LIVING with TRANSFER

(today I have more questions than answers)

Wilton Catford
University of Surrey, UK

LIVING WITH TRANSFER

- What do we want **to measure**, and why?
- What theory do we want **to compare with**, and why?
- How do we make the **measurements**, and why?
- What are the specific challenges in **interpreting the experiments**?

OUTLINE of TALK

- Address each of these questions, in order
- Be very brief with experimental methods
- Regarding interpretation, illustrate with our experiments at SPIRAL and ISAC

Thank you to all my collaborators in the TIARA, SHARC &TIGRESS collaborations

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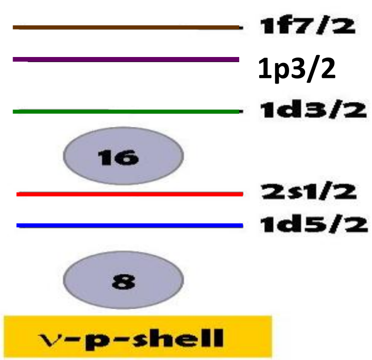
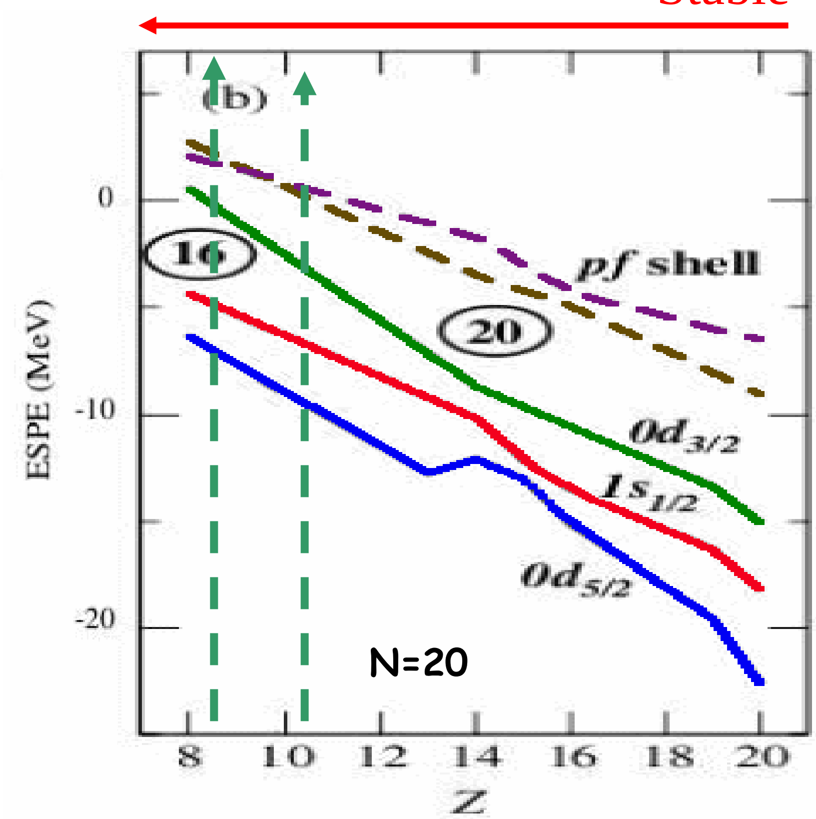
MOTIVATION: Monopole Shift and its impact on structure far from stability

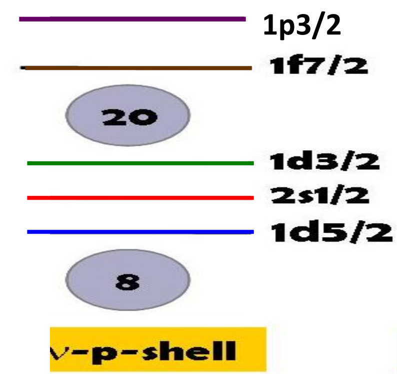
Utsuno et al., PRC,60,054315(1999)
Monte-Carlo Shell Model (SDPF-M)

Exotic ← Stable



Exotic





Stable

Removing d5/2 protons (Si →O)

gives relative rise in ν(d3/2)

MOTIVATION: means different things to different people, which has implications

What do we want to measure?

To locate states of particular, simple structure, embedded in harder-to-interpret states

Systematics, near magic numbers

Learn about evolution of nuclear structure
… and hence about the most exotic nuclei

Refining nuclear structure models

Measure reaction strength to certain nuclear states of specific interest

Interpret for astrophysics, in different reactions…
e.g. (d,p) for (p,γ) using mirror symmetry, or (d,p) for (n,γ)

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CONFRONTING THEORY: in the case of the structure motivation…

What do we want to compare with?

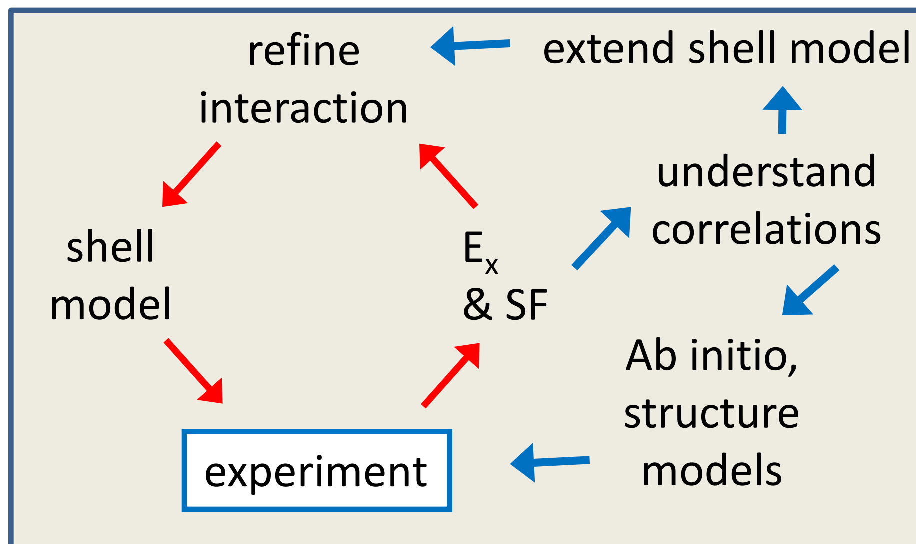
Spectroscopic Factors
(or way to measure
Single-particle strength)

- Quenched SFs, with quenching due to correlations (and dependent on binding energy)
- Unquenched SFs, as calculated by the shell model (in its present most common manifestation)

Or maybe just *relative* SFs

Is the answer different
- For nuclear structure?
- For astrophysics?

Is the identification of all of the SP strength for (l,j) needed?
i.e.
- Do we measure SPEs ? Or
- Do we measure individual states?



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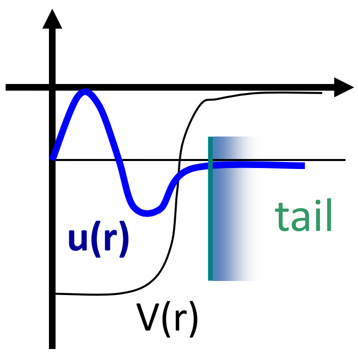
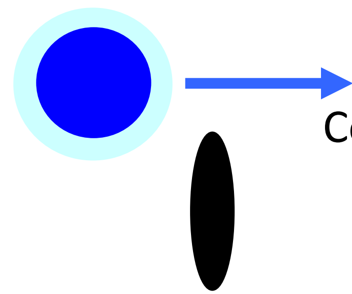
EXPERIMENTAL CHOICES for STUDYING SINGLE PARTICLE EVOLUTION

Why would we choose nucleon transfer? … **is transfer the BEST way** to isolate and study single particle structure and its evolution in exotic nuclei?

Transfer – decades of (positive) experience

Removal – high cross section, similar outputs, needs occupied orbitals





Complementary to (d,p)

(e,e'p) – a bit ambitious for general RIB application

(p,p'p) – more practical than (e,e'p) for RIB now, does have problems

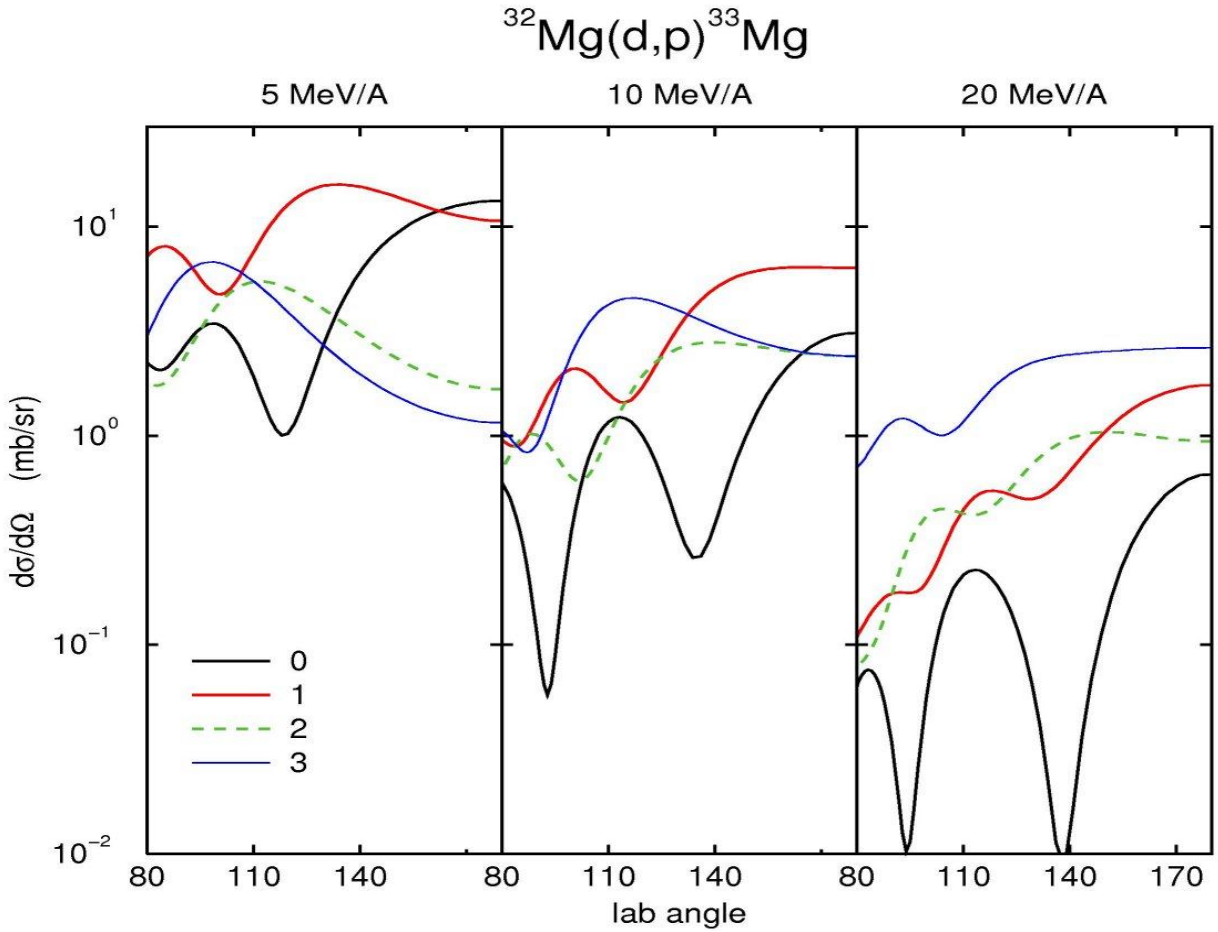
CERTAINLY, it's a GOOD way

Also:

Heavy Ion transfer (^{9}Be), not just (d,p)

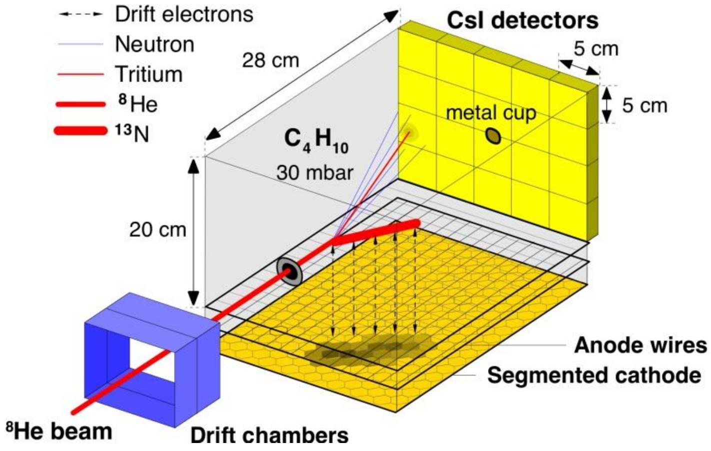
^{3,4}He-induced reactions

CHOICE of ENERGY of RADIOACTIVE BEAMS in INVERSE KINEMATICS



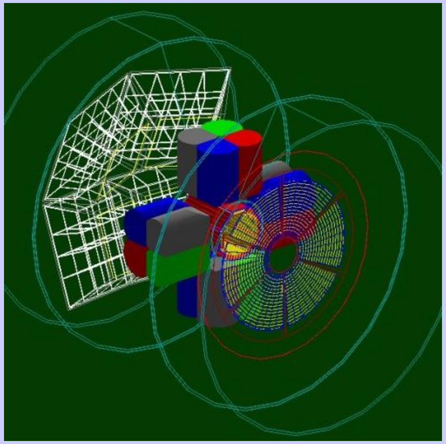
Calculated differential cross sections show that 10 MeV/A is good (best?)

EXPERIMENTAL SOLUTIONS for (weak) RADIOACTIVE BEAMS (in inverse kinematics)



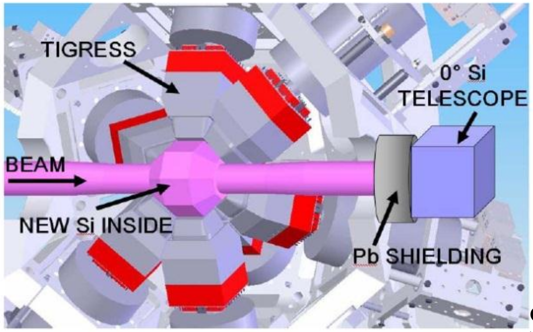
MAYA

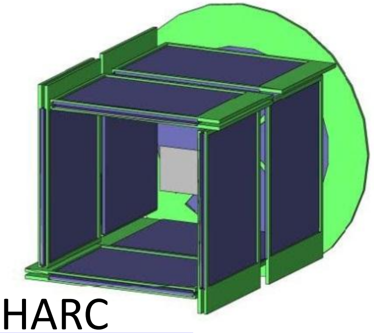
Now in use at
GANIL/SPIRAL
TRIUMF



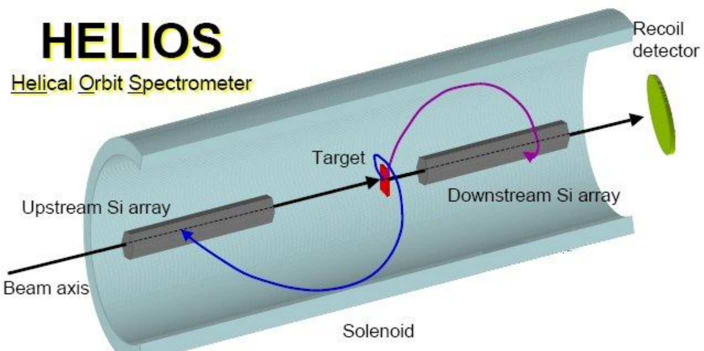
TIARA

Now in use at
GANIL/SPIRAL

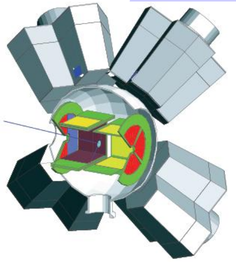


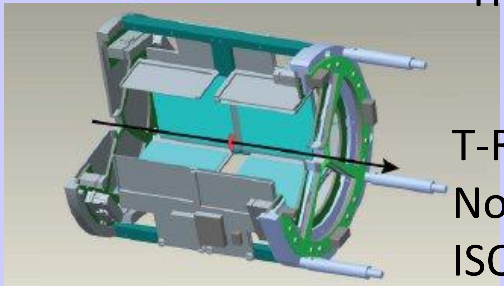


SHARC
Now in use at
TRIUMF



Now in use at
ANL





T-Rex
Now in use at
ISOLDE

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- What do we want to measure, and why?
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REACTION MODELS to interpret (d,p) TRANSFER – e.g. the ADWA

Spectroscopic Factor

Shell Model: overlap of **|ψ (N+1) ⟩ with |ψ (N) ⟩$_{core}$ ⊗ n (ℓ j)**

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

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

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

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

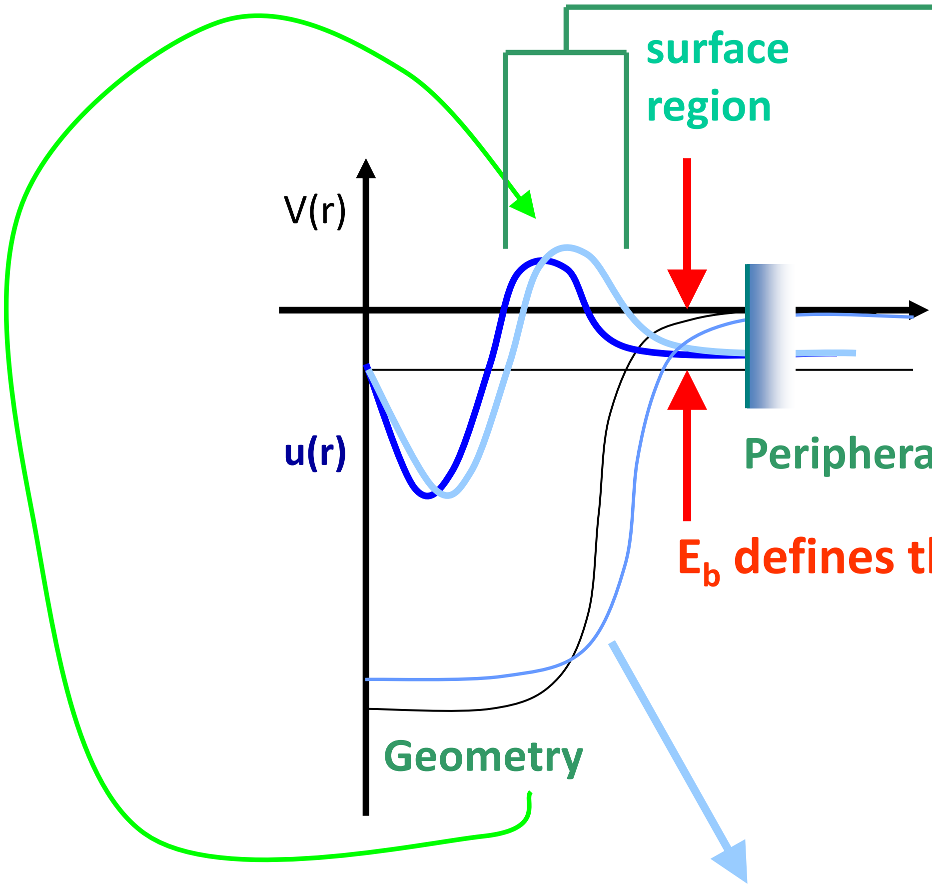
Hence the **observed yield**
depends on the radial wave function
and thus
it depends on the geometry of the
assumed potential well
or other structure model

… this is illustrated in the following slide…

SUMMARIZING: FOUR SETS OF REMARKS ABOUT INTERPRETING (d,p) TRANSFER

Geometry Correlations Desire Relatives

Dependence of high energy (d,p) on geometry



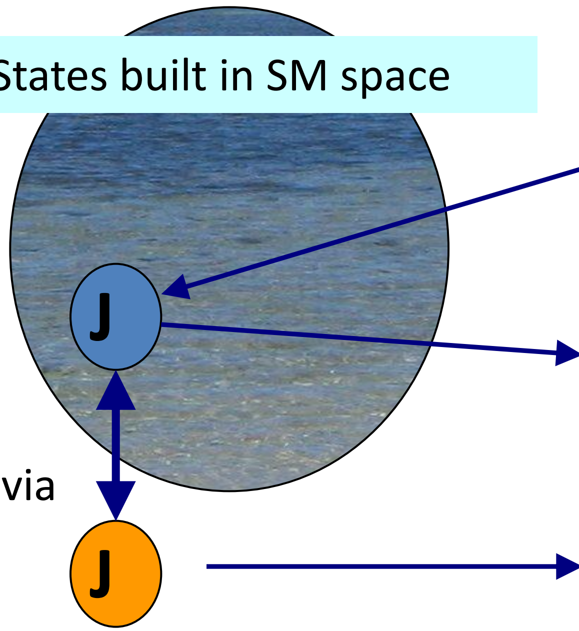
Independence of the ANC on geometry

Is the effective well geometry even the same for all orbitals?

