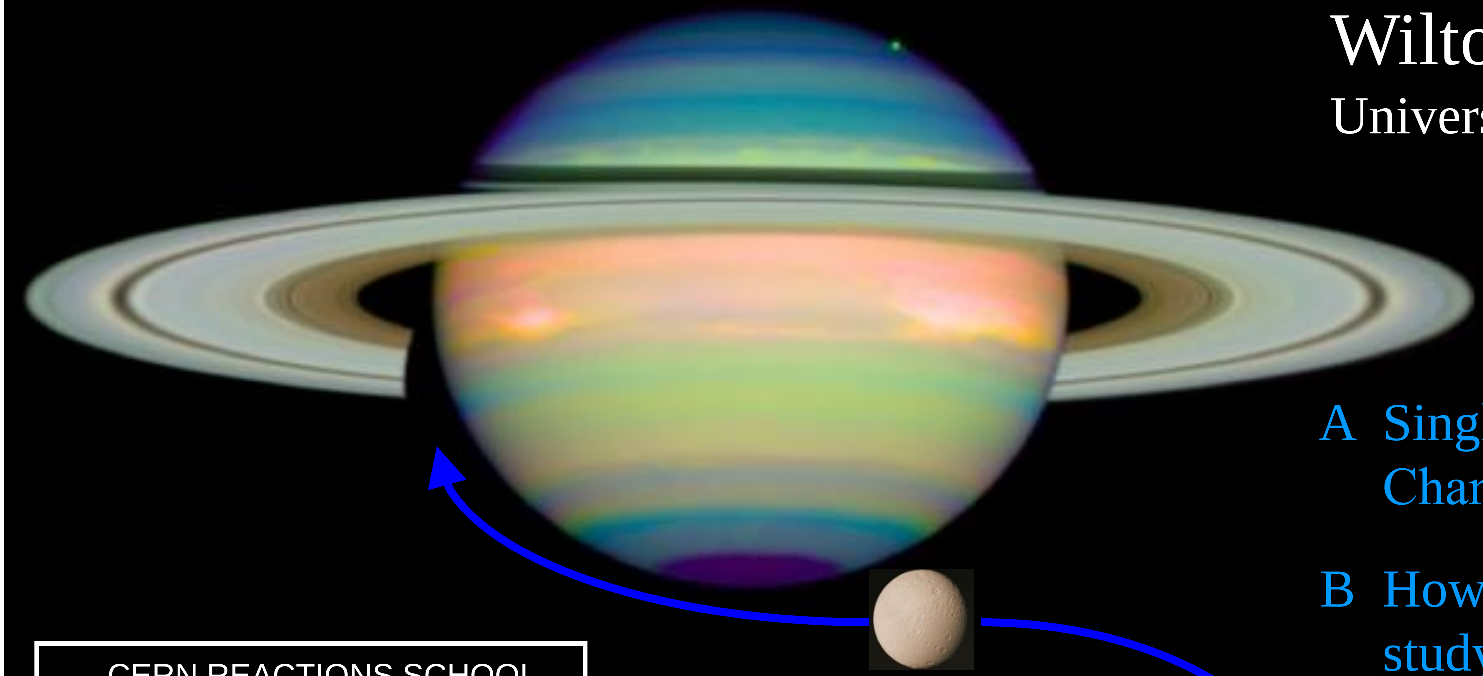
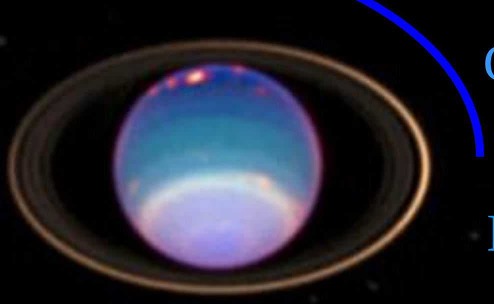
# What can we learn from transfer, and how is best to do it?

Wilton Catford
University of Surrey





SATURN HST/ IR 1998, TETHYS VOYAGER2 1981, URANUS HST/ IR 1986

A Single Particle States; Changing magic no.'s

B How reactions can study this physics

C Practicalities; Inverse Kinematics

D Experimental setups

E Results & Perspectives

CERN REACTIONS SCHOOL

CERN, Geneva ** 22-24 April 2014

# TIARA + MUST2 experiments at SPIRAL/GANIL:

Beam of $^{20}$O at $10^5$ pps and 10 MeV/A
(stripping at target to remove $^{15}$N $^{3+}$ with A/q = 5)
(This experiment not discussed, in these lectures).

Beam of $^{26}$Ne at $10^3$ pps (pure) and 10 MeV/A

The (d,p) could be studied to both BOUND and UNBOUND states

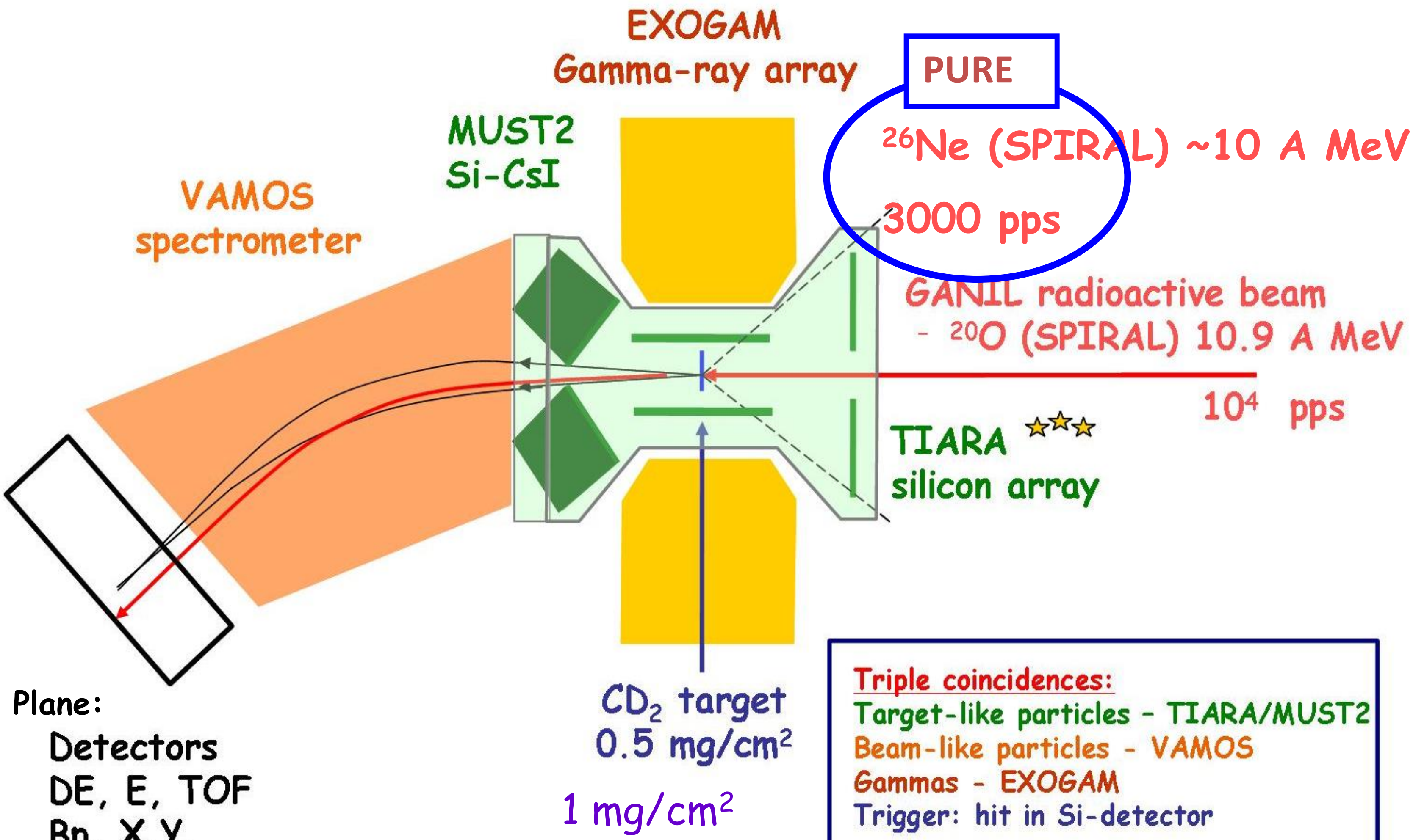
Gamma-ray coincidences were recorded for bound excited states

With MUST2 we could measure (d.t) at forward angles with good PID

The 16% of $^1$H in the $^2$H target allowed (p,d) measurements also

**BEA FERNANDEZ DOMINGUEZ, LIVERPOOL (GANIL)**
**JEFFRY THOMAS, SURREY**
**SIMON BROWN, SURREY**
**ALEXIS REMUS, IPN ORSAY**

# TIARA+MUST2+VAMOS+EXOGAM @ SPIRAL/GANIL



**Focal Plane:**

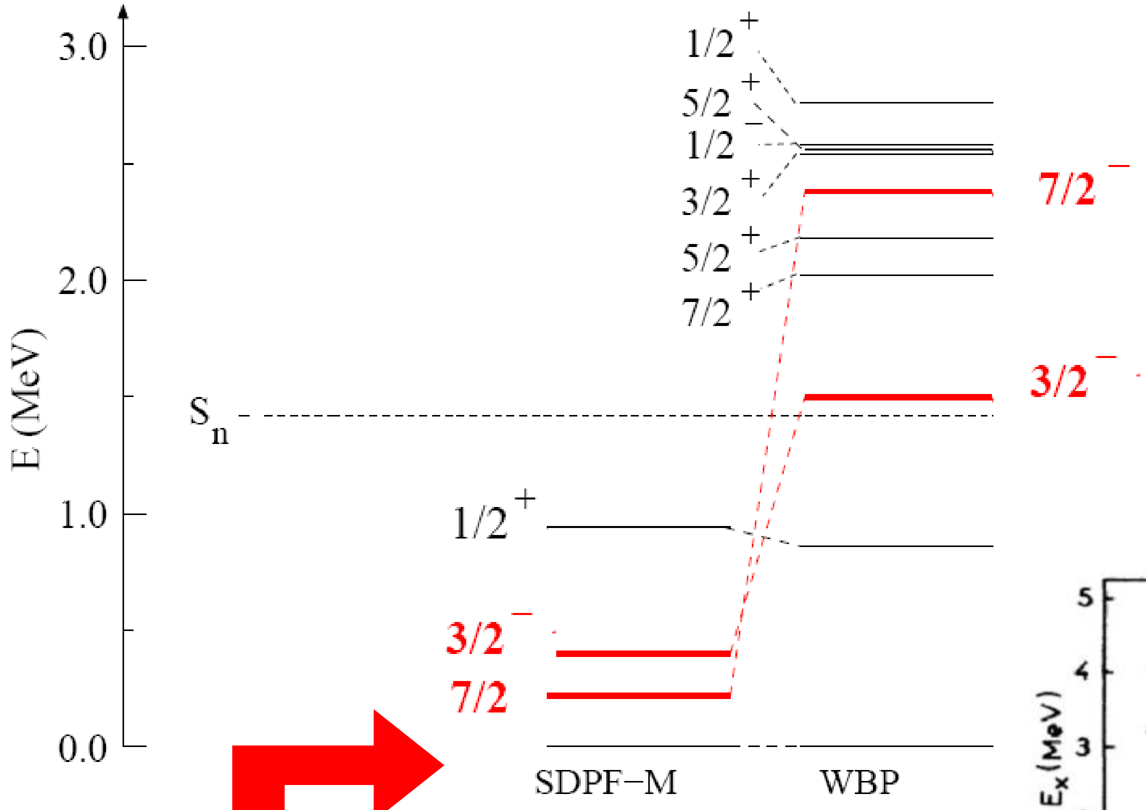
Detectors
DE, E, TOF
Bρ, X,Y,

**Triple coincidences:**
Target-like particles – TIARA/MUST2
Beam-like particles - VAMOS
Gammas - EXOGAM
Trigger: hit in Si-detector

## N=17 ISOTONES

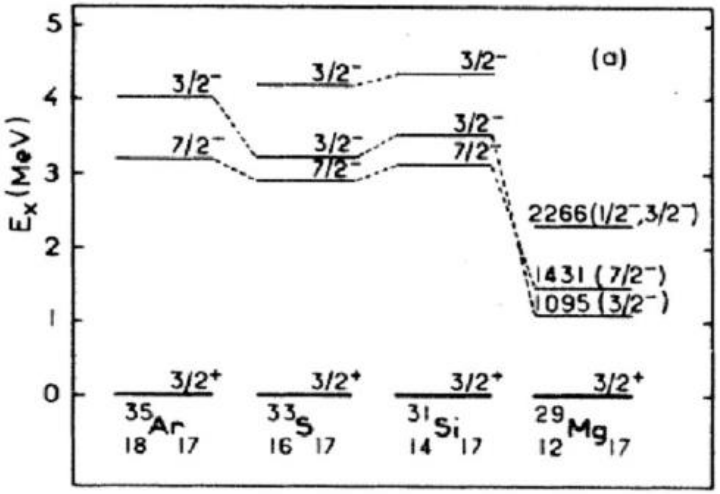
Shell model predictions **vary wildly** for fp intruders

Systematics show region of **dramatic change**



## $^{27}$Ne Predictions

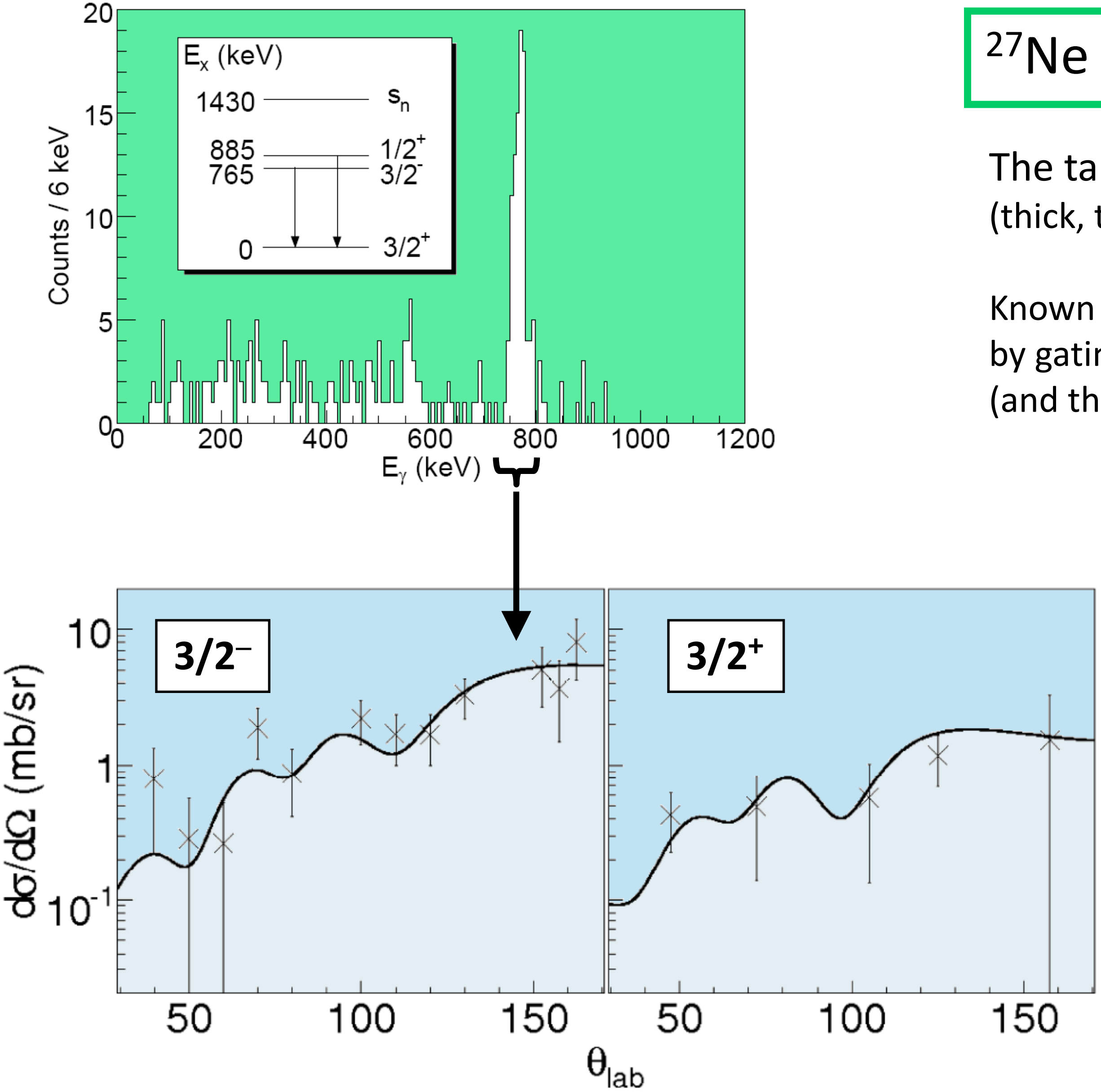
$7/2^-$ **never seen**
$3/2^-$ known



P. Baumann *et al.*, Phys. Rev. C36, 765 (1987).

**$^{27}$Ne IS THE NEXT ISOTONE**

# $^{27}$Ne BOUND STATES



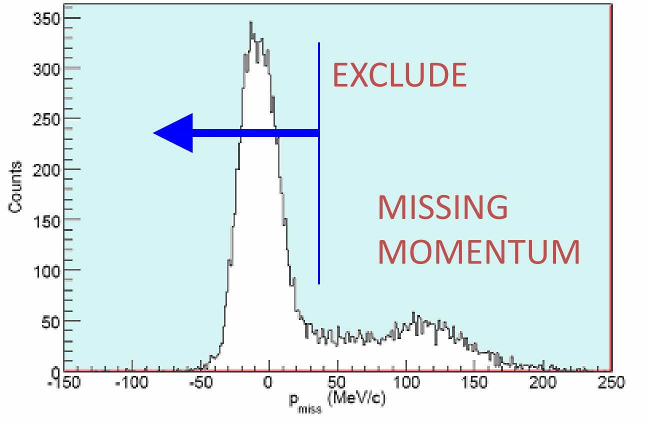
The target was 1 mg/cm$^2$ $CD_2$
(thick, to compensate for 2500 pps)

