UNIVERSITY OF SURREY
Department of Physics

Exploring Nuclear Shell Evolution with Nucleon Transfer Reactions

W.N. Catford[1], A. Matta[1], N.A. Orr[2], A.J. Knapton[1], I.C. Celik[1], G.L. Wilson[1], G. Lotay[1], B. Fernández Domínguez[3], C. Aa. Diget[4], G. Hackman[5]

and the TIARA and SHARC/TIGRESS collaborations

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WILTON CATFORD

University of Surrey, UK

Experiments performed at TRIUMF
and at Texas A&M University, USA

Inpc 2016
International Nuclear Physics Conference
Adelaide Convention Centre, Australia
11-16 September 2016

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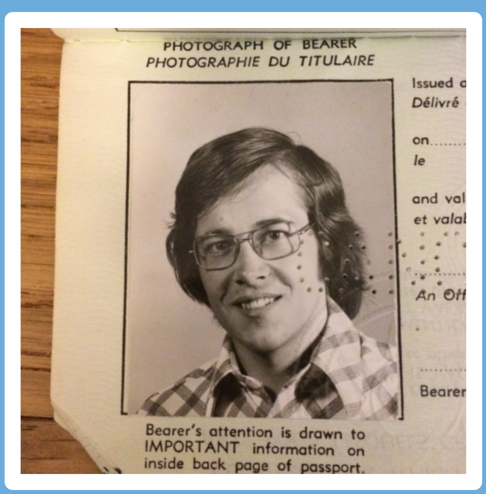
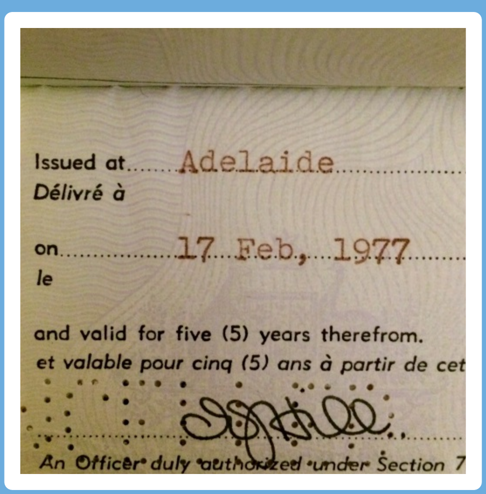




Adelaide, 1977

WILTON CATFORD

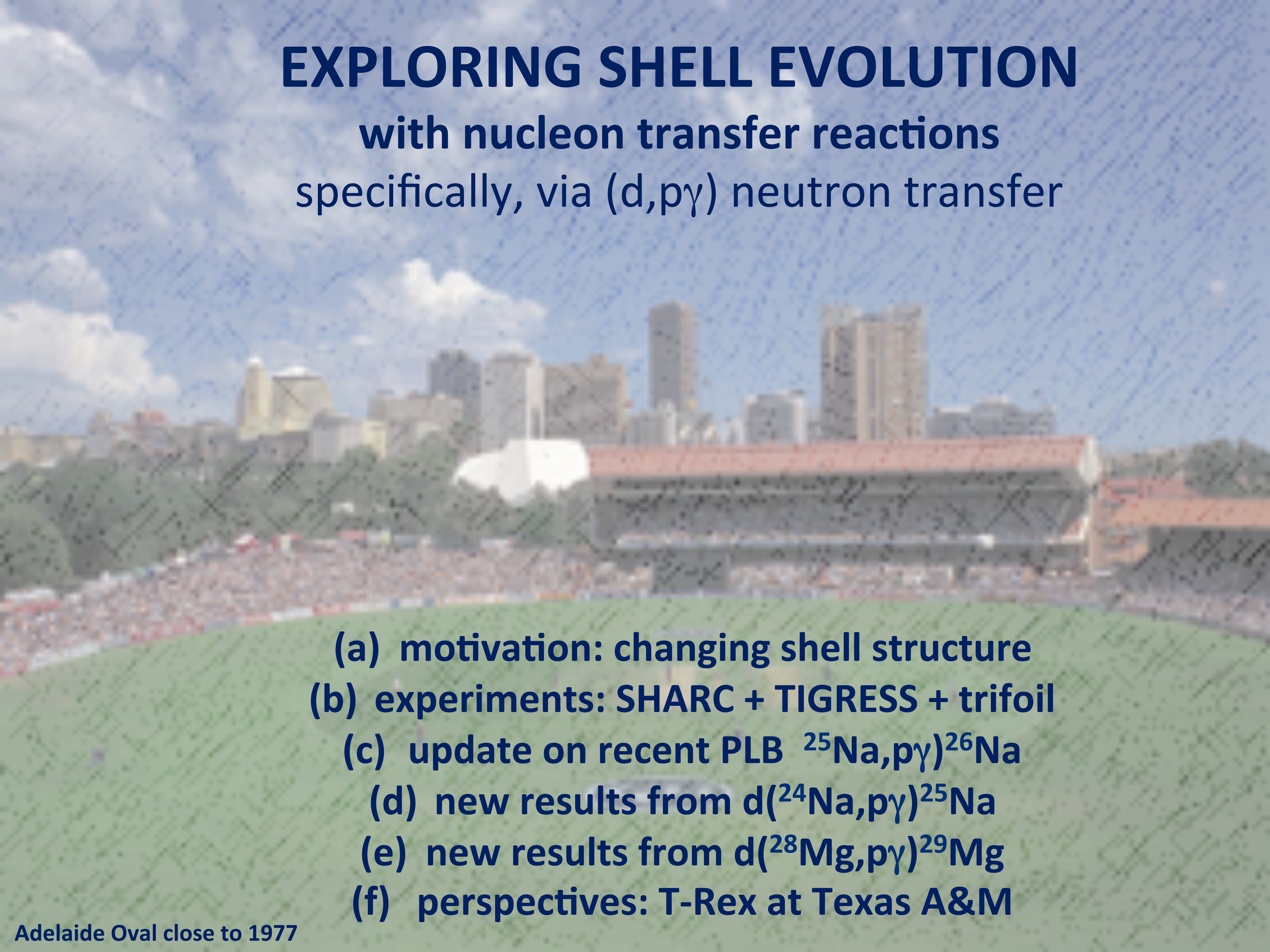
University of Surrey, UK

Experiments performed at TRIUMF
and at Texas A&M University, USA

EXPLORING SHELL EVOLUTION

with nucleon transfer reactions

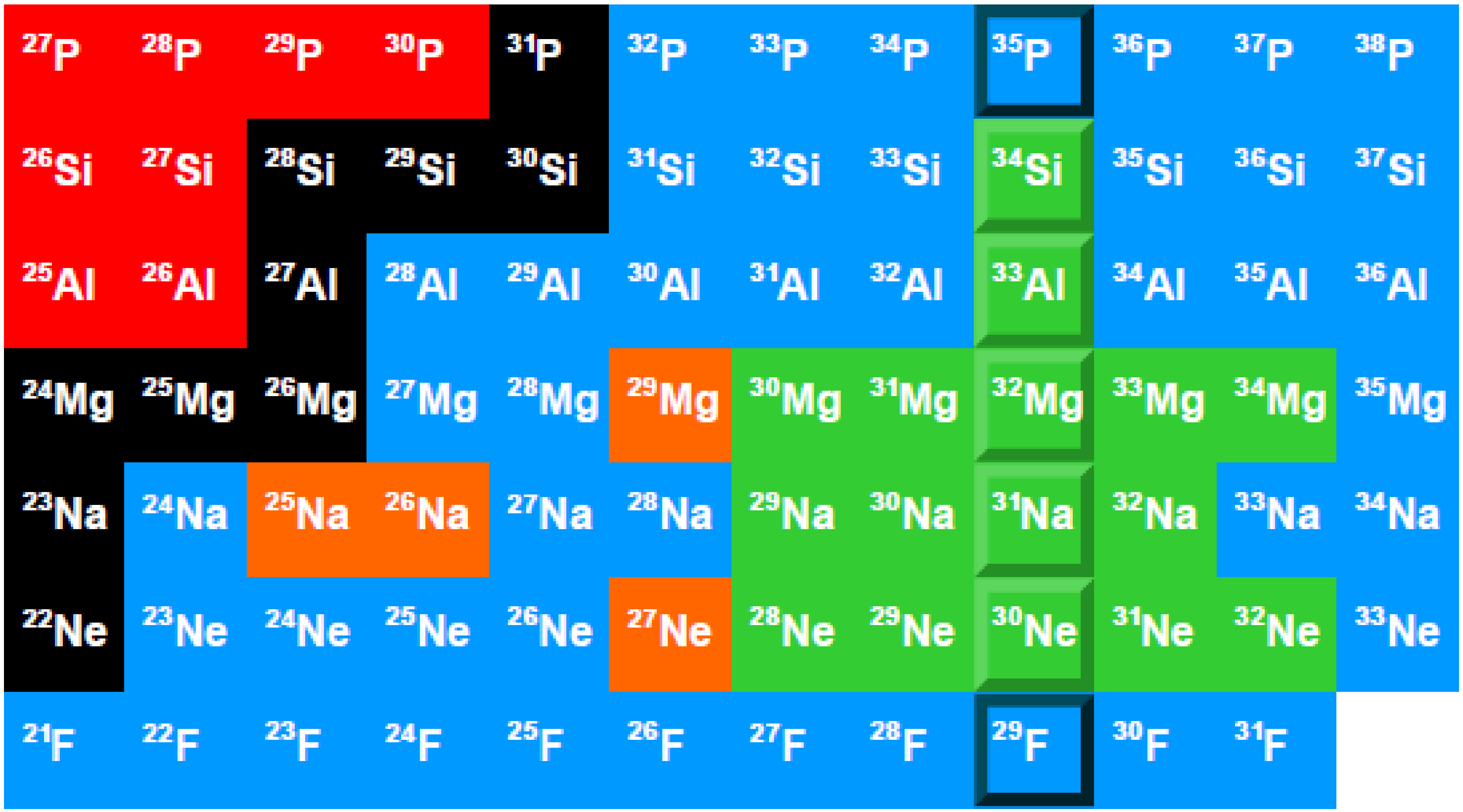
specifically, via (d,pγ) neutron transfer



(a) motivation: changing shell structure
(b) experiments: SHARC + TIGRESS + trifoil
(c) update on recent PLB ^{25}Na,pγ)^{26}Na
(d) new results from d(^{24}Na,pγ)^{25}Na
(e) new results from d(^{28}Mg,pγ)^{29}Mg
(f) perspectives: T-Rex at Texas A&M

Adelaide Oval close to 1977

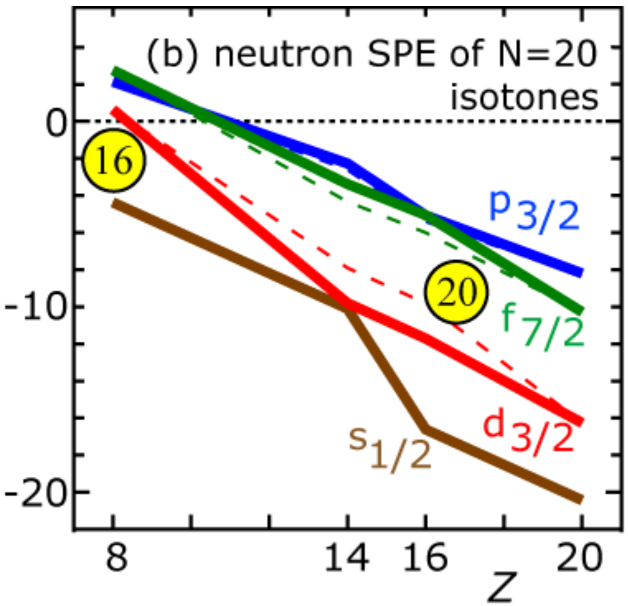
Region of Interest – Approaching the Island of Inversion



