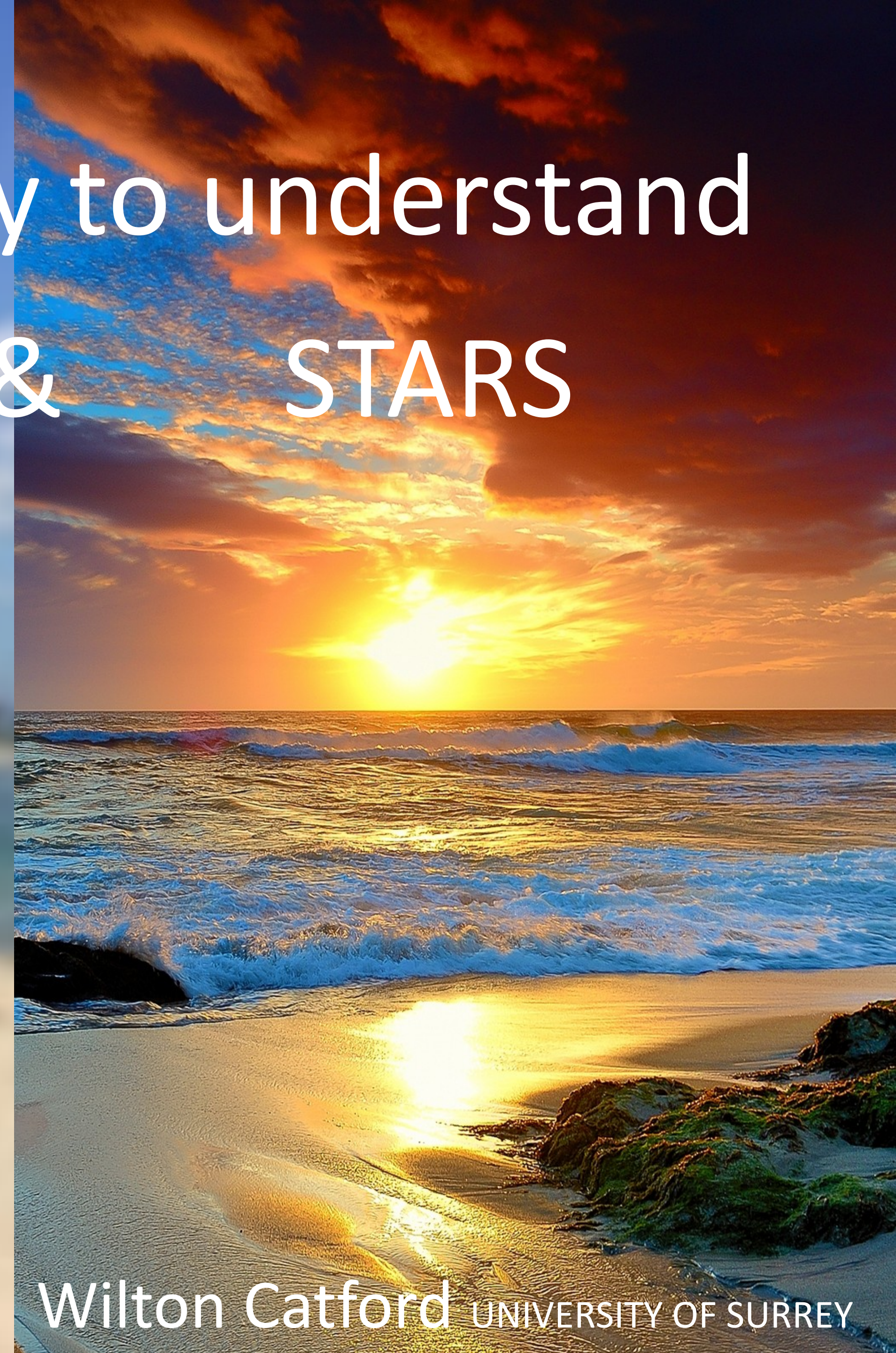
transfer as a way to understand

SHELLS & STARS



Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

WARSAW, JAN 2018

Wilton Catford UNIVERSITY OF SURREY

UNIVERSITY OF SURREY

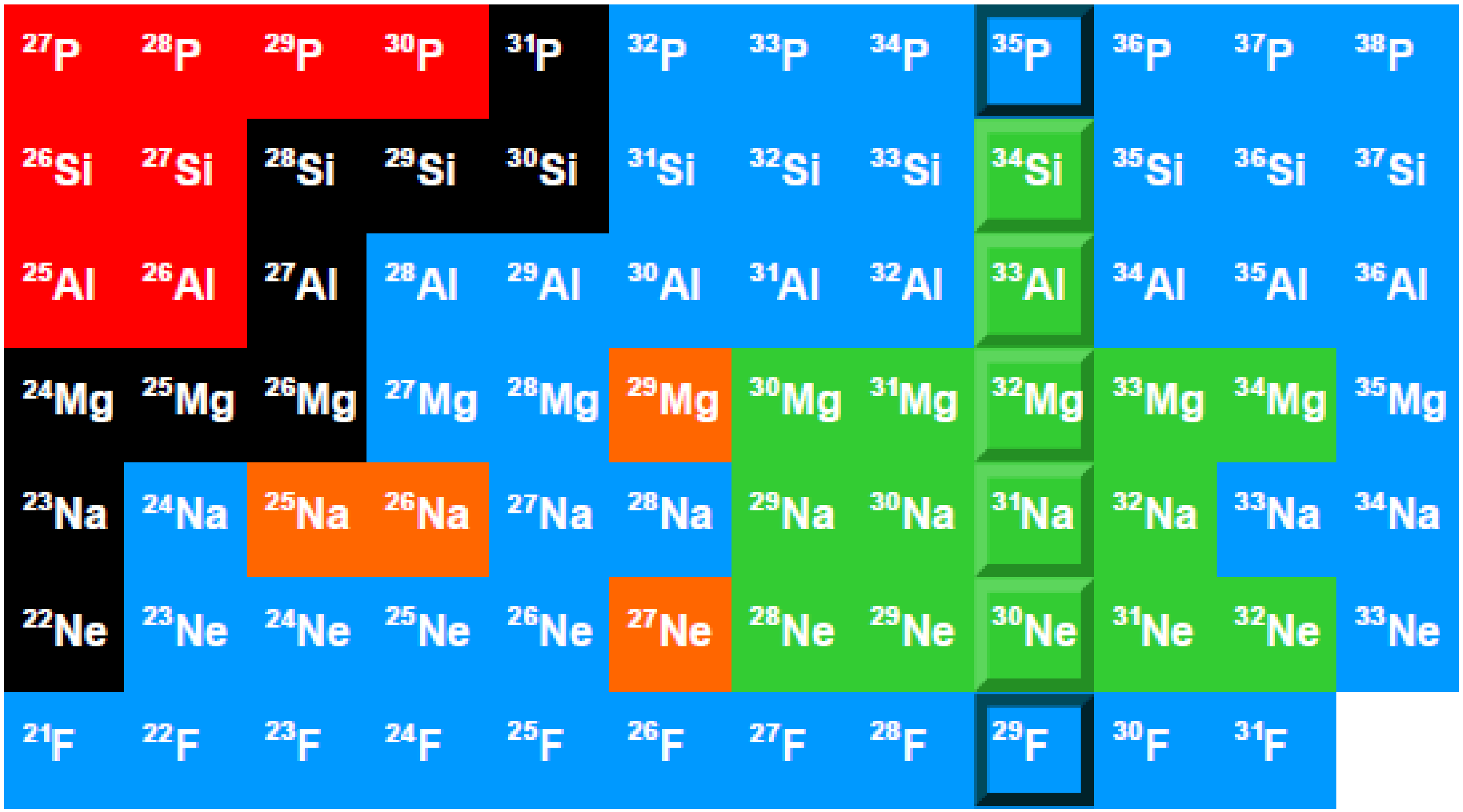
COLLABORATORS FOR THIS WORK

In Surrey:
Gavin Lotay, Dan Doherty, Mhd Moukaddam,
Adrien Matta (LPC Caen), Ryan Wilkinson, Sam Hallam,
Gemma Wilson, Andy Knapton, Ilker Can Celik

In TRIUMF:
Nigel Orr (LPC Caen), Greg Hackman, Jack Henderson,
Panu Ruotsalainen, Peter Bender, Carl Unsworth, Christian Aa. Diget,
Franck Delaunay (LPC Caen) and many more…

In Texas:
Greg Christian, Antii Saastamoinen, Shuya Ota, Eames Bennett

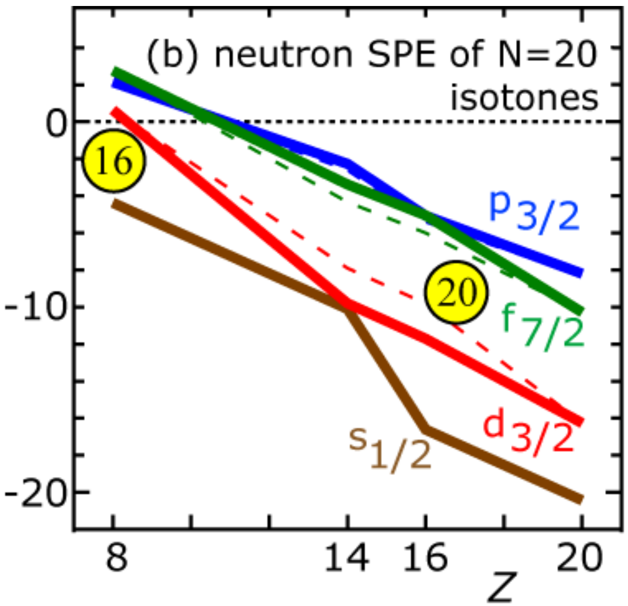
Region of Interest – Approaching the Island of Inversion



orange – nuclei studied by us, using (d,p)

green – (a) N=20,
(b) island of inversion
(intruder structure dominates ground state structure)

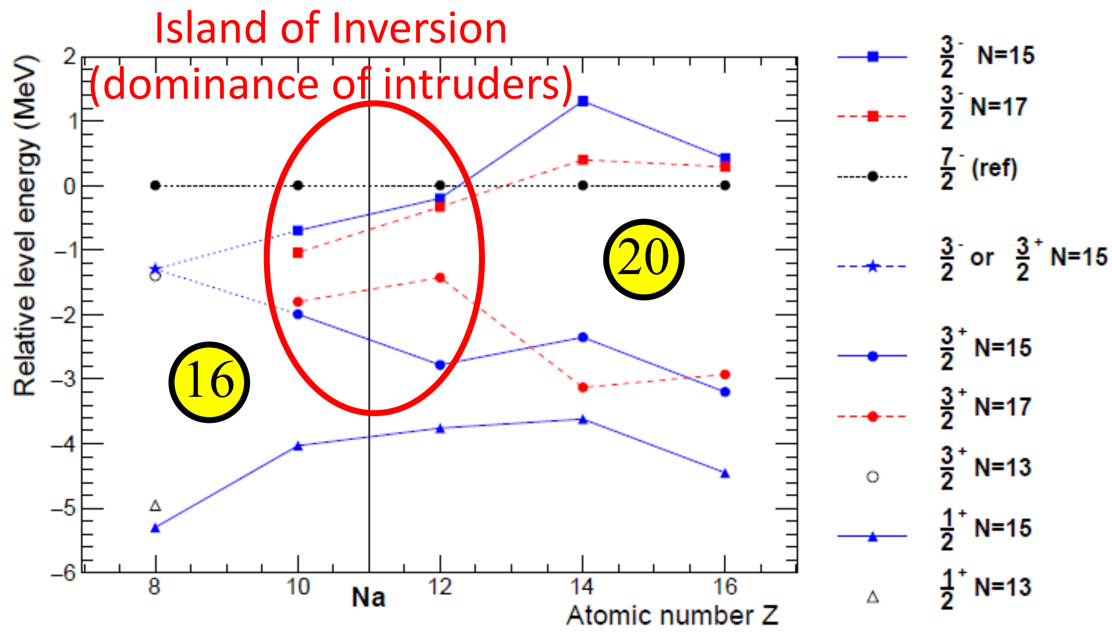
Theory: effective spe’s



PRL **104,** 012501 (2010)

Otsuka et al.

Experiment: energies of just the lowest levels

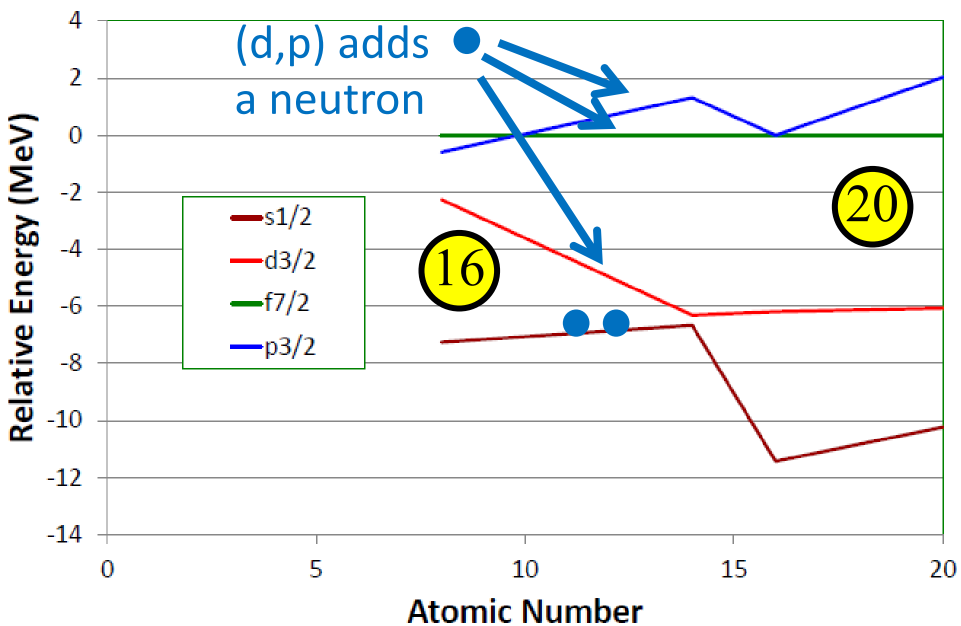


PLB (2016) N=15 and 17 isotones

http://dx.doi.org/10.1016/j.physletb.2016.05.093

G.L. Wilson et al.

Theory: effective spe's



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Otsuka et al.

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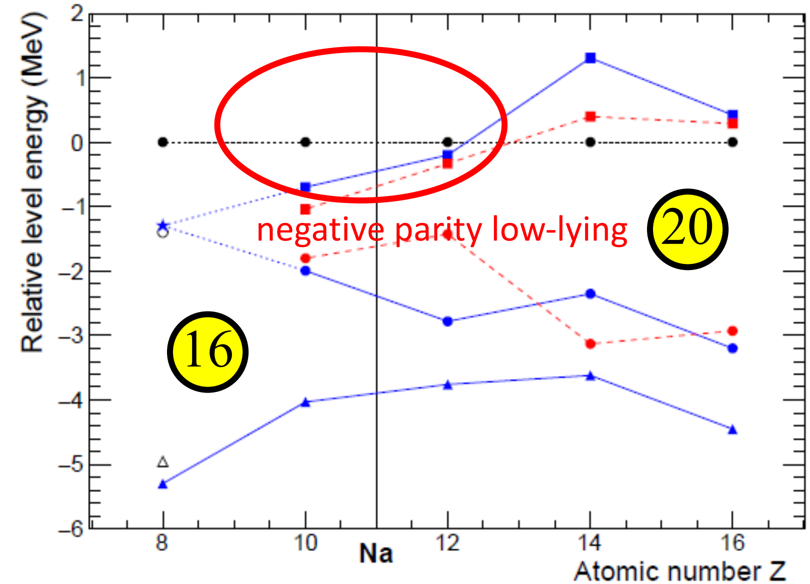

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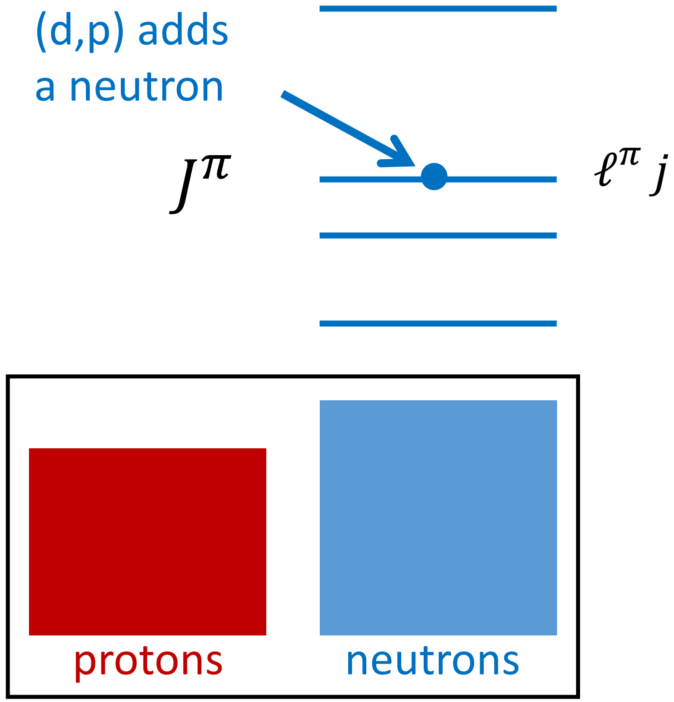
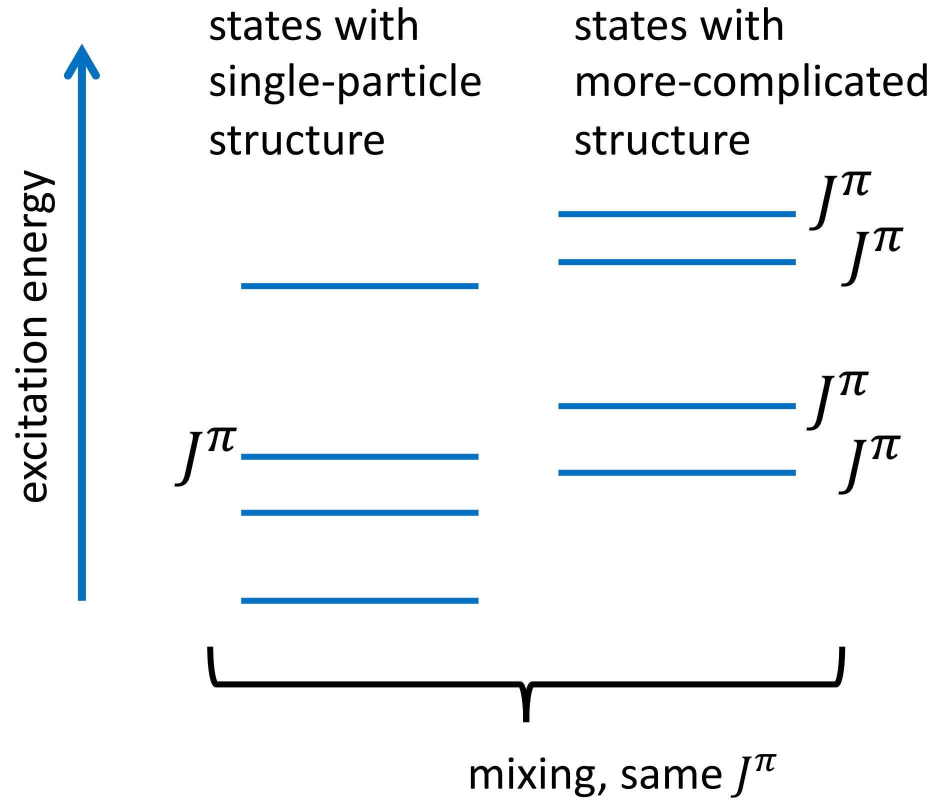
G.L. Wilson et al.

