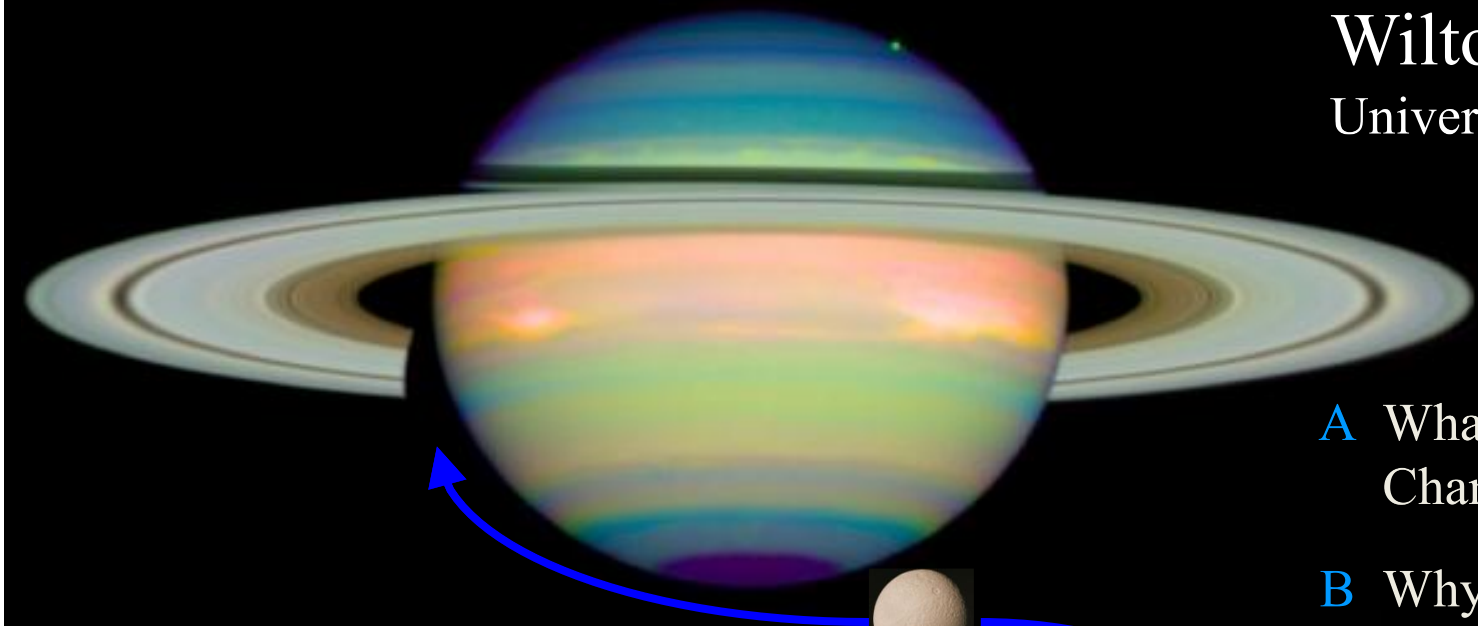
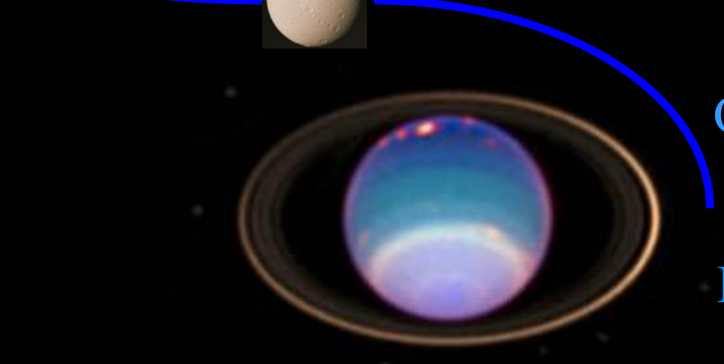
Exploring Unusual Nuclei with Nucleon Transfer Reactions





Wilton Catford
University of Surrey

- A What can we learn?; Changing magic no.'s
- B Why use transfer to study this physics?
- C What can we measure in specific nuclei?
- D Experimental setups
- E Examples of data & Interpretation

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

A PLAN for how to study nuclear STRUCTURE :

- 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 structure (e.g. shell model, ab initio) 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**.

- Motivation: nuclear structure reasons for transfer
- What quantities we actually measure
- What reactions/energies can we choose to use?
- Inverse Kinematics
- Implications for Experimental approaches
- Why do people make the choices that they do?
- Example experiments and results

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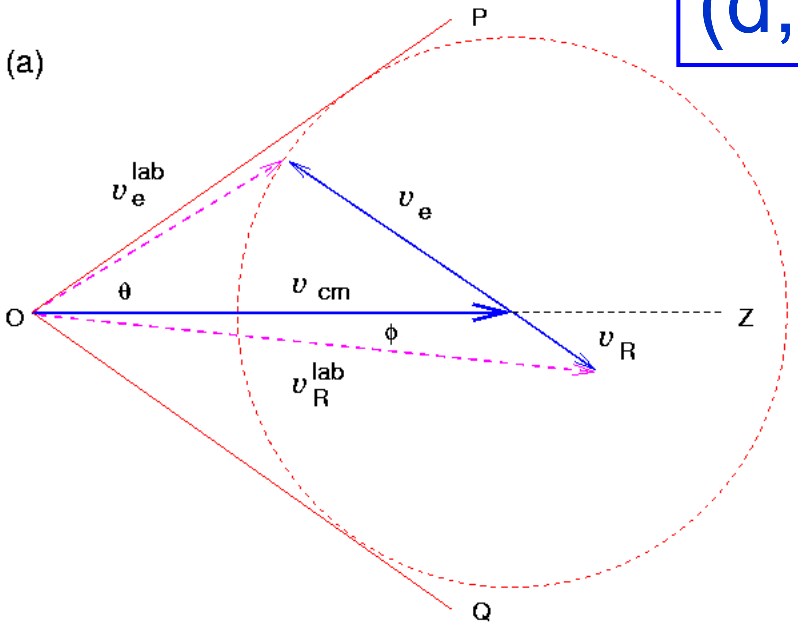
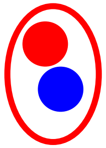
LE LAC DE PONT-L'ÉVÊQUE

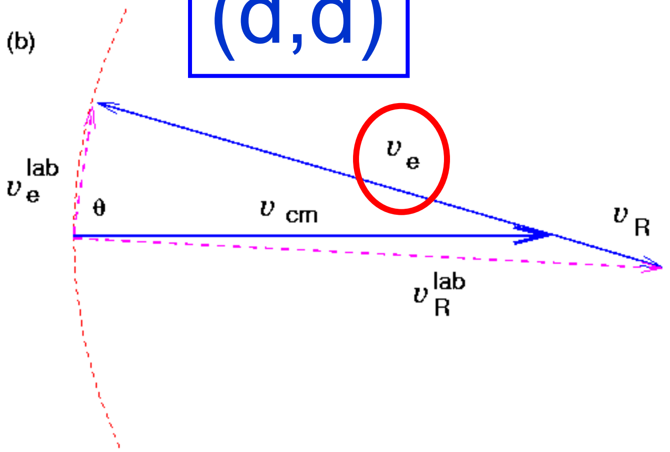
Using Radioactive Beams in Inverse Kinematics (heavy incident on light)

(d,t)

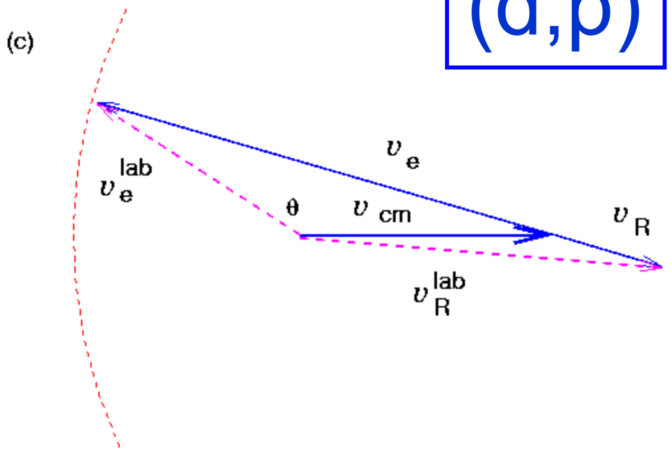




(d,d)



(d,p)



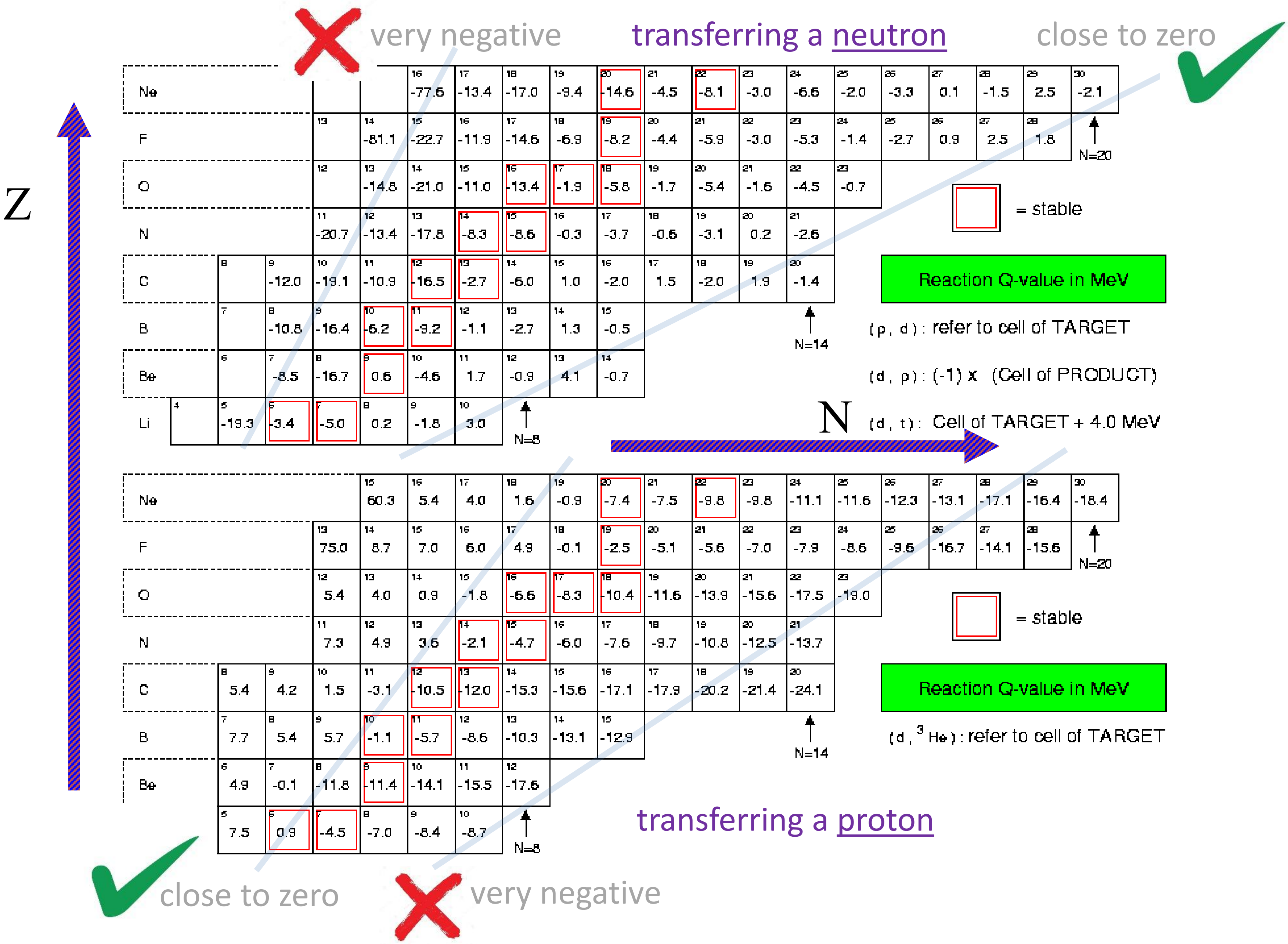
$$\frac{v_e}{v_{cm}} = \left(q\, f \frac{M_R}{M_P} \right)^{1/2} \cong \sqrt{q\, f}$$

$$\theta_{max} = \sin^{-1} \sqrt{f}$$

f = 1/2 for (p,d), 2/3 for (d,t)

$q \cong 1 + Q_{tot} / (E/A)_{beam}$

The reaction Q-value does have an effect (mainly on the cross section)



very negative

transferring a neutron

close to zero

Ne						16 -77.6	17 -13.4	18 -17.0	19 -9.4	**20 -14.6**	21 -4.5	**22 -8.1**	23 -3.0	24 -6.6	25 -2.0	26 -3.3	27 0.1	28 -1.5	29 2.5	30 -2.1
F				13	14 -81.1	15 -22.7	16 -11.9	17 -14.6	18 -6.9	**19 -8.2**	20 -4.4	21 -5.9	22 -3.0	23 -5.3	24 -1.4	25 -2.7	26 0.9	27 2.5	28 1.8	↑ N=20
O				12	13 -14.8	14 -21.0	15 -11.0	**16 -13.4**	**17 -1.9**	**18 -5.8**	19 -1.7	20 -5.4	21 -1.6	22 -4.5	23 -0.7					
N				11 -20.7	12 -13.4	13 -17.8	**14 -8.3**	**15 -8.6**	16 -0.3	17 -3.7	18 -0.6	19 -3.1	20 0.2	21 -2.6						
C		8	9 -12.0	10 -19.1	11 -10.9	**12 -16.5**	**13 -2.7**	14 -6.0	15 1.0	16 -2.0	17 1.5	18 -2.0	19 1.9	20 -1.4						
B		7	8 -10.8	9 -16.4	**10 -6.2**	**11 -9.2**	12 -1.1	13 -2.7	14 1.3	15 -0.5				↑ N=14						
Be		6	7 -8.5	8 -16.7	**9 0.6**	10 -4.6	11 1.7	12 -0.9	13 4.1	14 -0.7										
Li	4	5 -19.3	**6 -3.4**	**7 -5.0**	8 0.2	9 -1.8	10 3.0	↑ N=8												

□ = stable

Reaction Q-value in MeV

(p, d): refer to cell of TARGET

(d, p): (-1) x (Cell of PRODUCT)

(d, t): Cell of TARGET + 4.0 MeV

Ne					15 60.3	16 5.4	17 4.0	18 1.6	19 -0.9	**20 -7.4**	21 -7.5	**22 -9.8**	23 -9.8	24 -11.1	25 -11.6	26 -12.3	27 -13.1	28 -17.1	29 -16.4	30 -18.4
F				13 75.0	14 8.7	15 7.0	16 6.0	17 4.9	18 -0.1	**19 -2.5**	20 -5.1	21 -5.6	22 -7.0	23 -7.9	24 -8.6	25 -9.6	26 -16.7	27 -14.1	28 -15.6	↑ N=20
O				12 5.4	13 4.0	14 0.9	15 -1.8	**16 -6.6**	**17 -8.3**	**18 -10.4**	19 -11.6	20 -13.9	21 -15.6	22 -17.5	23 -19.0					
N				11 7.3	12 4.9	13 3.6	**14 -2.1**	**15 -4.7**	16 -6.0	17 -7.6	18 -9.7	19 -10.8	20 -12.5	21 -13.7						
C		8 5.4	9 4.2	10 1.5	11 -3.1	**12 -10.5**	**13 -12.0**	14 -15.3	15 -15.6	16 -17.1	17 -17.9	18 -20.2	19 -21.4	20 -24.1						
B		7 7.7	8 5.4	9 5.7	**10 -1.1**	**11 -5.7**	12 -8.6	13 -10.3	14 -13.1	15 -12.9				↑ N=14						
Be		6 4.9	7 -0.1	8 -11.8	**9 -11.4**	10 -14.1	11 -15.5	12 -17.6												
		5 7.5	**6 0.9**	**7 -4.5**	8 -7.0	9 -8.4	10 -8.7	↑ N=8												

□ = stable

Reaction Q-value in MeV

(d, ^{3}He): refer to cell of TARGET

transferring a proton

close to zero

very negative

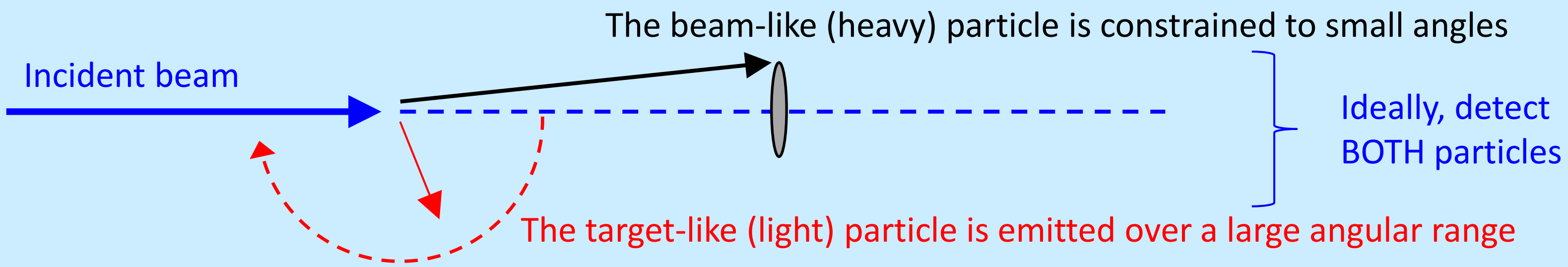
Possible experimental approaches to measuring transfer reactions…

1) Rely on detecting the beam-like ejectile in a spectrometer

- Kinematically favourable unless beam mass (and focussing) ***too*** great ✓
- Spread in beam energy (several MeV) translates to E_x measurement ✗
- Hence, need energy tagging, or a dispersion matching spectrometer ✗
- Spectrometer is subject to broadening from gamma-decay in flight ✗

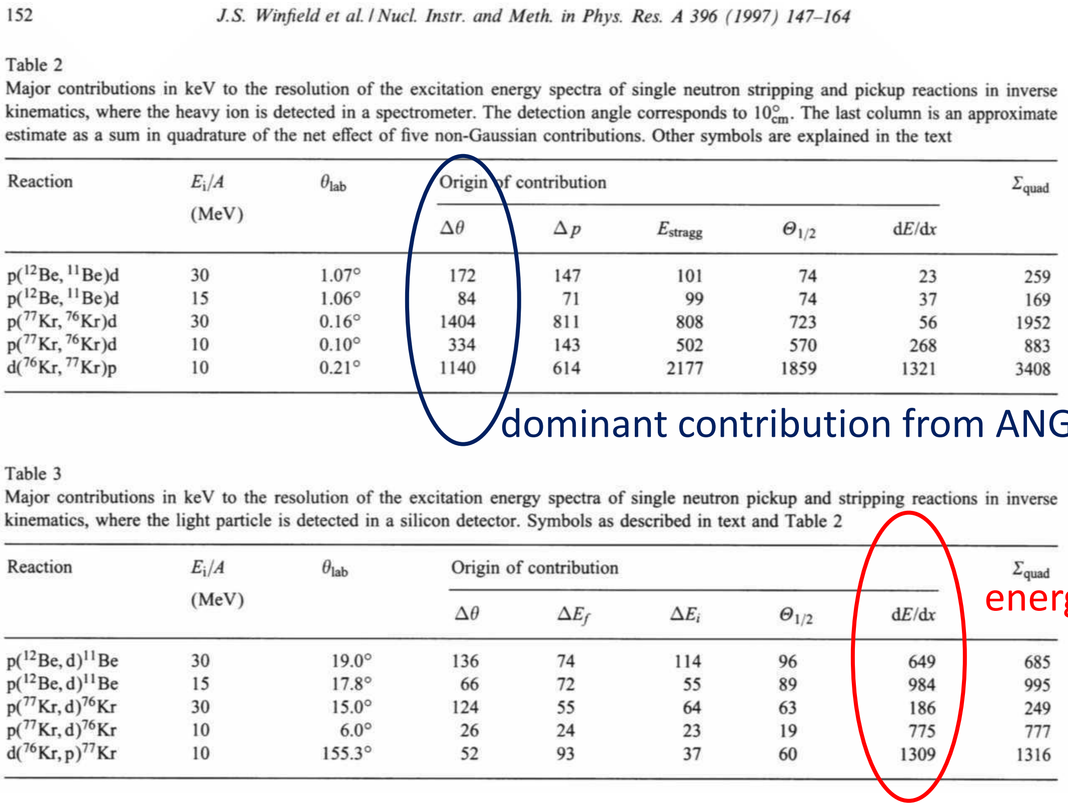
2) Rely on detecting the target-like ejectile in a Si detector

- Kinematically less favourable for angular coverage ✗
- Spread in beam energy generally gives little effect on E_x measurement ✓
- Resolution limited by difference [dE/dx(beam) - dE/dx(ejectile)] ✗
- Target thickness limited to 0.5-1.0 mg/cm^2 to maintain resolution ✗



J.S. Winfield, W.N. Catford and N.A. Orr, NIM A396 (1997) 147

Calculations of E_x resolution arising from particle detection…



152 J.S. Winfield et al. / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 147–164

beamlike particle detected

Table 2

Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to 10°_{cm}. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	Δp	E_{stragg}	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, ^{11}Be)d	30	1.07°	172	147	101	74	23	259
p(^{12}Be, ^{11}Be)d	15	1.06°	84	71	99	74	37	169
p(^{77}Kr, ^{76}Kr)d	30	0.16°	1404	811	808	723	56	1952
p(^{77}Kr, ^{76}Kr)d	10	0.10°	334	143	502	570	268	883
d(^{76}Kr, ^{77}Kr)p	10	0.21°	1140	614	2177	1859	1321	3408

dominant contribution from ANGLE measurement

light particle detected

Table 3

Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, d)^{11}Be	30	19.0°	136	74	114	96	649	685
p(^{12}Be, d)^{11}Be	15	17.8°	66	72	55	89	984	995
p(^{77}Kr, d)^{76}Kr	30	15.0°	124	55	64	63	186	249
p(^{77}Kr, d)^{76}Kr	10	6.0°	26	24	23	19	775	777
d(^{76}Kr, p)^{77}Kr	10	155.3°	52	93	37	60	1309	1316

energy loss leaving target

Lighter projectiles

Some minor advantages to detect
beam-like particle
(angular resolution difficult at higher energies)

Heavier projectiles

Better to detect light particle
(target thickness limits E_x resolution)

Possible Experimental Approaches to Nucleon Transfer

1) Rely on detecting the beam-like ejectile in a spectrometer

- Kinematically favourable unless beam mass (and focussing) ***too*** great
- Spread in beam energy (several MeV) translates to E_X measurement
- Hence, need energy tagging, or a dispersion matching spectrometer
- Spectrometer is subject to broadening from gamma-decay in flight

2) Rely on detecting the target-like ejectile in a Si detector

- Kinematically less favourable for angular coverage
- Spread in beam energy generally gives little effect on E_X measurement
- Resolution limited by difference [dE/dx(beam) - dE/dx(ejectile)]
- Target thickness limited to 0.5-1.0 mg/cm^2 to maintain resolution