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

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

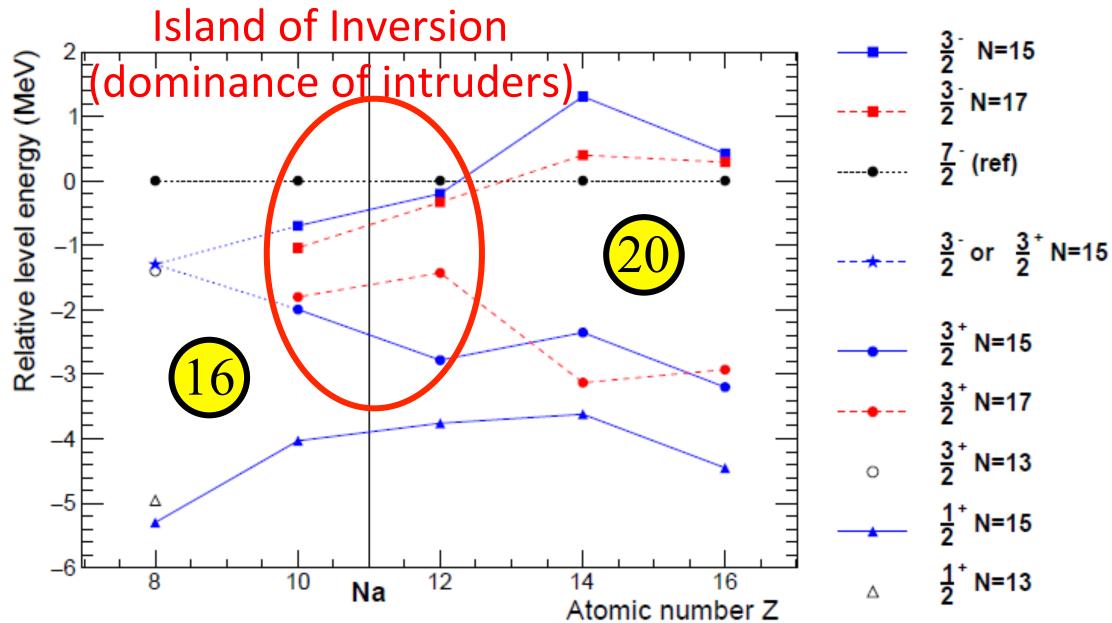
Theory: effective spe's



PRL 104, 012501 (2010)

Otsuka et al.

Experiment: energies of just the lowest levels



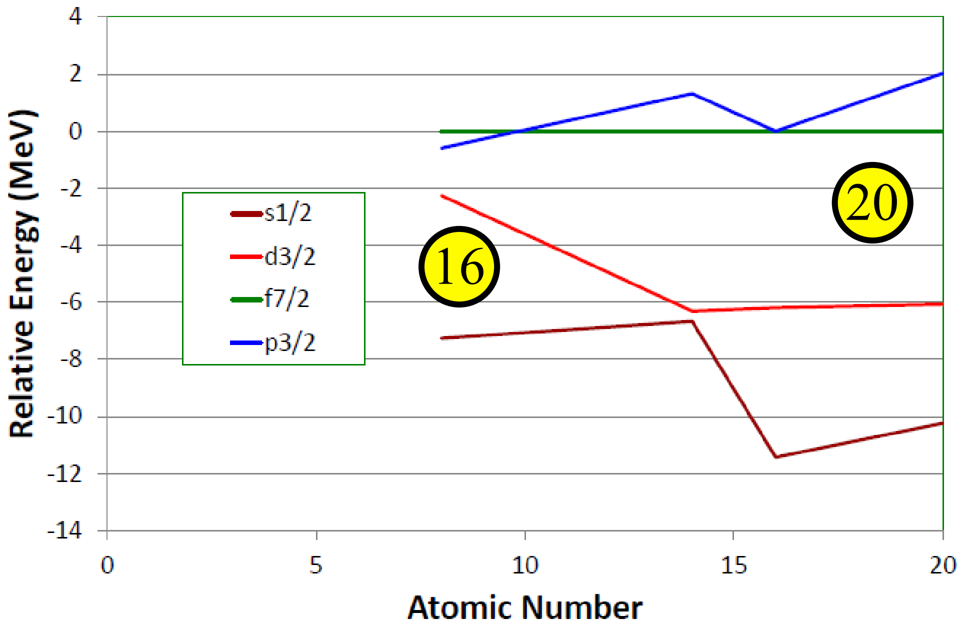
PLB (2016) N=15 and 17 isotones

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

G.L. Wilson et al.

Theory: effective spe's

Experiment: energies of just the lowest levels



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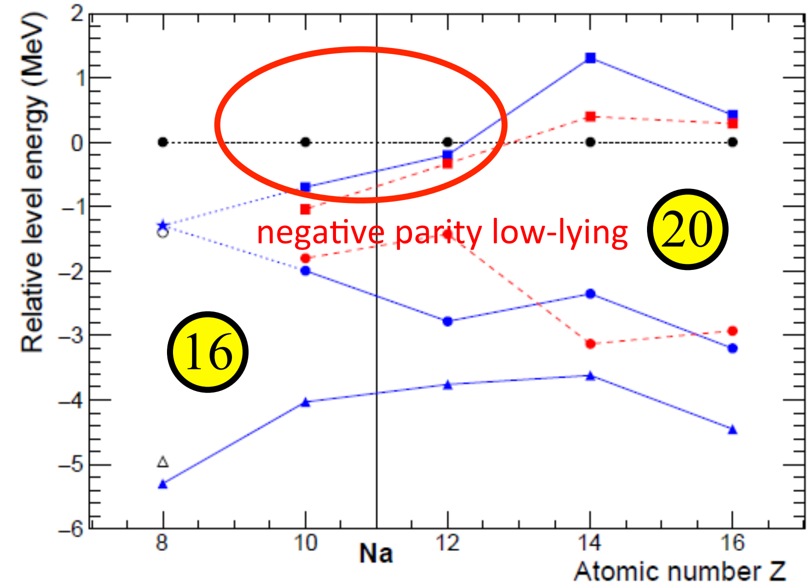
Otsuka et al.



PLB (2016) N=15 and 17 isotones

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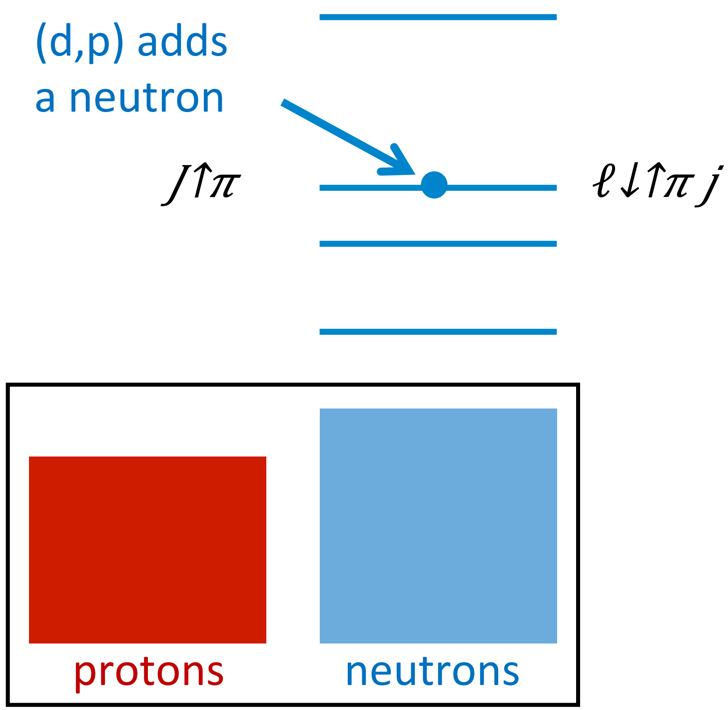
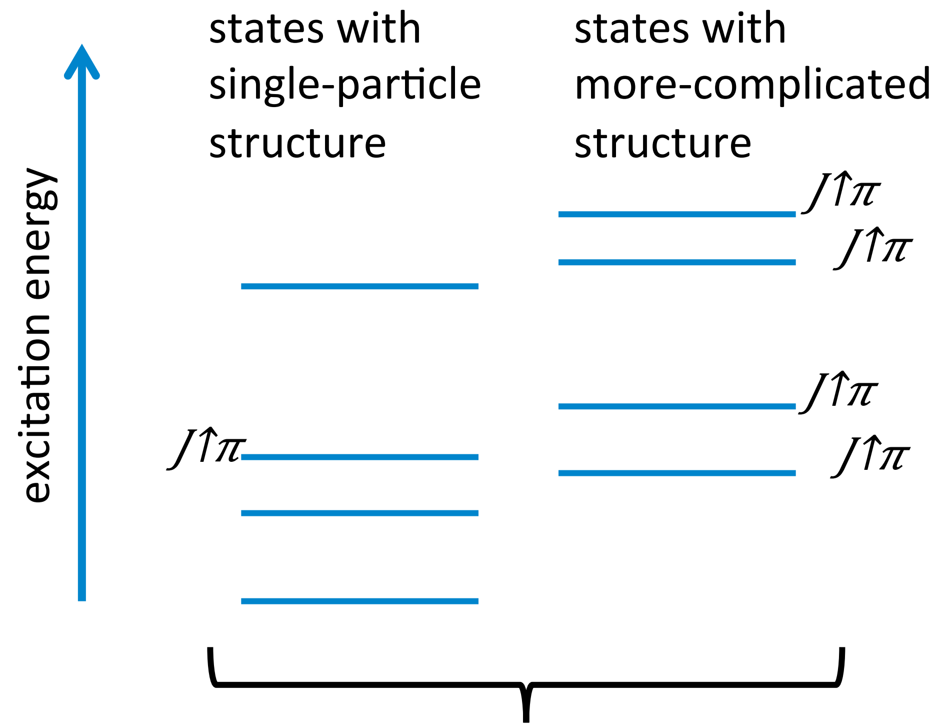
G.L. Wilson et al.

- 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



single-particle state,
unperturbed core
(idealized situation)

