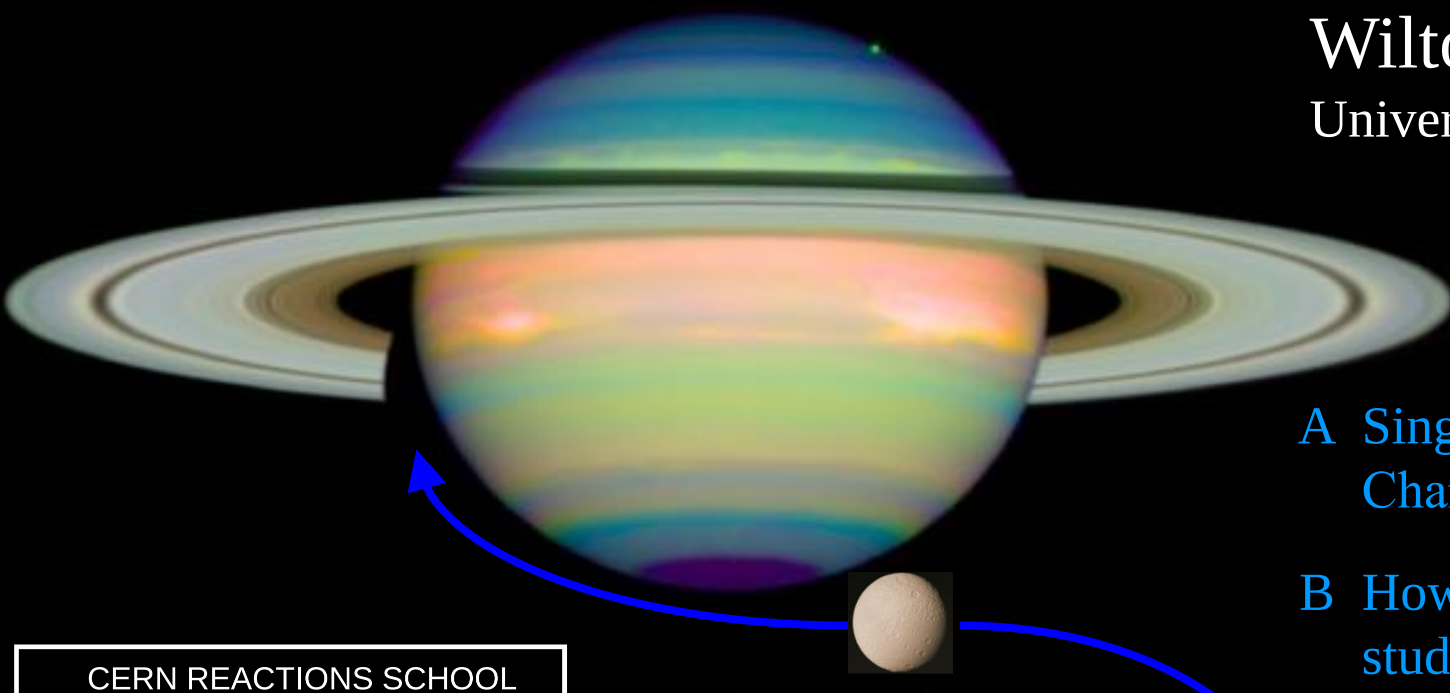
What can we learn from transfer, and how is best to do it?

Wilton Catford

University of Surrey



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

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

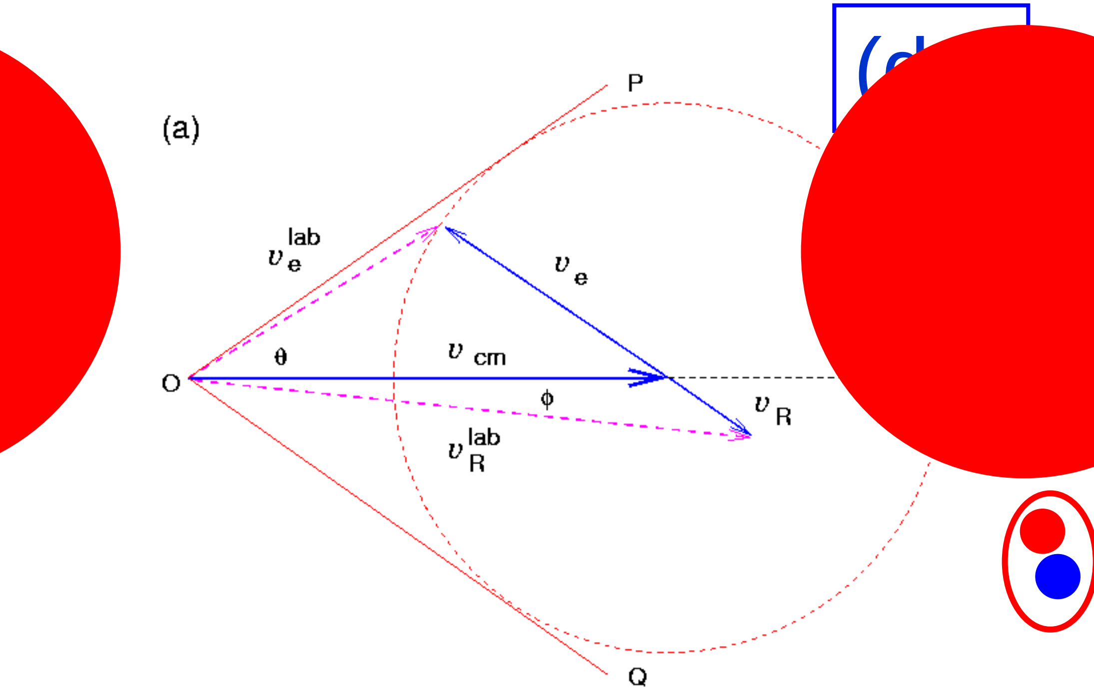
A PLAN for how to STUDY STRUCTURE

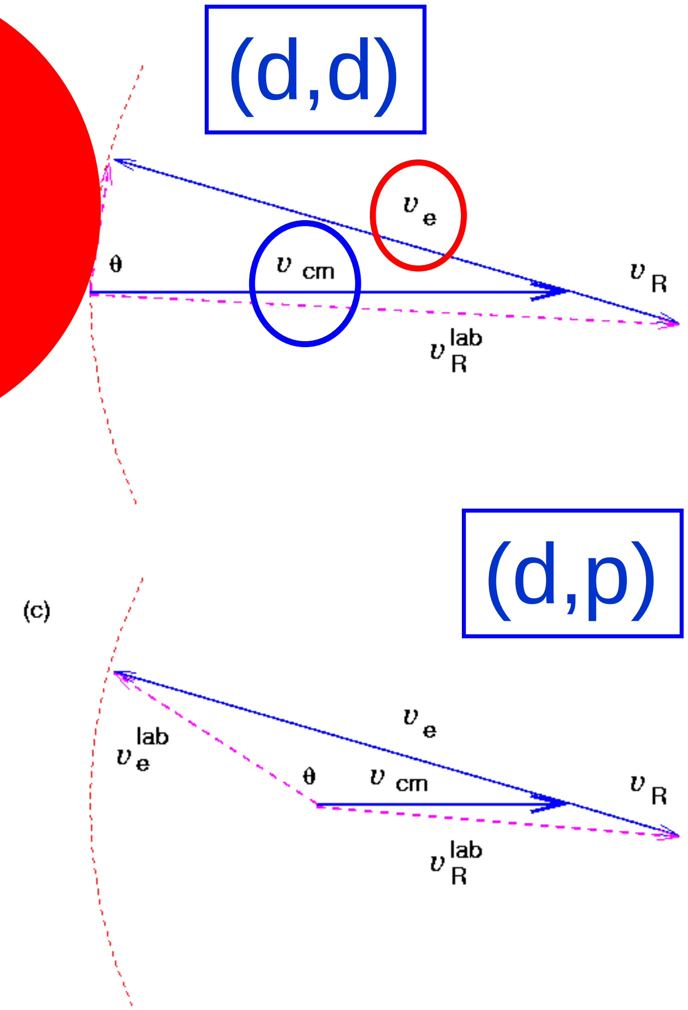
- Use **transfer reactions** to identify strong single-particle states, measuring their spins and strengths
- Use the energies of these states to compare with theory
- Refine the theory
- Improve the extrapolation to very exotic nuclei
- **Hence learn the structure of very exotic nuclei**

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.