(coupled channels treatments address this)

REMARKS ABOUT INTERPRETING (d,p) TRANSFER

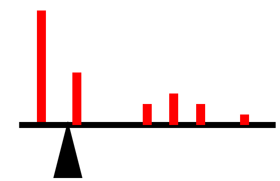
Geometry **Correlations** Desire Relatives



J states are mixed by residual interactions
… and are not pure SP states

Must use SM SF's (not quenched)

WEIGHTED $E_x \longrightarrow$ S.P. energies
(traditional approach)



mixing via
SHORT
RANGE
correlations

WEIGHTED $E_x \not\longrightarrow$ S.P. energies

If the quenched SF's are used

MY ANSWER:

- Don't use "traditional" method of calculating weighted SPE
- Do use the "traditional" SF that can be compared to SM
- Use SM SF to associate experimental and SM states
- Use this to refine SM residual interaction
- Gain improved understanding of important structural effects

REMARKS ABOUT INTERPRETING (d,p) TRANSFER

Geometry Correlations **Desire** Relatives

WHAT DO WE WANT TO MEASURE?

?

- Occupancy of SM geometry orbital (cf e.g. Oxbash output)
- Occupancy of actual nuclear orbital

THE SPECTROSCOPIC FACTOR HAS TWO (at least!) PROBLEMS:

!

- Is it the occupancy of some defined orbital that may not equal the actual orbital in the real nucleus?
- Do we want to measure the “quenched” (= “real”) or the “shell model” (= “comparable”) SF ?

Or do we just want to compare directly the cross section strength calculated using an overlap integral based on a structure model with the observed cross section, and thereby assess the model?

REMARKS ABOUT INTERPRETING (d,p) TRANSFER

Geometry Correlations Desire **Relatives**

ARE RELATIVE SF's MORE ACCURATE THAN ABSOLUTE? … ALWAYS?

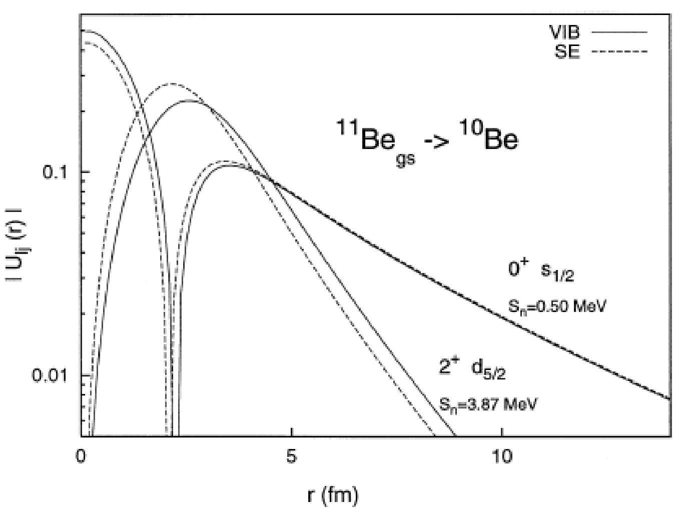
?

If so, is this good enough? Possible to live with?

If not, um… really? Can we really believe the quenching measured with transfer SF's ? As much as for knockout?

If not, what about astrophysics ?

A little extra warning from our 11Be(p,d)10Be experiment PL B461 (1999) 22



The relative magnitudes of the s- and d-wave form factors can be changed by changing the potential geometry OR by using a core excitation model and solving the coupled equations. The two have subtly different effects

NB: INPUT OF ACTUAL STRUCTURE WAVEFUNCTIONS
(DIRECT INPUT OF OVERLAP INTEGRAL INTO CALCULATION)

Pan·gloss·i·an HEAR [pan-**glos**-ee-*uh*n, -**glaw**-see-, pang-] Show IPA Pronunciation ?

–adjective

characterized by or given to extreme optimism, esp. in the face of unrelieved hardship or adversity.

PLAN ADOPTED for present work

- Use **transfer reactions** to identify strong single-particle states, measuring their spins and strengths

- Use the energies of these states to compare with theory

- Refine the theory

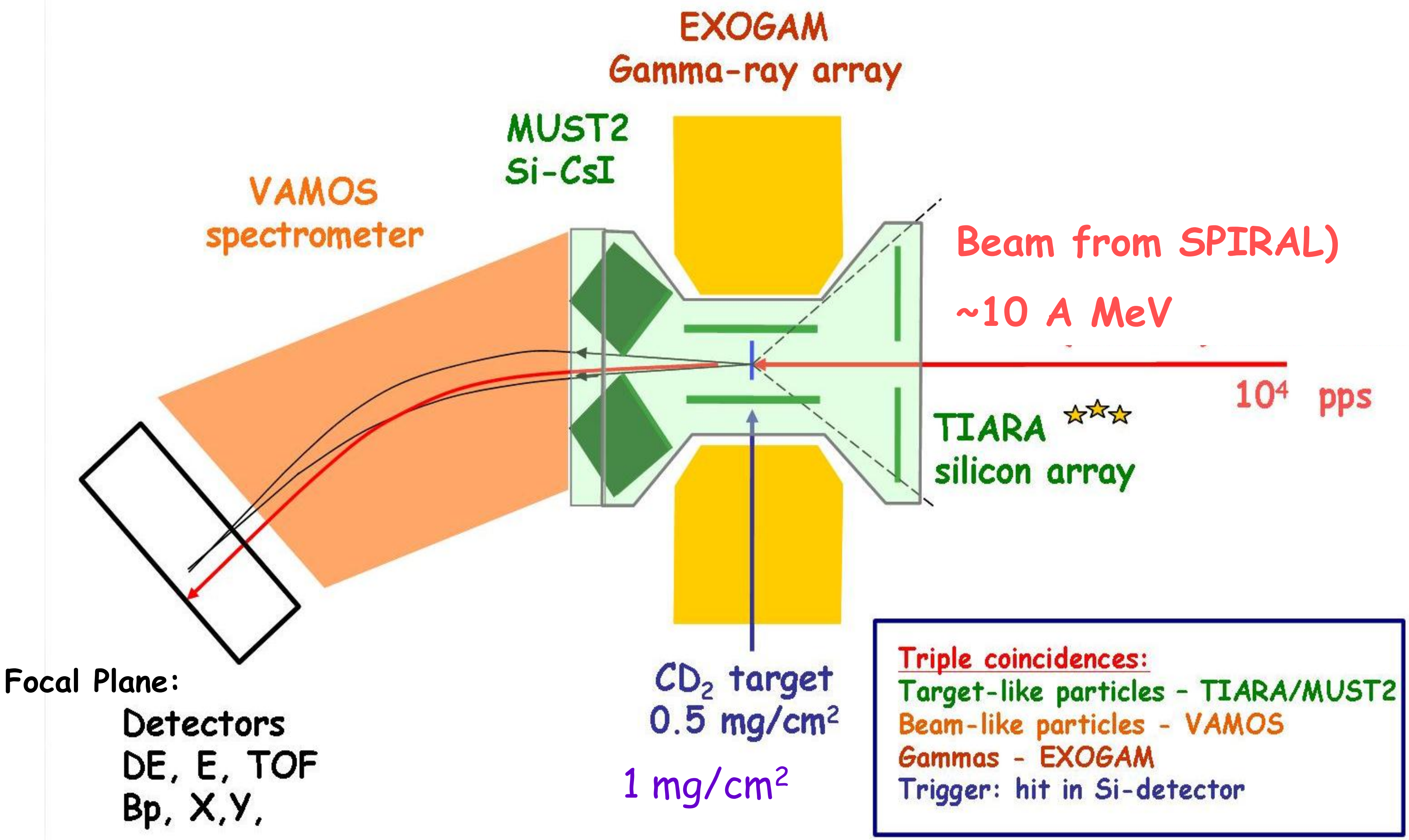
- Improve the extrapolation to very exotic nuclei

- **Hence learn the structure of very exotic nuclei**

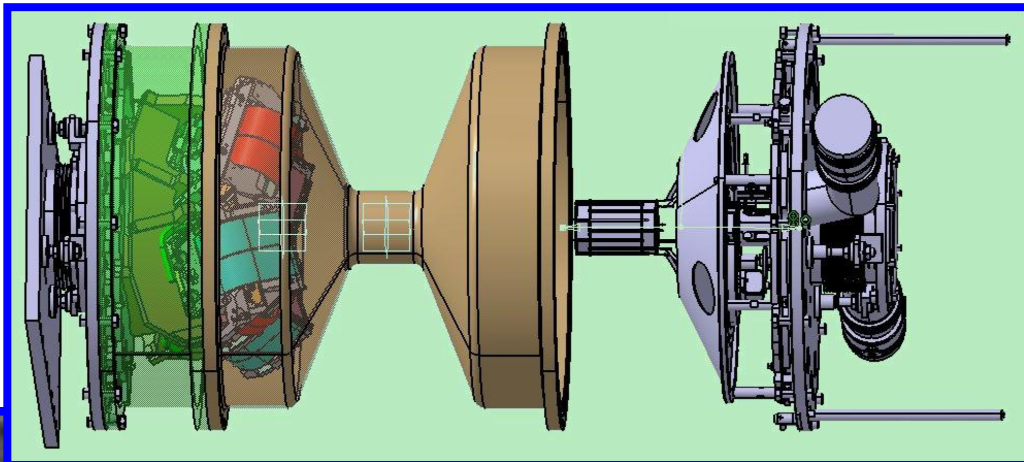
N.B. The **shell model** is arguably the best theoretical approach for us to confront with our results, but it's **not the only one**. The experiments are needed, no matter which theory we use.

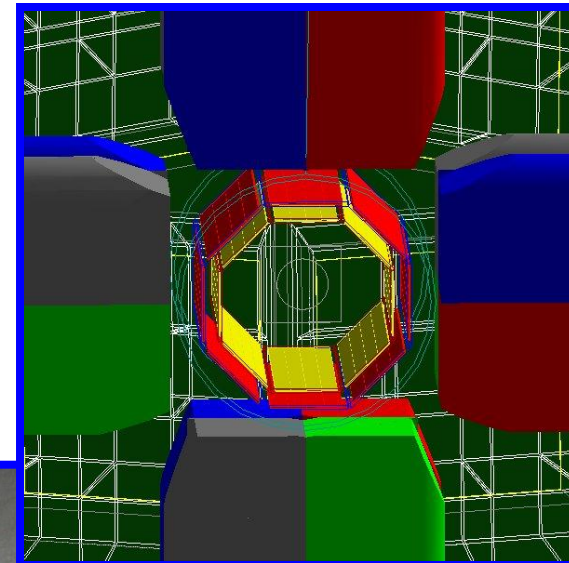
N.B. Transfer (as opposed to knockout) allows us to study orbitals that are empty, so **we don't need** quite such exotic beams.