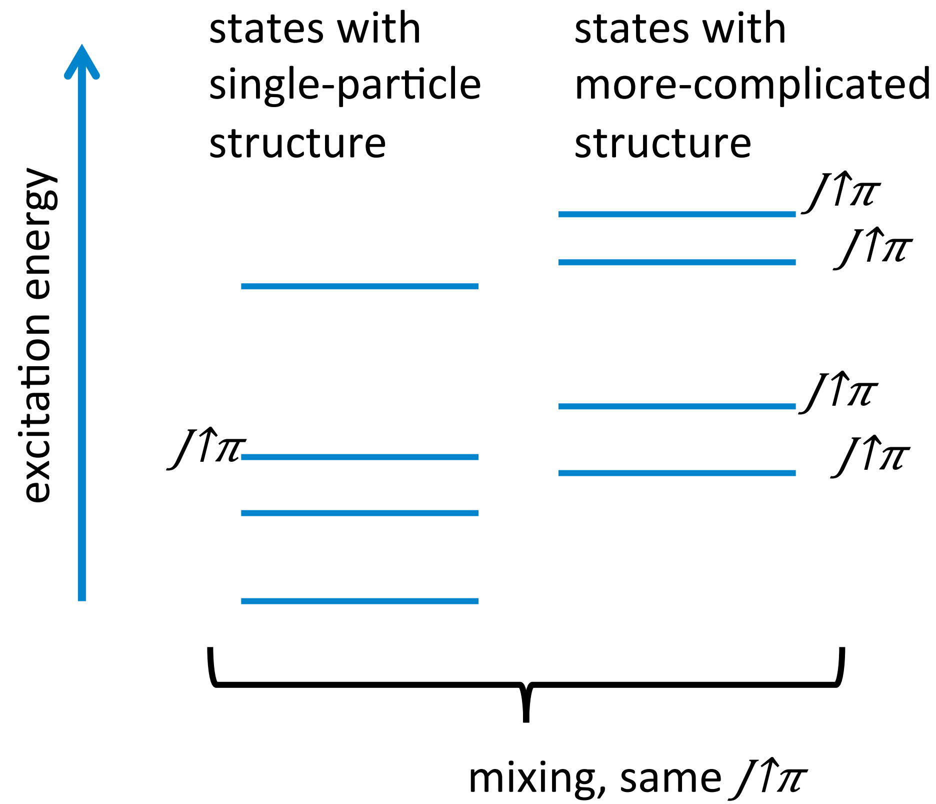


mixing, same J^π

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

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

spectroscopic factor
= overlap with pure SP state



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

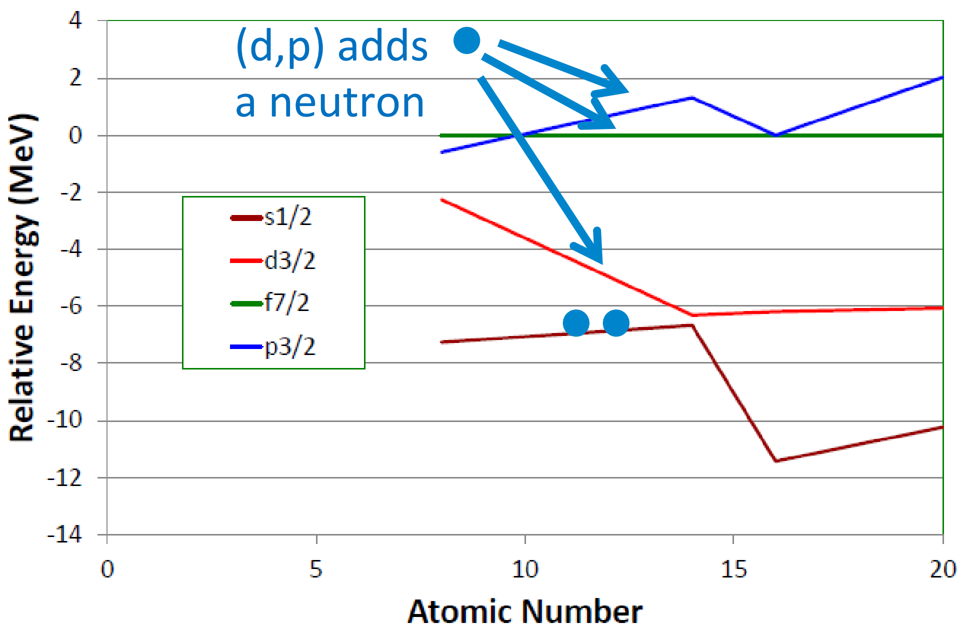
- we measure transferred ℓ_n
- we measure gamma-decays
- we aim to identify J and π
- we deduce S

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

spectroscopic factor
= overlap with pure SP state

Theory: effective spe's

Experiment: energies of just the lowest levels



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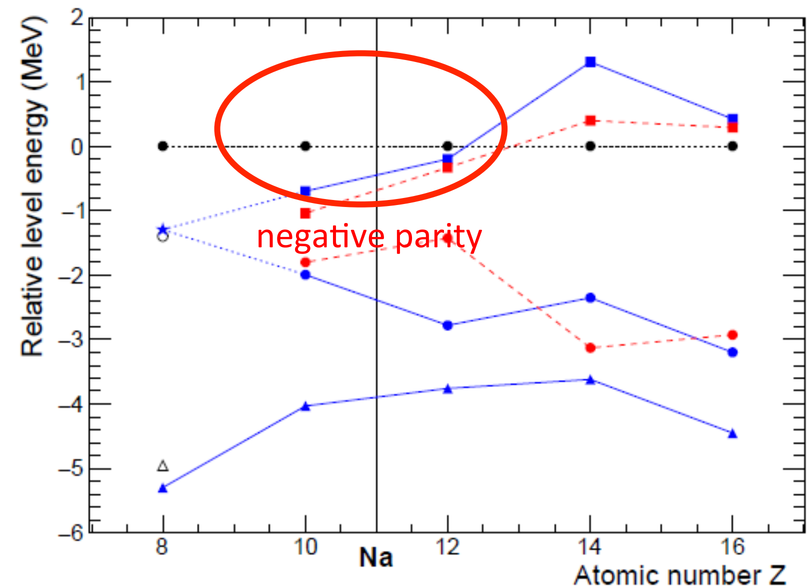

PLB (2016) N=15 and 17 isotones

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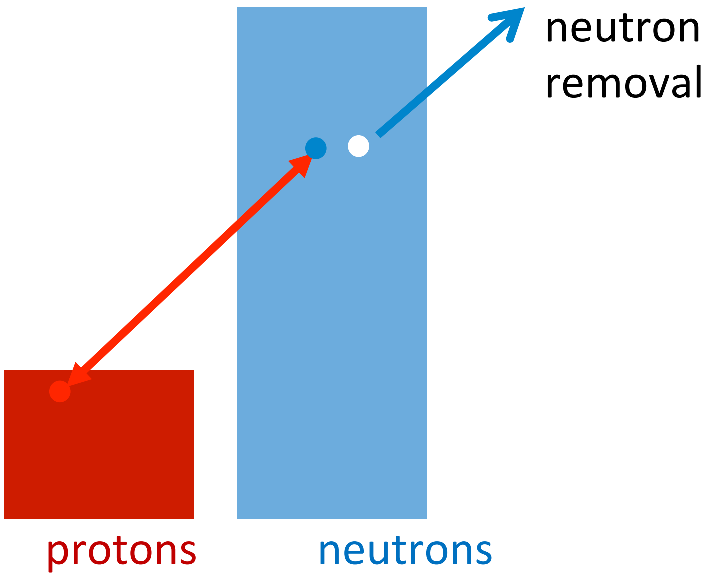
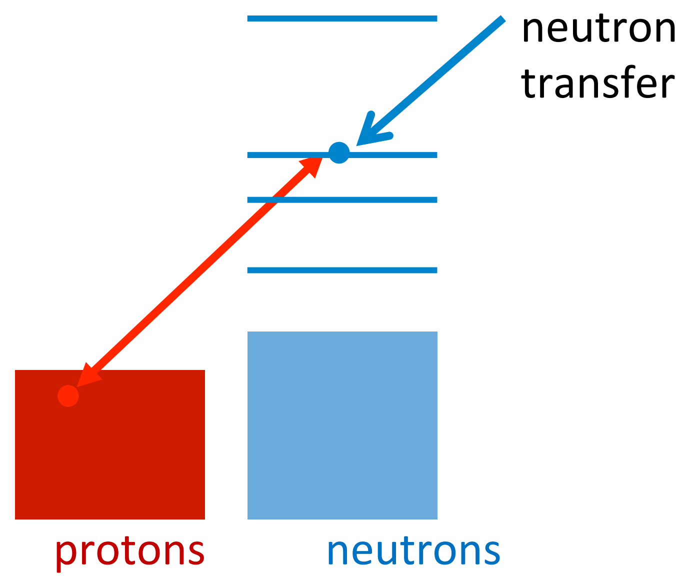
G.L. Wilson et al.

- 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

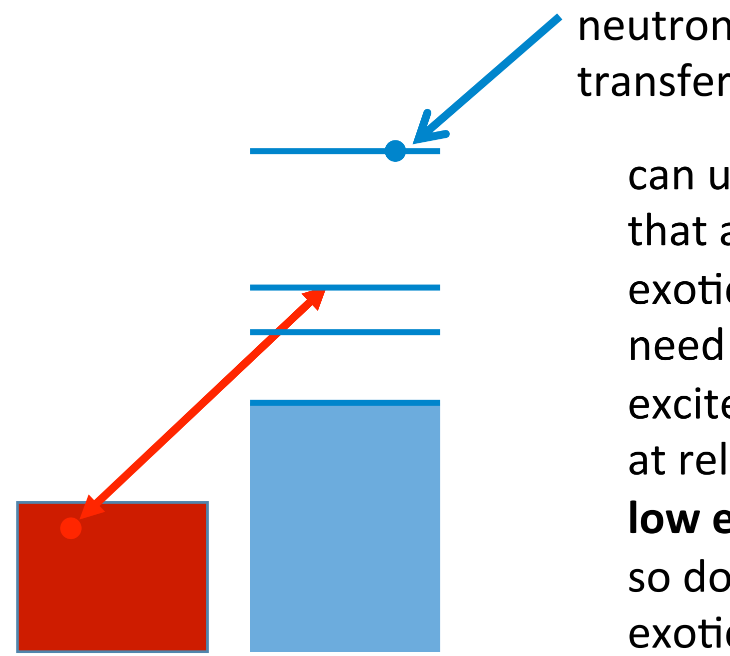


can make beams of VERY exotic nuclei and learn properties by removing neutrons

OR

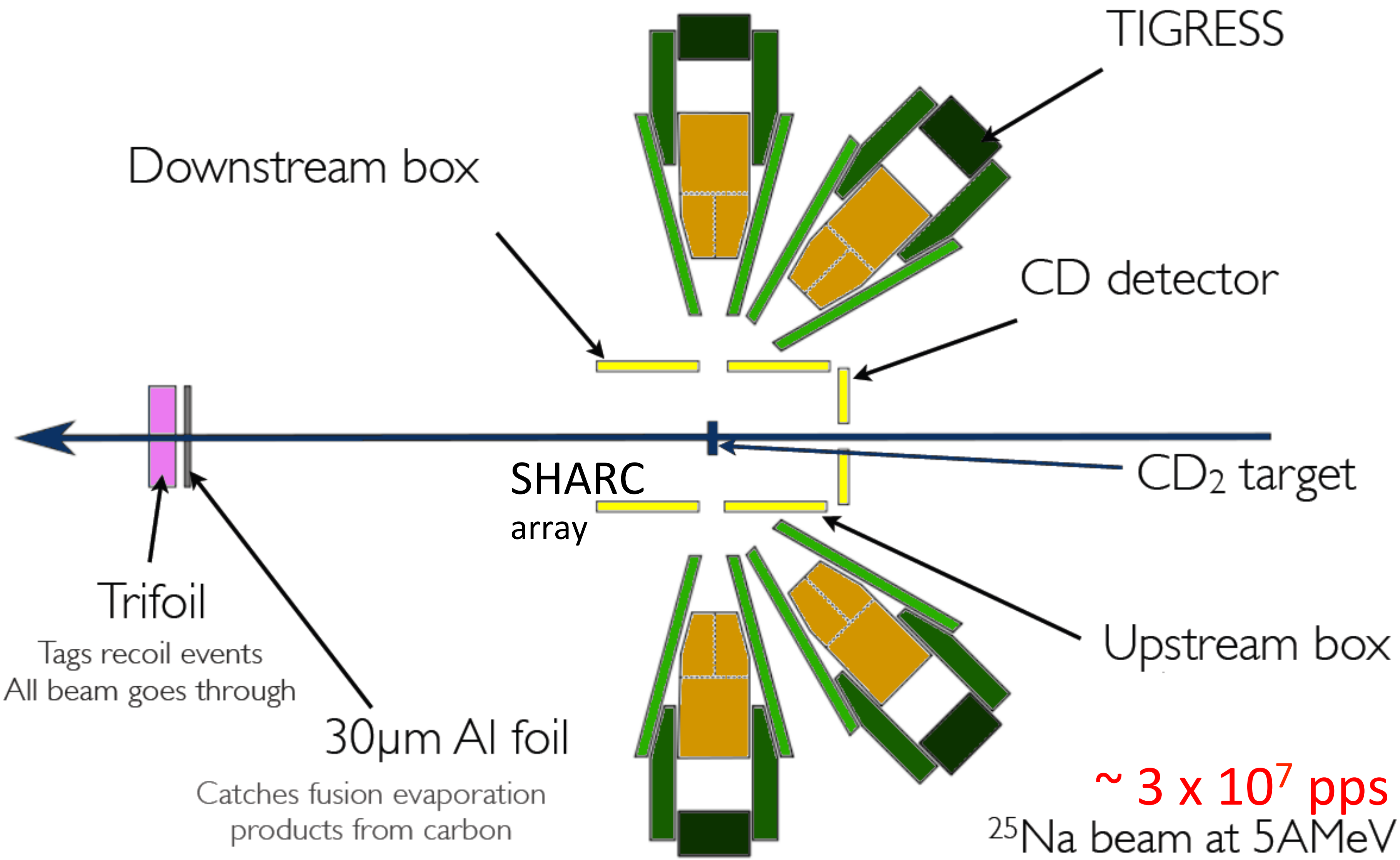
can learn the important interactions that explain the structure by isolating p-n interactions, using a **single nucleon** to probe the additional orbitals one at a time