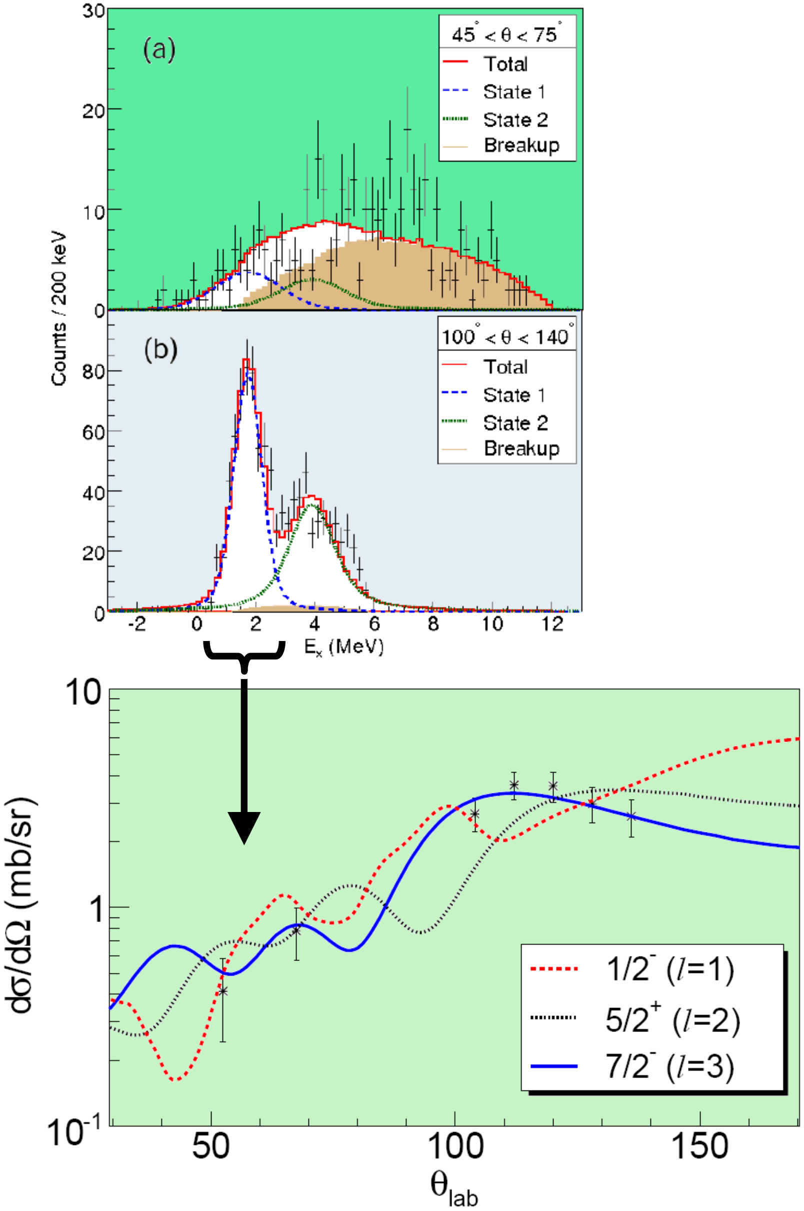
Known bound states were selected by gating on the decay gamma-ray (and the ground state by subtraction)

In these case, the spins were already known.

The magnitude was the quantity to be measured.

# $^{27}$Ne UNBOUND STATES

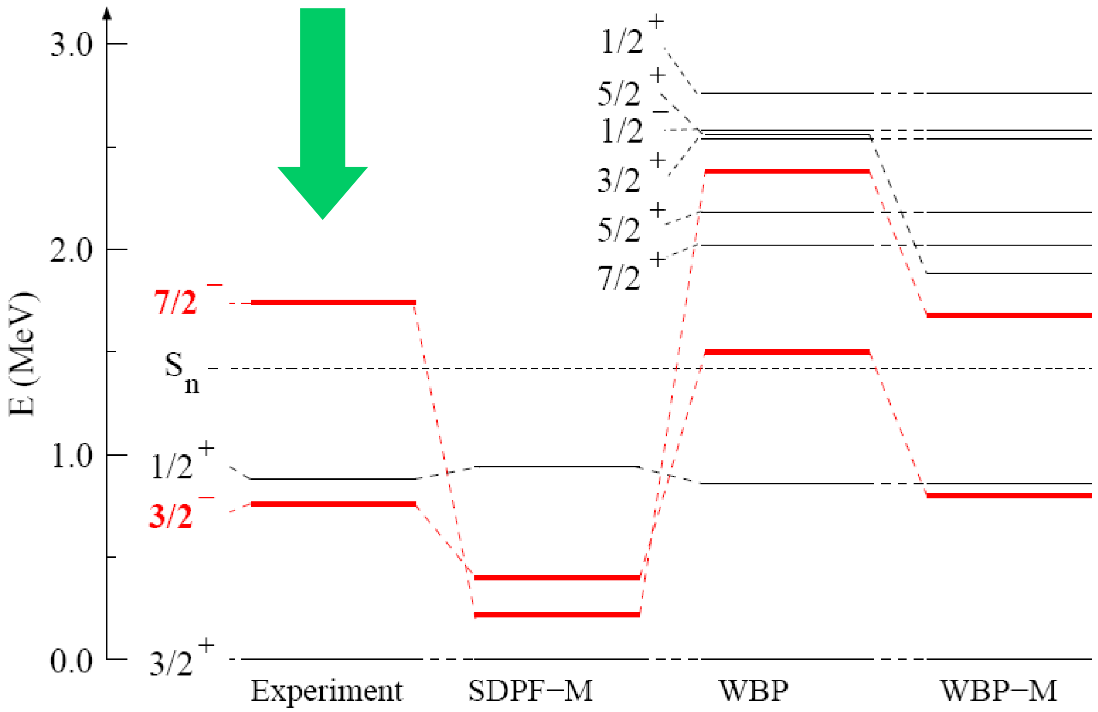




## $^{27}$Ne results

- level with main $f_{7/2}$ strength is <u>unbound</u>
- excitation energy measured
- spectroscopic factor measured
- the $f_{7/2}$ and $p_{3/2}$ states are <u>inverted</u>
- this inversion also in $^{25}$Ne experiment
- the natural width is just $3.5 \pm 1.0$ keV

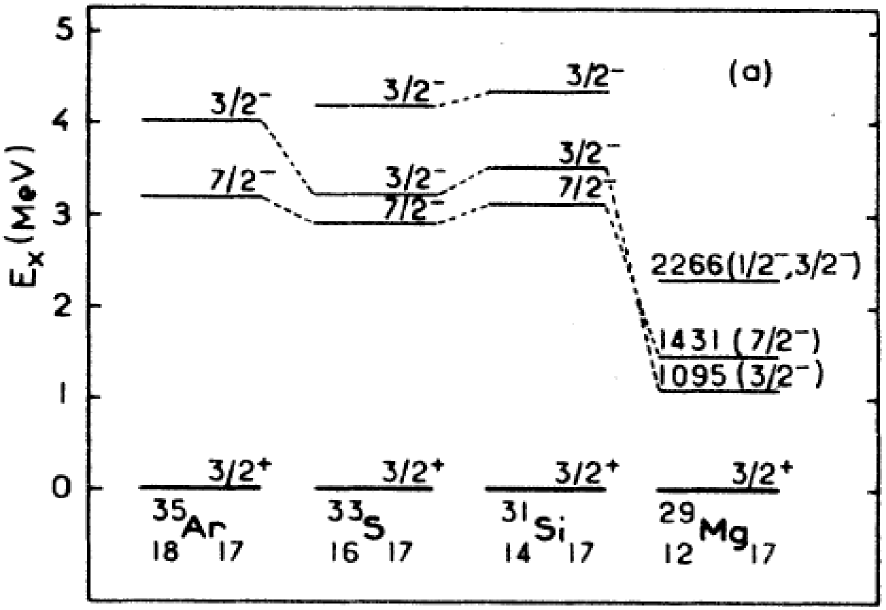
# $^{27}$Ne results

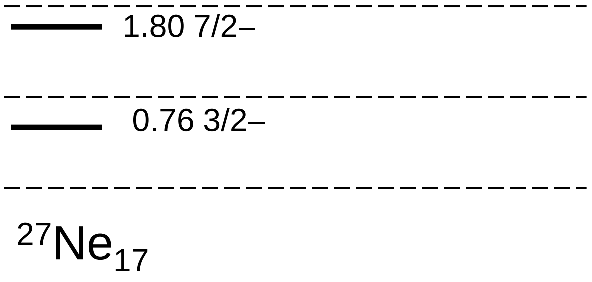


| $J^\pi$ | $E^*_{exp}$ (MeV) | $E^*_{WBP-M}$ (MeV) | $C^2S$ Ref. [9] | $C^2S$ Present | $C^2S$ WBP-M |
|---|---|---|---|---|---|
| $3/2^+$ | 0 | 0 | 0.2(2) | 0.42(22) | 0.63 |
| $3/2^-$ | 0.765 | 0.809 | 0.6(2) | 0.64(33) | 0.67 |
| $1/2^+$ | 0.885 | 0.869 | 0.3(1) | 0.17(14) | 0.17 |
| $7/2^-$ | 1.74 | 1.686 | - | 0.35(10) | 0.40 |

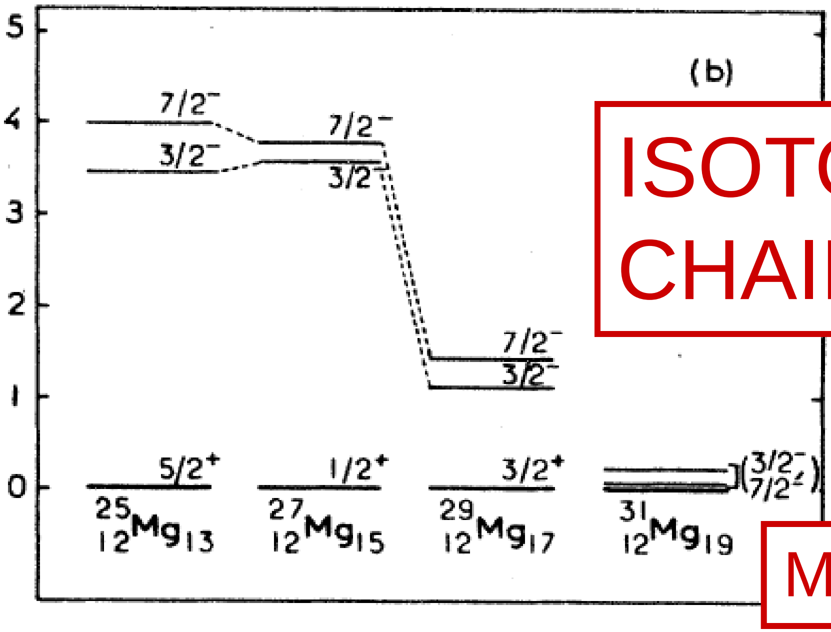
- we have been able to reproduce the observed energies with a modified WBP interaction, full 1hw SM calculation
- the SFs agree well also
- most importantly, the new interaction works well for $^{29}$Mg, $^{25}$Ne also
- so we need to understand why an *ad hoc* lowering of the fp-shell by 0.7 MeV is required by the data!

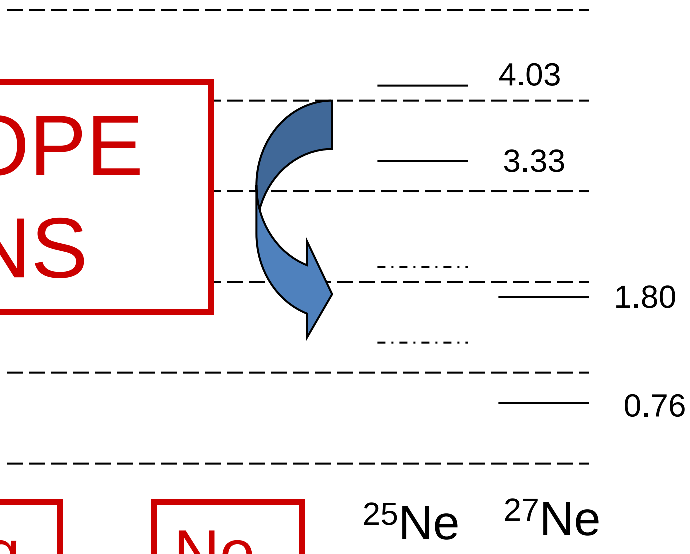
# N=17 ISOTONES





# ISOTOPE CHAINS





Mg

Ne

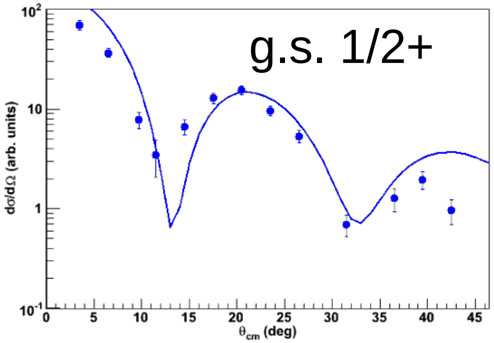
d3/2 level is 2.030 25Ne

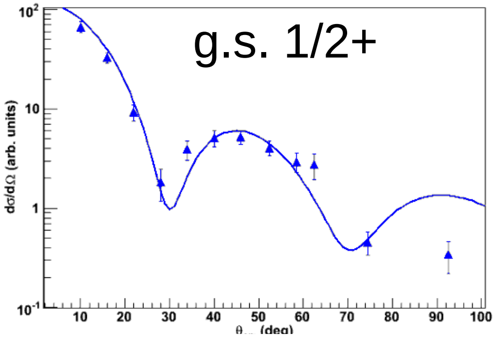
# Preliminary results for $^{26}$Ne(d,t)$^{25}$Ne and also (p,d)

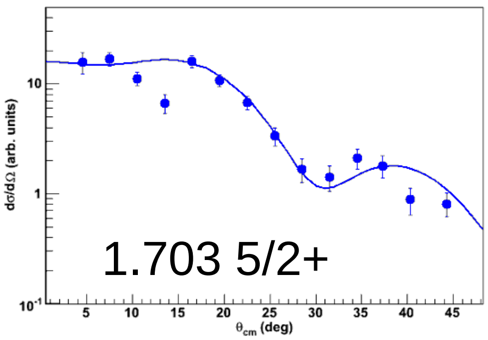
**JEFFRY THOMAS, SURREY**

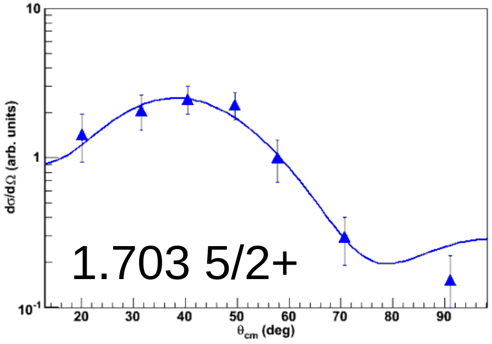
## $^{26}$Ne(d,t)$^{25}$Ne

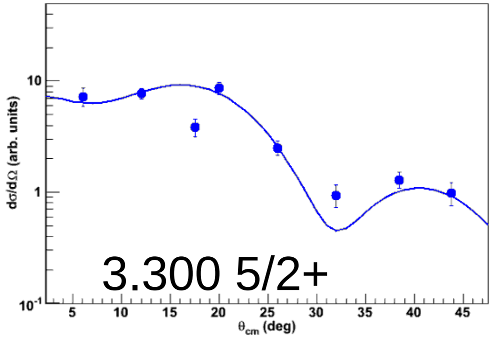
## $^{26}$Ne(p,d)$^{25}$Ne

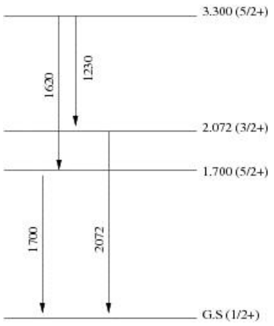




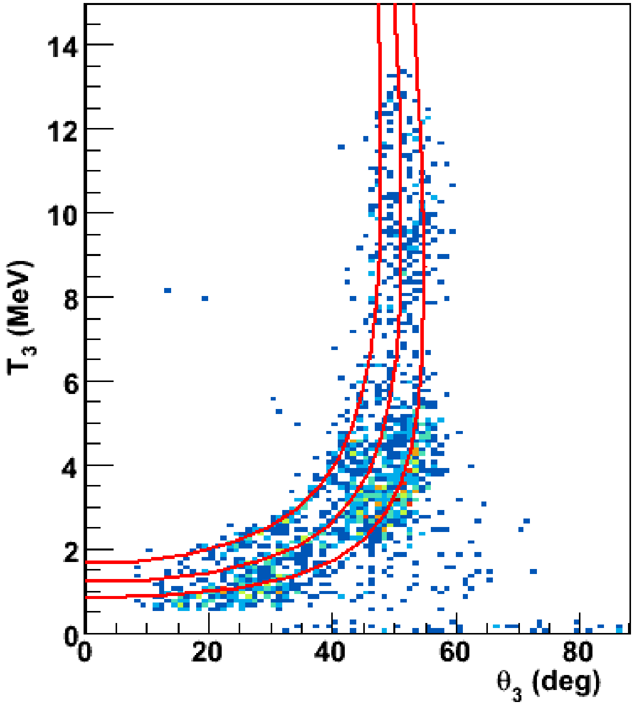


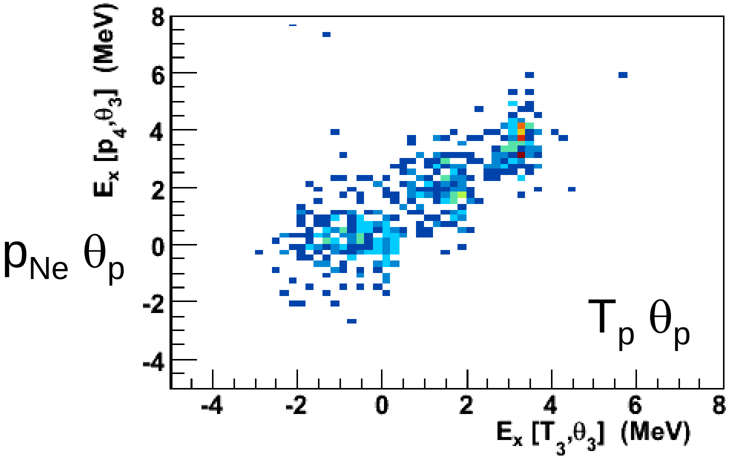






**POSITIVE IDENTIFICATION OF EXCITED 5/2+ STATE**





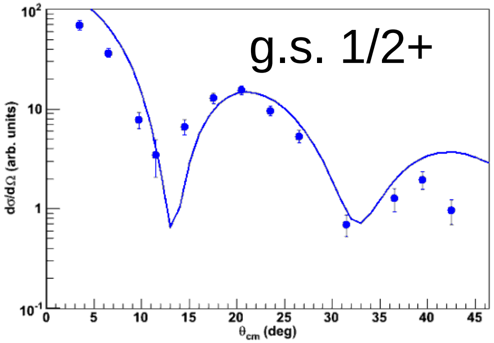
**NEW ALGORITHM FOR ENERGY**

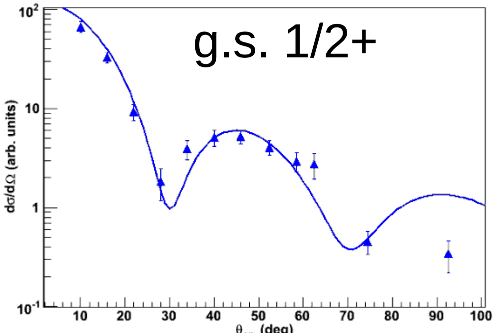
# Preliminary results for $^{26}$Ne(d,t)$^{25}$Ne and also (p,d)