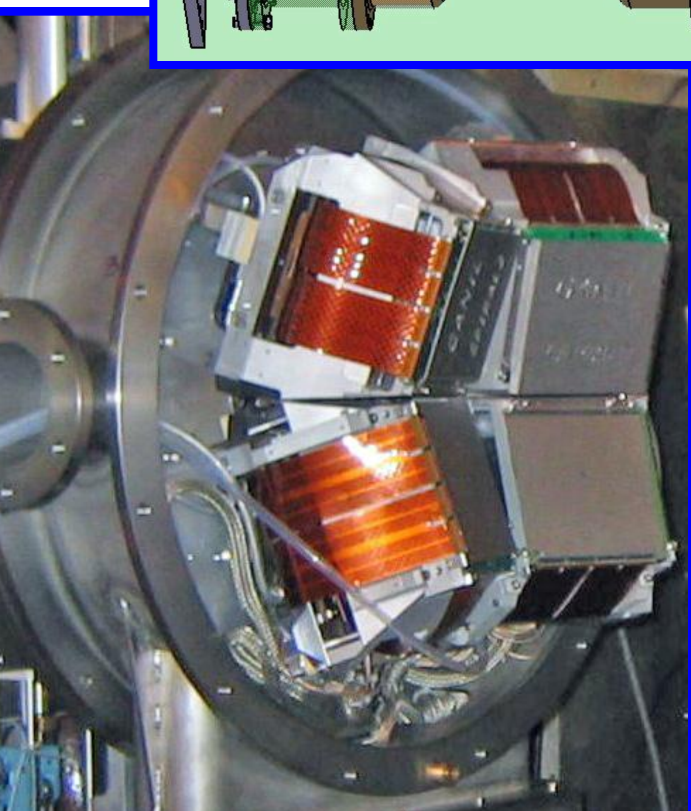
TIARA+MUST2+VAMOS+EXOGAM @ SPIRAL/GANIL

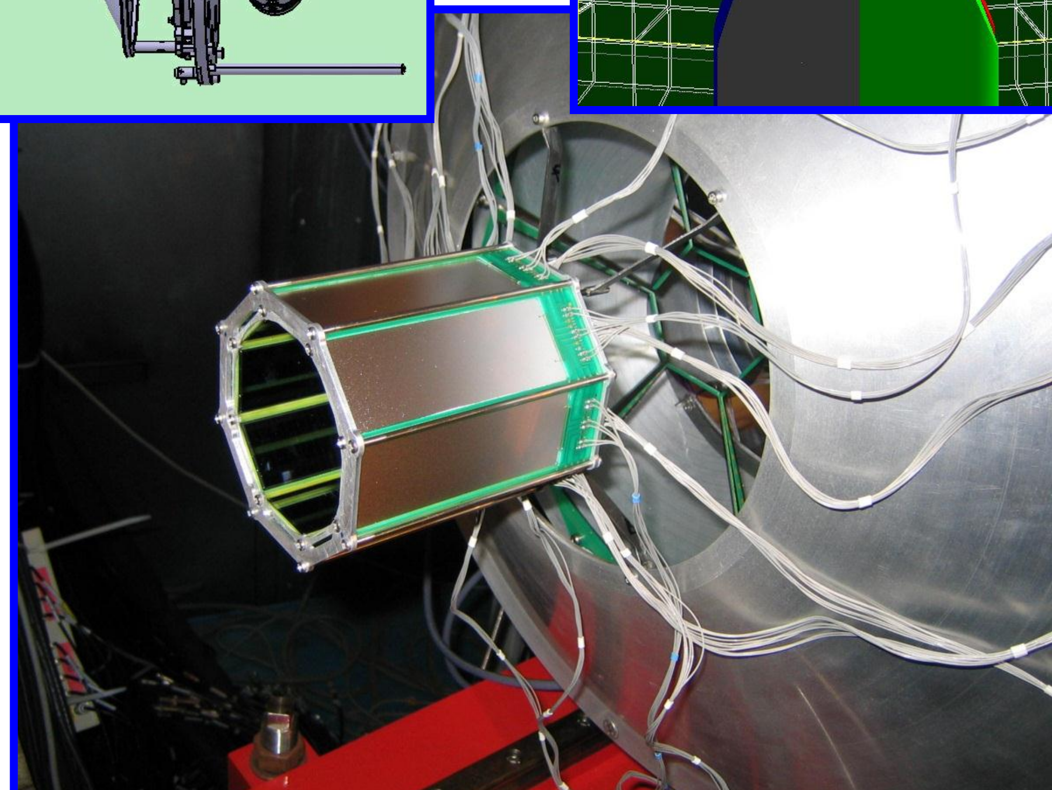


MUST2 TIARA EXOGAM









WILTON CATFORD INT, AUGUST 2011

EXAMPLE: SOME ACTUAL RESULTS

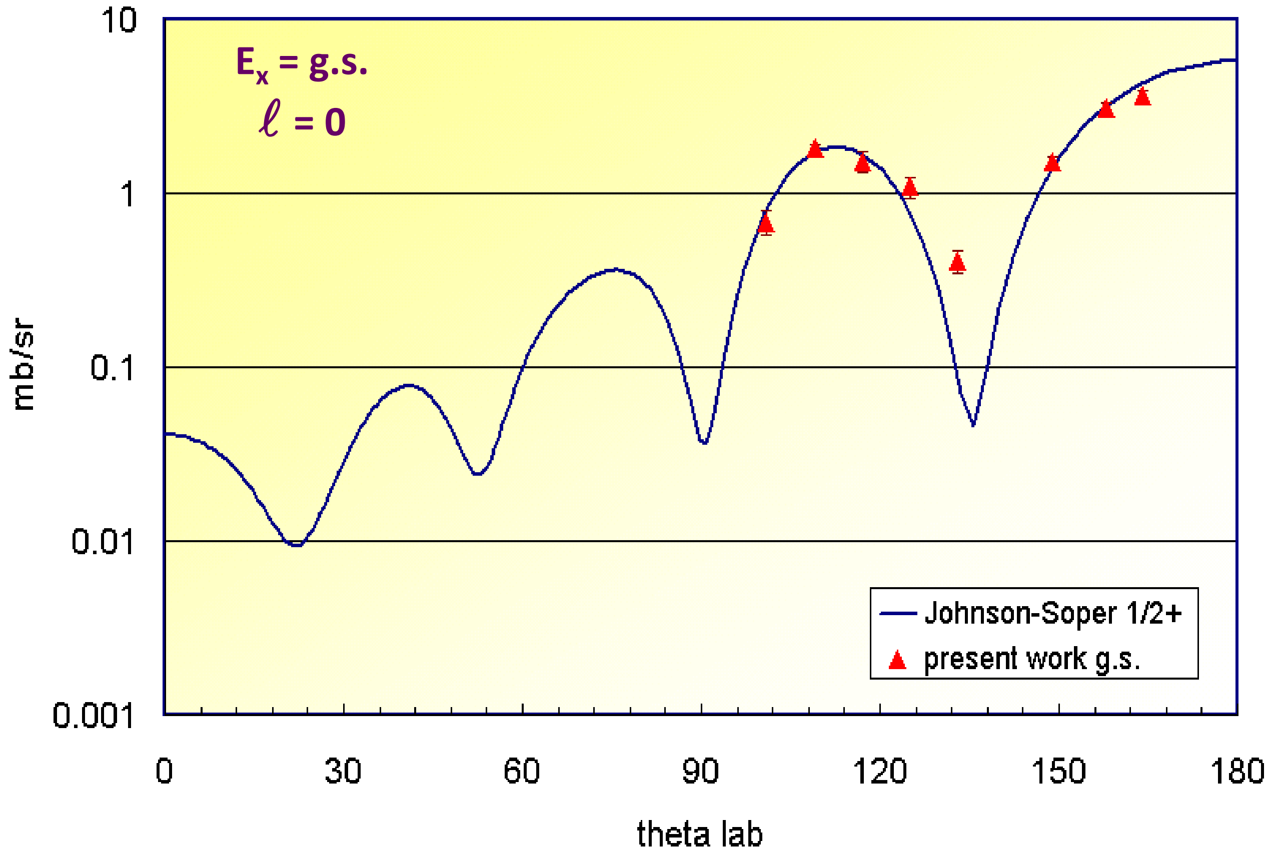
SPIRAL radioactive beam ^{24}Ne @ 10.5 A MeV on 1 mg/cm^2 CD_2 target

W.N. Catford et al., J. Phys. G 31 (2005) S1655
W.N. Catford et al., PRL **104**, 192501 (2010)

$^{24}Ne(d,p)^{25}Ne$

ground state

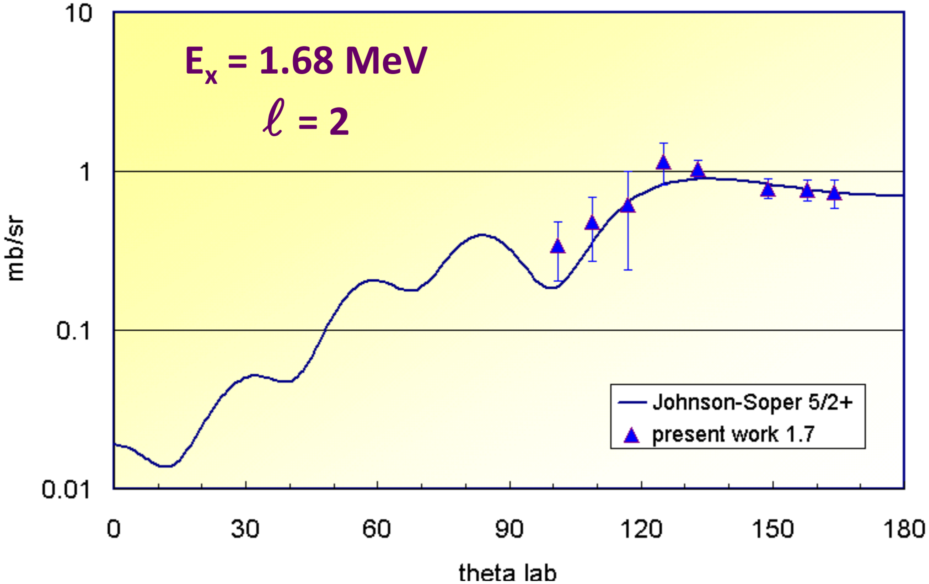
laboratory angles

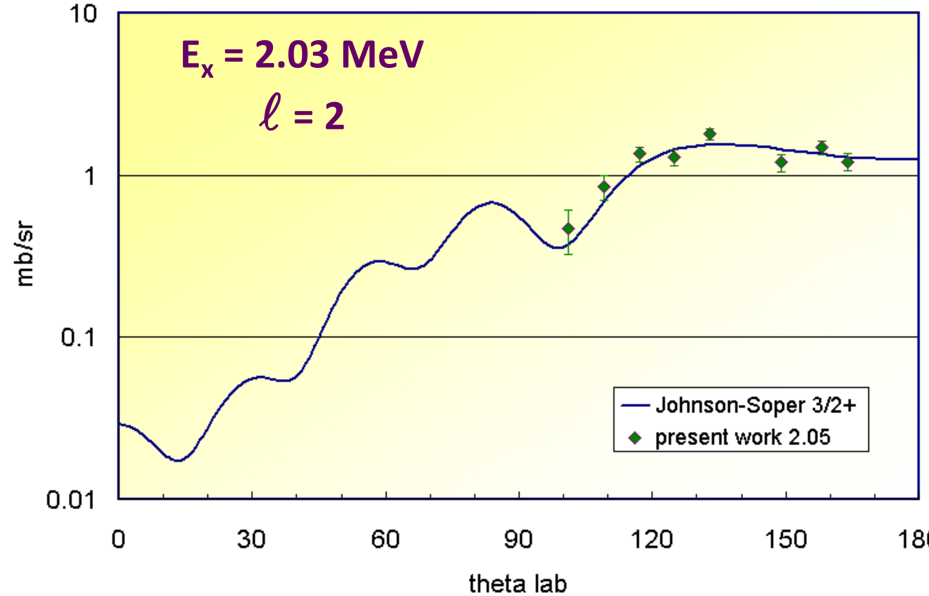


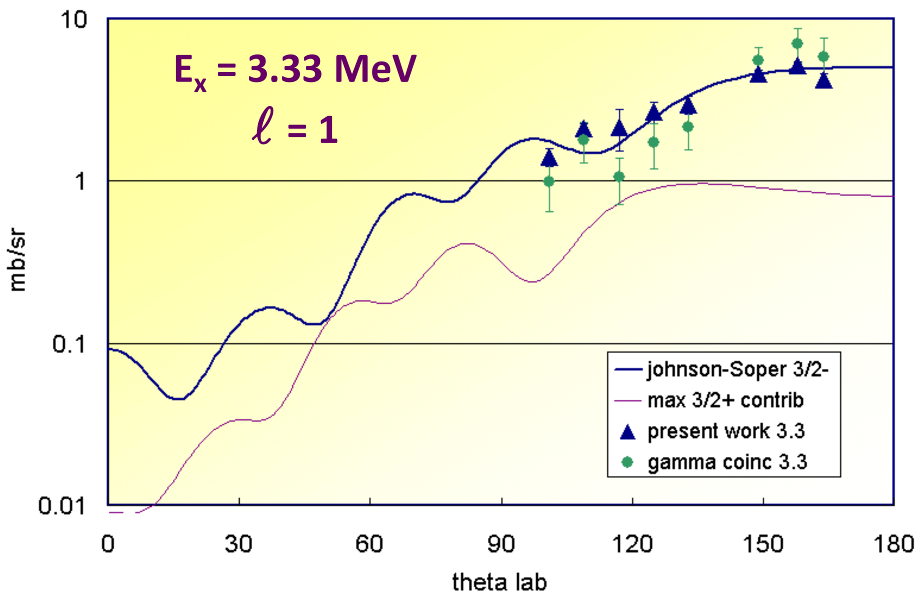
EXAMPLE: SOME ACTUAL RESULTS

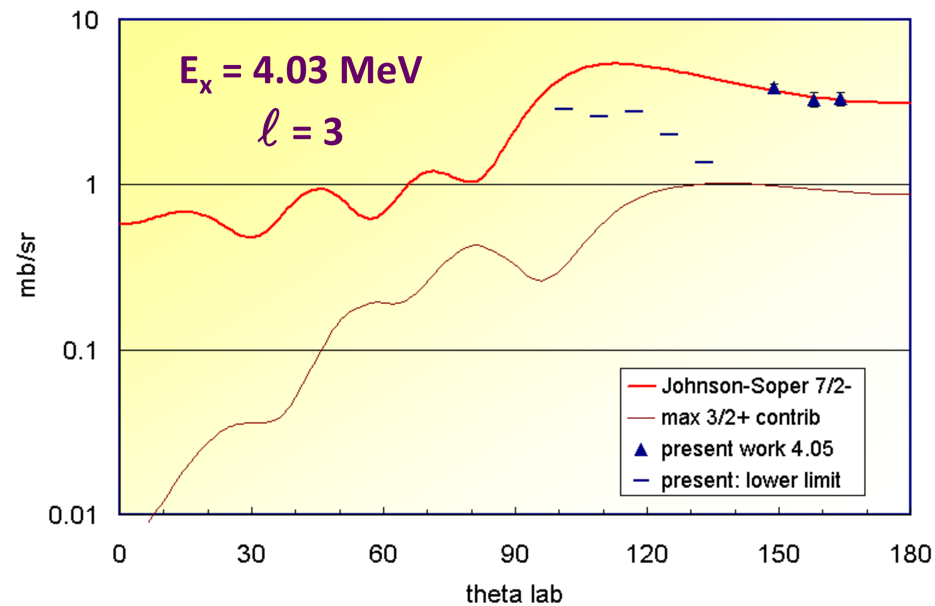
Results for $^{24}Ne(d,p)^{25}Ne^{*}$

bound excited states





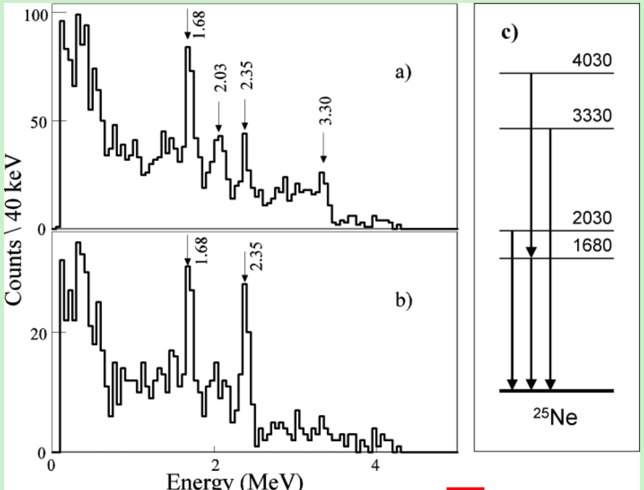




EXAMPLE: SOME ACTUAL RESULTS

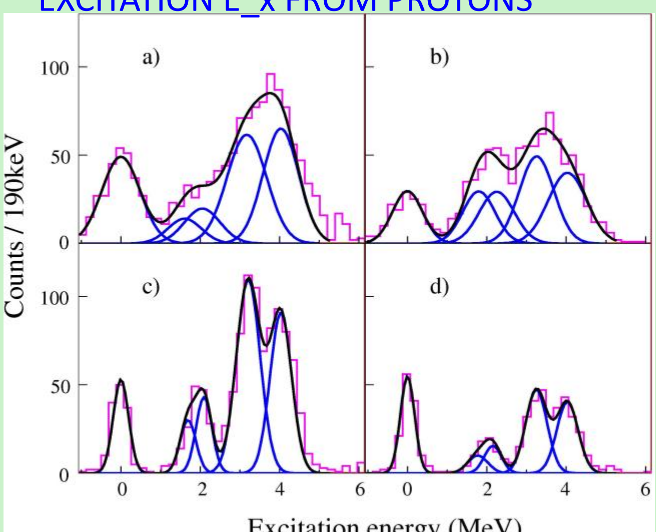
W.N. Catford et al., PRL **104**, 192501 (2010)

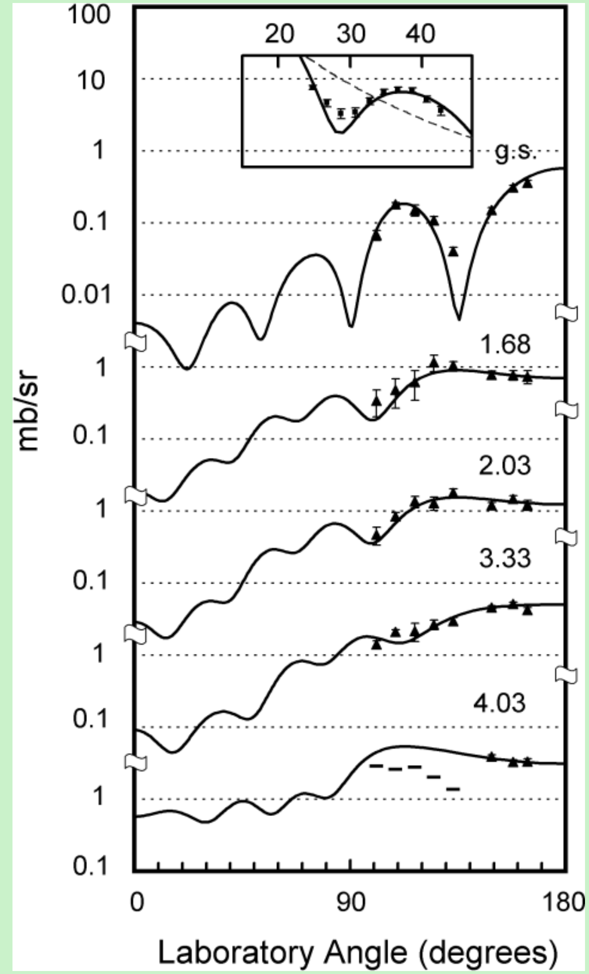
GAMMA RAY ENERGY SPECTRA



FIX E_x

EXCITATION E_x FROM PROTONS

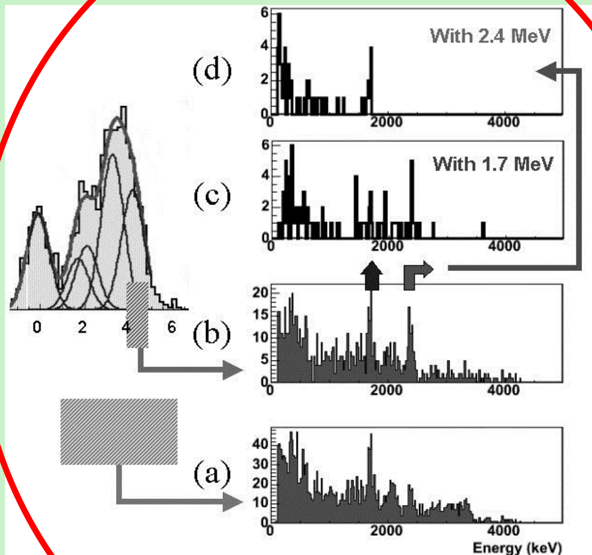


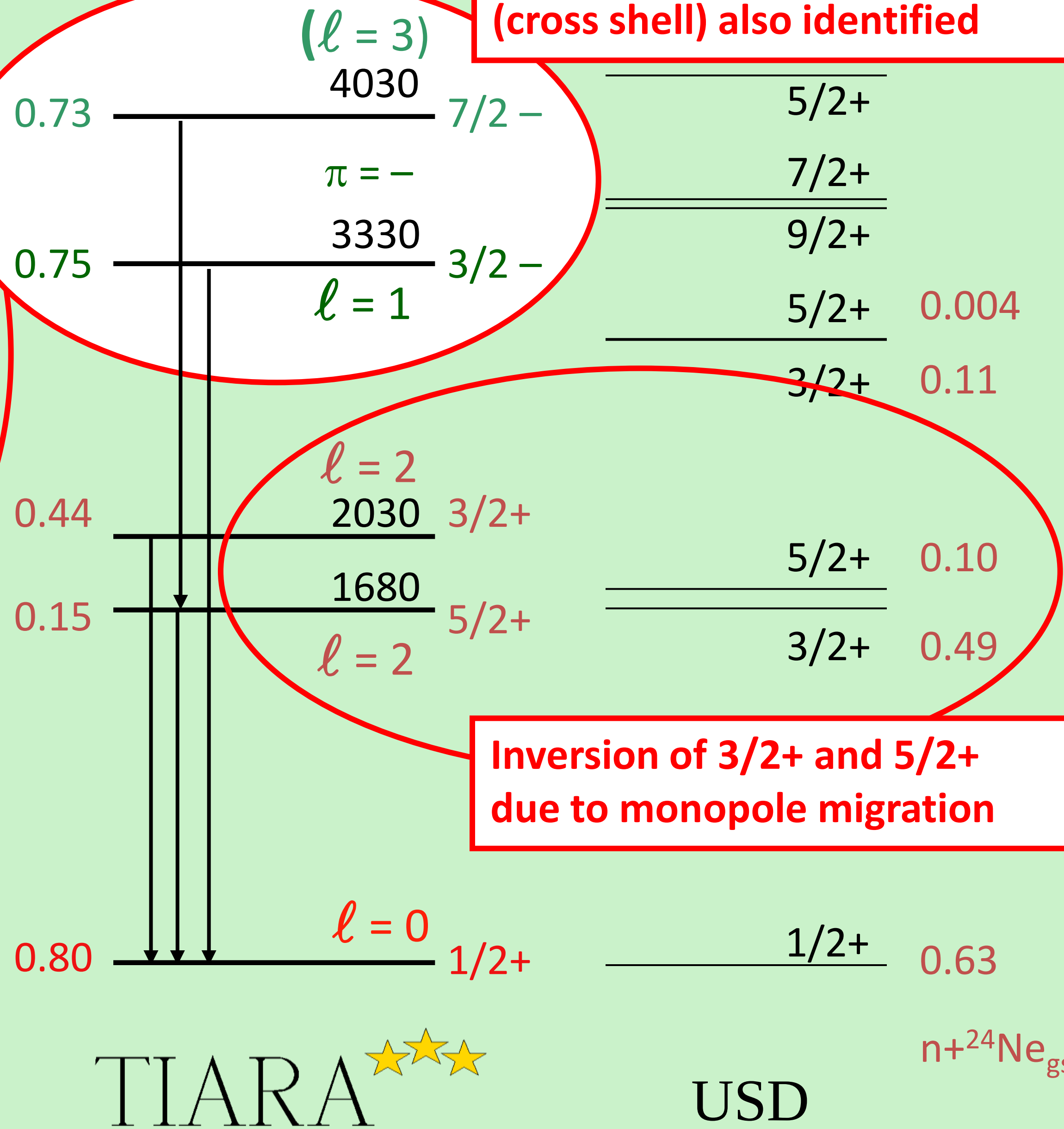


W.N. Catford et al., PRL **104**, 192501 (2010)