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

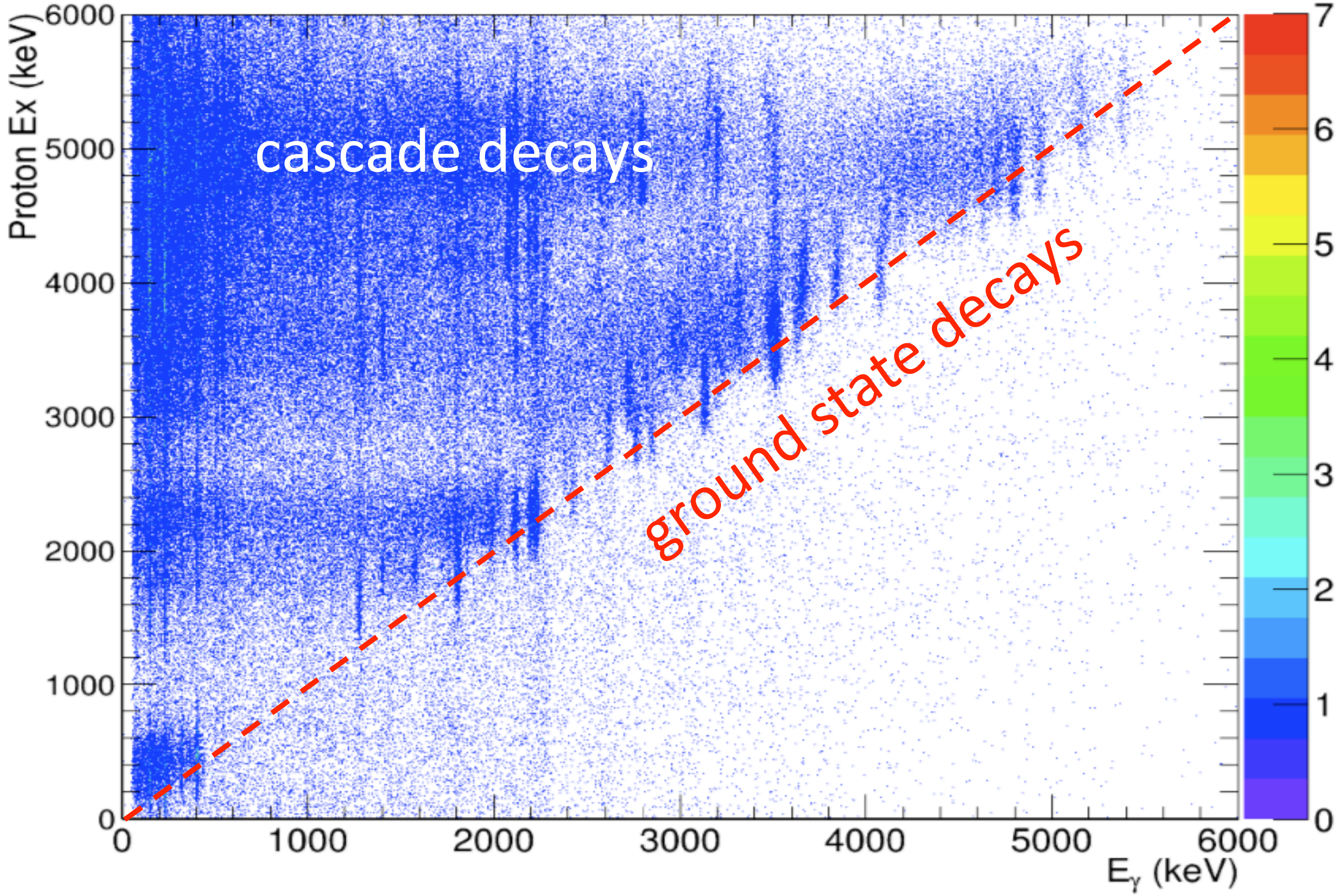


G.L. Wilson et al., Physics Letters B 759 (2016) 417

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

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

Negative parity states

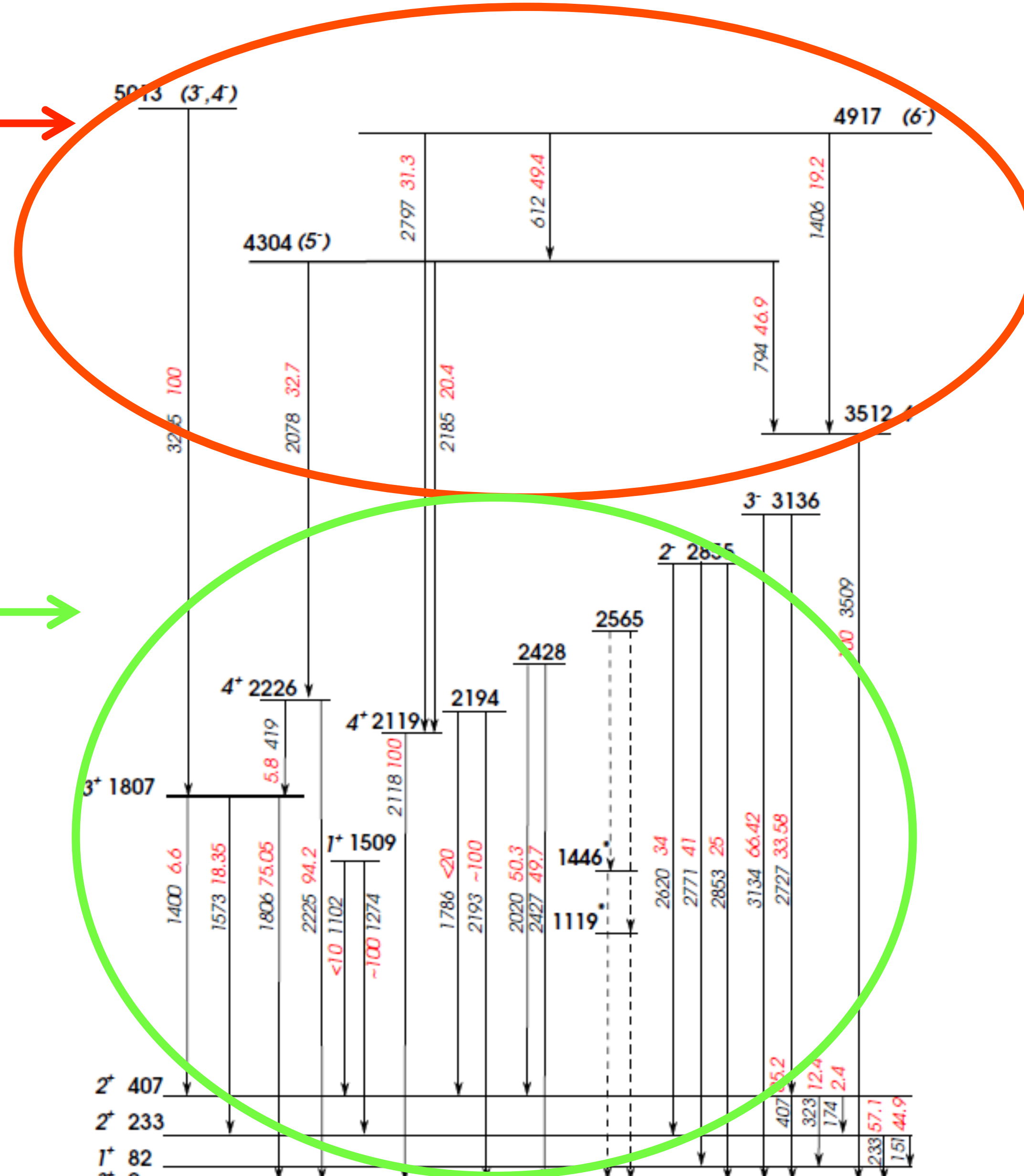
Levels never seen before, selected by (d,p)

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)

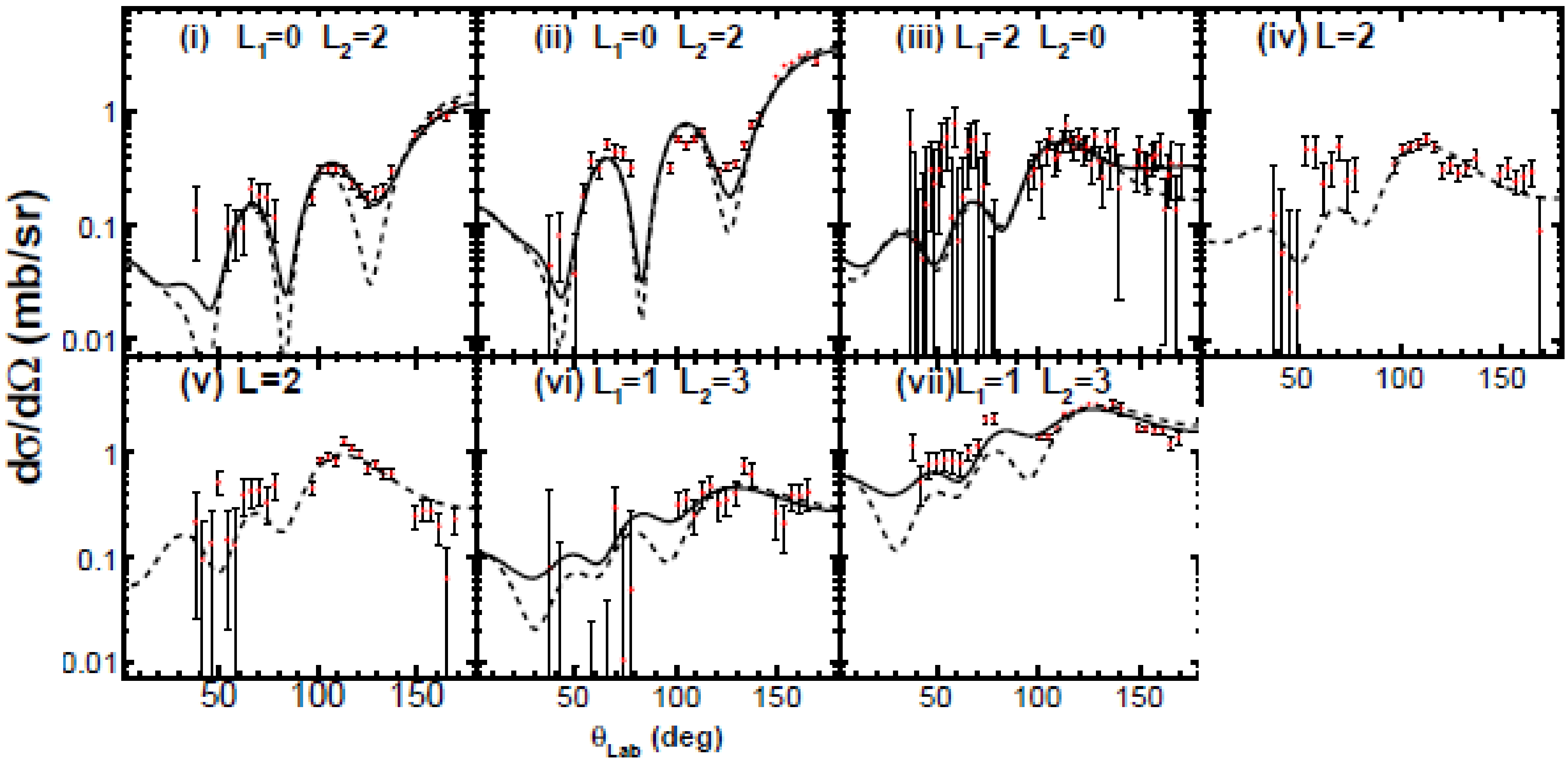


Differential cross sections and spectroscopic factors

<u>**First analysis**</u> of this type:

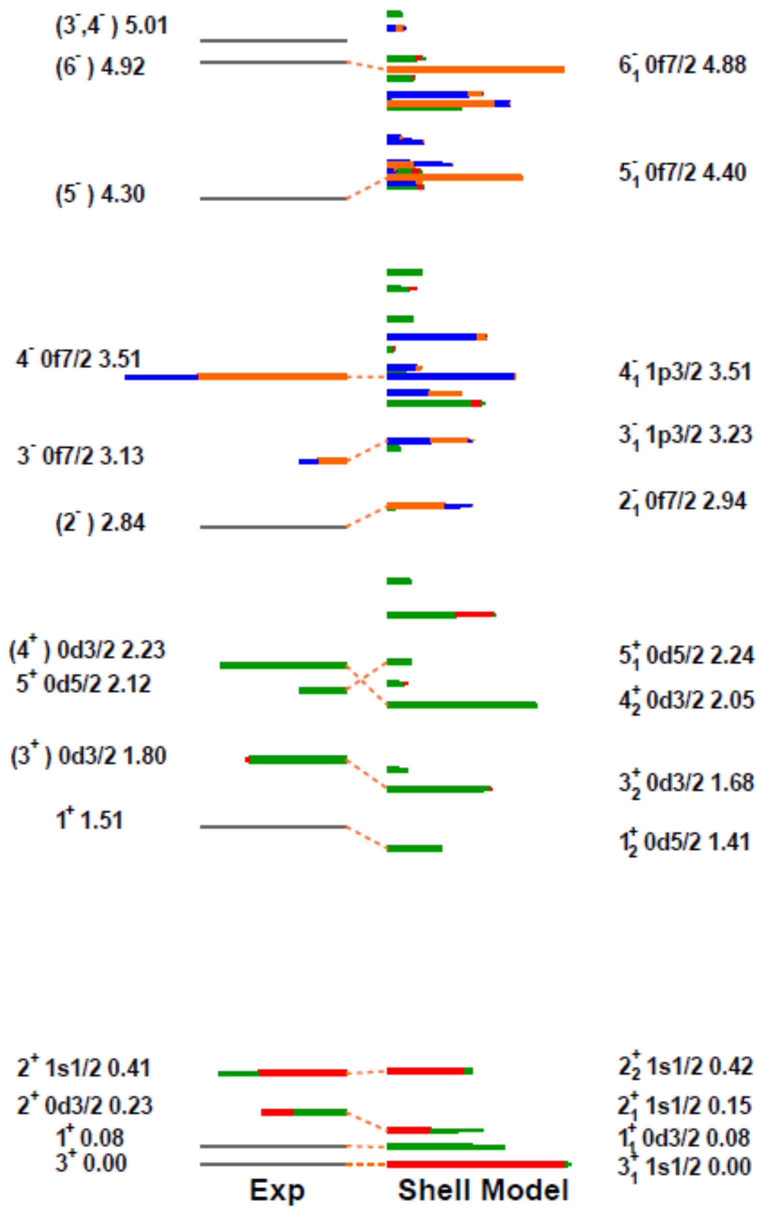
Each of these distributions is:

(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$\hbar\omega$

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

UPDATE

8 new states
plus
4 new ℓ values

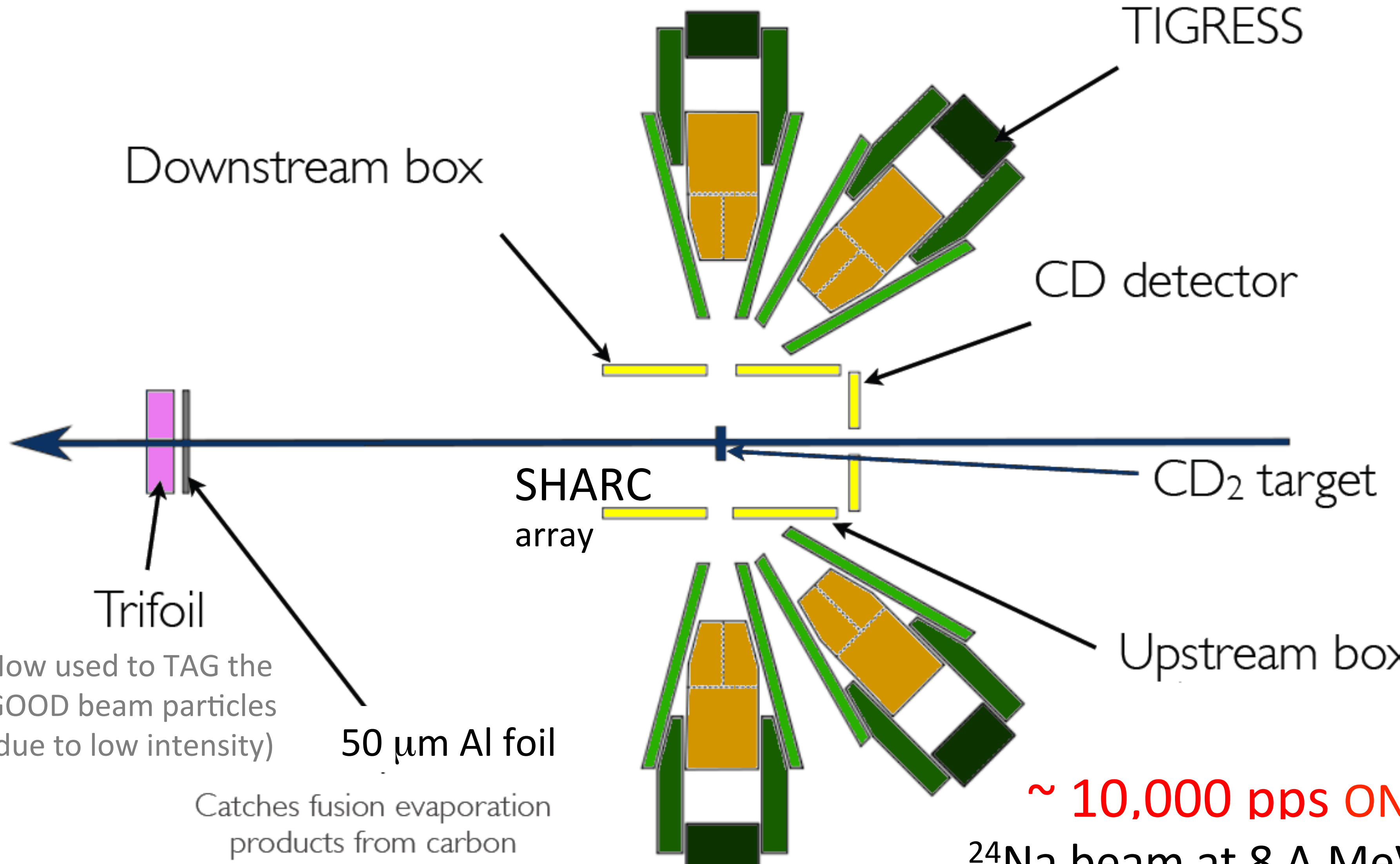
IMPROVED
background
subtraction

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		$(3^-,4^-)$		*											

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



Now used to TAG the GOOD beam particles (due to low intensity)

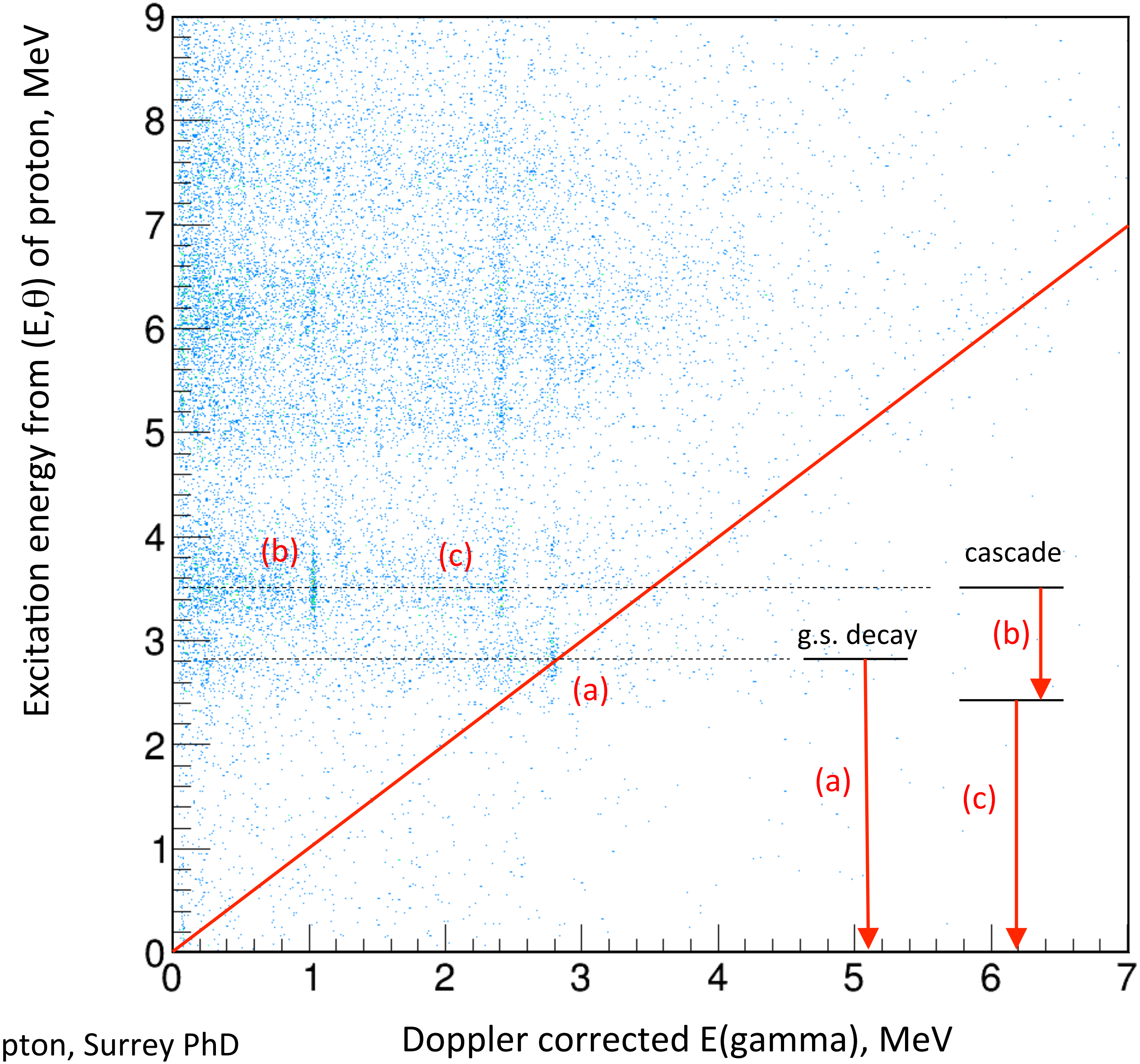
Catches fusion evaporation products from carbon

