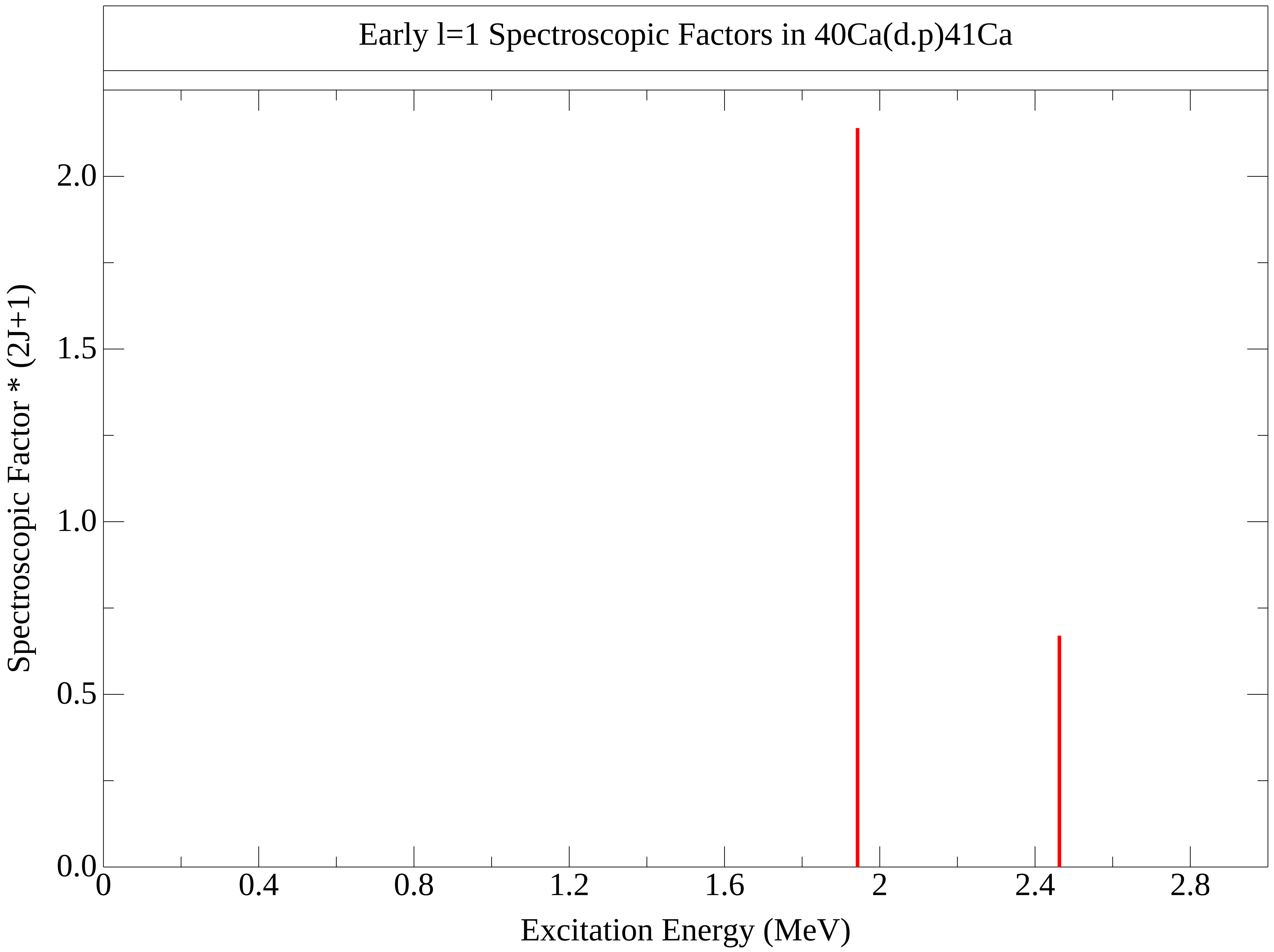
Cautions in using DWBA

- A common fallacy is that one has to measure elastic scattering on the particular nuclei to do a 'correct' DWBA