Summary of 25Ne Measurements

Negative parity states (cross shell) also identified





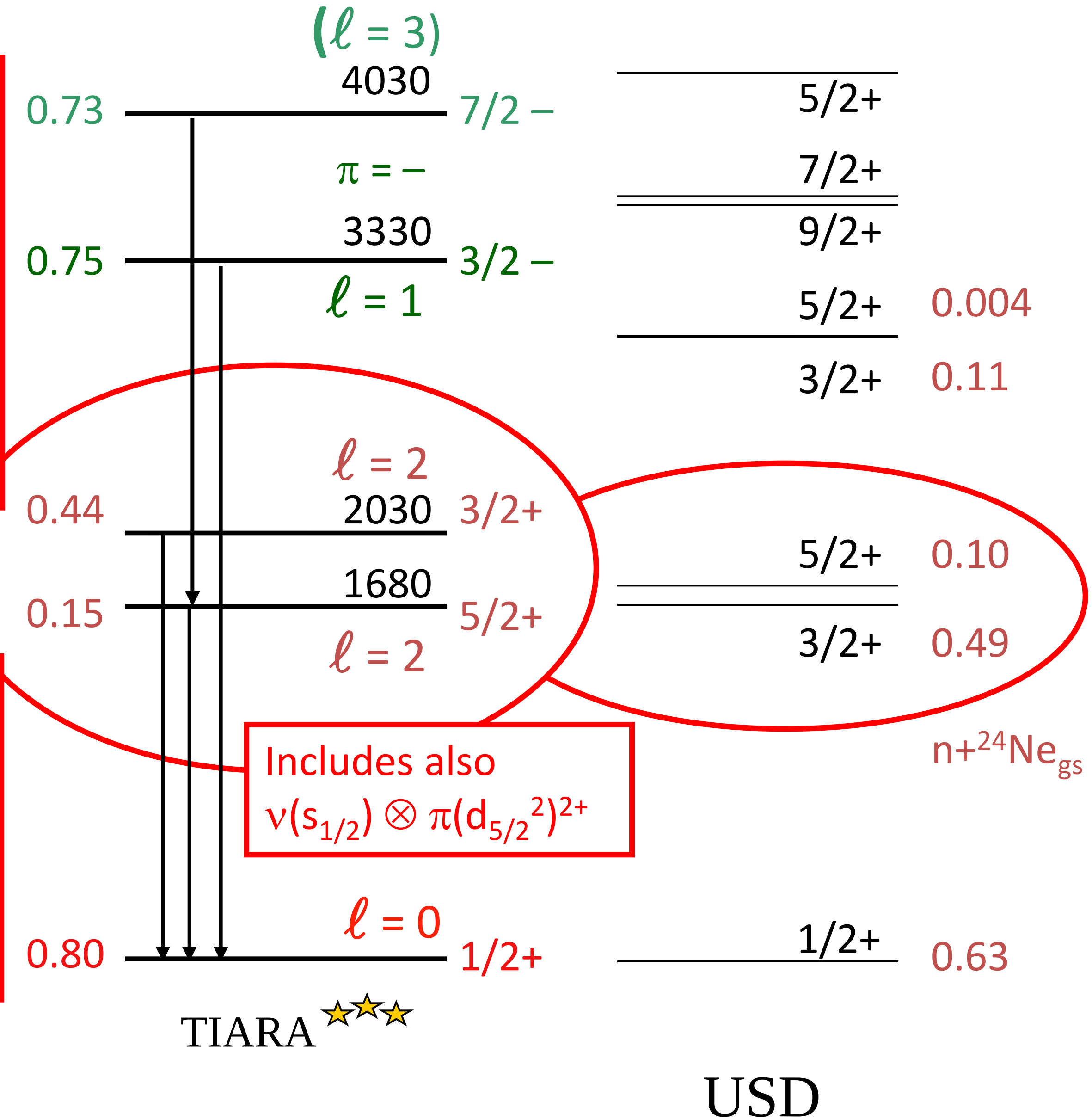
Inversion of 3/2+ and 5/2+ due to monopole migration

In ^{25}Ne we used gamma-gamma coincidences to **distinguish spins** and go beyond orbital AM
FIRST QUADRUPLE COINCIDENCE (p-HI-γ-γ) RIB TRANSFER DATA

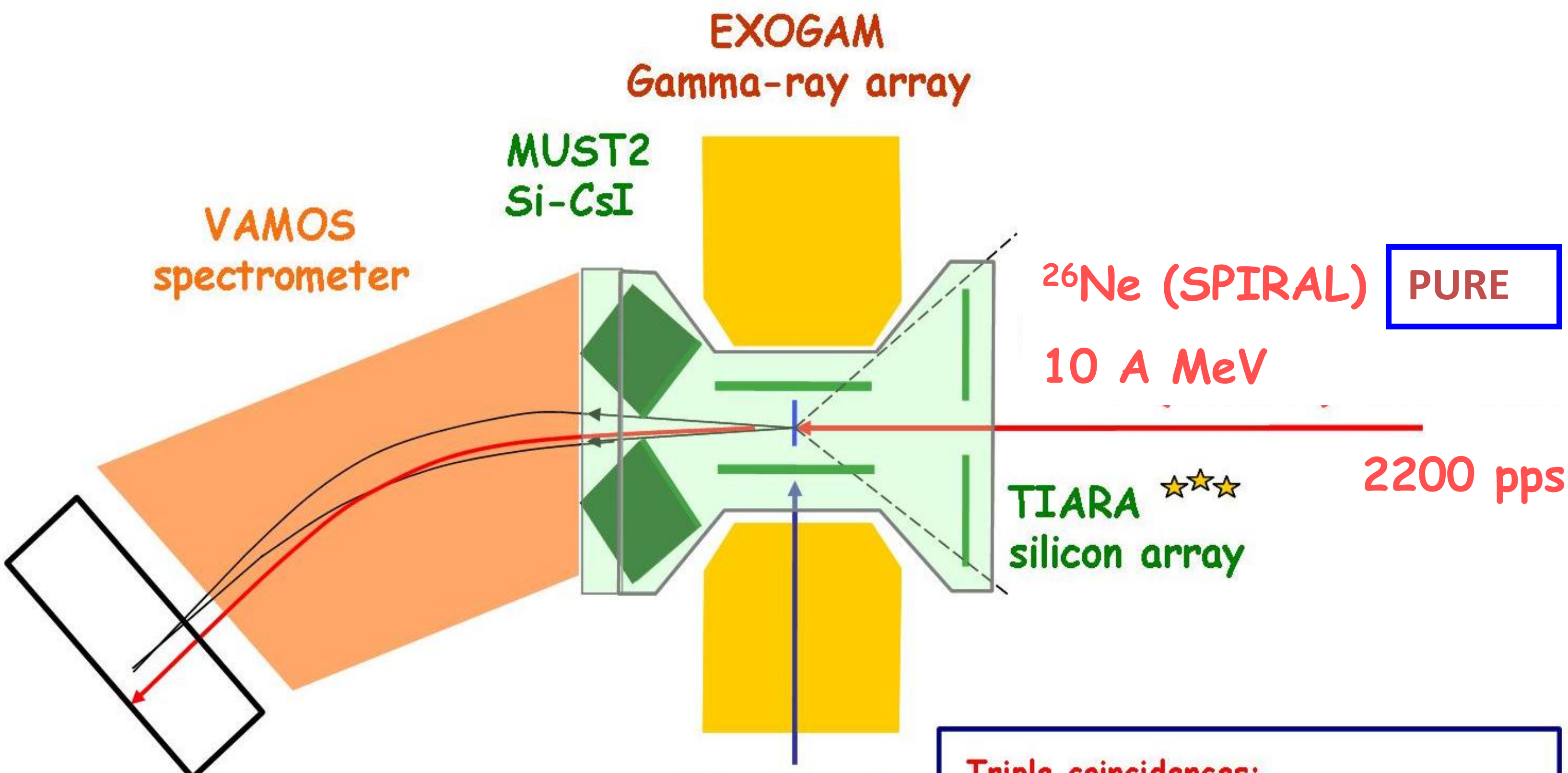
ANOTHER WORD ON RESULTS

In ^{25}Ne the 3/2$^+$ state was far from a pure SP state due to other couplings at higher energies, but it was clear enough in its ID and could be used to compare with its SM partner to improve the USD interaction

It is not always necessary to map the full SP strength which may be very much split
and
with radioactive beams it may not often be possible



TIARA+MUST2+VAMOS+EXOGAM @ SPIRAL/GANIL



CD_2 target
0.5 mg/cm^2

1 mg/cm^2

Focal Plane:

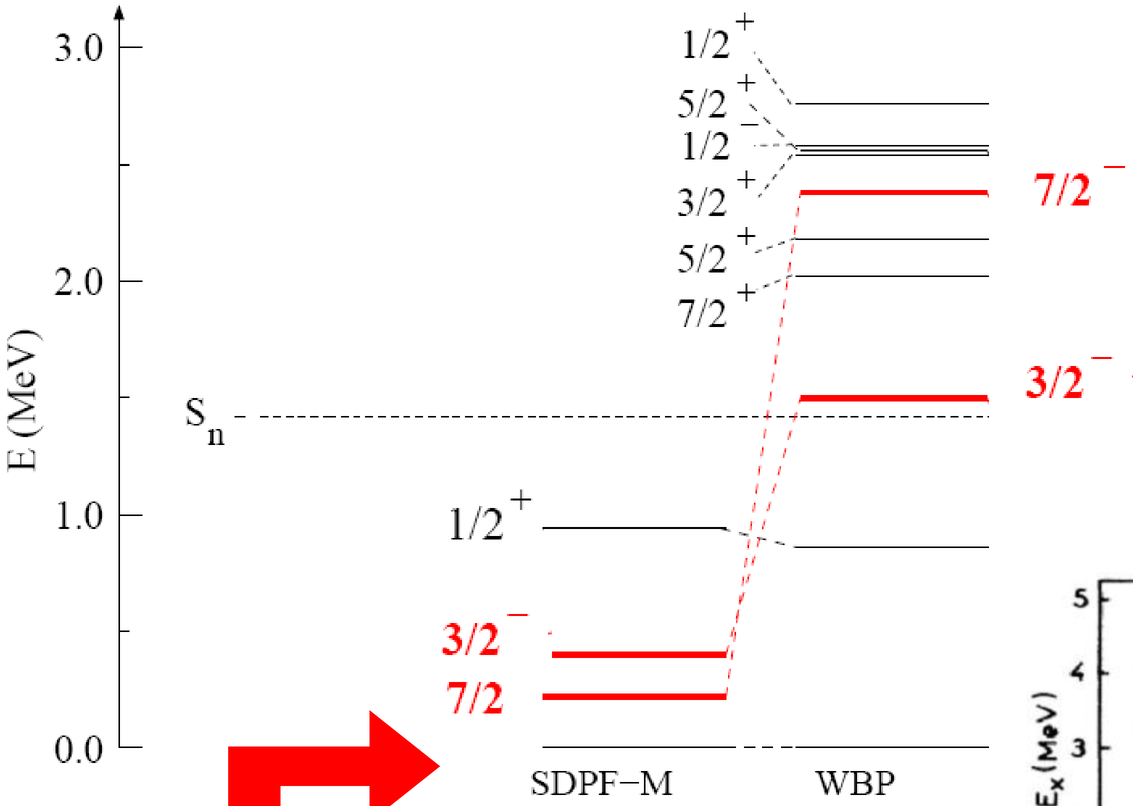
Detectors
DE, E, TOF
Bp, X,Y,

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

N=17 ISOTONES

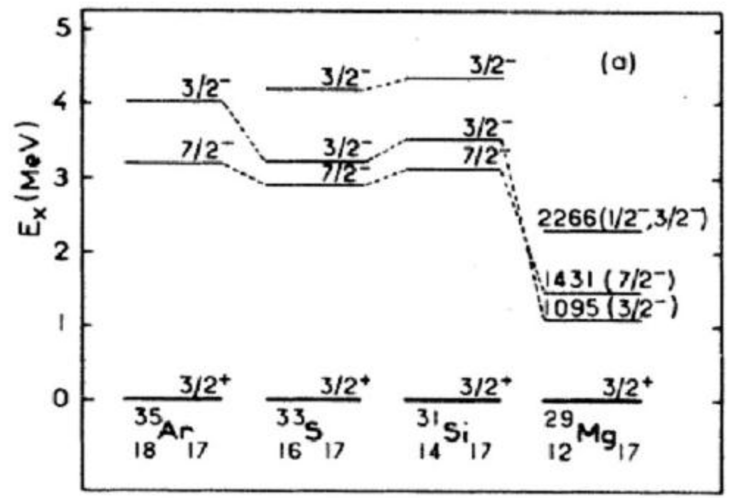
Shell model predictions **vary wildly** for fp intruders

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

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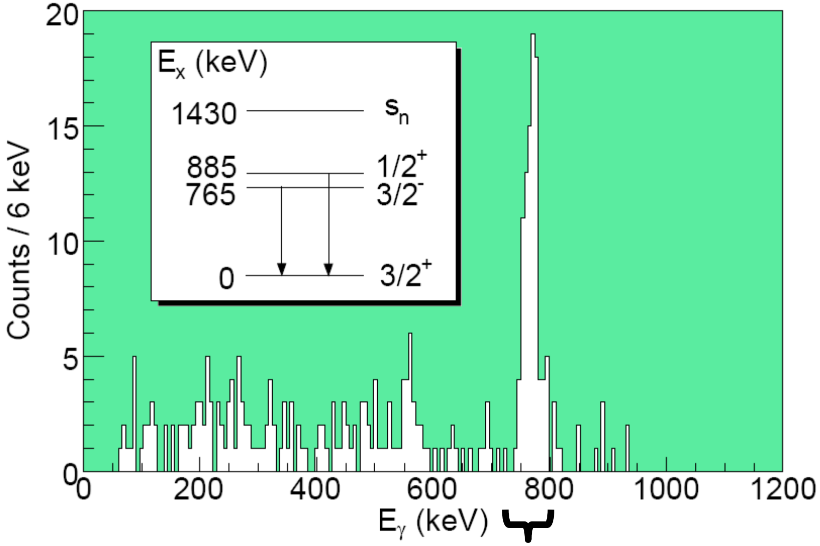
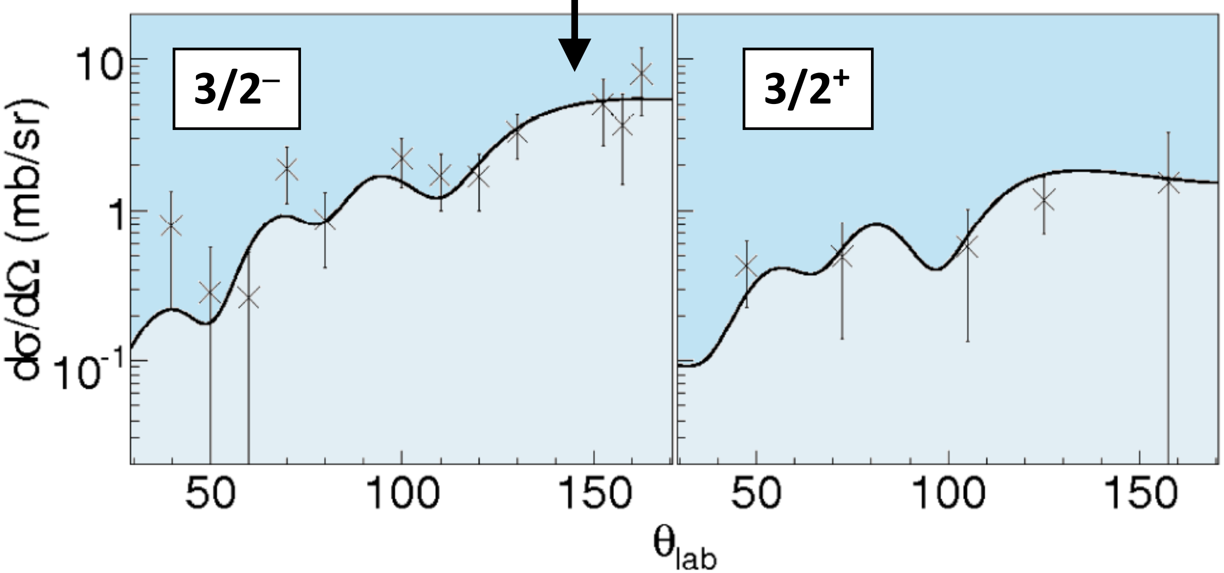


^{27}Ne BOUND STATES

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)

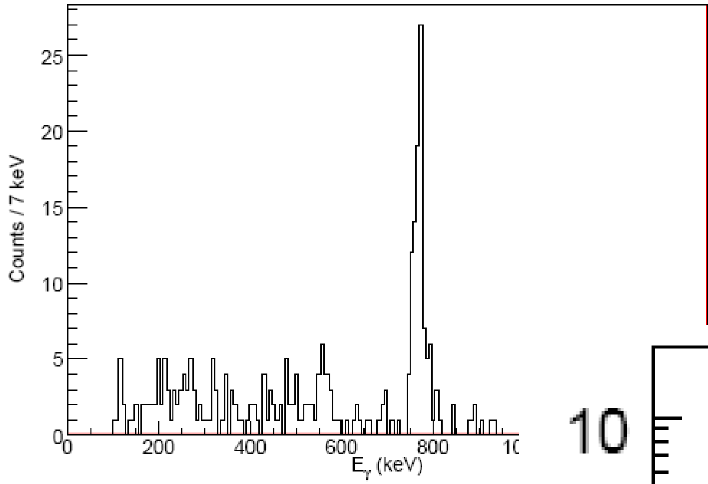


In these case, the spins had some information already known.
The 3/2⁻ spin is confirmed.