~ 10,000 pps ONLY

^{24}Na beam at 8 A.MeV

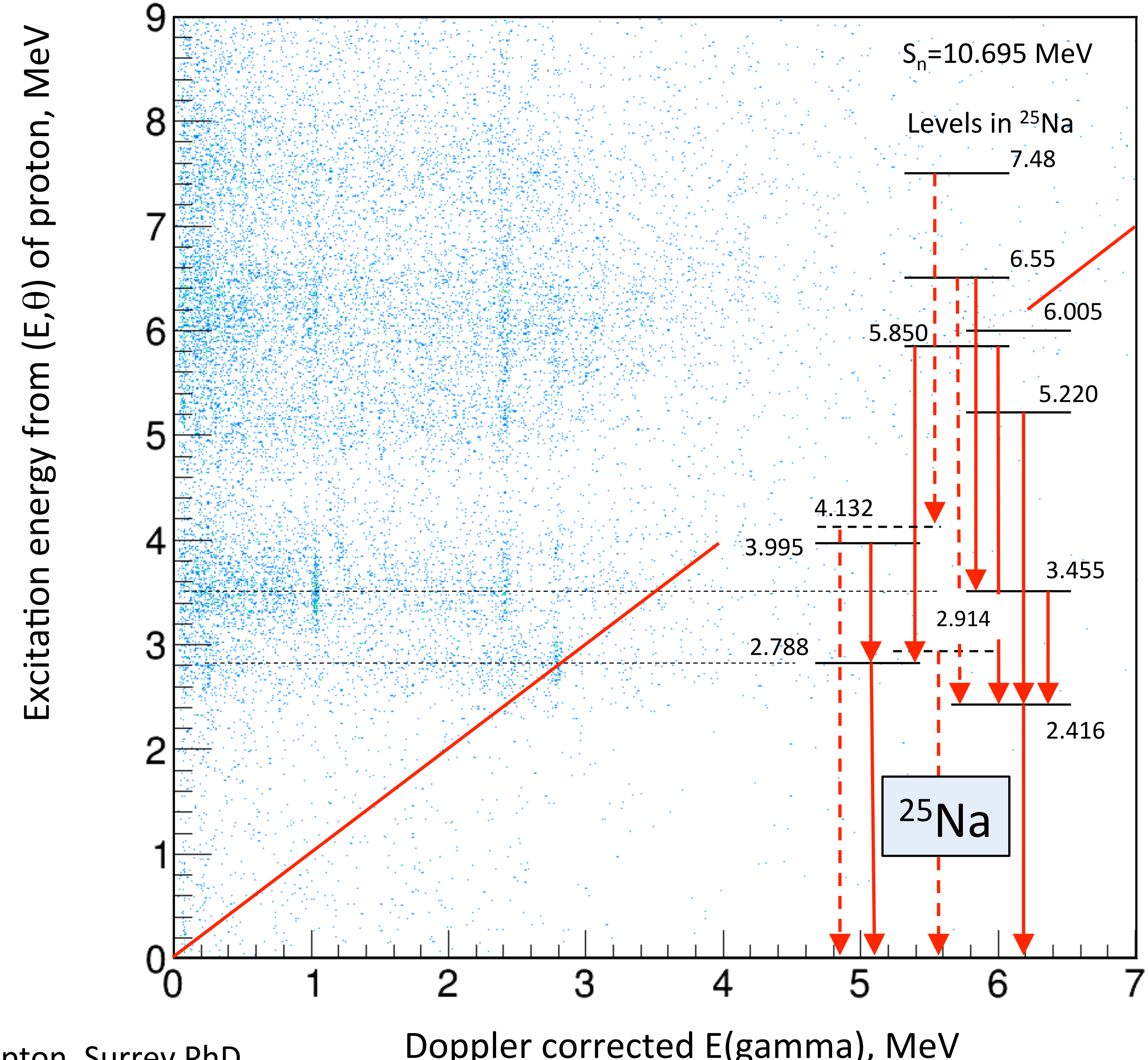
Andy Knapton, Surrey PhD (writing up)

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



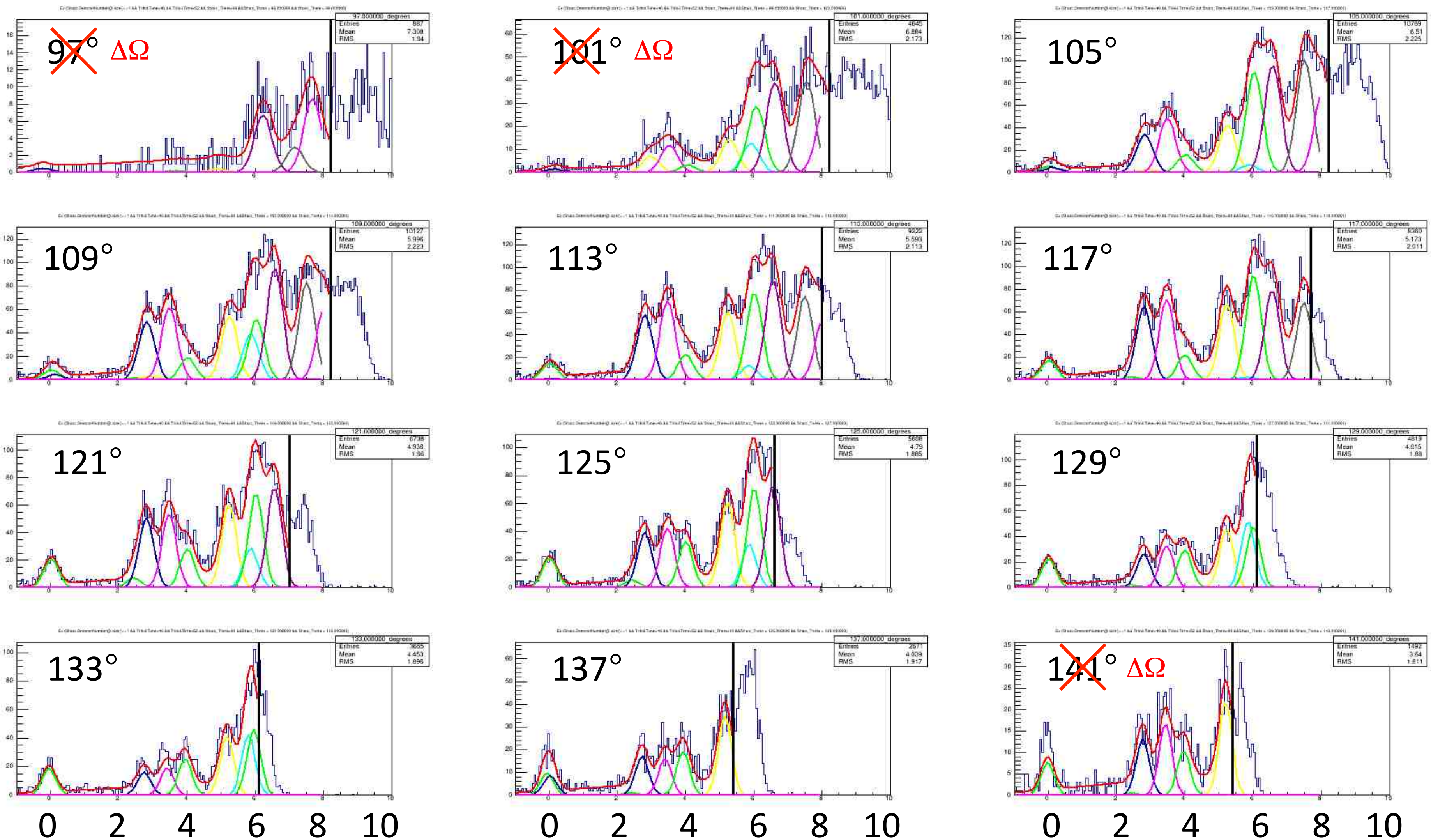
Andy Knapton, Surrey PhD

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 – fits to excitation energy spectrum at each angle

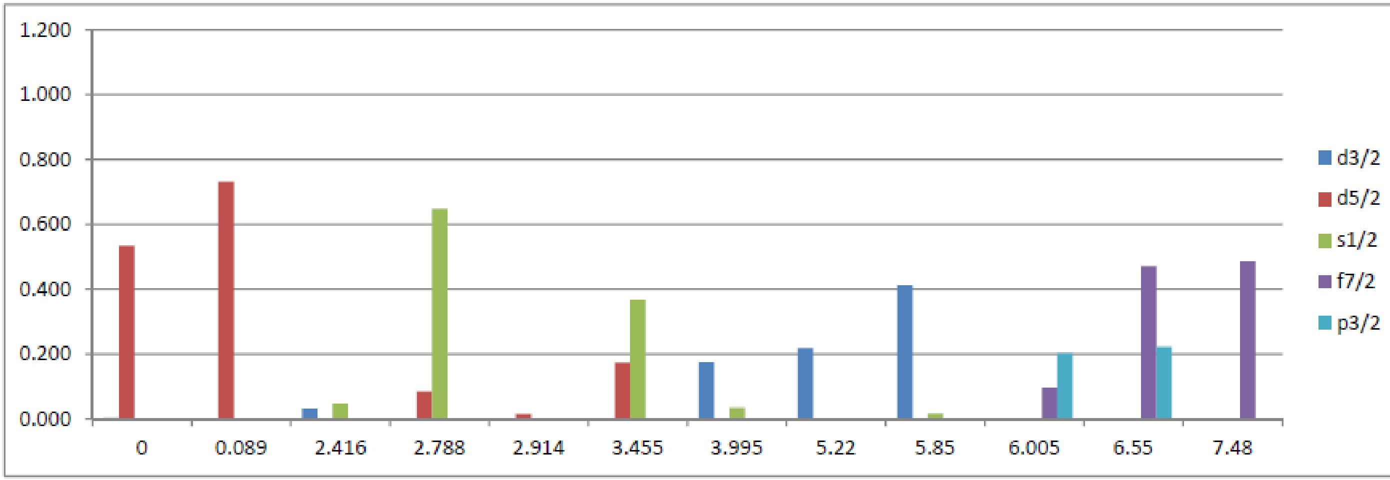


Excitation Energy in ^{25}Na (MeV)

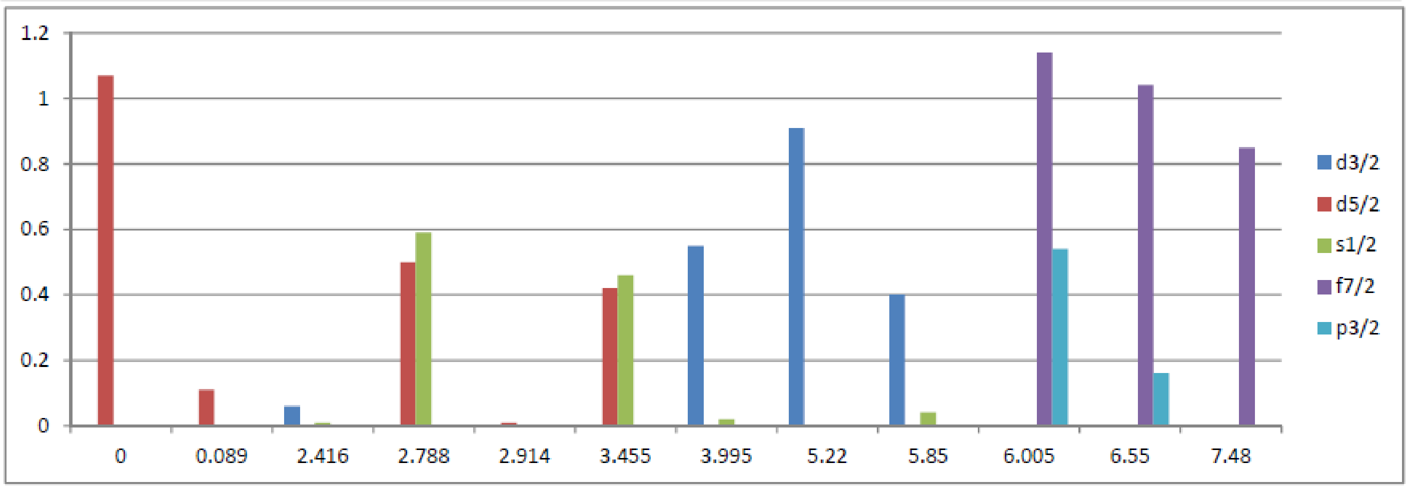
Andy Knapton, Surrey PhD

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



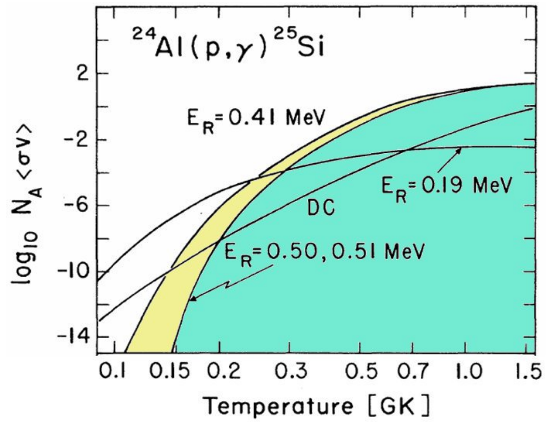
Excitation Energy in ^{25}Na (MeV)

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)-	?	?