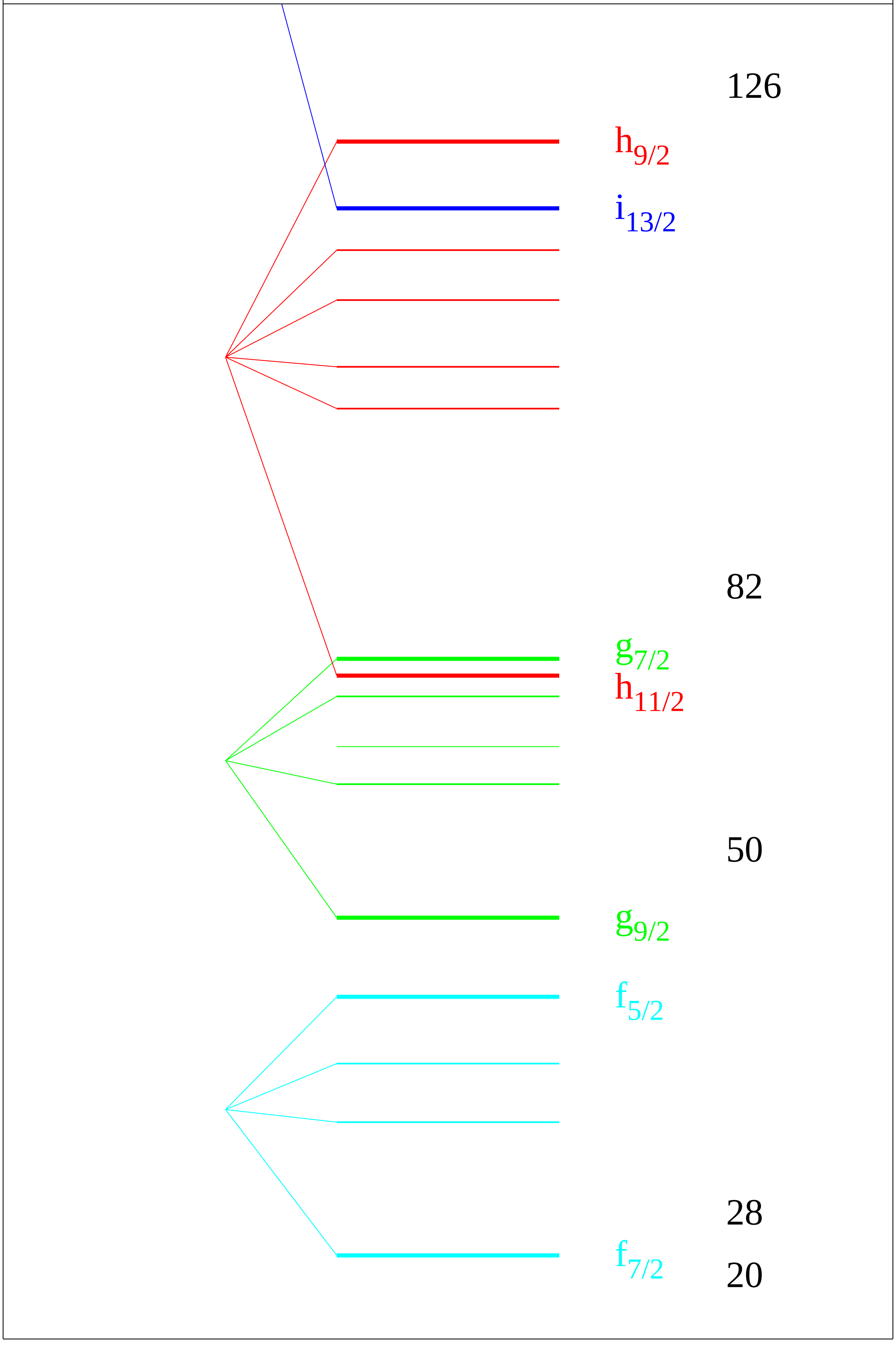
  This is <u>wrong</u>! Choice of distorting potentials should represent <u>averages</u> for that vicinity of nuclei; using specially fitted parameters causes troubles. A number of cases where poor results were extracted from good data by this misunderstanding.

