Probing single-particle states with the (t,α) reaction.

Sean J Freeman EP Department, CERN and Department of Physics and Astronomy, the University of Manchester

TRITON 2024 WORKSHOP

Plan of Action

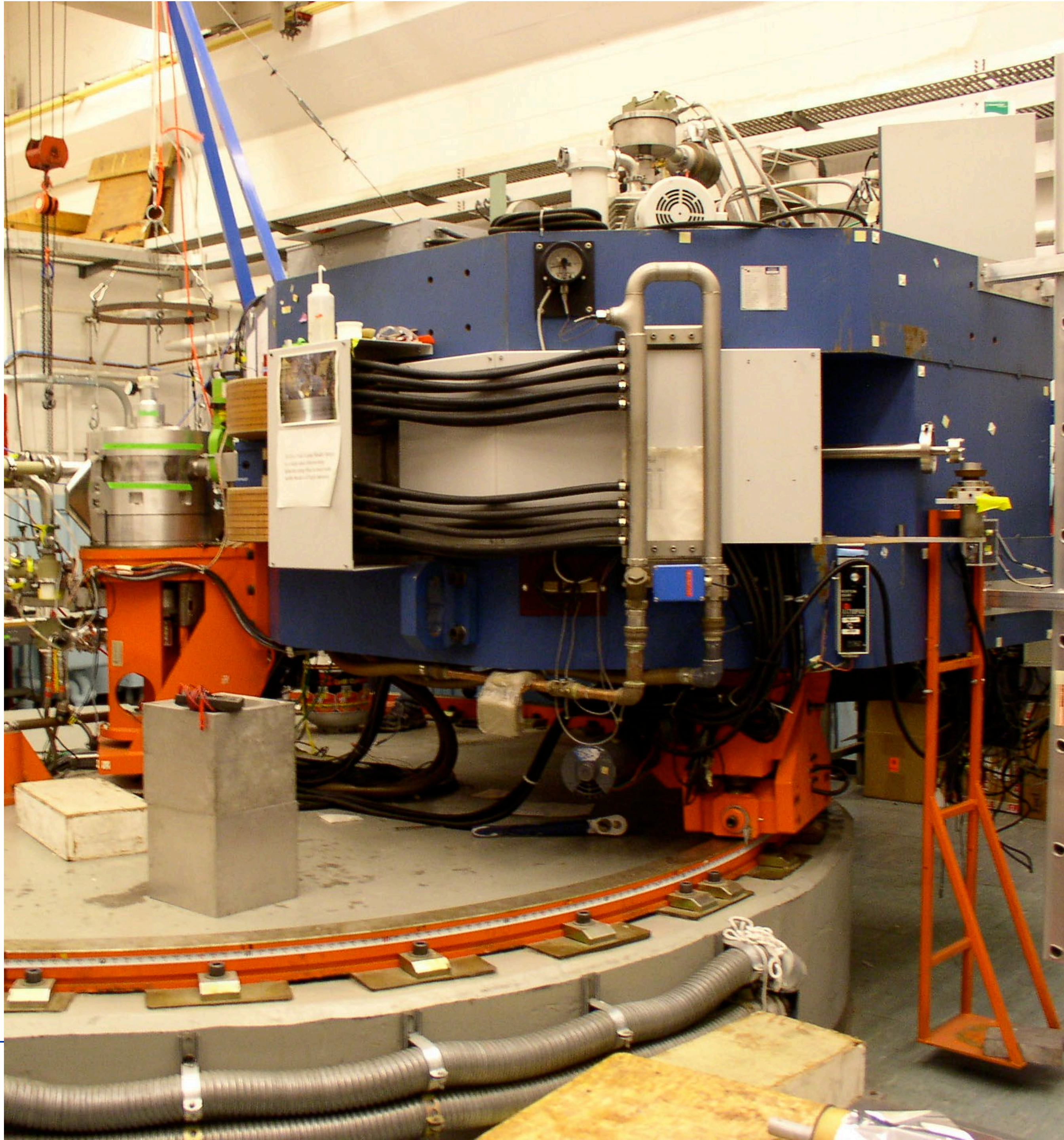
A quick comment about momentum matching.

A couple of examples of (t,α) proton-pickup reaction to complement other direct reactions as a spectroscopic probe of single-particle states:

a) *(t,α) reactions in ancient history:* single-particle basis of M1 modes in rare-earth nuclei.

b) *(t,α) reactions at FSU:* single-hole states below the Z=50 shell closure:

- Sn(α,t) – Yale Split Pole
- Sn(d,p)/(α,t) and Sn(p,d)/(t,α) – Munich Q3D
- Sn(t,α) – Florida State Split Pole



Momentum matching in transfer reactions

Classical cartoon:

L= r x p

Orbital angular momentum transfer ℓ is related to the linear momentum transfer *q* and the radius of the reaction, such that ℓ≈qr.

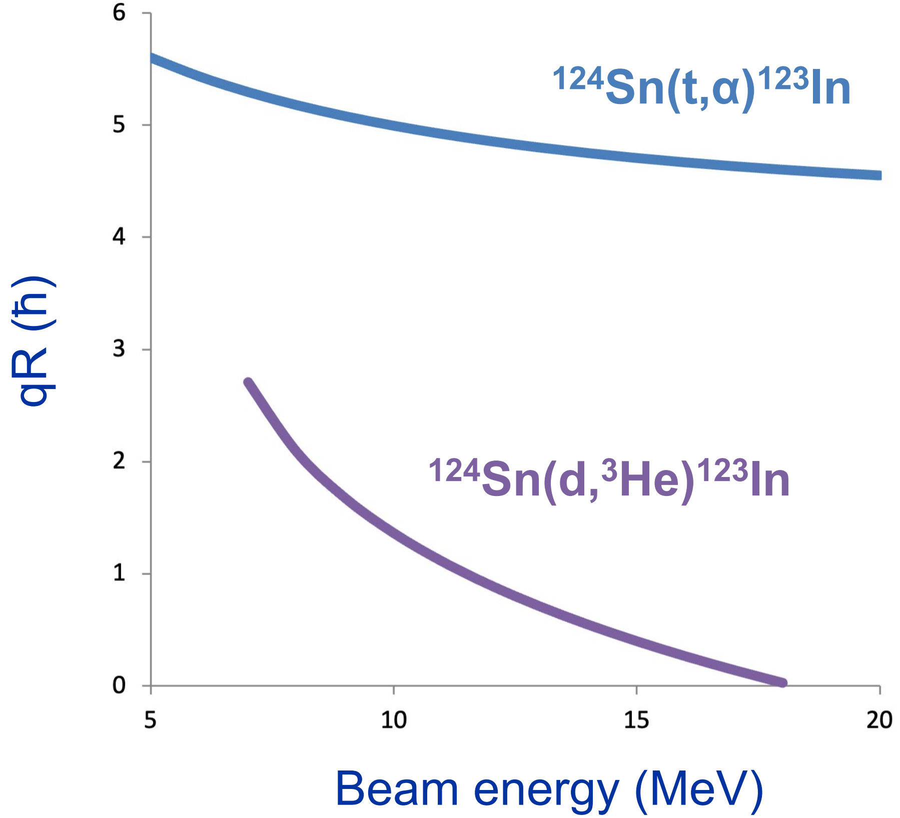
Direct transfer reactions mainly occur close the nuclear surface so ℓ≈qR.

Energetics and the Q value of the reaction determines q and therefore dictates the momentum matching. Reactions with large |Q| tend to be better matched for higher ℓ transfer.

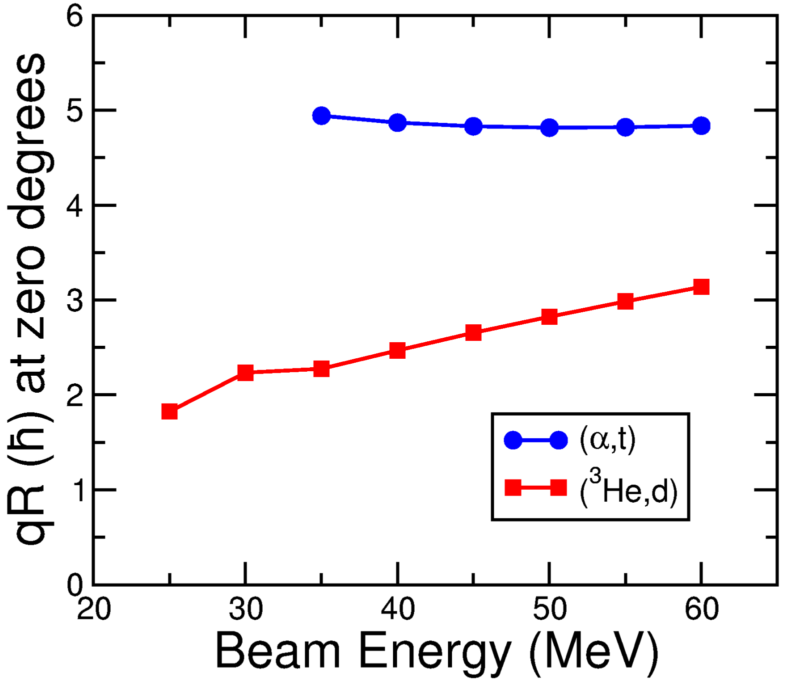
Classical cartoon reflected in DWBA calculations and in experimental data….