- Our aim is to identify single-particle-like levels and determine their spin/parity
- We use the selective nature of (d,p) neutron transfer (with radioactive beams)
- We aim to track the evolution of these levels and compare to the shell model



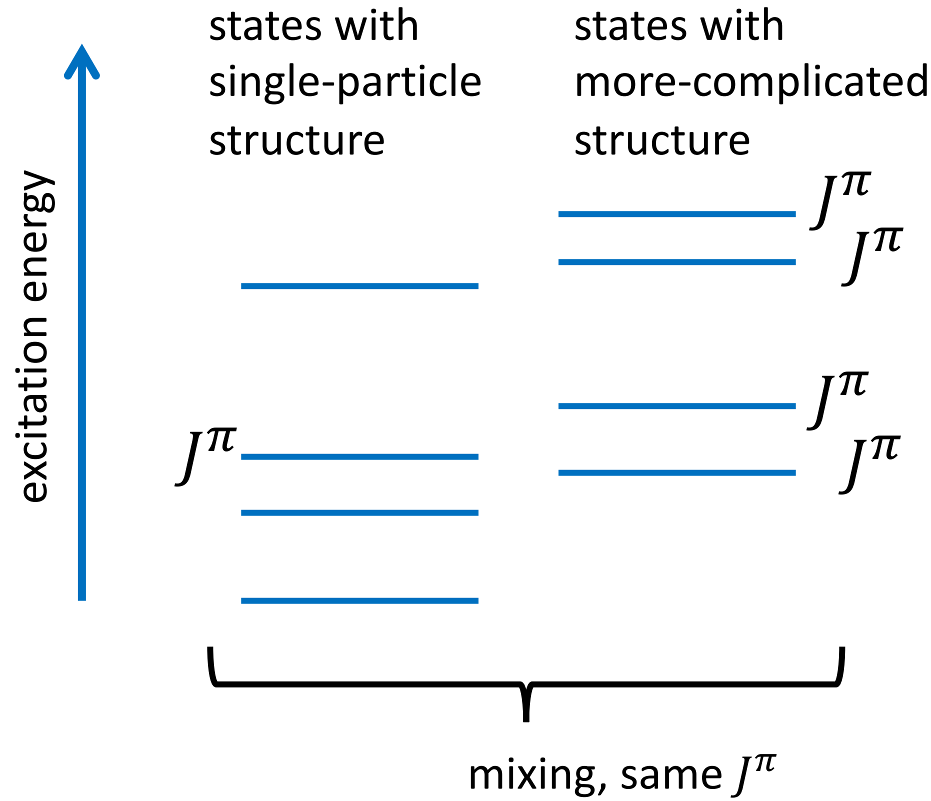
single-particle state,
unperturbed core
(idealized situation)



$$| \ J_i^\pi > \ = \sqrt{S} \ |J_{SP}^\pi > + \sum_k \alpha_k \ |J_k^\pi >$$

$$S = | \ \langle J_{SP}^\pi \ | \ J_i^\pi \ \rangle|^2$$

spectroscopic factor
= overlap with pure SP state



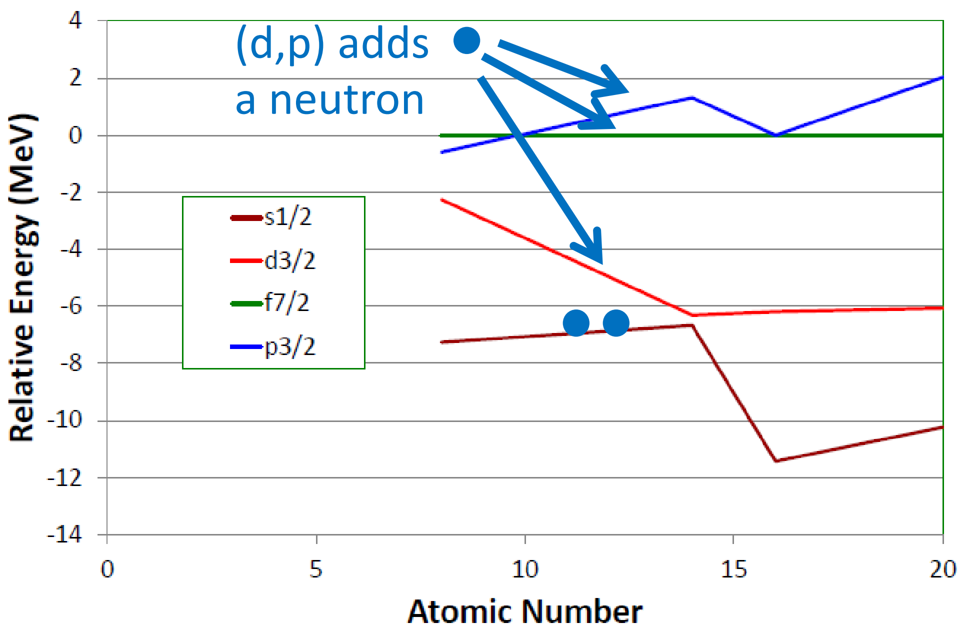
$$| \; J_i^\pi > \; = \sqrt{S} \; |J_{SP}^\pi > + \sum_k \alpha_k \, |J_k^\pi >$$

- we measure transferred ℓ_n
- we measure gamma-decays
- we aim to identify J and π
- we deduce S

$$S = | \, \langle J_{SP}^\pi \mid J_i^\pi \rangle |^2$$

spectroscopic factor
= overlap with pure SP state

Theory: effective spe's



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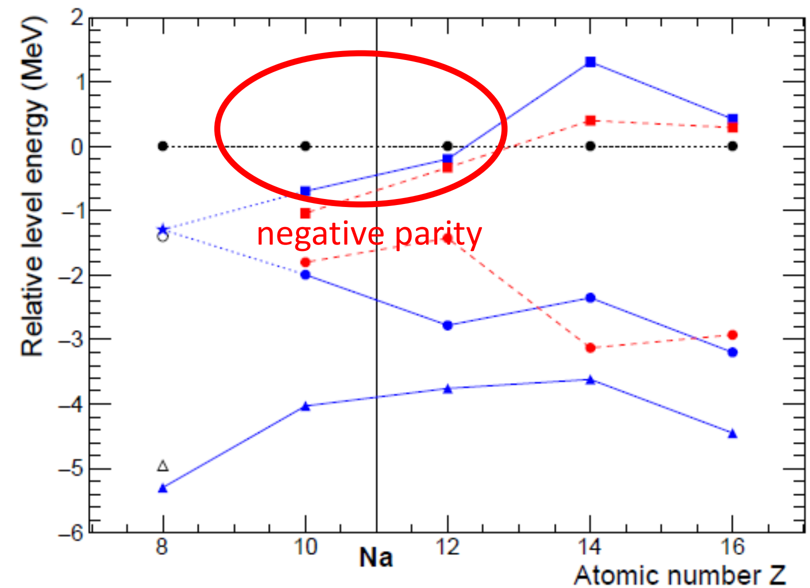

PLB (2016) N=15 and 17 isotones

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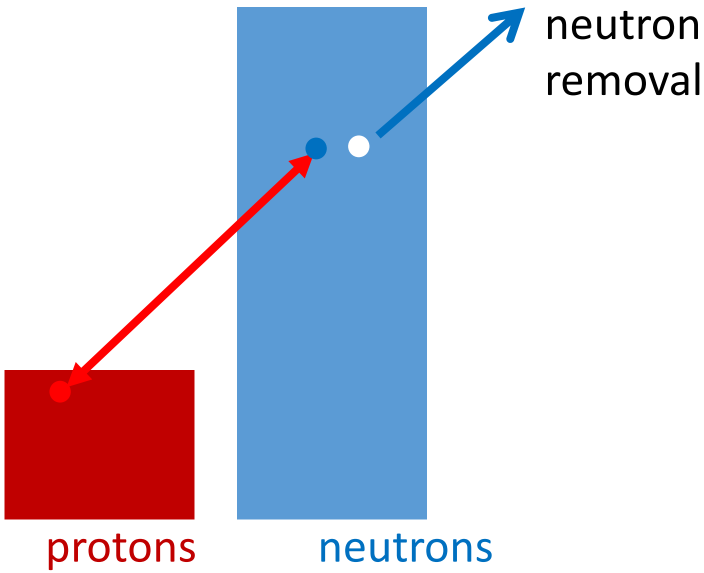
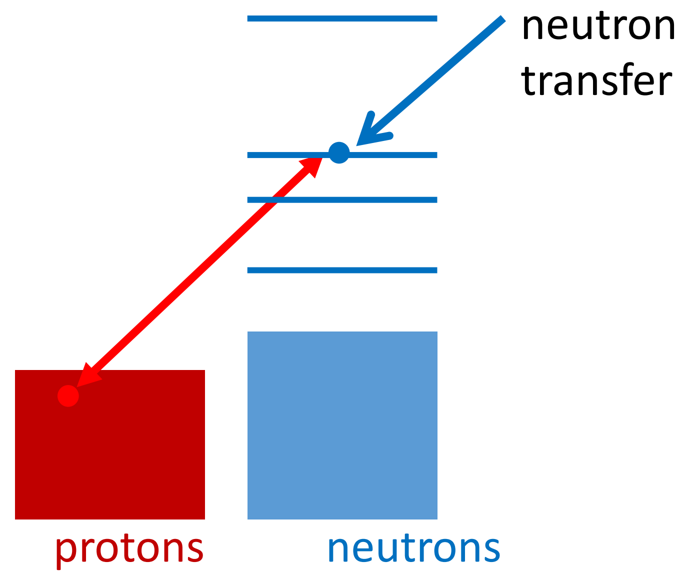
G.L. Wilson et al.

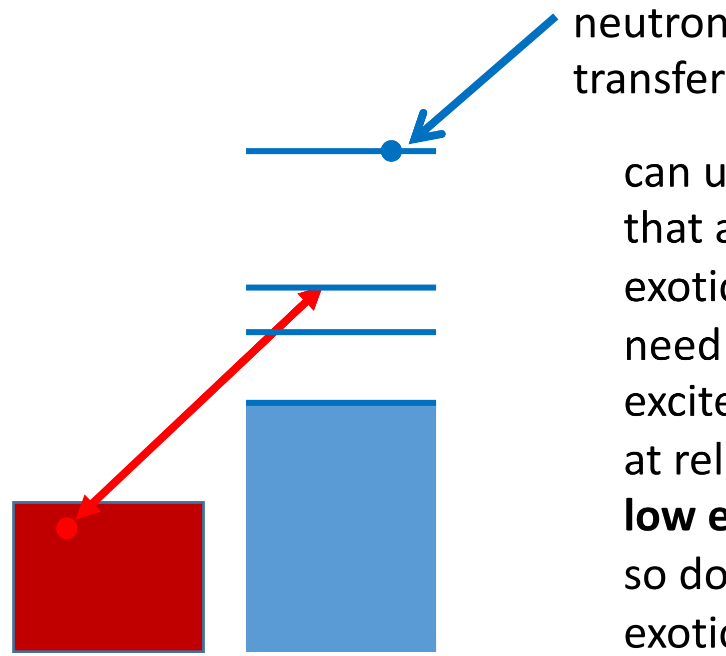
- Our aim is to identify single-particle-like levels and determine their spin/parity
- We use the selective nature of (d,p) neutron transfer (with radioactive beams)
- We aim to track the evolution of these levels and compare to the shell model
- We use the large SF for theory/experimental states to associate them with each other
- Details of the precise numerical value of the SF don't affect this process
- Results will be shown here for Z=11,12 for N=14,15,17, **probing higher orbitals**

KNOCKOUT



WHY TRANSFER IS SUCH A GOOD CHOICE



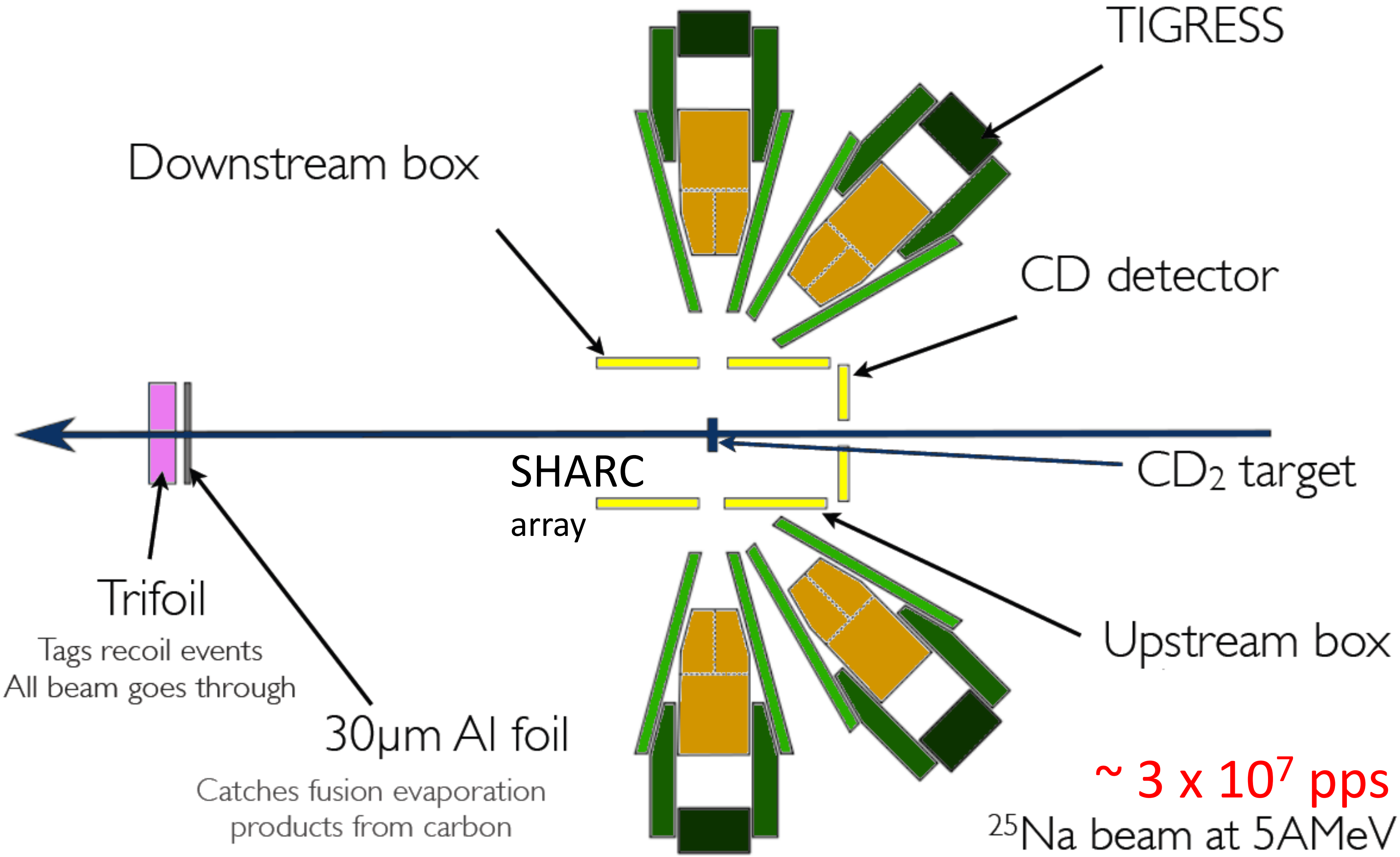


can make beams of VERY exotic nuclei
and learn properties by removing neutrons
OR
can learn the important interactions that explain the structure by isolating p-n interactions, using a **single nucleon** to probe the additional orbitals one at a time

thus **transfer** is an excellent way to isolate the separate interactions

can use beams that are less exotic, but do need to keep excited states at relatively **low energies**, so do need exotic beams