USING RADIOACTIVE BEAMS in INVERSE KINEMATICS





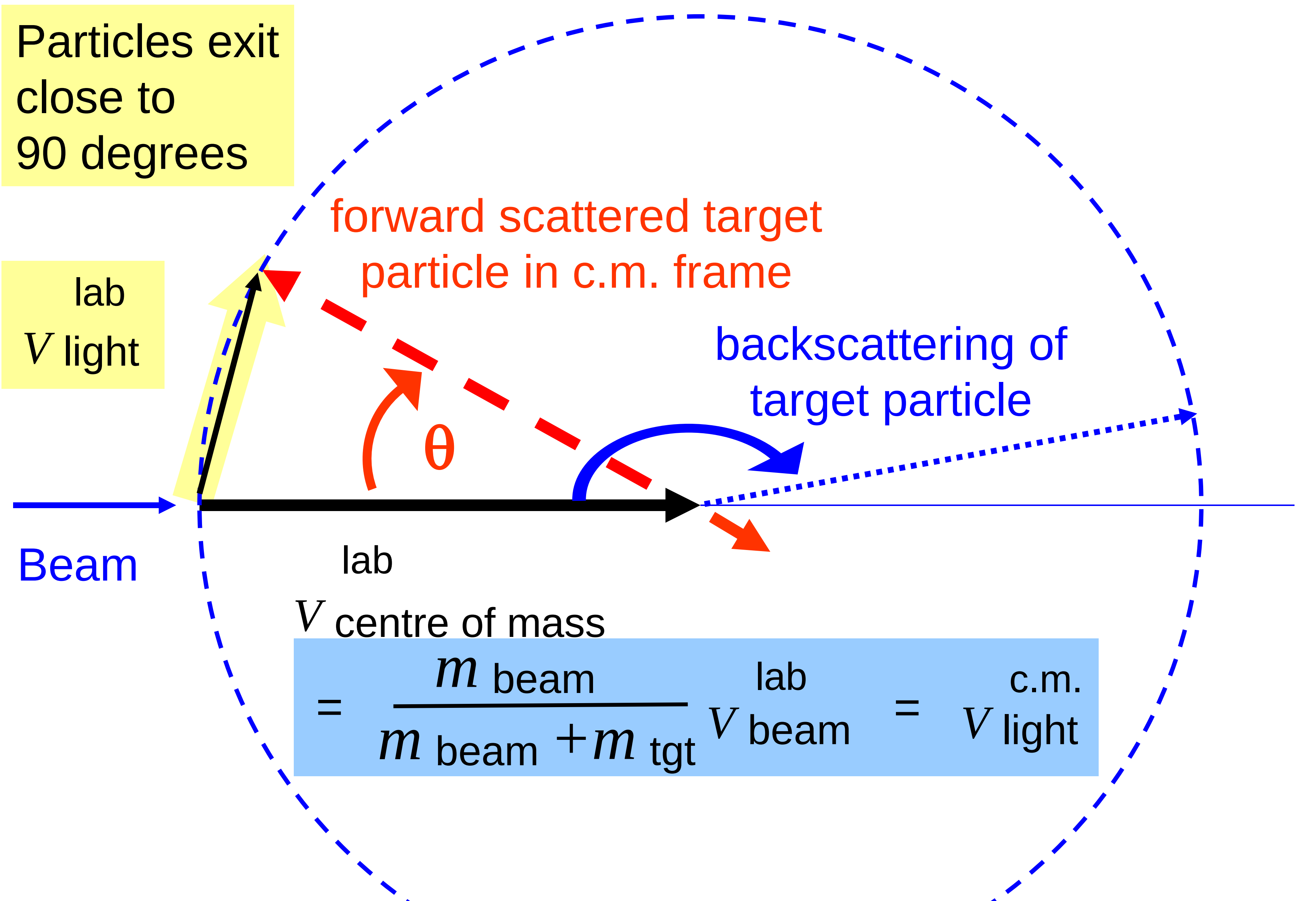
$$\frac{v_e}{v_{cm}} = \left(q\, f \frac{M_R}{M_P} \right)^{1/2} \cong \sqrt{q\, f}$$

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

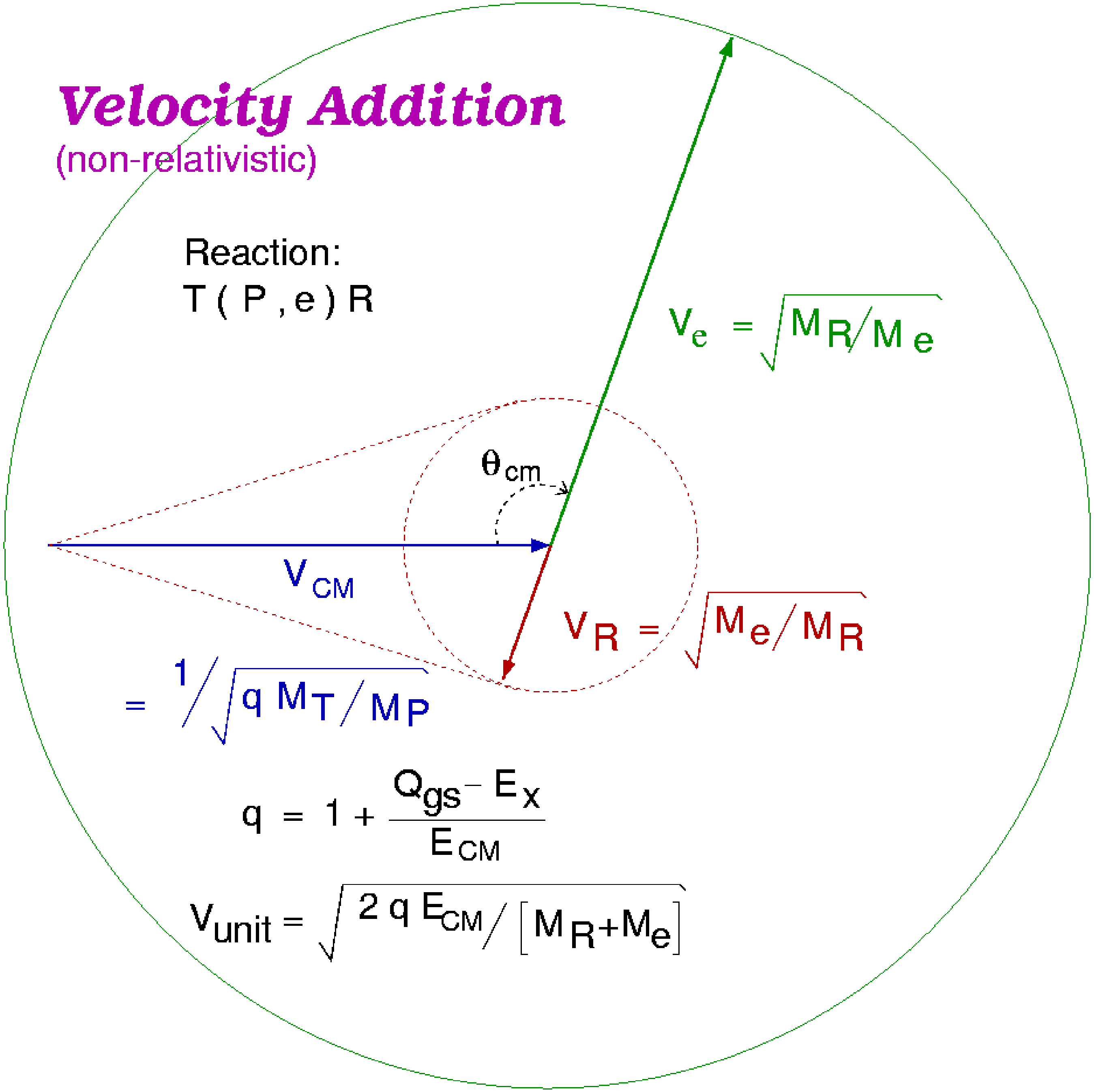
f = 1/2 for (p,d), 2/3 for (d,t)