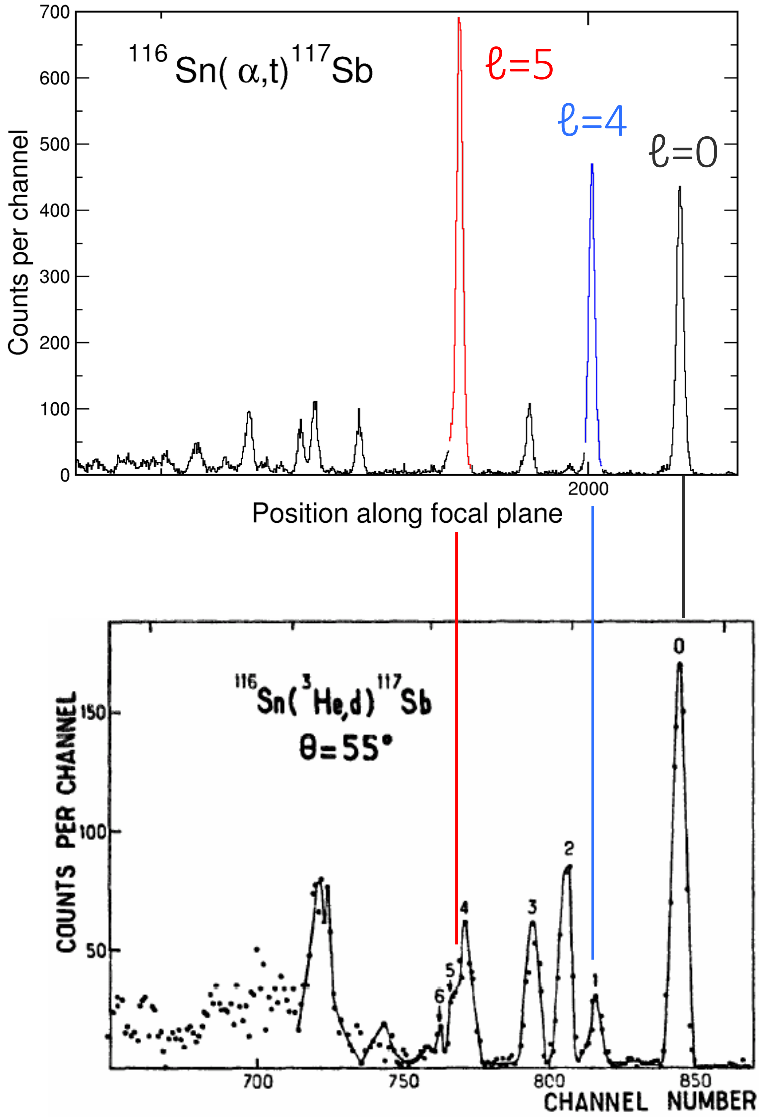
Example:

Across the Sn isotopes, (t,α) has Q values around 14 MeV more positive than (d,^{3}He), leading to matching at higher ℓ transfer.



Illustrating with some data for the inverse reactions, (α,t) and (3He,d).

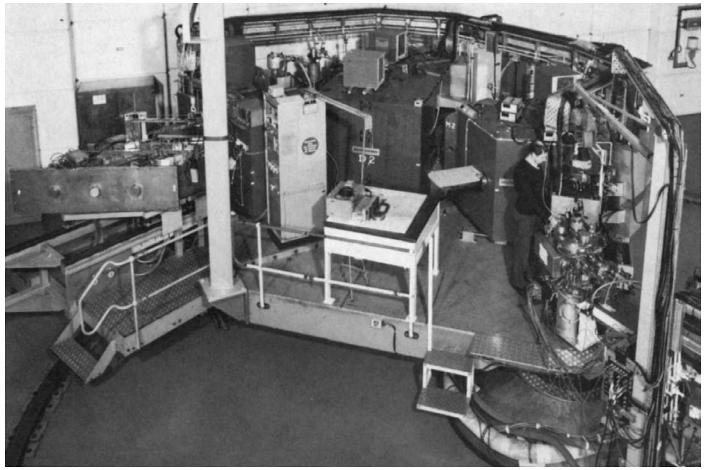


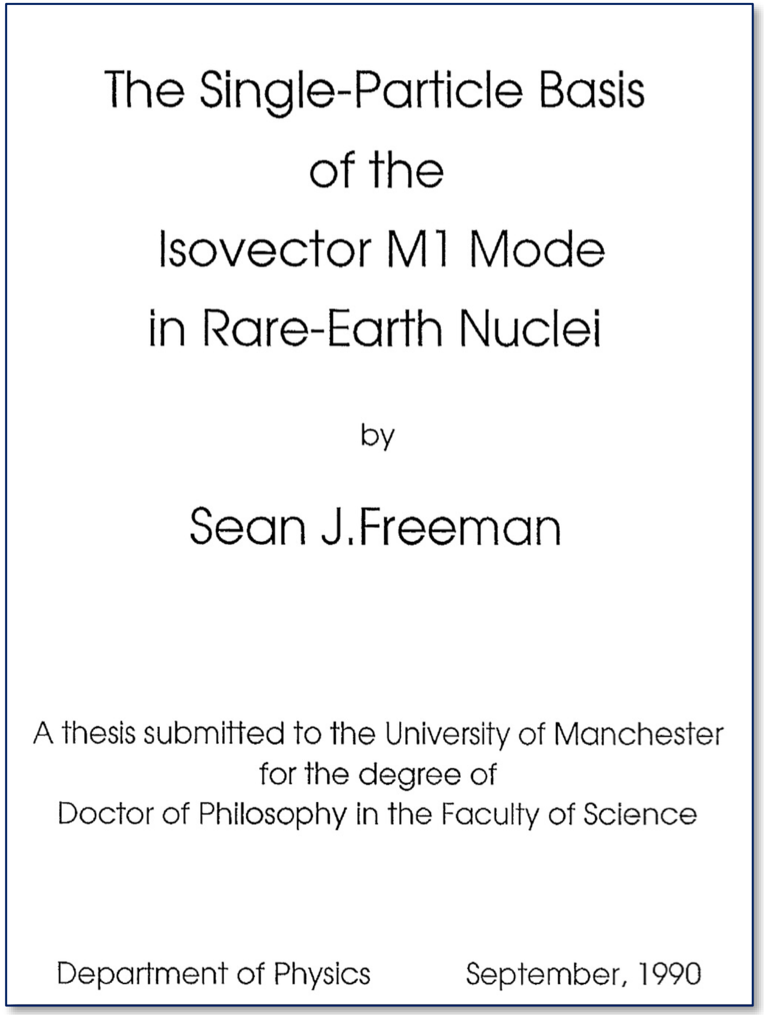


(α,t) and (t,α) reactions enhance large ℓ transfers needed to probe high-j single particle states.

Example 1 of (t,α)

Journey Back in Time…




The Single-Particle Basis
of the
Isovector M1 Mode
in Rare-Earth Nuclei

by

Sean J.Freeman

A thesis submitted to the University of Manchester
for the degree of
Doctor of Philosophy in the Faculty of Science

Department of Physics September, 1990

Tritium beam at energies of up to 40 MeV.

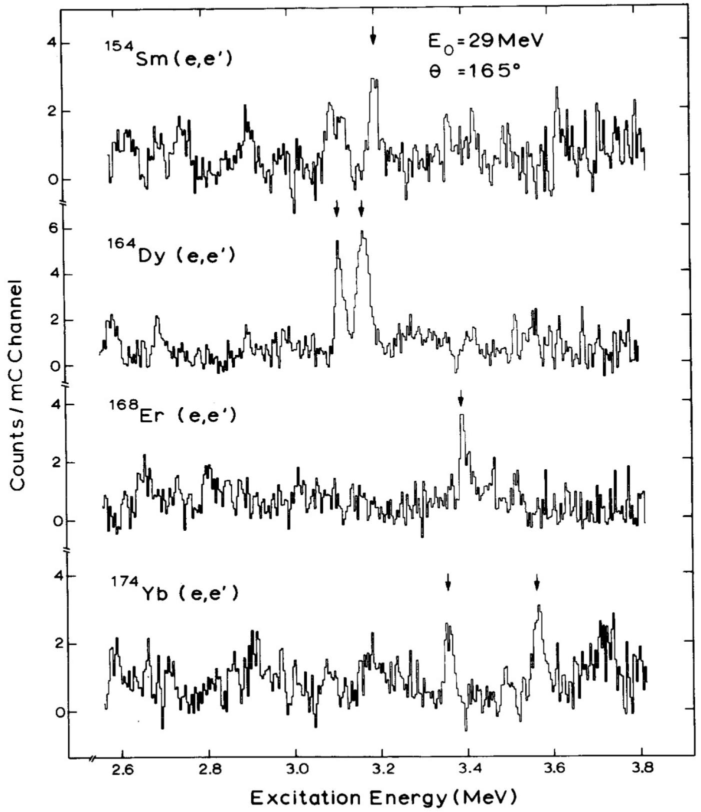
M1 strengths and scissors modes

At the time interest in 1+ states excited with large M1 transitions in (e,e’) and (γ,γ’) reactions in rare earth nuclei..

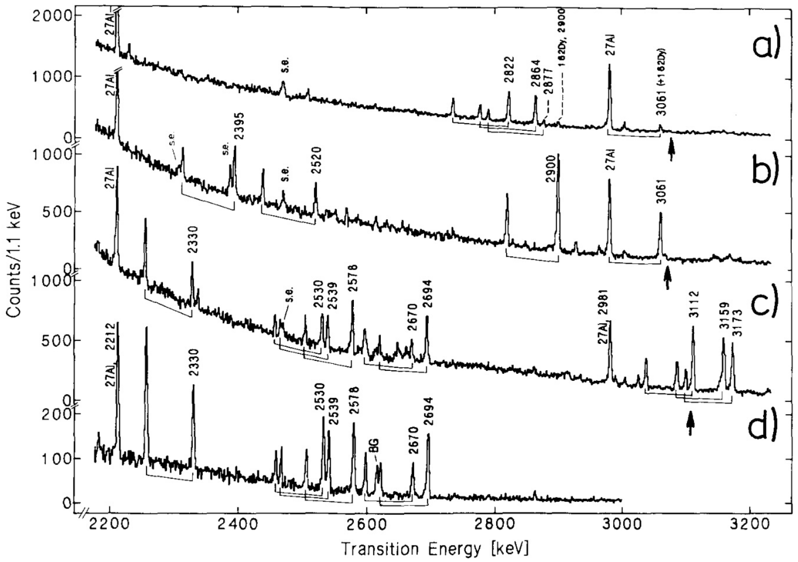
Interpreted as scissors mode – rotational vibrations of deformed proton and neutron distributions generating a large orbital current. First predicted in two-rotor models and then in IBM.

QRPA calculations suggested large M1 transition strength from motion of high- ℓ orbitals..e.g. $h^2_{11/2}$ proton excitations.