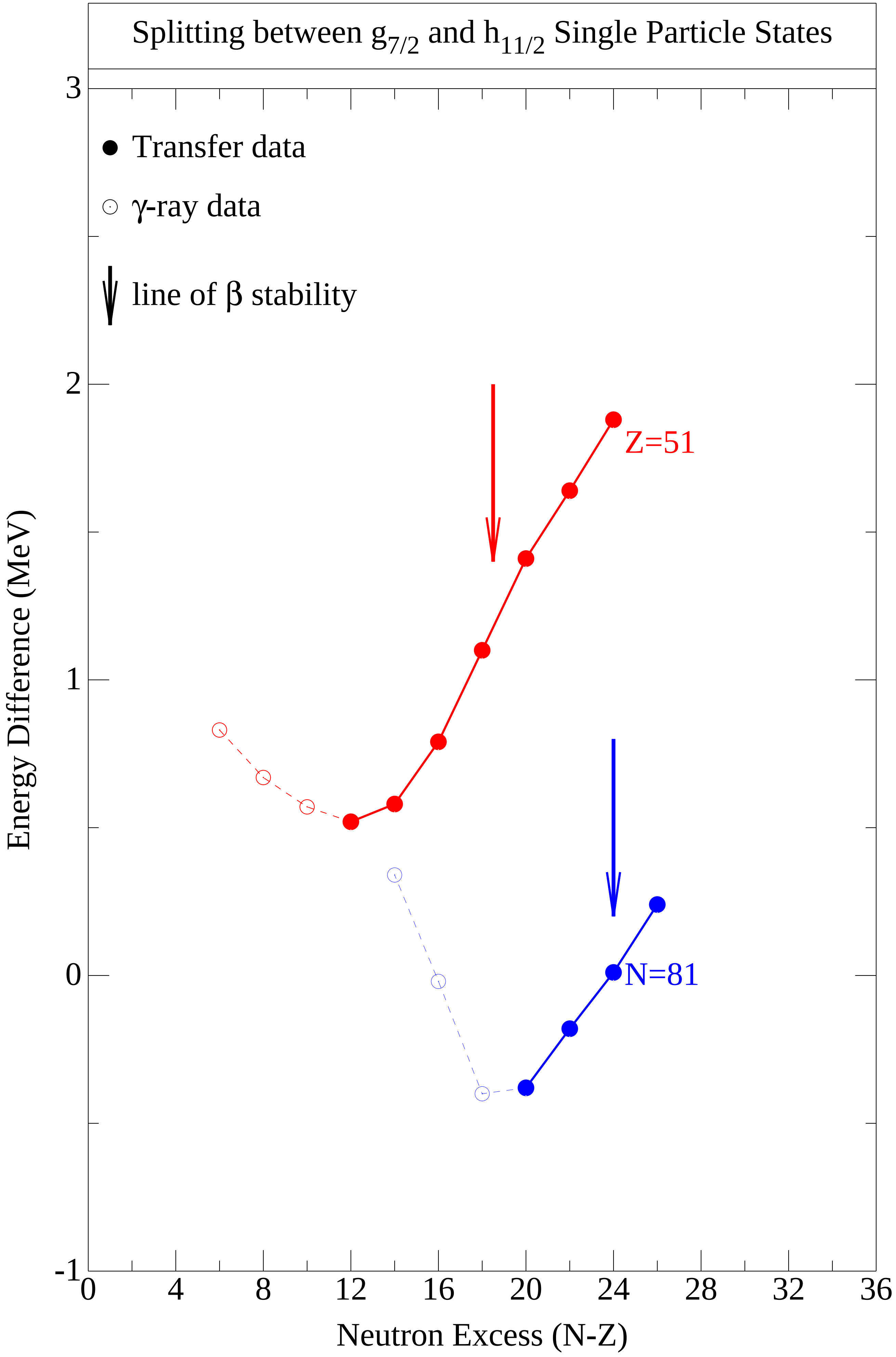
- If the calculations are sensitive to the interior form-factor then there is a problem.
- For small cross sections (mismatched in momentum or small spectroscopic factors) more complicated mechanisms (coupled channels, etc) can become significant and the results ambiguous.


Accepted l=1 Spectroscopic Factors in 40Ca(d.p)41Ca
Spectroscopic Factor * (2J+1)
0.0
0.5
1.0
1.5
2.0
Excitation Energy (MeV)
0
1
2
3
4
5
6
7
8
J=3/2
J=1/2


Early l=1 Spectroscopic Factors in 40Ca(d.p)41Ca
Spectroscopic Factor * (2J+1)
0.0
0.5
1.0
1.5
2.0
0
0.4
0.8
1.2
1.6
2
2.4
2.8
Excitation Energy (MeV)

Schematic Single-Particle Levels




Splitting between $g_{7/2}$ and $h_{11/2}$ Single Particle States
● Transfer data
○ γ-ray data
line of β stability
Z=51
N=81
Energy Difference (MeV)
Neutron Excess (N-Z)
3
2
1
0
-1
0
4
8
12
16
20
24
28
32
36

Some Examples on Stable Nuclei with Implications to Unstable Region

Single Particle states: Investigate the splitting between the $h_{11/2}$ and $g_{7/2}$ states in Z=51 and N=81 nuclei.