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

Velocity vector addition diagram



$$V_{\text{centre of mass}}^{\text{lab}} = \frac{m_{\text{beam}}}{m_{\text{beam}} + m_{\text{tgt}}} V_{\text{beam}}^{\text{lab}} = V_{\text{light}}^{\text{c.m.}}$$

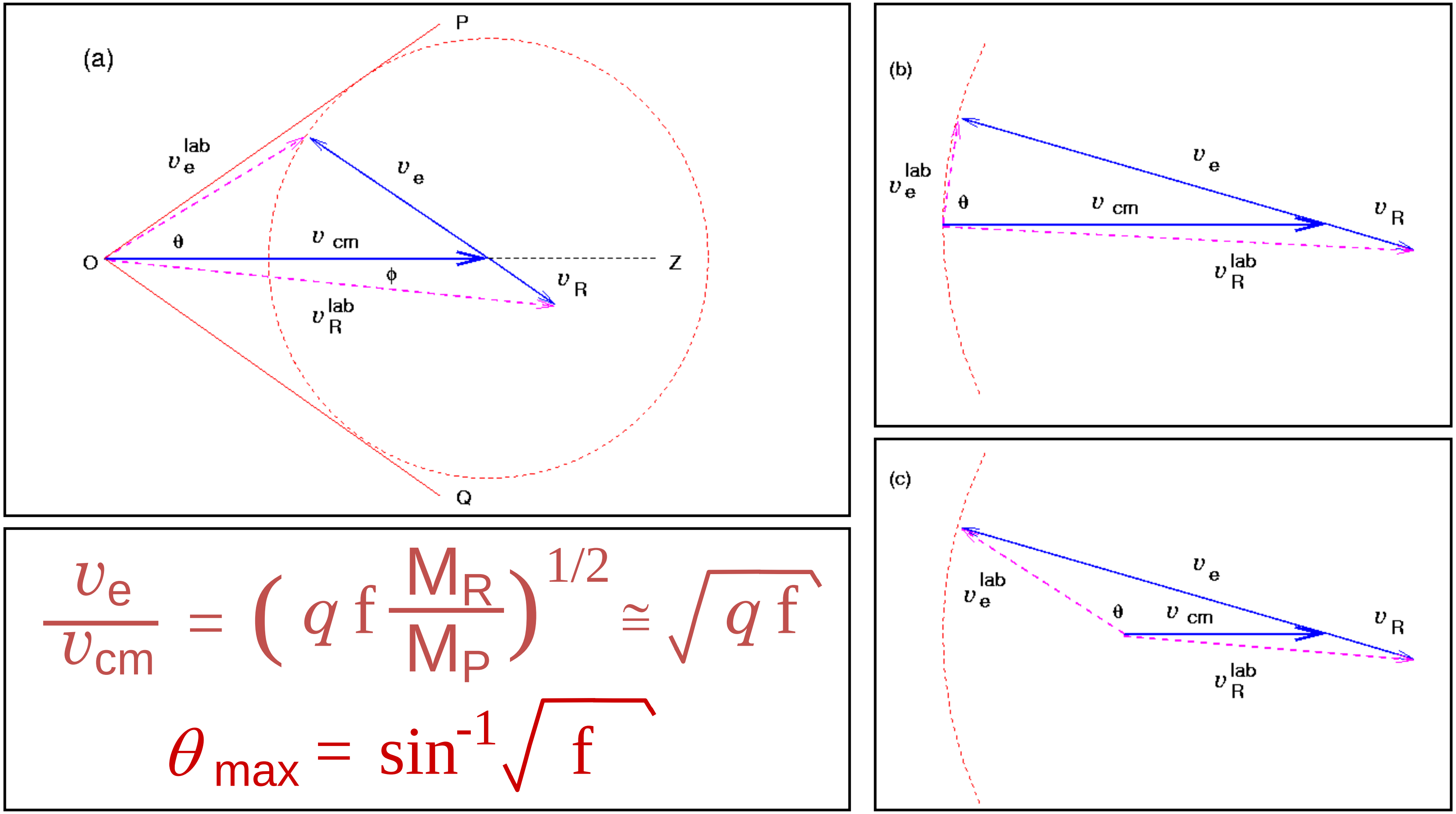


Velocity Addition
(non-relativistic)
Reaction:
T (P , e) R
$V_e = \sqrt{M_R / M_e}$
θ_{cm}
V_{CM}
$= 1 / \sqrt{q\, M_T / M_P}$
$V_R = \sqrt{M_e / M_R}$
$q = 1 + \frac{Q_{gs} - E_x}{E_{CM}}$
$V_{unit} = \sqrt{2\, q\, E_{CM} / [M_R + M_e]}$

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

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

Inverse Kinematics



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

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

υ_{cm} is the velocity of the centre of mass, in the laboratory frame

Reaction Q-values in MeV

Z ↑ / N →

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

[box] = stable (stable nuclei shown in **bold**; each cell: mass number: Q-value)