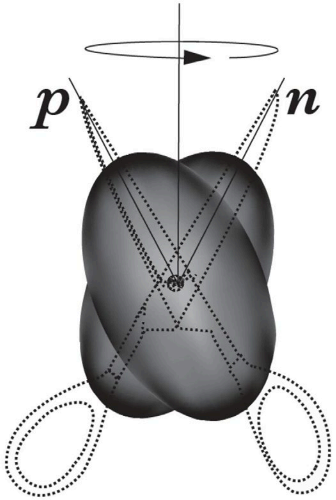
Hamamoto and Aberg, PLB 145 163 (1984)



Bohle et al., PLB 148, 260 (1984)

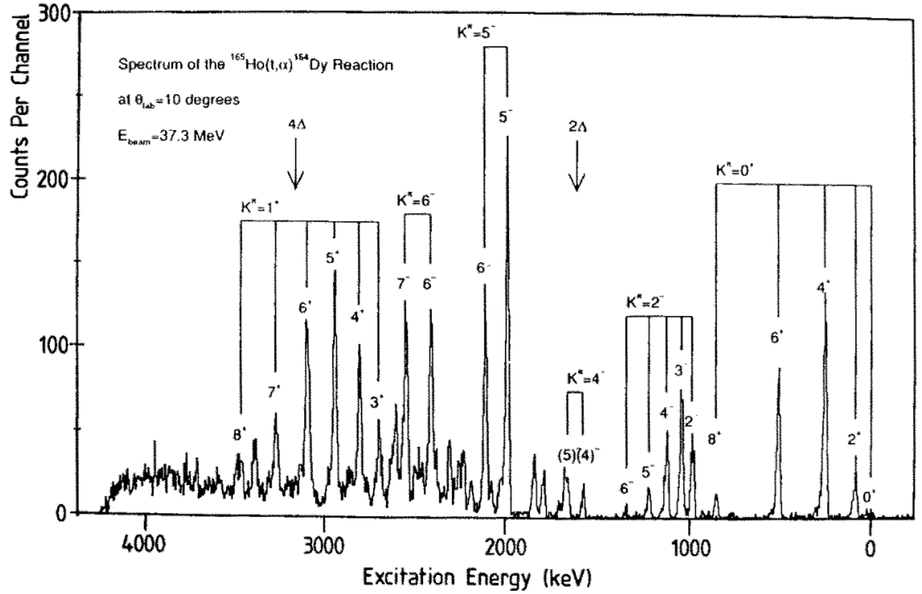


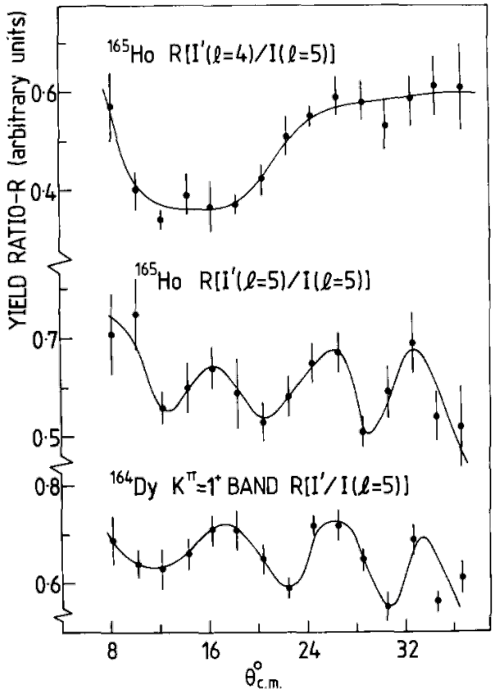
Wesselborg et al., PLB 207, 22 (1989)

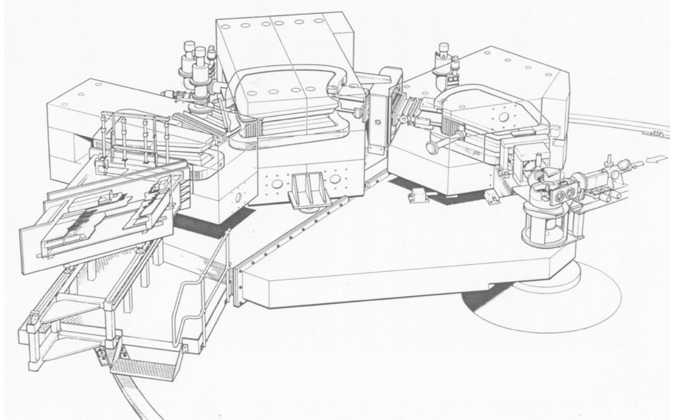


Lo Iudice and Palumbo, PRL 41, 1532 (1978)

Iachello, PRL 53, 1427 (1984)



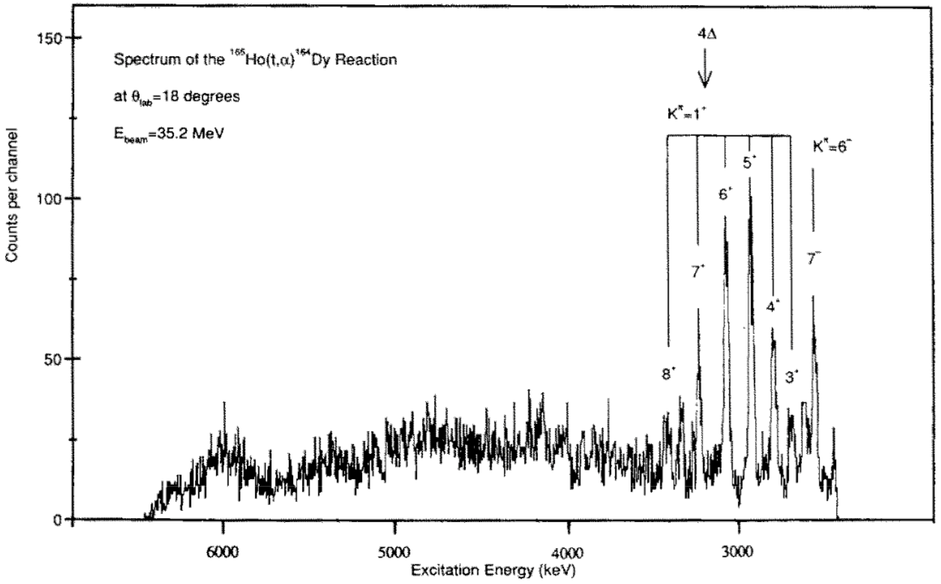


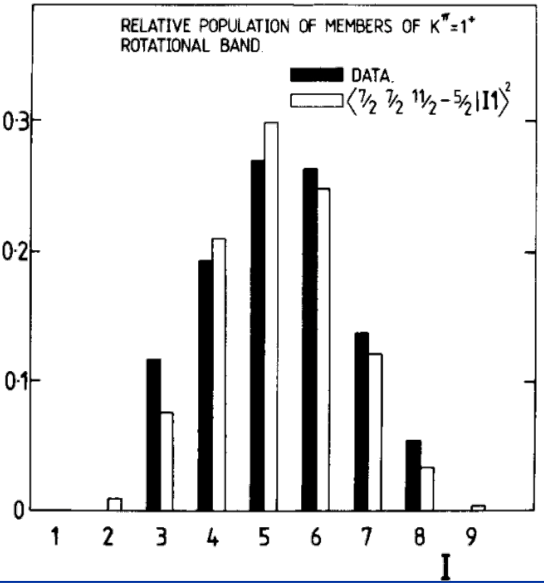


Harnessed (t,α) reactions on odd-Z rare earth nuclei with odd proton in Nilsson state with large $h_{11/2}$ or $g_{7/2}$ parentage.

^{165}Ho(t,α)^{164}Dy @ 37.3 MeV.

^{175}Lu(t,α)^{174}Yb @ 35.5 MeV.





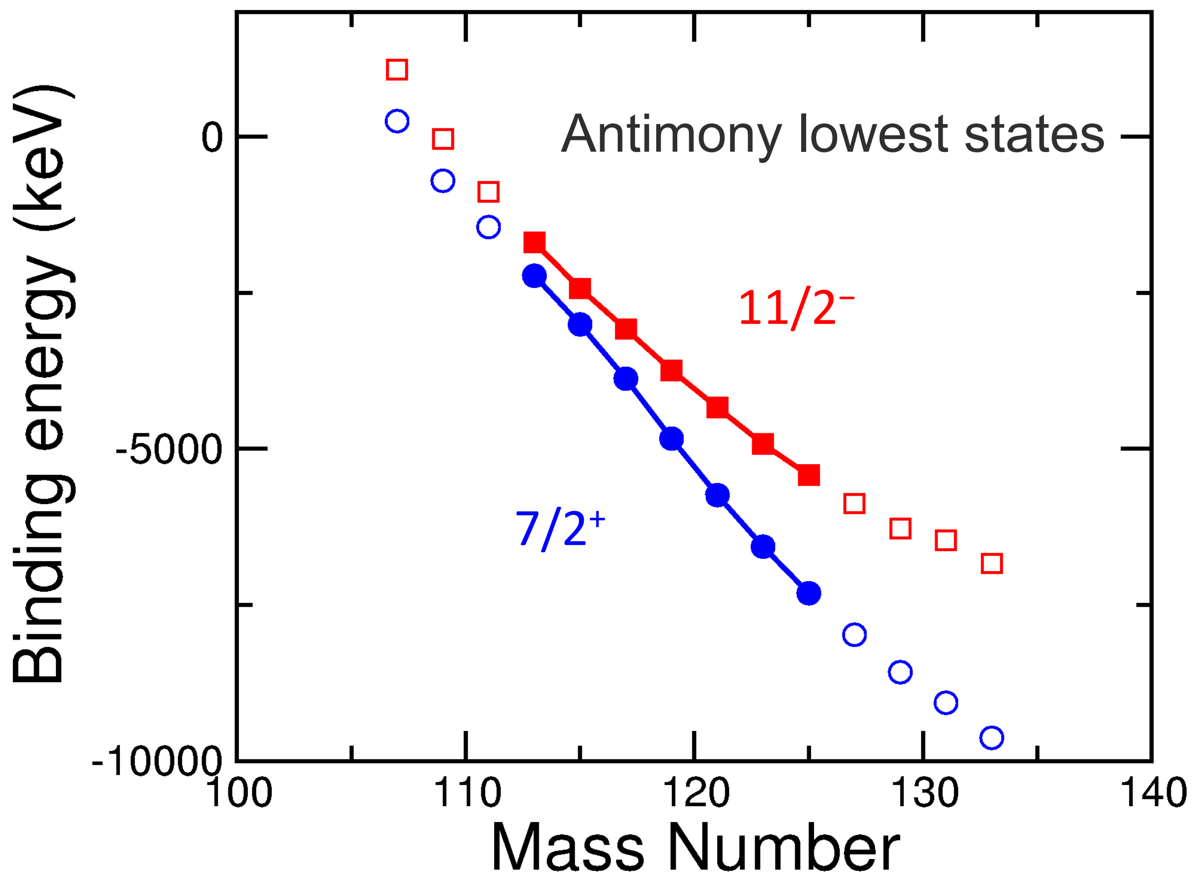
Populated sequence of states with experimental characteristics consistent with an $h^2_{11/2}$ two quasi-proton band. Band head energy consistent with a 1^+ state seen in (γ,γ′).
And lots of other spectroscopy in ^{174}Yb and ^{164}Dy.