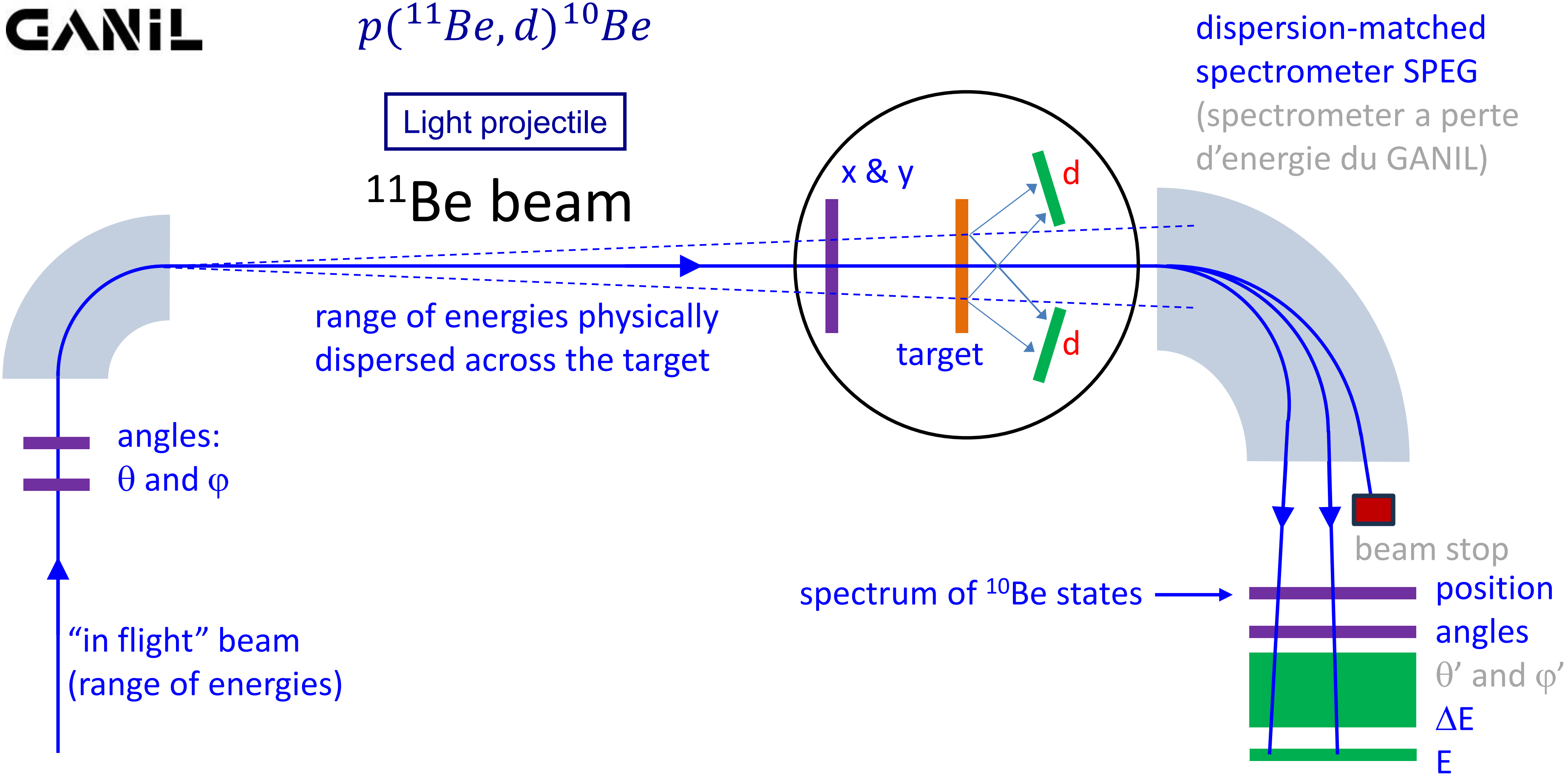
3) Detect decay gamma-rays in addition to particles

- Need exceptionally high efficiency, of order > 25%
- Resolution limited by Doppler shift and/or broadening
- Target thickness increased up to factor 10 (detection cutoff, mult scatt'g)

J.S. Winfield, W.N. Catford and N.A. Orr, NIM A396 (1997) 147

An experiment where we measured the beam-like particle…

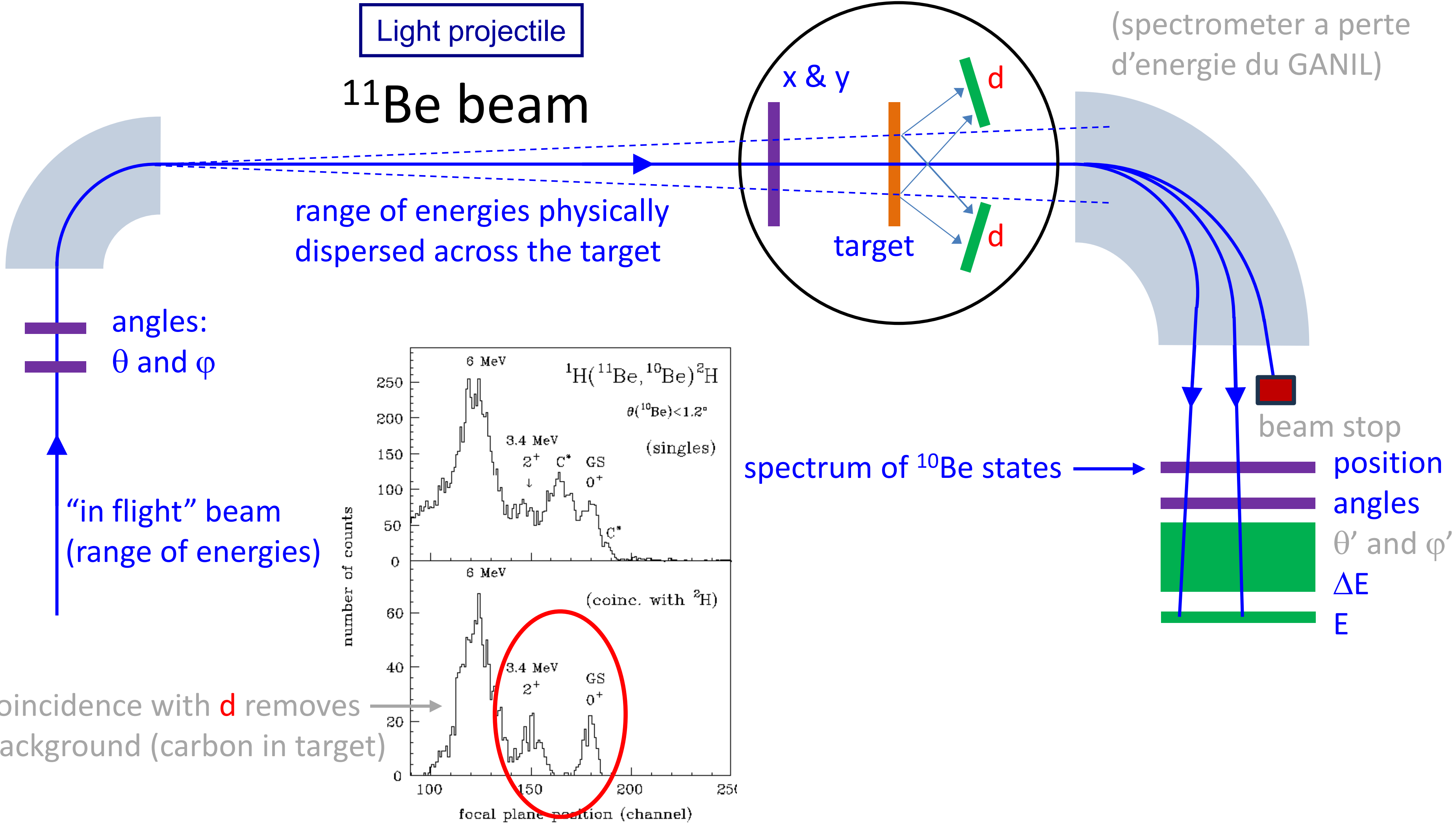
$p(^{11}Be, d)^{10}Be$



An experiment where we measured the beam-like particle…

GANIL

$p(^{11}Be,d)^{10}Be$



Light projectile

^{11}Be beam

range of energies physically dispersed across the target

x & y

target

dispersion-matched spectrometer SPEG (spectrometer a perte d'energie du GANIL)

angles: θ and φ

"in flight" beam (range of energies)

spectrum of ^{10}Be states →

beam stop

position

angles

θ' and φ'

ΔE

E

coincidence with d removes background (carbon in target) →

An experiment where we measured the beam-like particle…

GANIL

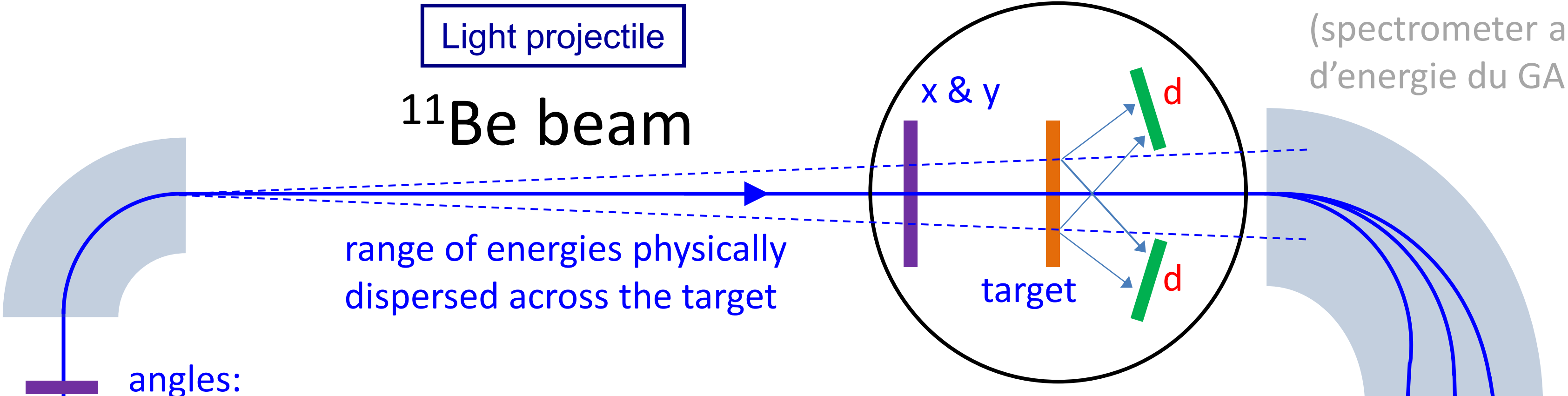
$p(^{11}Be,d)^{10}Be$

Light projectile

^{11}Be beam

dispersion-matched spectrometer SPEG

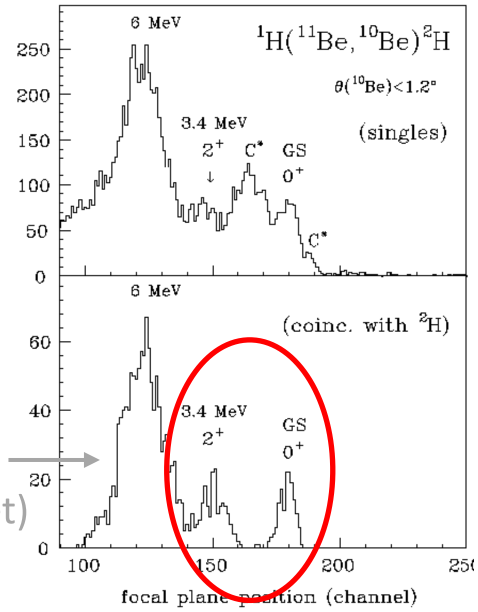
(spectrometer a perte d'energie du GANIL)



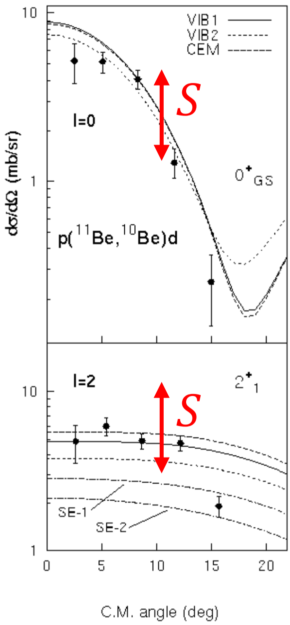
range of energies physically dispersed across the target

angles:
θ and φ

"in flight" beam
(range of energies)

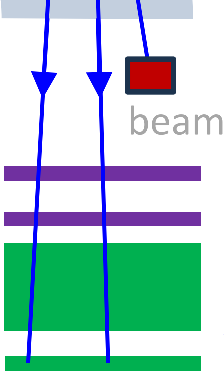


coincidence with d removes background (carbon in target)



$\ell = 0$

$\ell = 2$



beam stop

position

angles

θ' and φ'

ΔE

E

this is the angle that gets harder to measure for heaver projectiles

Physics Letters B 461 (1999) 22–27 S. Fortier [a], S. Pita [a], J.S. Winfield [a,b], W.N. Catford [b], N.A. Orr [c], *et al.*

#1 !!

Possible experimental approaches to measuring transfer reactions…

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- Target thickness limited to 0.5-1.0 mg/cm^2 to maintain resolution

3) Detect decay gamma-rays in addition to particles

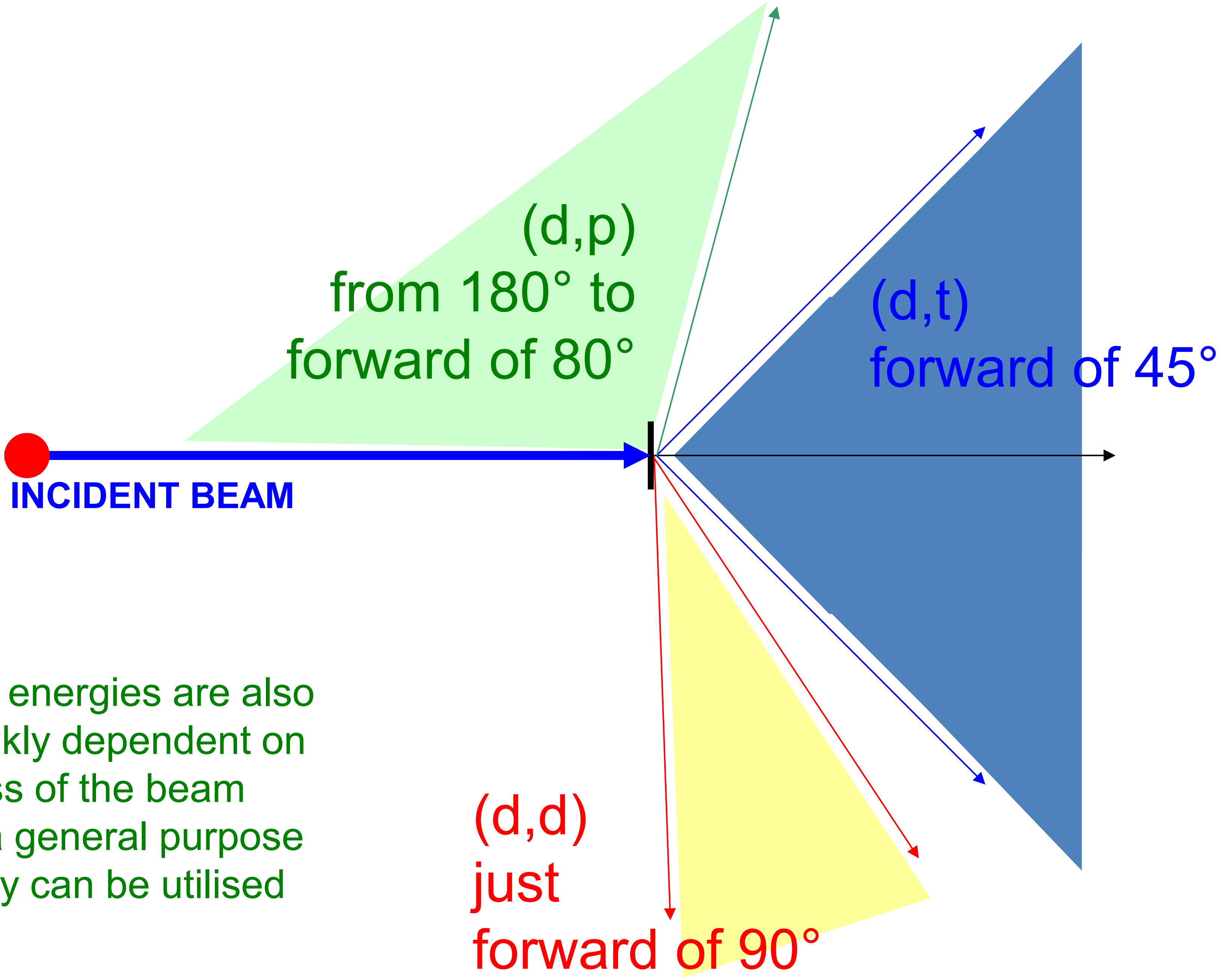
- Need exceptionally high efficiency, of order > 25%
- Resolution limited by only by Doppler shift and/or broadening
- Gamma-ray decay scheme gives valuable structure information

✓

Energy
resolution
improved
by a factor
up to TEN

J.S. Winfield, W.N. Catford and N.A. Orr, NIM A396 (1997) 147

Using Radioactive Beams in Inverse Kinematics…



INCIDENT BEAM

(d,p)
from 180° to
forward of 80°

(d,t)
forward of 45°

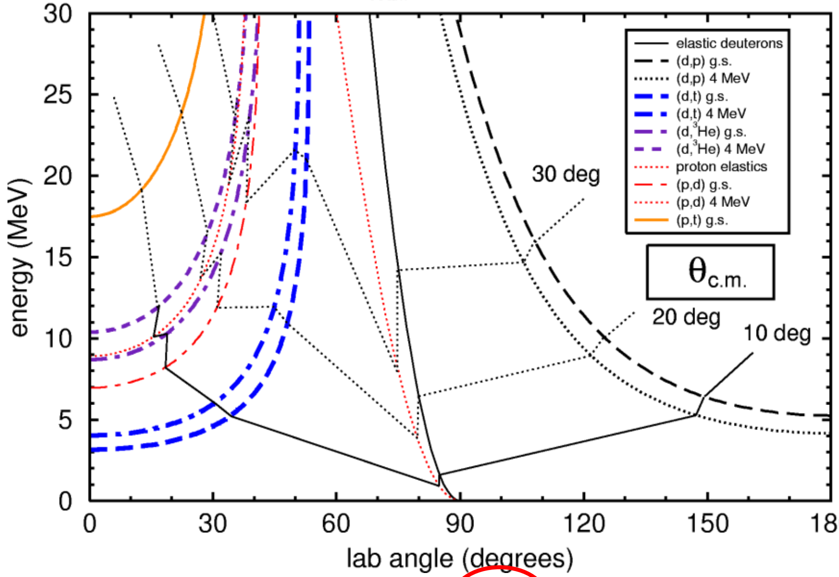
(d,d)
just
forward of 90°

The energies are also
weakly dependent on
mass of the beam
so a general purpose
array can be utilised

The **general form** of the kinematic diagrams is determined by the light particle masses, and has **little dependence** on the beam mass or beam velocity

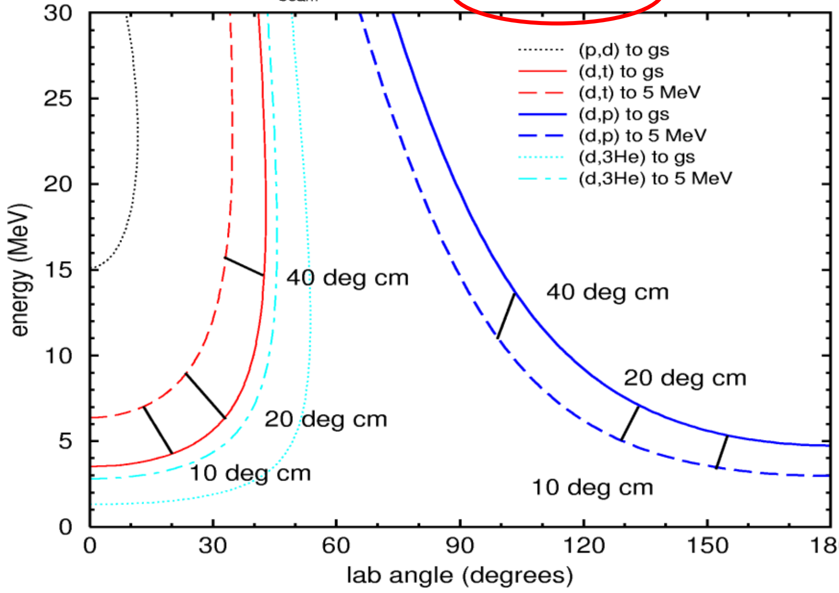
^{16}C incident on ^{2}H at 35 MeV/u

E_{beam} = 560 MeV

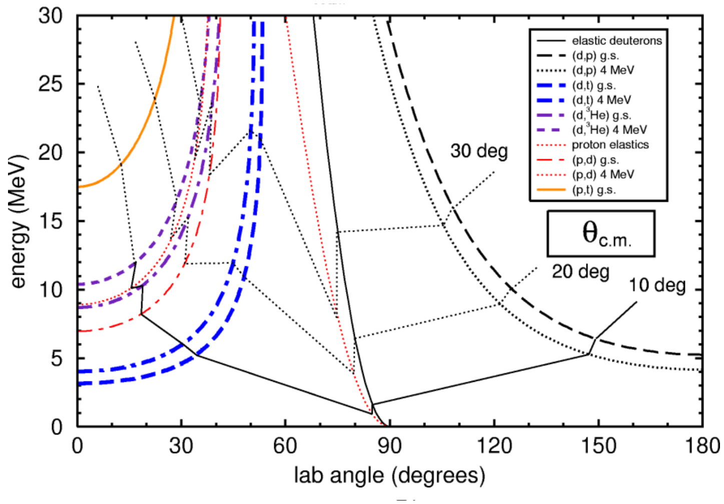


(p,d) and (d,t) and (d,p) on ^{74}Kr in inverse kinematics

E_{beam} = 900 MeV (12.16 MeV/A)



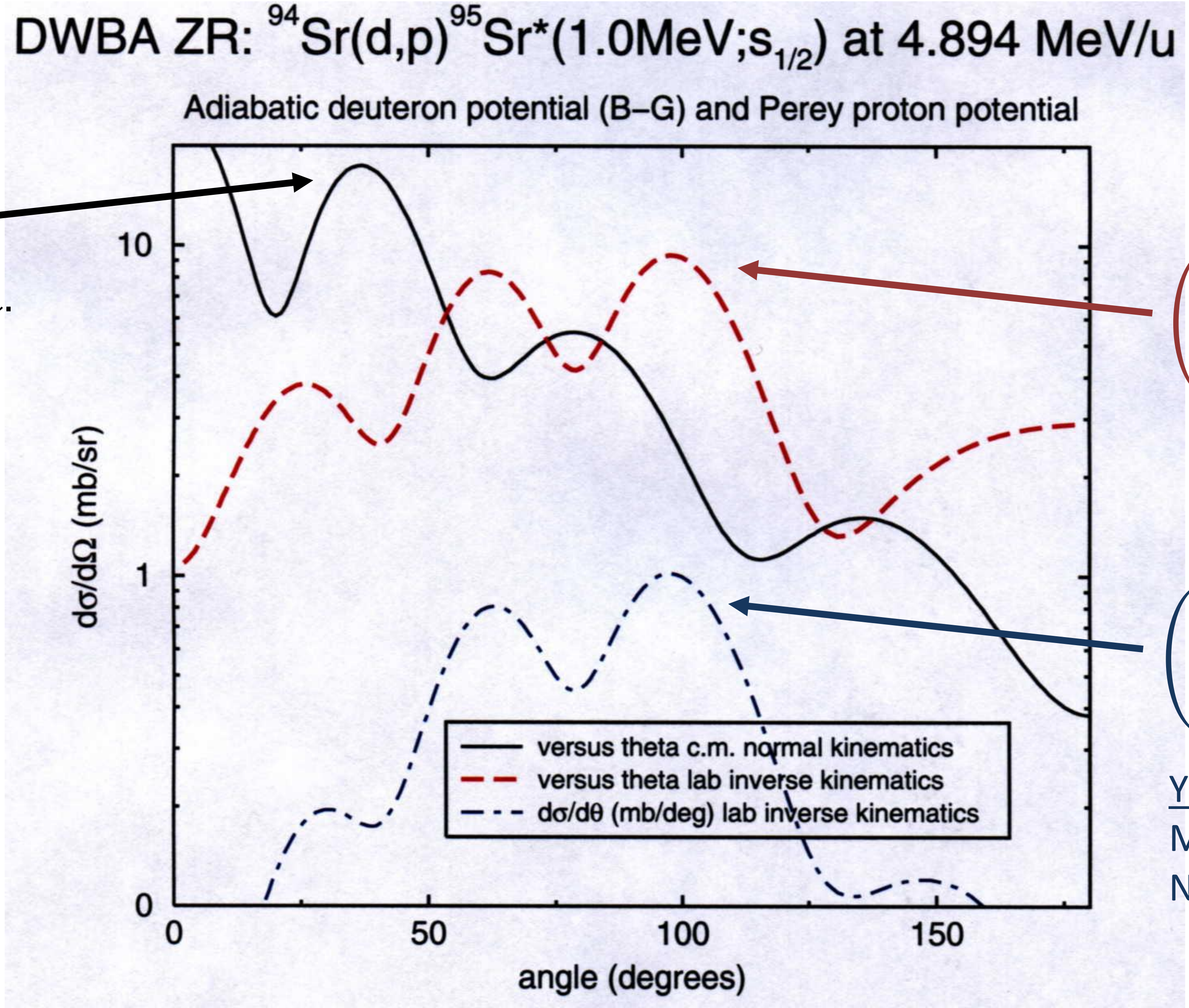
The **general form** of the kinematic diagrams is determined by the light particle masses, and has **little dependence** on the beam mass or beam velocity



THIS IS IMPORTANT BECAUSE

it means that we can design a fixed experimental setup that will work for all experiments with all beams

By the way: remember the difference between $\frac{d\sigma}{d\Omega}$ and $\frac{d\sigma}{d\theta}$!!



$$\left(\frac{d\sigma}{d\Omega}\right)_{c.m.}$$

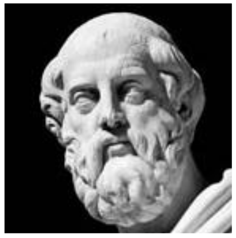
$$\left(\frac{d\sigma}{d\Omega}\right)_{lab}$$

$$\left(\frac{d\sigma}{d\theta}\right)_{lab}$$

YIELD IS AT MAXIMUM NEAR 90°

- We need to measure:
    - Energies
    - Angles
    - Particle identification
- We know the kinematics
- We know the angular distributions
- Nobody will give us more than 10 days

- Motivation: nuclear structure reasons for transfer
- What quantities we actually measure
- What reactions/energies can we choose to use?
- Inverse Kinematics
- Implications for Experimental approaches
- **Why do people make the choices that they do?**
- **Example experiments and results**



"People seldom do what they believe in. They do what is convenient, then repent."
— *Bob Dylan*

let's explore some options…

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Which is the best way to implement the "light particle" option?