Experimental Setup to Measure d(^{25}Na,p)^{26}Na at TRIUMF

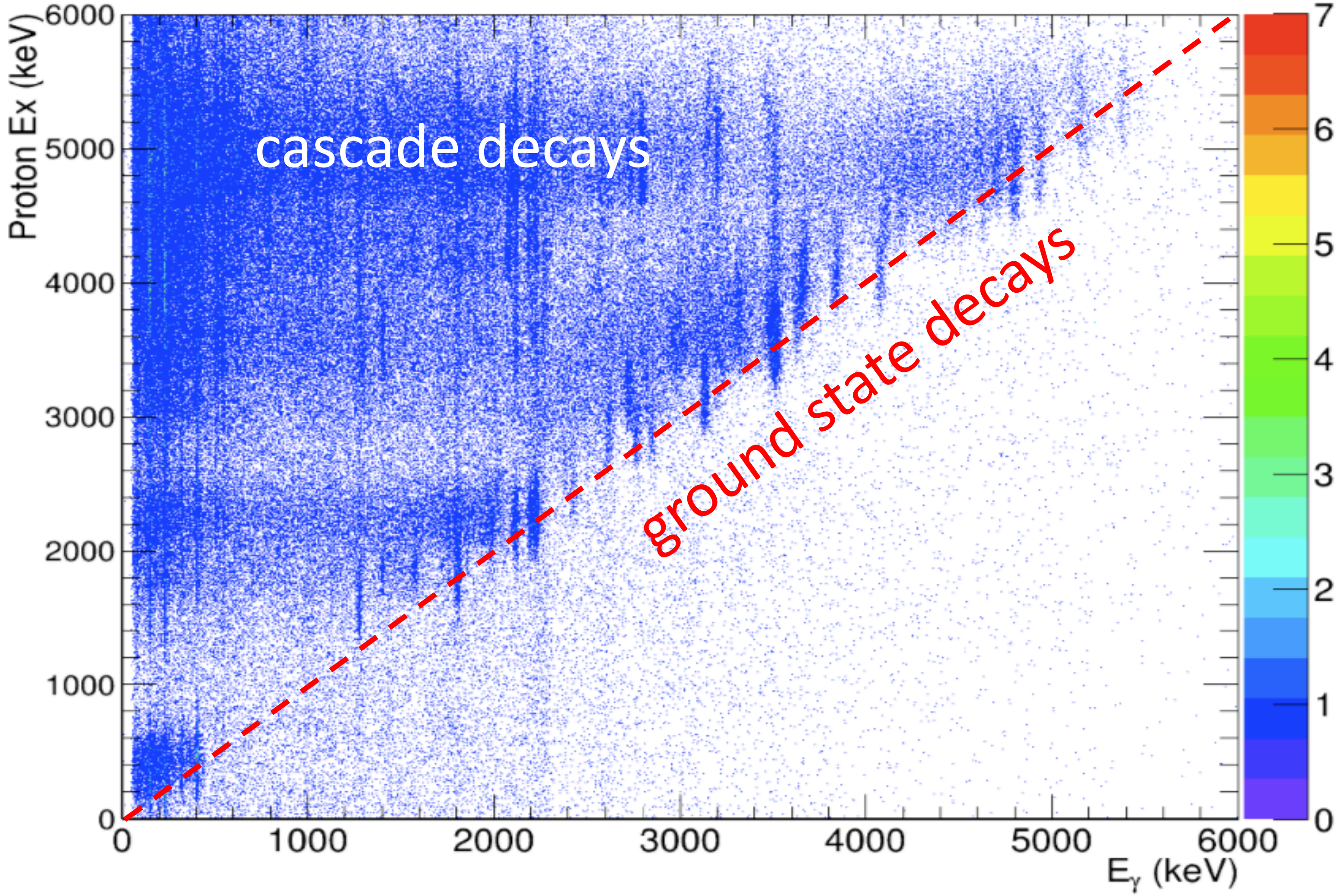


G.L. Wilson et al., Physics Letters B 759 (2016) 417

Data from d(^{25}Na,p)^{26}Na at 5 MeV/A using SHARC at ISAC2 at TRIUMF

Gemma Wilson, Surrey

Excitation energy deduced from proton energy and angle



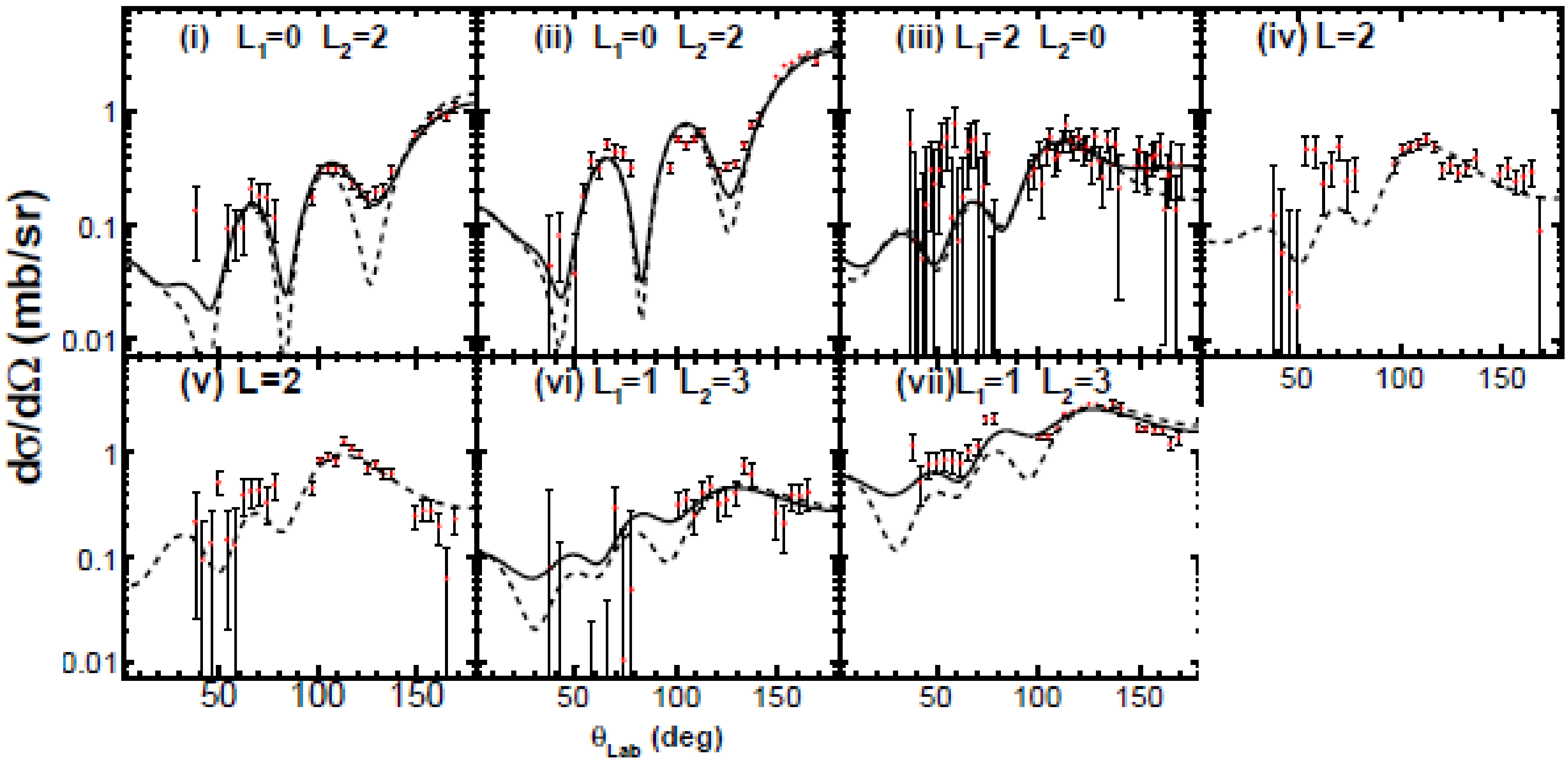
Doppler corrected (β=0.10) gamma ray energy measured in TIGRESS

Differential cross sections and spectroscopic factors

First analysis of this type:

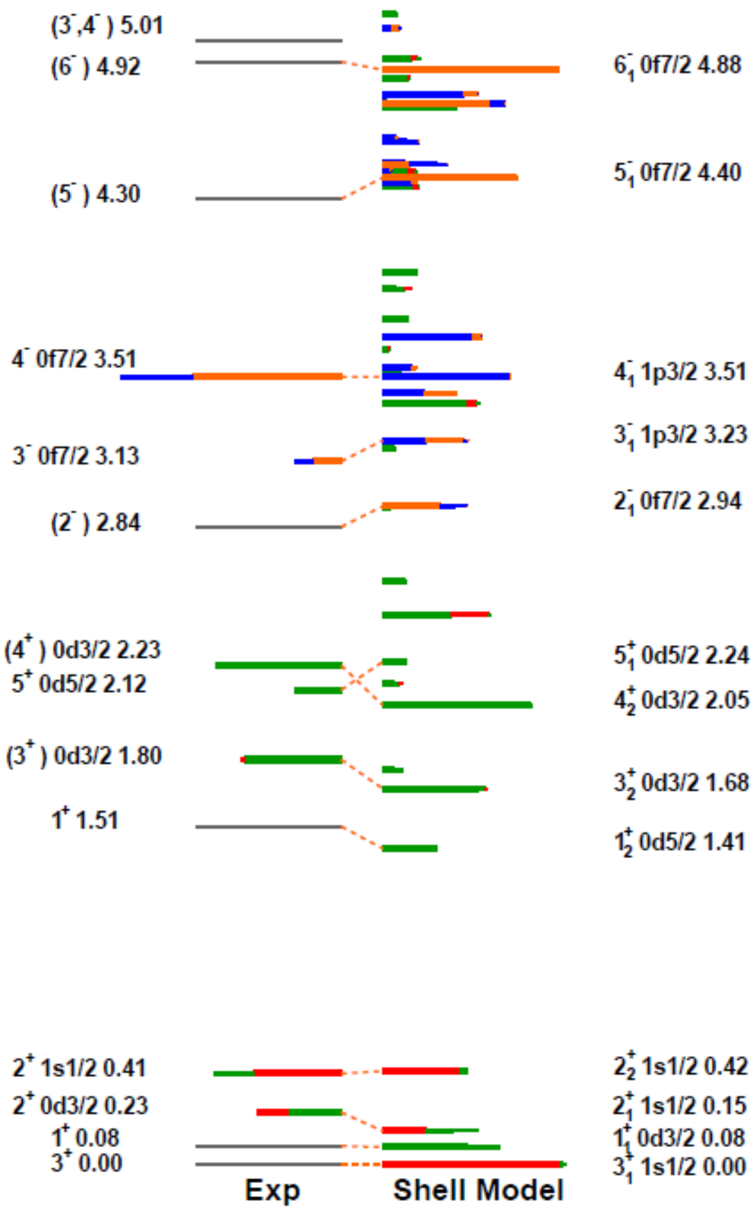
Each of these distributions is:

- (a) gated on a gamma-ray peak
- (b) background-subtracted
- (c) corrected for gamma ray efficiency
- (d) corrected for gamma ray branching ratio



G.L. Wilson et al., Physics Letters B 759 (2016) 417

Experimental Results from studying d(^{25}Na,p)^{26}Na at TRIUMF



comparison between revised shell model energies and SFs

the results are somewhat subtle

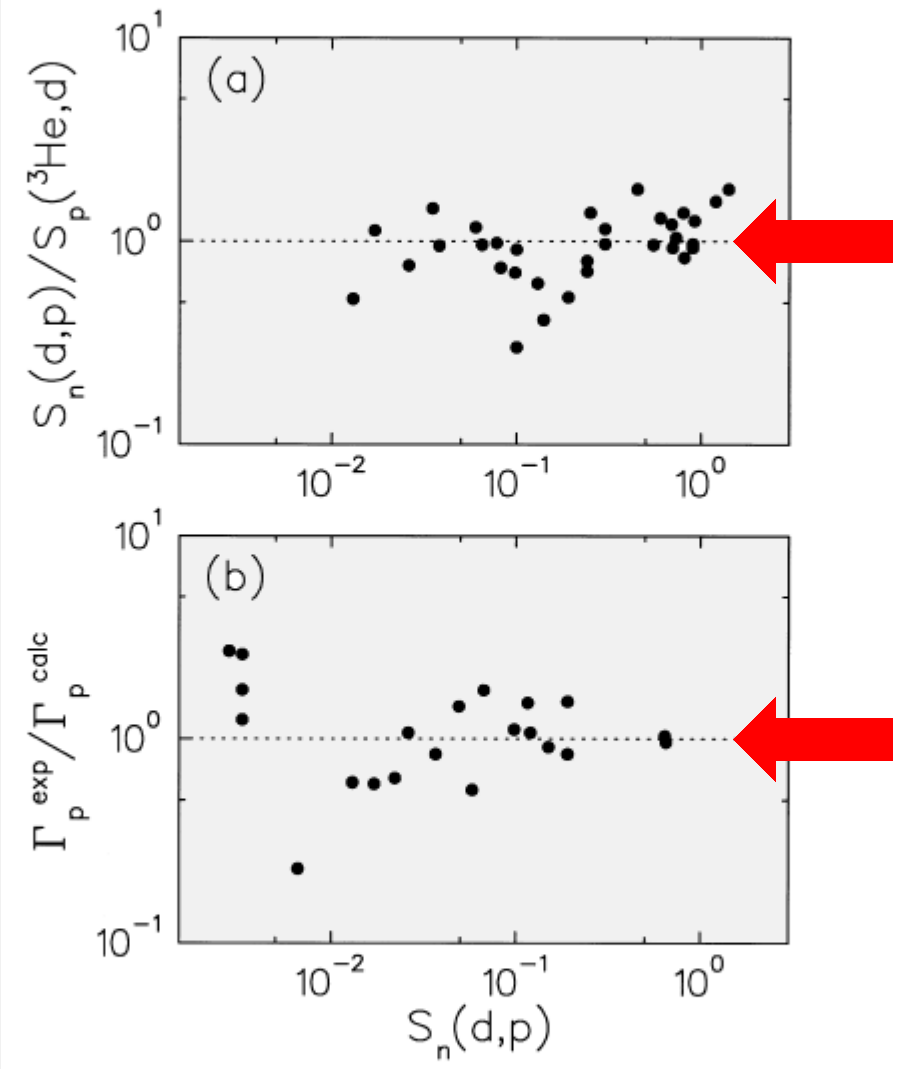
evidence for stronger influence of the 1p3/2 orbital in the low-lying negative parity states, compared to the less exotic isotone ^{28}Al

this is evidence for the 1p3/2 orbital becoming lower, relative to the 0f7/2 orbital which is clear, in ^{27}Ne and ^{29}Mg

the shell model works surprisingly well

wbc spsdpf 0+1$\hbar\omega$

Measuring SF_n via (d,p) on n-rich conjugate $\Rightarrow \Gamma_p$ width in p-rich



strengths of states in neutron transfer
= strengths in proton transfer on mirror

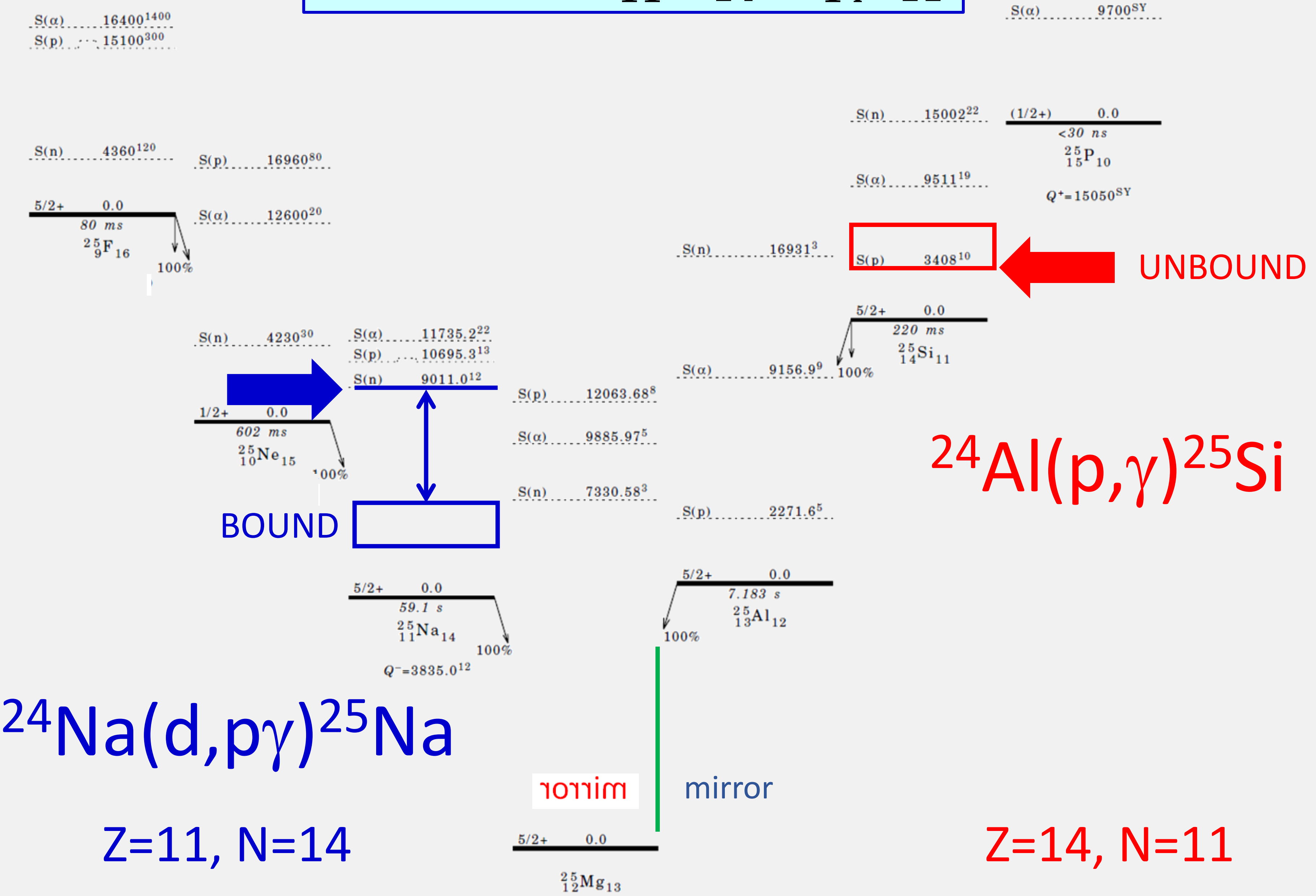
within a factor of 1.5 (and a bias of 6%)

proton widths deduced from neutron transfer strength and single-particle decay width calculation
= actual measured proton decay width

within a factor of 1.7 (and a bias of 3%)