The magnitude was the quantity to be measured.

On the topic of
angular correlations…

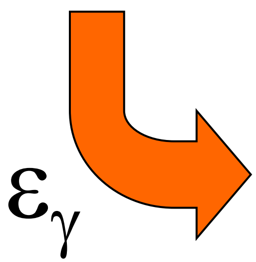
BOUND STATES : $d(^{26}Ne,p)^{27}Ne$

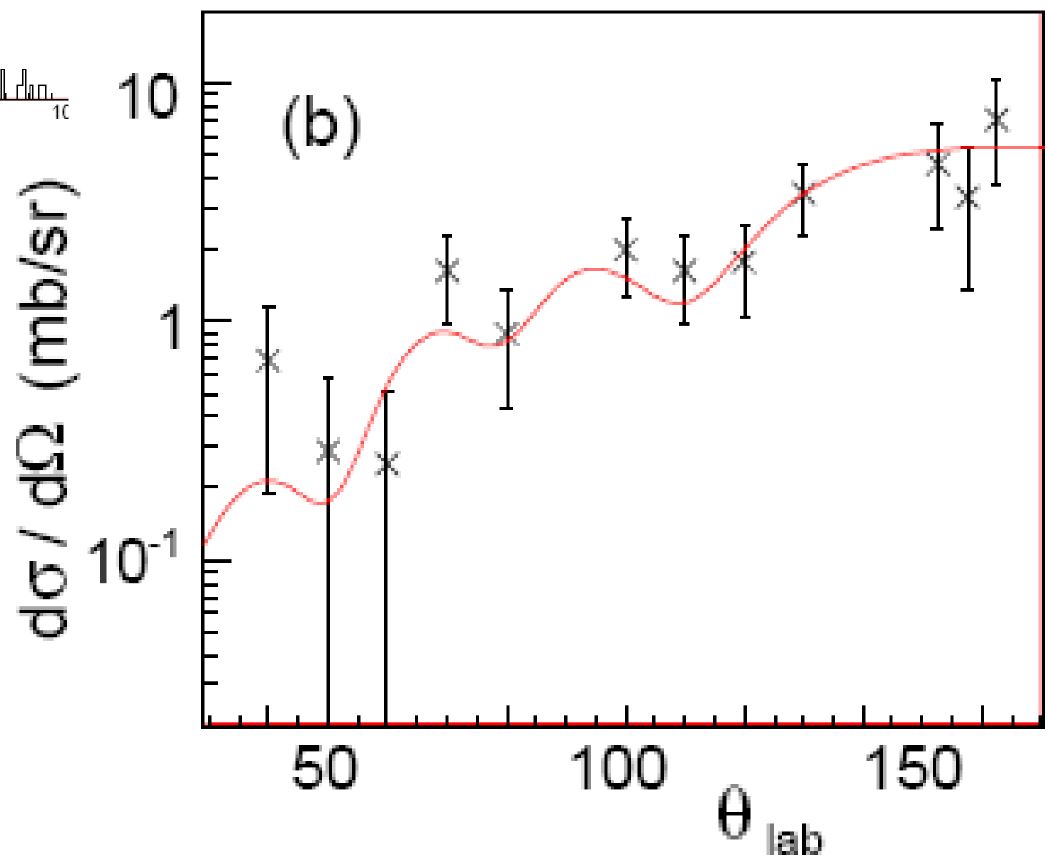


If we gate on a gamma ray, to get the angular distribution for protons we simply correct for the gamma efficiency
(slight complication due to Doppler shift)

IF THE GAMMA rays ARE ISOTROPIC

(or, more exactly, the isotropy is independent of θ_p)





BOUND STATES : d(^{26}Ne,p)^{27}Ne

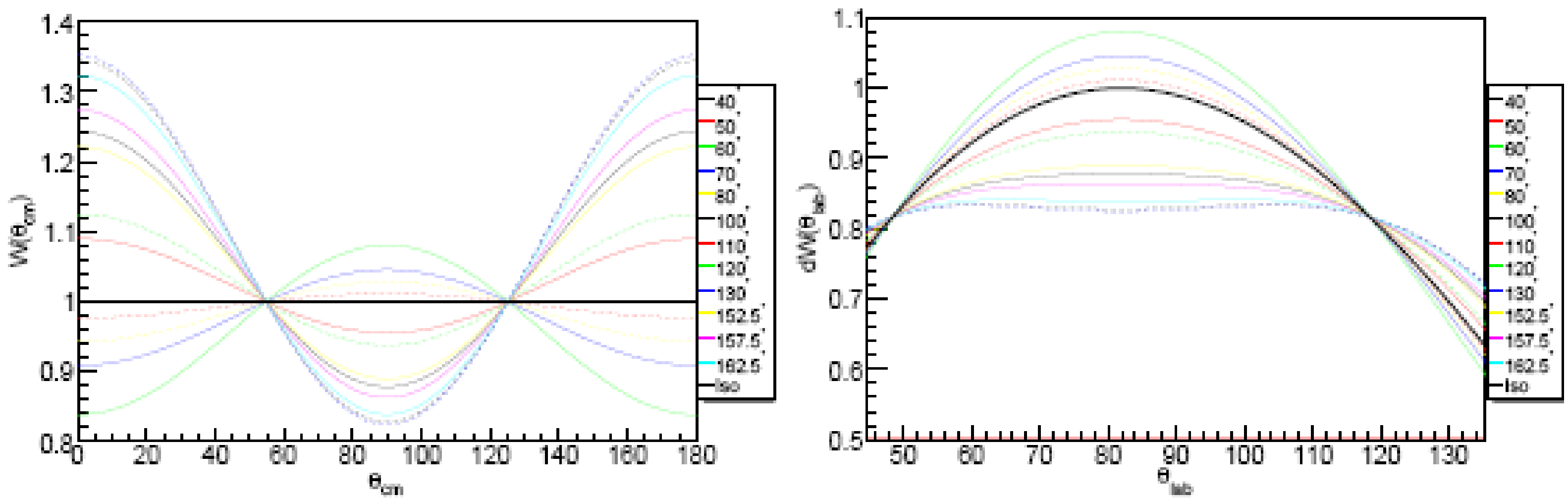
Rose & Brink

$$W(\theta) = \sum_{K\ even} B_K(J_1) R_K(J_1 J_2) P_K(cos\theta)$$

W(θ) is γ-ray angular dist

$$B_K(J_1) = \sum_{M_1=0\ or\ 1/2}^{M_1=J_1} w(M_1)\rho_K(J_1 M_1)$$

Substate distribution depends on the proton angle



(a) W($\theta_{c.m.}$) for all angles

(b) dW(θ_{lab}) in the angle range covered by EXOGAM

Figure 5.13: γ-ray angular distribution for the transition $3/2^-$ to $3/2^+$ in ^{27}Ne. The solid black lines represent the angular distribution that is isotropic in the centre of mass frame.

^{27}Ne BOUND STATES

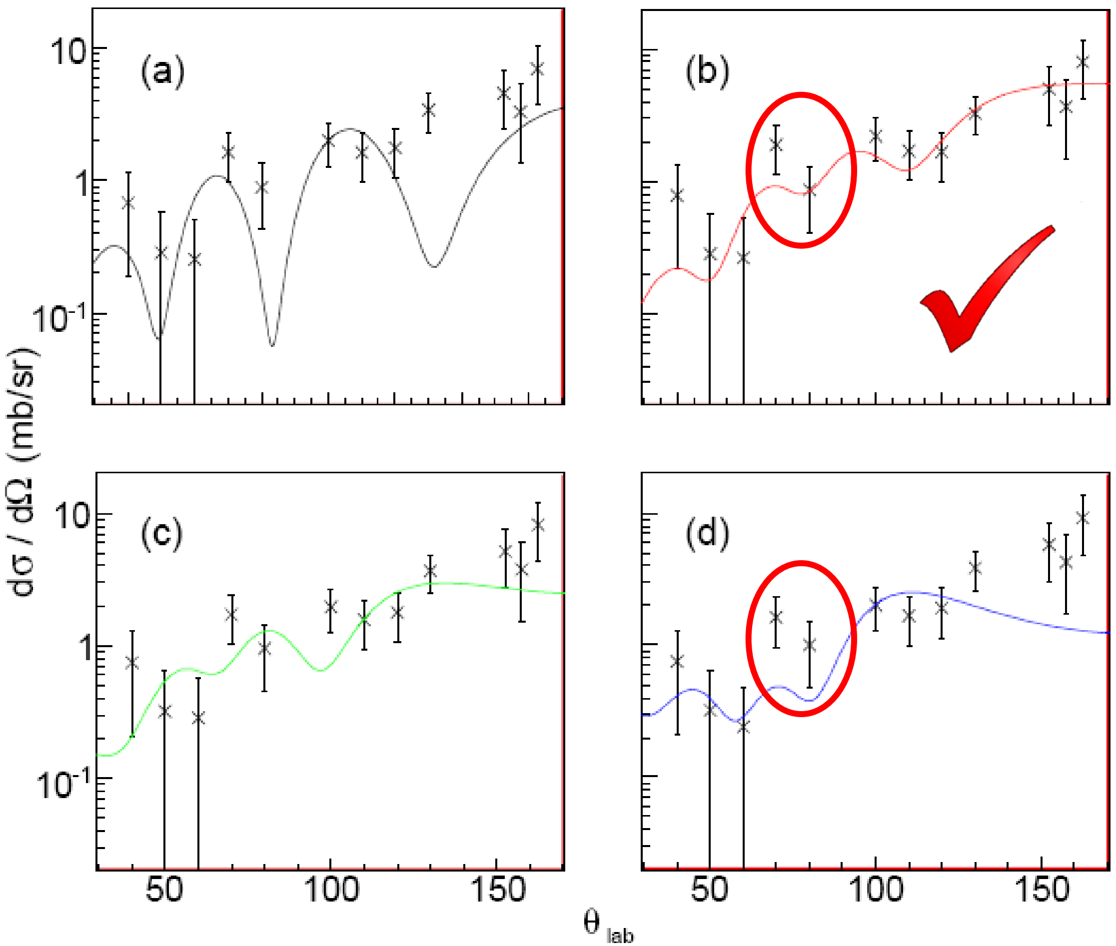


Figure 5.15: Angular distribution for events gated on 765 keV γ-rays in ^{27}Ne. The EXOGAM photopeak efficiency for each proton angle bin was determined from GEANT4 simulations using calculated γ-ray angular distributions based on the J^π assumption of the state in ^{27}Ne. Superimposed are ADWA calculations for various final states in ^{27}Ne that have been scaled to the data by χ^2 fits. The J^π of the states shown are a) $1/2^+$ (ℓ=0), b) $3/2^-$ (ℓ=1), c) $3/2^+$ (ℓ=2) and d) $7/2^-$ (ℓ=3).

^{27}Ne UNBOUND STATES

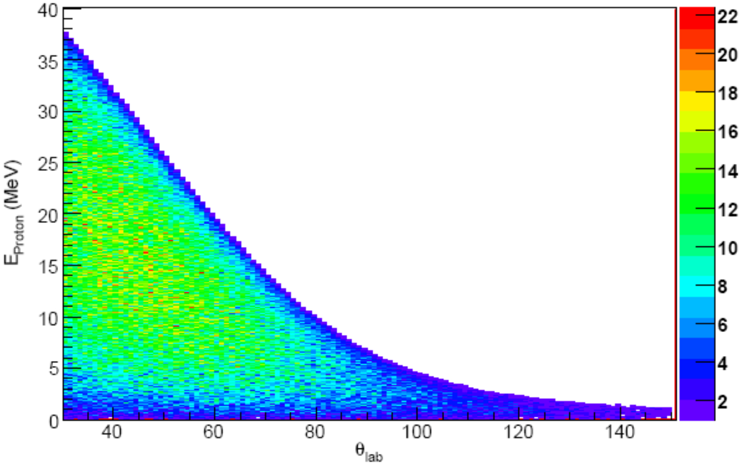


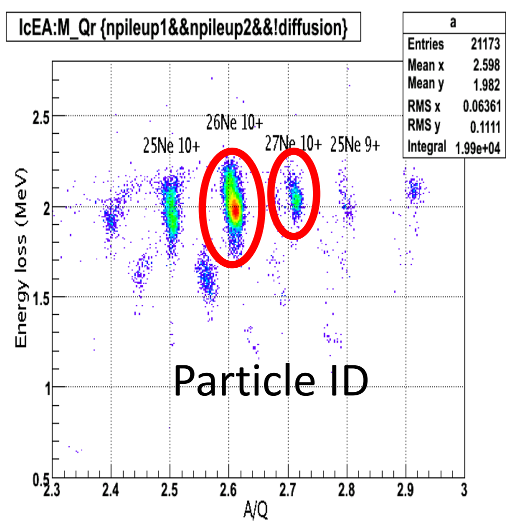
Figure 5.20: Simulation of the proton kinematics from deuteron breakup. The majority of the counts are focused to the forward laboratory angles due to the Lorentz boost.

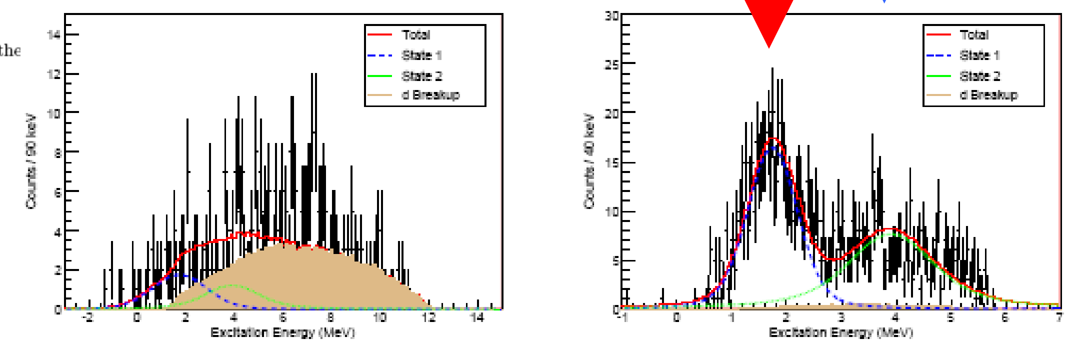
E_p vs θ_p for phase-space sampling

Almost no background seen in this case, when maximum allowable normalisation used at forward angles…

^{26}Ne(d,p)^{27}Ne

S M Brown et al





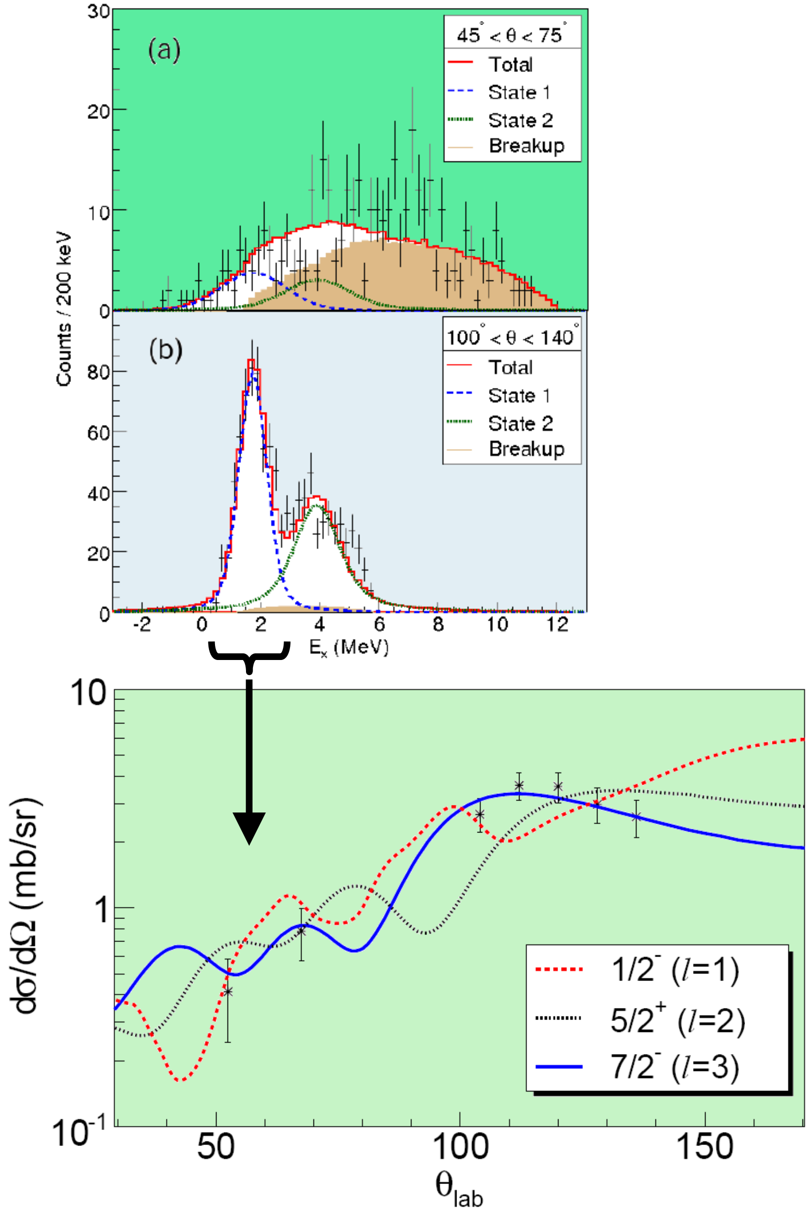
(a) 45° - 75°   (b) 100° - 140°

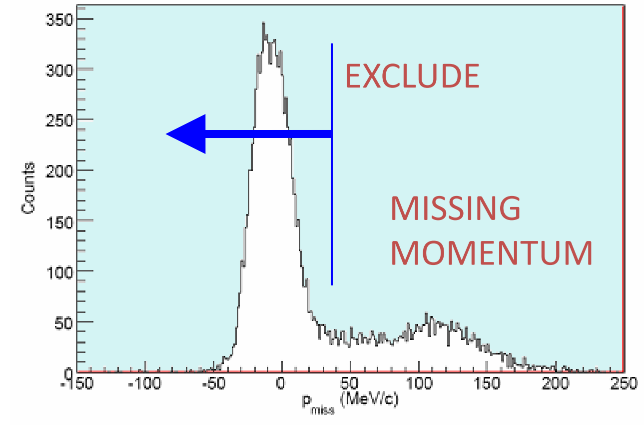
Figure 5.24: Fits to forward and backward excitation energy spectra with the finalised deuteron breakup scaling factor. The fit functions used are described in the text.