Ne				14:	15:	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												

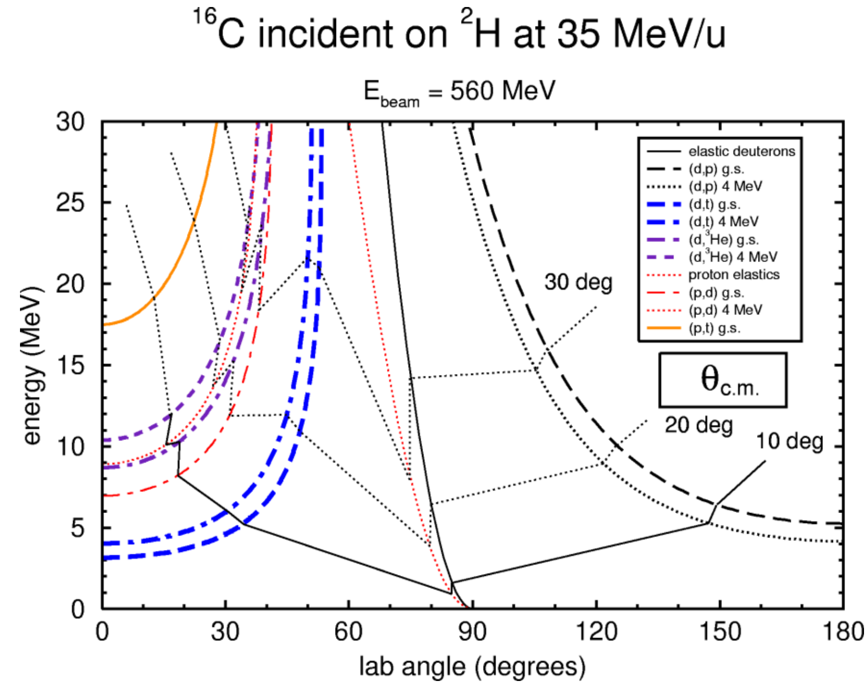
Reaction Q-value in MeV

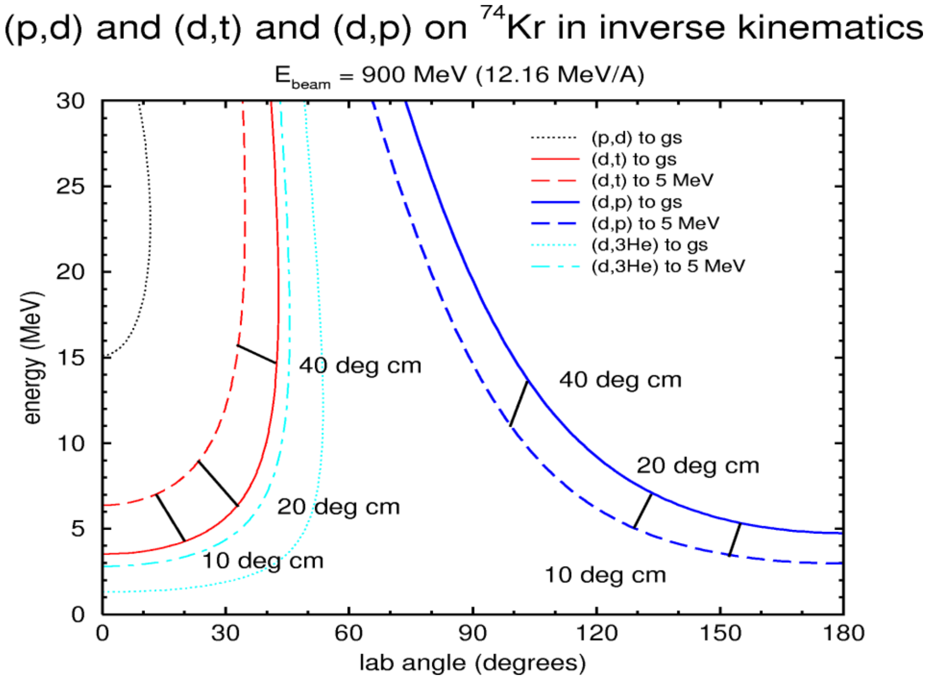
(d, ^{3}He): refer to cell of TARGET

[box] = stable

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												
Li	4: 8.4	5: 7.5	**6: 0.9**	**7: -4.5**	8: -7.0	9: -8.4	10: -8.7	↑ N=8												

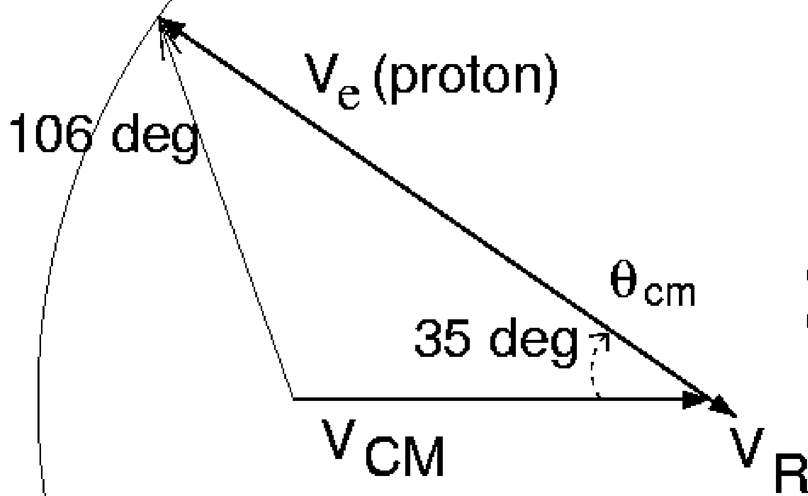
The general form of the kinematic diagrams is determined by the light particle masses, and has little dependence on the beam mass or velocity





4.0 MeV/A
(~24MV 15+)
376 MeV

$^{94}Sr\ (d,p)\ ^{95}Sr$

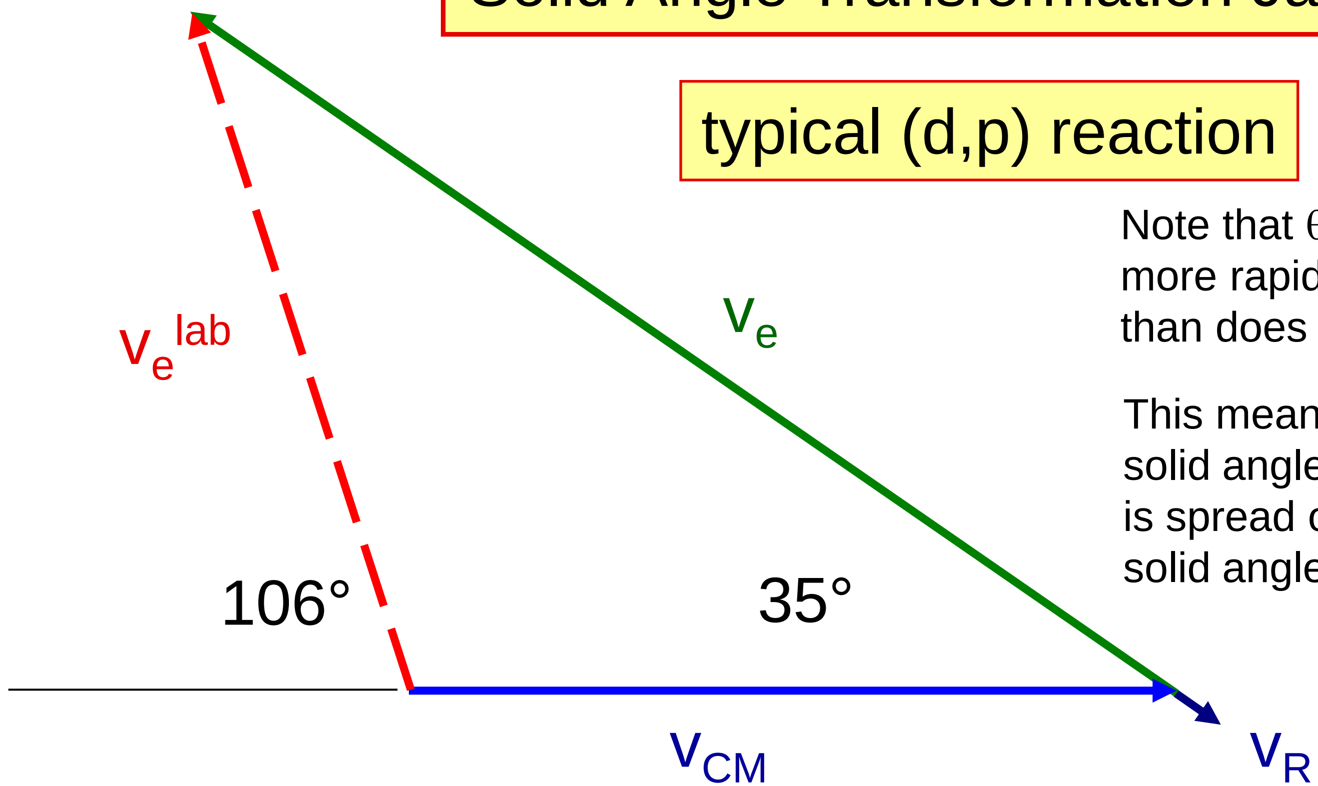


experiment to study
θ_{cm} between 10, 32 deg

θ_{lab}	θ_{cm}	E_{proton}	0.2 deg $\Delta\theta$	35 keV E_{res}	ENRGY STRAG	MULT/ SCATT	DIFF'L DE/DX TARG	TOTAL IN QUAD	DE(Ex) /DE(Ep)
112	32	3.33	23	50	19	56	393	401	-1.43
154	10	1.58	7	87	21	23	389	400	-2.53