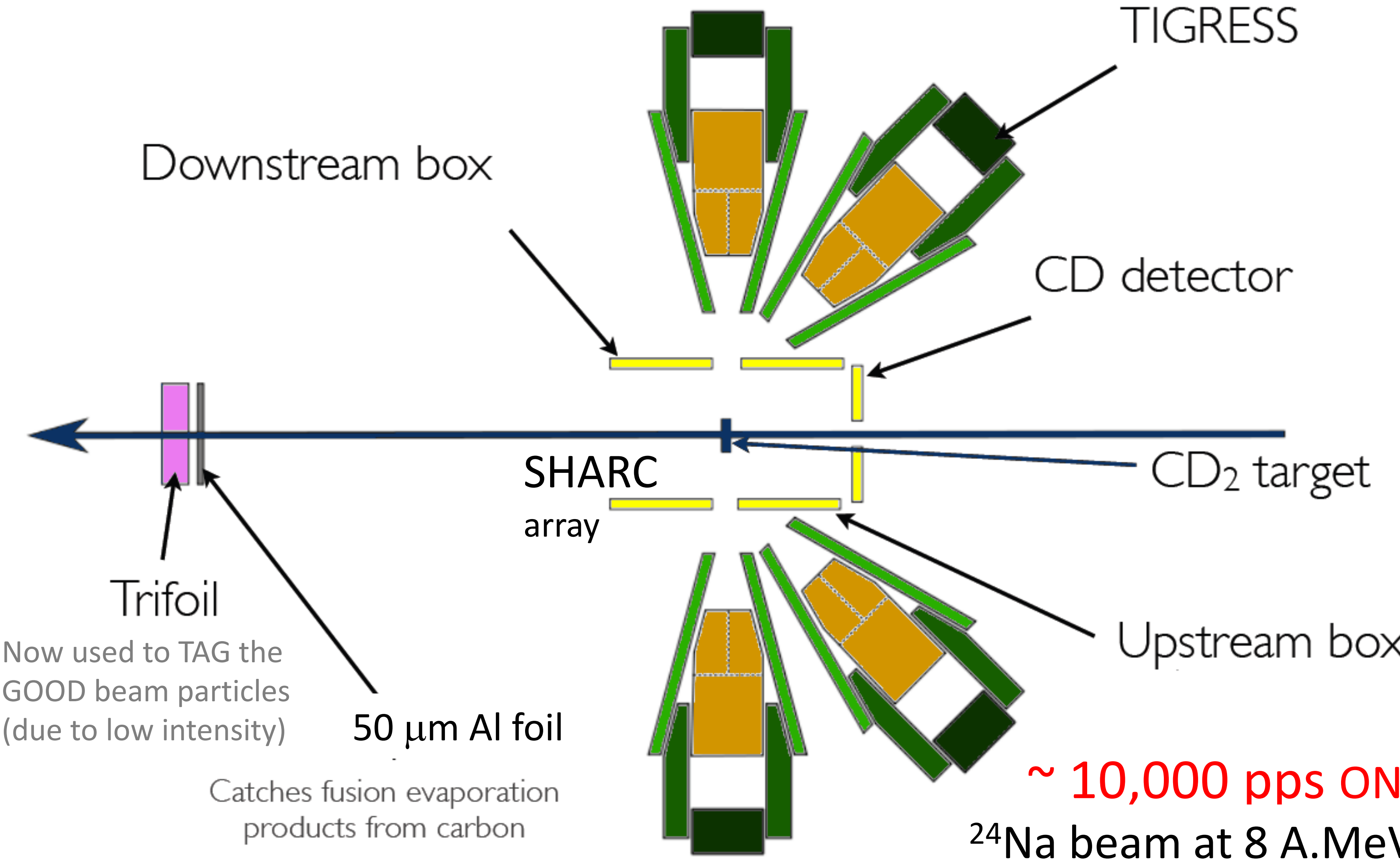
Iliadis, Endt, Prantzos and Thompson, Ap.J. 524, 434 (1999)

A=25 Isobars: $^{25}_{11}Na_{14}$ $^{25}_{14}Si_{11}$



Experimental Setup to Measure d(^{24}Na,p)^{25}Na at TRIUMF

conjugate of ^{24}Al(p,γ)^{25}Si

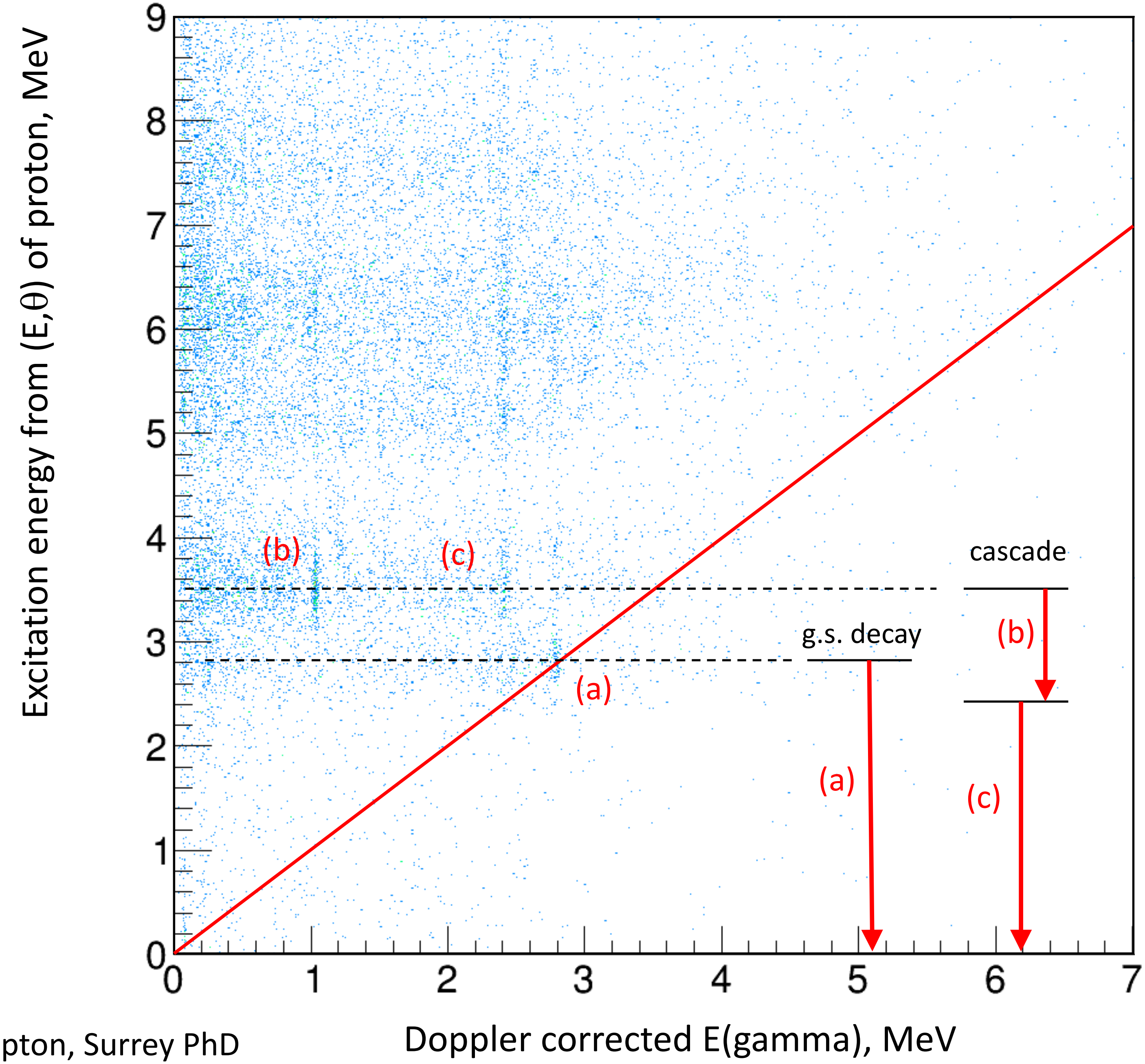


~ 10,000 pps ONLY

^{24}Na beam at 8 A.MeV

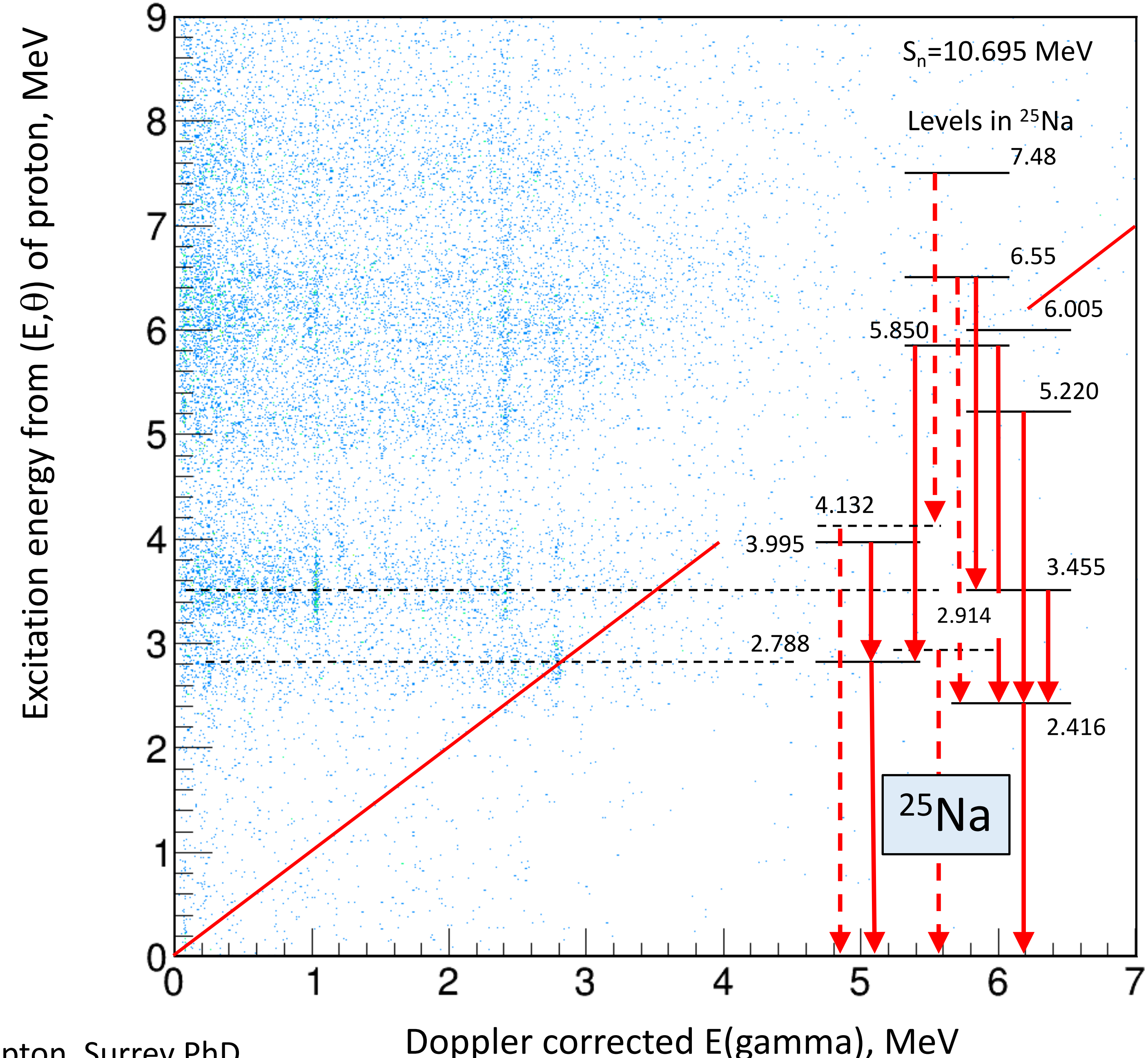
Andy Knapton, Surrey PhD (writing up)

$d(^{24}Na,p)^{25}Na$ at 8.0 MeV/u with 10,000 pps



Andy Knapton, Surrey PhD

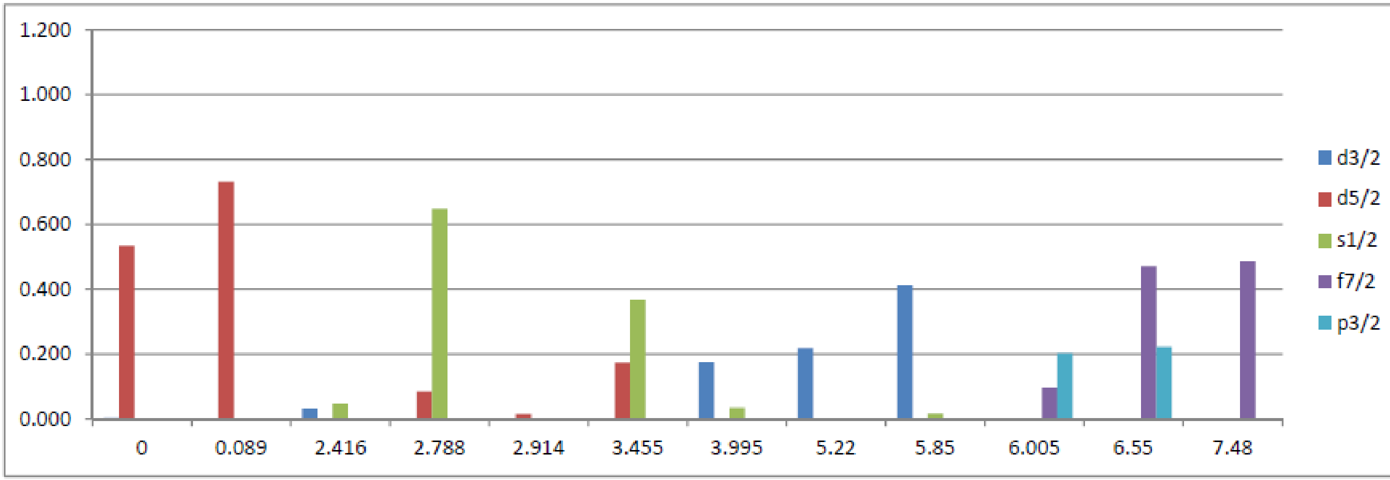
d(^{24}Na,p)^{25}Na at 8.0 MeV/u with 10,000 pps



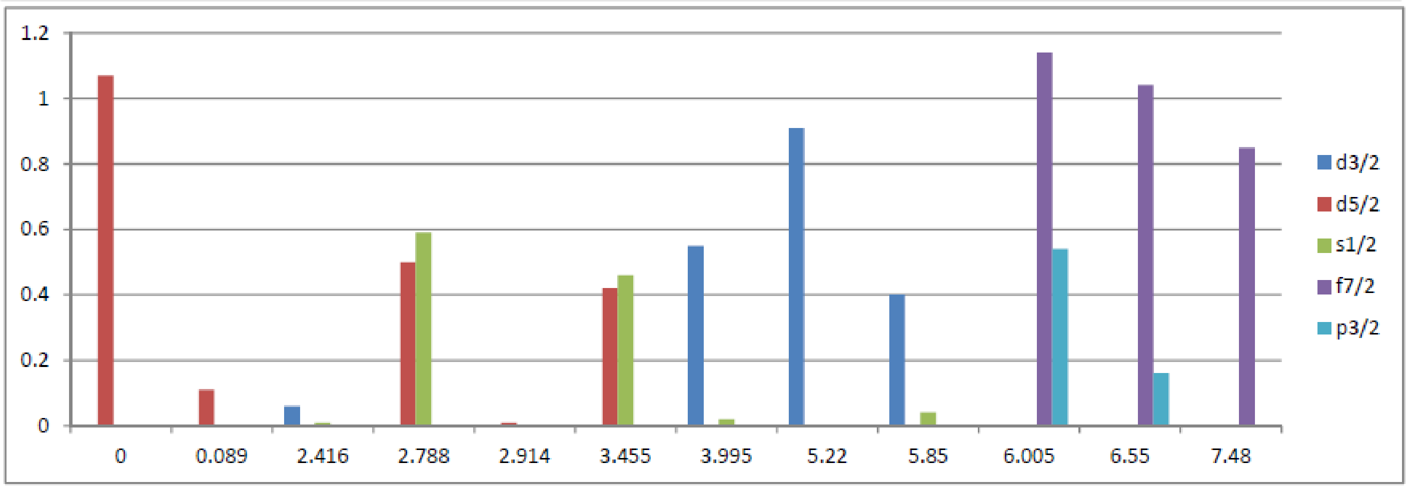
Andy Knapton, Surrey PhD

d(^{24}Na,p)^{25}Na – spectroscopic factors in ^{25}Na compared to theory

wbc
nushellx
(0+1)$\hbar\omega$



this work
ADWA
std geom



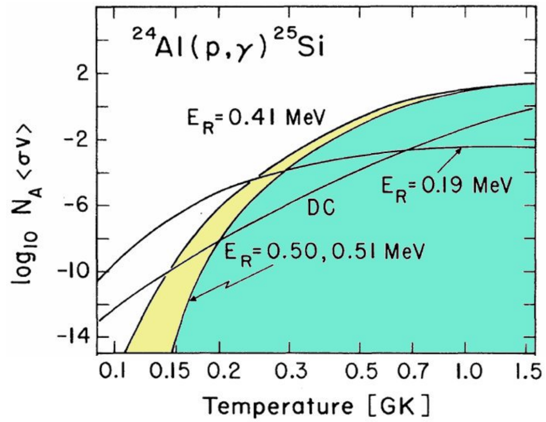
Excitation Energy in ^{25}Na (MeV)

present work	5/2+	3/2+	9/2+	7/2+	5/2+	9/2+	9/2+	11/2+	7/2+	7/2–	11/2–	13/2–
literature	5/2+	3/2+	?	3/2	5/2+	3/2+?	1/2–	?	?	(1/2, 3/2)–	?	?