	State 1	State 2
E_x (MeV)	1.741(88)	3.906(95)
Γ (MeV)	0.234(155)	1.084(339)

Compare 3.5 ± 1.0 keV for natural width, from $d\sigma/d\Omega$

^{27}Ne UNBOUND STATES

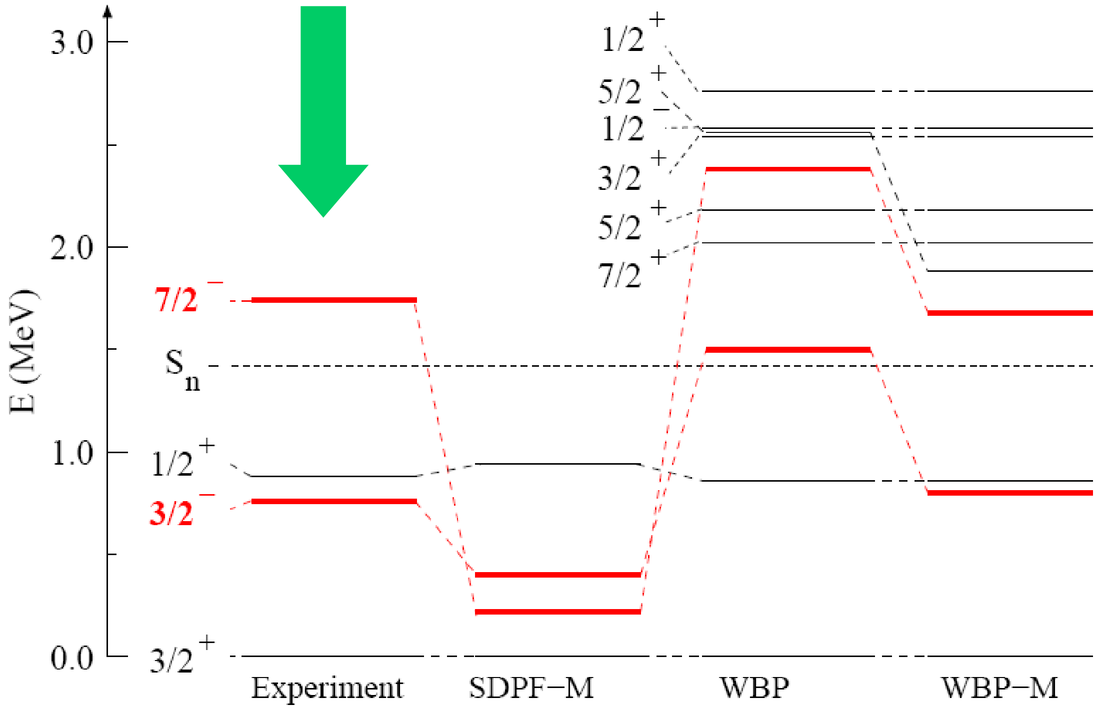




^{27}Ne results

- 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 ± 1.0 keV

^{27}Ne results



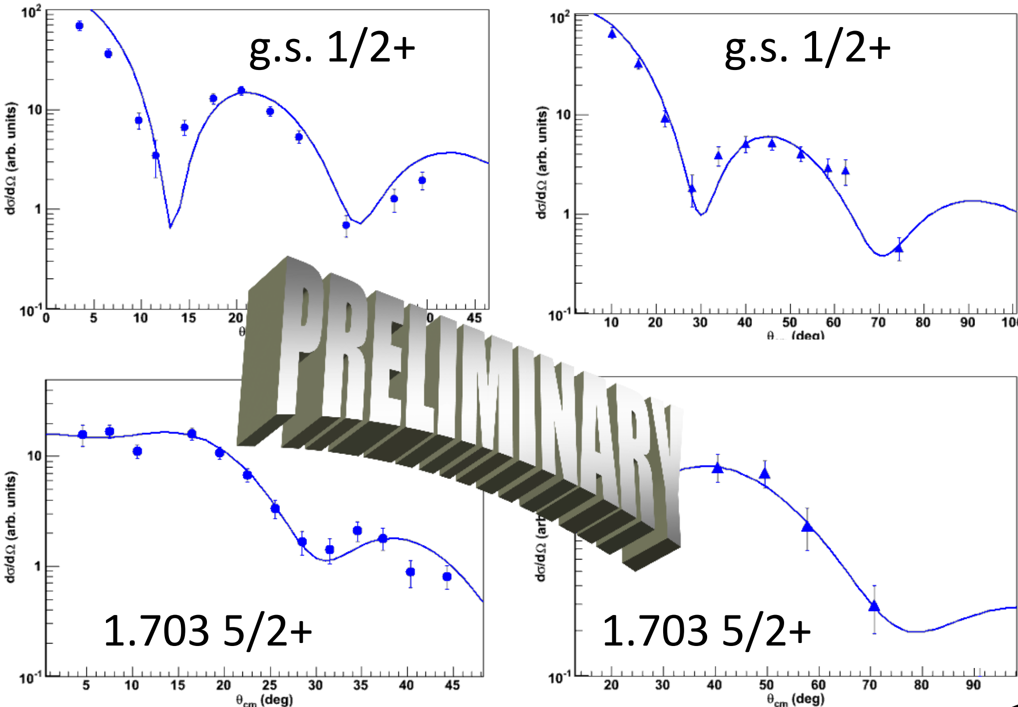
J^π	E^*_{exp} (MeV)	E^*_{WBP-M} (MeV)	C^2S Ref. [9]	C^2S Present	C^2S WBP-M
$3/2^+$	0	0	0.2(2)	0.42(22)	0.63
$3/2^-$	0.765	0.809	0.6(2)	0.64(33)	0.67
$1/2^+$	0.885	0.869	0.3(1)	0.17(14)	0.17
$7/2^-$	1.74	1.686	-	0.35(10)	0.40

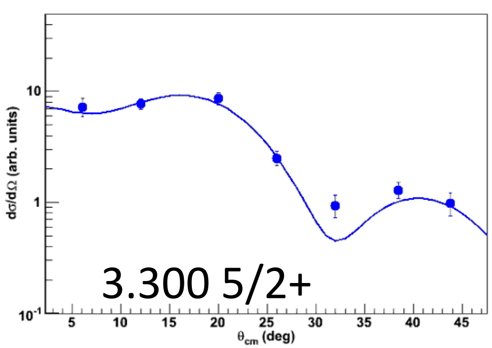
- we have been able to reproduce the observed energies with a modified <u>WBP interaction</u>, full 1hw SM calculation
- the <u>SFs agree</u> well also
- most importantly, the new interaction works well for ^{29}Mg, ^{25}Ne also
- so we need to understand why an <u>*ad hoc* lowering</u> of the fp-shell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

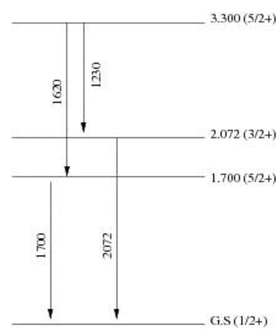
Preliminary results for ^{26}Ne(d,t)^{25}Ne and also (p,d)

JEFFRY THOMAS, SURREY

^{26}Ne(d,t)^{25}Ne ^{26}Ne(p,d)^{25}Ne

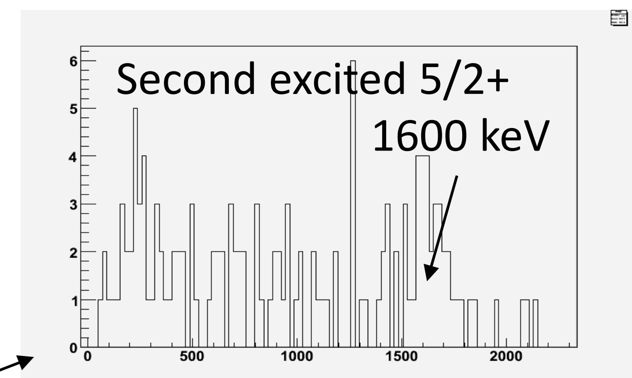


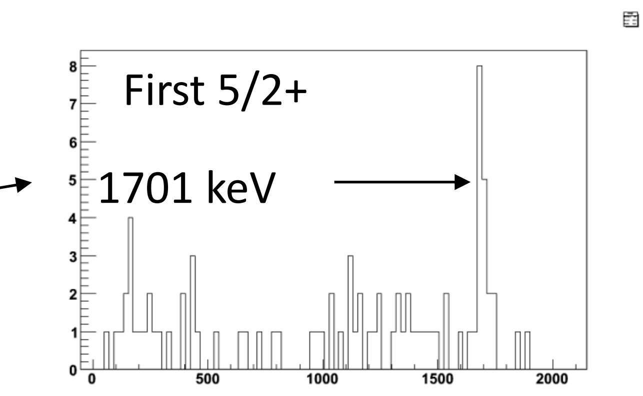




^{26}Ne(d,tγ)^{25}Ne

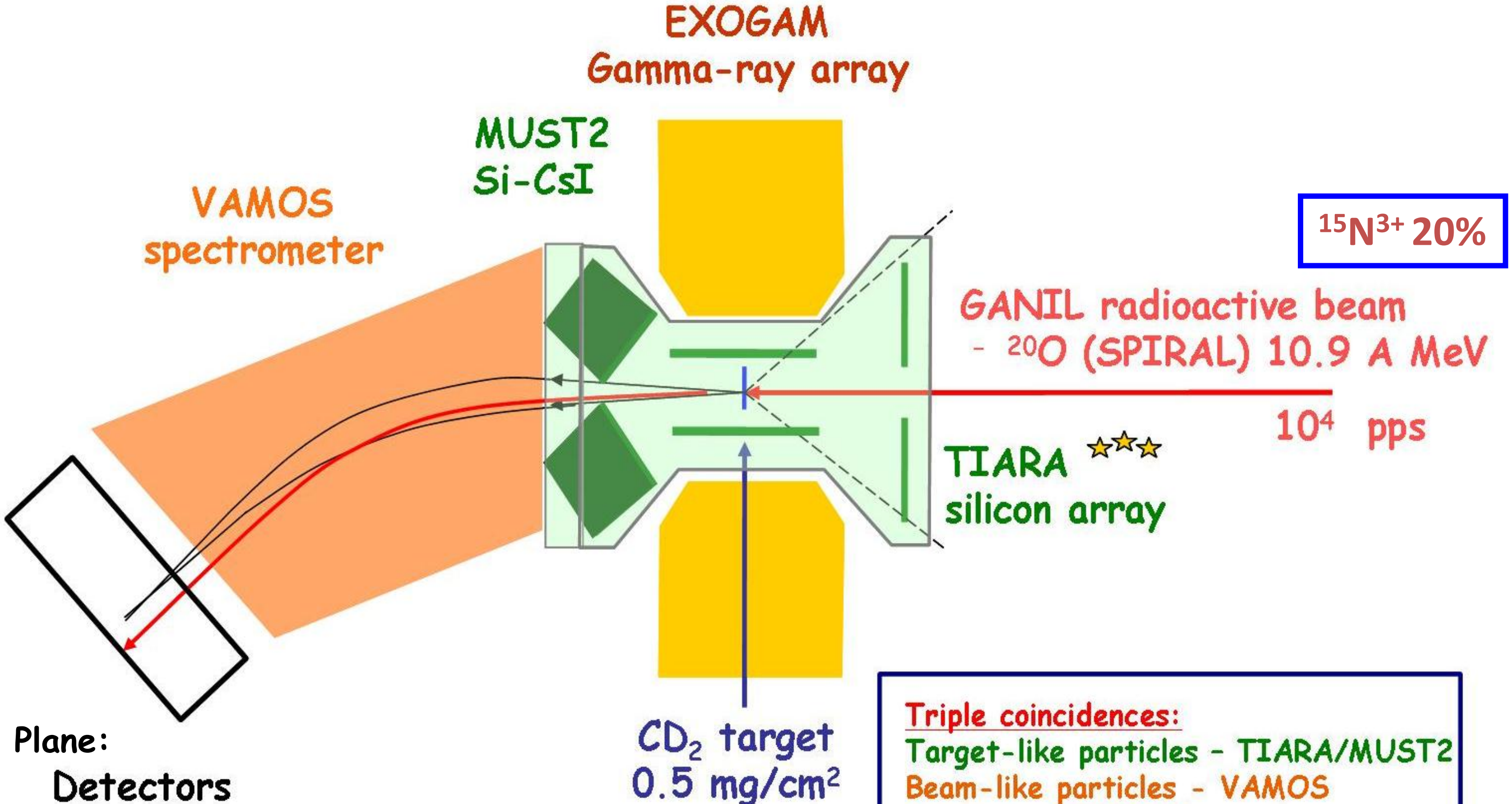
GAMMA ENERGY





INDIVIDUAL DECAY SPECTRA OF EXCITED 5/2+ STATES

TIARA+MUST2+VAMOS+EXOGAM @ SPIRAL/GANIL



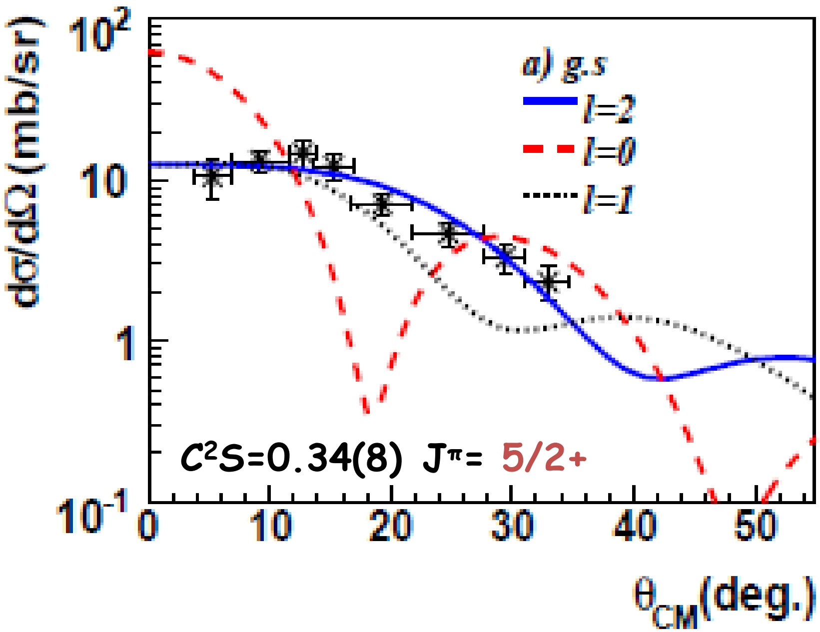
1 mg/cm^2

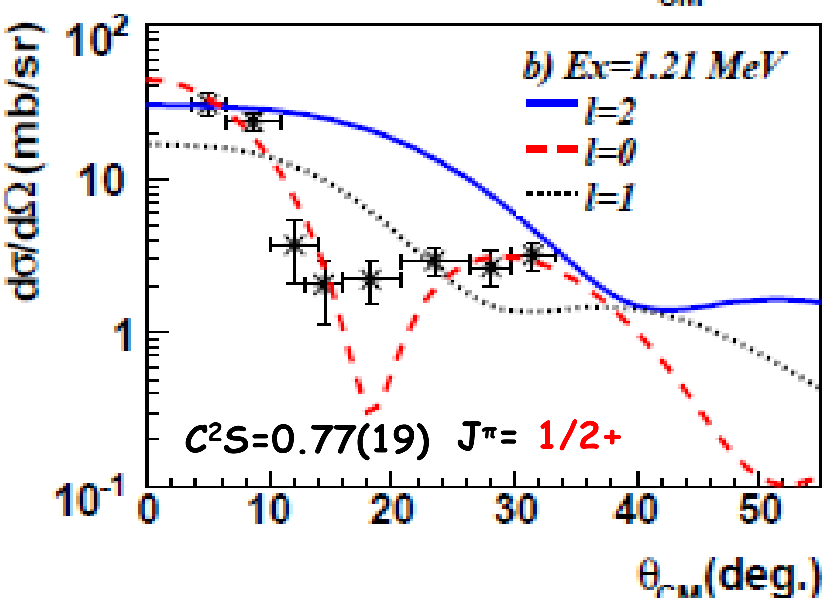
Focal Plane:

Detectors
DE, E, TOF
Bρ, X,Y,

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

BOUND STATES: d(^{20}O,p)^{21}O (stripping)