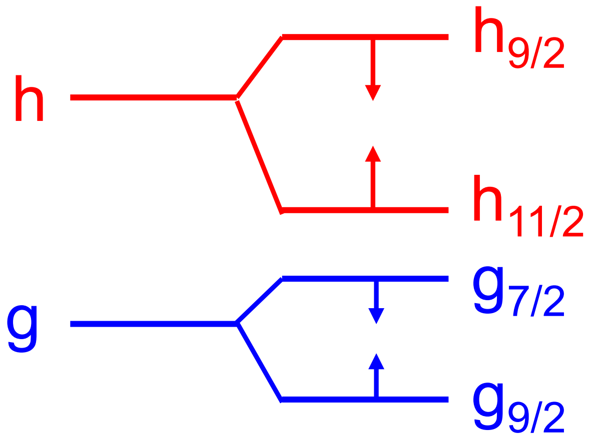
Freeman et al., PLB 222, 347 (1989)
Freeman et al., NPA 554, 333 (1993)
Freeman et al., NPA 552, 10 (1993)
Heyde, De Coster, Rombouts, Freeman, NPA 596, 30 (1996)

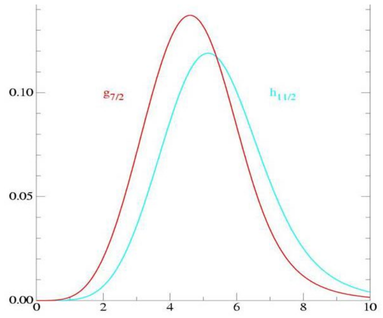
Example 2 of (t,α)

Skip onwards 12 years…
…and start with a bit of context

Systematics of low-lying proton states outside the Sn core.







VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

J. P. Schiffer,[1] S. J. Freeman,[1,2] J. A. Caggiano,[3] C. Deibel,[3] A. Heinz,[3] C.-L. Jiang,[1] R. Lewis,[3] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] S. Sinha,[1] and J. S. Thomas[4]
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(Received 17 December 2003; published 20 April 2004)

PRL 95, 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Evolution of Nuclear Shells due to the Tensor Force

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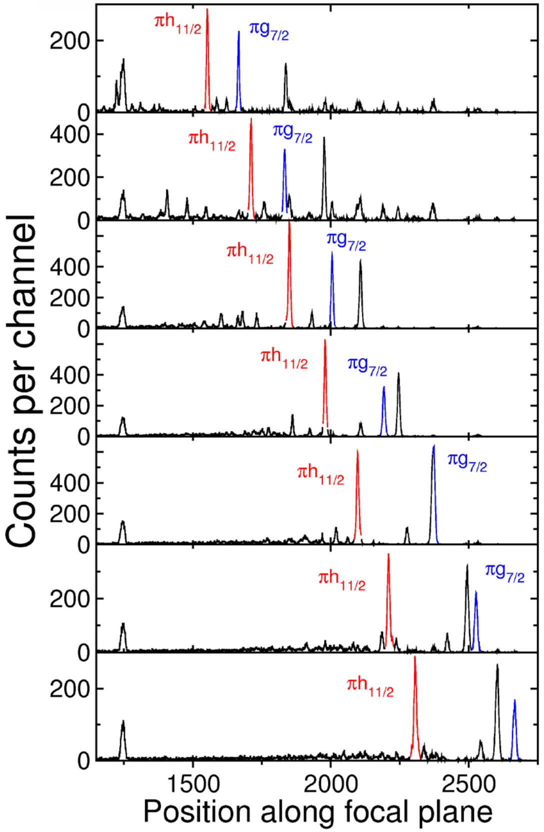
(Received 22 February 2005; published 30 November 2005)

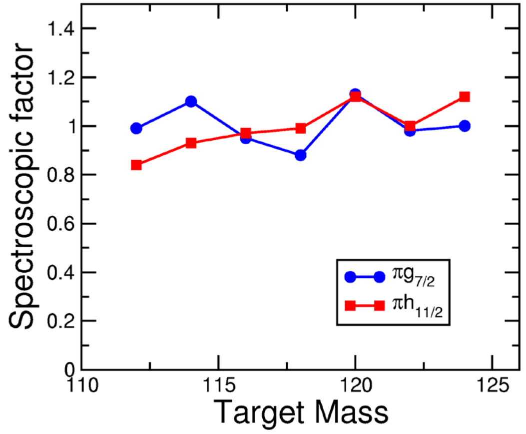


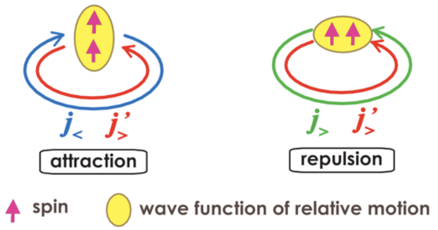
Systematic measurement of protons addition to Sn Z=50:

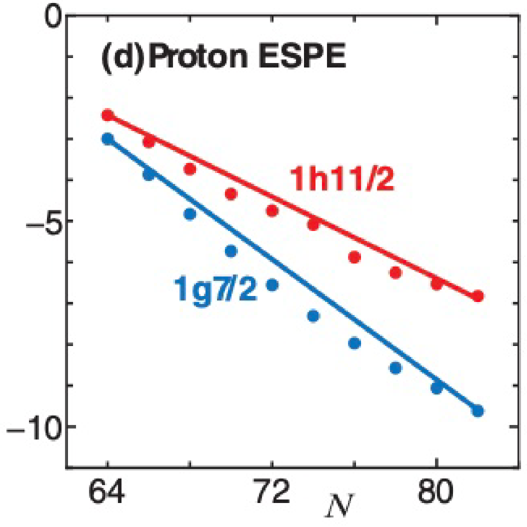
$^{112-124}$Sn(α,t)$^{113-125}$Sb @ 40 MeV.

Yale Split-Pole Spectrograph

A few well-chosen angles.







PRL **108,** 022501 (2012) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2012

Test of Sum Rules in Nucleon Transfer Reactions

J. P. Schiffer,[1,*] C. R. Hoffman,[1] B. P. Kay,[1,†] J. A. Clark,[1] C. M. Deibel,[1,2,‡] S. J. Freeman,[3] A. M. Howard,[3,§] A. J. Mitchell,[3] P. D. Parker,[4] D. K. Sharp,[3] and J. S. Thomas[3]

PRL **111,** 042502 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

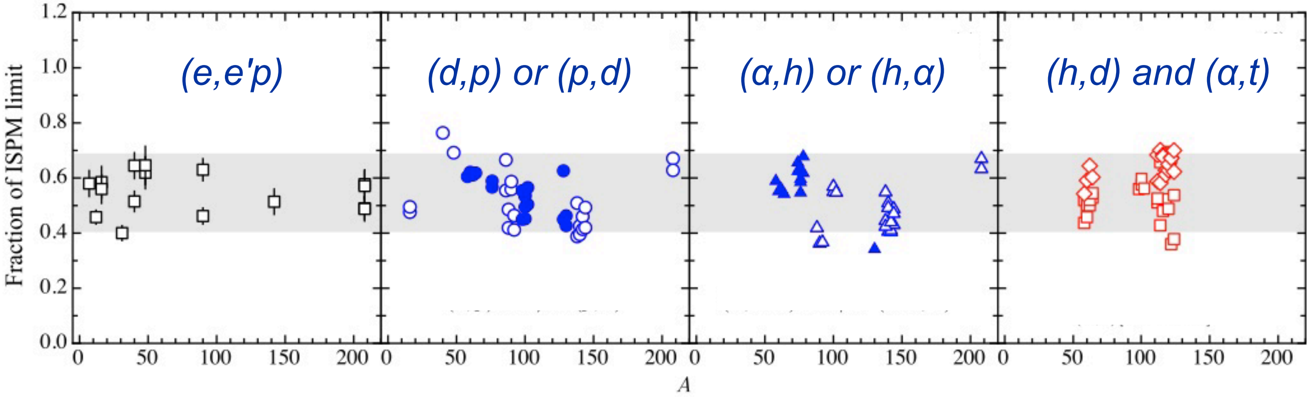
Quenching of Cross Sections in Nucleon Transfer Reactions

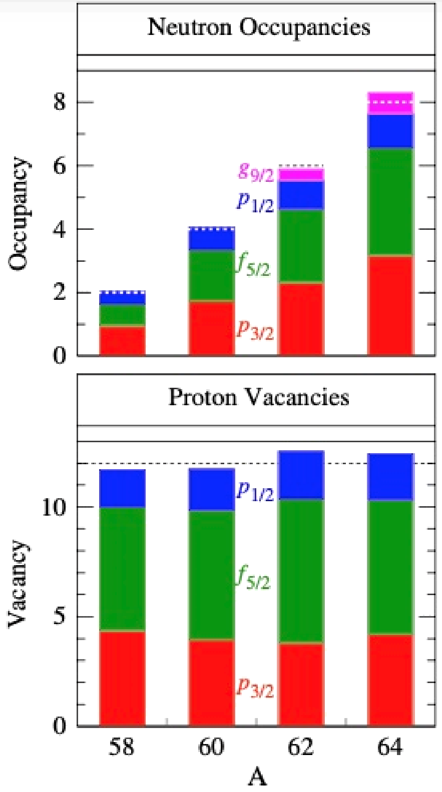
B. P. Kay,[1,2,*] J. P. Schiffer,[1] and S. J. Freeman[3]