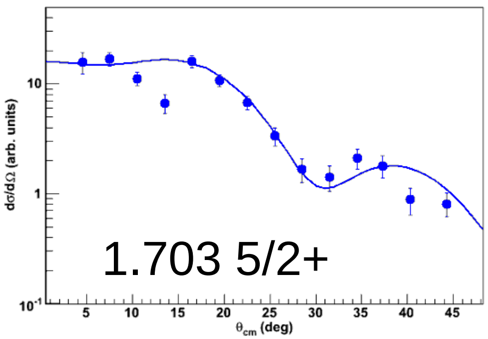
**JEFFRY THOMAS, SURREY**

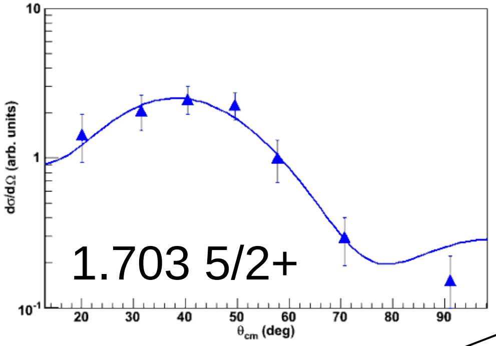
## $^{26}$Ne(d,t)$^{25}$Ne

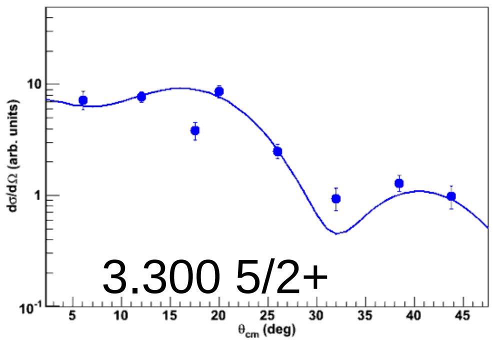
## $^{26}$Ne(p,d)$^{25}$Ne





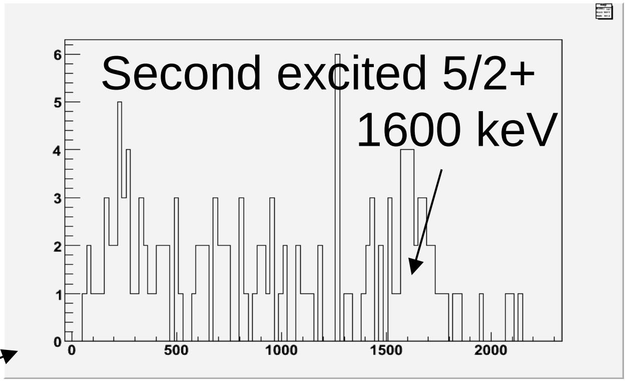


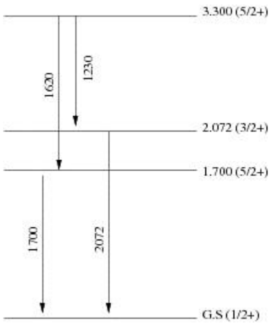


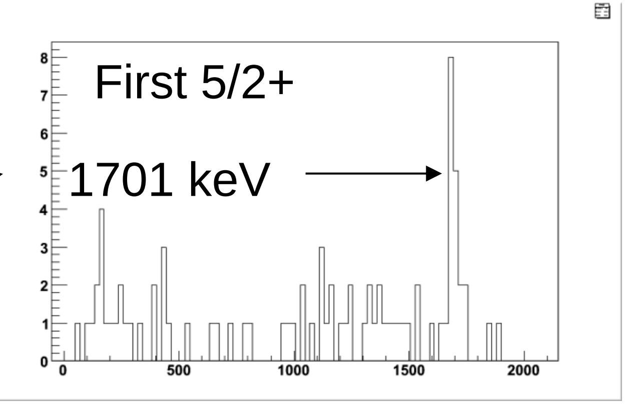


## $^{26}$Ne(d,tγ)$^{25}$Ne

GAMMA ENERGY

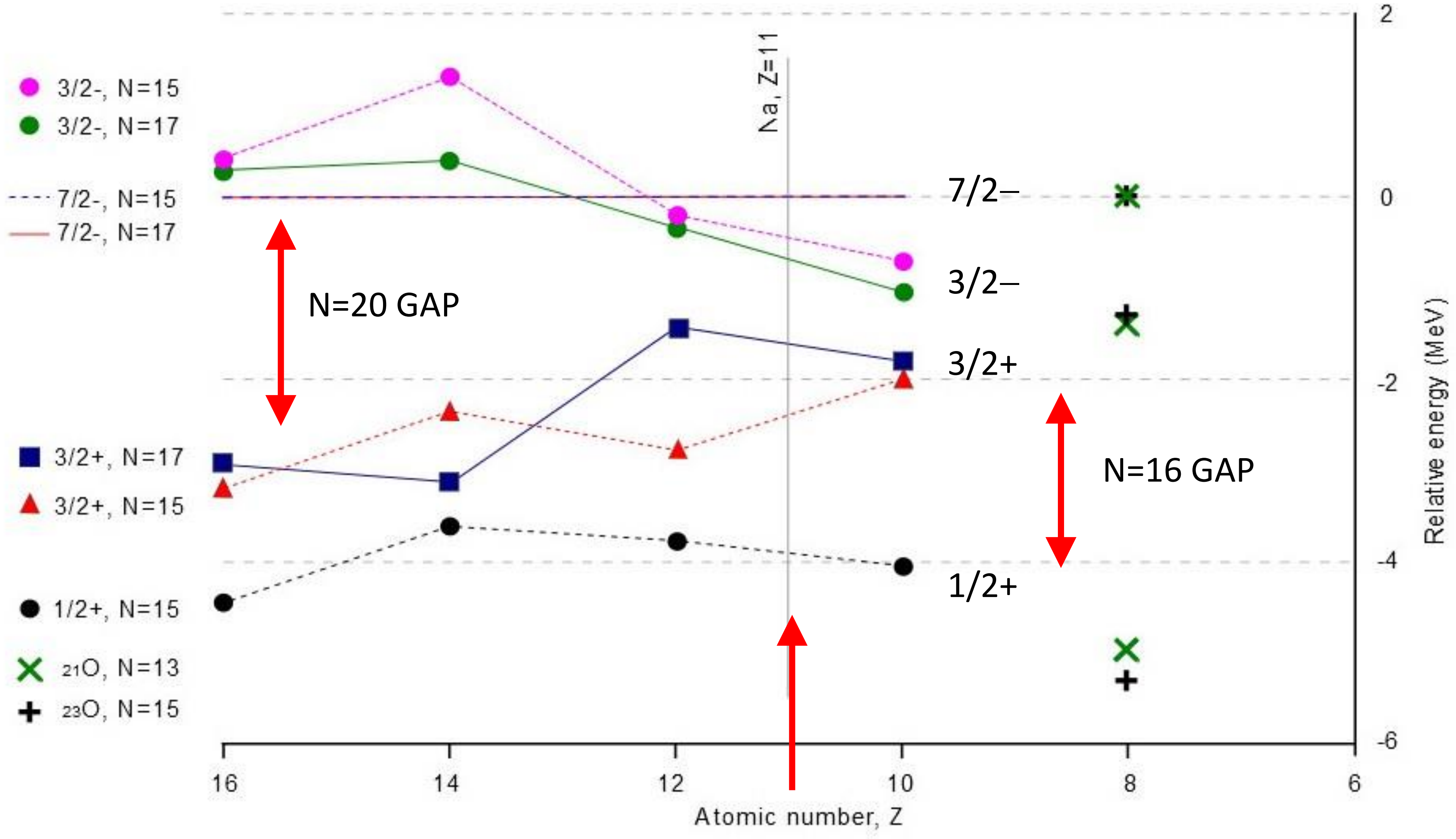






INDIVIDUAL DECAY SPECTRA OF EXCITED 5/2+ STATES

# Migration of Levels as nuclei become more exotic, normalised to 7/2– energy



7/2–

3/2–

3/2+

1/2+

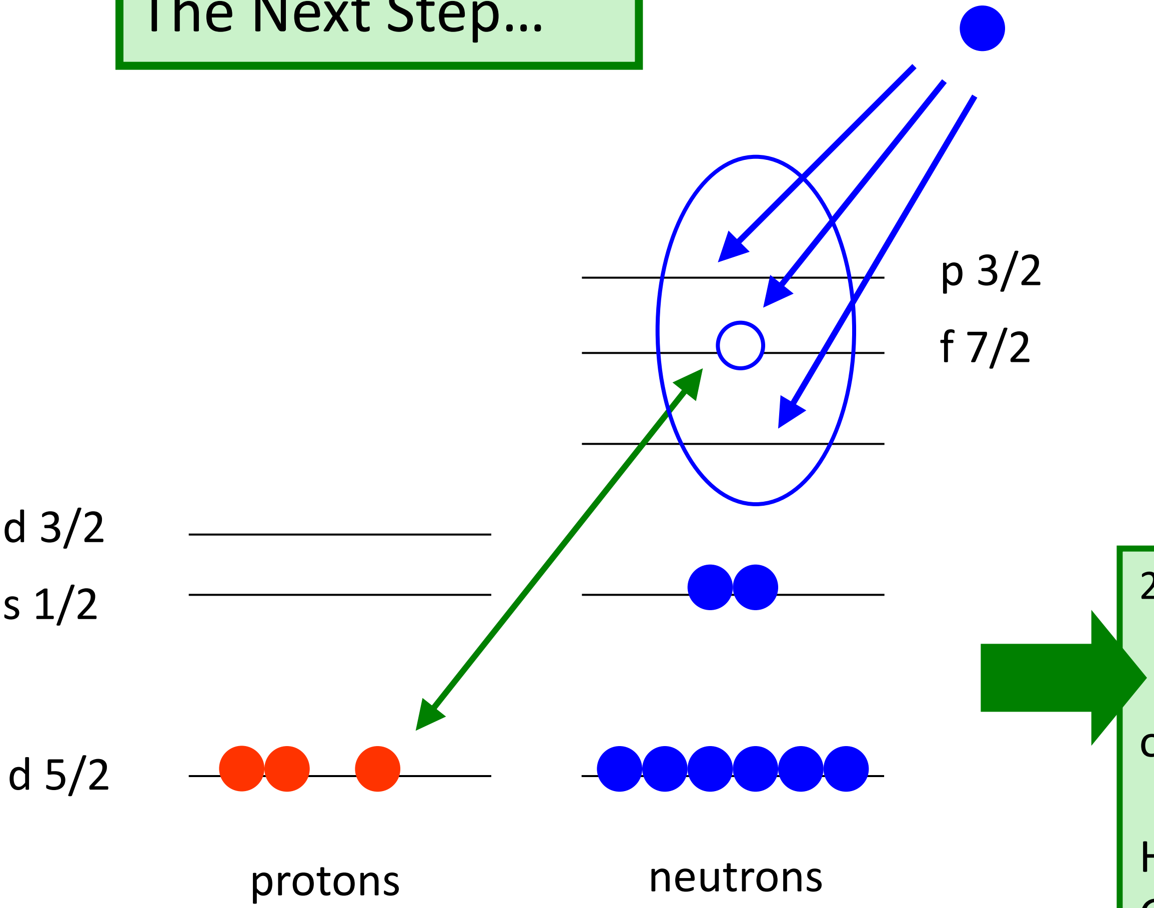
N=20 GAP

N=16 GAP

**sodium**
**$^{26}$Na**

Dashed: N=15
Full line: N=17

# The Next Step…



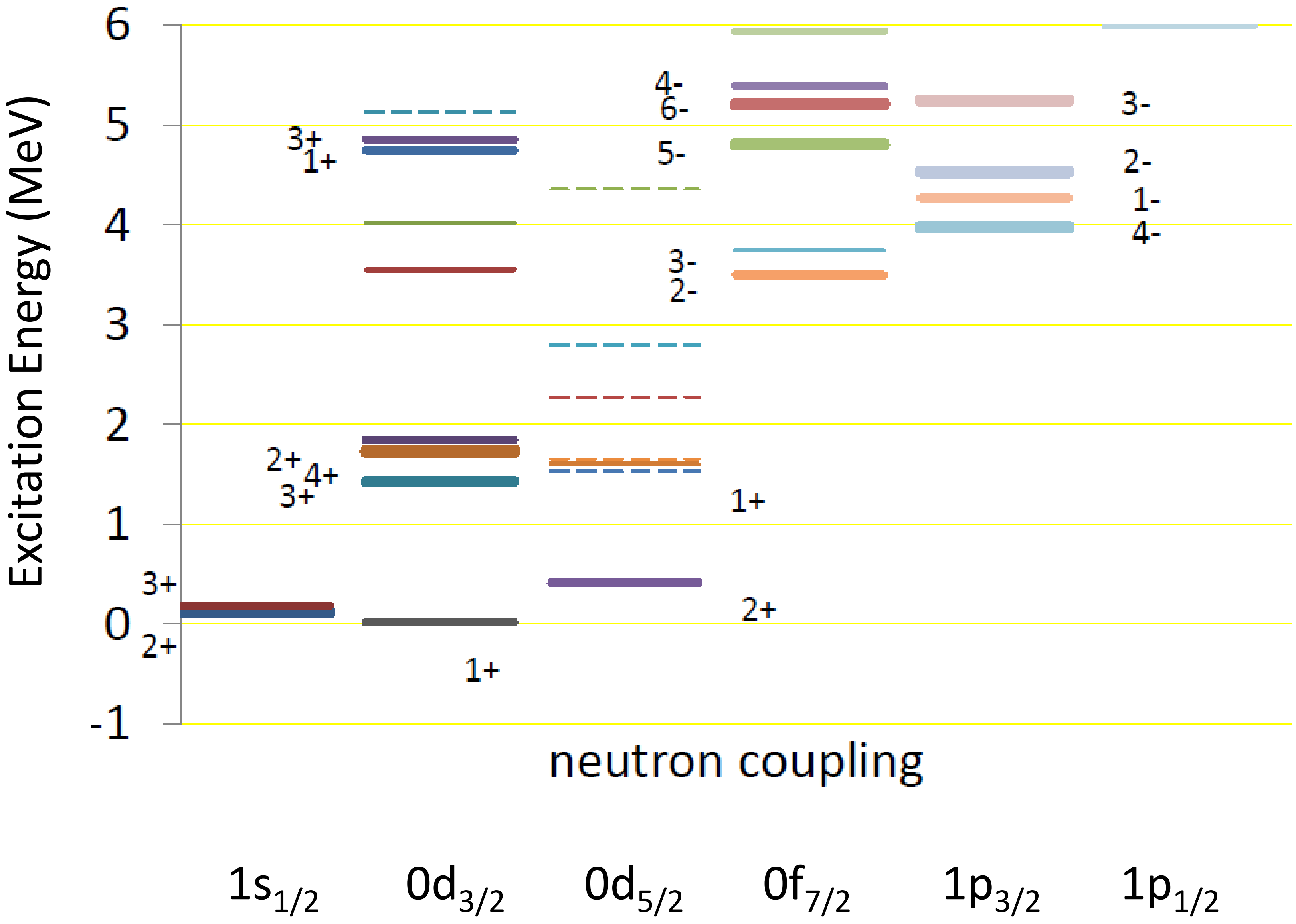
$^{25}$Na (d,p) $^{26}$Na