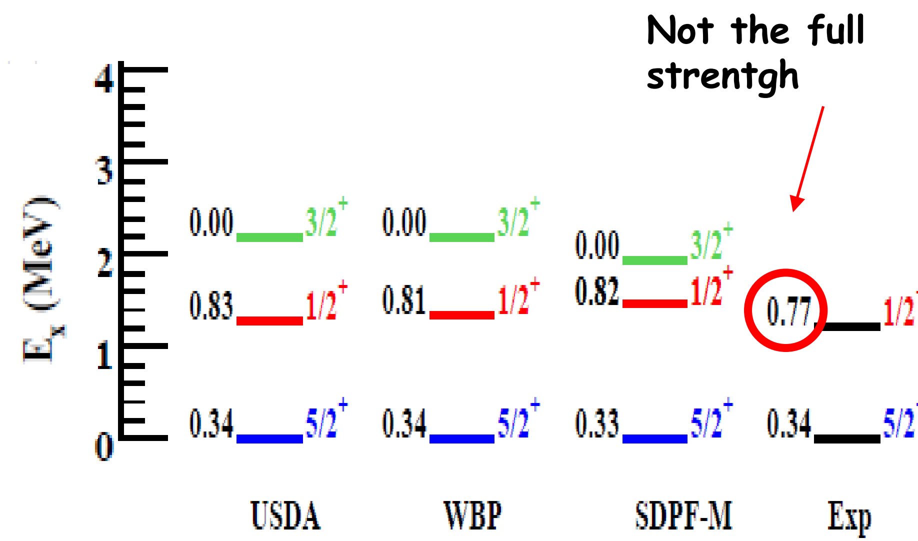




ADWA

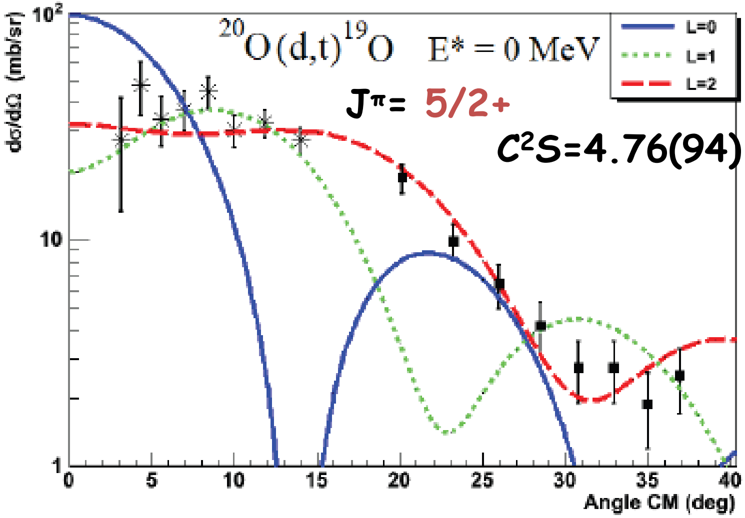
Adiabatic Distorted Wave Approximation

Deuteron Continuum Effects to all orders
R.C. Johnson & P.J.R. Soper (1970)

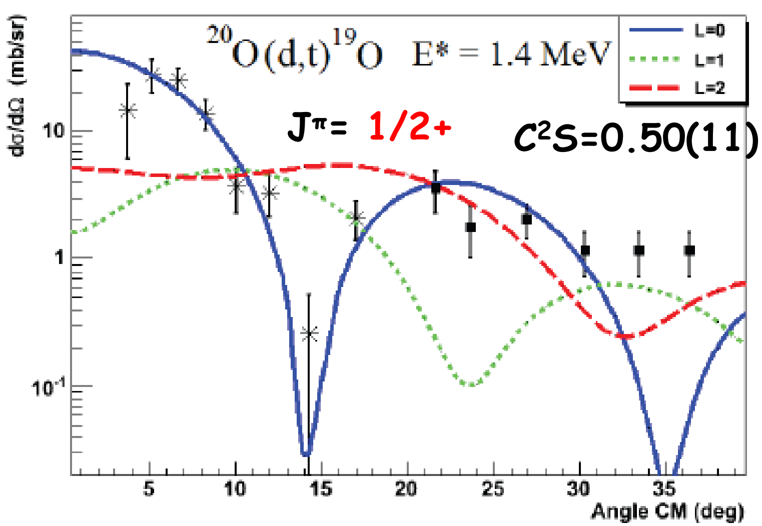


+ first **measure** of **1/2^{+}** state's spin
(previously inferred; Catford et al, NPA 1989)

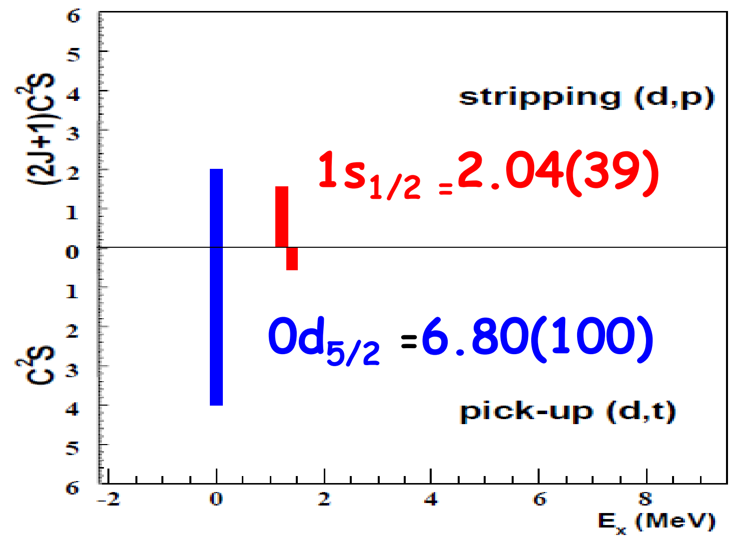
BOUND STATES: d(^{20}O,t)^{19}O (pick-up)



A. Ramus PhD. Thesis Universite Paris XI



Full strength for $0d_{5/2}$ and $1s_{1/2}$ measured !

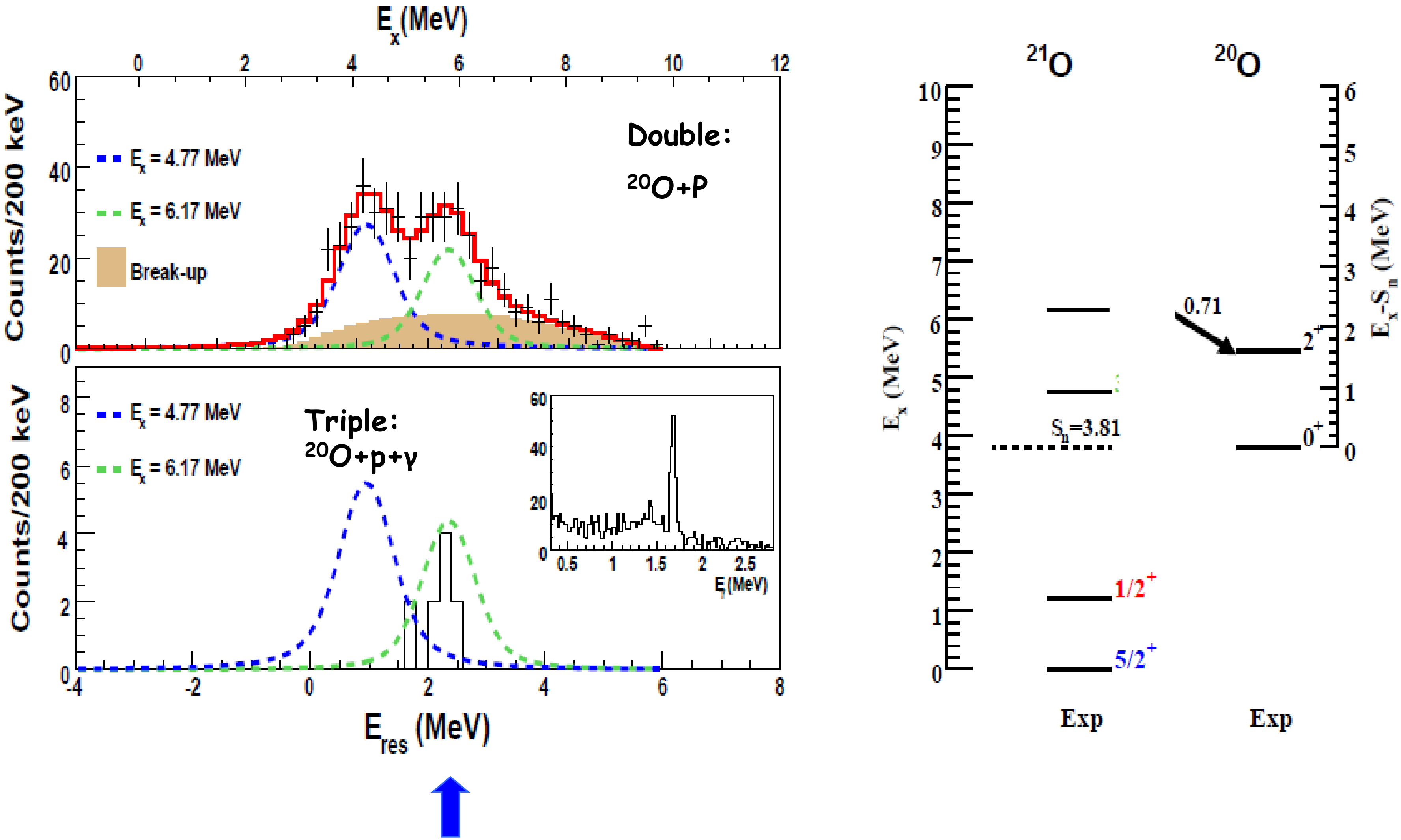


Sum Rules:
M. Baranger et al., NPA 149, 225 (1970)

ν1s1/2 partially occupied in ^{20}O : correlations

WILTON CATFORD INT, AUGUST 2011

UNBOUND STATES: d(^{20}O,p)^{21}O → ^{20}O + n



Triple coincidence: particle+γ+recoil

Nuclear Physics **A202** (1973) 97 – 122

PERIPHERAL-MODEL APPROACH TO STRIPPING INTO RESONANT STATES

E. I. DOLINSKY, P. O. DZHAMALOV and A. M. MUKHAMEDZHANOV
Institute of Nuclear Physics, Moscow State University, USSR

form of the theoretical angular distributions

essentially independent of l_n

In some cases the form of the theoretical angular distributions is essentially independent of l_n so that varying L one may obtain practically the same angular distributions for various l_n. This circumstance makes it difficult to obtain the spectroscopic information from the stripping data alone†.

† Similar difficulty appears in the analysis of stripping to a resonant state in the Butler theory [51]) and DWBA [8]).

$$d\sigma/d\Omega_p \approx \hbar^{-2}\Gamma\mu_{An}k_{An}(E_R)[d\sigma^F(E_R)/d\Omega_p]$$

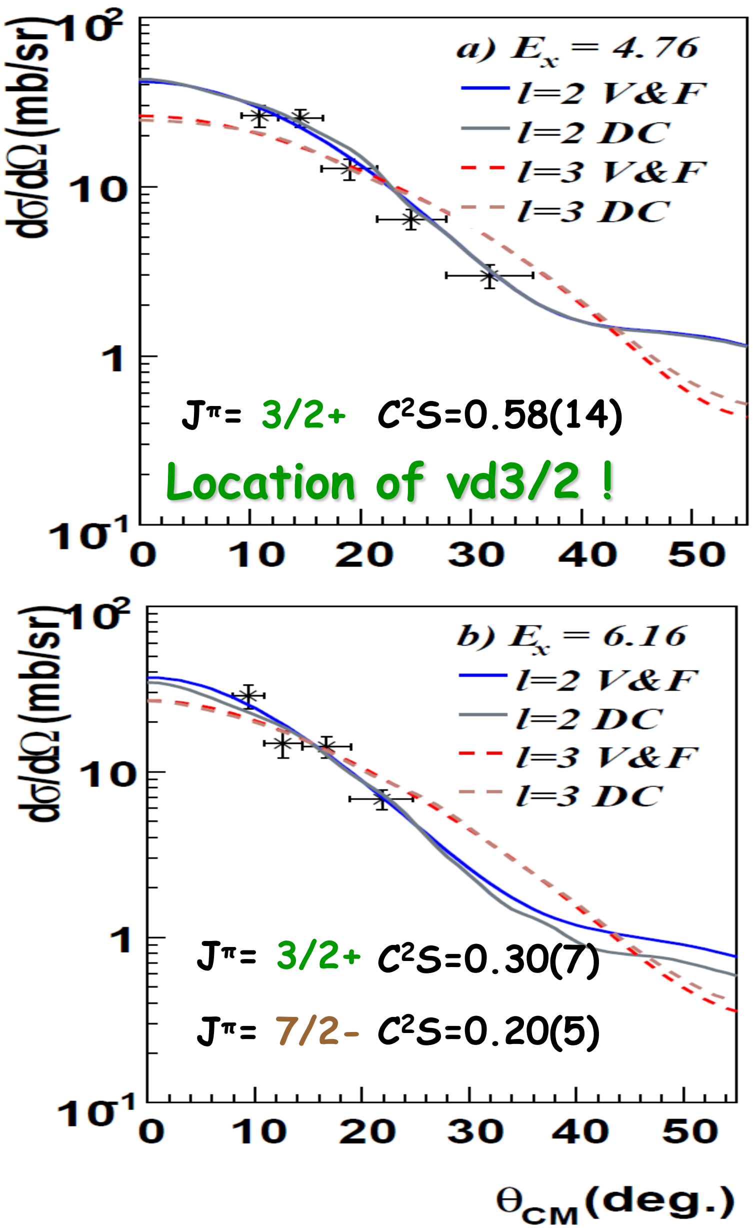
PHYSICAL REVIEW C VOLUME 2, NUMBER 3 SEPTEMBER 1970

New Method for Distorted-Wave Analysis of Stripping to Unbound States*

C. M. Vincent and H. T. Fortune†
Argonne National Laboratory, Argonne, Illinois 60439

Formalism used in present work

UNBOUND STATES: $d(^{20}O,p)^{21}O \rightarrow {}^{20}O + n$ (stripping)

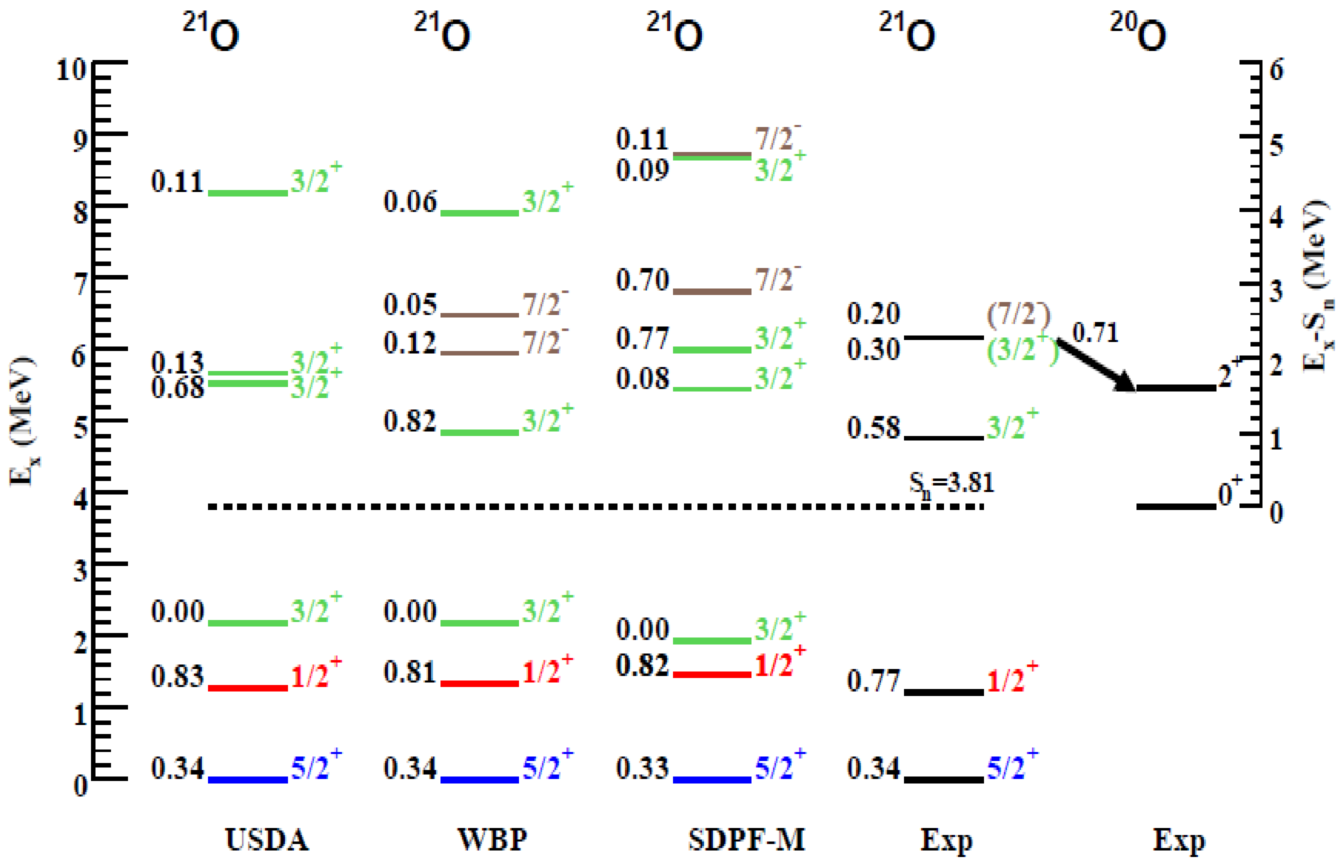


- Vincent & Fortune reaction model shown
- Also, **discretized continuum** calculations
- Agreement seen, in this case

- From V&F method, the natural width is extracted from the magnitude of the cross section
- This width needs to be consistent with the observed width (if that is not masked by experimental resolution)

OXYGEN BOUND AND UNBOUND STATES: d(^{20}O,p)^{21}O

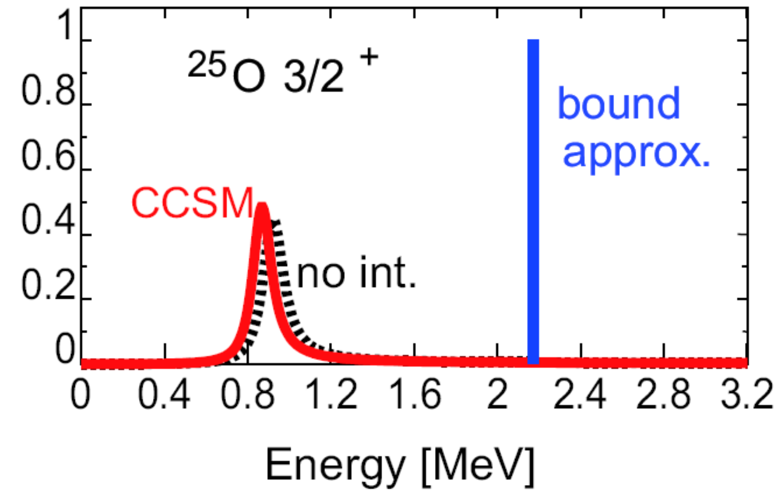
B. Fernandez Dominguez et al.,
Accepted as PRC Rapid Communication