It turns out that the target thickness is a real limitation on the energy resolution…

Several hundred keV is implicit, when tens would be required,
So the targets should be as thin as possible…

But RIBs, as well as being heavy compared to the deuteron target, are:
(a) Radioactive
(b) Weak

Issues arising:
(a) Gamma detection useful for improving resolution
(b) Active target (TPC) to minimize loss of resolution
(c) Need MAXIMUM efficiency for detection

Experimental solutions can be classed roughly as:
(a) For beams < 10^3 pps ACTIVE TARGET
(b) 10^3 < beam < 10^6 pps Si BOX in a γ-ARRAY
(c) For beams > 10^6 pps MANAGE RADIOACTIVITY

Solutions for beam intensities from 10^2 to 10^4 pps using TPCs*

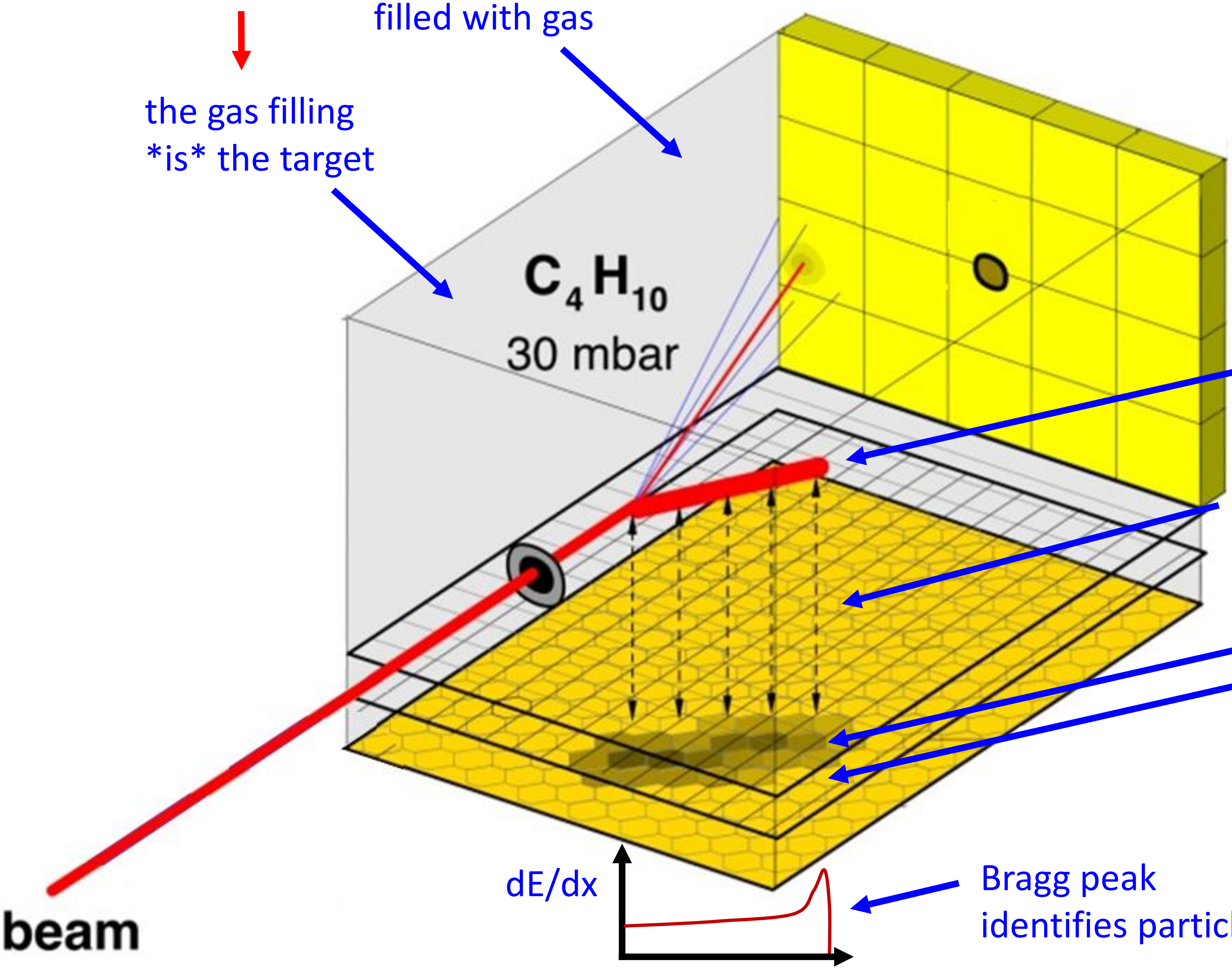
* TIME PROJECTION CHAMBERS

the TARGET is
the DETECTOR →

the vessel is
filled with gas

↓

the gas filling
is the target



MAYA

Pioneered at
GANIL/SPIRAL
TRIUMF

particles ionise
the gas & stop

electrons in gas
drift in electric
field: measure t_{drift}

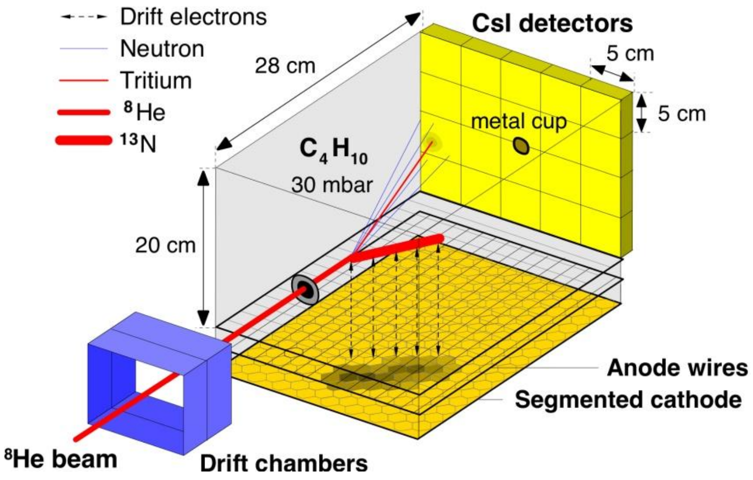
gas amplification

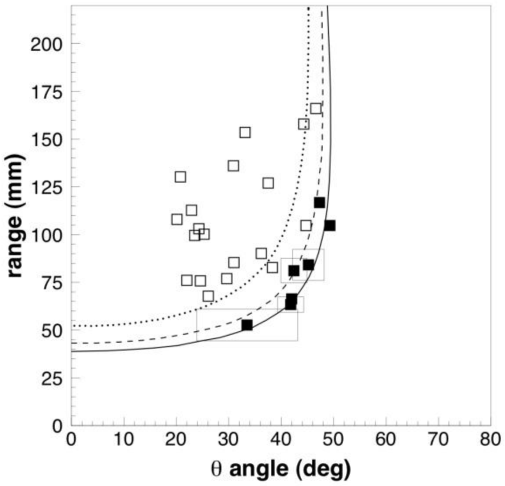
measure x & y
along the track

then, $t_{drift} \rightarrow z$

Bragg peak
identifies particle

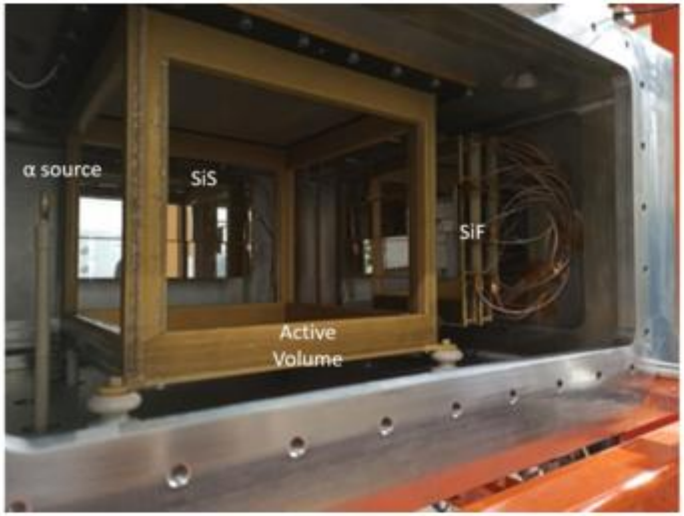
Solutions for beam intensities from 10^2 to 10^4 pps using TPCs*

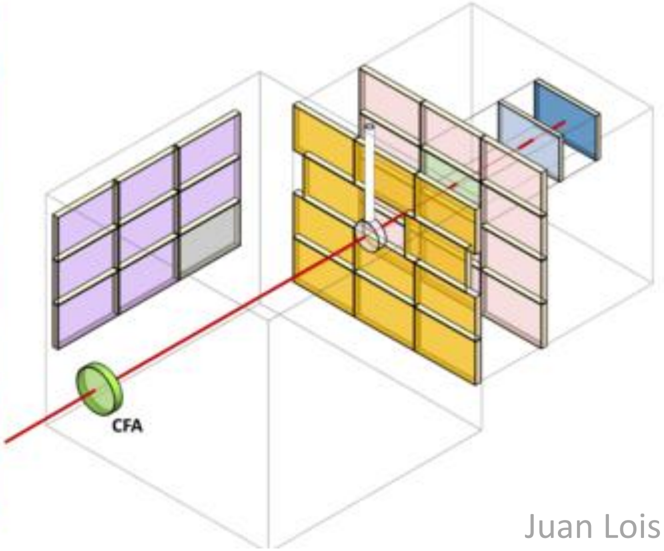




MAYA

Pioneered at
GANIL/SPIRAL
TRIUMF





ACTAR

Currently in
operation at
GANIL/SPIRAL
TRIUMF

Juan Lois Fuentes, PhD Thesis (2023)

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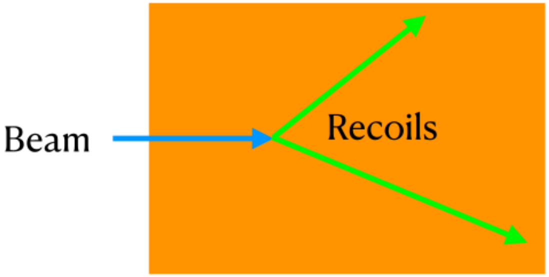
* TIME PROJECTION CHAMBERS