BIG IMPROVEMENTS IN LEVEL IDENTIFICATIONS

Andy Knapton, Surrey PhD

Using the ^{25}Na SFs to calculate ^{24}Al(p,γ)^{25}Si widths and $\omega\gamma$'s for novae



Wiescher, Brown PRC52, 1078 (1995)
revised the rate for ^{24}Al(p,γ) upwards $\times 100$

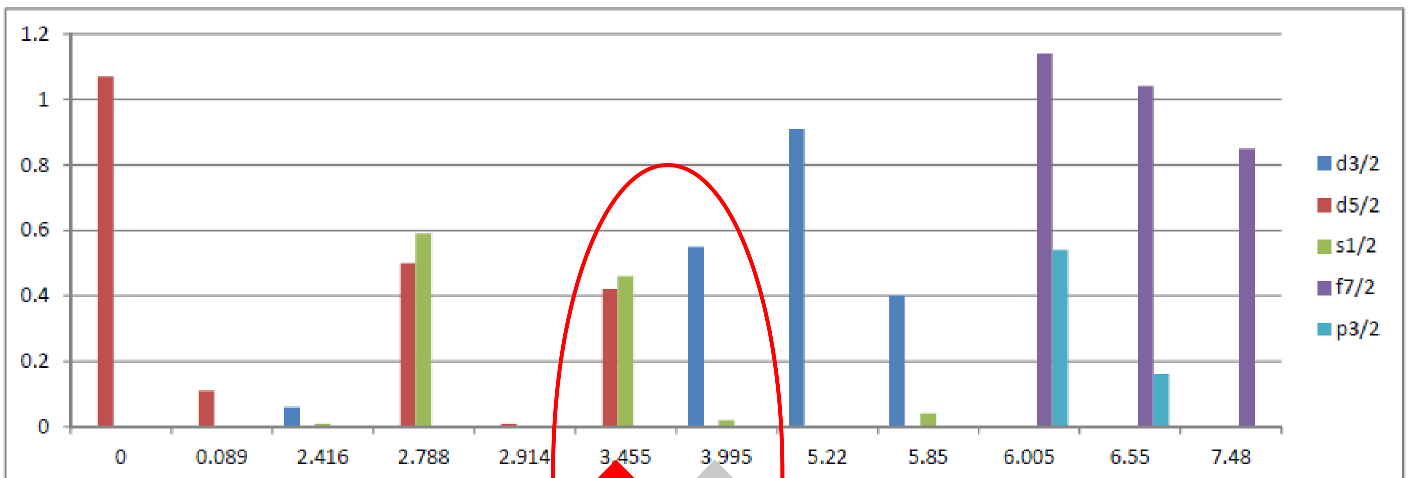
0.41 = 3.995 in ^{25}Na

resonance states in ^{25}Si

0.02 = 3.455 in ^{25}Na
(not considered important before, due to misidentification)

^{24}Al + p

this work
ADWA
std geom



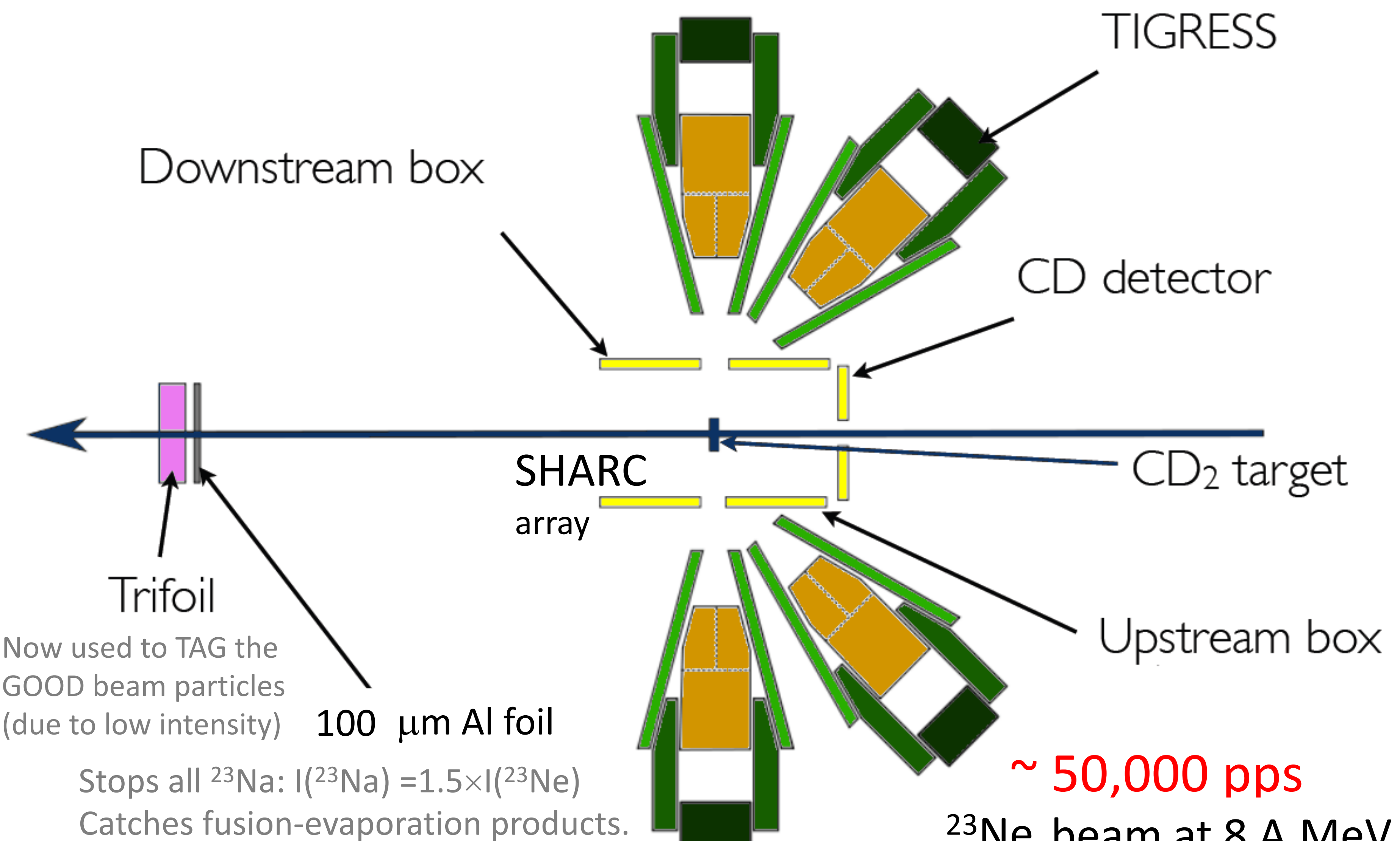
Excitation Energy in ^{25}Na (MeV)

present work	5/2+	3/2+	9/2+	7/2+	5/2+	9/2+	9/2+	11/2+	7/2+	7/2–	11/2–	13/2–
literature	5/2+	3/2+	?	3/2	5/2+	3/2+?	1/2–	?	?	(1/2, 3/2)–	?	?

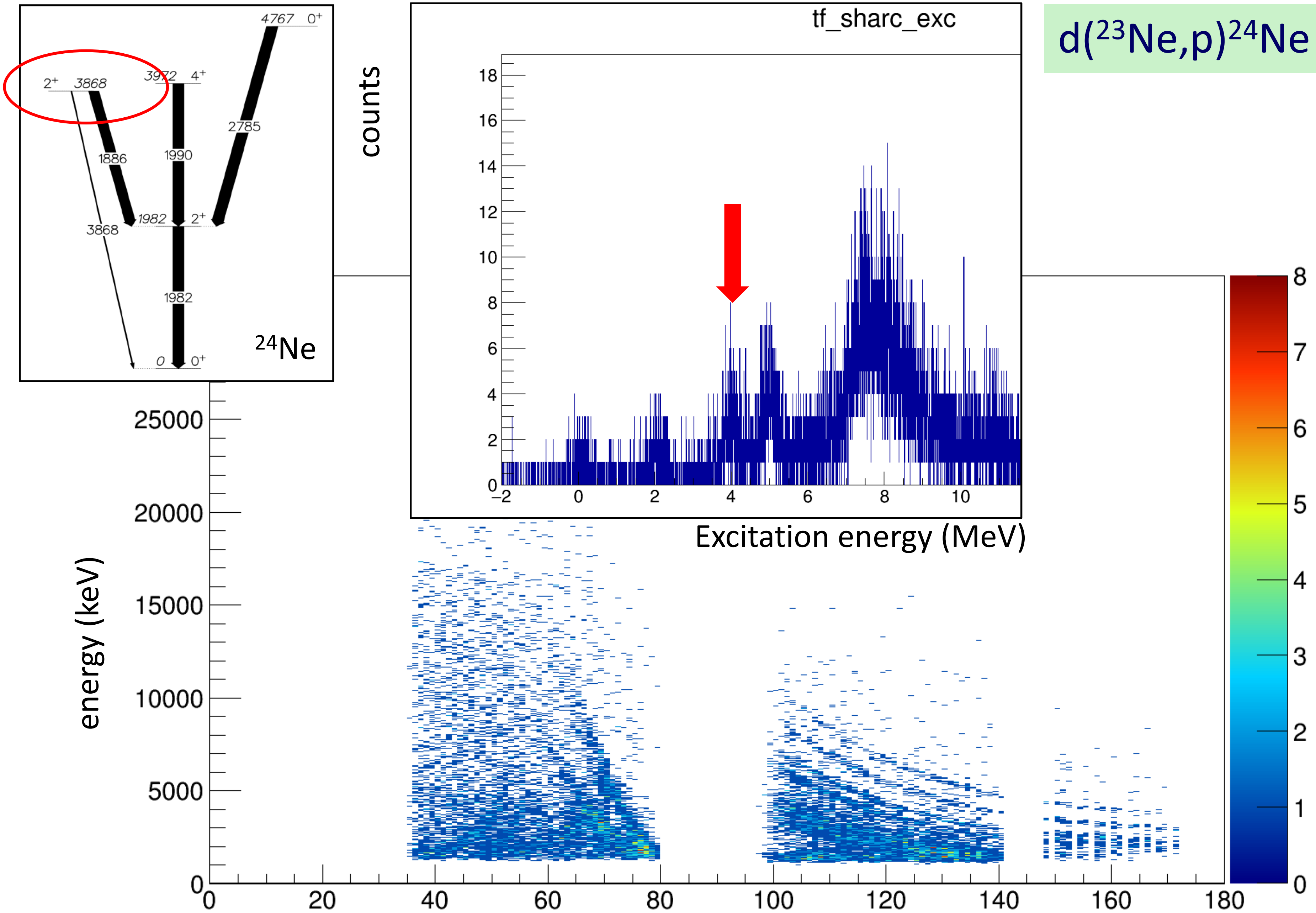
bound states in mirror ^{25}Na

Experimental Setup to Measure d(^{23}Ne,p)^{24}Ne at TRIUMF

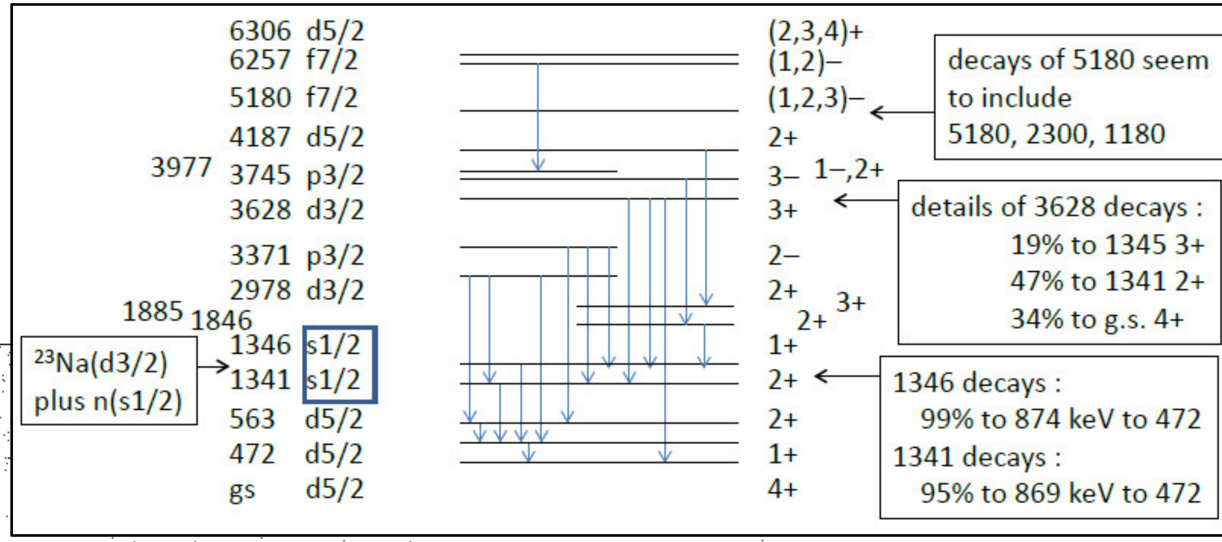
conjugate of ^{23}Al(p,γ)^{24}Si

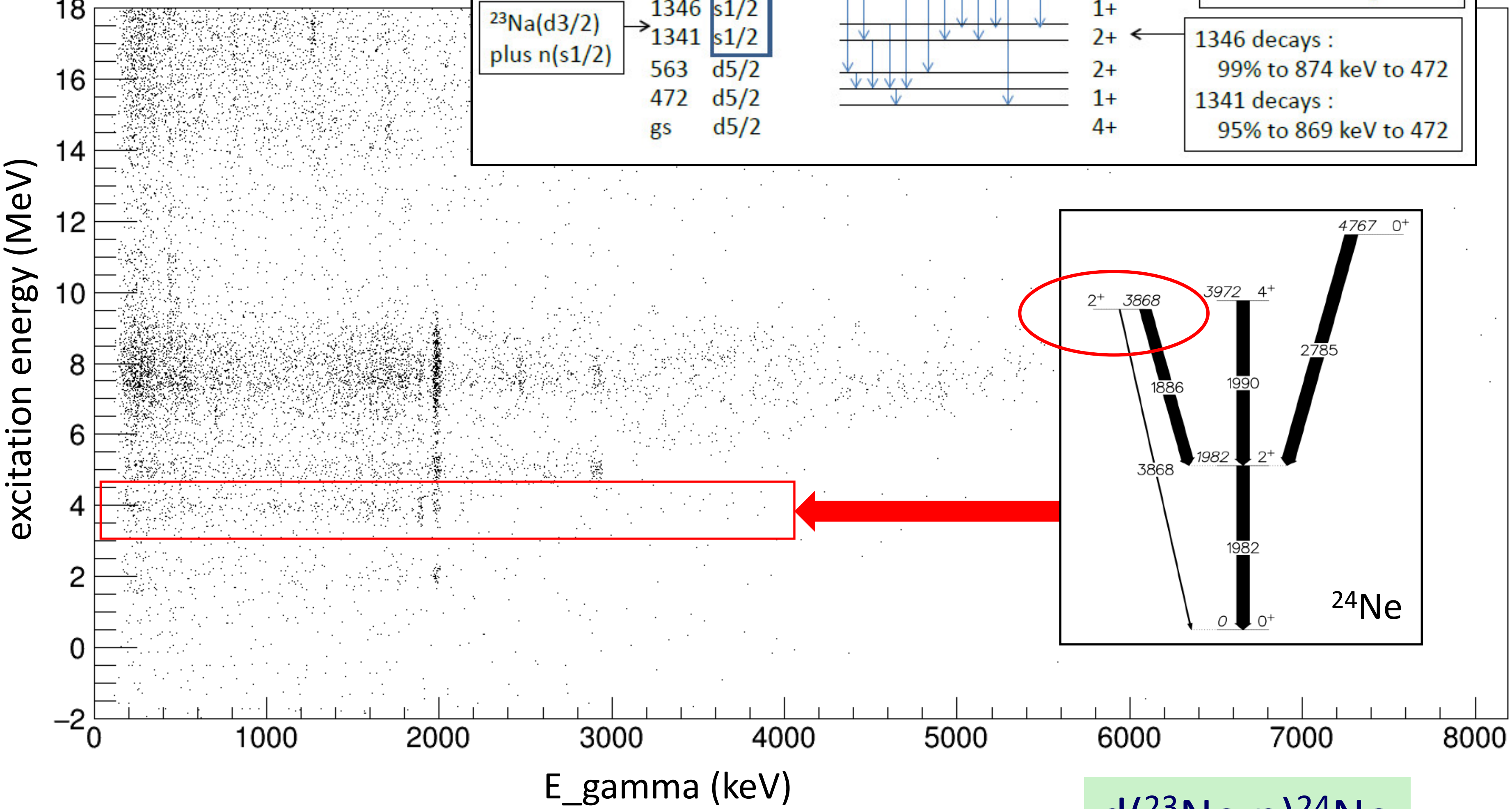


G Lotay, M Moukaddam, Surrey July 2017


d(^{23}Ne,p)^{24}Ne
^{24}Ne
4767 0+
2+ 3868
3972 4+
2785
1886
1990
1982 2+
3868
1982
0 0+
tf_sharc_exc
counts
Excitation energy (MeV)
energy (keV)
Laboratory angle (degrees)
ON-LINE RESULTS

- The ^{24}Na gamma-rays are eliminated.
- The ^{24}Ne gamma-rays indicate that ONLY the state of interest is made.





ON-LINE RESULTS

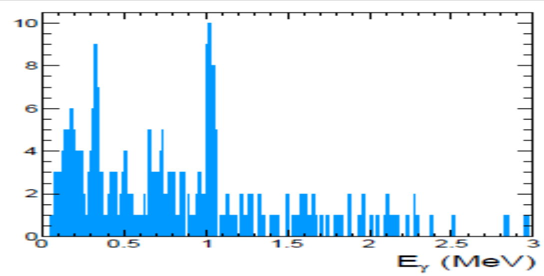
d(^{23}Ne,p)^{24}Ne

d(^{28}Mg,p)^{25}Na at 8.0 MeV/u with 3,000 pps

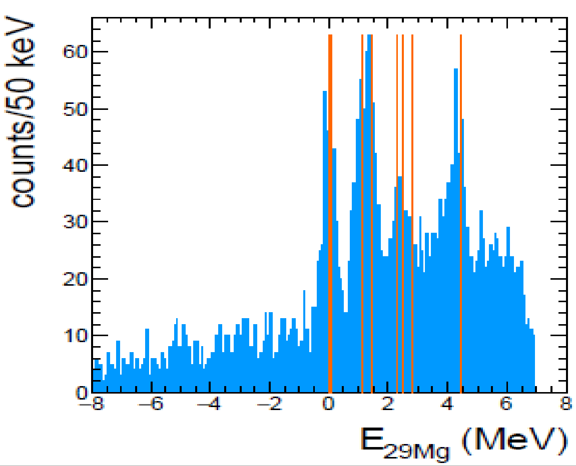
Secondary Beam

- ^{28}Mg beam 3000 pps at 8 AMeV
  → With strong contamination
  ^{28}Si cont. (3. 10^5 pps)
  ^{28}Al cont. (300 pps)