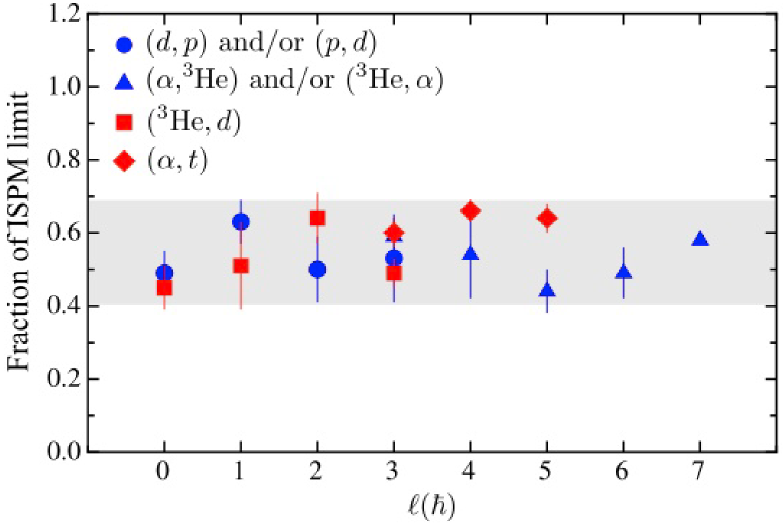
PHYSICAL REVIEW C **87**, 034306 (2013)

Valence nucleon populations in the Ni isotopes

J. P. Schiffer,[1,*] C. R. Hoffman,[1] B. P. Kay,[1,†] J. A. Clark,[1] C. M. Deibel,[1,2,‡] S. J. Freeman,[3] M. Honma,[4] A. M. Howard,[3,§] A. J. Mitchell,[3,∥] T. Otsuka,[5] P. D. Parker,[6] D. K. Sharp,[3] and J. S. Thomas[3]







PHYSICAL REVIEW C **104**, 054308 (2021)

Neutron occupancies and single-particle energies across the stable tin isotopes

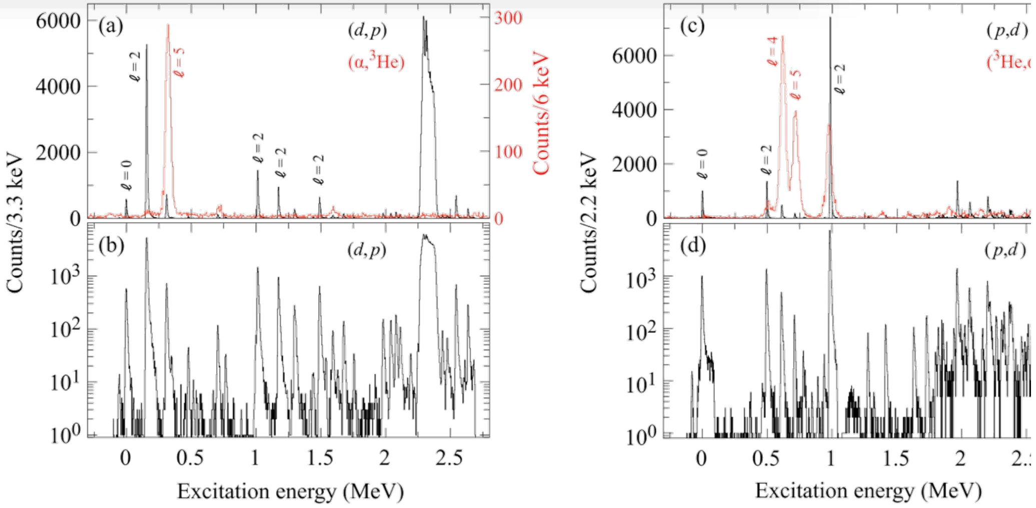
S. V. Szwec,[1,*] D. K. Sharp,[1,†] B. P. Kay,[2,‡] S. J. Freeman,[1] J. P. Schiffer,[2] P. Adsley,[3,§] C. Binnersley,[1] N. de Séréville,[3] T. Faestermann,[4,5] R. F. Garcia Ruiz,[1,‖] F. Hammache,[3] R. Hertenberger,[5,6] A. Meyer,[3] C. Portail,[3] I. Stefan,[3] A. Vernon,[1,‖] S. Wilkins,[1,‖] and H.-F. Wirth[5,6]

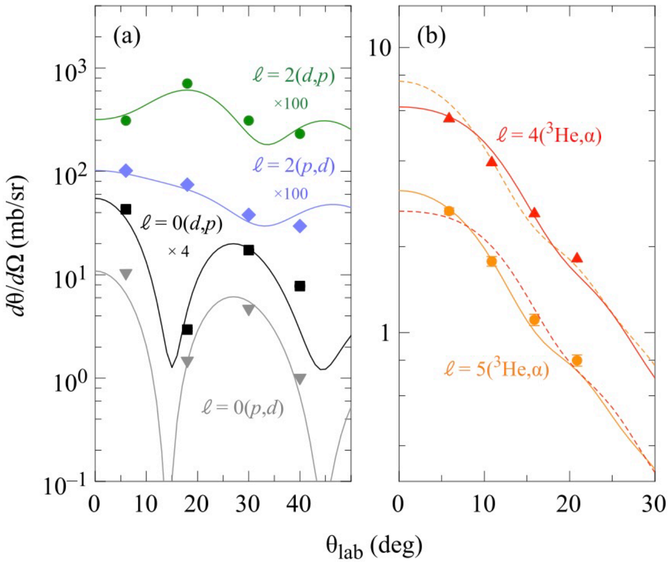
Systematic measurement of neutron addition and removeal on Sn Z=50:

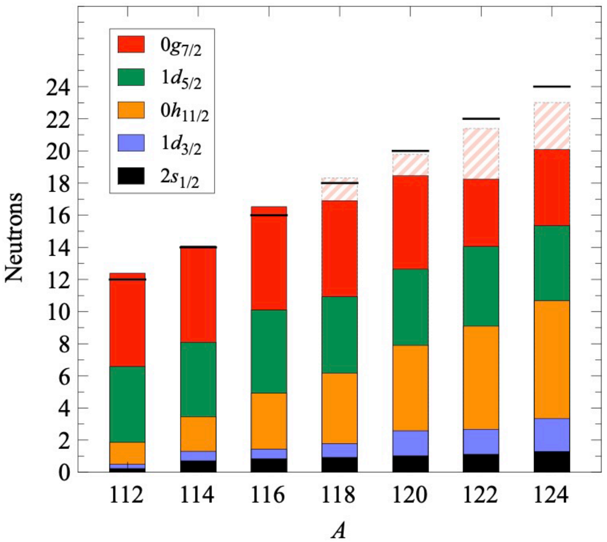
$^{112-124}$Sn(α,h),(h,α),(d,p) and (p,d)

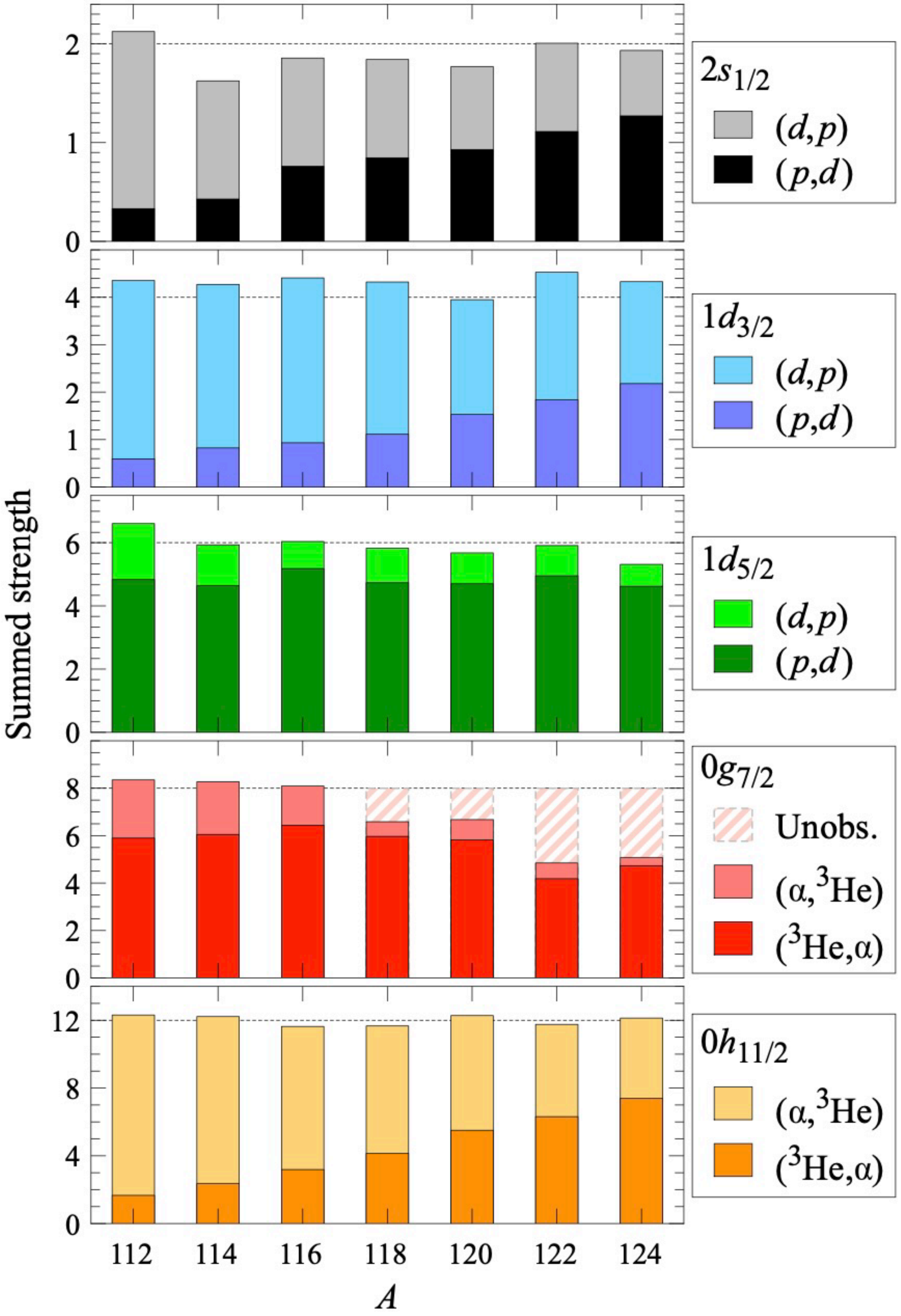
Munich MP + Q3D

A few well-chosen angles.