AT-TPC @ SOLARIS

D. Bazin, DREB 2024, June 24-28, 2024, Wiesbaden, Germany

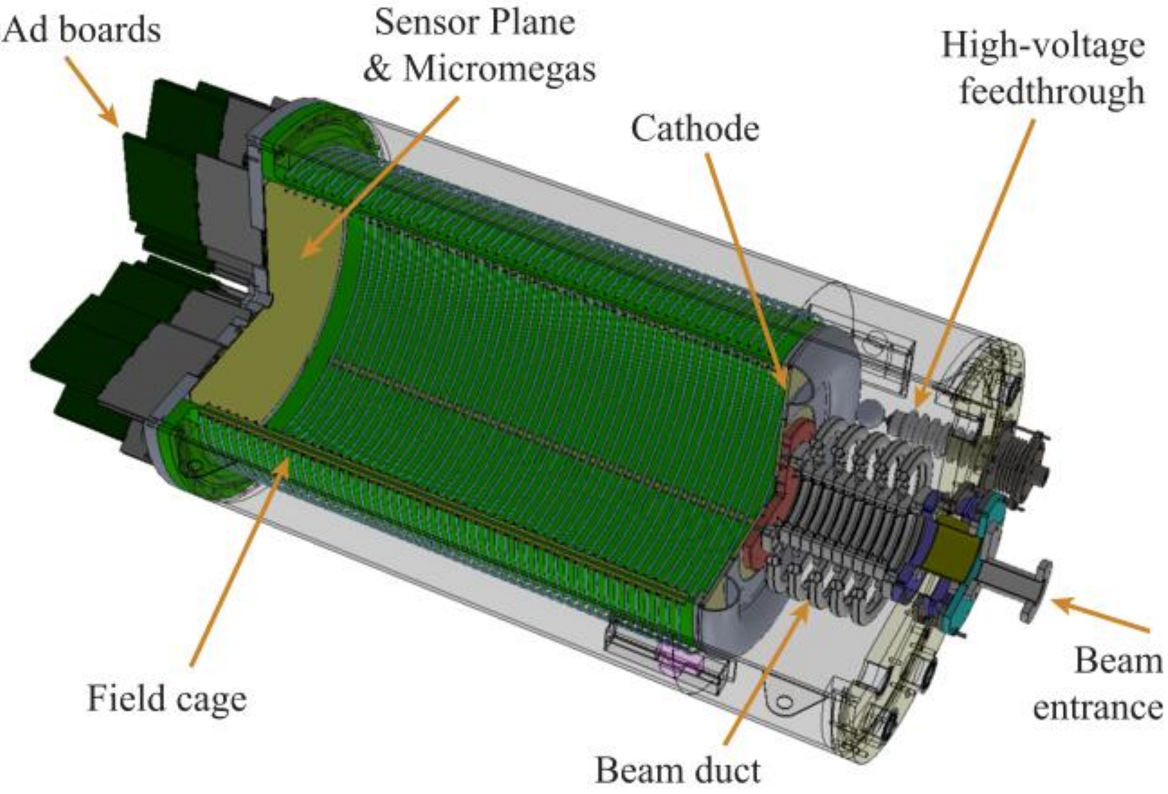


Target = Detector

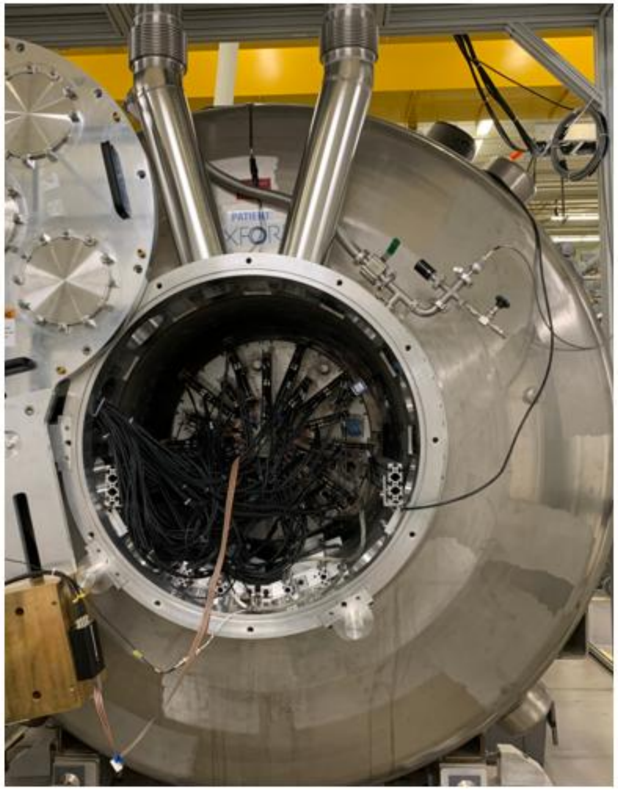
FRIB

FRIB + ReA6

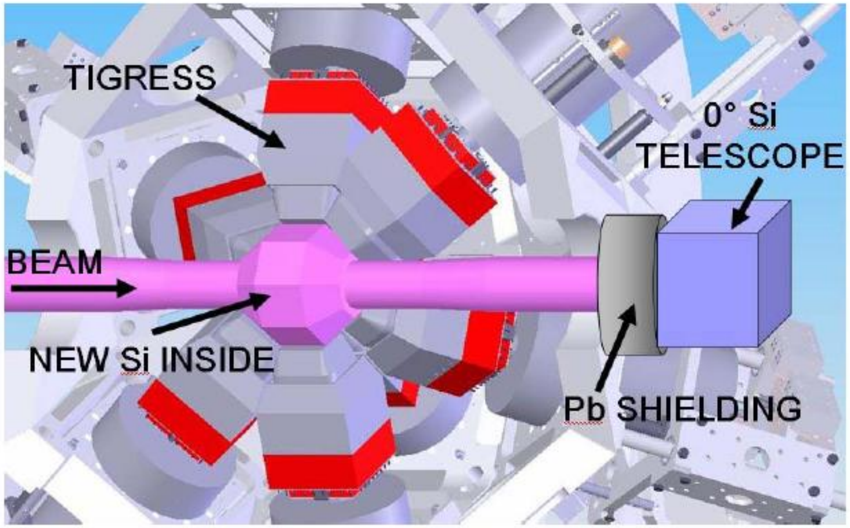
Active Target Time Projection Chamber

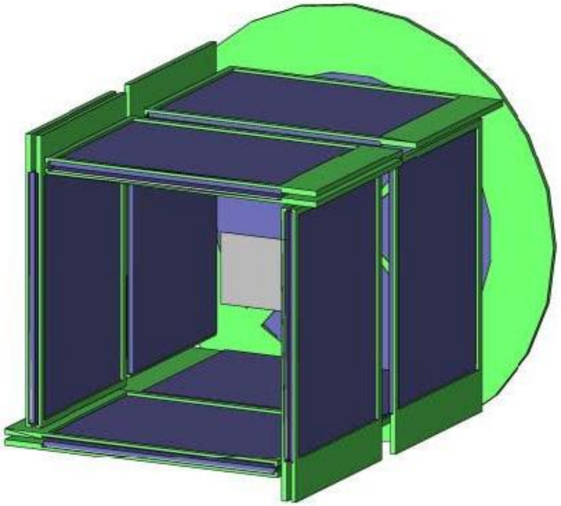


SOLARIS @ FRIB



Solutions for more-intense beams of 10^4 to 10^6 pps, using gammas

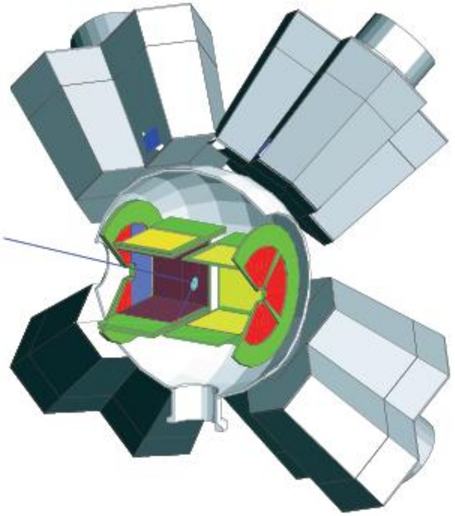


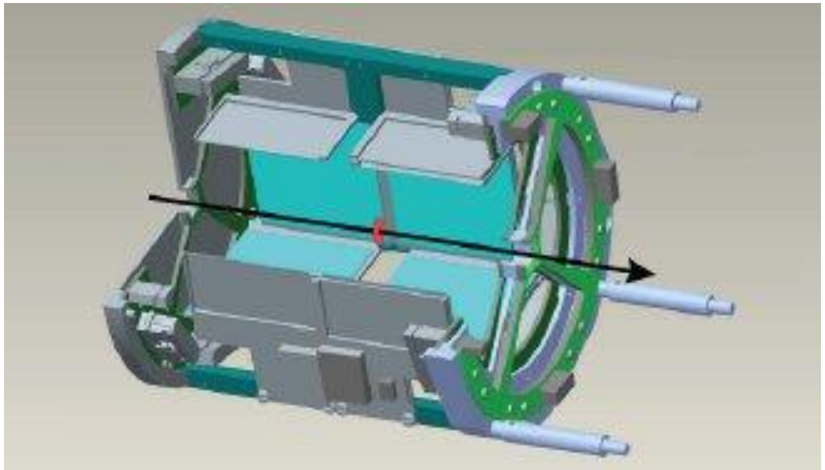


SHARC

TIGRESS
TRIUMF

TIGRESS COLLABORATION
York
Surrey





T-REX

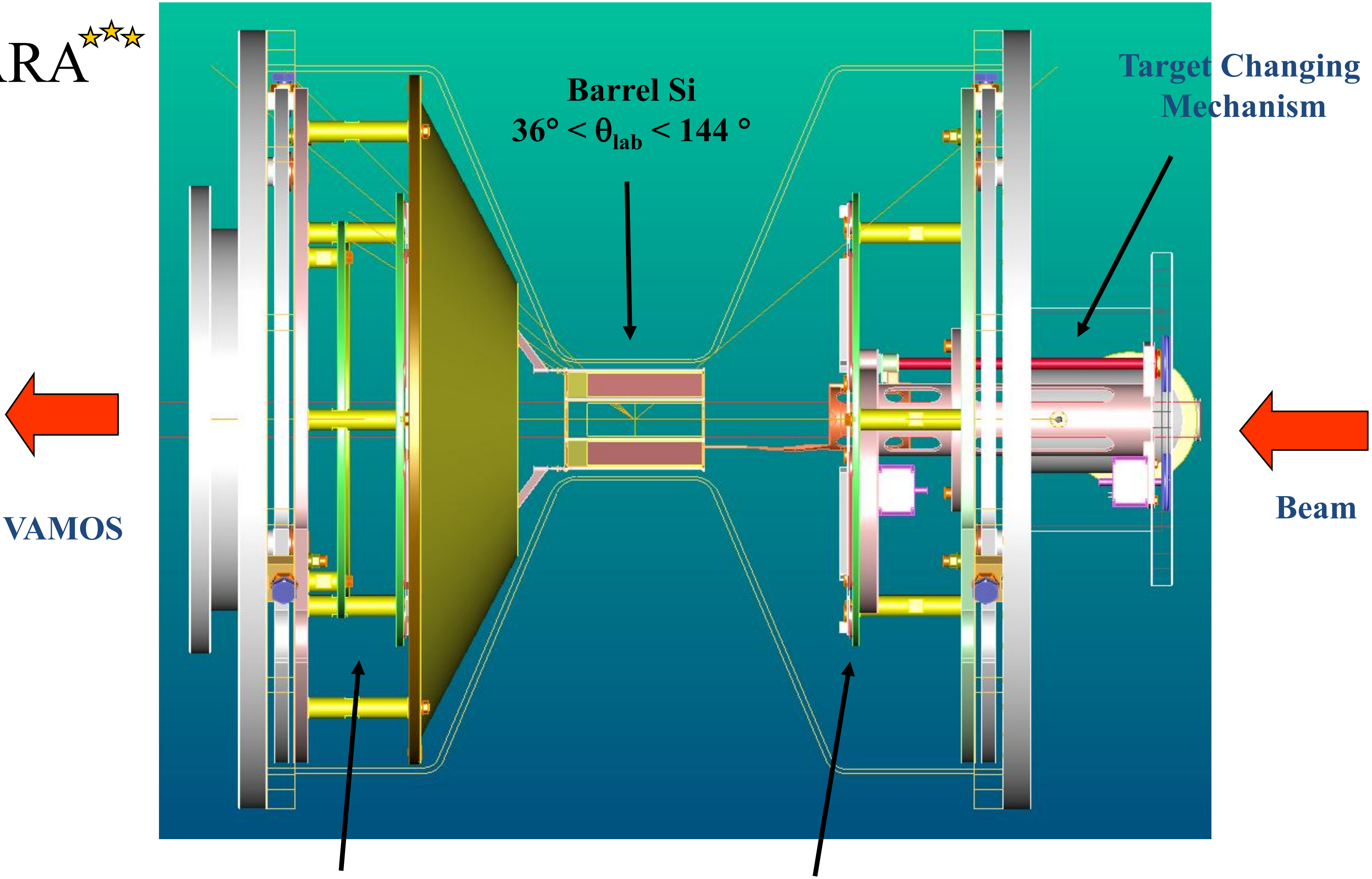
MINIBALL
REX-ISOLDE

MINIBALL COLLABORATION
Munich
Leuven

ORRUBA & GODDESS OAK RIDGE

Solutions for very intense beams of up to 10^9 pps, using gammas

TIARA



Barrel Si

36° < θ_{lab} < 144 °

Target Changing Mechanism

VAMOS

Beam

Forward Annular Si

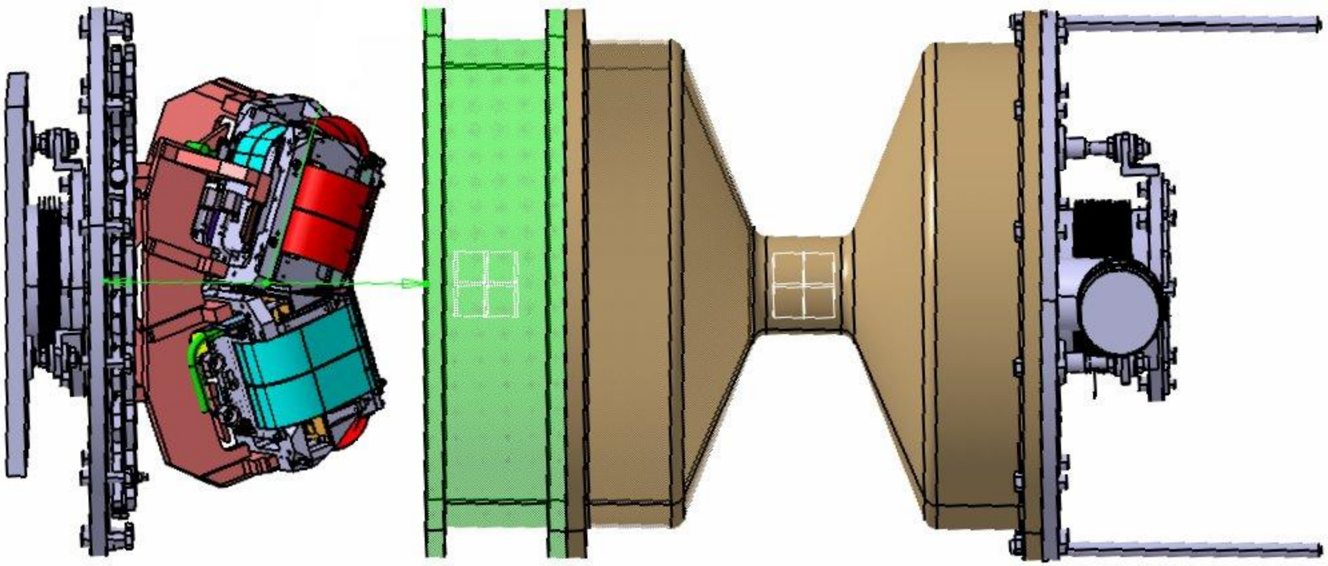
5.6° < θ_{lab} < 36 °

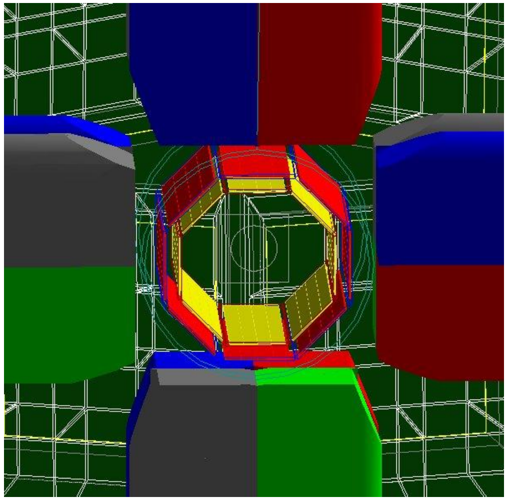
Backward Annular Si

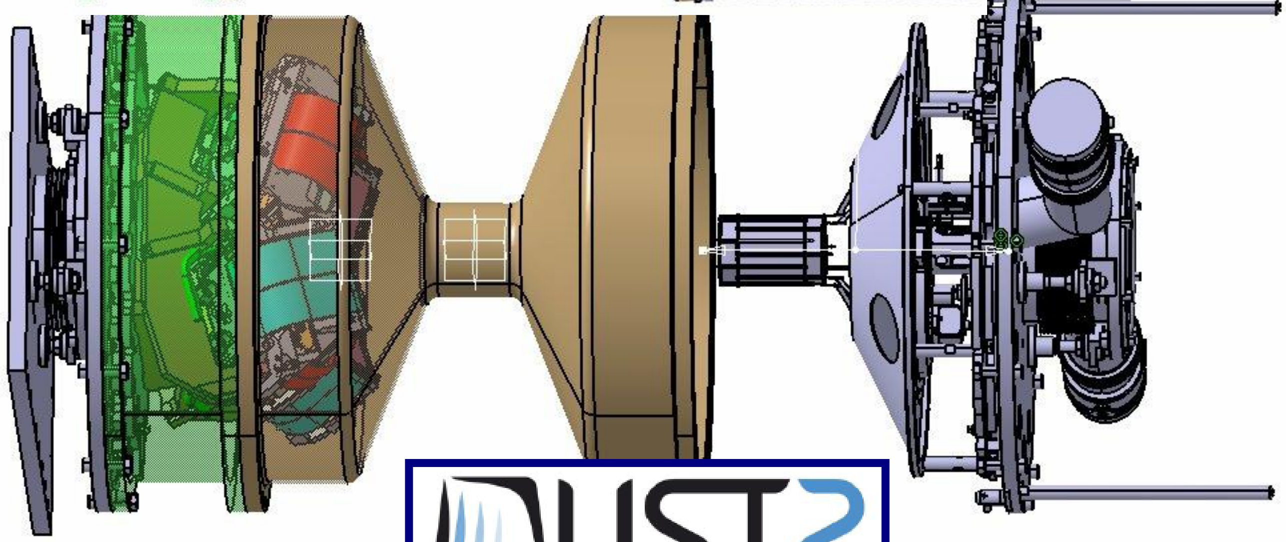
144° < θ_{lab} < 168.5 °

UNIVERSITY OF SURREY

Solutions for very intense beams of up to 10^9 pps, using gammas





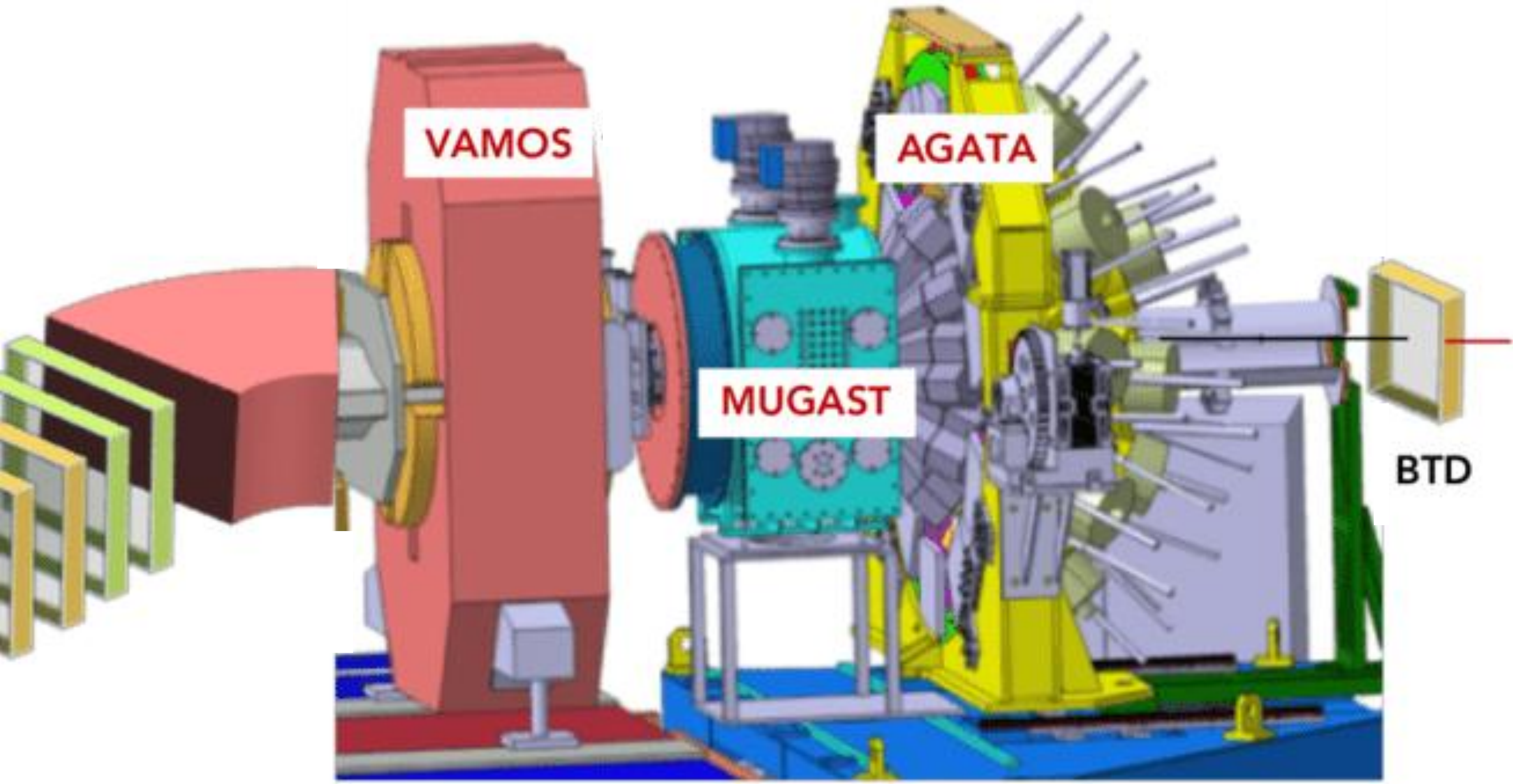


MUST2

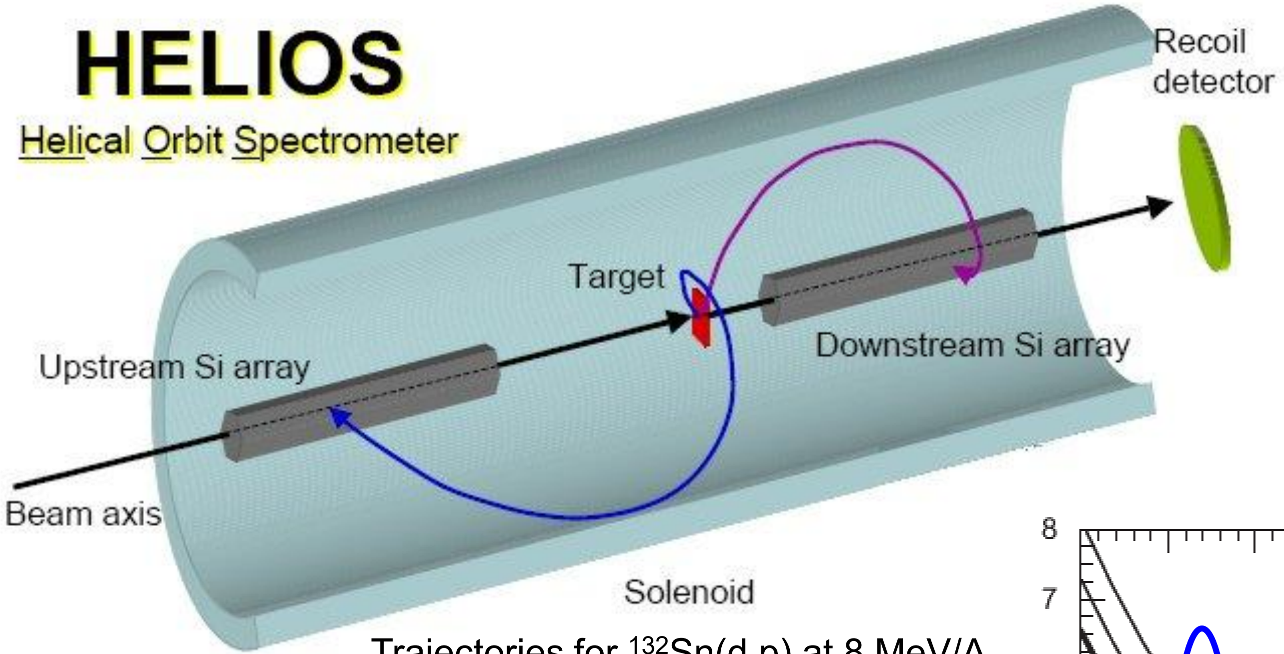
TIARA

2019-2021

Beam: ^{47}K at 7.7 MeV/u (SPIRAL1)
Intensity: 5×10^5 pps
Purity: ~ 100%

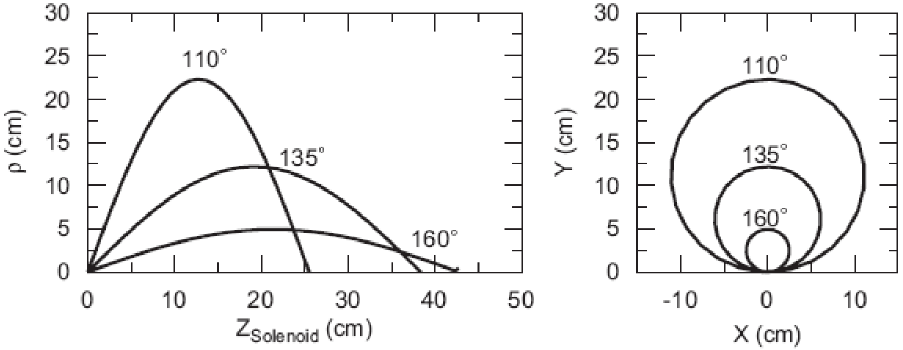


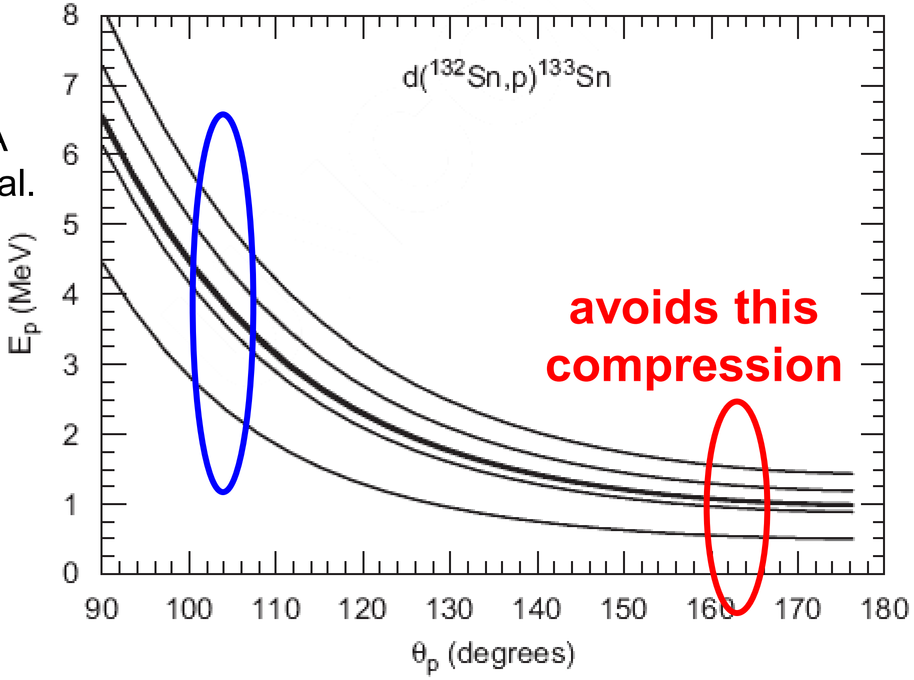
Solenoidal detector for 4π detection & to *de-compress* the kinematics



Actual solenoid – from MRI

Trajectories for ^{132}Sn(d,p) at 8 MeV/A
HELIOS: Kay, Wuosmaa, Schiffer et al.





avoids this compression

Superconducting solenoid = second-hand MRI magnet (2.5 - 4.0 T)

"J'ai passé une IRM"

Superconducting solenoid = second-hand MRI magnet

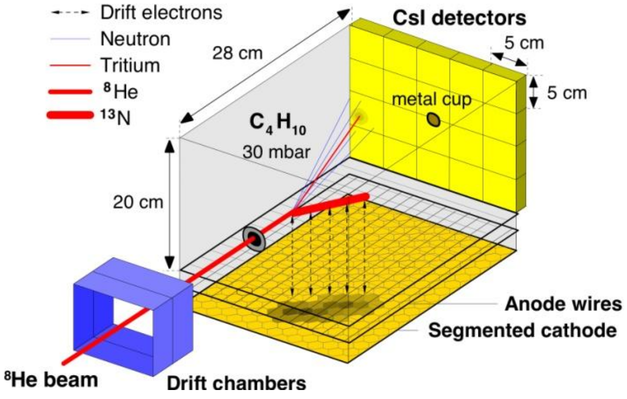
"J'ai passé une IRM"

“C’est vrai“

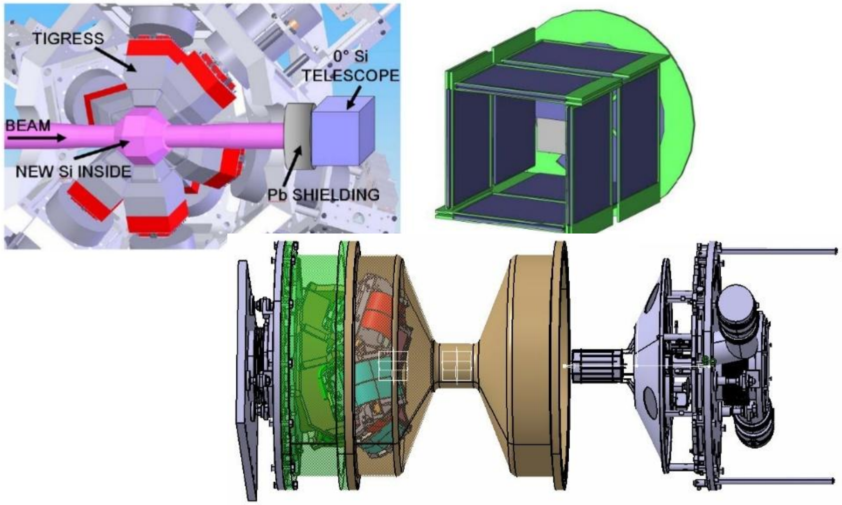
(not as bad as I thought)

The experimental choice is strongly driven by the beam intensity:

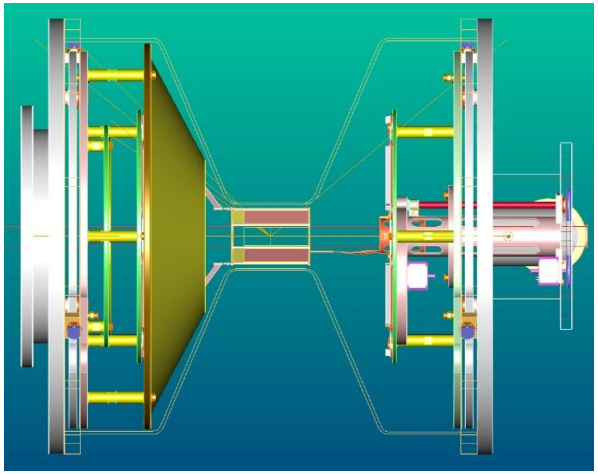
Below 10^4 pps MAYA, ACTAR…



Below 10^6 pps SHARC, MUGAST…

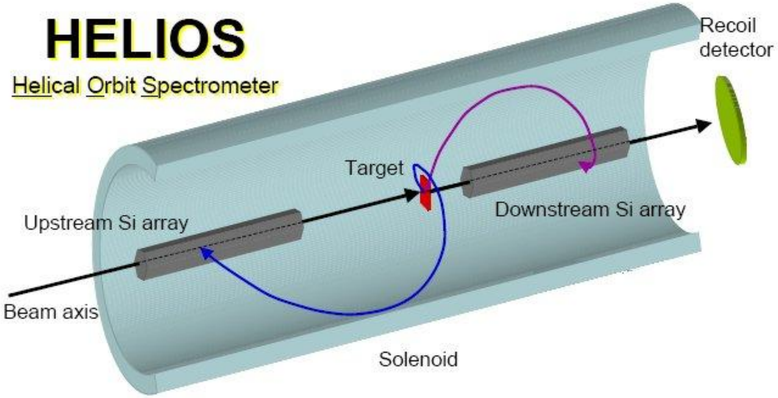


Up to 10^9 pps TIARA or MUGAST, or…



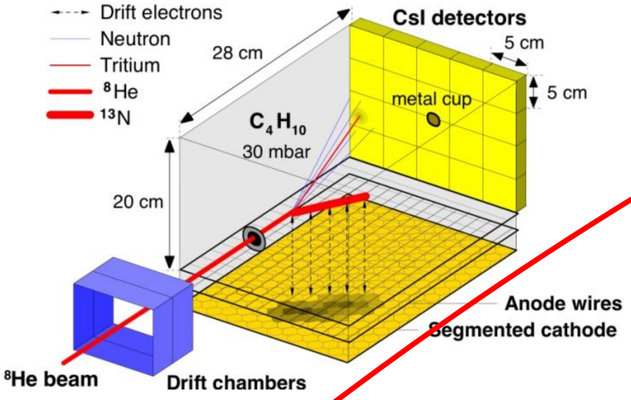
TIARA

A solenoid device (no gammas)…

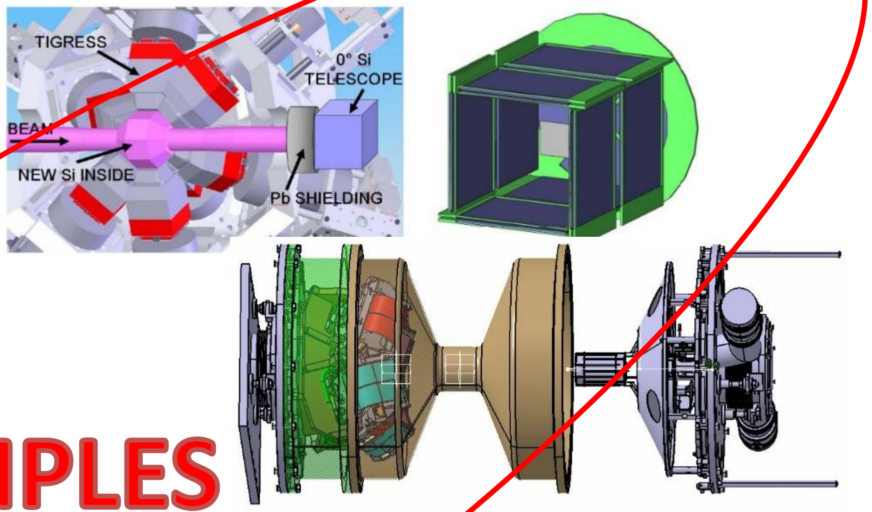


The experimental choice is strongly driven by the beam intensity:

Below 10^4 pps MAYA, ACTAR…

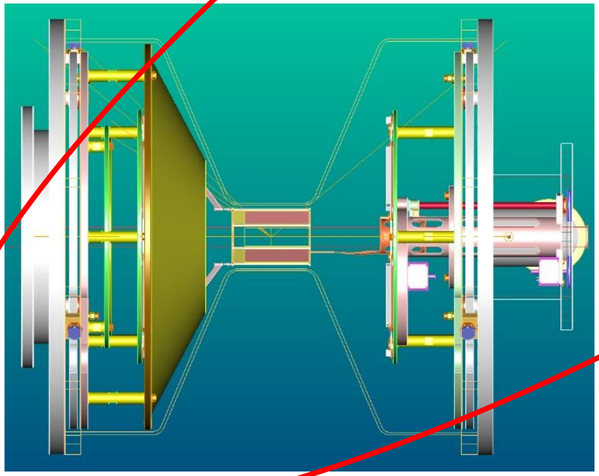


Below 10^6 pps SHARC, MUGAST…



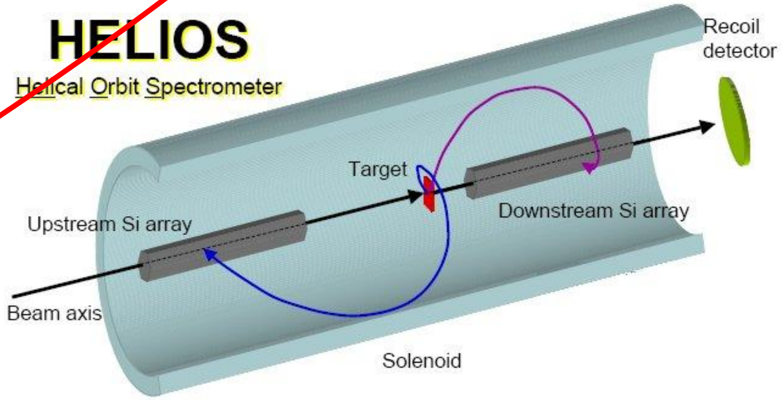
THREE EXAMPLES

Up to 10^9 pps TIARA or MUGAST, or…

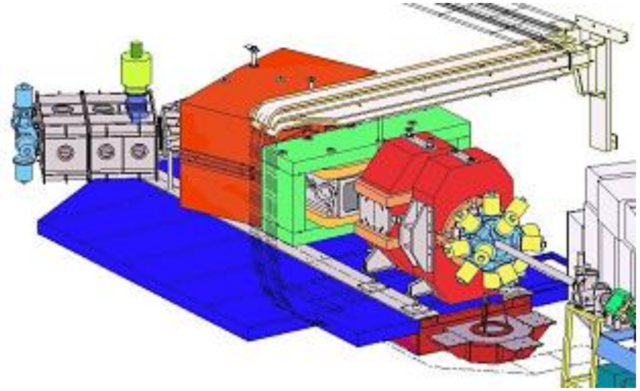


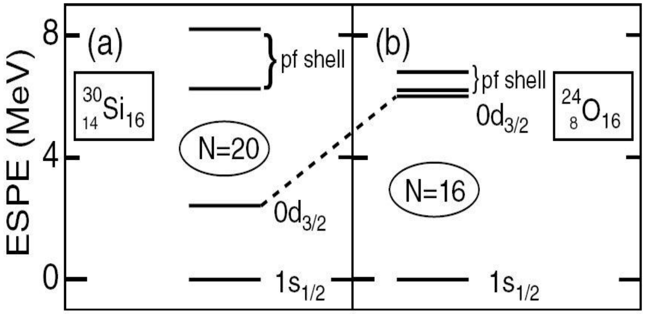
TIARA

A solenoid device (no gammas)…

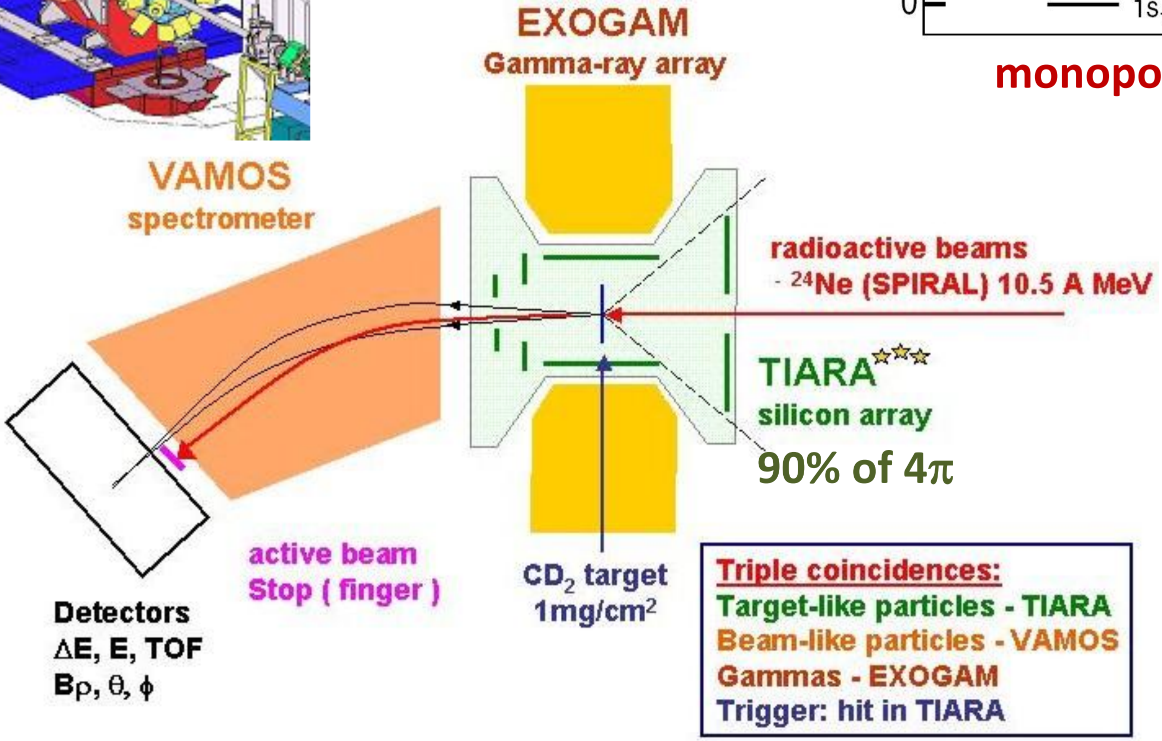


^{24}Ne(d,pγ) ^{25}Ne – we discovered that N=16 replaces the broken N=20





monopole migration



10^5 pps (pure)

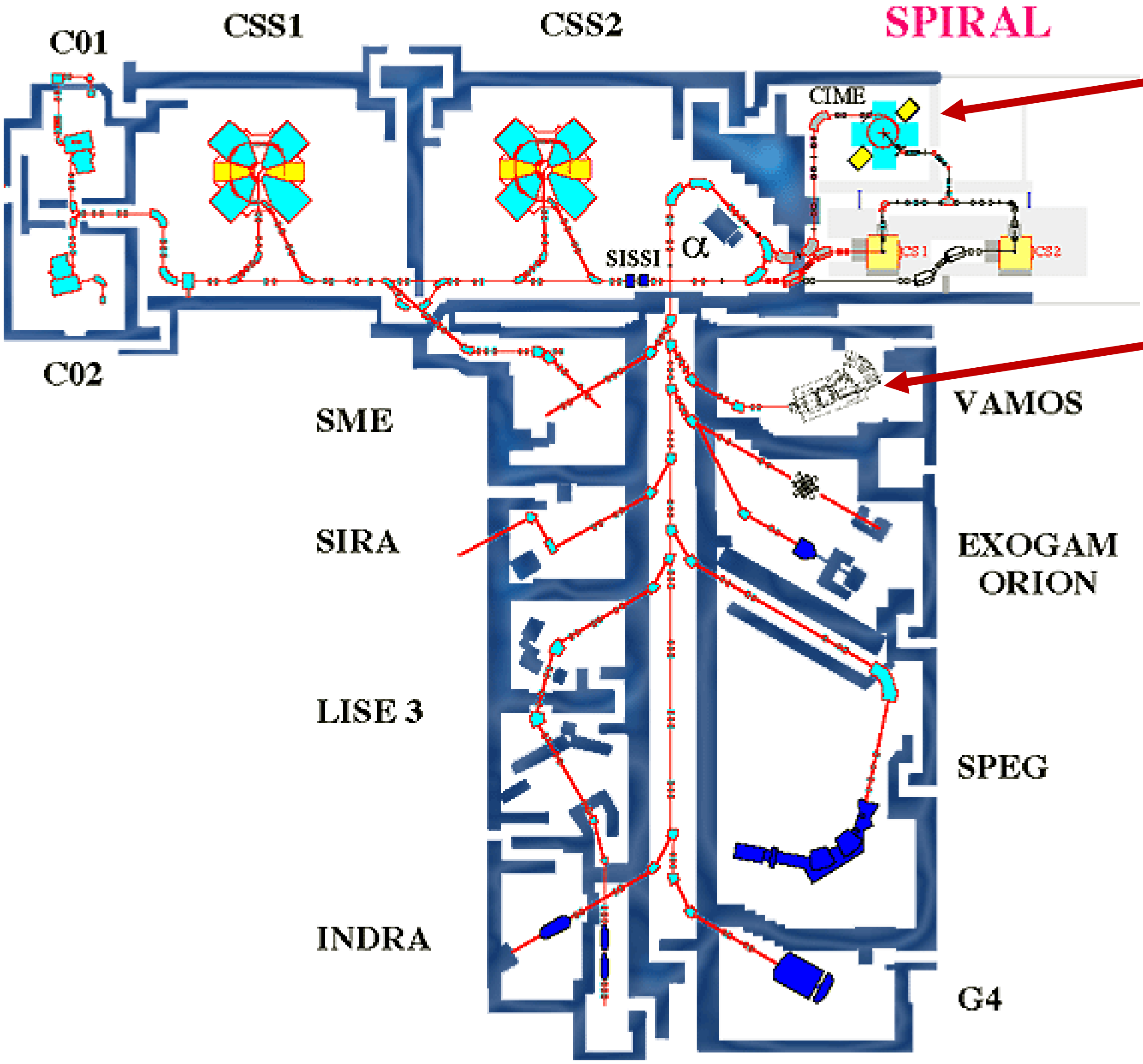
90% of 4π

Triple coincidences:
Target-like particles - TIARA
Beam-like particles - VAMOS
Gammas - EXOGAM
Trigger: hit in TIARA

TIARA

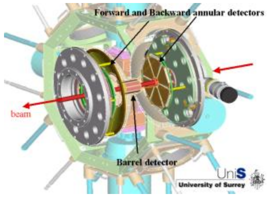
W.N. Catford *et al.*, Eur. Phys. J. **A25**, Suppl. 1, 245 (2005)
W.N. Catford *et al.*, Phys. Rev. Lett. **104**, 192501 (2010)

GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS



^{24}Ne ISOL
τ = 3.38 min
100,000 pps
SPIRAL 1

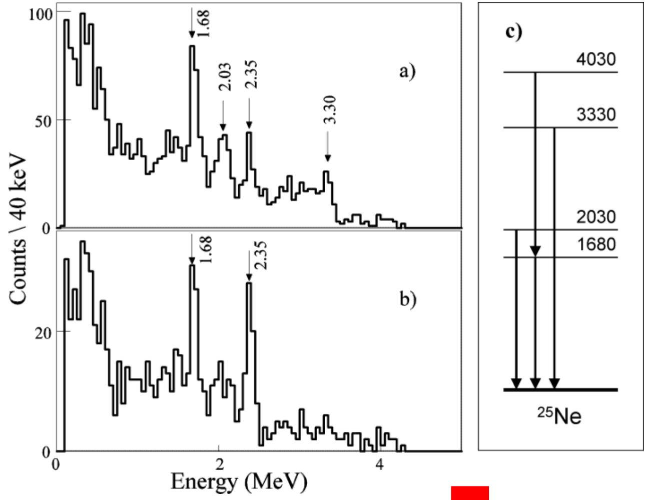
TIARA ☆☆☆



^{24}Ne + d
→ ^{25}Ne* + p

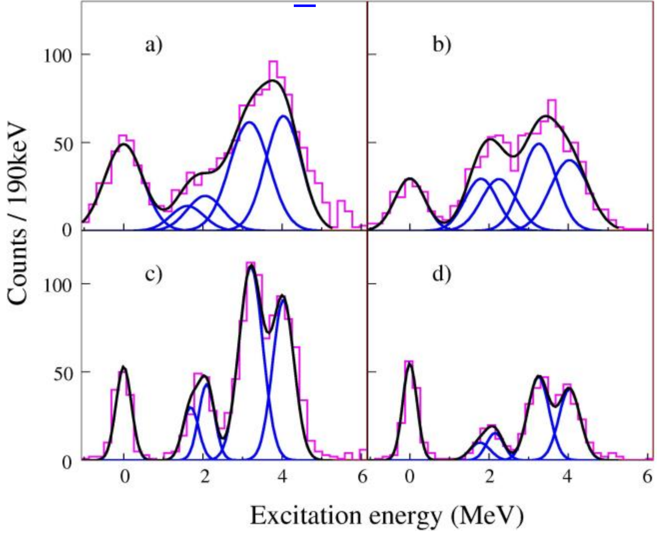
^{24}Ne(d,pγ) ^{25}Ne – ANALYSIS

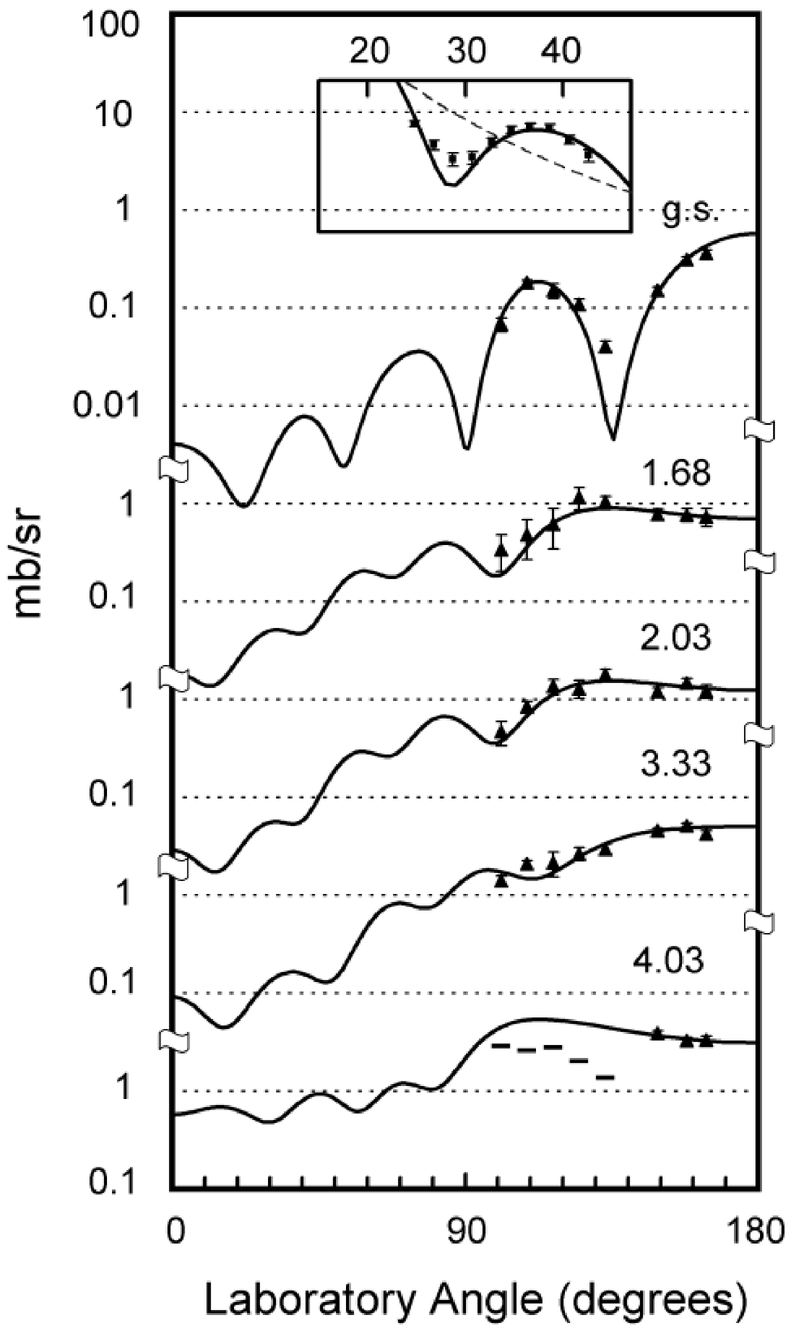
GAMMA RAY ENERGY SPECTRA



FIX E_x

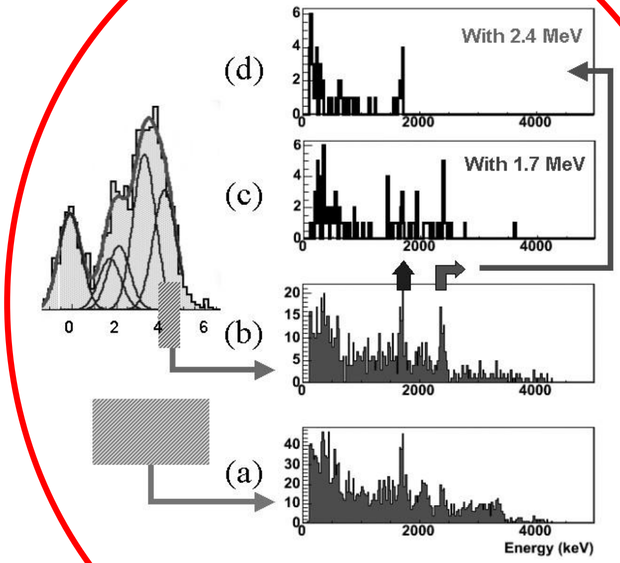
EXCITATION E_x FROM PROTONS

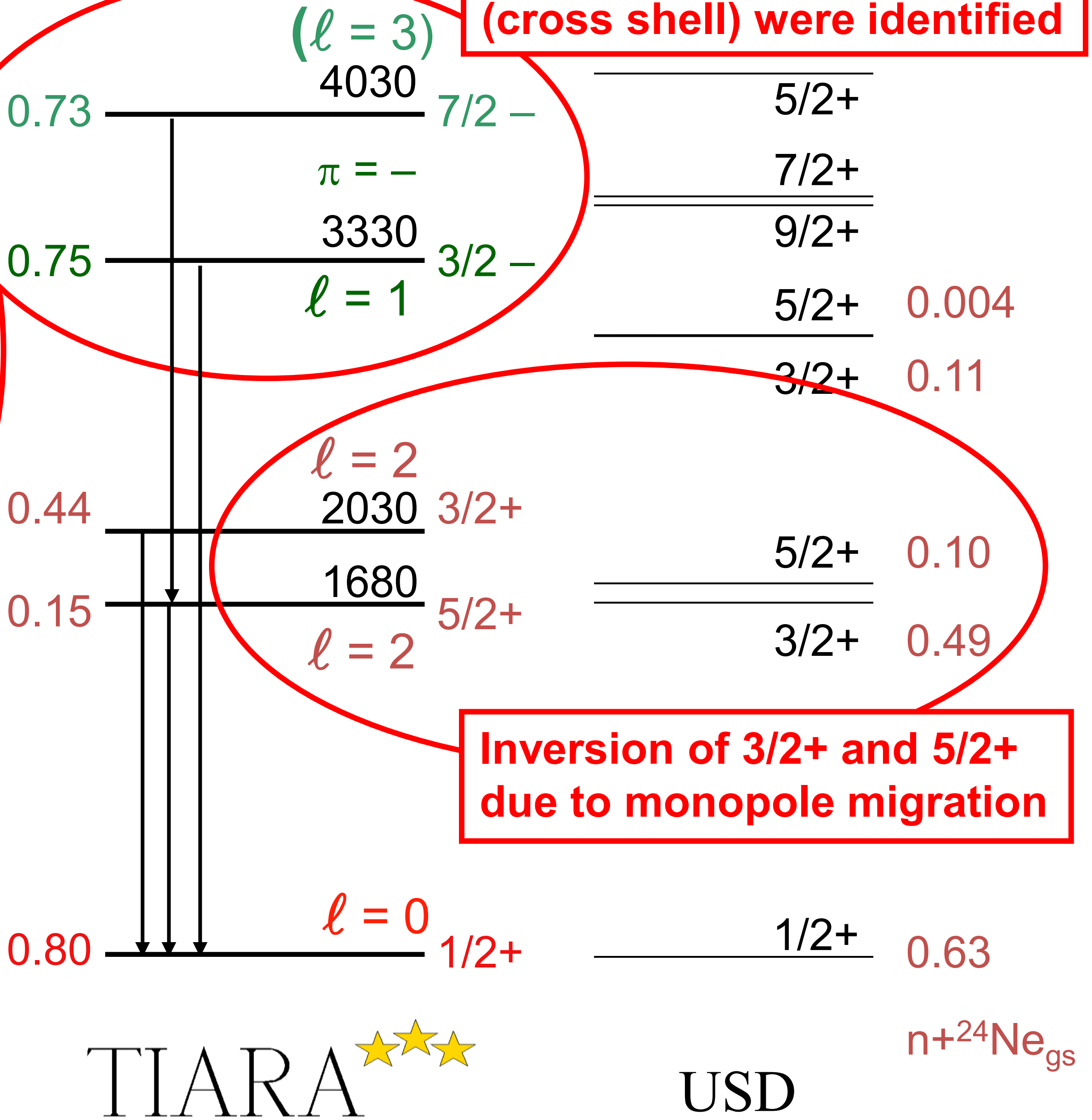




^{24}Ne(d,pγ) ^{25}Ne – ANALYSIS

Negative parity states (cross shell) were identified





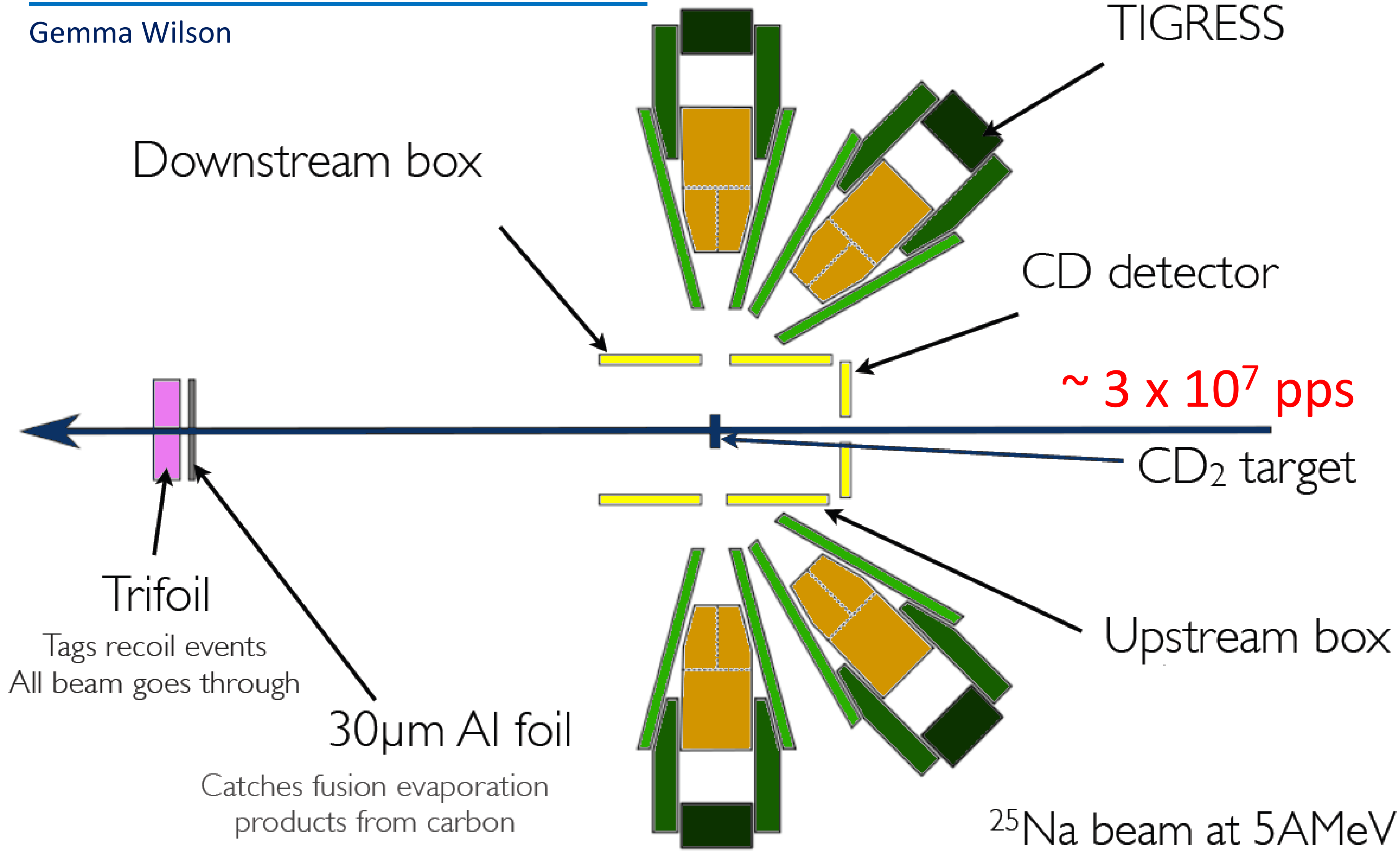
Inversion of 3/2+ and 5/2+ due to monopole migration