odd-odd final nucleus

High density of states
Gamma-gating needed

MULTIPLETS e.g. $\pi(d_{5/2}) \otimes \nu(p_{3/2}) \rightarrow (1,2,3,4)^{-}$

# Shell Model Predictions (modified WBP) for $^{26}$Na states expected in (d,p)

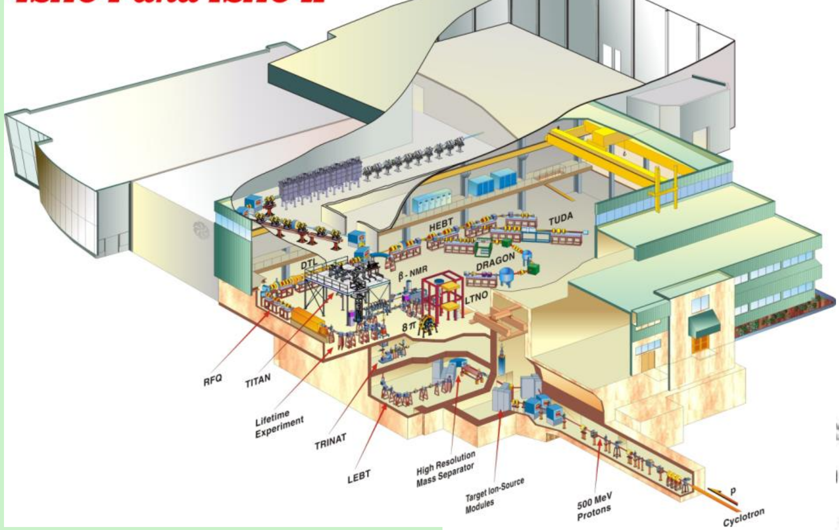


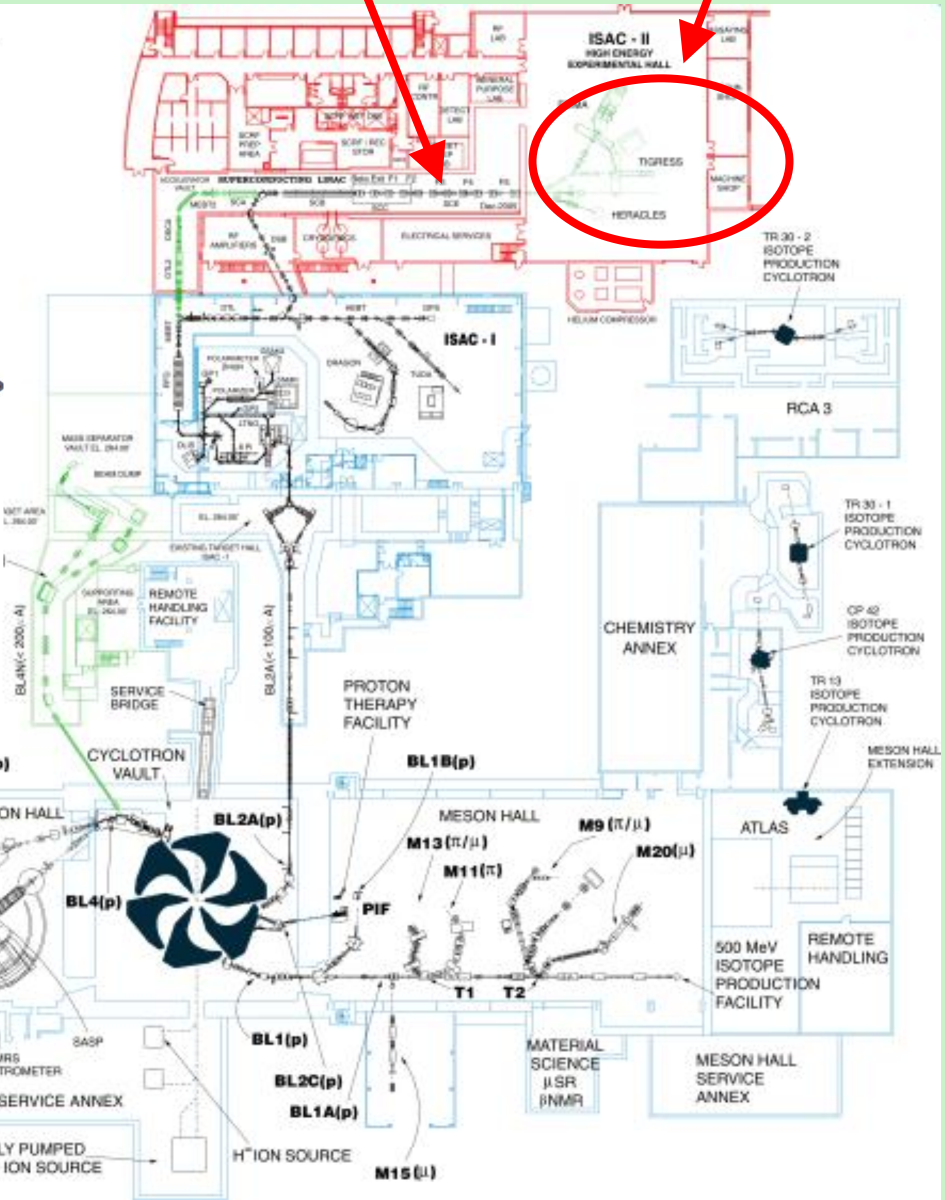
TRIUMF ISAC

**ISAC2**

**TIGRESS**

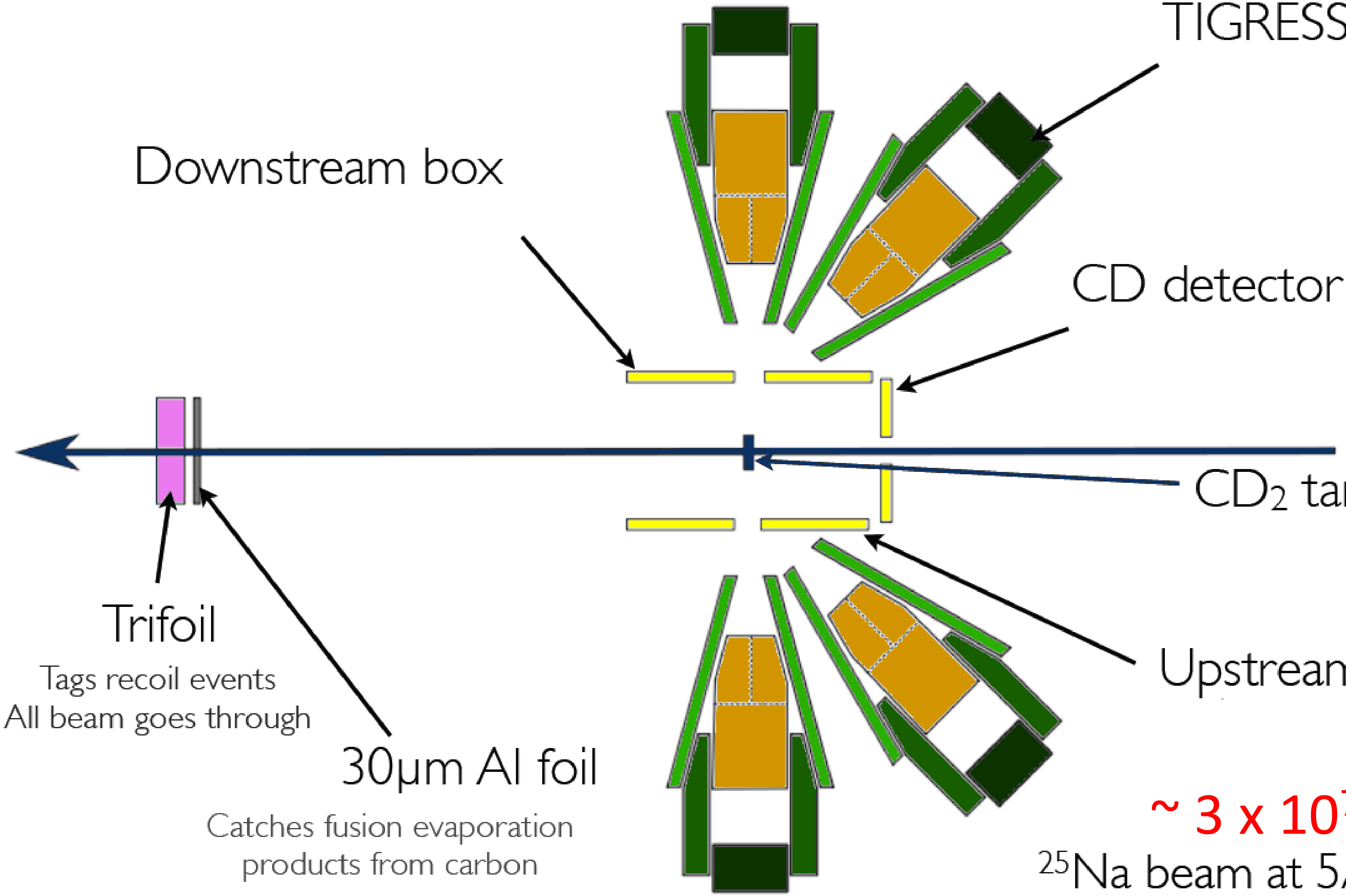
## *ISAC I and ISAC II*





# SHARC at ISAC2 at TRIUMF

Christian Diget



TIGRESS

Downstream box

CD detector

$CD_2$ target

Trifoil

Tags recoil events
All beam goes through

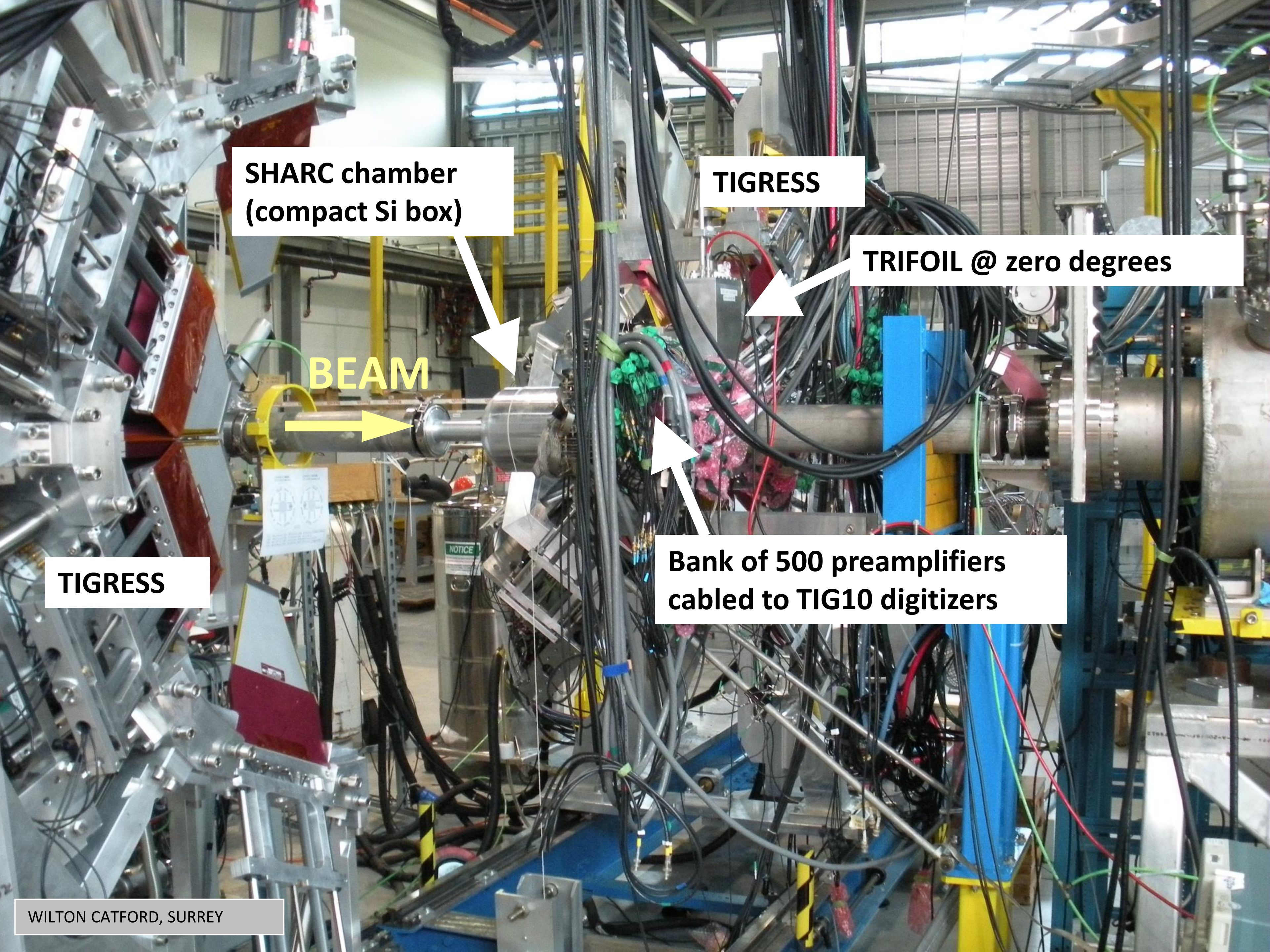
30μm Al foil

Catches fusion evaporation
products from carbon

Upstream box

~ $3 \times 10^7$ pps

$^{25}$Na beam at 5AMeV



SHARC chamber
(compact Si box)