What about proton holes in the Sn core?

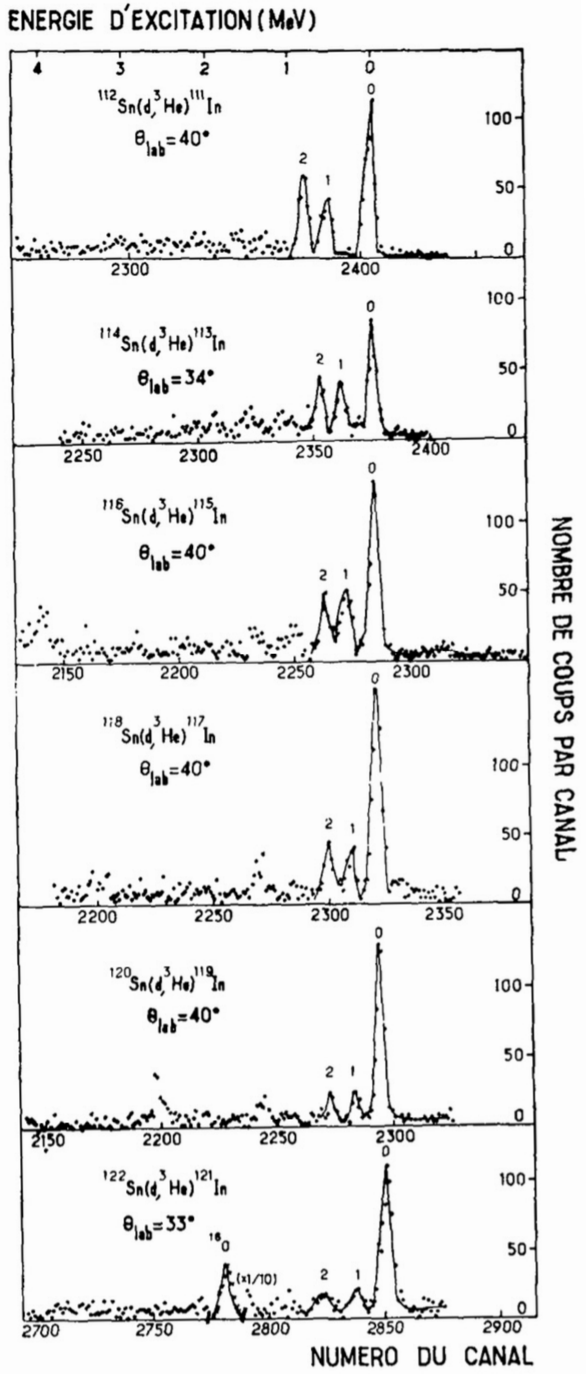
Would be nice to complete systematic studies of single-particle states around Sn by looking at proton removal.
Would be nice to see tensor-driven trends in $\pi g_{9/2}$ orbital.

What data exists? Some (d,^{3}He)…

Data from Saclay (d,^{3}He) @22 MeV on $^{112-122}$Sn (^{124}Sn missing)
Main strengths determined $g_{9/2}$, $p_{1/2}$ and $p_{3/2}$ using Si.
[Conjeaud et al., NPA 129, 10 (1969).]

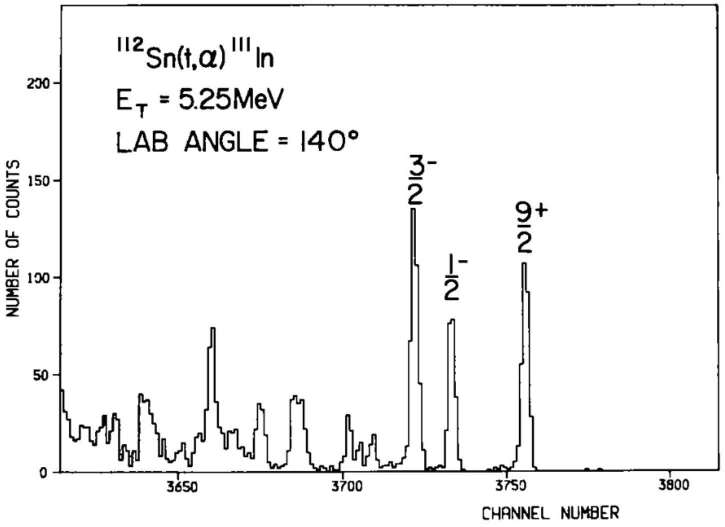
Data from U.Michigan (d,^{3}He) @28.9 MeV on $^{114-124}$Sn (^{112}Sn missing)
Main strengths and fragments down to 25% using magnetic spectrograph.
[Weiffenbach and Tickle, PRC 3, 1668 (1971)]

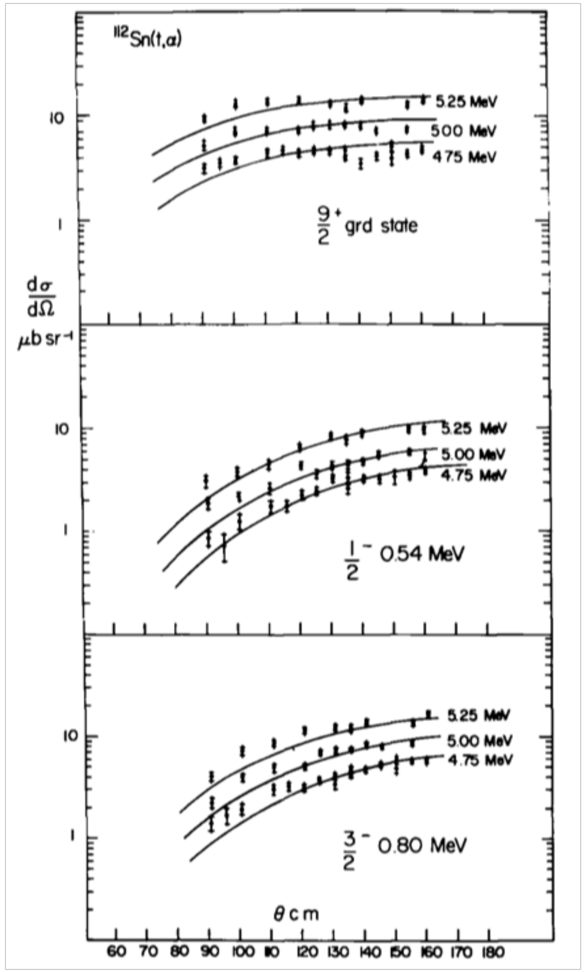
Detailed isolated studies at KVI of ^{120}Sn(d,^{3}He) @52MeV using QMG2 and ^{116}Sn(d,^{3}He) @52 MeV using Si
Fragmentation of all orbitals down to 1%.
[Langevin-Joliot et al., ZPhysA 334, 133 (1989)]
[Hesselink et al. NPA 226, 229 (1974)]



Only one (t,α) study, at Manchester with CN VDG

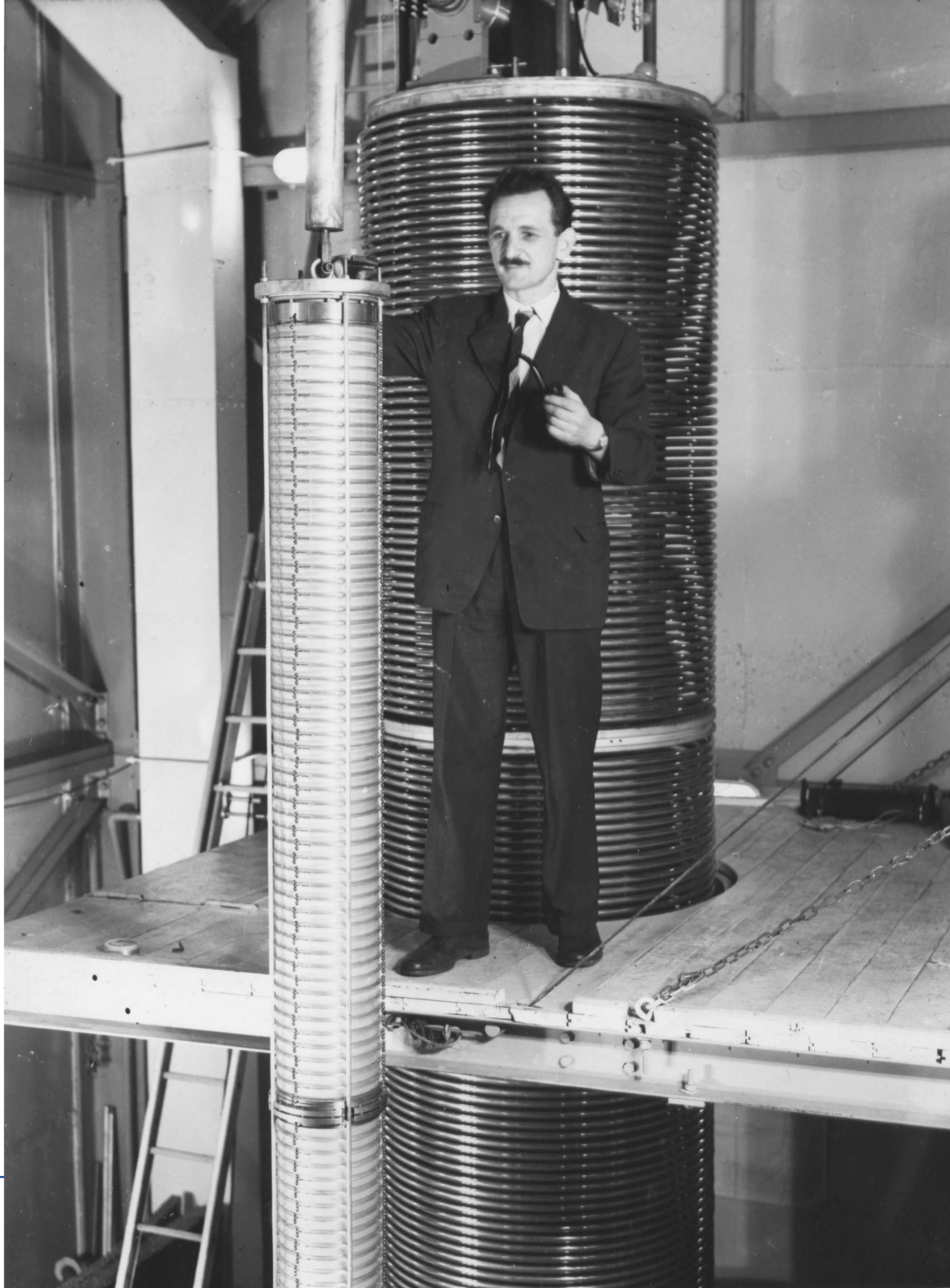
^{112,116,118,120,124}Sn(t,α) @ 4.75, 5.00, 5.25 MeV





extracted proton-orbit radii from sub-Coulomb transfer
only main fragments reported
missed ^{114,122}Sn

Warwick et al., NPA 391, 9 (1982)



CERN | MANCHESTER 1824 The University of Manchester

Fragments matter!