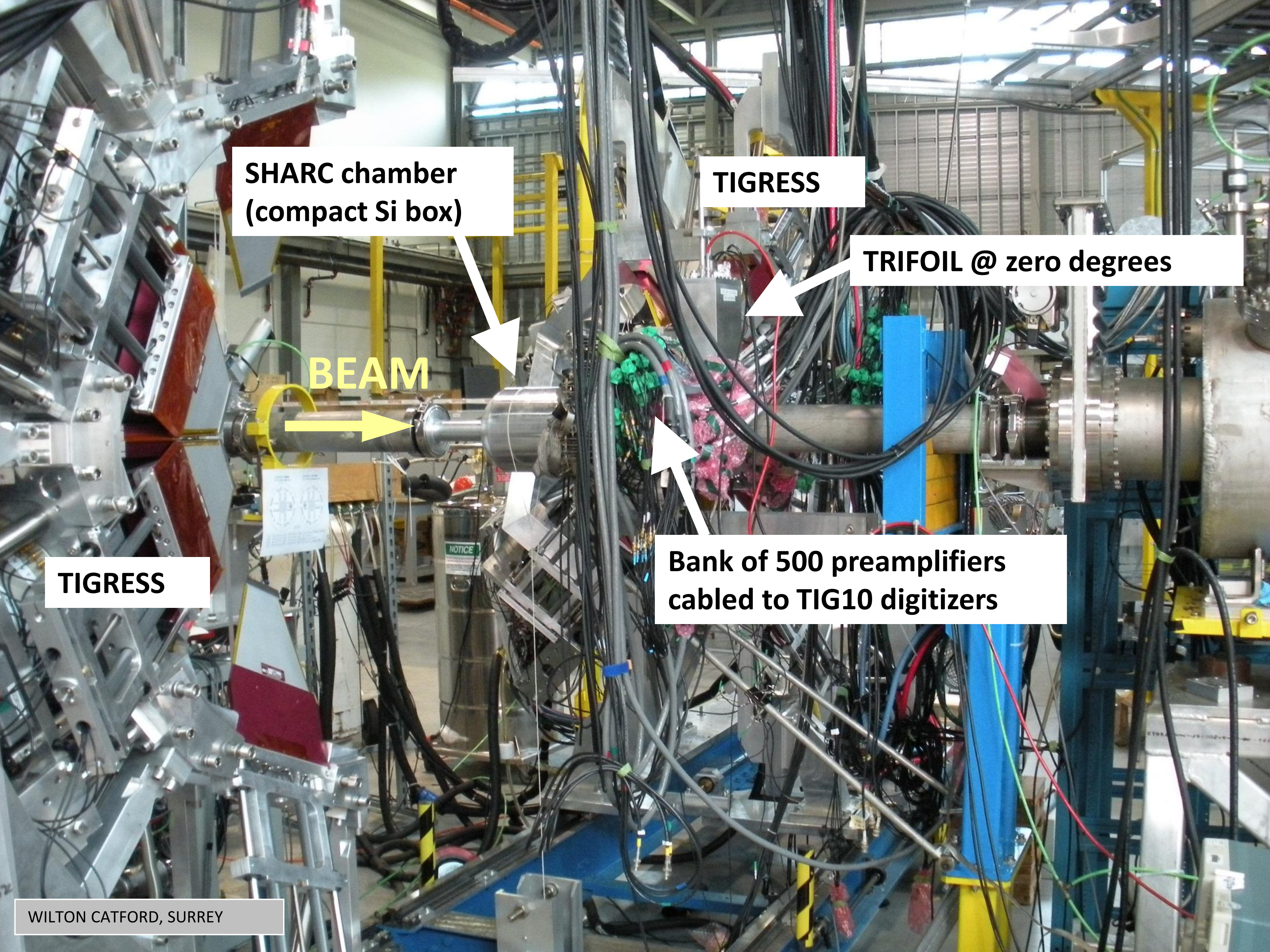
In ^{25}Ne we used gamma-gamma coincidences to **distinguish spins** and go beyond orbital AM
FIRST QUADRUPLE COINCIDENCE (p-HI-γ-γ) RIB TRANSFER DATA

^{25}Na(d,pγ) ^{26}Na – we saw how one extra $d_{5/2}$ proton interacts near N=16

SHARC at ISAC2 at TRIUMF

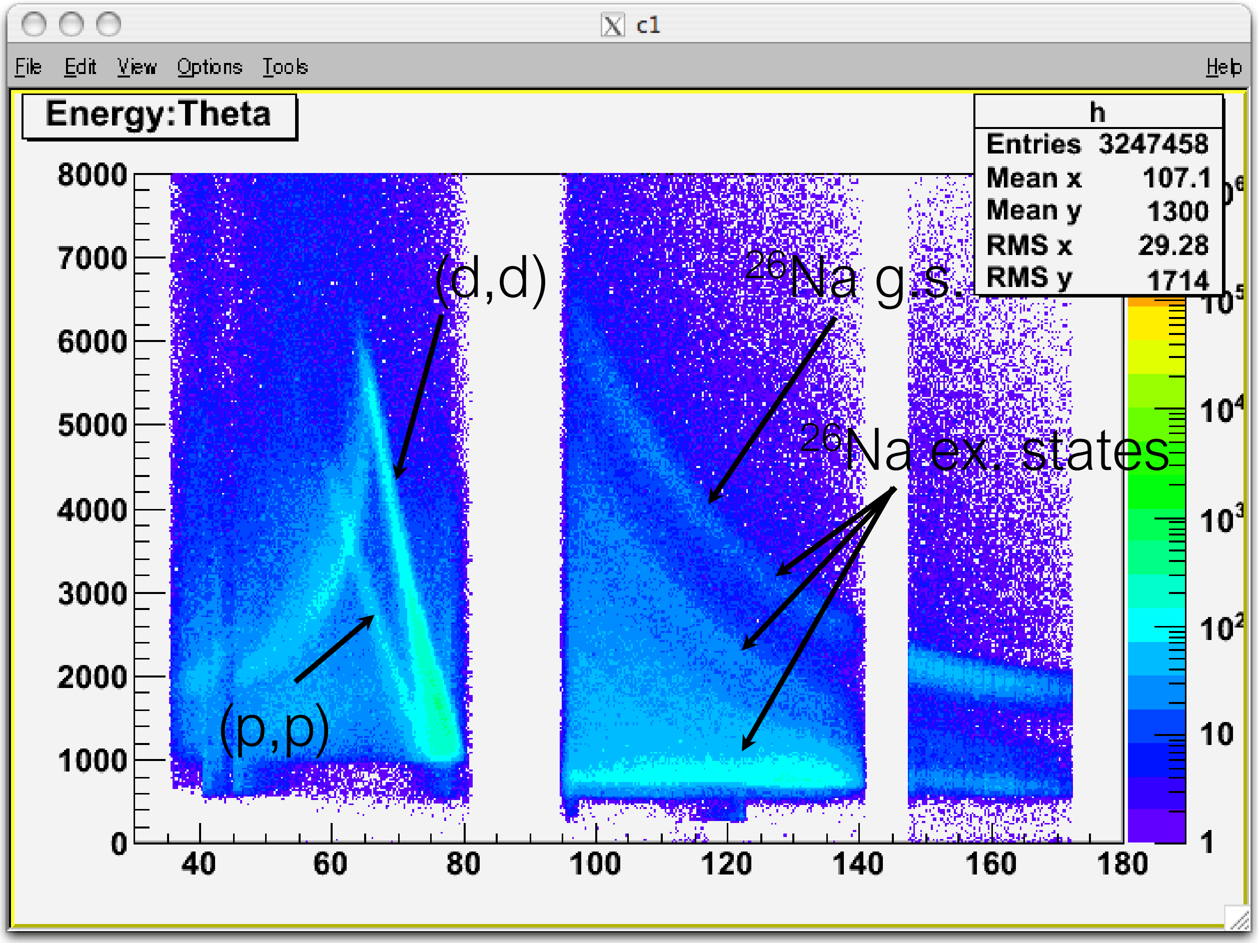
Gemma Wilson





SHARC chamber (compact Si box)
TIGRESS
TRIFOIL @ zero degrees
BEAM
Bank of 500 preamplifiers cabled to TIG10 digitizers
TIGRESS
WILTON CATFORD, SURREY

Kinematical Analysis: E vs θ

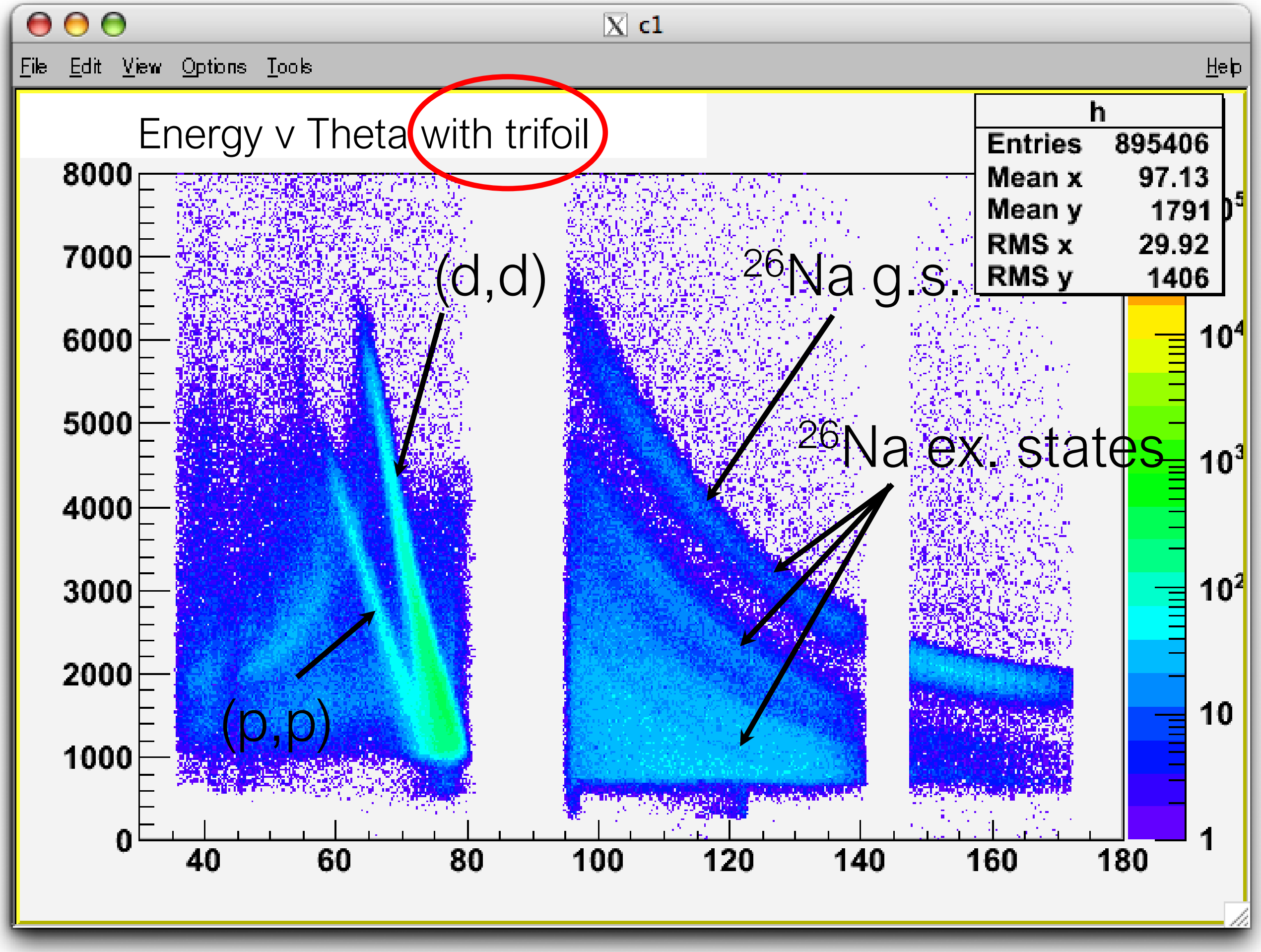


h	
Entries	3247458
Mean x	107.1
Mean y	1300
RMS x	29.28
RMS y	1714

G.L. Wilson, W.N. Catford *et al.*, Phys. Lett. B759, 417 (2016)

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

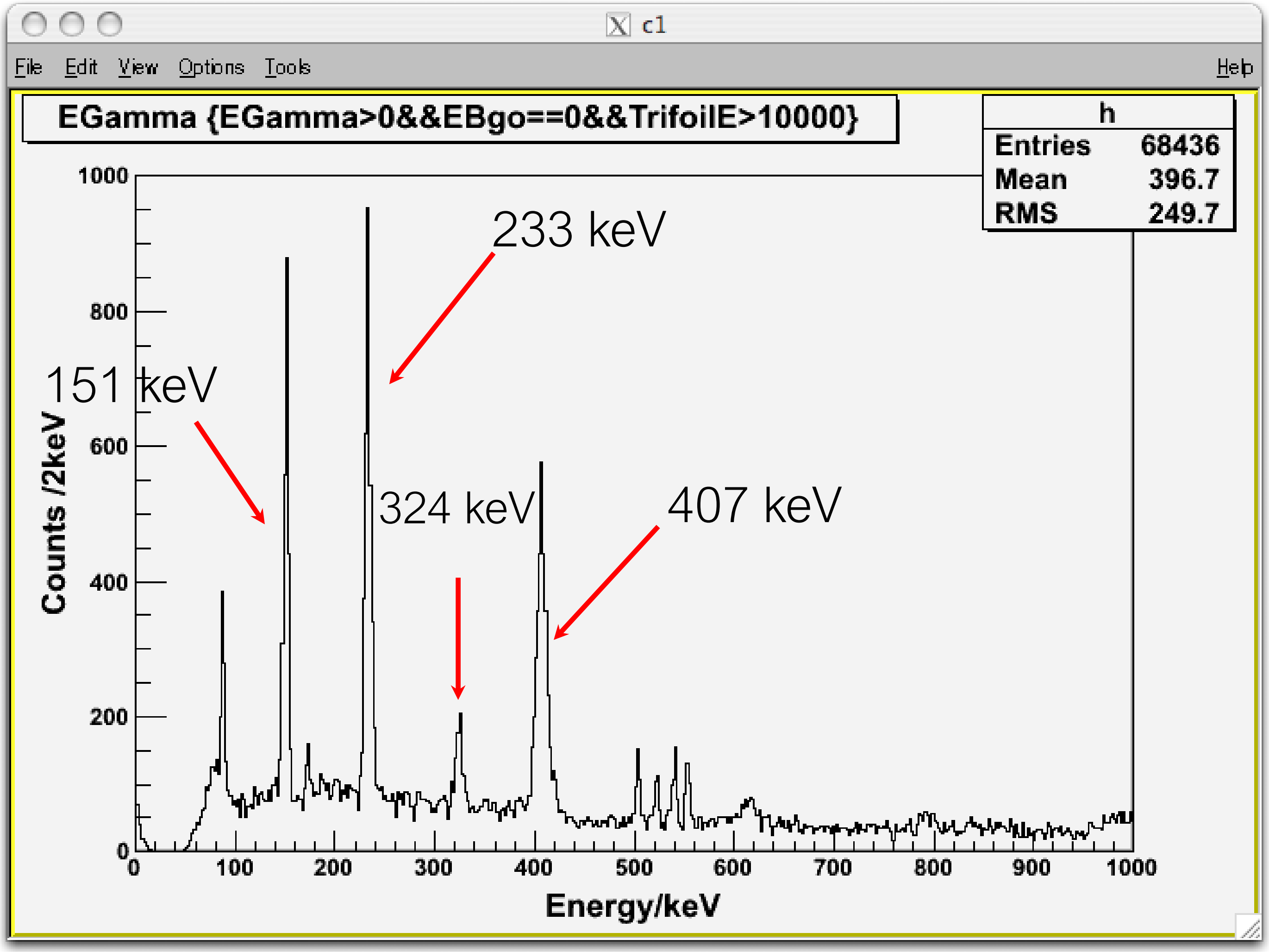
Kinematical Analysis: E vs θ



G.L. Wilson, W.N. Catford *et al.*, Phys. Lett. B759, 417 (2016)

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

Gamma-ray Analysis: precise energies



EGamma {EGamma>0&&EBgo==0&&TrifoilE>10000}

h	
Entries	68436
Mean	396.7
RMS	249.7

233 keV

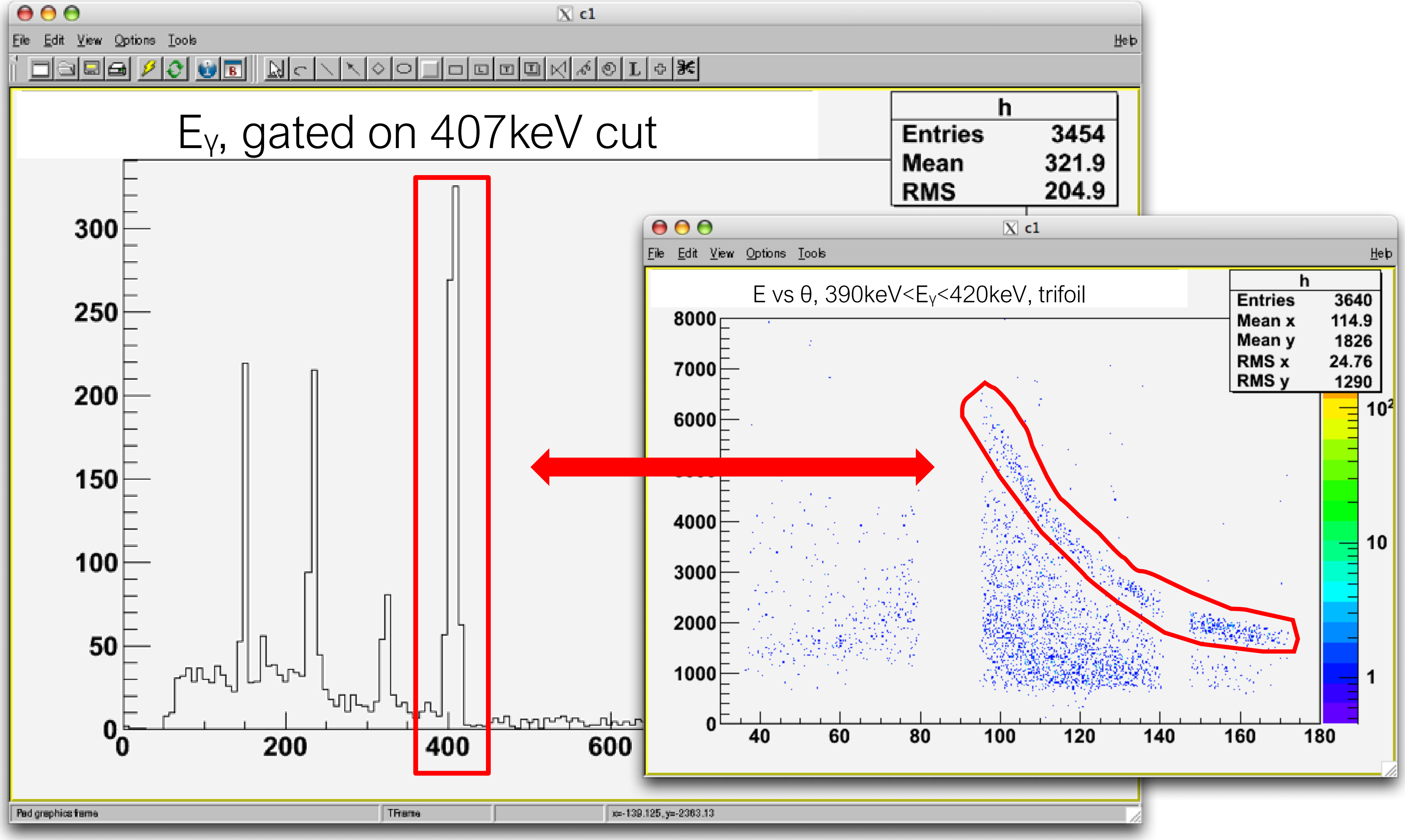
151 keV

324 keV

407 keV

^{25}Na(d,pγ) ^{26}Na

Combining the particle and γ-ray Analyses



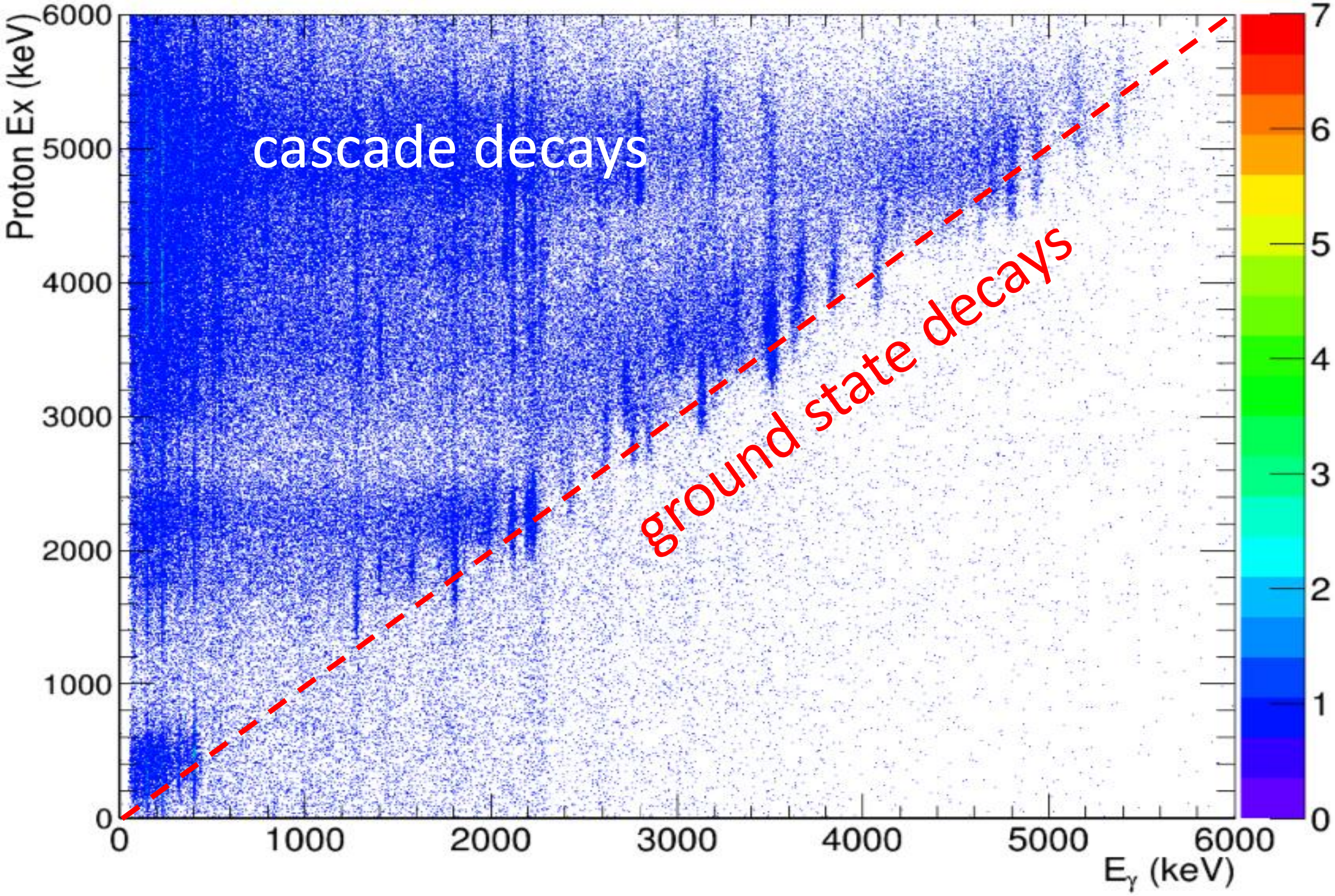
h	
Entries	3454
Mean	321.9
RMS	204.9

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

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

Gemma Wilson, Surrey

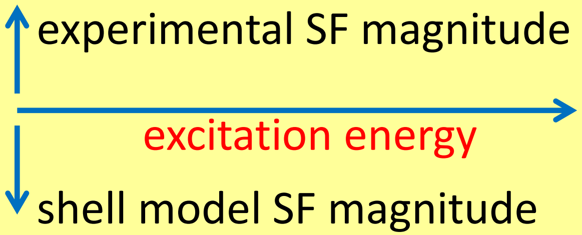
Excitation energy deduced from proton energy and angle