Two-body interaction: Look at pp, ph, hh nuclei near doubly closed shells.

Occupation of Quasi-Particle Orbits: Use summed spectroscopic factors to determine occupation numbers in a string of isotopes.

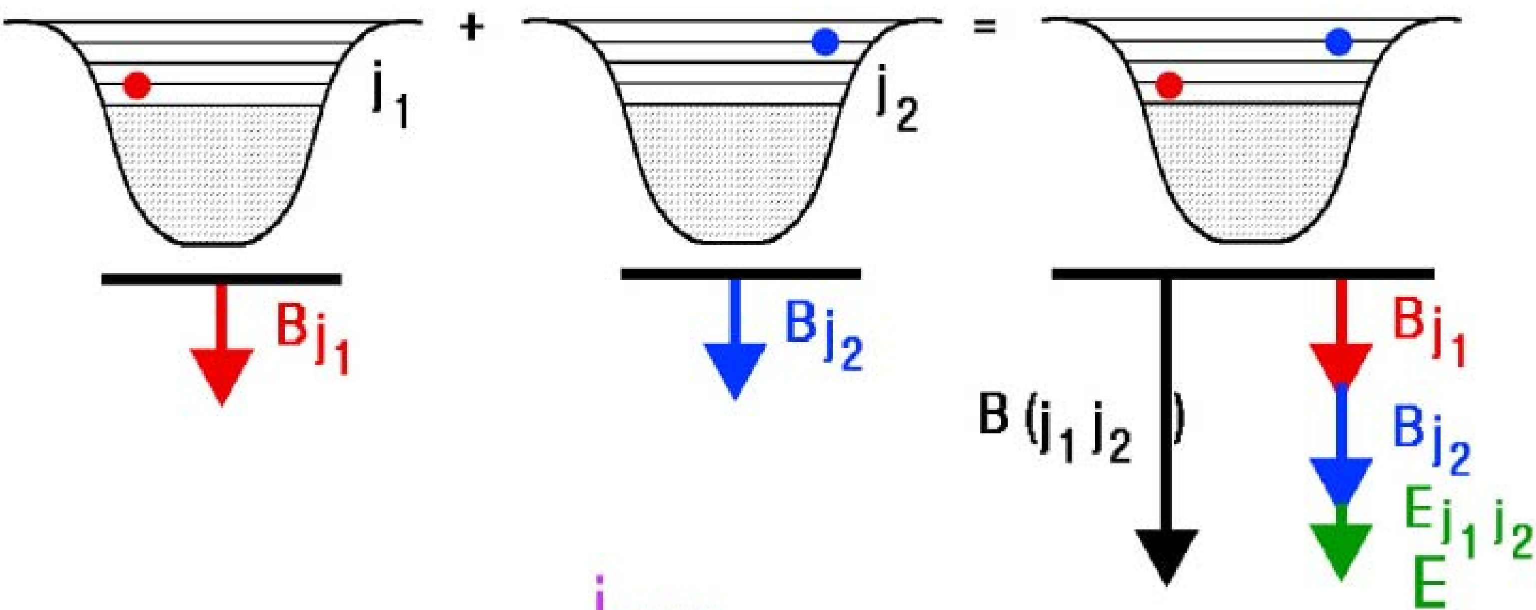
Another look at Stable Nuclei?
There are many things on stable nuclei that could be done better, in part to sharpen our tools for unstable ones. (e.g. s.p. states in Sb isotopes were done 35 years ago at one lab with poor resolution).