TIGRESS

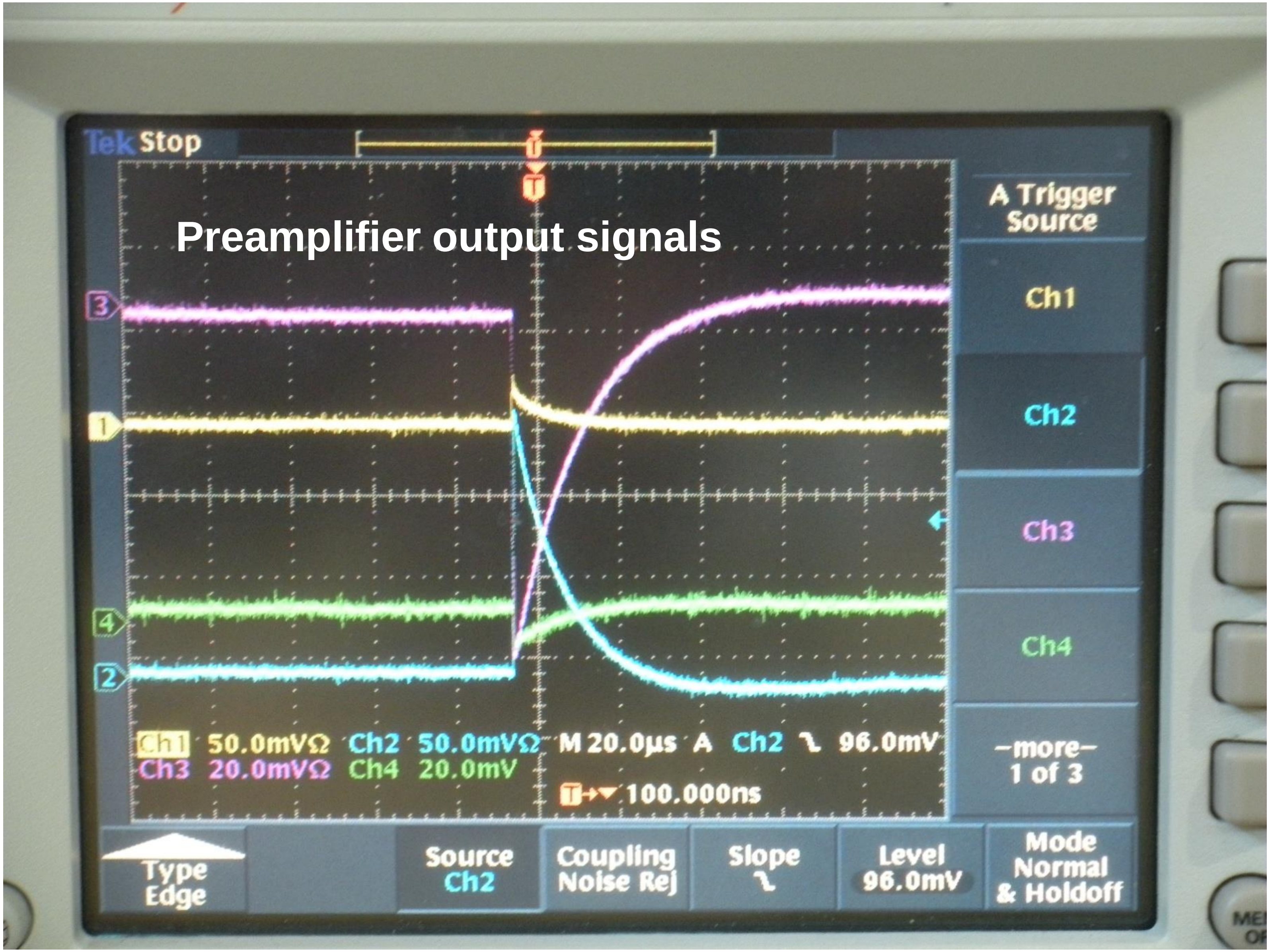
TRIFOIL @ zero degrees

BEAM

Bank of 500 preamplifiers
cabled to TIG10 digitizers

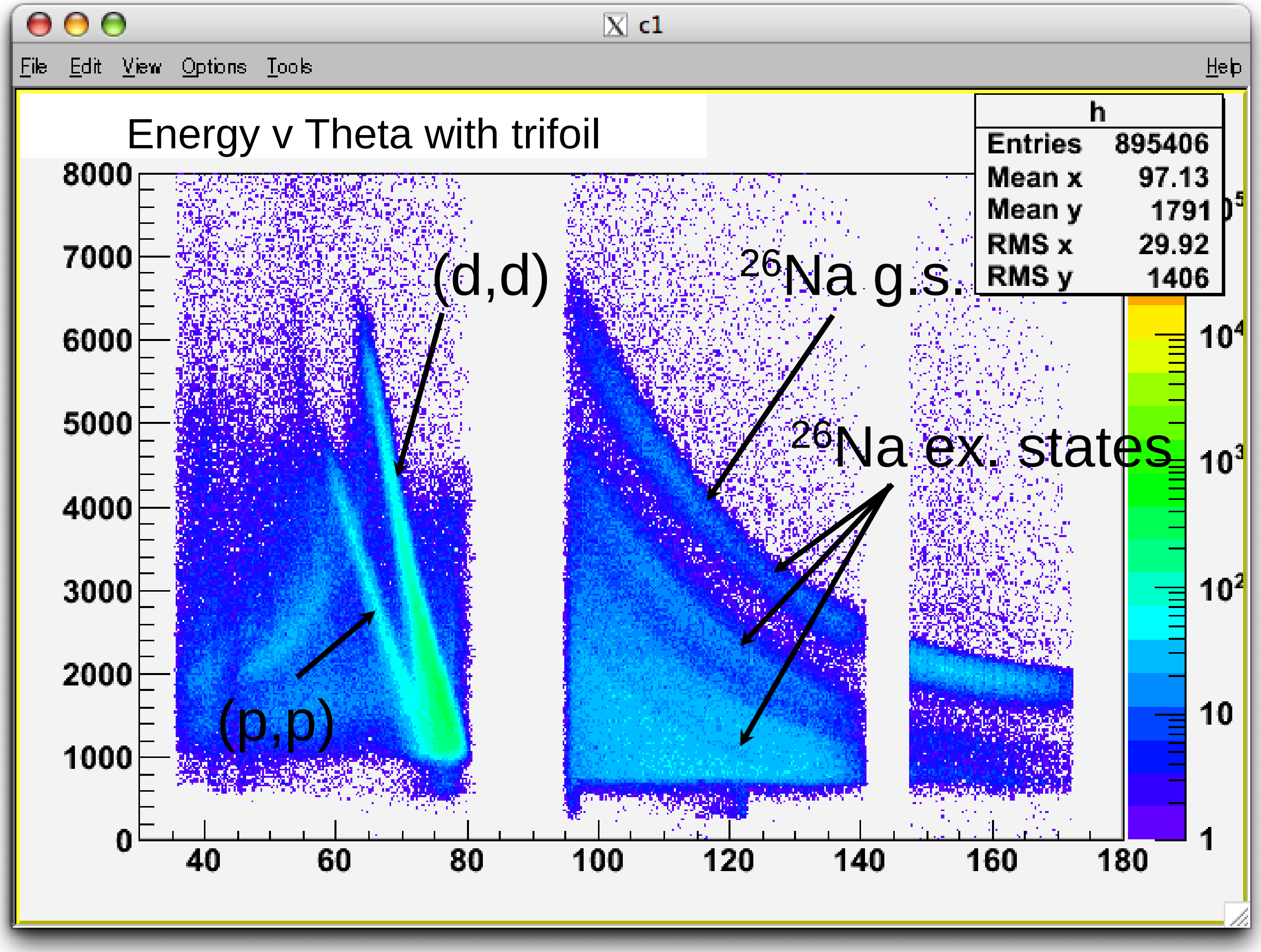
TIGRESS

Digital signal processing was used for **all Ge** and **all Si** signals, via TIG10 modules



Preamplifier output signals

# Preliminary Analysis: E vs θ



```
h
Entries   895406
Mean x     97.13
Mean y      1791
RMS x      29.92
RMS y       1406
```

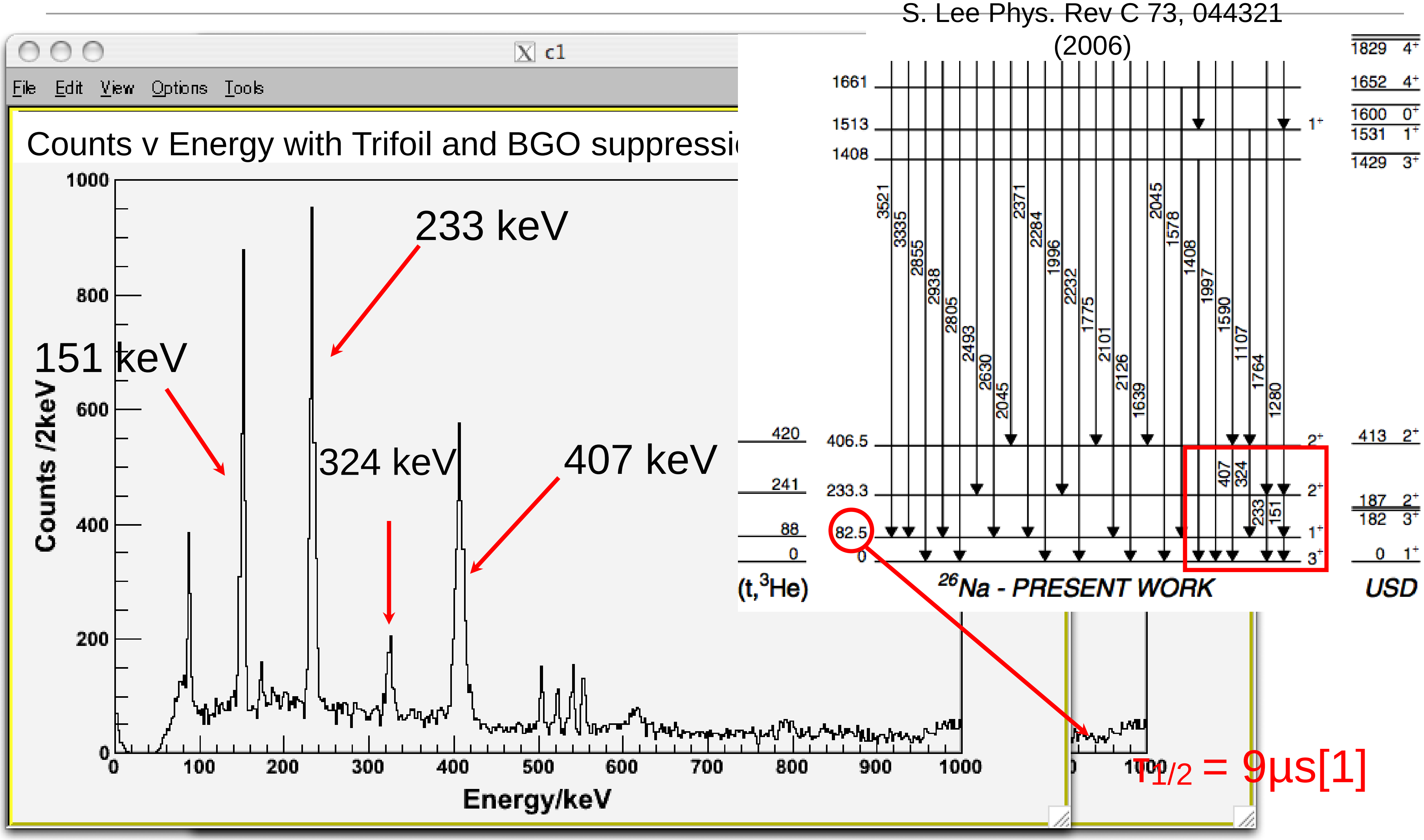
(d,d)

$^{26}$Na g.s.

$^{26}$Na ex. states

(p,p)

# Preliminary Analysis: γ ray spectra



S. Lee Phys. Rev C 73, 044321 (2006)

$\tau_{1/2}$ = 9µs[1]

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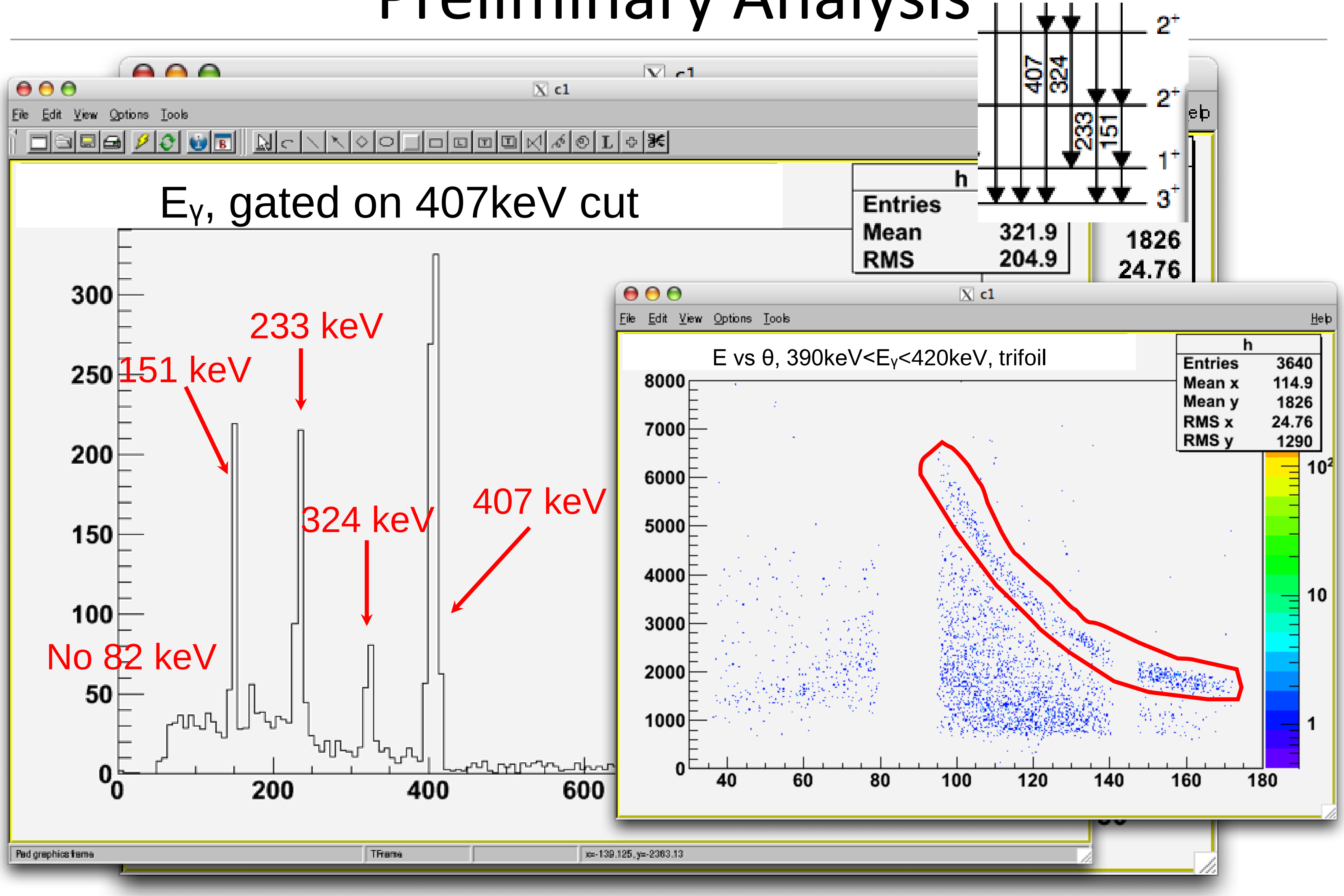
[1] Contrib.Proc. 5th Int.Conf.Nuclei Far from Stability, Rosseau Lake, Canada, D1 (1987)

# Preliminary Analysis



Eγ, gated on 407keV cut

| h | |
|---|---|
| Entries | |
| Mean | 321.9 |
| RMS | 204.9 |

151 keV

233 keV

324 keV

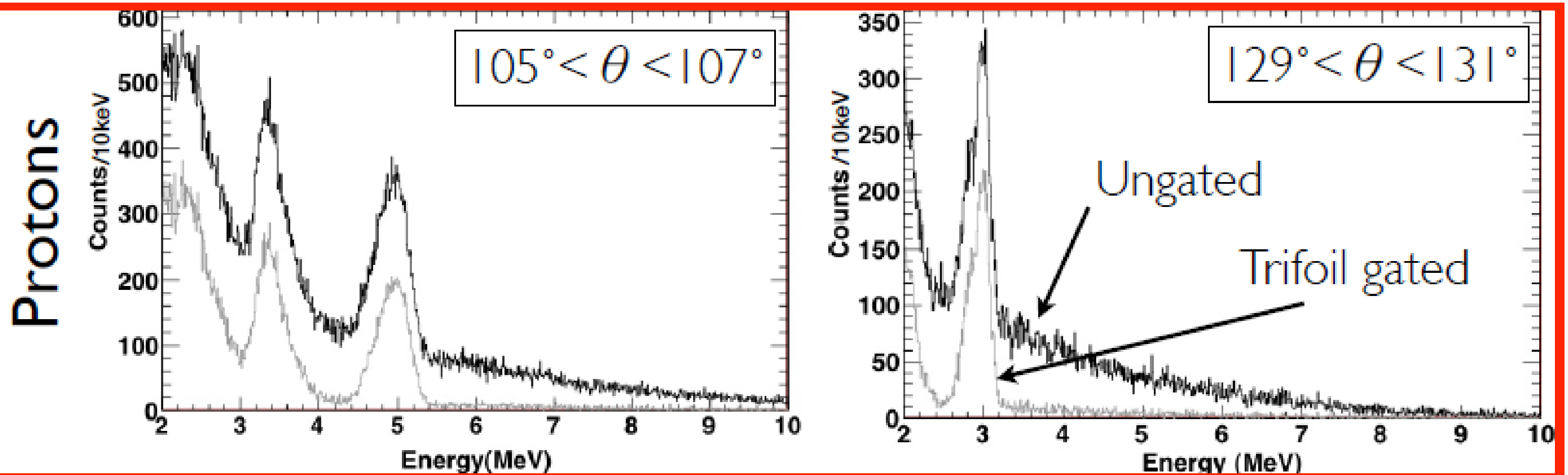
407 keV

No 82 keV

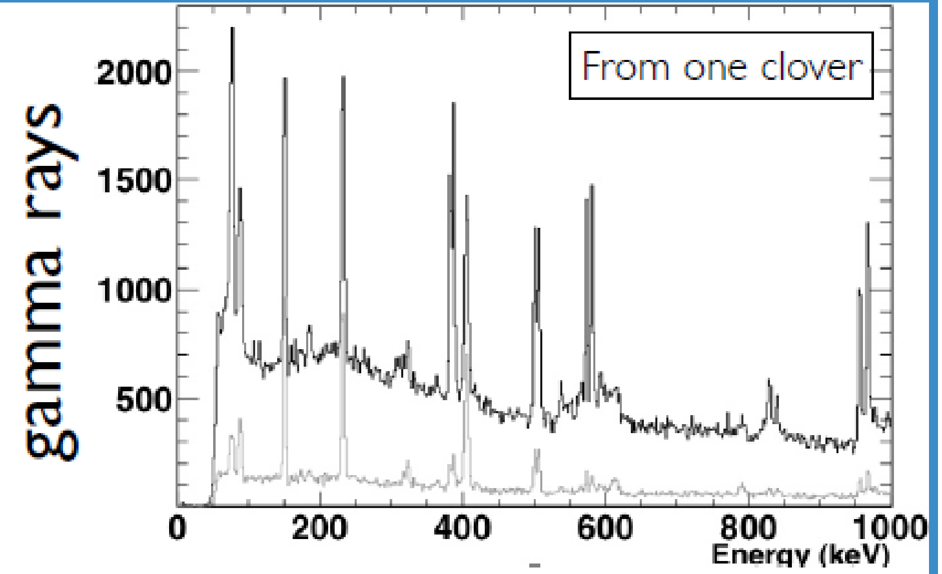
E vs θ, 390keV<Eγ<420keV, trifoil

| h | |
|---|---|
| Entries | 3640 |
| Mean x | 114.9 |
| Mean y | 1826 |
| RMS x | 24.76 |
| RMS y | 1290 |

# Measuring Trifoil performance



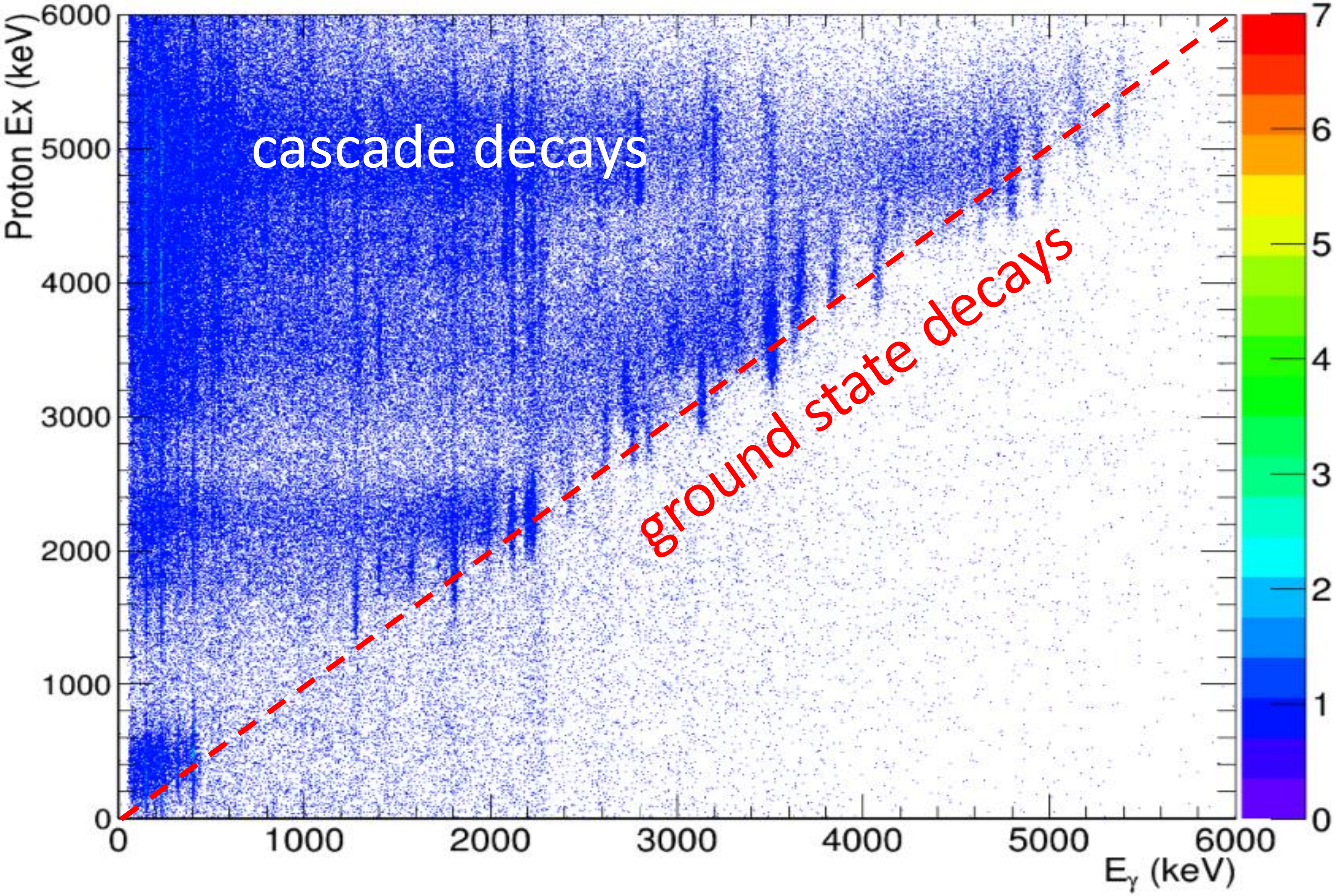
- 80% of protons tagged
- Signal to background improved by factor of 10