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

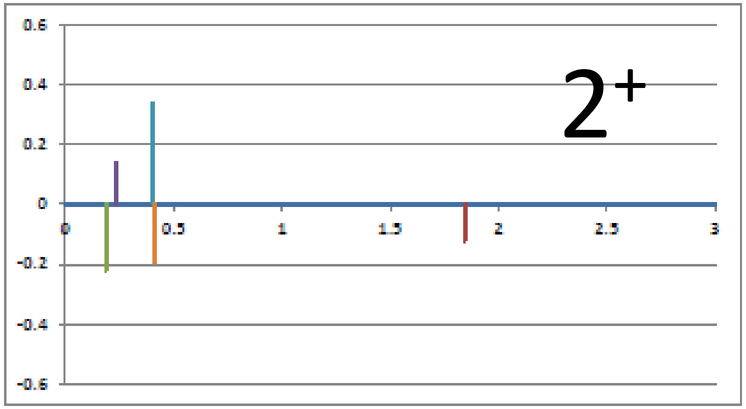
Shell Model Predictions (and new candidates) for ^{26}Na states expected in (d,p)…

Comparison of spectroscopic strength in theory and experiment

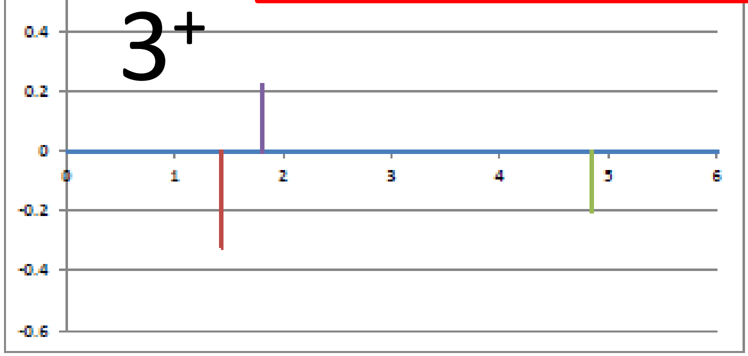

experimental SF magnitude

excitation energy

shell model SF magnitude

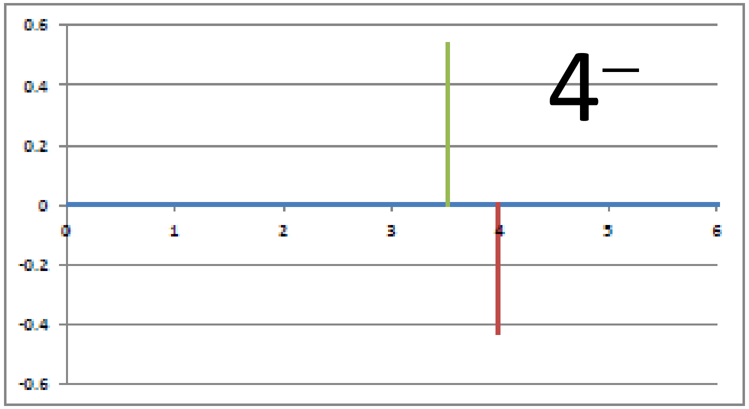


Above: s1/2 strength for 2+ states

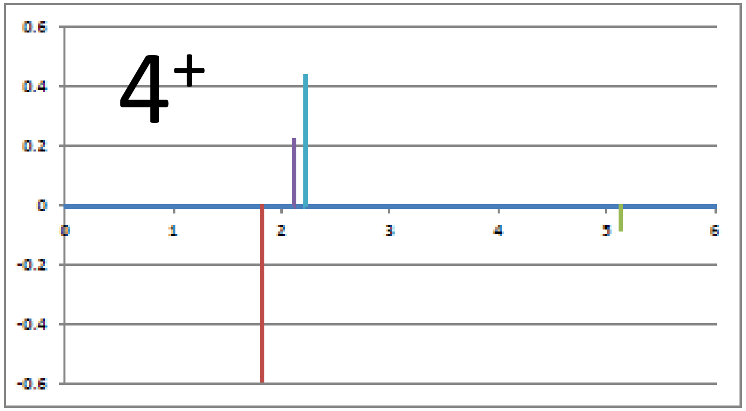


Above: d3/2 to 3+ states

Below: p3/2 to 4- states



Below: d3/2 to 4+ states



G.L. Wilson, W.N. Catford *et al.*, Phys. Lett. B759, 417 (2016)

Study of d(^{47}K,p)^{48}K at 7.7 MeV/A using MUGAST/AGATA/SPIRAL1

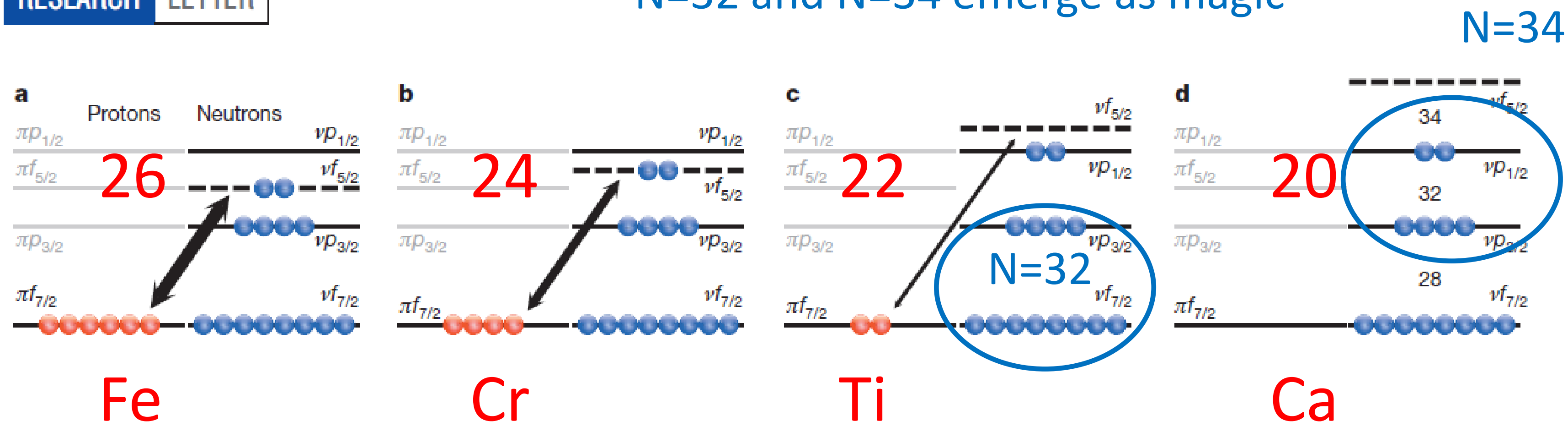
We measured how proton filling affects neutron energies; example –

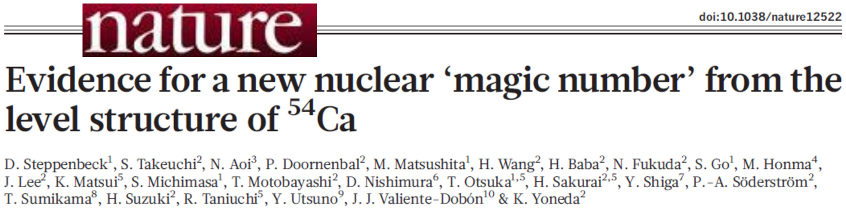
Removing $\pi(f_{7/2})$

$\nu(f_{5/2})$ rises above $\nu(p_{1/2})$

N=32 and N=34 emerge as magic

RESEARCH LETTER




nature

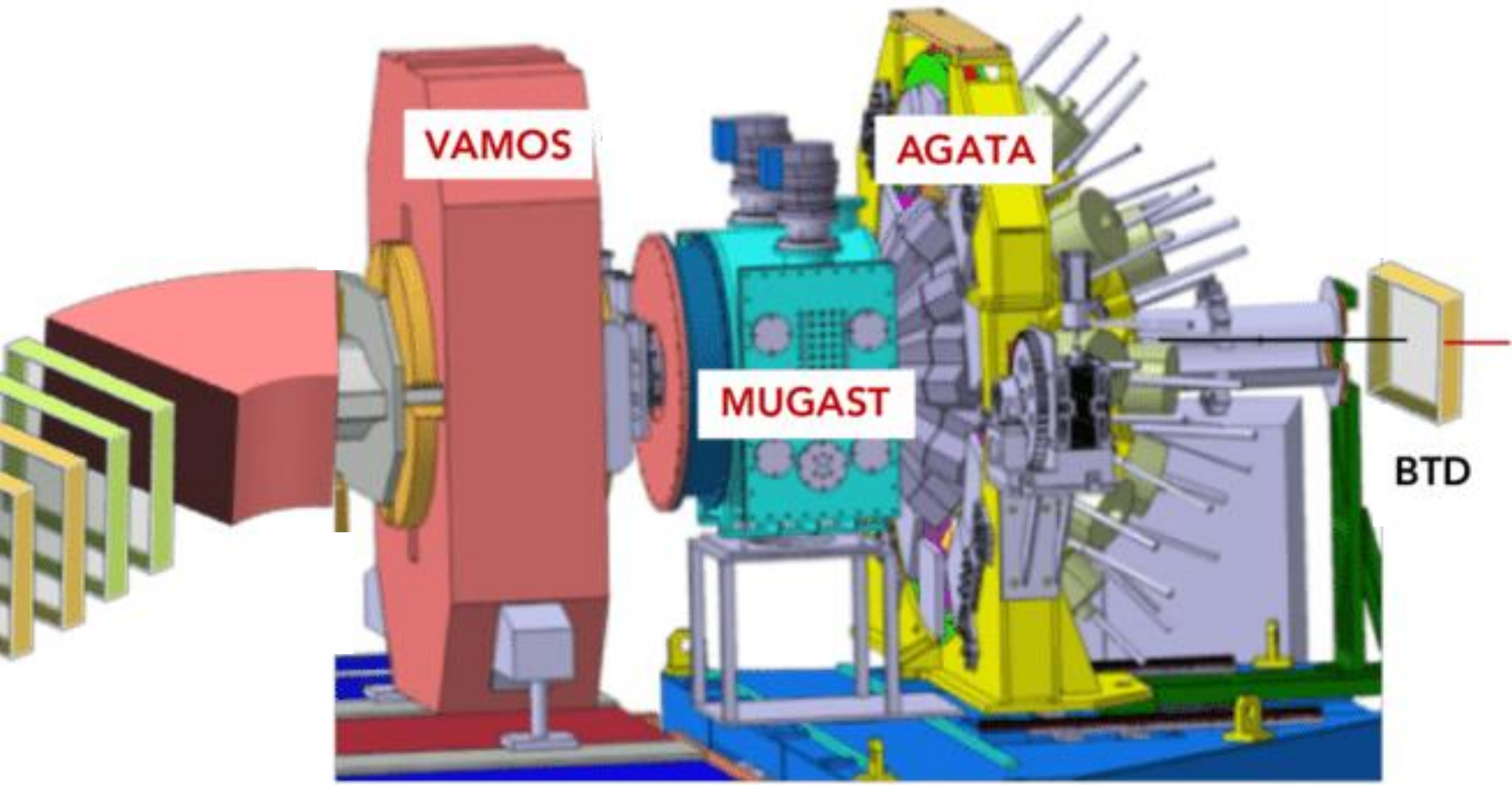
doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

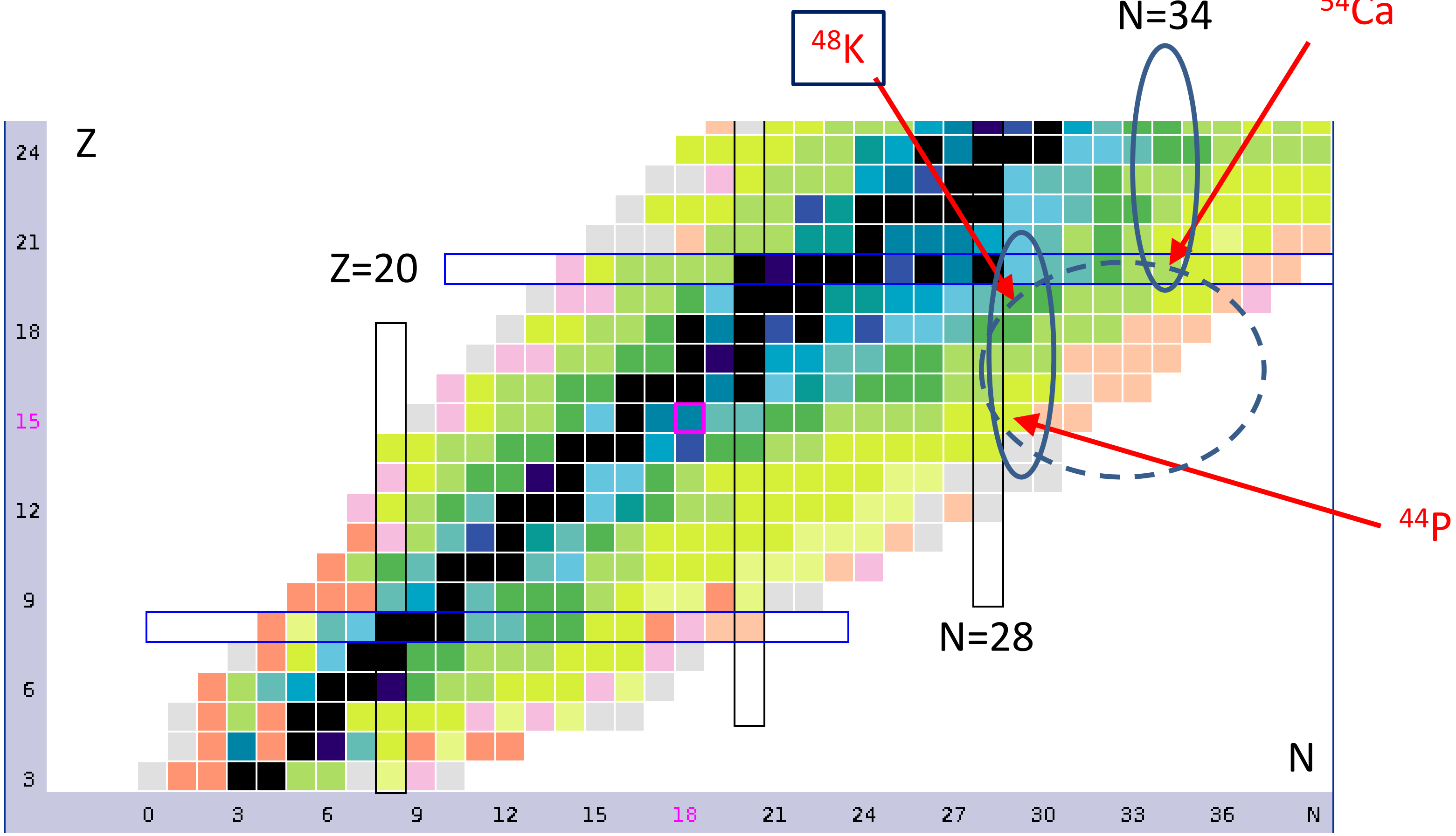
Study of d(^{47}K,p)^{48}K

Beam: ^{47}K at 7.7 MeV/u (SPIRAL1)
Intensity: 5×10^5 pps
Purity: ~ 100%



C.J. Paxman, A. Matta, W.N. Catford *et al.*, Phys. Rev. Lett. **134**, 162504 (2025)

Study of d(^{47}K,p)^{48}K



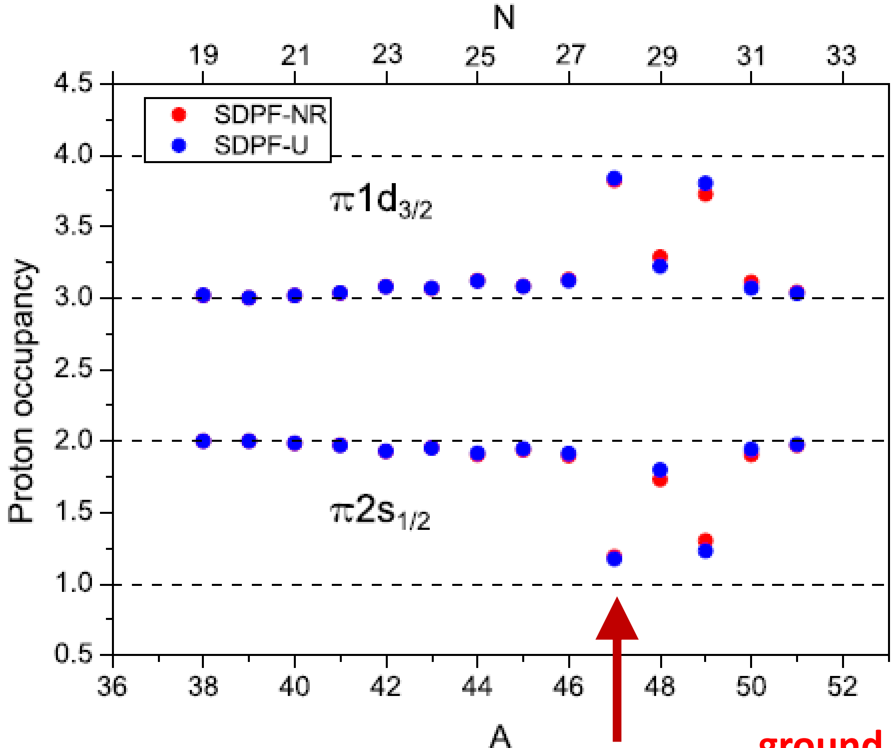
PLAN: use the reaction (d,p) to add a neutron to $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$

… study the interaction with the odd proton way down in $s_{1/2}$

PHYSICAL REVIEW C **90**, 034321 (2014)

Shell structure of potassium isotopes deduced from their magnetic moments

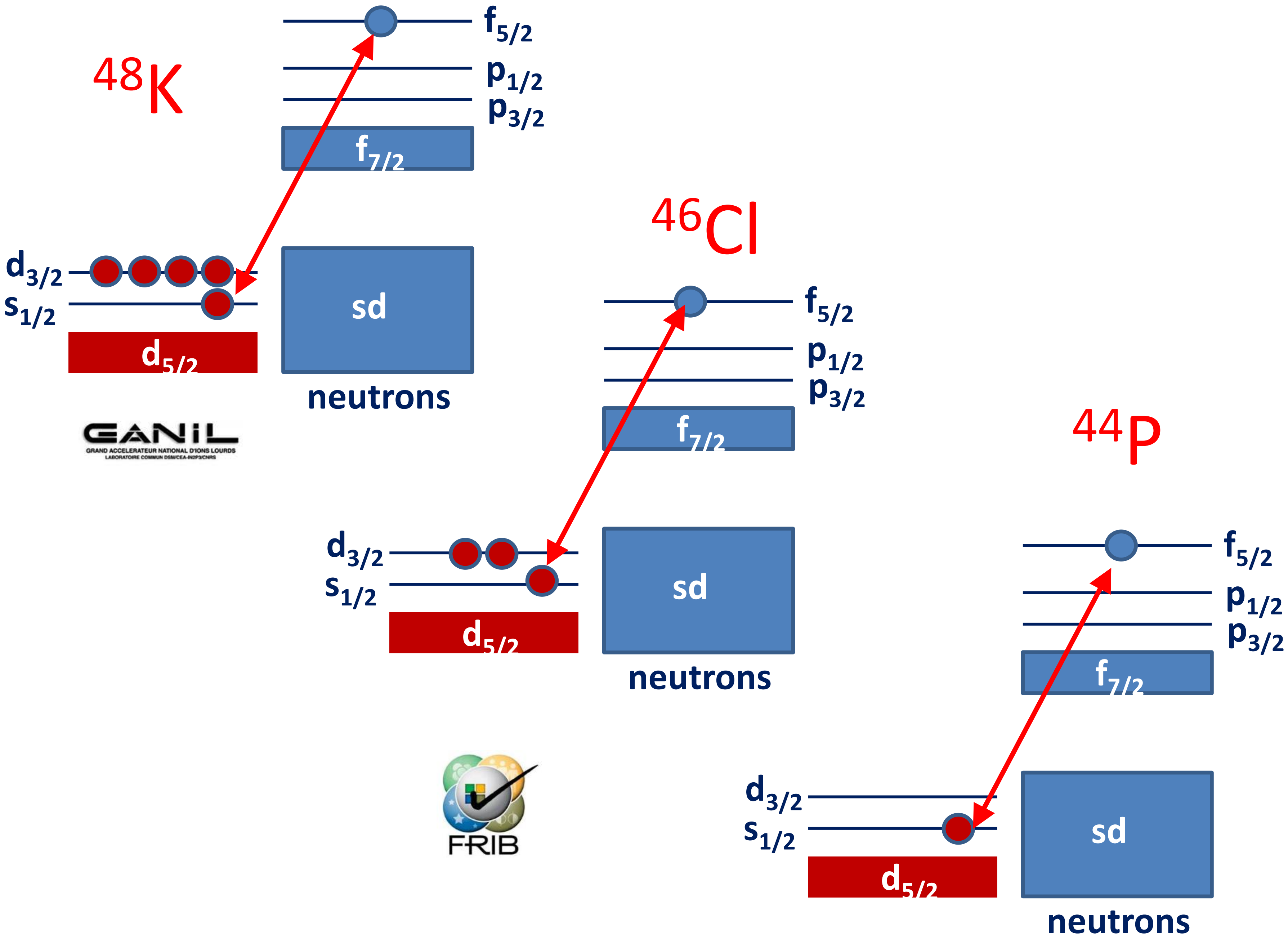
J. Papuga,[1,*] M. L. Bissell,[1] K. Kreim,[2] C. Barbieri,[3] K. Blaum,[2] M. De Rydt,[1] T. Duguet,[4,5] R. F. Garcia Ruiz,[1] H. Heylen,[1]
M. Kowalska,[6] R. Neugart,[7] G. Neyens,[1] W. Nörtershäuser,[7,8] M. M. Rajabali,[1] R. Sánchez,[9,10]
N. Smirnova,[11] V. Somà,[4] and D. T. Yordanov[2,12]

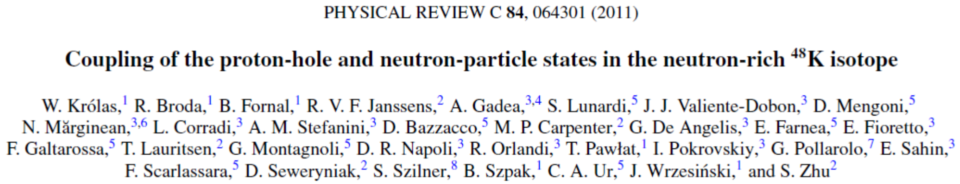


experimentally confirmed inversion of proton orbital occupancies

^{47}K

ground state is $1/2^+$ (odd proton in $s_{1/2}$)
(same happens in ^{45}Cl)


^{48}K
$f_{5/2}$
$p_{1/2}$
$p_{3/2}$
$f_{7/2}$
$d_{3/2}$
$s_{1/2}$
$d_{5/2}$
sd
neutrons
GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS
LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS
^{46}Cl
$f_{5/2}$
$p_{1/2}$
$p_{3/2}$
$f_{7/2}$
$d_{3/2}$
$s_{1/2}$
$d_{5/2}$
sd
neutrons
FRIB
^{44}P
$f_{5/2}$
$p_{1/2}$
$p_{3/2}$
$f_{7/2}$
$d_{3/2}$
$s_{1/2}$
$d_{5/2}$
sd
neutrons



PHYSICAL REVIEW C **84**, 064301 (2011)

Coupling of the proton-hole and neutron-particle states in the neutron-rich ^{48}K isotope