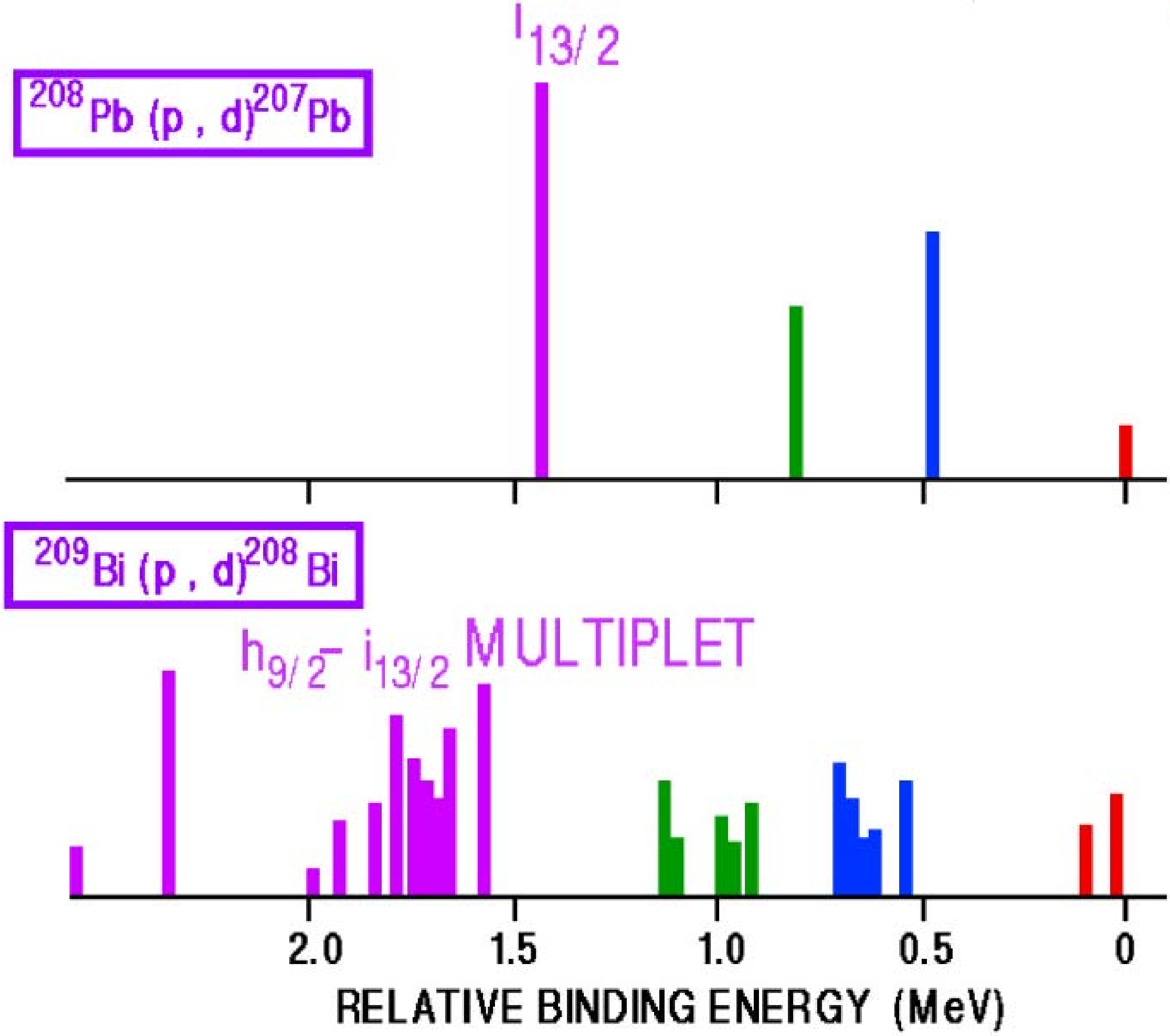
Summary of Transfer Data on Proton States in Sb Isotopes