Taking the detailed L=4 data from KVI $^{120}Sn(d,{}^{3}He)$ @ 52 MeV…

Limit for SF	Sum rule	Deduced centroid (keV)
>20%	4.1	0
>10%	5.8	421
>2%	6.4	561
>1%	6.8	693

Not checked the details of their absolute normalisation but 68% strength roughly consistent with modern analyses of quenching.

No detailed study of proton-hole strength across all Sn isotopes performed in a consistent fashion.

Could think about (i) a (d,^{3}He) study at 50-100 MeV to extend KVI studies or (ii) (t,α) experiment at FSU

Should aim for a systematic study of all Sn isotopes down to 1% fragments.

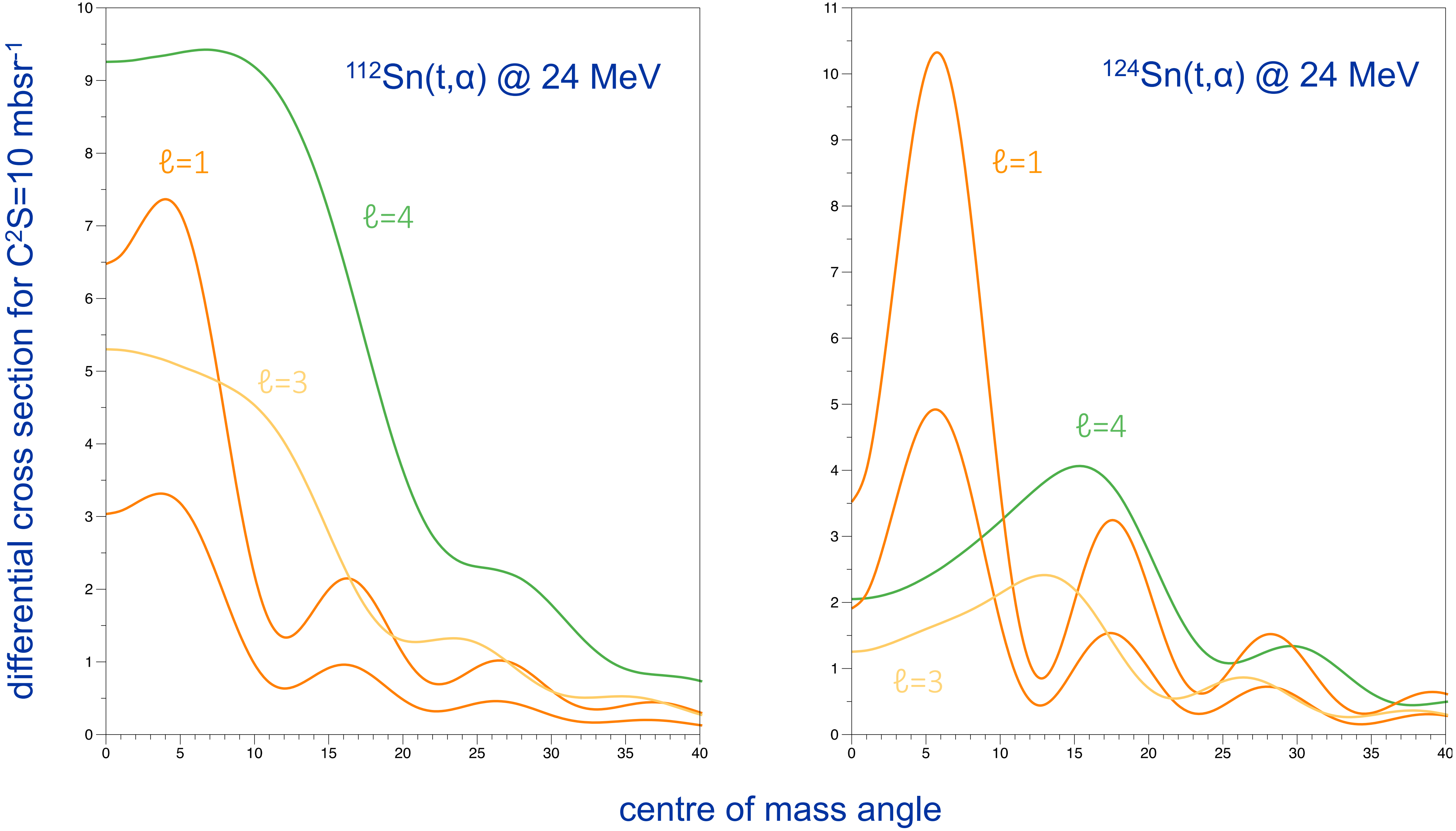
(t,α) reaction to generates higher cross sections for L=4:

Ground state had peak ^{120}Sn(d,^{3}He) cross section at 52 MeV of ~0.7 mbsr $^{-1}$ (reading from figure in KVI paper) for C^2S=4.1.
For C^2S =10 cross section is ~1.7 mbsr $^{-1}$

c.f. DWBA calculations for (t,α) of around 6 mbsr $^{-1}$

A (t,α) experiment at FSU is better!

DWBA Calculations @24MeV



(cross sections @17MeV roughly x0.5)

Rates

20 pnA currents and 100 ugcm^{-2} targets and 2.8 msr (as in Yale experiments).

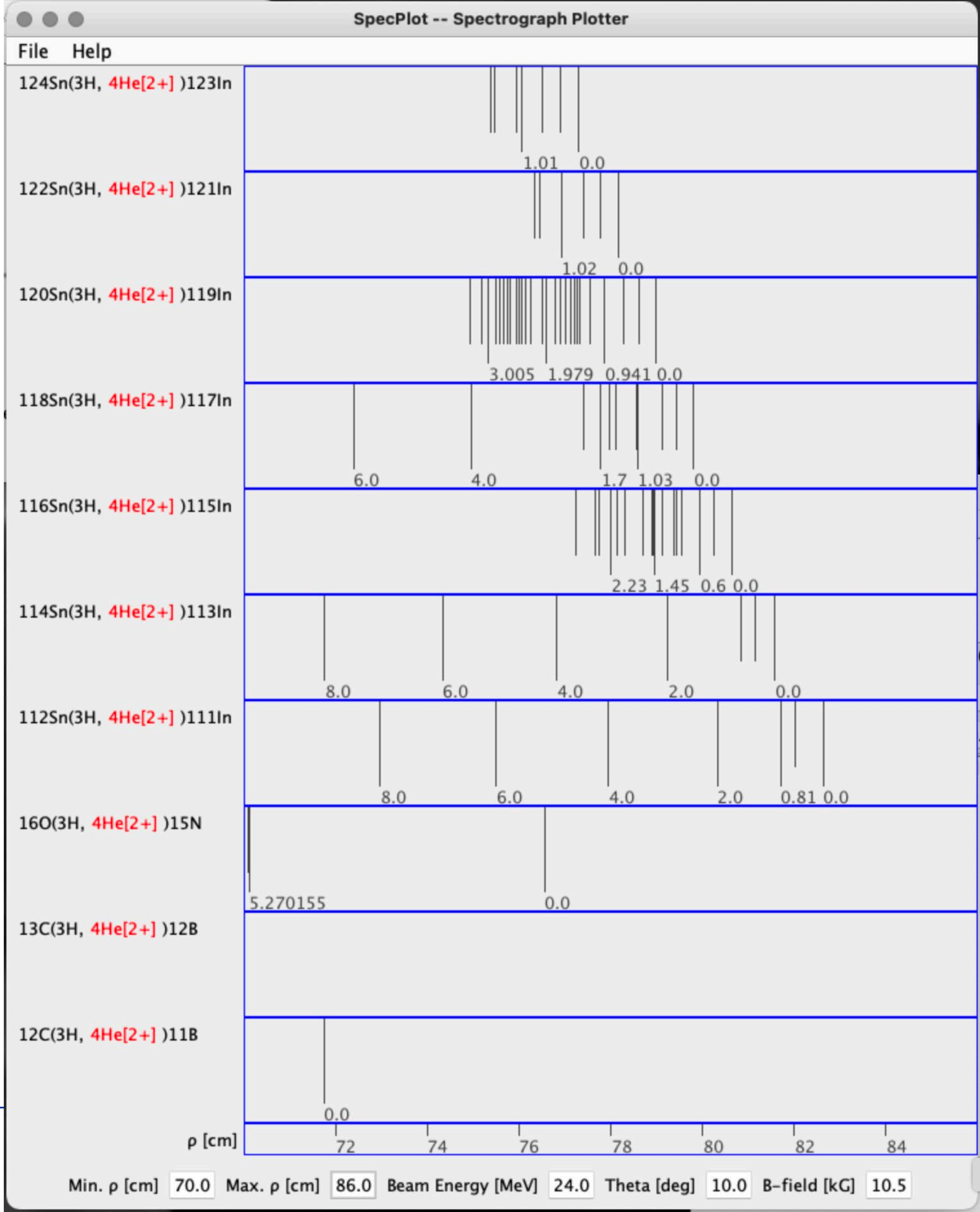
Time for 1000 in S=1 fragment:
^{112}Sn =1.6 hours and ^{124}Sn = 4.0 hours so average of around 2.8 hours per target.
With estimates of time for target/angle changes = 24 hours for measurements at peak of L=4.