W. Królas,[1] R. Broda,[1] B. Fornal,[1] R. V. F. Janssens,[2] A. Gadea,[3,4] S. Lunardi,[5] J. J. Valiente-Dobon,[3] D. Mengoni,[5]
N. Mărginean,[3,6] L. Corradi,[3] A. M. Stefanini,[3] D. Bazzacco,[5] M. P. Carpenter,[2] G. De Angelis,[3] E. Farnea,[5] E. Fioretto,[3]
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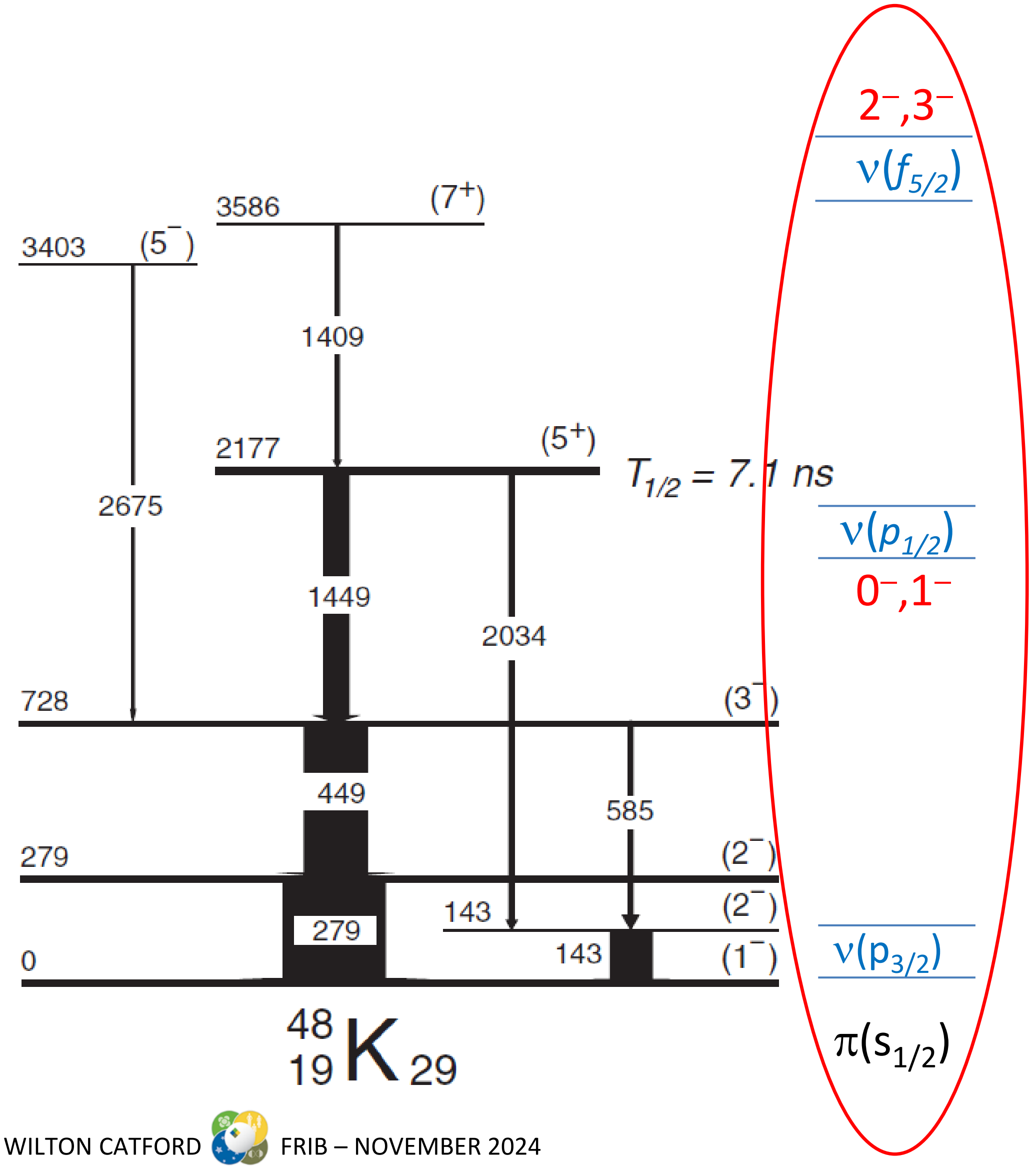

Doublet for each neutron orbital

(coupling to odd proton in $s_{1/2}$)

PHYSICAL REVIEW C 84, 064301 (2011)

Coupling of the proton-hole and neutron-particle states in the neutron-rich ^{48}K isotope

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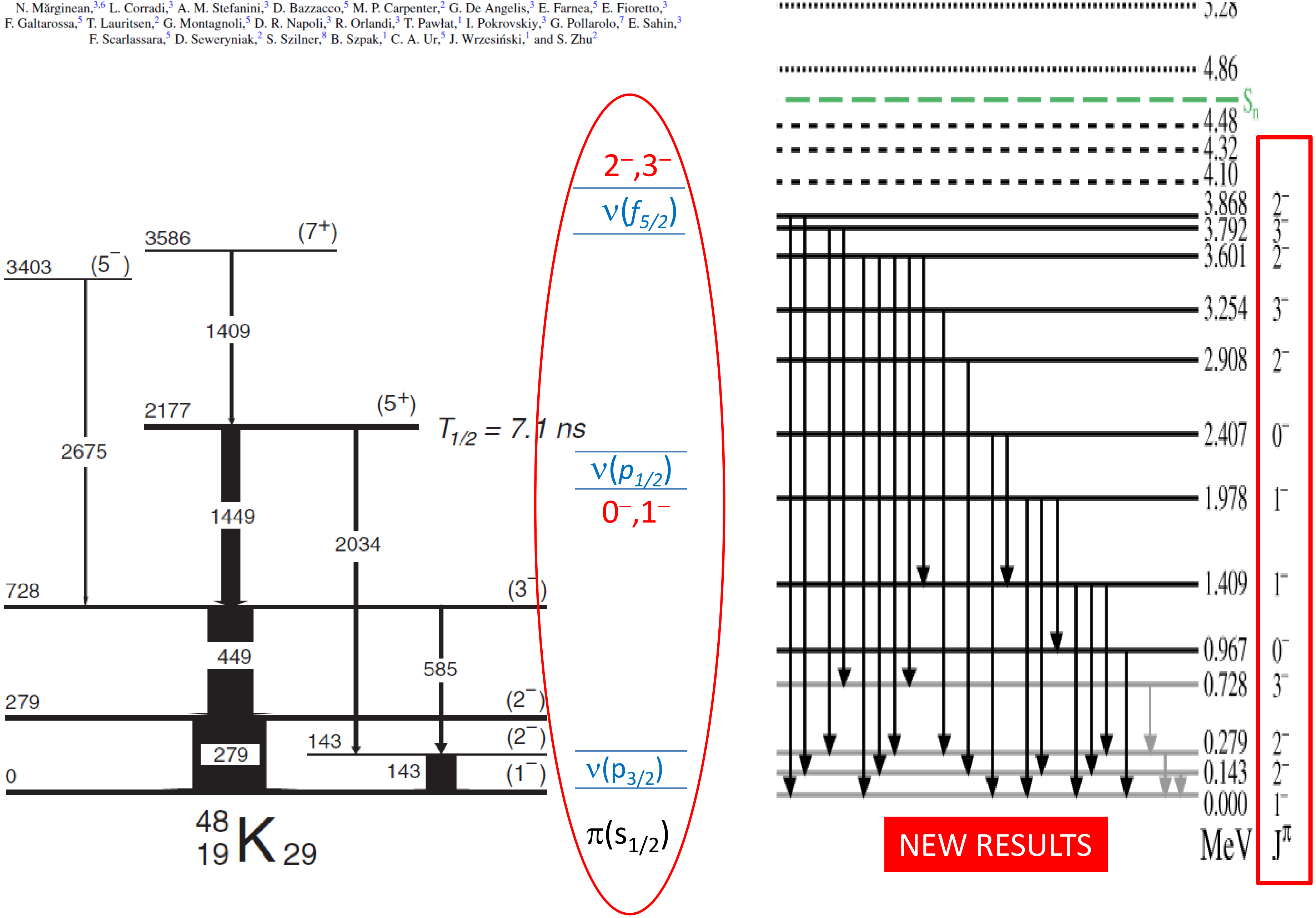
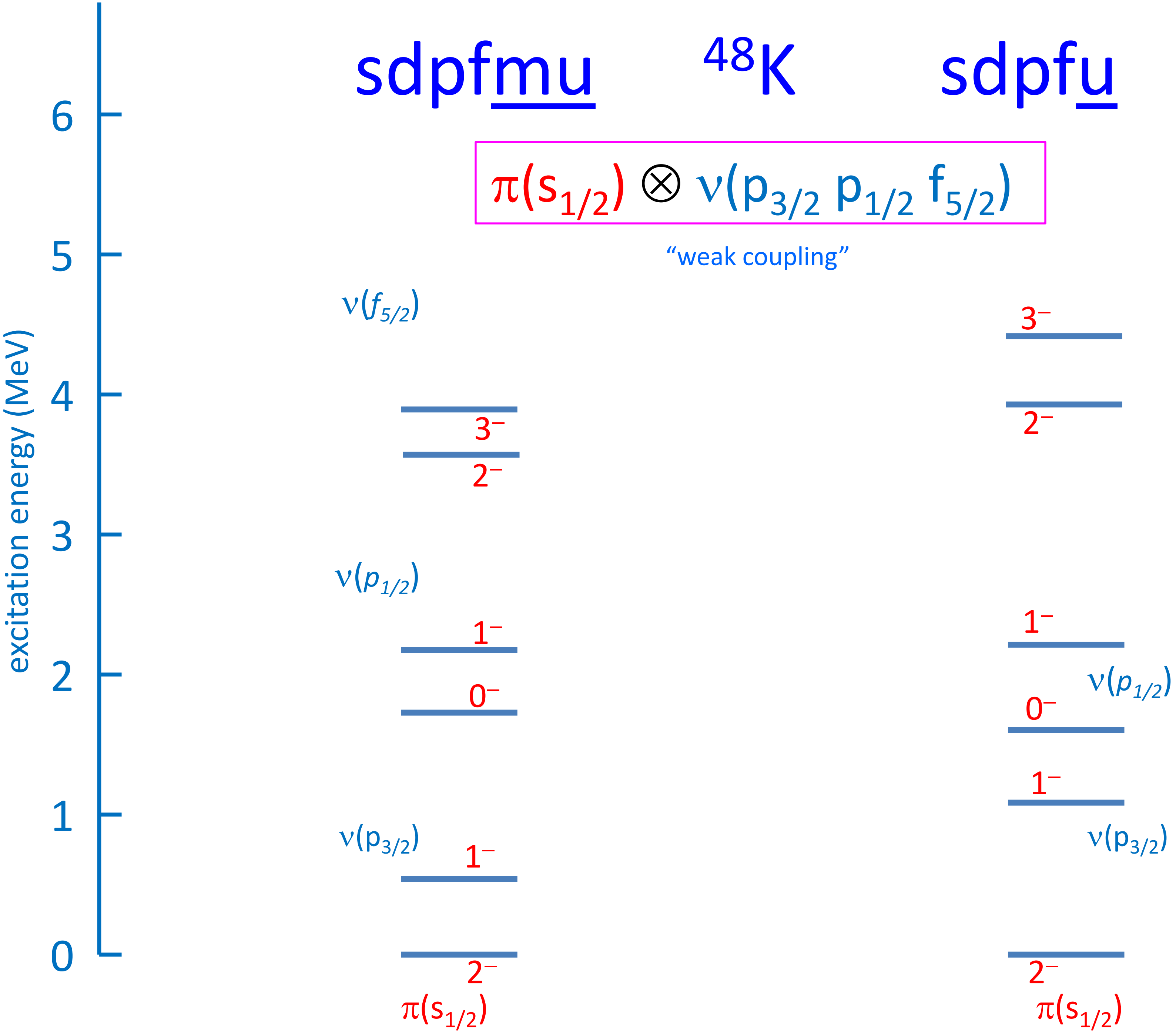
C.J. Paxman, A. Matta, W.N. Catford *et al.*, Phys. Rev. Lett. **134**, 162504 (2025)



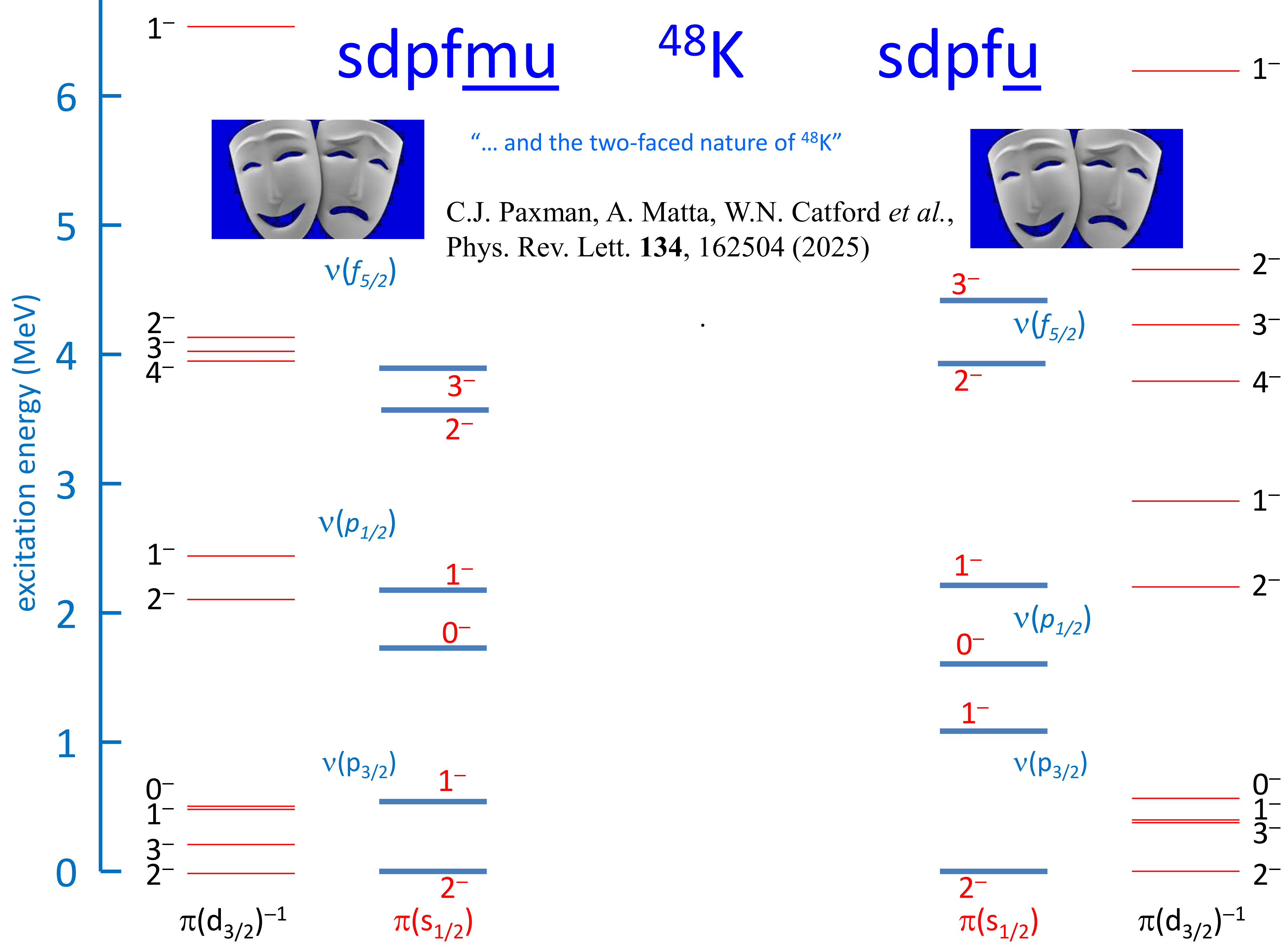
sdpfmu ^{48}K sdpfu

$\pi(s_{1/2}) \otimes \nu(p_{3/2}\ p_{1/2}\ f_{5/2})$

“weak coupling”



sdpfmu ^{48}K sdpfu

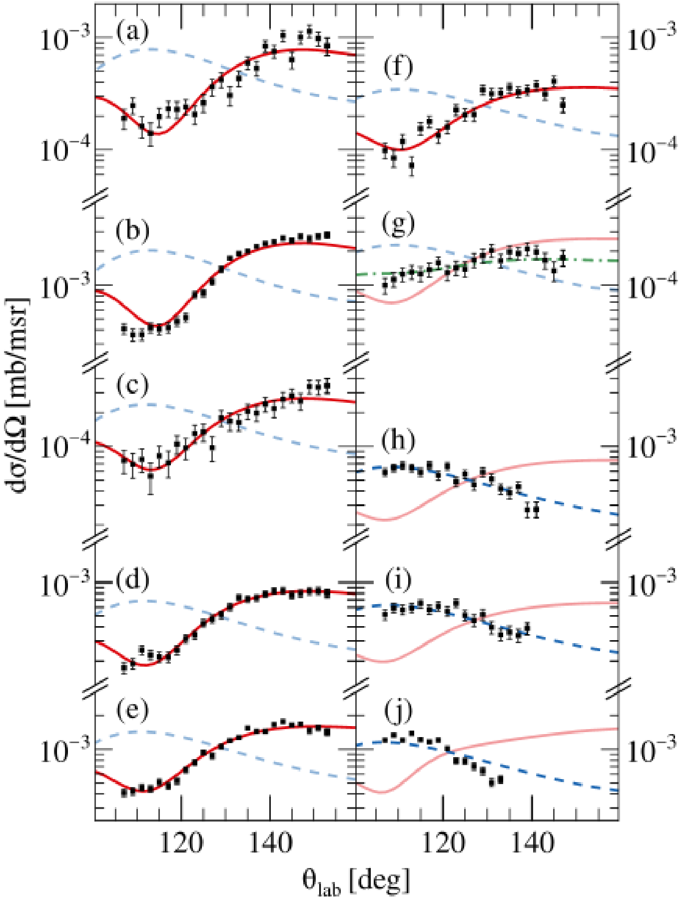


"… and the two-faced nature of ^{48}K"

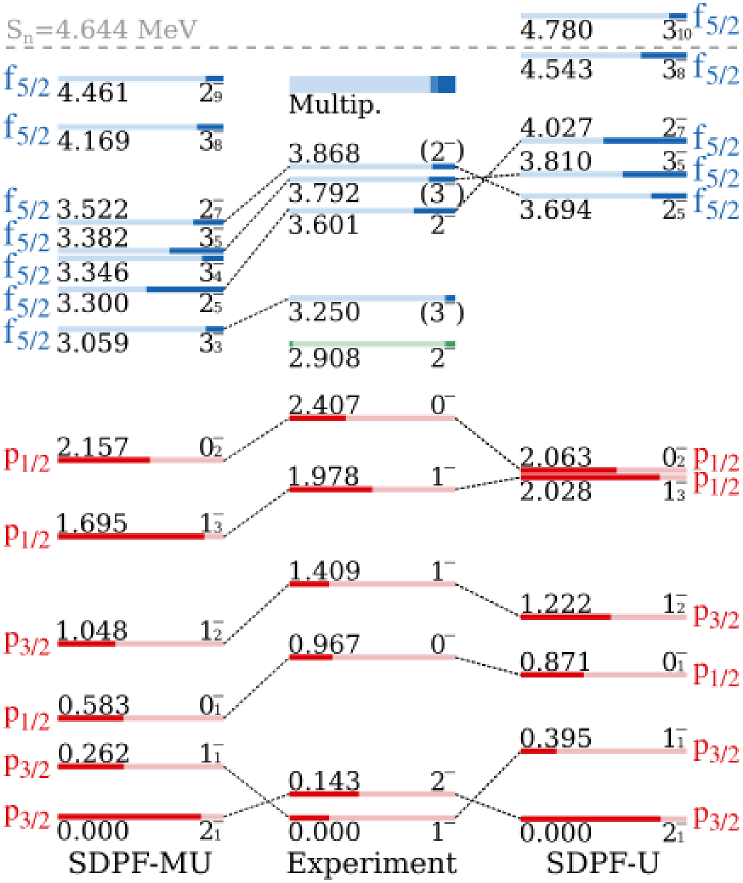
C.J. Paxman, A. Matta, W.N. Catford *et al.*,
Phys. Rev. Lett. **134**, 162504 (2025)

Study of d(^{47}K,p)^{48}K at 7.7 MeV/A using MUGAST/AGATA/SPIRAL1

Angular momentum transfer from $d\sigma/d\Omega$,
Spin/parity using gamma-decay branching



Use measured spectroscopic factors to link
to shell model states and choose best model



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Some future perspectives…

Remember, for very low beam intensities we have ACTAR, AT-TPC
There are also solenoidal detectors (HELIOS, ISS, SOLARIS)

Whenever possible, we benefit from also measuring gamma-rays…

GANIL

AGATA GRIT

France, Italy, Spain, UK
2029
ISOL beams, 10 MeV/u

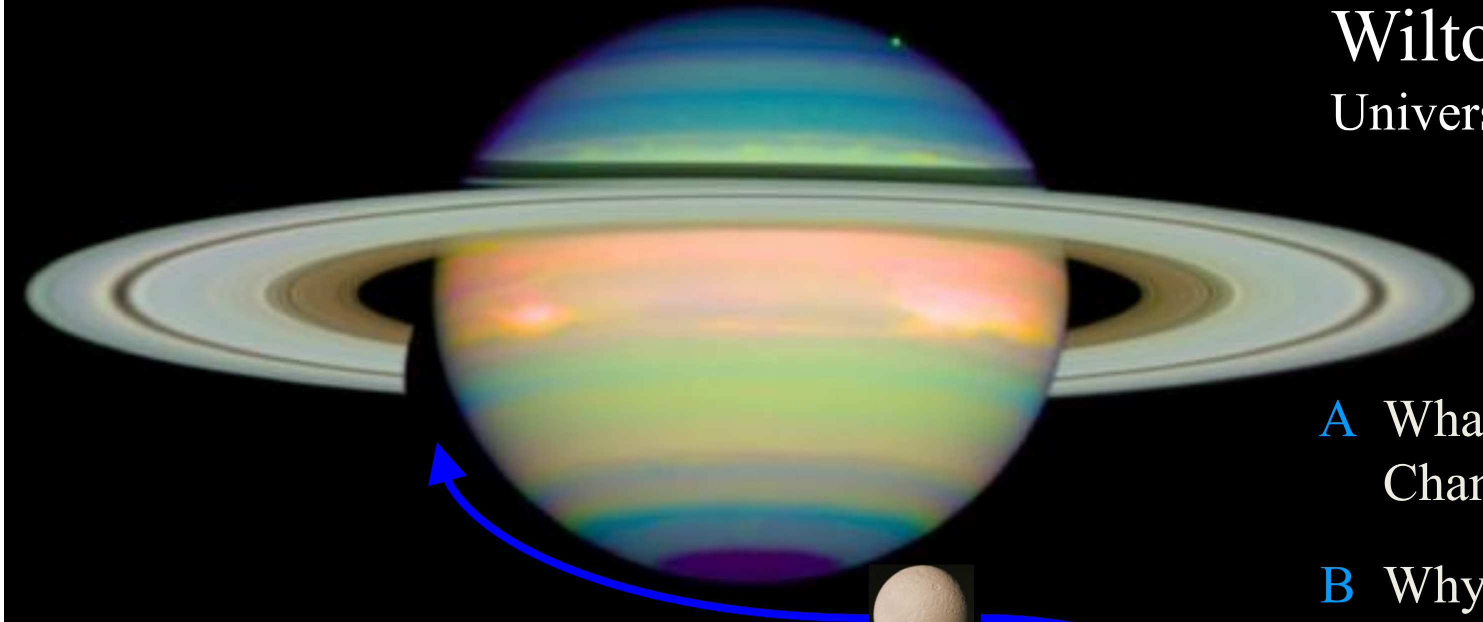
FRIB

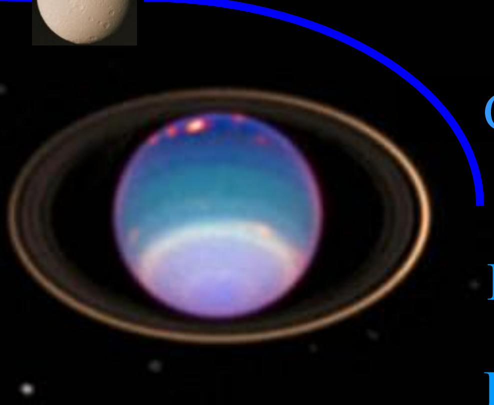
GRETA FAUST

UK, USA
2028
In-flight beams, 40 MeV/u

Exploring Unusual Nuclei with Nucleon Transfer Reactions

Wilton Catford
University of Surrey





A What can we learn?; Changing magic no.'s

B Why use transfer to study this physics?

C What can we measure in specific nuclei?

D Experimental setups

E Examples of data & Interpretation

FIRST CaeSar SUMMER SCHOOL

5 WAYS TO SAY
Thank You
IN FRENCH

MERCI
mekh-see
Thank you

CIMER
see-mekh
Thanks

MERCI INFINIMENT
mekh-see an-fee-nee-man
Thanks infinitely

MERCI DE TOUT COEUR
mekh-see dah tu ker
Thank you with all my heart

C'EST TRÈS GENTIL À TOI / VOUS
seh tkheh jan-tee a twa/voo
That's very kind of you

Pont L'Évêque**3-5 September 2025