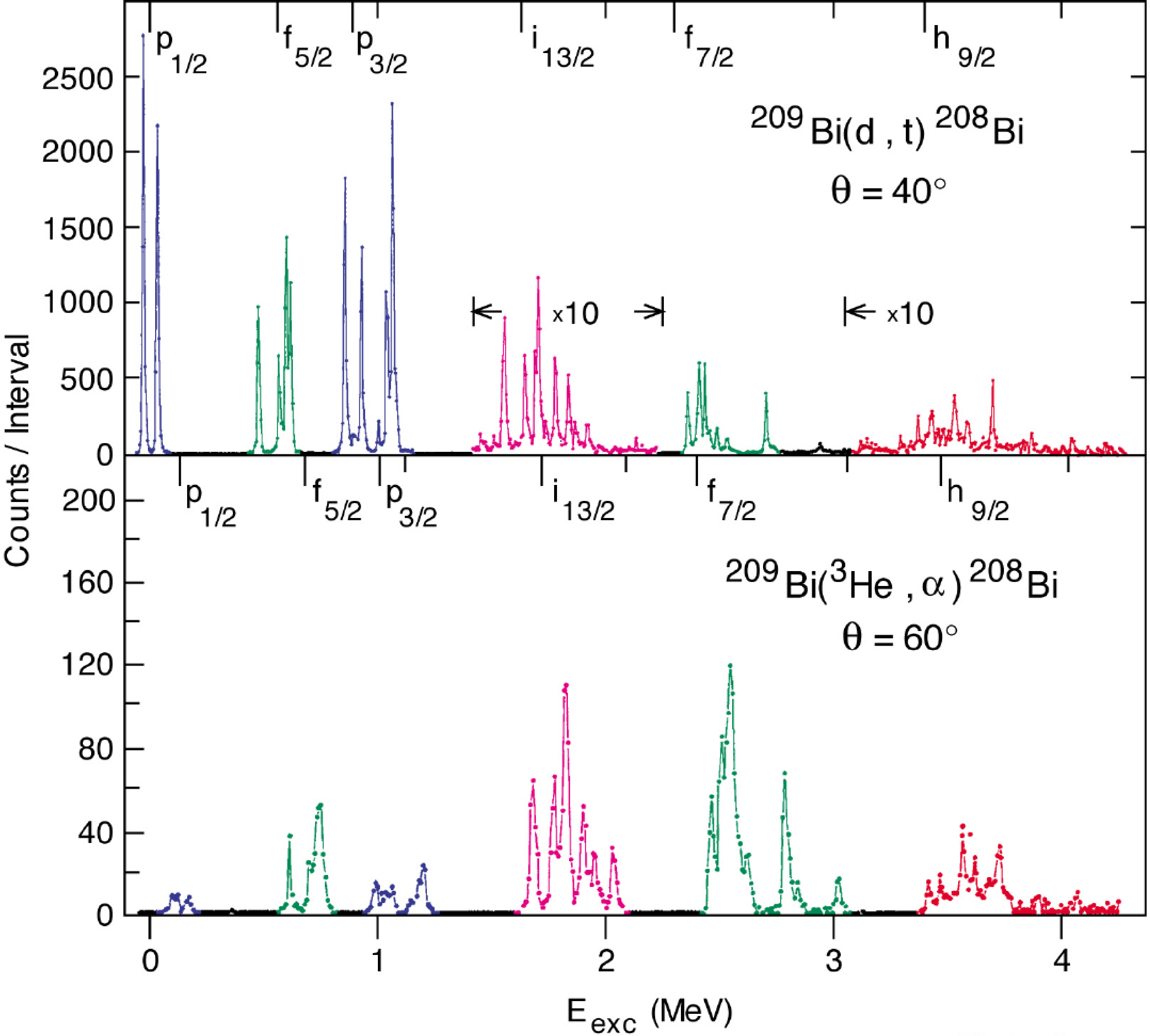
Isotope	**Ref.**	**$E_{3He}/\Delta E$**	**$S_{g7/2}$(8)**	**$S_{h11/2}$(12)**
^{113}Sb	Co68	18/.1	**7.5**	**4.8**
^{115}Sb	Ka78	30/.045		
^{117}Sb	Co68		**6.5**	**6.3**
^{119}Sb	Is67	28/.08	**5.3**	**12**
^{121}Sb	Is67		**--**	**13**
^{123}Sb	Co68		**6.7**	**5.9**
^{125}Sb	Au67	25/.025	**6.3**	**9-14**

4 different experiments:
different energies,
different resolution,
different DWBA procedures

Not clear whether differences (e.g. in $S_{h11/2}$) are real.


+
=
j_1
j_2
B_j1
B_j2
B (j_1 j_2)
B_j1
B_j2
E_j1 j2
E


i_13/2
208Pb (p , d)207Pb
209Bi (p , d)208Bi
h_9/2 – i_13/2 MULTIPLET
2.0
1.5
1.0
0.5
0
RELATIVE BINDING ENERGY (MeV)



Alford et al.
PRL 3 860 (1970)

CONCLUSIONS

- There is a rich area in nuclei away from stability for transfer reactions, the **only** technique for mapping out the single-particle degree of freedom.
- There are a few cases that can be addressed now – and continue sharpening techniques for low-intensity beams.
- Some of what was 'well known' may get lost between generations and will have to be re-learned and refined.
- There are still significant questions that need to be revisited on stable nuclei.
- These are the first steps in our major quest to explore a new frontier in nuclear structure that we hope to address with **RIA**. Just as in the 1960-s, transfer reactions are a first crucial step in this quest.