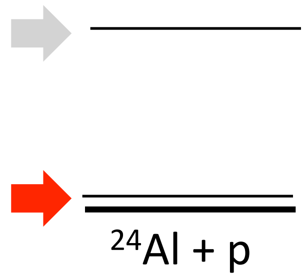
BIG IMPROVEMENTS IN LEVEL IDENTIFICATIONS

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

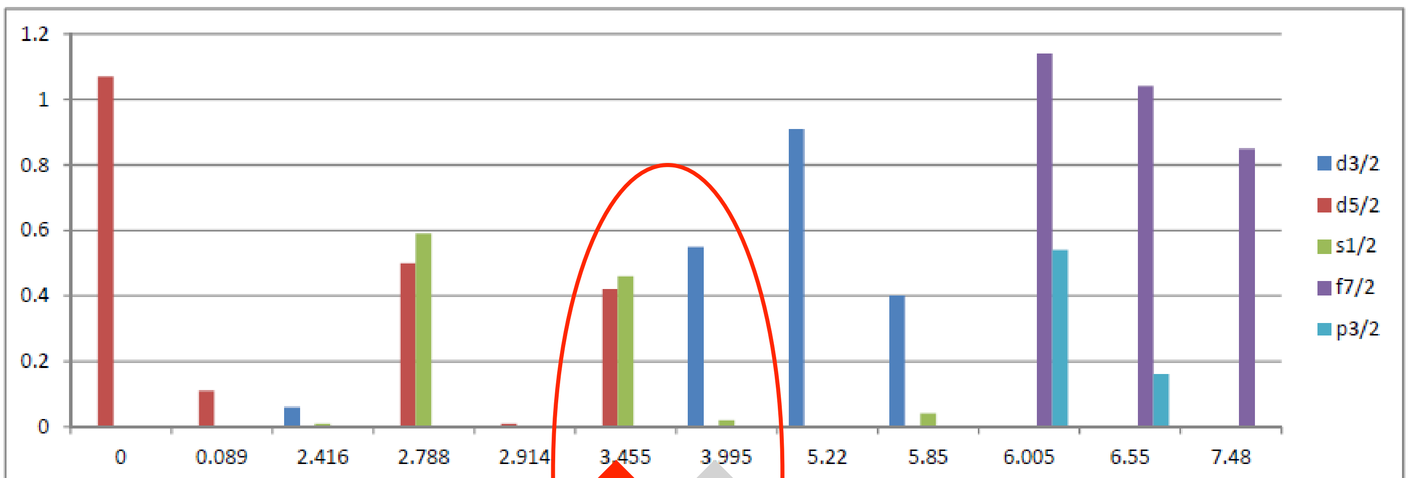


0.41 = 3.995 in ^{25}Na

resonance states in ^{25}Si

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

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)-	?	?

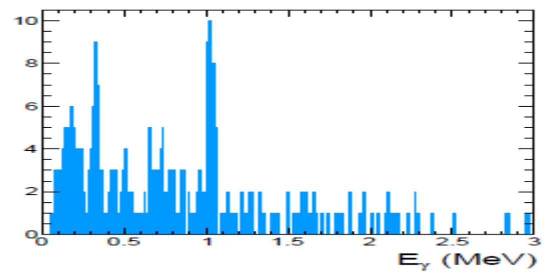
bound states in mirror ^{25}Na

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

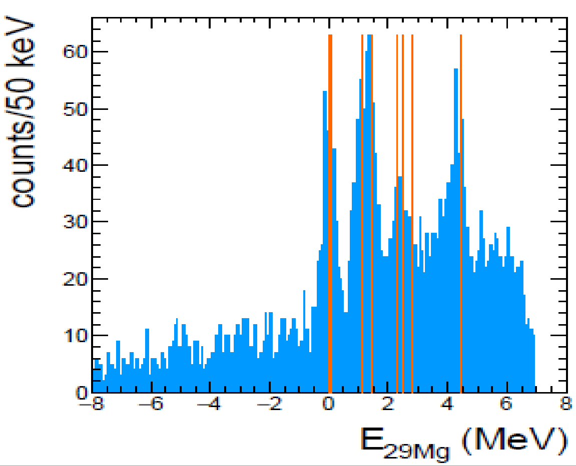
Secondary Beam

- ^{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

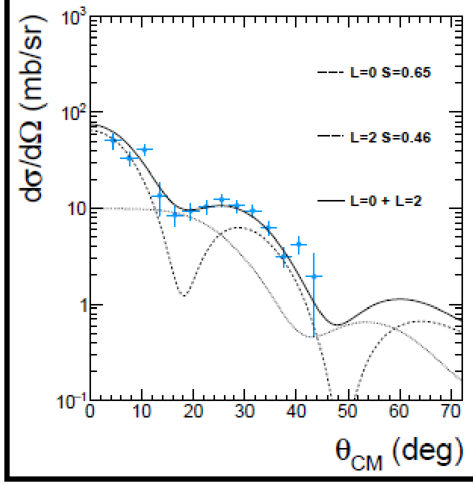


Gated Excitation Energy

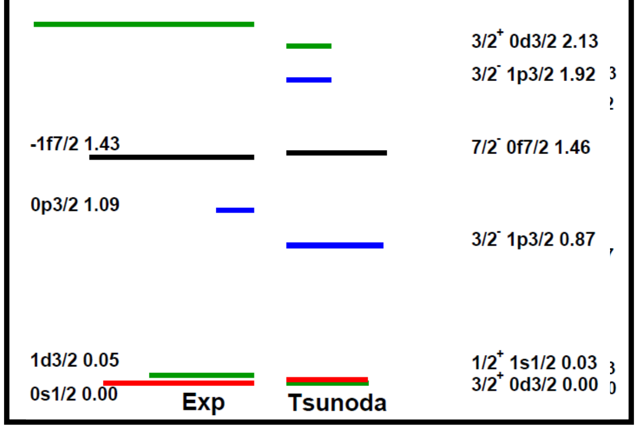


Experiment – SHARC and TIGRESS at TRIUMF

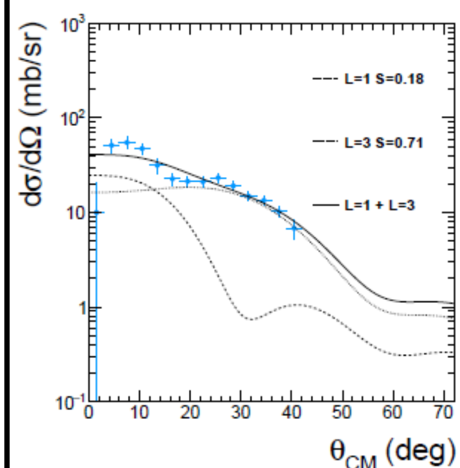
Ground State Doublet



Microscopic Shell Model



1 MeV Doublet



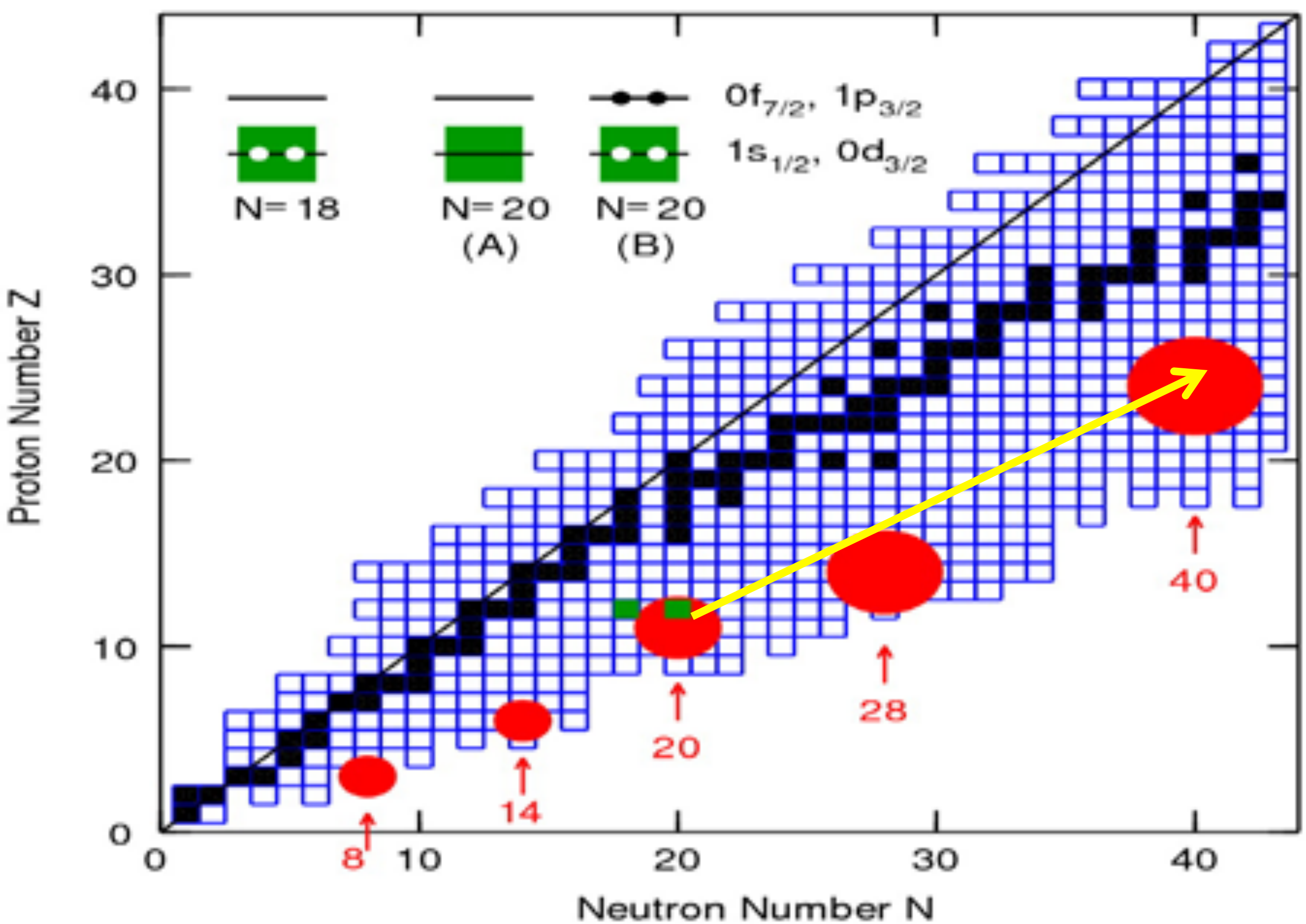
We have preliminary results from this experiment using a heavily contaminated beam.

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

Too early to judge agreement.