Gated Eγ

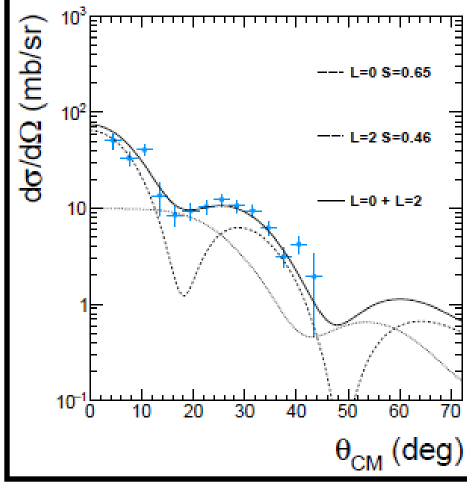


Gated Excitation Energy

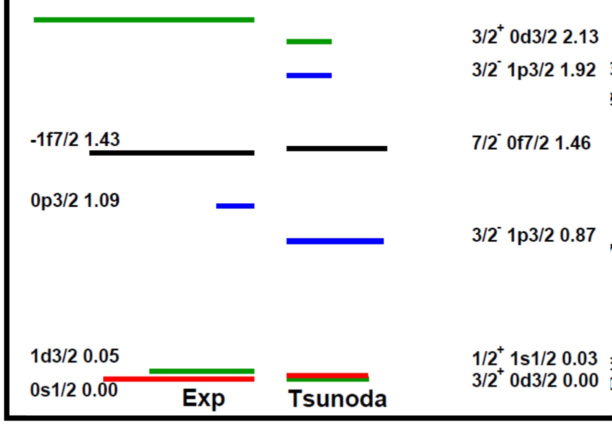


Experiment – SHARC and TIGRESS at TRIUMF

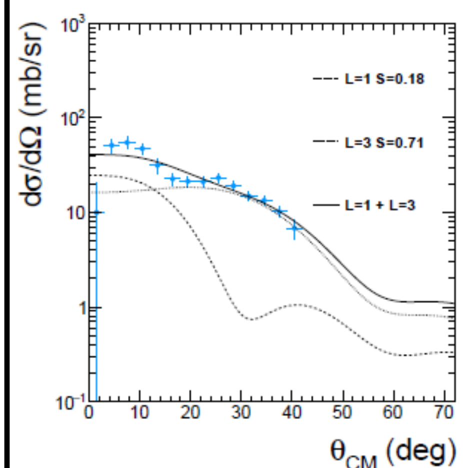
Ground State Doublet



Microscopic Shell Model



1 MeV Doublet

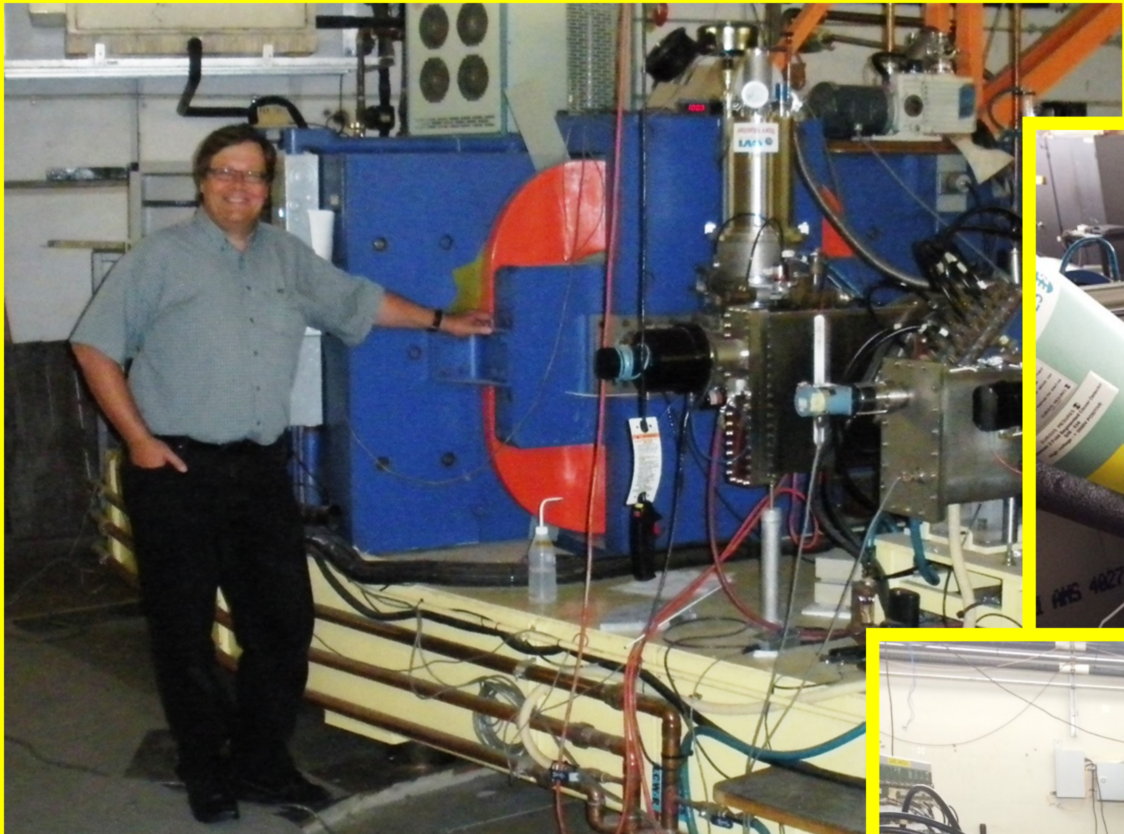


We have preliminary results from this experiment using a heavily contaminated beam.

New shell model calculations with realistic interactions and expanded sdpf model space… Tsunoda, Otsuka EEdf1 (EKK)

Too early to judge agreement.

Texas A&M– radioactive beams using gas catcher and cyclotron reacceleration



zero-degree detection using Oxford MDM

THE OXFORD MDM-2 MAGNETIC SPECTROMETER

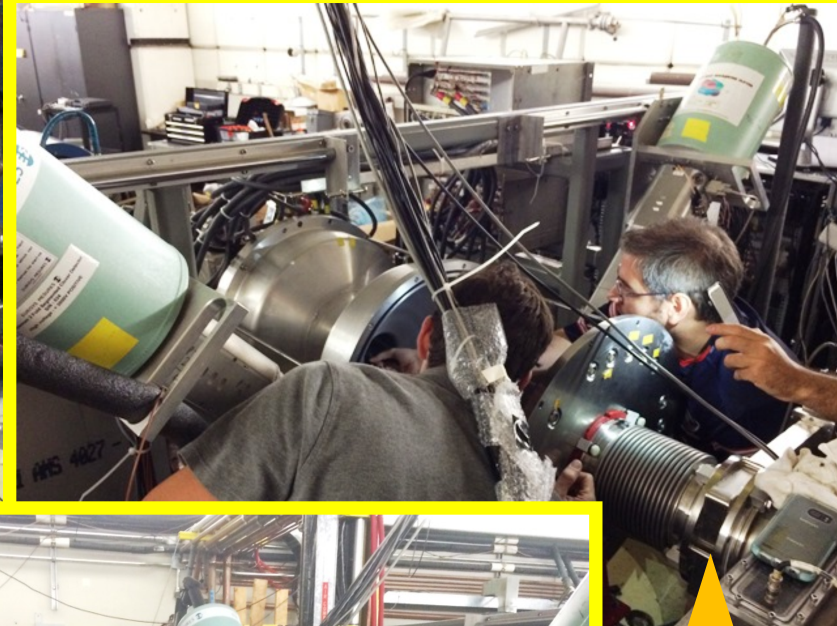
D.M. PRINGLE, W.N. CATFORD *, J.S. WINFIELD **, D.G. LEWIS, N.A. JELLEY and K.W. ALLEN

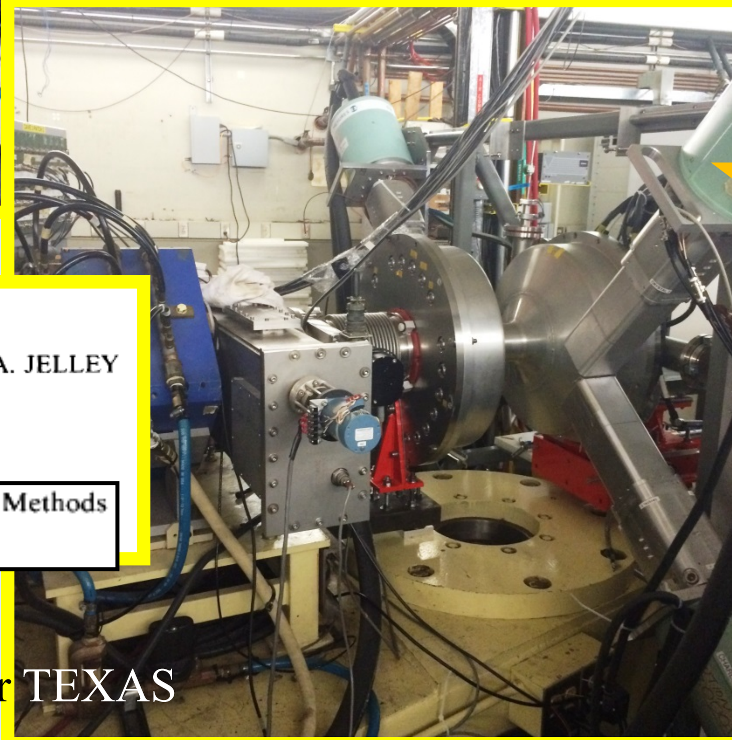
University of Oxford, Nuclear Physics Laboratory, Keble Road, Oxford, England

J.H. COUPLAND

Rutherford Appleton Laboratory, Chilton, Didcot, England

Nuclear Instruments and Methods
A245 (1986) 230





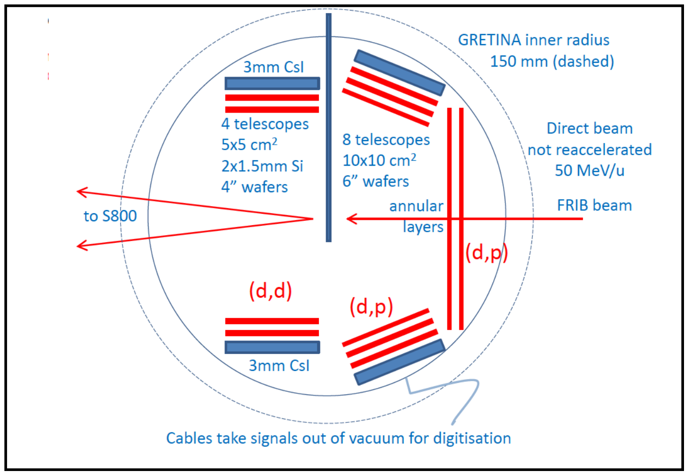
installed,
first run
Aug 2016

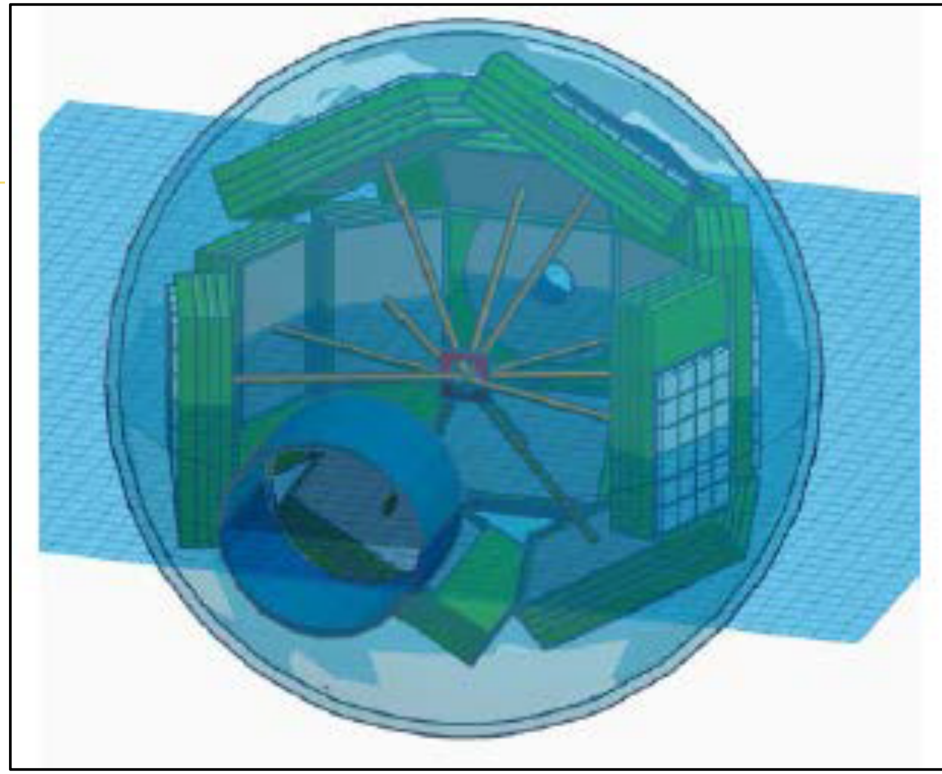
TIARA for TEXAS

FRIB

DRACULA

DIRECT REACTION ARRAY





- Propose to develop a new array consisting of silicon telescopes and annular detectors to cover light-particle emission angles, in front of the S800 spectrometer
- Detectors backed with CsI in order to provide adequate stopping for high-energy particles – exploit direct in-flight beam at 30-50 MeV/u.
- Placed inside GRETA gamma-ray tracking array
- Large number of channels (~1500) instrumented with 300 MHz digital electronics

Summary

UNIVERSITY OF SURREY

- We found that just outside the borders of the island of inversion, the shell model that was adapted for the island (i.e. USD-A, wbc) seems to work reasonably well – we have very useful discussions with those developing the new EEdf1 interaction

- Even in some less exotic nuclei, the selectivity of (d,p) has been shown to be hugely powerful in identifying the most interesting states (for the first time) e.g. ^{25}Na, and WE STUDY THE SAME orbitals and physics as in much more exotic nuclei.

- The relatively new technique of gating on the coincident gamma rays to separate states that are not otherwise resolved has worked well

- We are edging closer towards the island of inversion to test the shell model further and improve it, and have plans to move attention to the second island of inversion

- We are preparing for new availability of beams at Texas A&M (also HIE-ISOLDE and MUGAST at GANIL and hopefully DRACULA at FRIB)

COLLABORATORS FOR THIS WORK

UNIVERSITY OF SURREY

In Surrey:
Gavin Lotay, Dan Doherty, Mhd Moukaddam,
Adrien Matta (LPC Caen), Ryan Wilkinson, Sam Hallam,
Gemma Wilson, Andy Knapton, Ilker Can Celik

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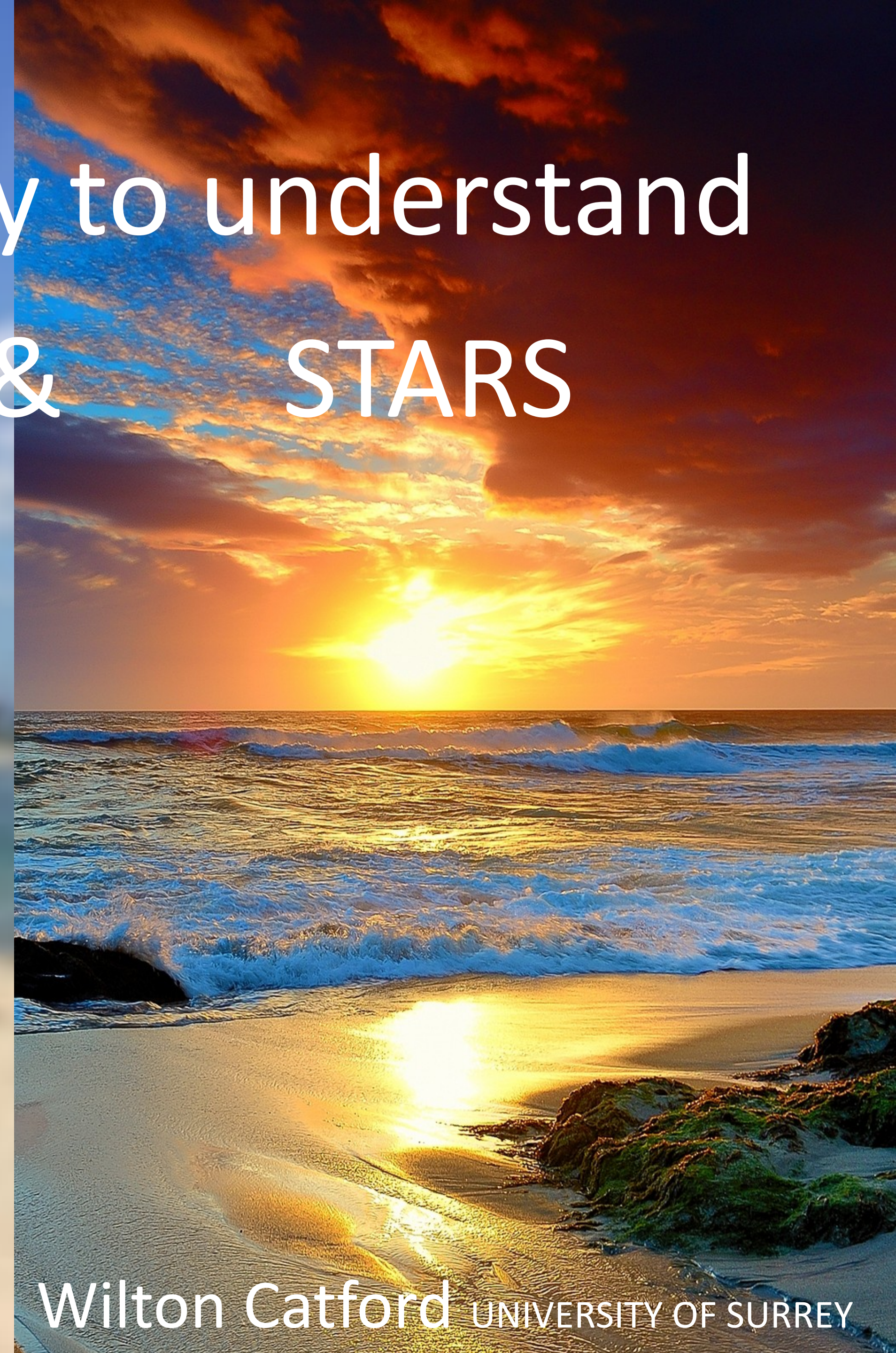
transfer as a way to understand