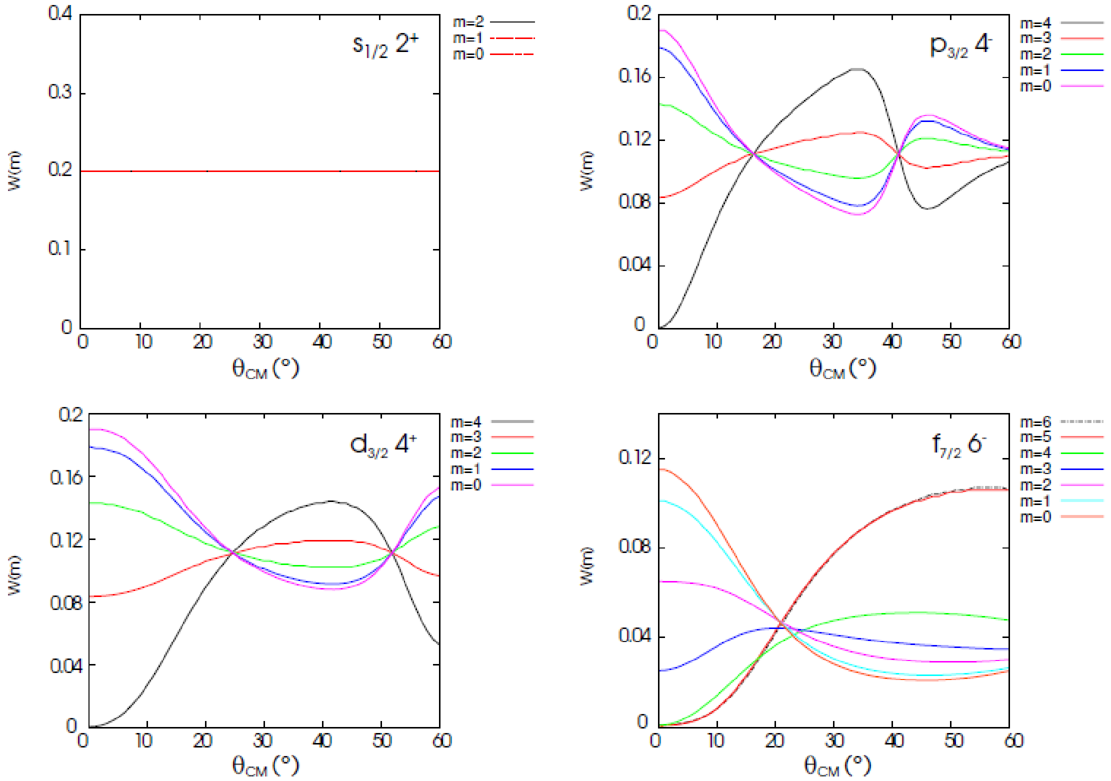
Data from d($^{25}$Na,p)$^{26}$Na at 5 MeV/A using SHARC at ISAC2 at TRIUMF

Gemma Wilson, Surrey

Excitation energy deduced from proton energy and angle



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

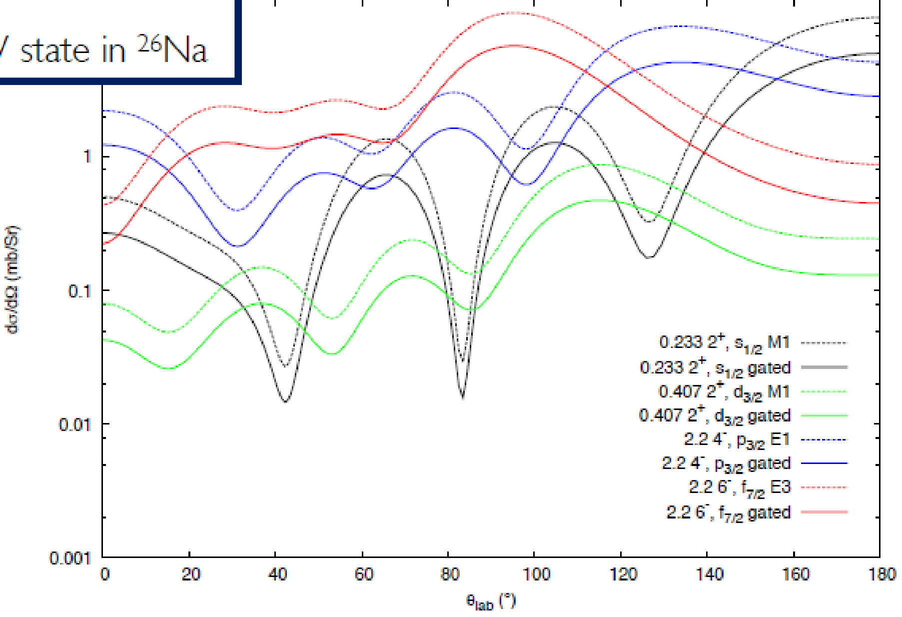


Substate populations over proton CM angle for a 2.2 MeV state in $^{26}$Na

If we **gate** on a **gamma-ray**, then we **bias** our proton measurement, if the gamma **detection probability** depends on the **proton angle**.

And it does depend on the proton angle, because the gamma-ray correlation is determined by magnetic substate populations.

However, our **gamma-ray** angular coverage is sufficient that the integrated efficiency for gamma detection remains very similar and the SHAPE of the **proton** angular distribution is unchanged by gating.

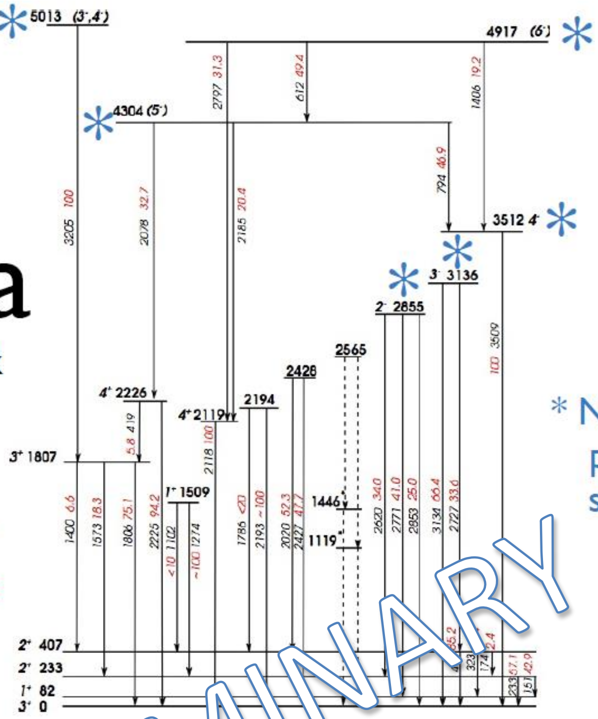


# $^{26}$Na

This work

Energies in keV

Branching ratios in red



* Negative parity states

| $E_x$ $^{a)}$ (keV) | $J^{\pi\,b)}$ | $n(\ell, j)$ | S.F. $^{c)}$ exp | ANC$^{2\ c)}$ | $E_x$ $^{d)}$ (keV) | $E_x$ $^{e)}$ (keV) | n $^{f)}$ | S.F. $^{g)}$ theory |
|---|---|---|---|---|---|---|---|---|
| 233 | $2^+$ | $0s_{1/2}$ | 0.14 | | 233 | 187 | 1 | 0.22 |
| 407 | $2^+$ | $0s_{1/2}$ | 0.34 | | 407 | 414 | 2 | 0.19 |
| 1509 | $1^+$ | | * | | 1513 | 1532 | 1 | $^{h)}$ |
| 1806 | $3^+$ | $0d_{3/2}$ | 0.22 | | | 1430 | 2 | 0.32 |
| 2118 | $4^+$ | $0d_{3/2}$ | 0.34 | | | | | |
| 2225 | $4^+$ | $0d_{3/2}$ | 0.43 | | | 1830 | 2 | 0.59 |
| 2853 | $2^-$ | | * | | | 3499 | 1 | 0.23 |
| 3134 | $3^-$ | $0f_{7/2}$ | 0.10 | | | 3742 | 1 | 0.17 |
| 3509 | $4^-$ | $1p_{3/2}$ | 0.54 | | | 3977 | 1 | 0.43 |
| 4303 | $(5^-)$ | $0f_{7/2}$ | * | | | 4807 | 1 | 0.44 |
| 4915 | $(6^-)$ | $0f_{7/2}$ | * | | | 5208 | 1 | 0.64 |
| 5011 | $(3,4)^-$ | | * | | | | | |

* not possible to extract differential cross section

$^{a)}$ present work, from gamma-ray energies

$^{b)}$ inferred in present work

$^{c)}$ present work, using the indicated nucleon transfer

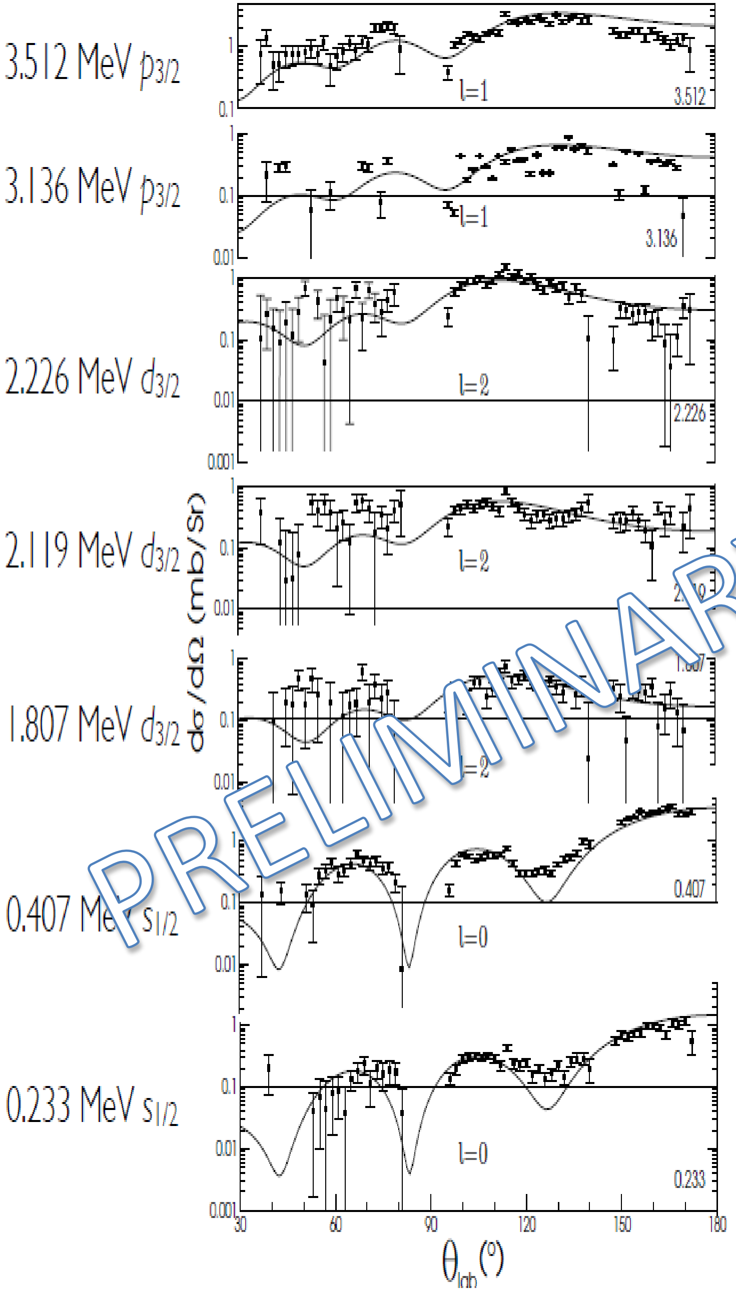
$^{d)}$ from fusion-evaporation study, ref. [22]

$^{e)}$ shell model using modified WBP interaction (see text)

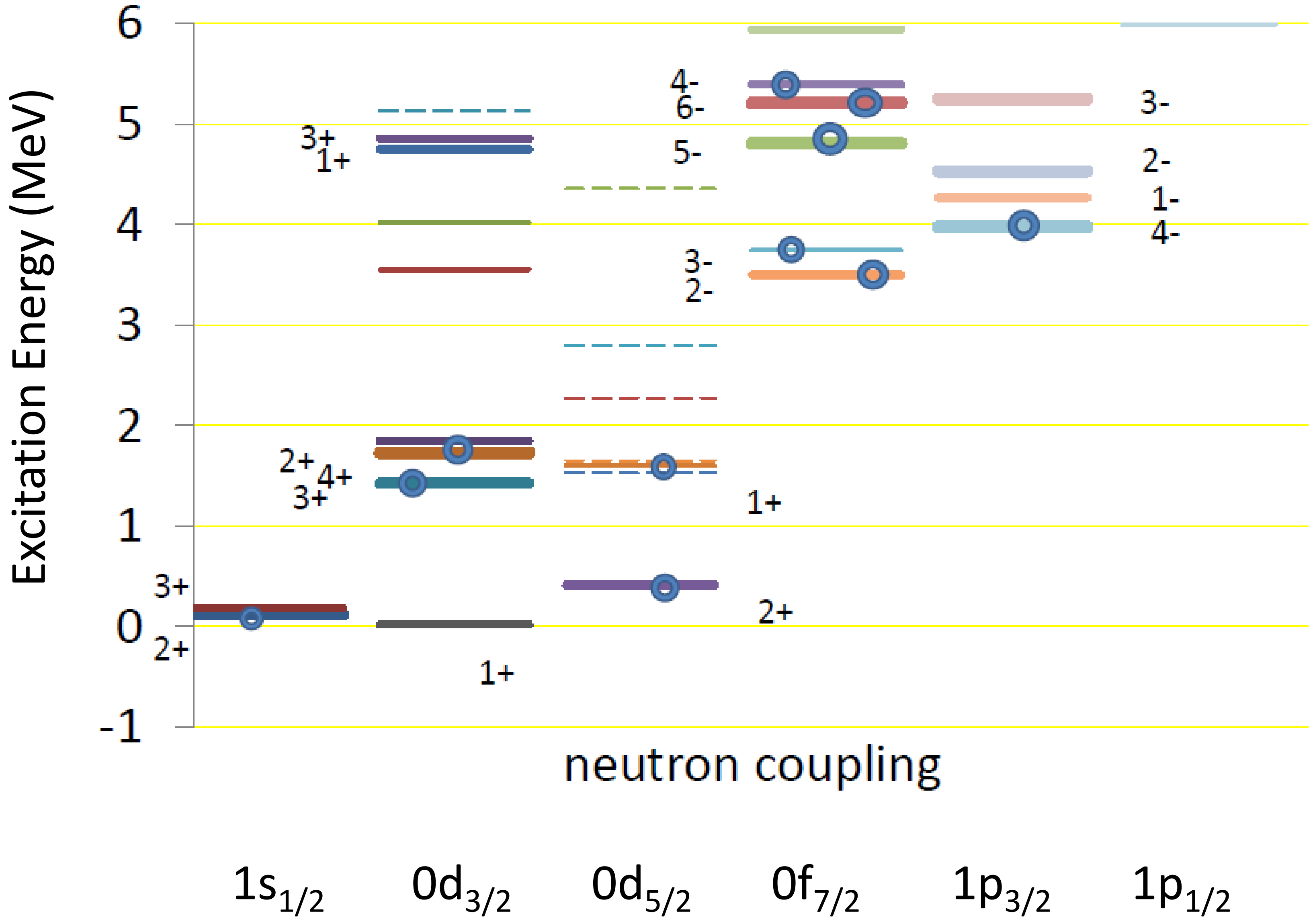
$^{f)}$ numbering of shell model state (lowest = 1)