Solid Angle Transformation Jacobian

typical (d,p) reaction



Note that θ_{lab} changes much more rapidly (at back angles) than does θ_{CM}

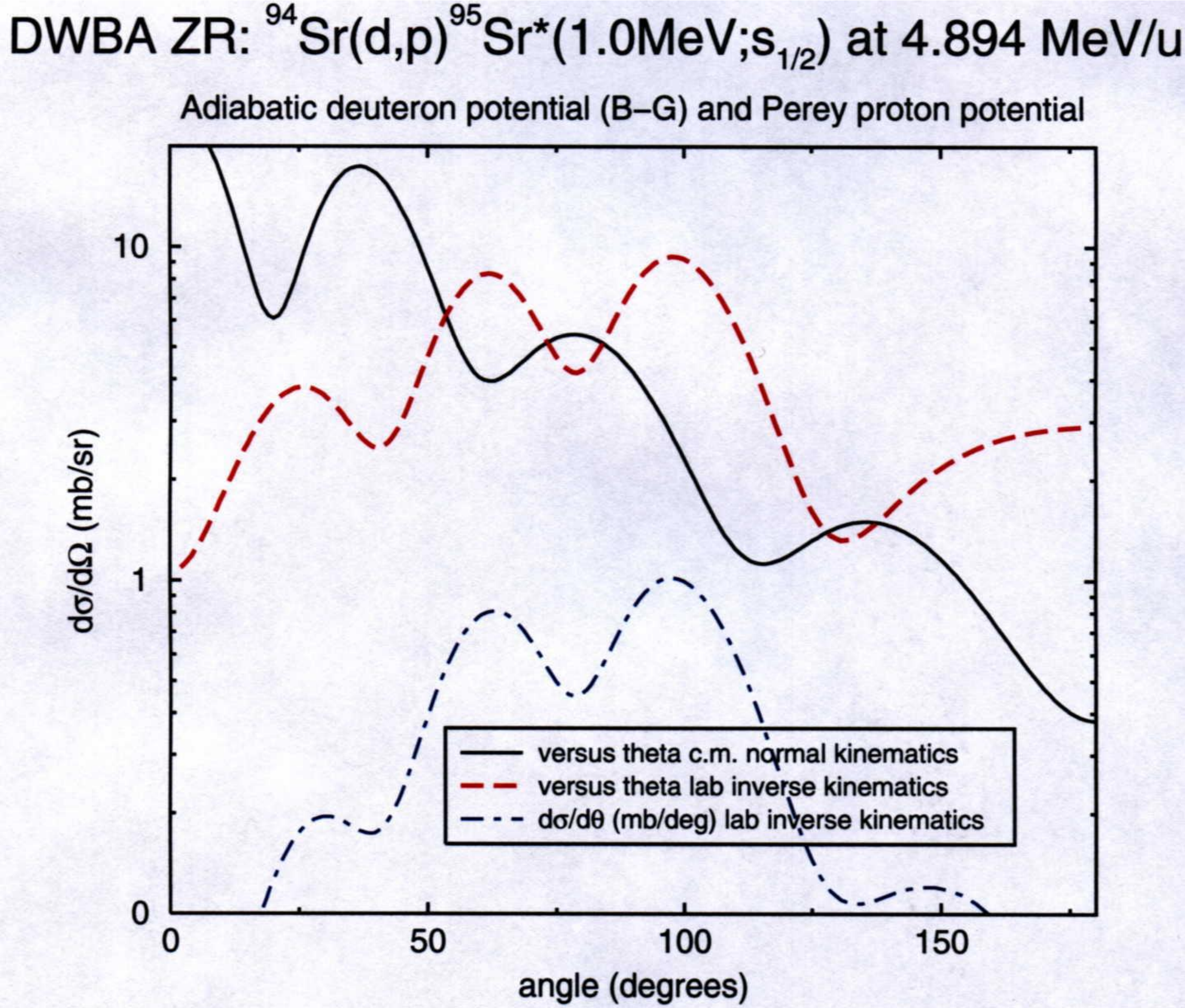
This means that a small solid angle in the CM, $d\Omega_{CM}$ is spread over a rather large solid angle $d\Omega_{lab}$ in the lab

Defining: $\gamma = v_{CM} / v_e$

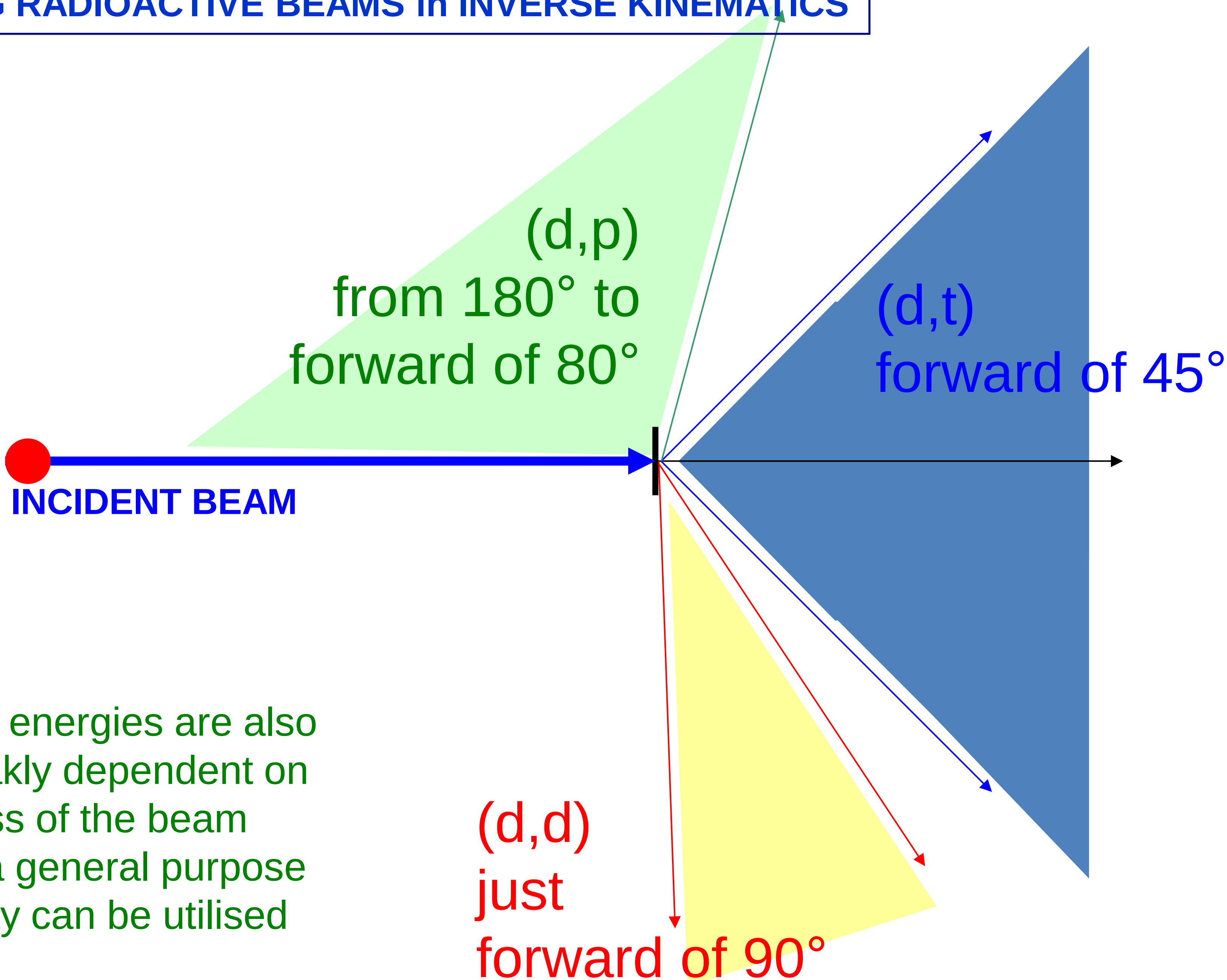
$$\frac{d\sigma}{d\Omega_{lab}} = \frac{(1 + \gamma^2 + 2\gamma \cos\theta)^{3/2}}{|1 + \gamma \cos\theta|} \frac{d\sigma}{d\Omega_{CM}}$$