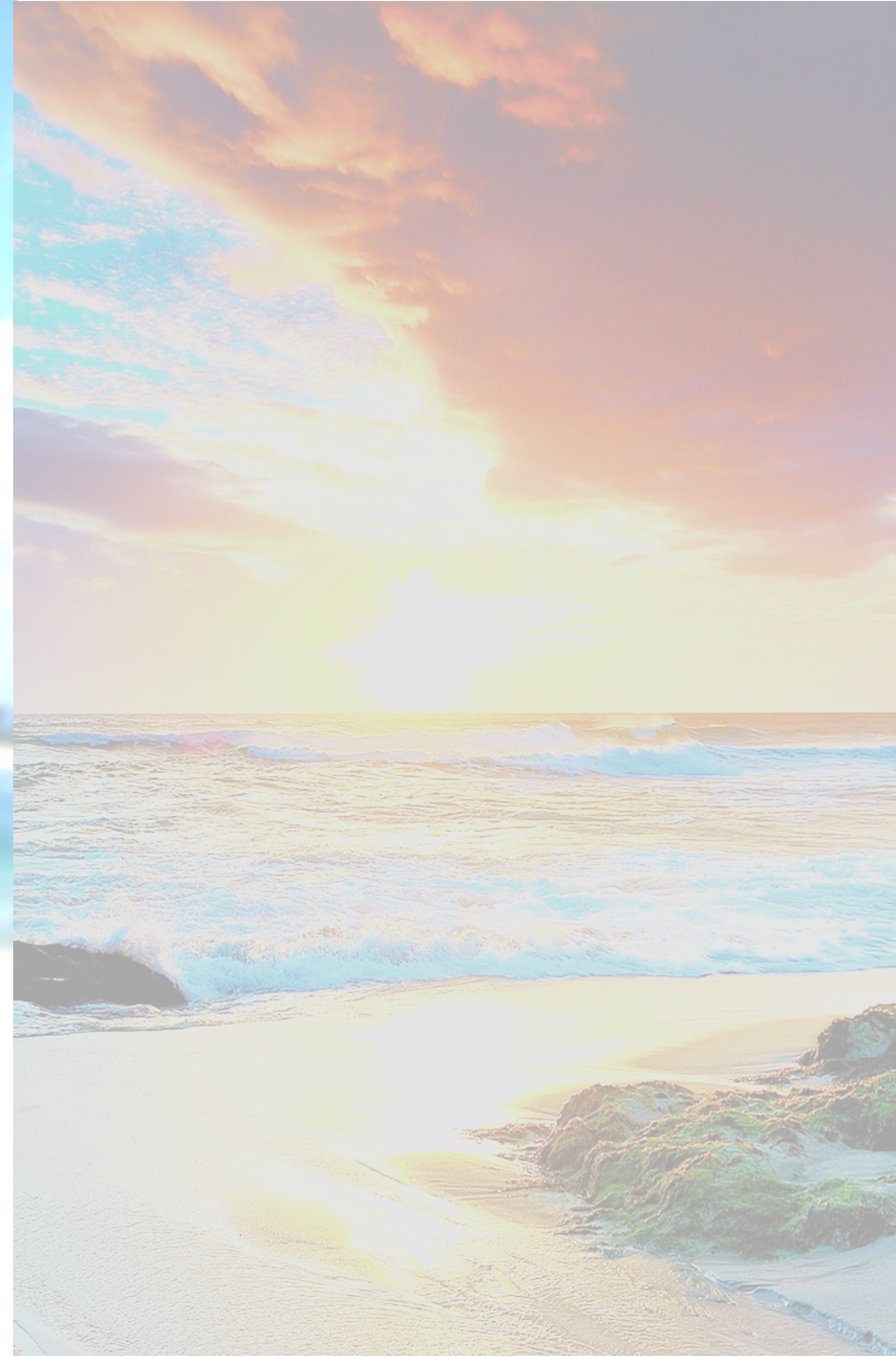
SHELLS & STARS



NuSPRASEN ENSAR2
Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

WARSAW, JAN 2018

Wilton Catford UNIVERSITY OF SURREY

REACTION MODEL FOR (d,p) TRANSFER – the ADWA

Spectroscopic Factor

Shell Model: overlap of $|\psi\,(N{+}1)\rangle$ **with** $|\psi\,(N)\rangle_{core} \otimes n\,(\ell\, j)$

Reaction: the observed yield is not just proportional to this, because the **overlap integral** has a radial-dependent weighting or sampling

Hence the **observed yield**
depends on the radial wave function
and thus
it depends on the geometry of the
assumed potential well
or other structure model

Many-body theory of $d + A(N,Z) \rightarrow B(N+1,Z) + p$

overlap integral

$$\phi_n^{BA}(\vec{r}_n) = \sqrt{N+1}\int d\xi_A \phi_B^*(\xi_A, \vec{r}_n)\phi_A(\xi_A)$$

spectroscopic factor

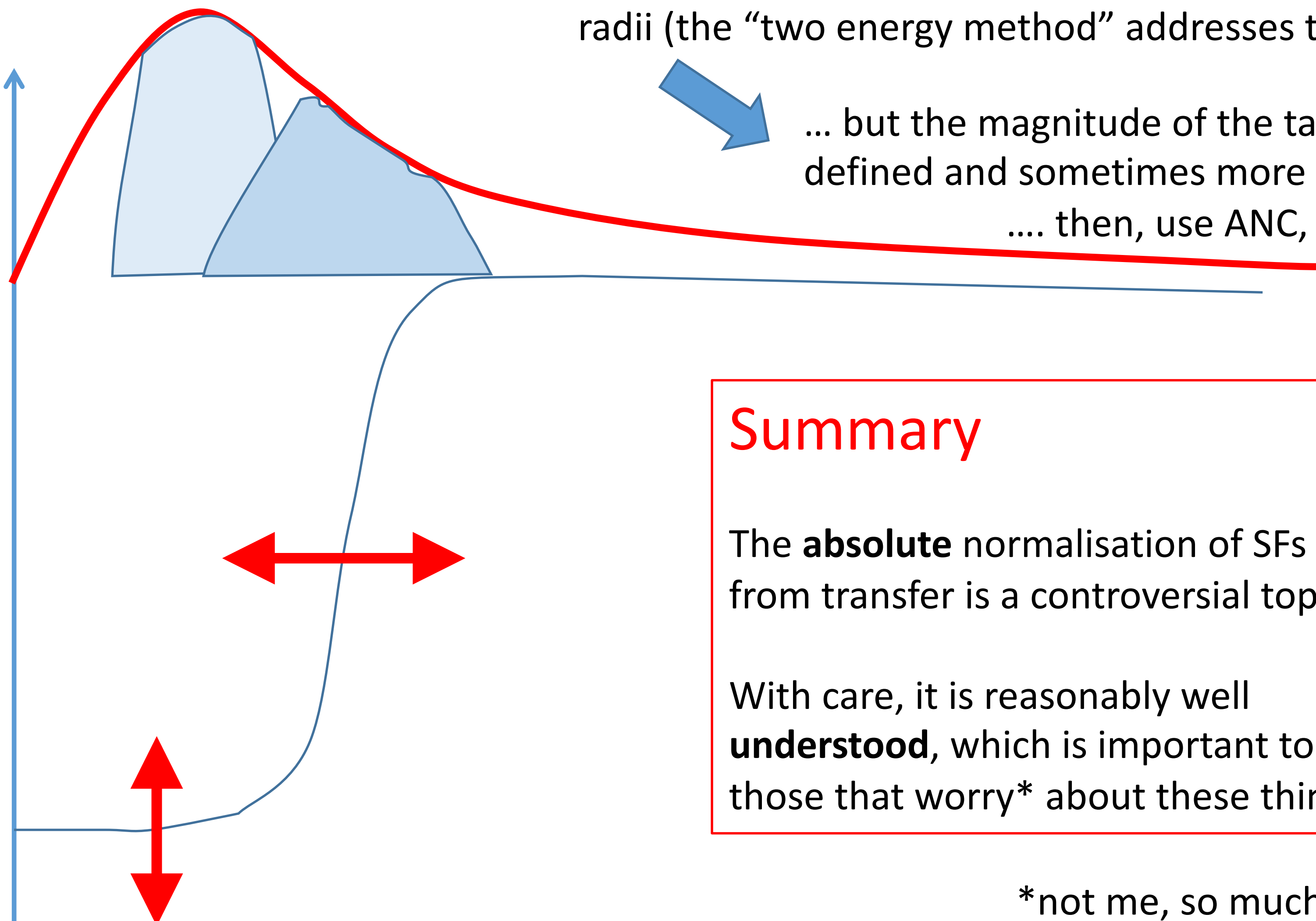
$$S^{AB} = \int d\vec{r}_n \, |\phi_n^{AB}(\vec{r}_n)|^2$$

$$T_{d,p} = \langle \chi_p^{(-)} \phi_n^{BA} | V_{np} | \Psi_{\vec{K}_d} \rangle$$

Different assumptions about the geometry of the binding for the transferred particle

… lead to different spectroscopic factors, and there is an energy dependence due to sampling at restricted radii (the “two energy method” addresses this)

… but the magnitude of the tail is better defined and sometimes more relevant – …. then, use ANC, not SF



Summary

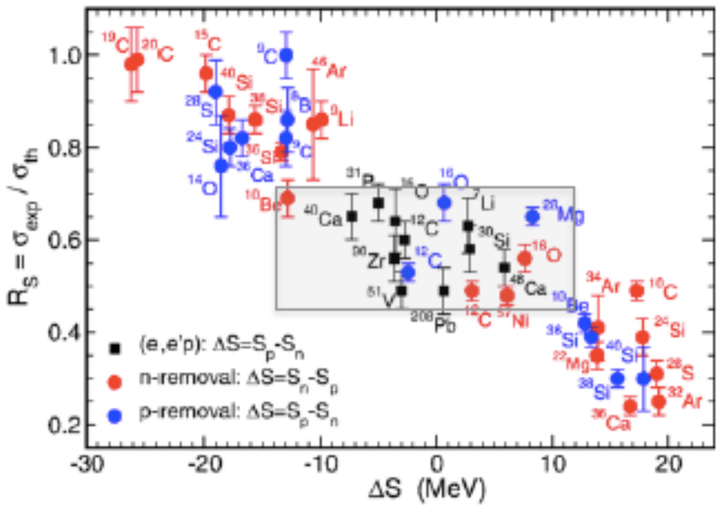
The **absolute** normalisation of SFs from transfer is a controversial topic

With care, it is reasonably well **understood**, which is important to those that worry* about these things

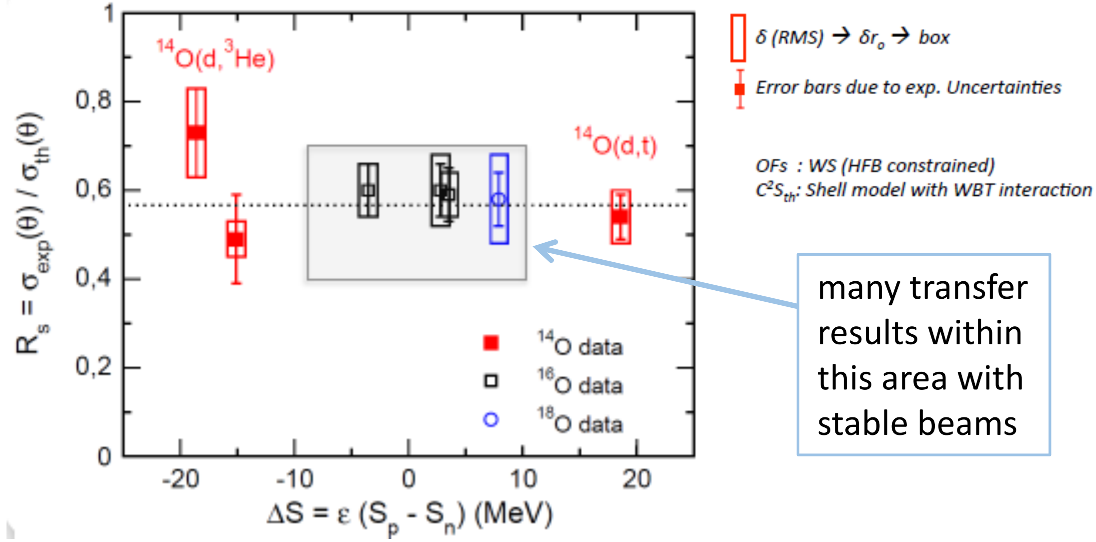
*not me, so much

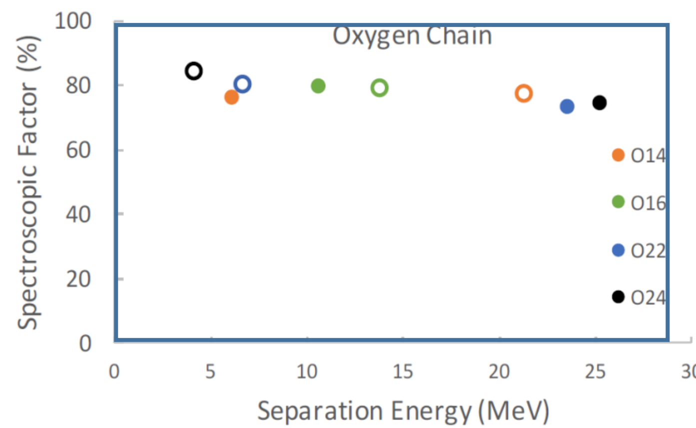
Freddy Flavigny - Slides 22/4/2016

J.A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014)



F. Flavigny *et al.*, Phys. Rev. Lett. **110**, 122503 (2013).





★ (p,2p)
supports GANIL transfer results
for ^{14}O, ^{16}O, ^{17}O, ^{21}O, ^{22}O, ^{23}O
Leila Atar, Monday

★ Ab initio structure (not reaction theory) ★
for ^{14}O, ^{16}O, ^{22}O, ^{24}O
Andrea Idini, Monday

Experimental Results from studying d(^{25}Na,p)^{26}Na at TRIUMF

Negative parity states

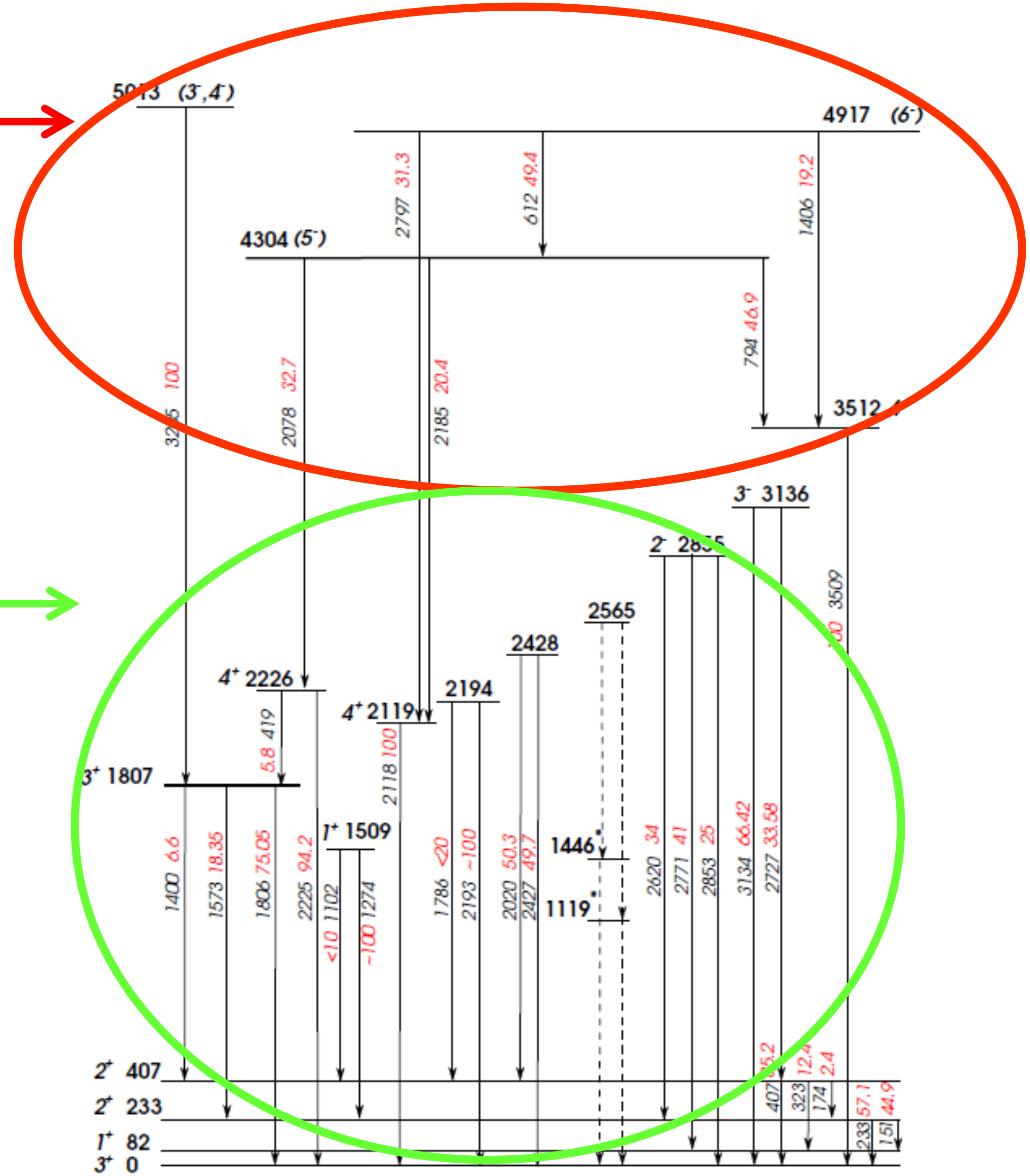
Levels never seen before, selected by (d,p)

Gamma-ray decay scheme
Gamma-ray branching ratios

Positive parity states

GATE on the gamma rays, take advantage of 30 keV energy resolution

CHECK that this does not bias the proton distribution
(gamma angular efficiency)