$^{g)}$ shell model value, for indicated nucleon transfer

$^{h)}$ mixed strength 0.08 $0d_{5/2}$ and 0.10 $0d_{3/2}$

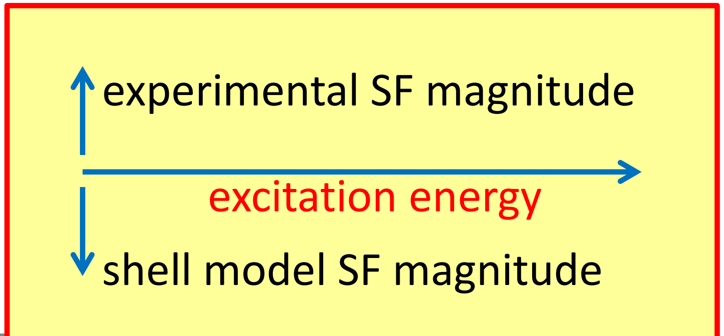


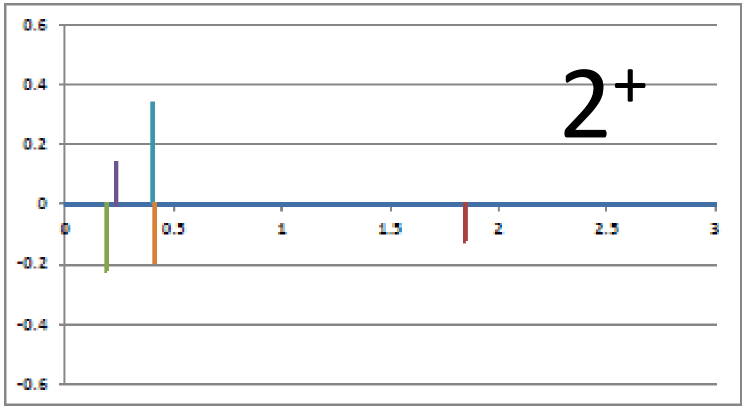
# Shell Model Predictions (and new candidates) for $^{26}$Na states expected in (d,p)



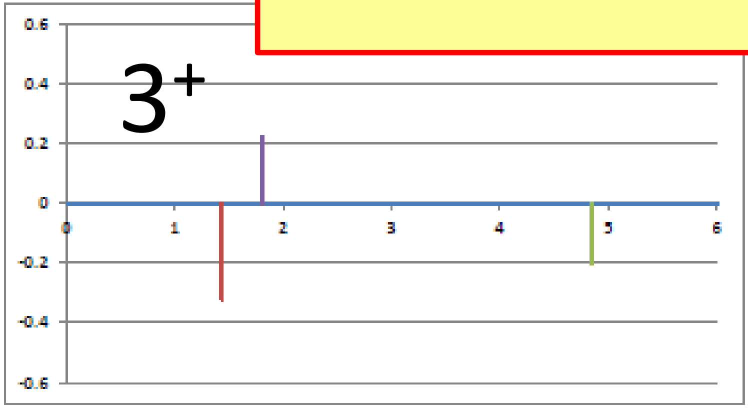
# Shell Model Predictions (and new candidates) for $^{26}$Na states expected in (d,p)…

## Comparison of spectroscopic strength in theory and experiment



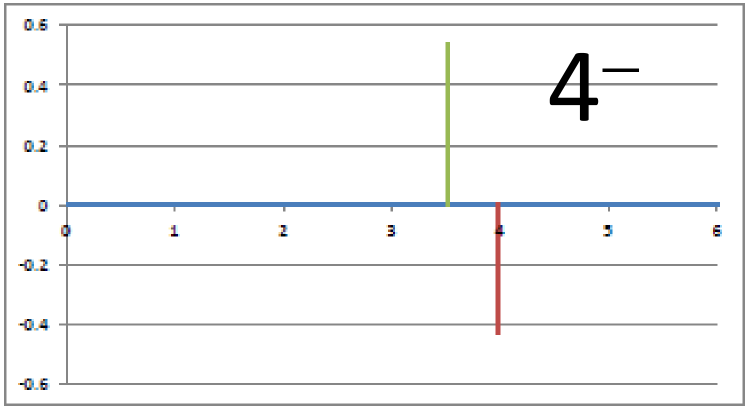


Above: s1/2 strength for 2+ states

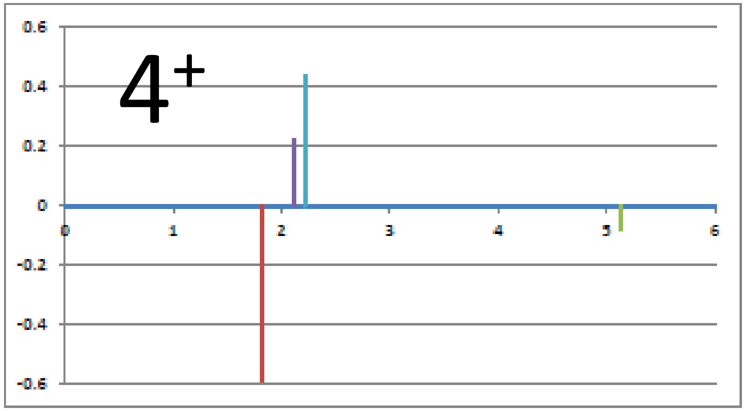


Above: d3/2 to 3+ states

Below: p3/2 to 4- states



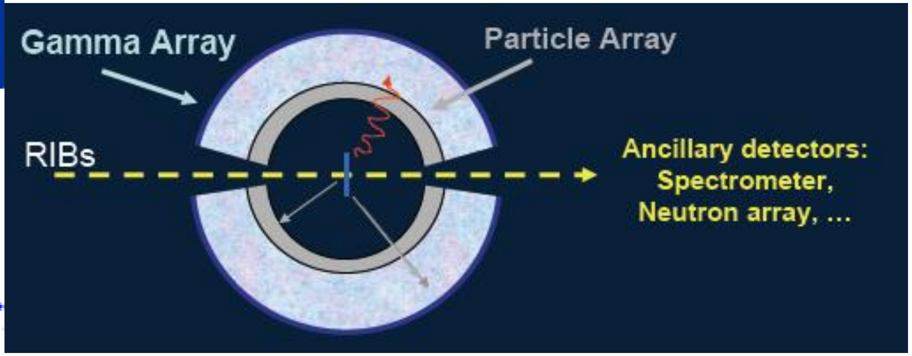
Below: d3/2 to 4+ states



# SOME FUTURE PERSPECTIVES

GASPARD

Spiral2



EURISOL

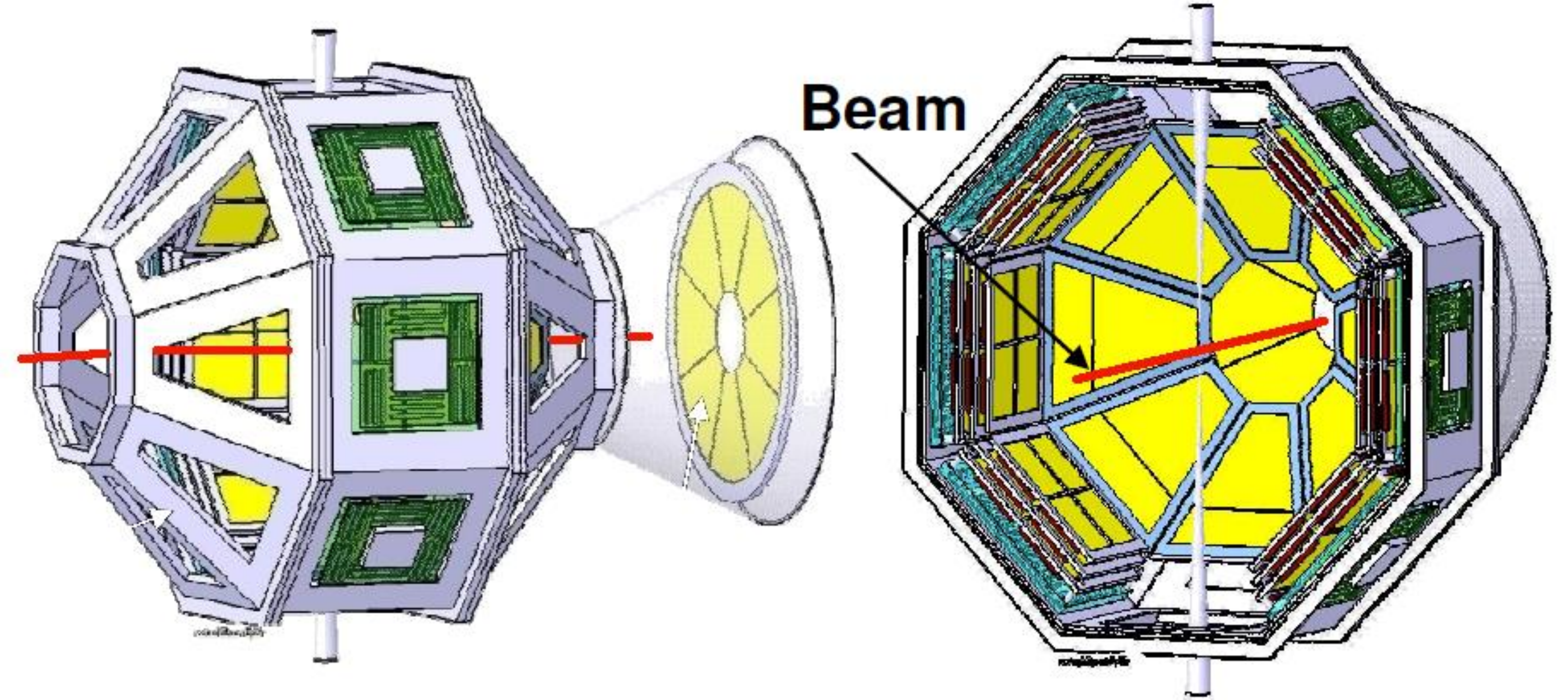
GRAPA

GAMMA RAY AND PARTICLE ARRAY

"… WORK IN PROGRESS"

FUTURE:

- We have experiments planned with $^{16}C$, $^{64}Ge$ at GANIL & $^{28}Mg$ and others at TRIUMF
- Many other groups are also busy! T-REX at ISOLDE, ORRUBA at ORNL etc
- New and extended devices are planned for SPIRAL2, HIE-ISOLDE and beyond

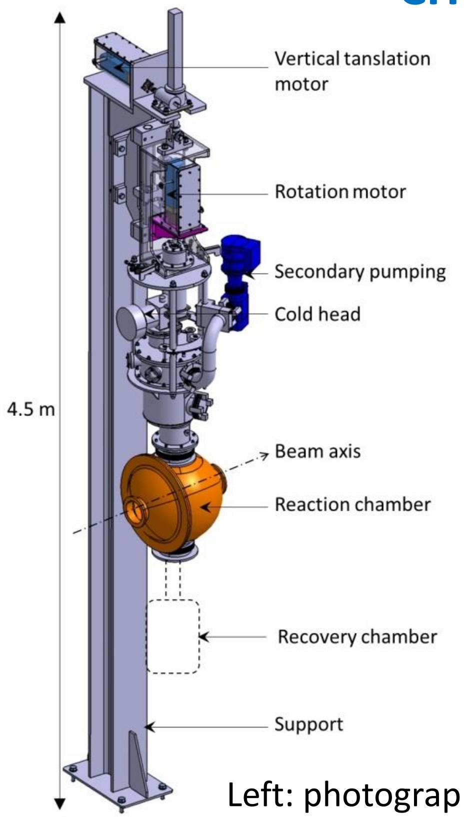


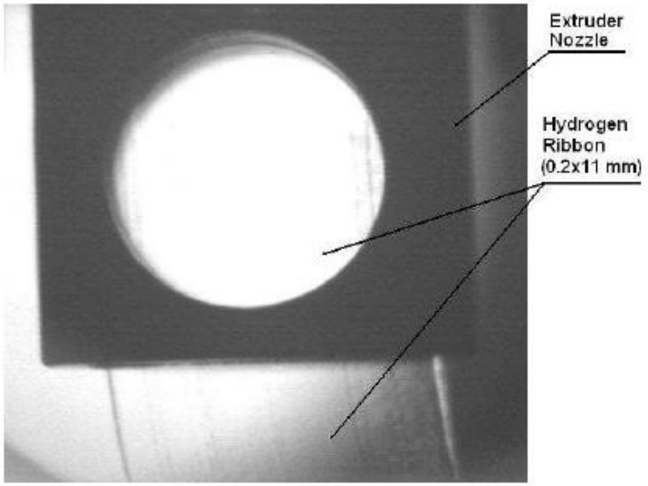
**GASPARD**

Designed to use cryogenic target CHyMENE and gamma-arrays PARIS, AGATA…

A development of the GRAPA concept originally proposed for EURISOL.

# CHyMENE (Saclay/Orsay/…) SOLID Hydrogen TARGET





Left: photograph from 2007 of a 200µm pure solid hydrogen film being extruded.
Right: more recent photograph of 100µm pure solid hydrogen film being extruded.

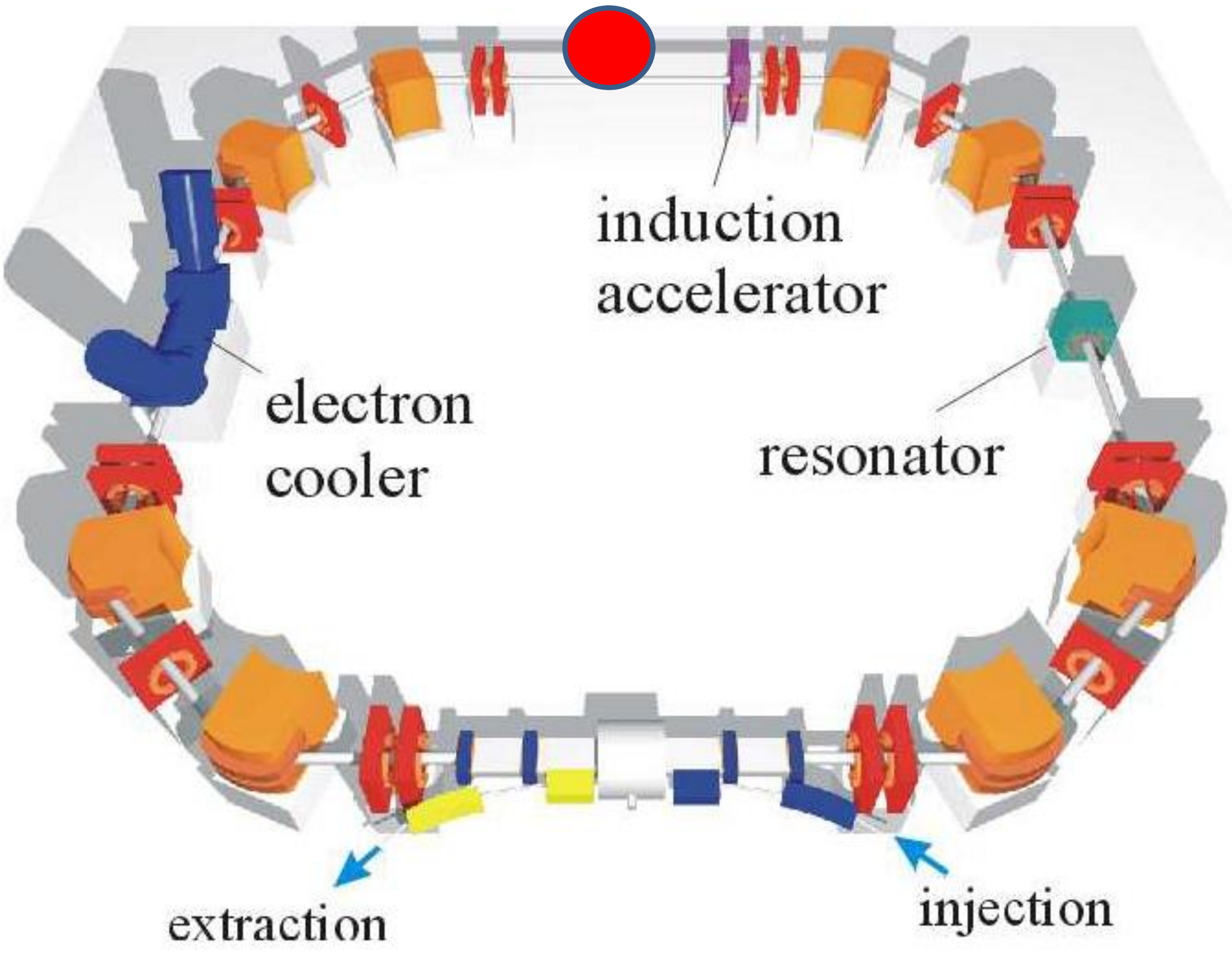
The CHyMENE project has achieved 100µm and is designed to achieve 50µm uniform films.

For 100µm target, the energy loss by a typical beam is equivalent to a 1 mg/cm$^2$ $CD_2$ target.

For 100µm target, the number of hydrogen atoms is **<u>THREE TIMES</u>** that of a 1 mg/cm$^2$ $CD_2$.

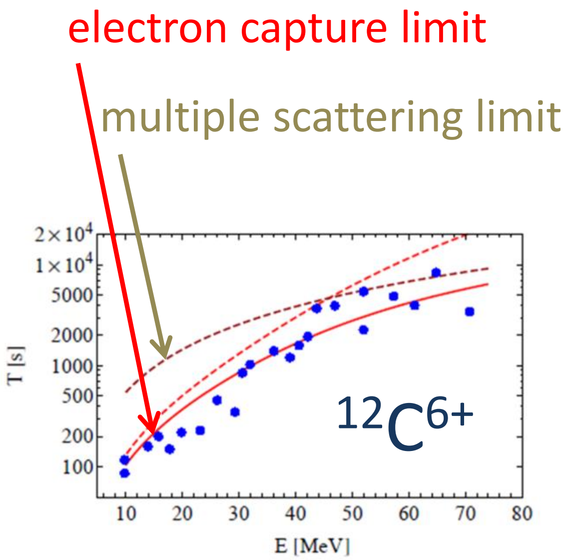
GASPARD

# TSR@ISOLDE



Circumference 55.4m

- Existing storage ring
- Re-deploy at ISOLDE
- Thin gas jet targets
- Light beams will survive
- Increased luminosity
- Supported by CERN
- In-ring initiative led by UK
- Also linked to post-ring helical spectrometer



**Ultimately, with single particle transfer reactions, we can certainly:**

- make the measurements to highlight **strong** SP states

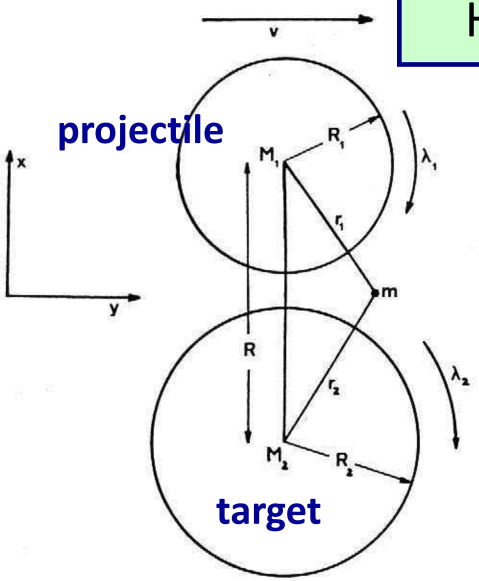
- measure the **spin/parity** for strong states

- **associate** experimental and Shell Model states and see

    - when the shell model **works** (energies and spectroscopic factors)
    - when the shell model **breaks down**
    - whether we can adjust the interaction and **fix** the calculation
    - how any such modifications can be interpreted in terms of NN interaction

And clearly:

- monopole shifts need to be measured and understood because the changes In energy gaps fundamentally affect nuclear structure (collectivity, etc.)