Focal plane seems relatively clean – but potential for $^{16}O(t,\alpha)^{15}N_{gs}$ contamination for heavier targets.

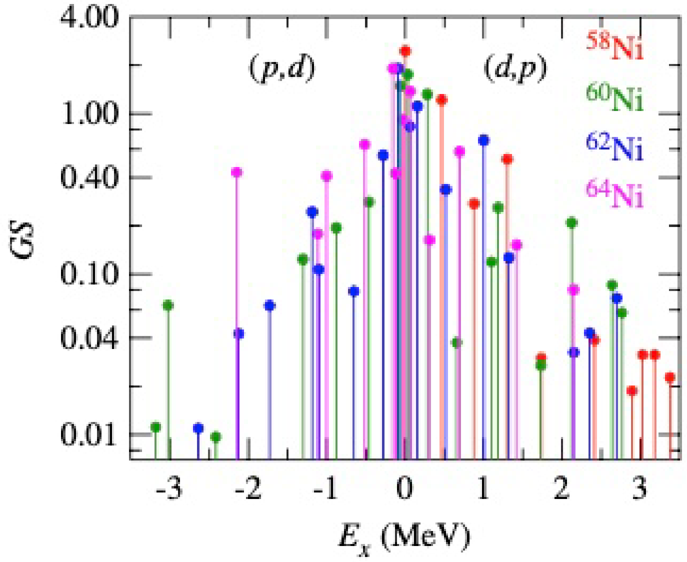
If similar for peaks of L=1 and 3, and one other angle for redundancy/contaminant shifting with one day for elastic scattering measurements gives a 5-day run.

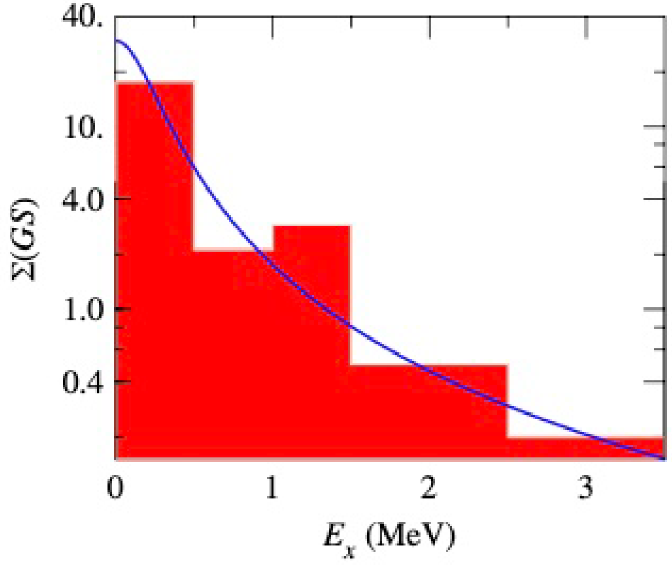
Resolution >15 keV depending on final target thickness.

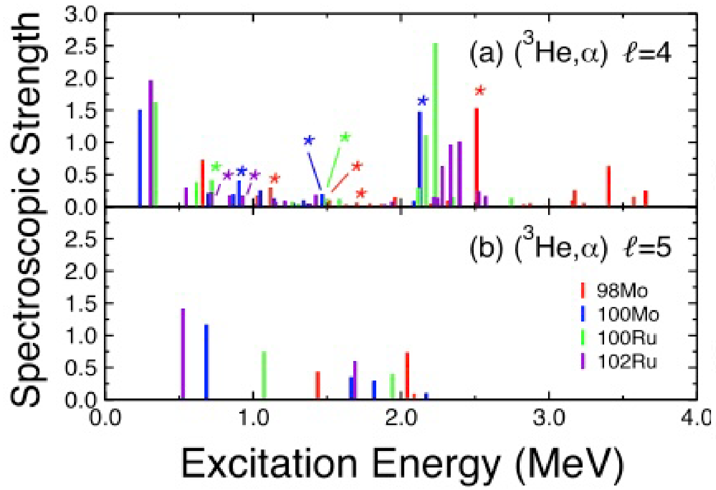
Assuming that FSU operations are like Yale and no additional RP constraints.

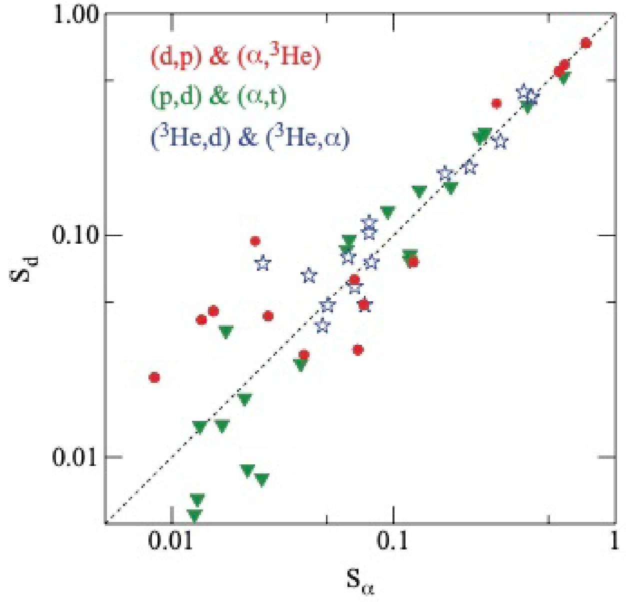


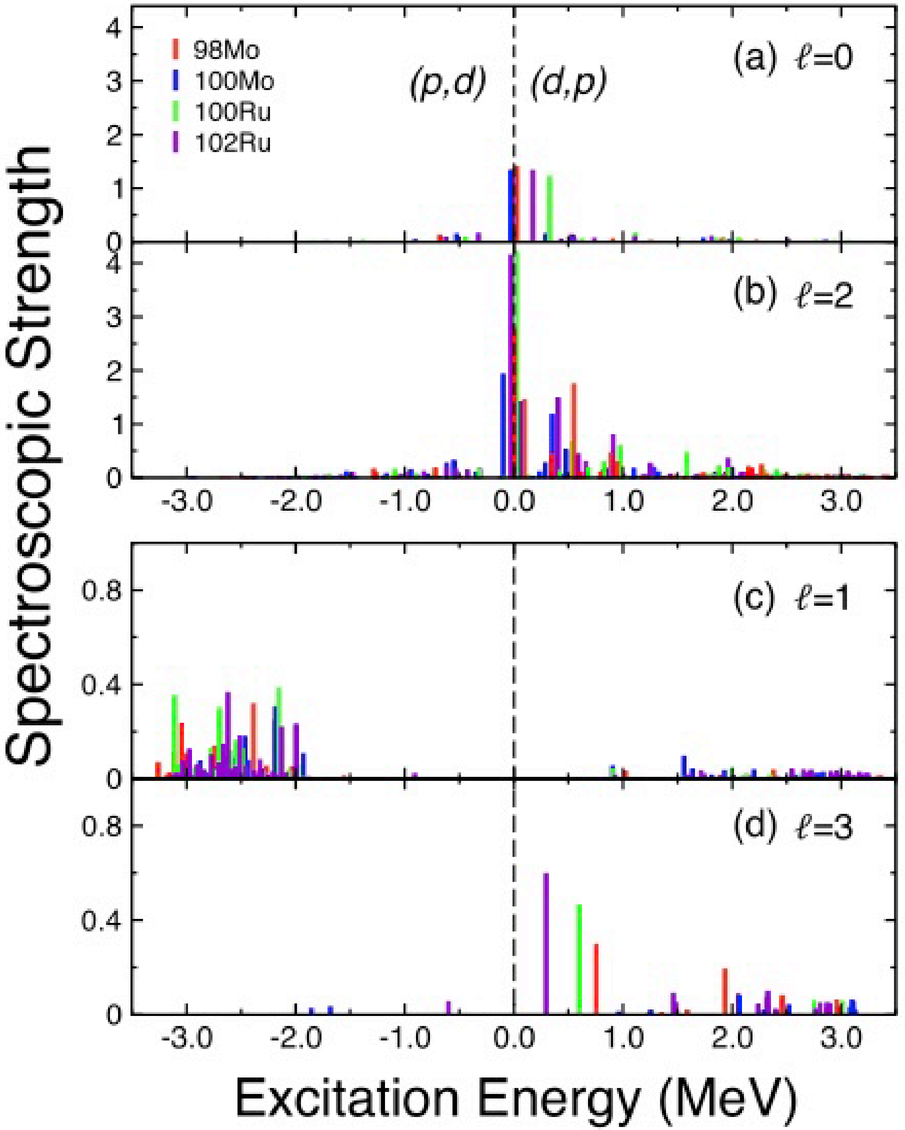
home.cern


(p,d)
(d,p)
58Ni
60Ni
62Ni
64Ni
GS
Ex (MeV)


Σ(GS)
Ex (MeV)


(a) (3He,α) ℓ=4
(b) (3He,α) ℓ=5
98Mo
100Mo
100Ru
102Ru
Spectroscopic Strength
Excitation Energy (MeV)


(d,p) & (α,3He)
(p,d) & (α,t)
(3He,d) & (3He,α)
Sd
Sα


98Mo
100Mo
100Ru
102Ru
(p,d)
(d,p)
(a) ℓ=0
(b) ℓ=2
(c) ℓ=1
(d) ℓ=3
Spectroscopic Strength
Excitation Energy (MeV)

Direct Reactions

- Single-step mechanism to specific final states or resonances.
- Via "one-degree of freedom" – transferring a single nucleon, exciting a single mode of vibration …
- Reaction amplitudes have explicit dependency on initial and final state.
- Cross sections plus reaction modelling can deduce overlaps (albeit in a model-dependent way).
- Angular distributions characteristic of ℓ transfer and polarized beams give sensitivity to j.