Experimental Results from studying d(^{25}Na,p)^{26}Na at TRIUMF

UPDATE

8 new states
plus
4 new ℓ values

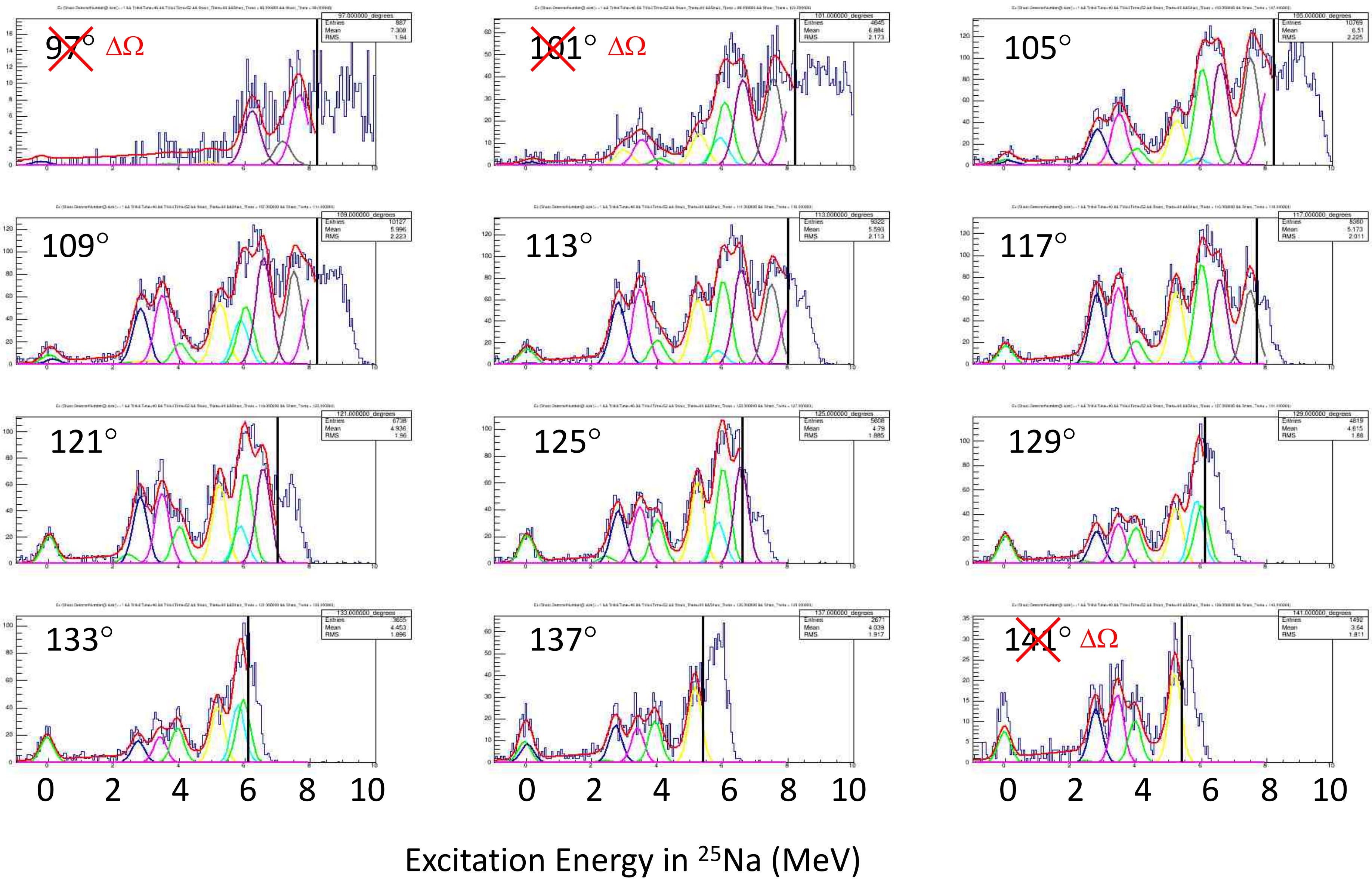
IMPROVED
background
subtraction

NEW
gamma-ray
angular
correlations

I.C. Celik
PhD thesis
Surrey 2015

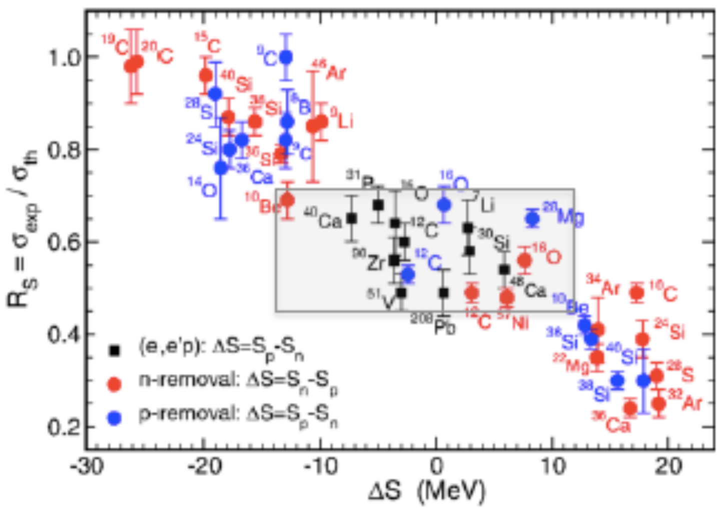
					single L analysis				two L analysis (where applicable)							
No.	E_x a)	E_x^{SM} b)	J^π c)	J^π_{SM}	L	nlj	S	S^{SM}	L_1	$n_1l_1j_1$	S_1	S_1^{SM}	L_2	$n_2l_2j_2$	S_2	S_2^{SM}
	0	0	3^+	3^+_1	*	$1s_{1/2}$		0.61	*	$1s_{1/2}$		0.61	*	$0d_{3/2}$		0.01
														$0d_{5/2}$		0.01
	0.082 d)	0.077	1^+	1^+_1	*	$0d_{3/2}$		0.29								
						$0d_{5/2}$		0.11								
	0.232	0.149	2^+	2^+_1	0	$1s_{1/2}$	0.13	0.15	0	$1s_{1/2}$	0.10	0.15	2	$0d_{3/2}$	0.19†	0.10
														$0d_{5/2}$		0.09
	0.405	0.416	2^+	2^+_2	0	$1s_{1/2}$	0.33	0.27	0	$1s_{1/2}$	0.30	0.27	2	$0d_{5/2}$	0.13†	0.03
														$0d_{3/2}$		0.03
	1.507	1.409	1^+	1^+_2	2	$0d_{3/2}$	0.39	0.09								
						$0d_{5/2}$		0.10								
	1.805	1.676	(3^+)	3^+_2	2	$0d_{3/2}$	0.37	0.33	2	$0d_{3/2}$	0.33†	0.33	0	$1s_{1/2}$	0.01‡	0.00
						$0d_{5/2}$		0.02	2	$0d_{5/2}$		0.02				
	1.992	1.758	4^+	4^+_1	2	$0d_{3/2}$	0.07	0.07								
	2.116	2.241	5^+	5^+_1	2	$0d_{5/2}$	0.16	0.08								
	2.195	2.142	2^+	2^+_3	2	$0d_{3/2}$	0.49	0.06								
	2.225	2.048	(4^+)	4^+_2	2	$0d_{3/2}$	0.43	0.51								
						$0d_{5/2}$		0.01								
	2.423	2.452	2^+	2^+_4					0	$1s_{1/2}$	0.00	0.13	2	$0d_{3/2}$	0.14	0.23
	2.843	2.936	(2^-)	2^-_1	3	$1p_{3/2}$		0.20	3	$0f_{7/2}$	1.10	0.20	1	$1p_{3/2}$	0.10	0.05
						$0f_{5/2}$		0.00		$0f_{5/2}$		0.00		$1p_{1/2}$		0.04
	3.135	3.228	3^-	3^-_1	1	$1p_{3/2}$	0.07†	0.15	1	$1p_{3/2}$	0.06†	0.15	3	$0f_{7/2}$	0.10‡	0.13
						$1p_{1/2}$		0.02		$1p_{1/2}$		0.02		$0f_{5/2}$		0.00
	3.511	3.513	4^-	4^-_1	1	$1p_{3/2}$	0.30	0.44	1	$1p_{3/2}$	0.25	0.44	3	$0f_{7/2}$	0.51†	0.00
														$0f_{5/2}$		0.00
	4.087	3.690	2^-	2^-_2	3				1	$1p_{3/2}$	0.34	0.31	3	$0f_{7/2}$	0.78	0.03
	4.239	3.975	4^+	4^+_5	2	$0d_{3/2}$	0.12	0.12								
	4.305	4.401	(5^-)	5^-_1	3				1	$1p_{3/2}$	0.01	0.00	3	$0f_{7/2}$	0.25	0.46
	4.597	4.460	3^-	3^-_2	3	$0f_{7/2}$			1	$1p_{3/2}$	0.02	0.10	3	$0f_{7/2}$	0.76	0.10
	4.800	4.730	4^-	4^-_2	3	$0f_{7/2}$			1	$1p_{3/2}$	0.00	0.05	3	$0f_{7/2}$	0.62	0.37
	4.917	4.881	(6^-)	6^-_1	3	$0f_{7/2}$	0.51	0.61								
	4.932	4.770	3^-	3^-_4	3	$0f_{7/2}$			1	$1p_{3/2}$	0.00	0.28	3	$0f_{7/2}$	0.63	0.05
	5.009		$(3^-,4^-)$		*											

d(^{24}Na,p)^{25}Na – fits to excitation energy spectrum at each angle

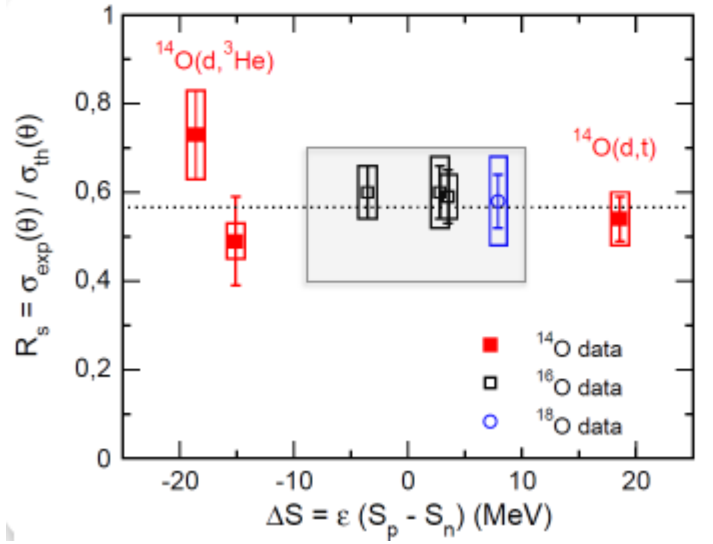


Andy Knapton, Surrey PhD

J.A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014)



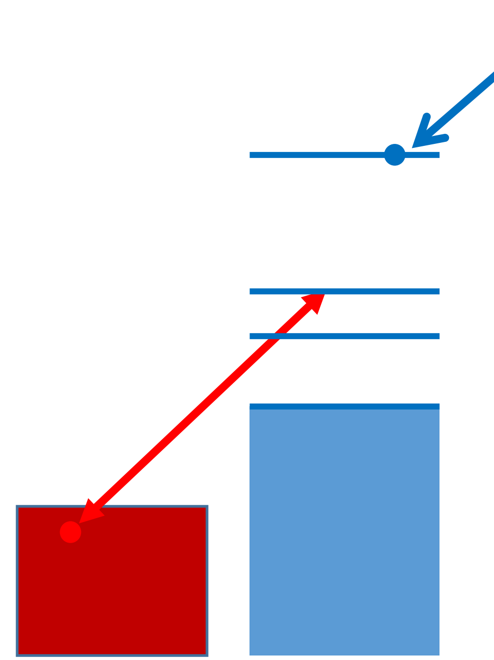
F. Flavigny *et al.*, Phys. Rev. Lett. **110**, 122503 (2013).

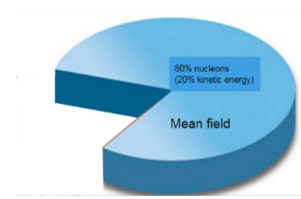


Transfer

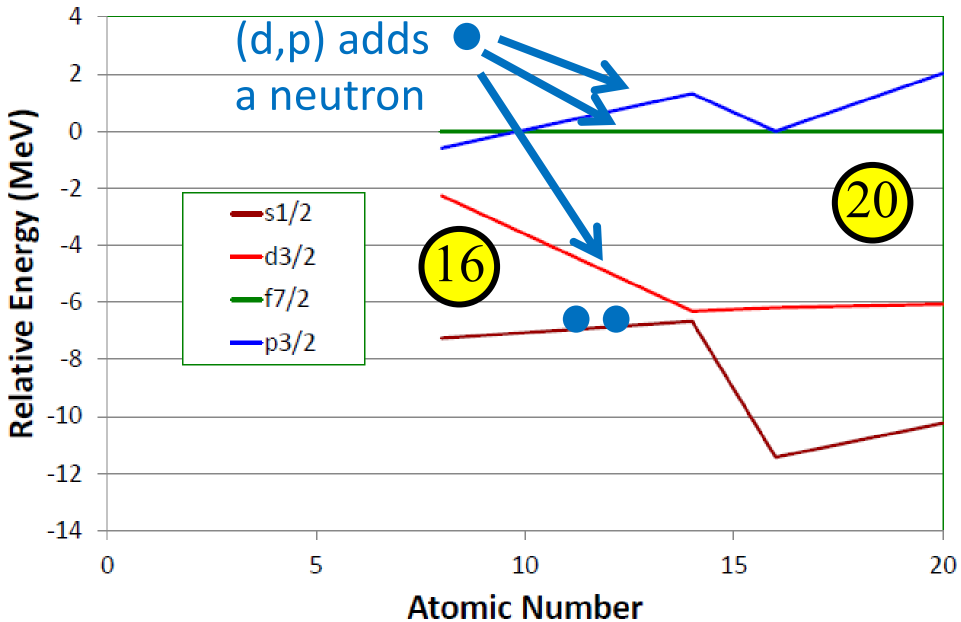
Some "conflict" with knockout, understanding quenched SFs, possible effect of correlations…

An excellent tool to uncover and study the evolution of nuclear structure produced via the mean field and the 85% of the physics





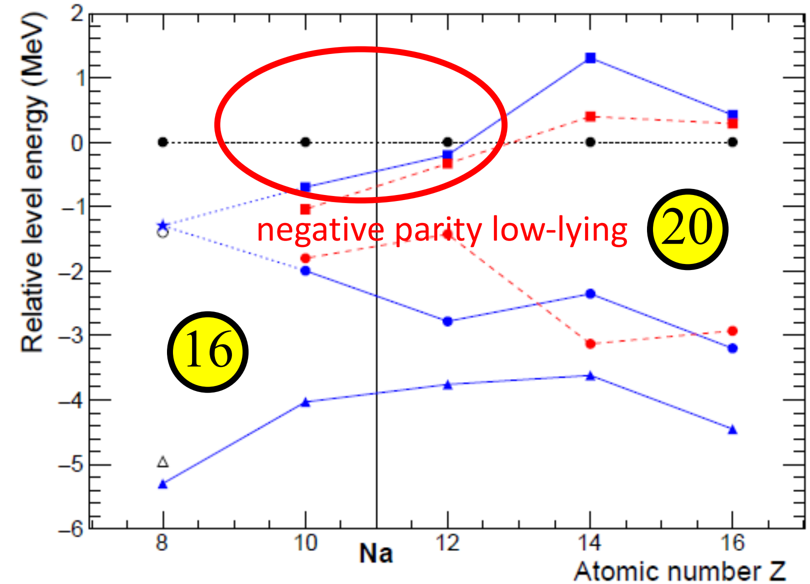
Theory: effective spe's



PRL **104**, 012501 (2010)

Otsuka et al.

Experiment: energies of just the lowest levels



PLB (2016) N=15 and 17 isotones

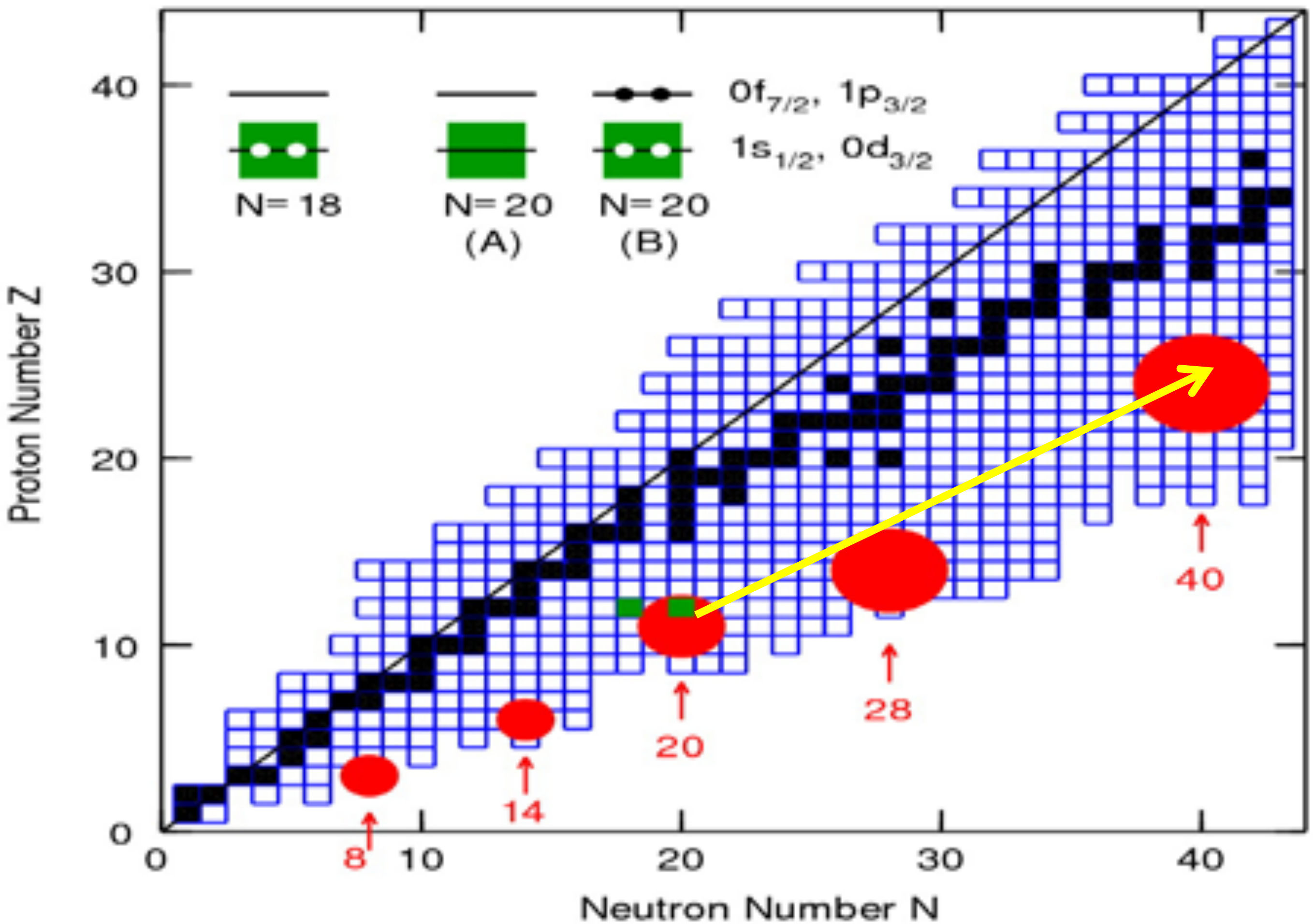
http://dx.doi.org/10.1016/j.physletb.2016.05.093

G.L. Wilson et al.

- Our aim is to identify single-particle-like levels and determine their spin/parity
- We use the selective nature of (d,p) neutron transfer (with radioactive beams)
- We aim to track the evolution of these levels and compare to the shell model

Future plans – d(^{60}Cr,p)^{61}Cr at 10.0 MeV/u

We have plans to move towards studying the second island of inversion e.g. via ^{60}Cr(d,p) at Texas A&M…



reduced gap $\nu(f_{5/2}\text{-}g_{9/2})$ with depleted $\pi(f_{7/2})$

reduced gap $\nu(d_{3/2}\text{-}f_{7/2})$ with depleted $\pi(d_{5/2})$

B.A. Brown, http://link.aps.org/doi/10.1103/Physics.3.104