e.g. L.I. Schiff, *Quantum Mechanics*, 3rd Ed., p.113

This means that although
$d\sigma / d\Omega_{CM}$
is largest at small θ_{CM} or near 180° in the lab, the effect of the Jacobian is that
$d\sigma / d\Omega_{lab}$
near 180° is reduced relative to less backward angles


DWBA ZR: 94Sr(d,p)95Sr*(1.0MeV;s1/2) at 4.894 MeV/u
Adiabatic deuteron potential (B–G) and Perey proton potential
dσ/dΩ (mb/sr)
10
1
0
0
50
100
150
angle (degrees)
versus theta c.m. normal kinematics
versus theta lab inverse kinematics
dσ/dθ (mb/deg) lab inverse kinematics

USING RADIOACTIVE BEAMS in INVERSE KINEMATICS



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

Calculations of E_x resolution from particle detection

beamlike particle detected

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

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

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

Lighter projectiles

Some advantages to detect beam-like particle
(gets difficult at higher energies)

Heavier projectiles

Better to detect light particle
(target thickness lilmits 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

- Motivation: nuclear structure reasons for transfer
- Choices of reactions and beam energies
- Inverse Kinematics
- Implications for Experimental approaches
- **Early Experiments: examples**
- **Why do people make the choices they do?**
- **Some recent examples: TIARA, MUST2, SHARC**
- **Brief mention of Heavy Ion transfer reactions**

LAKE GENEVA

CERN REACTIONS SCHOOL

CERN, Geneva ** 22-24 April 2014

Possible Experimental Approaches to Nucleon Transfer

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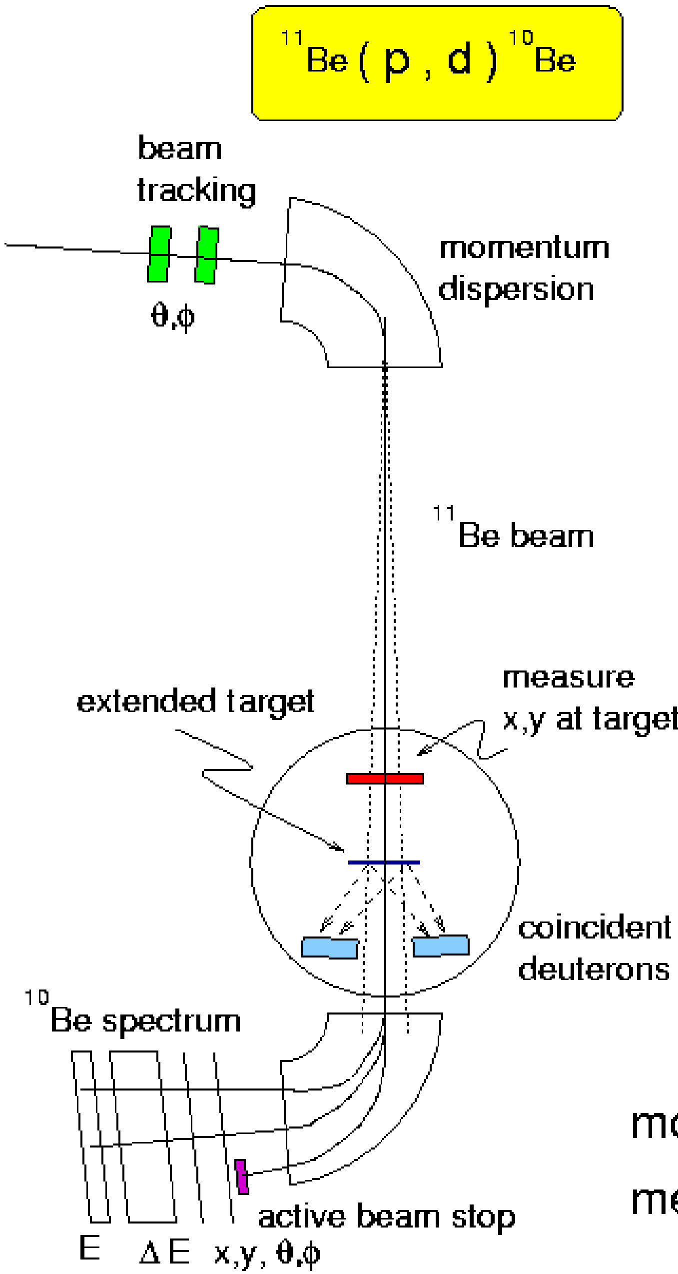
J.S. Winfield, W.N. Catford and N.A. Orr, NIM A396 (1997) 147



beam energy resolution 2.0-3.0 MeV

angular spread ±1 °

dispersion-matched spectrometer "SPEG"
(Spectromètre à Perte d'Energie du Ganil)