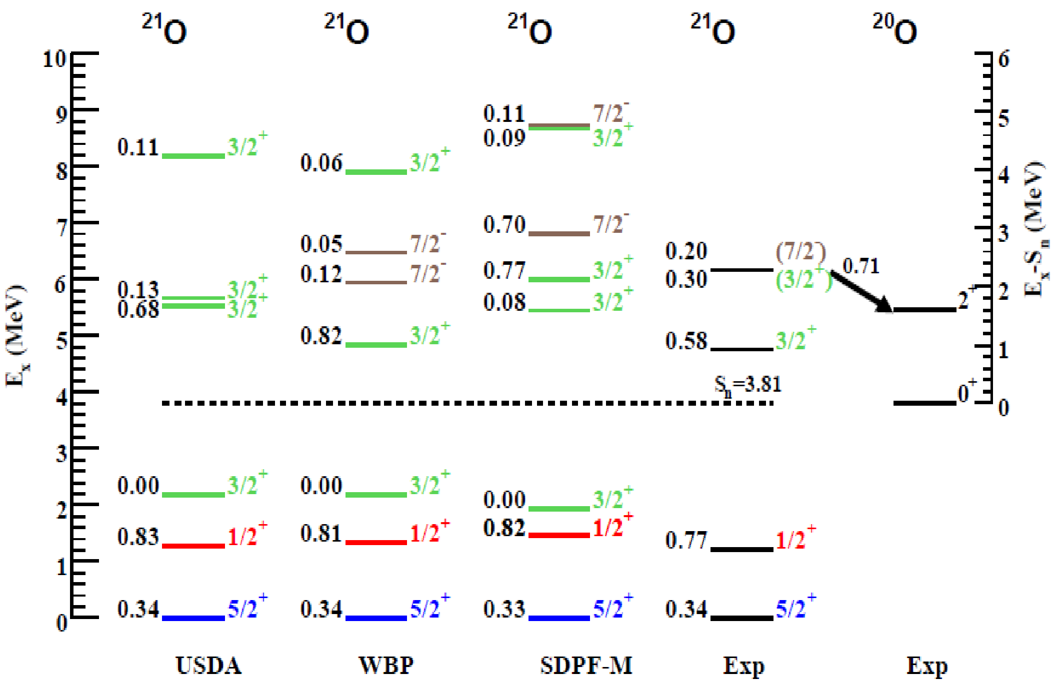


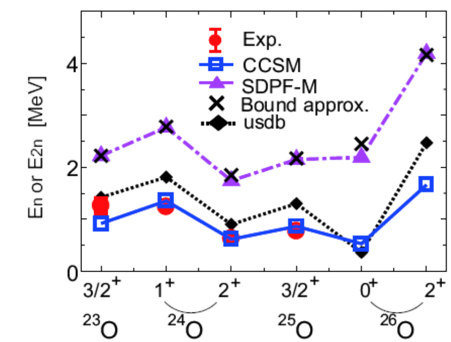
Difficult to interpret unbound states with standard SM. But 3/2+ state seems to favour USDA which predicts ^{26}O unbound

OXYGEN BOUND AND UNBOUND STATES: $d(^{20}O,p)^{21}O$

B. Fernandez Dominguez et al.,
Accepted as PRC Rapid Communication



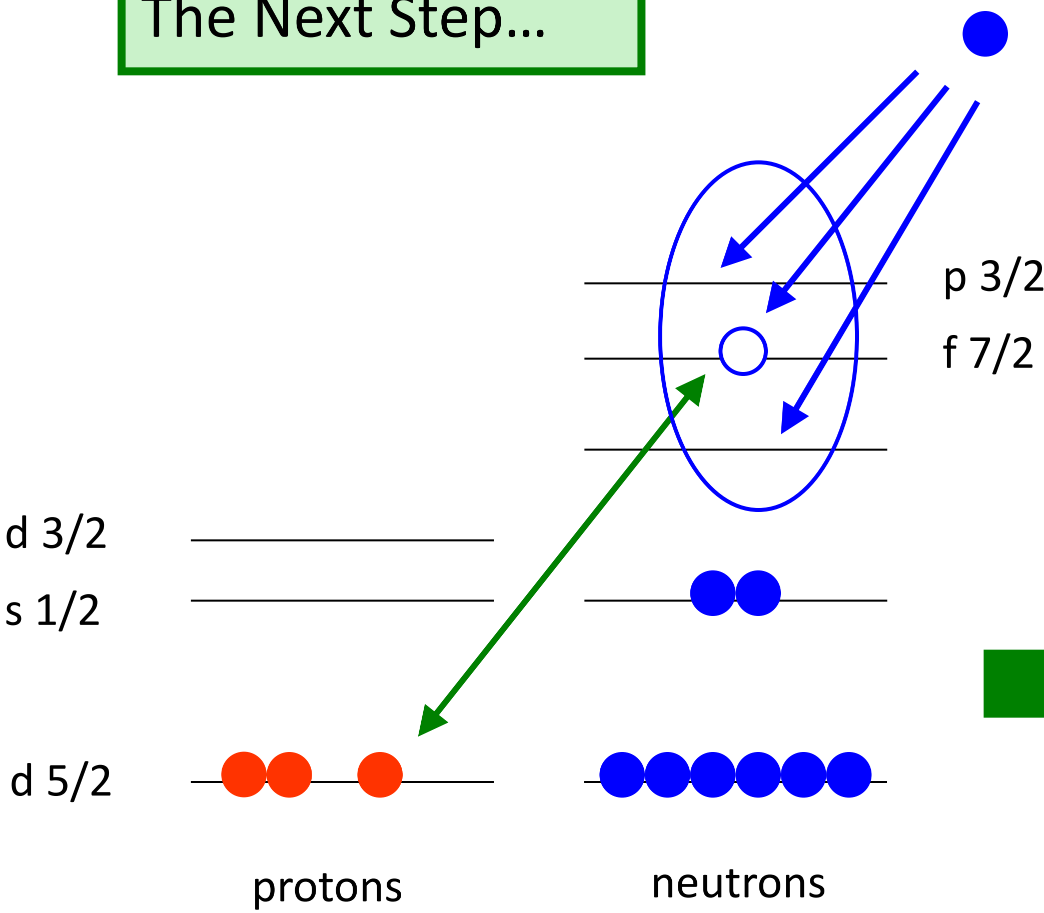




Tsukiyama, Otsuka and Fujimoto
arXiv 2010 preprint

CONTINUUM EFFECTS IN SHELL MODEL

The Next Step…

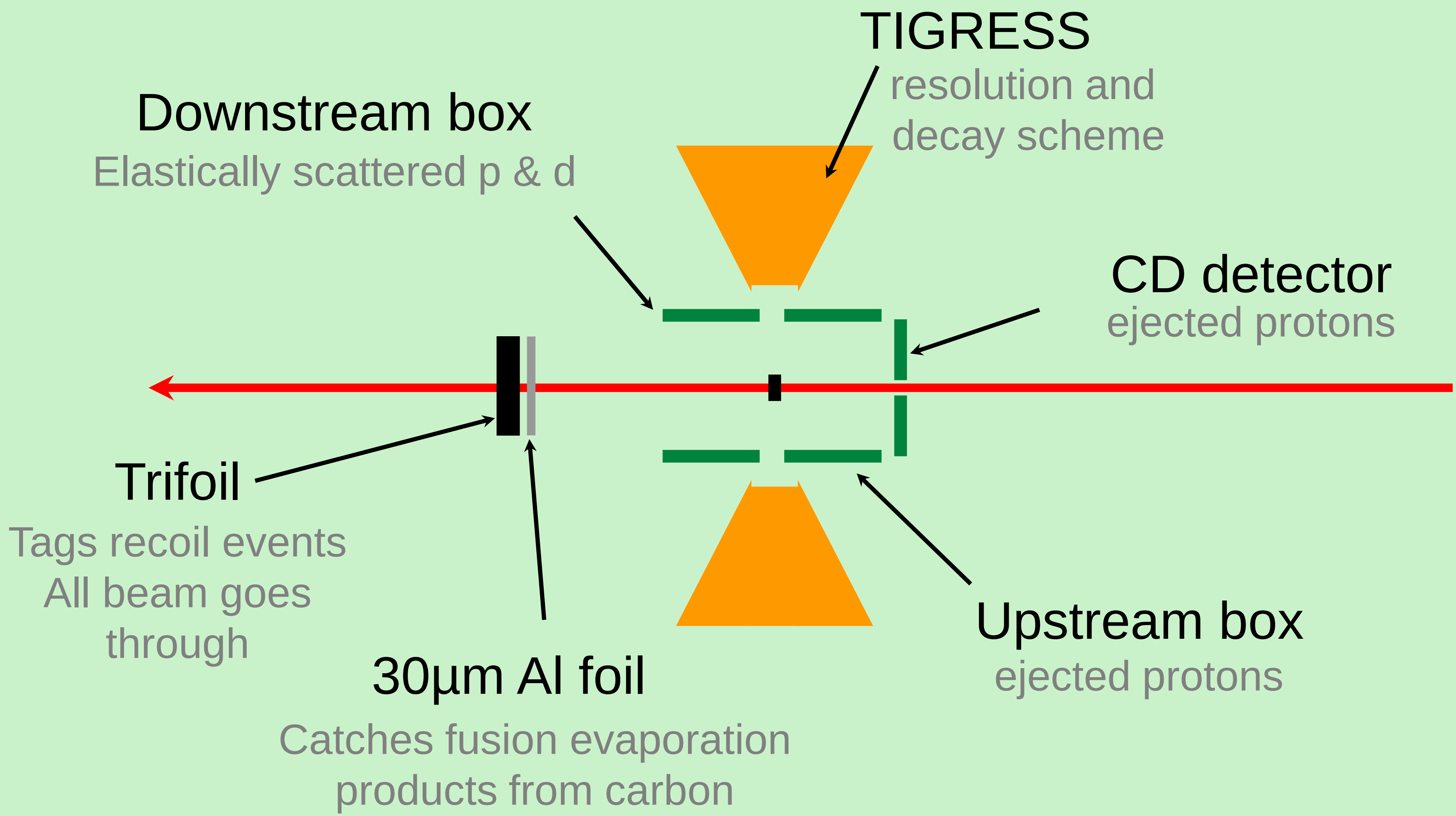


^{25}Na (d,p) ^{26}Na

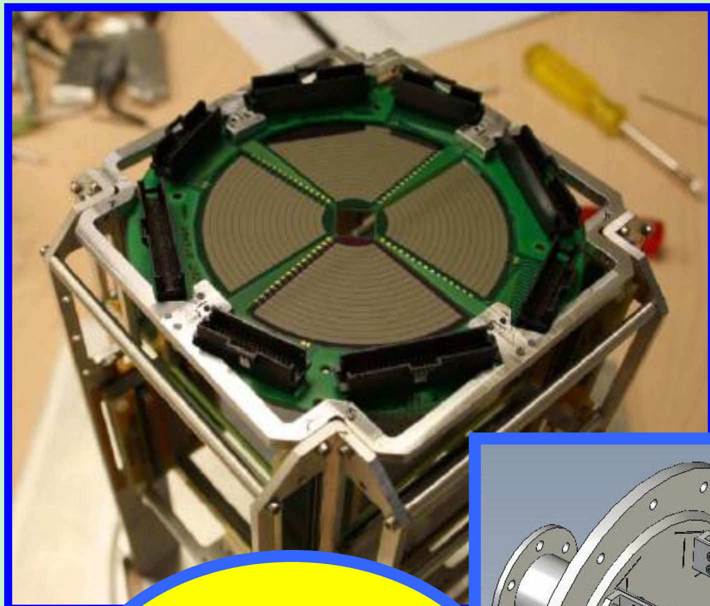
odd-odd final nucleus

High density of states
Gamma-gating needed

Schematic

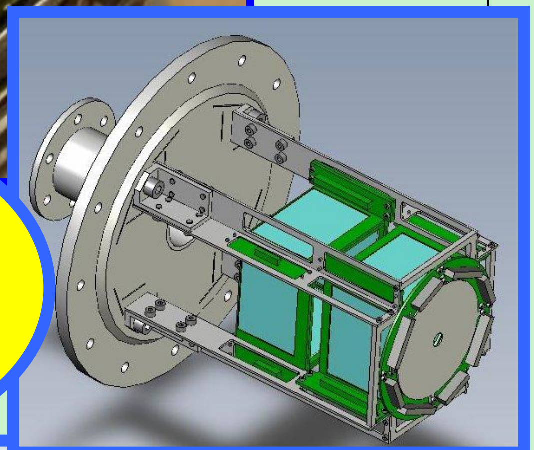

TIGRESS
resolution and decay scheme
Downstream box
Elastically scattered p & d
CD detector
ejected protons
Trifoil
Tags recoil events
All beam goes through
30µm Al foil
Catches fusion evaporation products from carbon
Upstream box
ejected protons

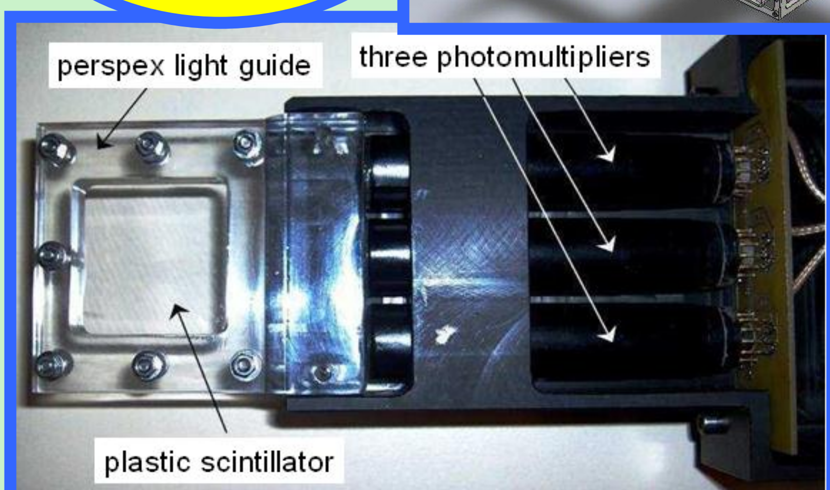
ZERO DEGREE = SCINTILLATOR



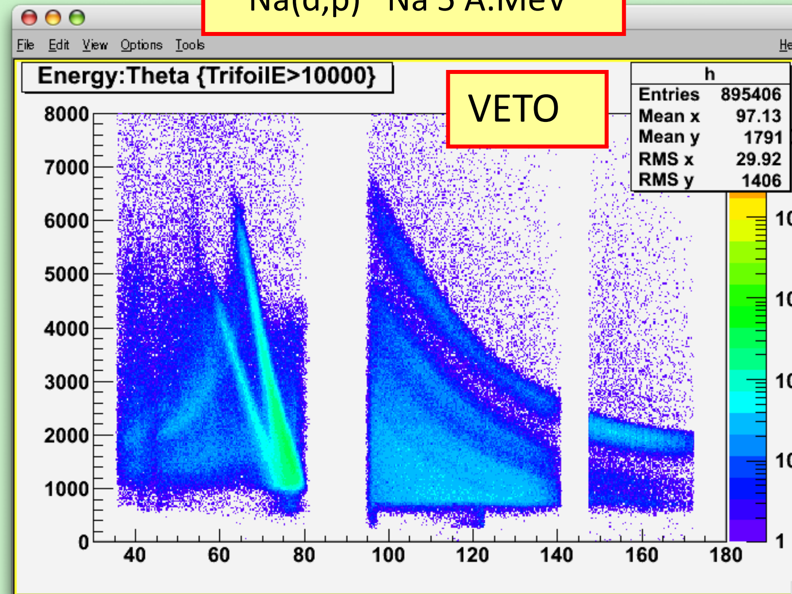
Beam

10^7 pps (pure)

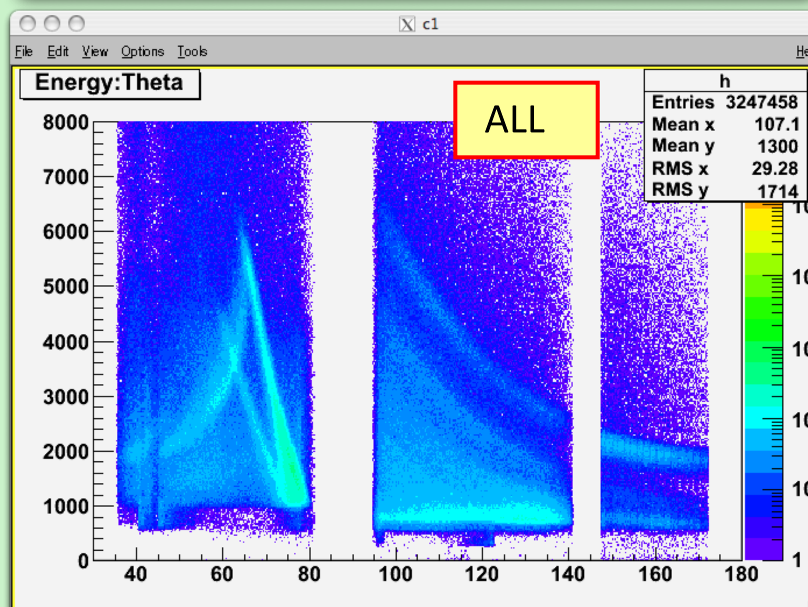




$^{25}Na(d,p)^{26}Na$ 5 A.MeV



VETO



ALL

RESULTS from SHARC Aug2009

LIVING with TRANSFER

Wilton Catford

For the TIARA, SHARC/TIGRESS Collabs

LIVING WITH TRANSFER

- This work is motivated by nuclear structure, which affects our choices
- We choose to use traditional transfer at ISOL energies to measure states
- We are presently comparing our extracted SFs directly with SM values
- We adopt ADWA for (d,p) with a set of “standard parameters” to allow this
- This allows us to compare SM states directly with experiment
- The ^{11}Be experiment compared with overlap integrals from structure model
- Other reactions using 4He, 3He etc require DWBA or related methods
- For bound states, we are (re-)developing gamma-correlation methods
- For unbound states, we need better reaction methods: CDCC
- Unbound states have less distinctive angular distributions to deduce ell
- Because we can study empty orbitals, we don’t need such exotic beams
- The experimental techniques are there, and just await the beams

Thank you to all my collaborators in the TIARA, SHARC &TIGRESS collaborations