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…

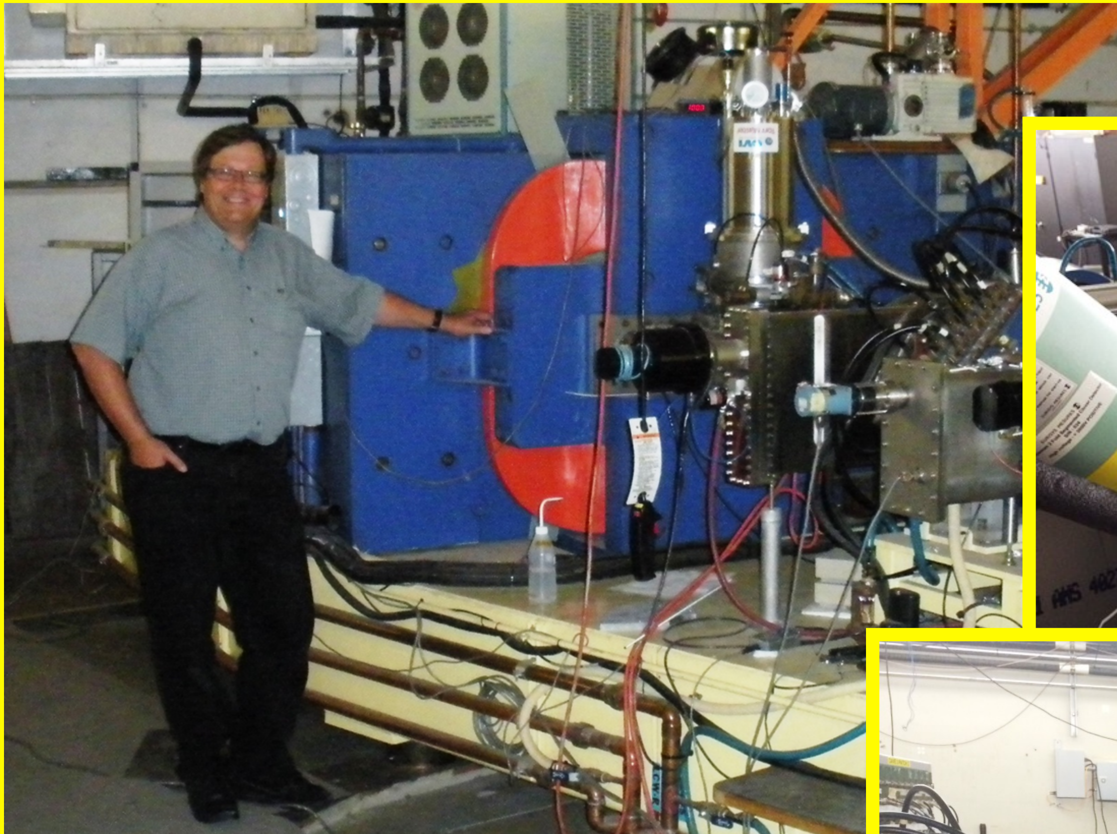


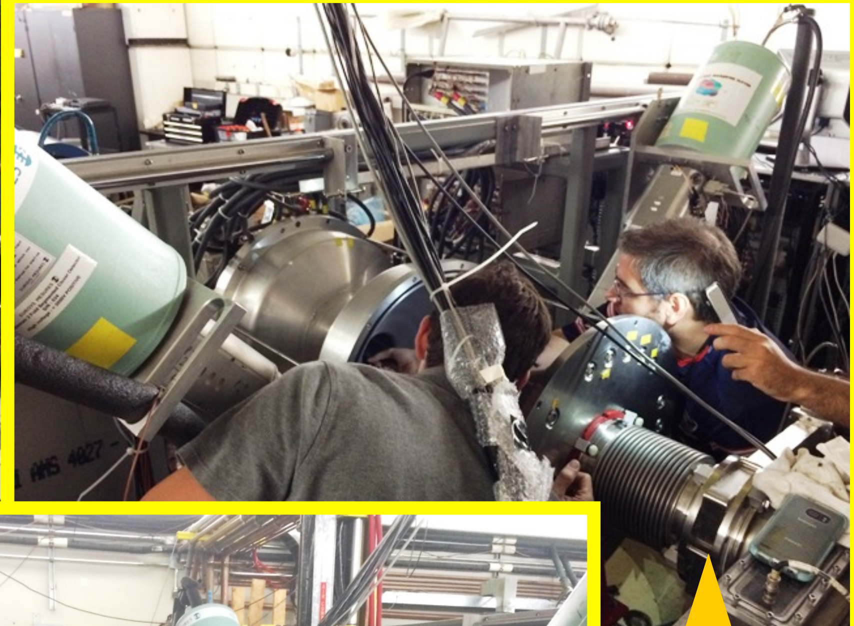
reduced gap $\nu(f_{5/2}-g_{9/2})$ with depleted $\pi(f_{7/2})$

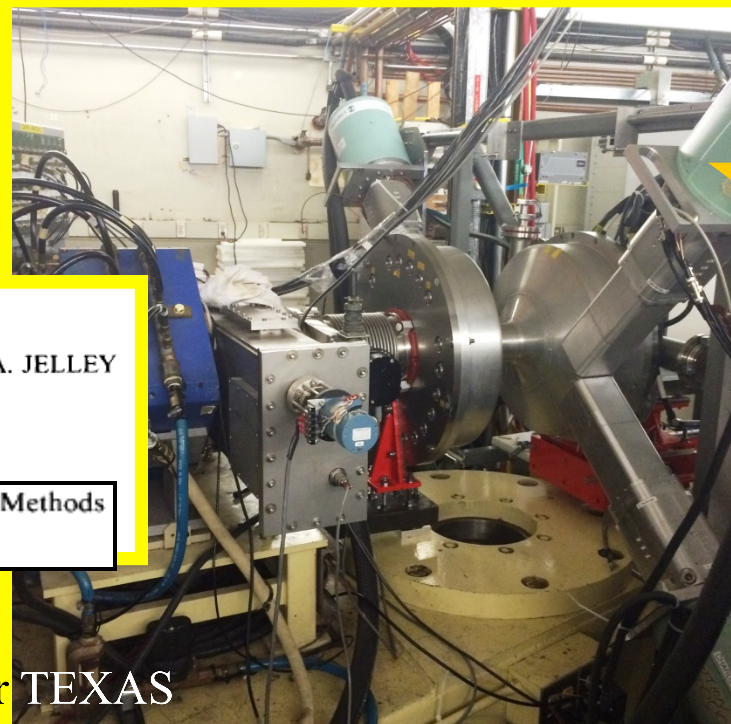
reduced gap $\nu(d_{3/2}-f_{7/2})$ with depleted $\pi(d_{5/2})$

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

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







installed, first run Aug 2016

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

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Rutherford Appleton Laboratory, Chilton, Didcot, England

Nuclear Instruments and Methods A245 (1986) 230

T4T TIARA for TEXAS

Summary

UNIVERSITY OF SURREY
Department of Physics

- 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 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)

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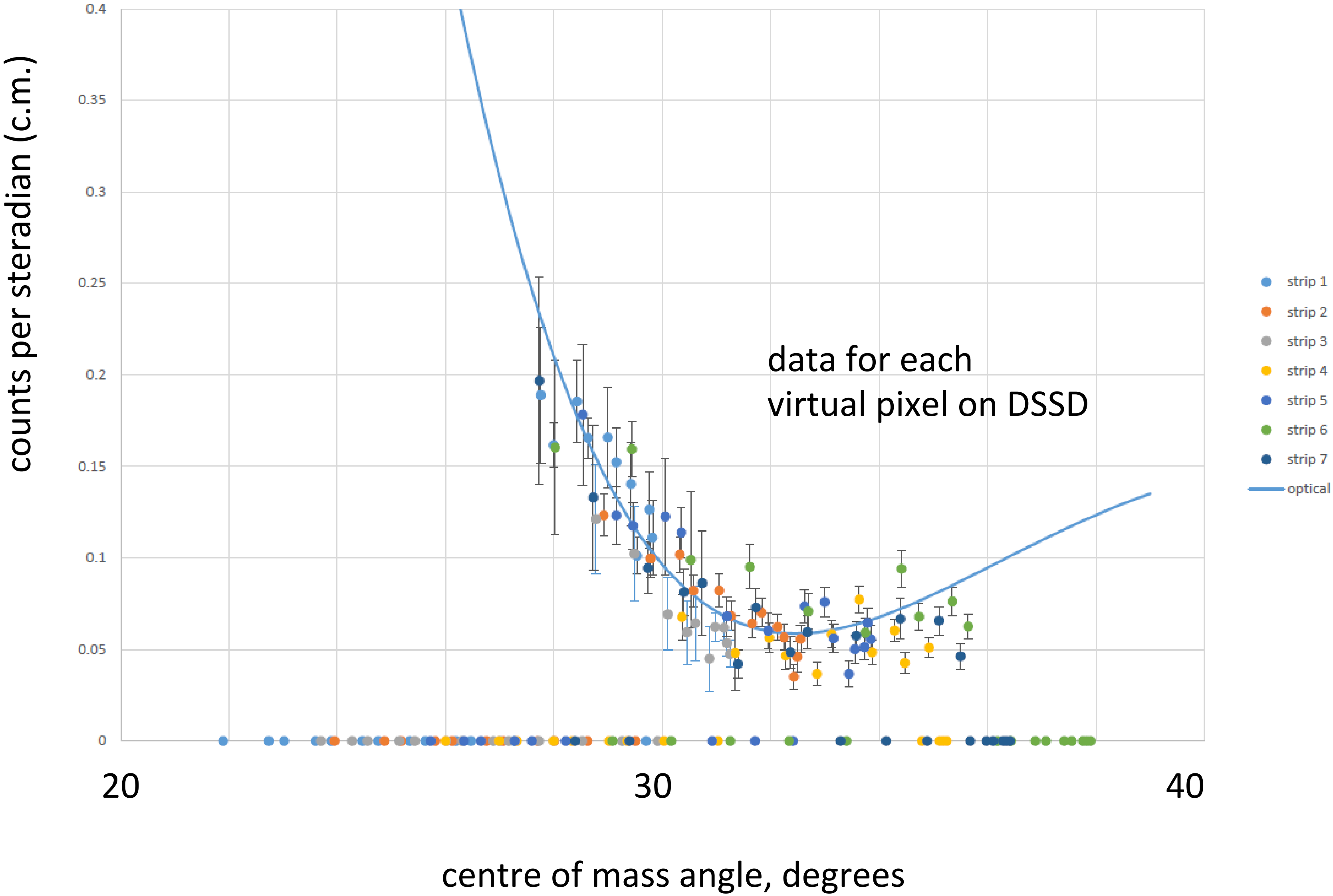
In-built normalisation from d(^{24}Na,d)^{24}Na near 70° (lab)



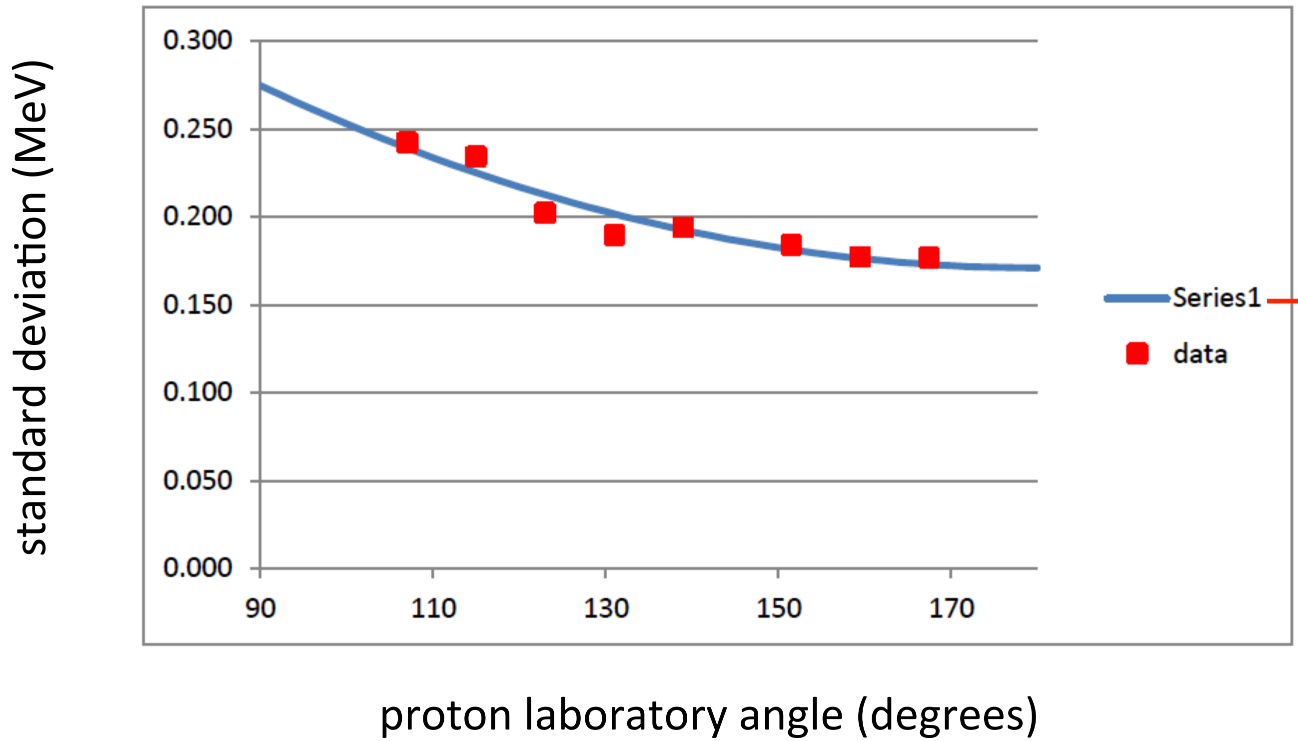
Andy Knapton, Surrey PhD

AIM:

Perform fits to spectra of E_x for each of a number of angle bins

Constraints in fitting:

- Excitation energy scale calibration checked using states of known E_x e.g. 3.455 MeV
- Allow for slight shift from angle to angle, in case corrections are imperfect
- Constrain energies of peaks using evidence from E_x spectra and supporting gamma rays
- Constrain the widths guided by simulations (observe little E_x change, but angular dependence)



this variation built into fit