microchannel plate

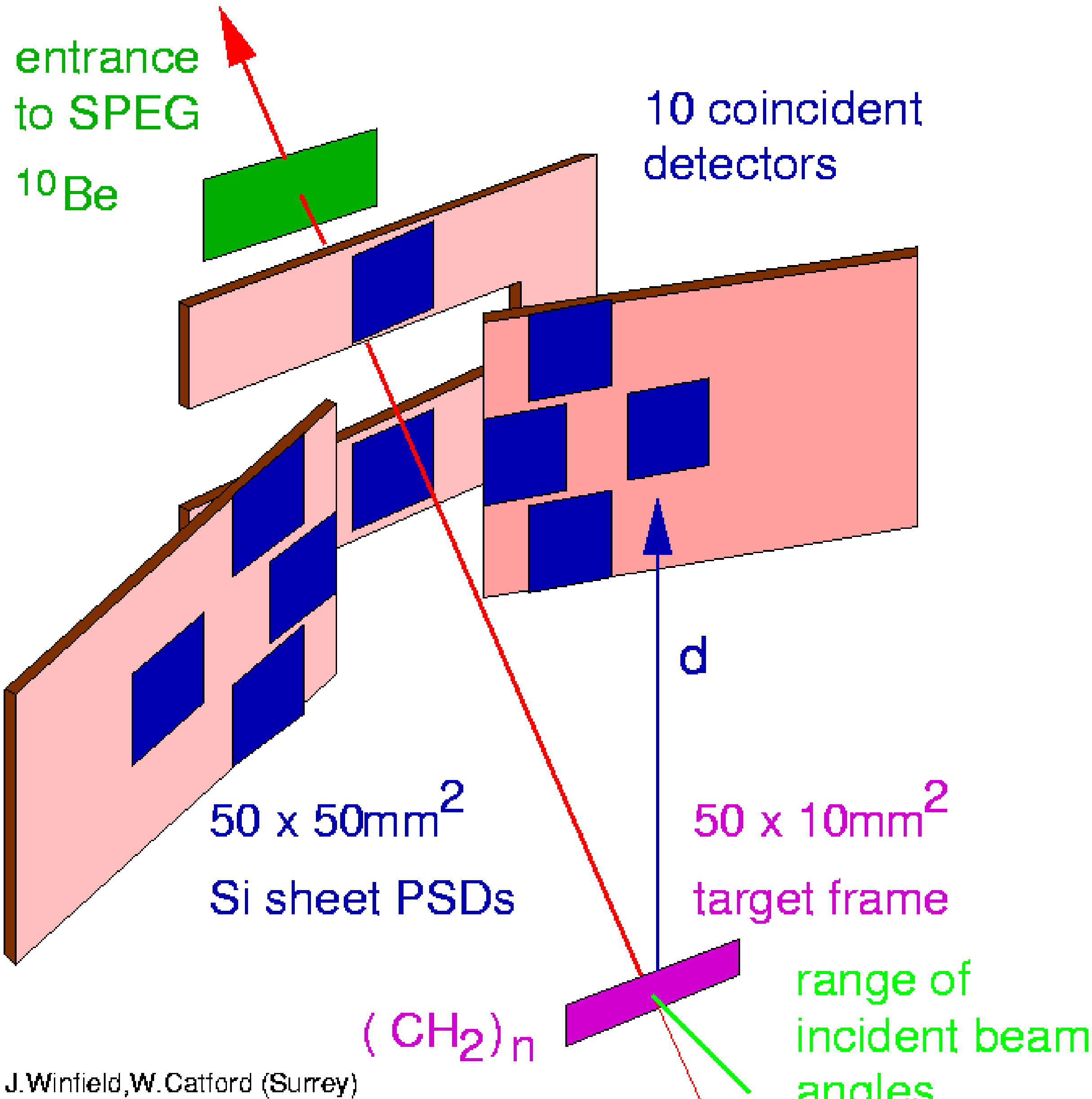
polythene target

ten Silicon PSD's

momentum analysis

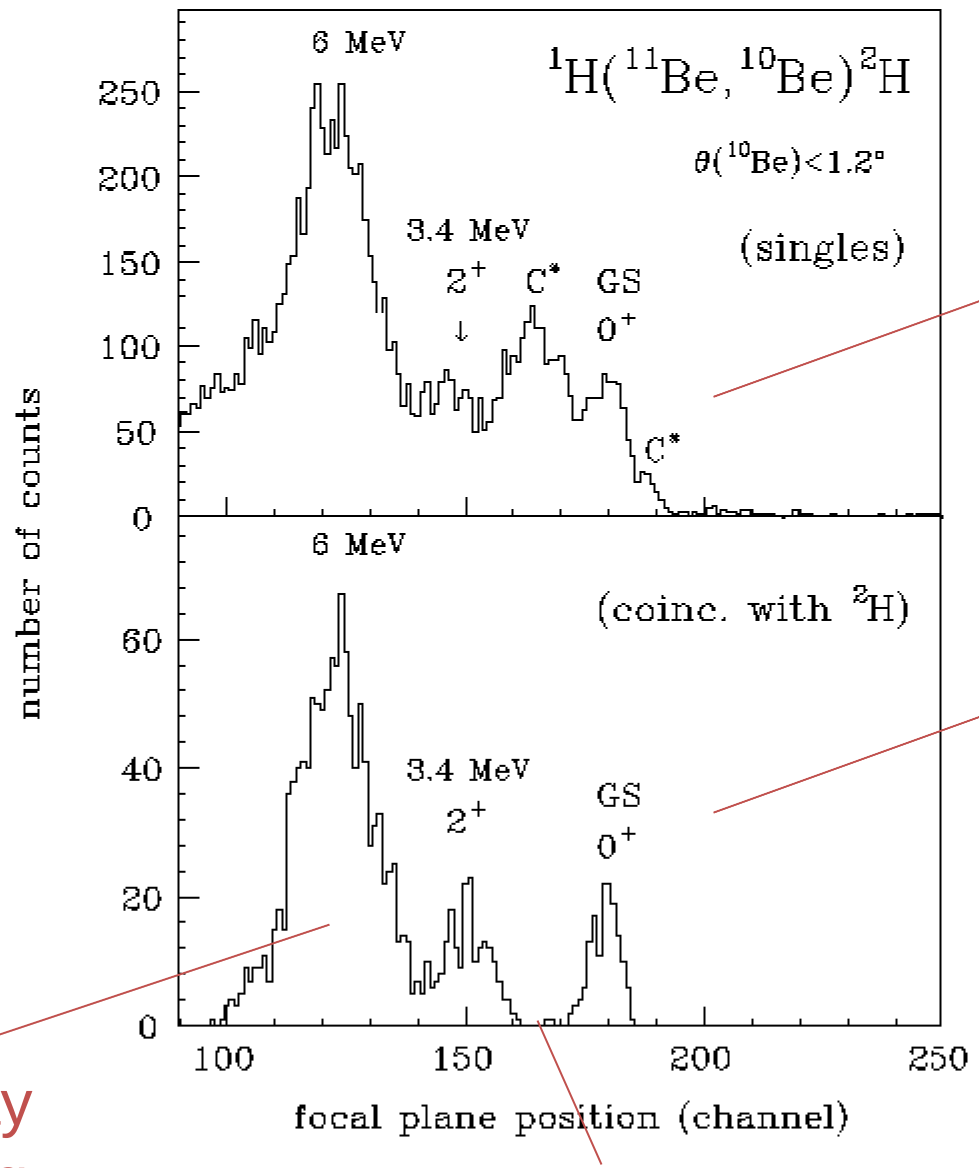
measure reaction angle

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



J.Winfield,W.Catford (Surrey)