# Heavy-Ion induced nucleon transfer reactions

David M. Brink, *Phys. Lett.* **B40** (1972) 37
N. Anyas-Weiss *et al.*, *Physics Reports*, **12** (1974) 201

**IDEA:** for the transferred nucleon, we match the initial and final values of the **linear** momentum and of the **angular** momentum

**Linear momentum** in y-direction (relative motion), before and after:

$$p_i = m\upsilon - \hbar\lambda_1 / R_1 \qquad p_f = \hbar\lambda_2 / R_2 \qquad \Delta p = p_f - p_i \approx 0$$

Set $\Delta p=0$ within accuracy of Uncertainty Principle $\Delta p \sim \hbar/\Delta y$ ; $\Delta y \sim R/2$

$$\boxed{\text{k-matching:} \quad \Delta k = k_0 - \lambda_1 / R_1 - \lambda_2 / R_2 \approx 0 \quad ; \quad \Delta k \leq 2\pi/R}$$

**Angular momentum** projected in the z-direction (perpendicular to relative motion) is given by

$$L_{init} = L(\text{relative motion})_i + \lambda_1 \hbar = \mu\upsilon R + \lambda_1 \hbar \quad \text{and} \quad L_{final} = L(\text{relative})_f + \lambda_2 \hbar$$

$$\Delta L \hbar = L_{final} - L_{init} = (\lambda_2 - \lambda_1)\hbar + \delta(\mu\upsilon R) \text{ where each of } \mu, \upsilon \text{ and } R \text{ changes}$$

$$\boxed{\Delta L \hbar = (\lambda_2 - \lambda_1)\hbar + ½\, m\upsilon (R_1 - R_2) + R\, Q_{eff} / \upsilon \ ; \ Q_{eff} = Q - (Z_1^f Z_2^f - Z_1^i Z_2^i)\, e^2 / R}$$

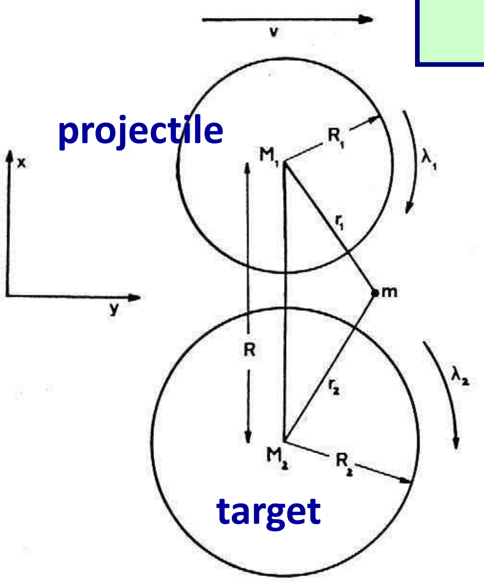
$\ell$-matching

Q-value Coulomb-corrected for nucleon rearrangement

Set $\Delta L = 0$ precisely, in principle (in practice, classical treatment of $E_{rel} \Rightarrow$ allow $\Delta L \leq 2$)

And finally, there is a simple requirement that $\ell_1 + \lambda_1 = \text{even}$ and $\ell_2 + \lambda_2 = \text{even}$

# Heavy-Ion induced nucleon transfer reactions - 2



David M. Brink, *Phys. Lett.* **B40** (1972) 37
N. Anyas-Weiss *et al.*, *Physics Reports*, **12** (1974) 201

**Linear momentum** in y-direction (relative motion), before and after:

k-matching: $\Delta k = k_0 - \lambda_1 / R_1 - \lambda_2 / R_2 \approx 0$ ; $\Delta k \leq 2\pi/R$

**Angular momentum** projected in the z-direction (perpendicular):

$$\Delta L \hbar = (\lambda_2 - \lambda_1)\hbar + \tfrac{1}{2} m \upsilon (R_1 - R_2) + R\, Q_{eff} / \upsilon \;;$$

$\ell$-matching

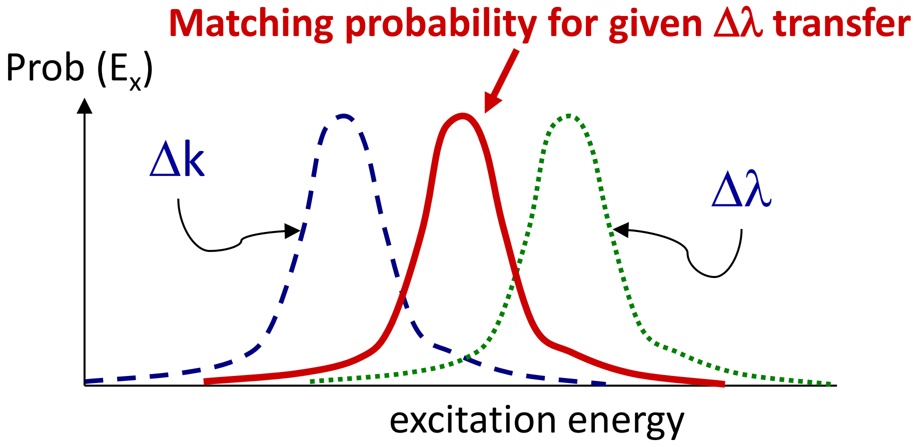
$Q_{eff} = Q - (Z_1^f Z_2^f - Z_1^i Z_2^i)\, e^2 / R$

And finally, there is a simple requirement that $\ell_1 + \lambda_1 = \text{even}$ and $\ell_2 + \lambda_2 = \text{even}$

Initial $\psi_1 = u_1(r_1)\, Y_{\ell_1,\lambda_1}(\theta_1,\phi_1)$
Final $\psi_2 = u_2(r_2)\, Y_{\ell_2,\lambda_2}(\theta_2,\phi_2)$

*and the main contribution to the transfer is at the reaction plane:*
$\Rightarrow \theta_1 = \theta_2 = \pi/2$

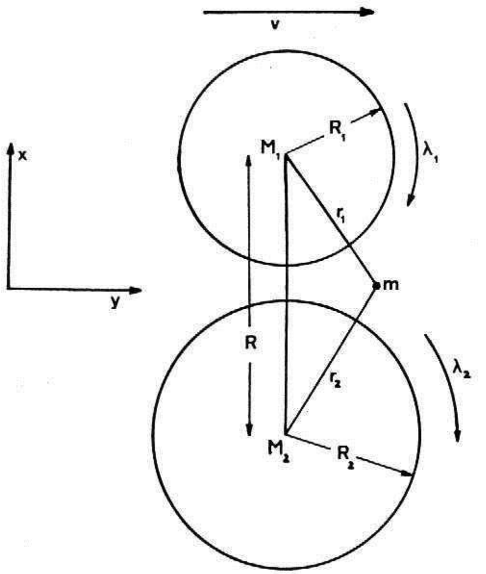
But $Y_{\ell\lambda}(\pi/2, \phi) = 0$ *unless*
$\ell + \lambda = \text{even}$



# Example of Brink matching conditions

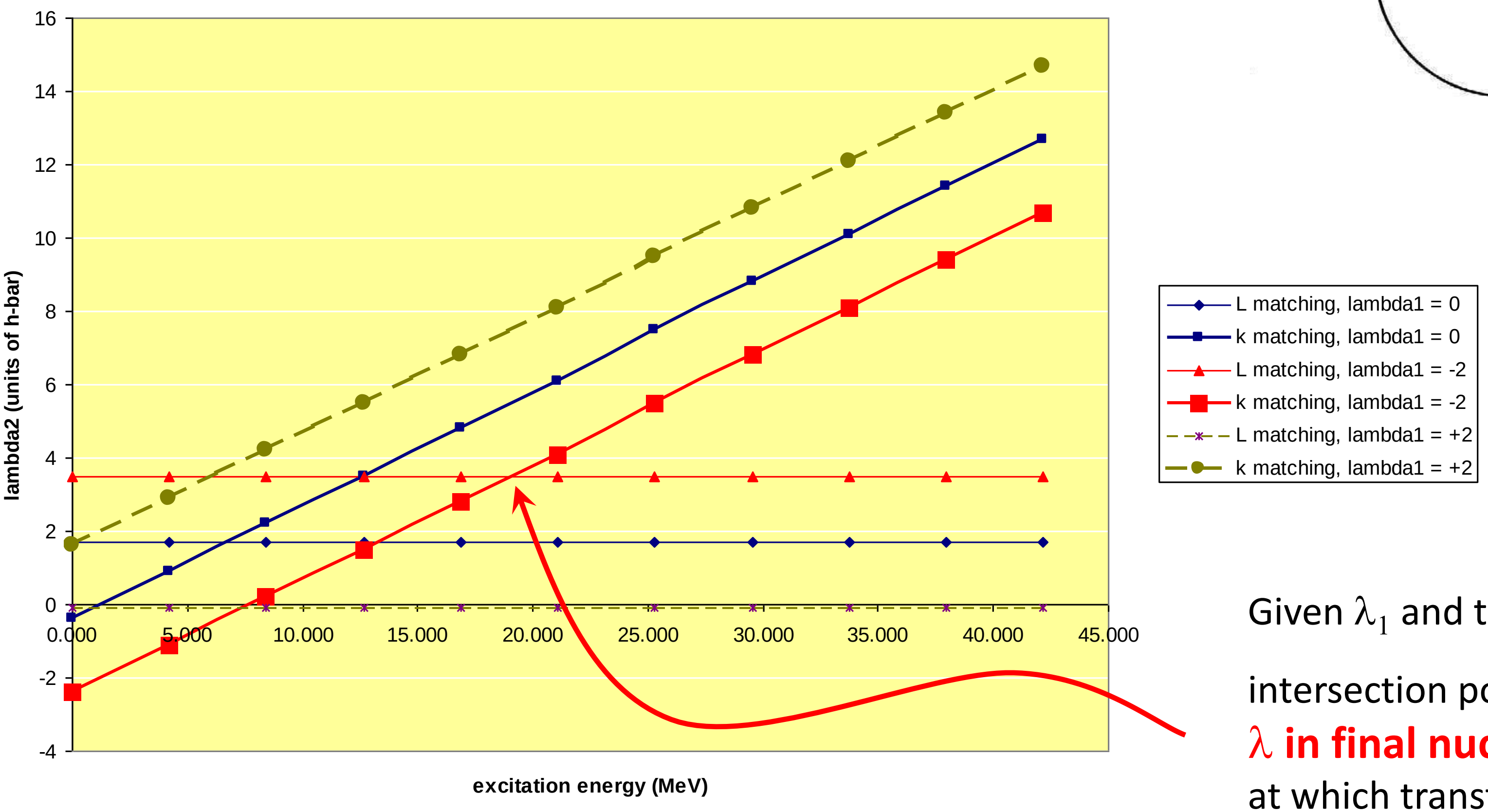
$^{12}C\ (\,^{17}O,^{16}O\,)\ ^{13}C^{*}$

$E_{beam}$ = 100 MeV



Projectile is $^{17}O$ which has transferred nucleon in $d_{5/2}$ orbital which can have $\lambda_1 = 0, \pm 2$ ($\pi$ selection rules)

**best matched lambda2 vs. excitation energy for (17o,16o) on 12c at 100 MeV**



Given $\lambda_1$ and the reaction:

intersection point gives
**$\lambda$ in final nucleus and** $E_x$
at which transfer is **matched**

# $j_> / j_<$ selectivity

P.D. Bond, *Phys. Rev.*, **C22** (1980) 1539

P.D. Bond, *Comments Nucl. Part. Phys.*, **11** (1983) 231-240

The application of $j_> / j_<$ selectivity is difficult if considering experiments with complete kinematics with RNBs

However, detecting just the beam-like particle in coincidence with decay gamma-rays has much potential (recent experiments at ORNL, F. Liang)

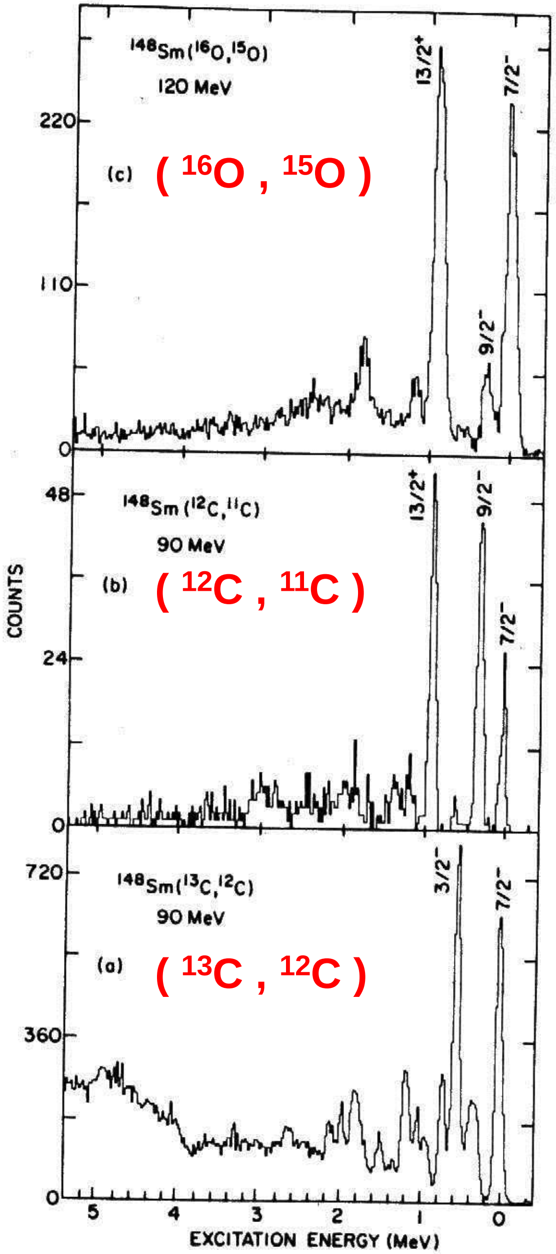


FIGURE 1 Single neutron transfer reactions for $^{148}$Sm → $^{149}$Sm. Spectra were taken at the peaks of the bell-shaped angular distributions. Note the strong difference in the relative population of final states with (a) the ($^{13}$C, $^{12}$C) reaction, (b) the ($^{12}$C, $^{11}$C) reaction and (c) the ($^{16}$O, $^{15}$O) reaction.

$Q = -9.8$ MeV $<< 0$
high j values populated

Initial orbit $p_{1/2} = j_<$

favours $j_>$ e.g. $f_{7/2}$

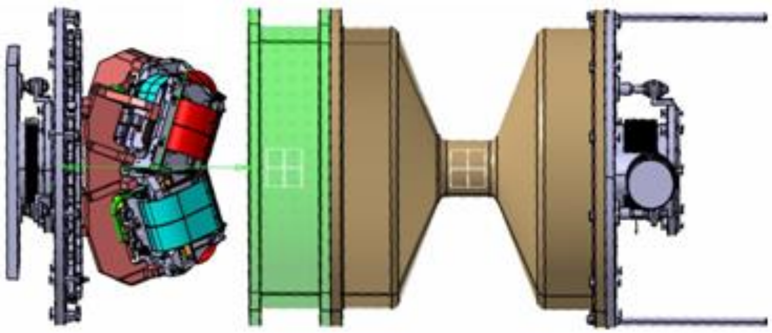
$Q = -12.8$ MeV $<< 0$
high j values populated

Initial orbit $p_{3/2} = j_>$

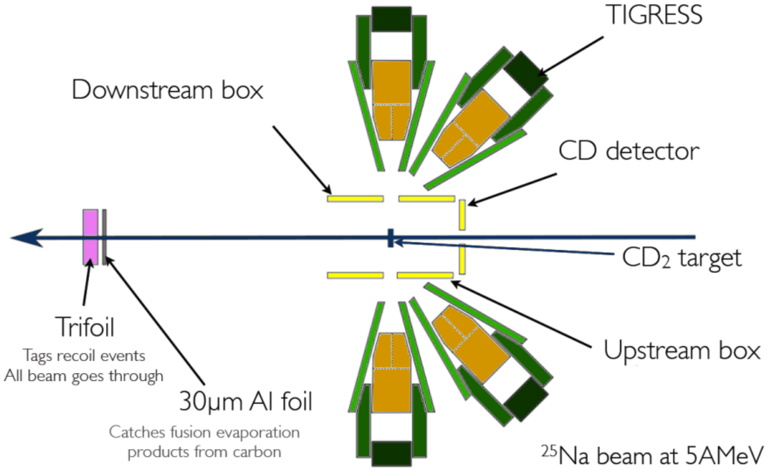
favours $j_<$ e.g. $h_{9/2}$

$Q = 0.925$ MeV $\approx 0$
lower j values seen

Less $j_> / j_<$ selectivity



**Thank you to all of the Collaborators…**



**And thank you to all of the Audience…**