Focal plane spectrum from SPEG magnetic spectrometer



singles

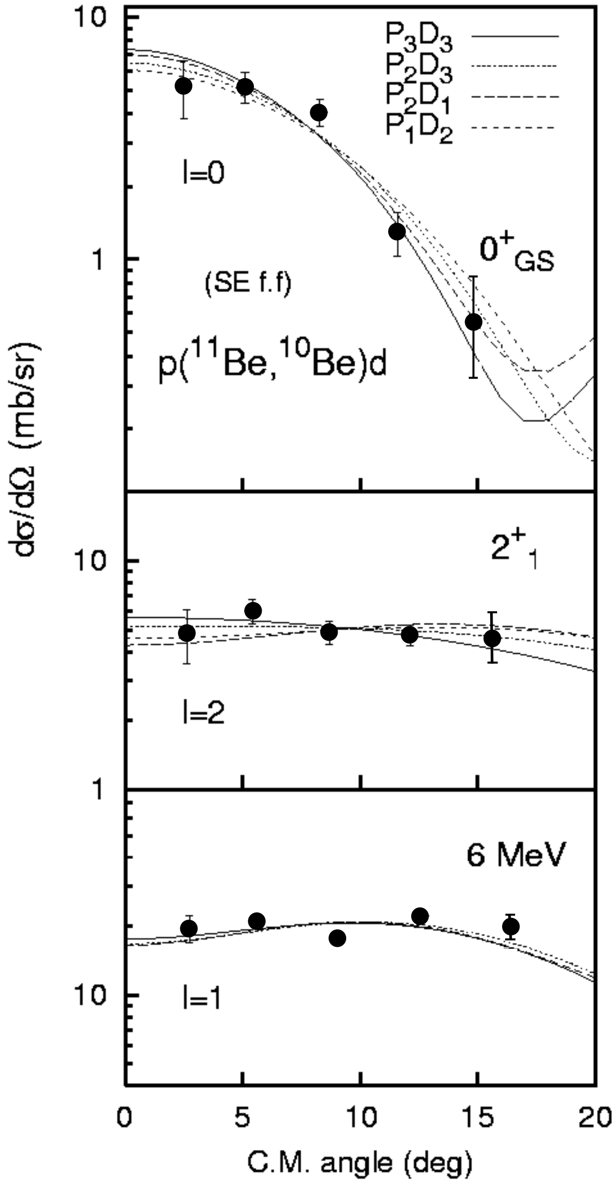
coincidence

gamma-ray broadening

carbon background removed

Separation Energy form factor

Vibrational form factor



0^+ 2^+

α^2 β^2

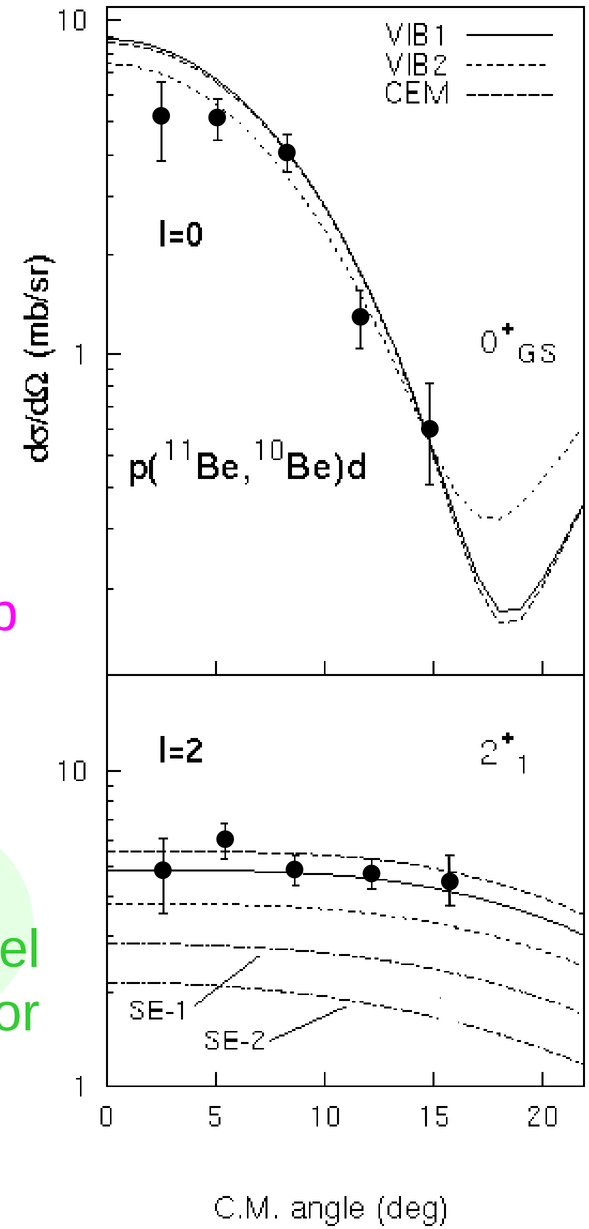
~~0.49~~ ~~0.51~~

- poor form factor
- no core coupling
- no ^{11}Be/d breakup

0.84 0.16

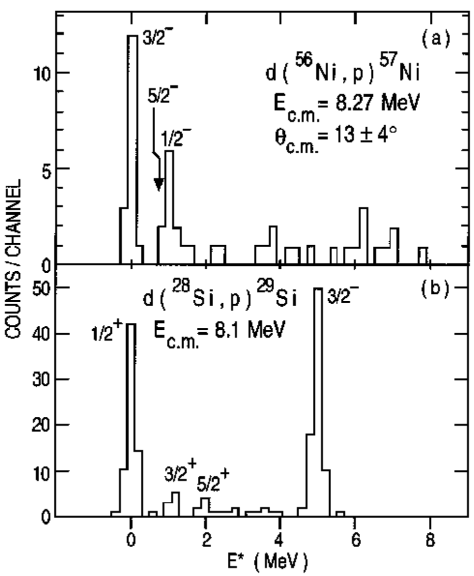
- vibrational model
- core-excited model
- realistic form factor

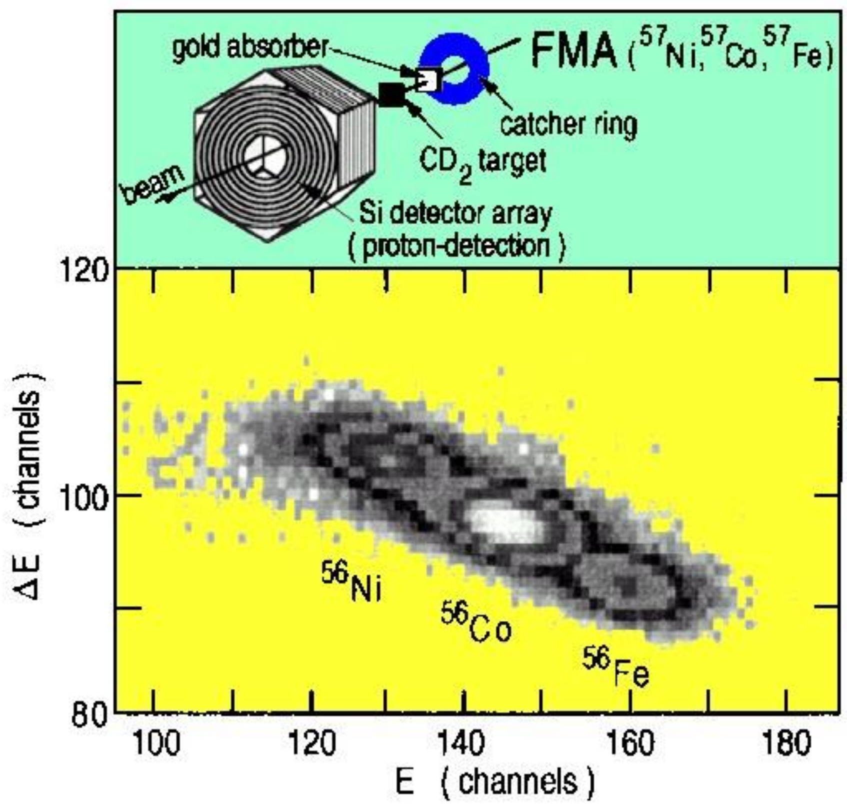
{ 0.74 0.19
Shell model }

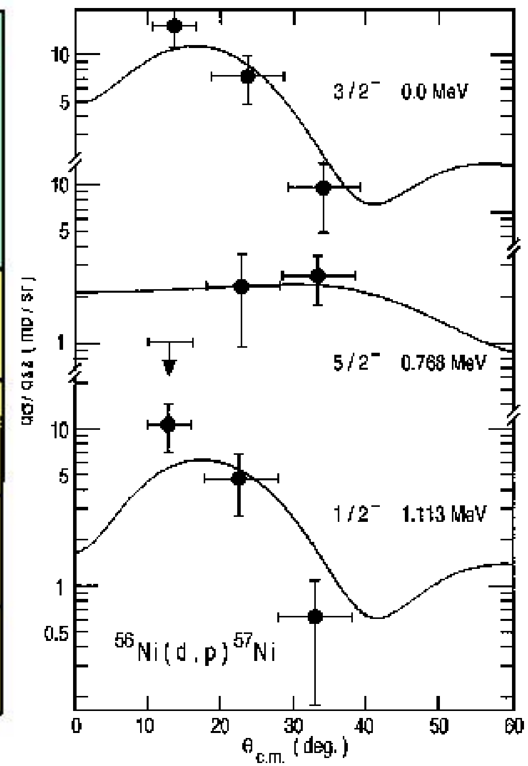


Study of the ^{56}Ni(d,p)^{57}Ni Reaction and the Astrophysical ^{56}Ni(p,γ)^{57}Cu Reaction Rate

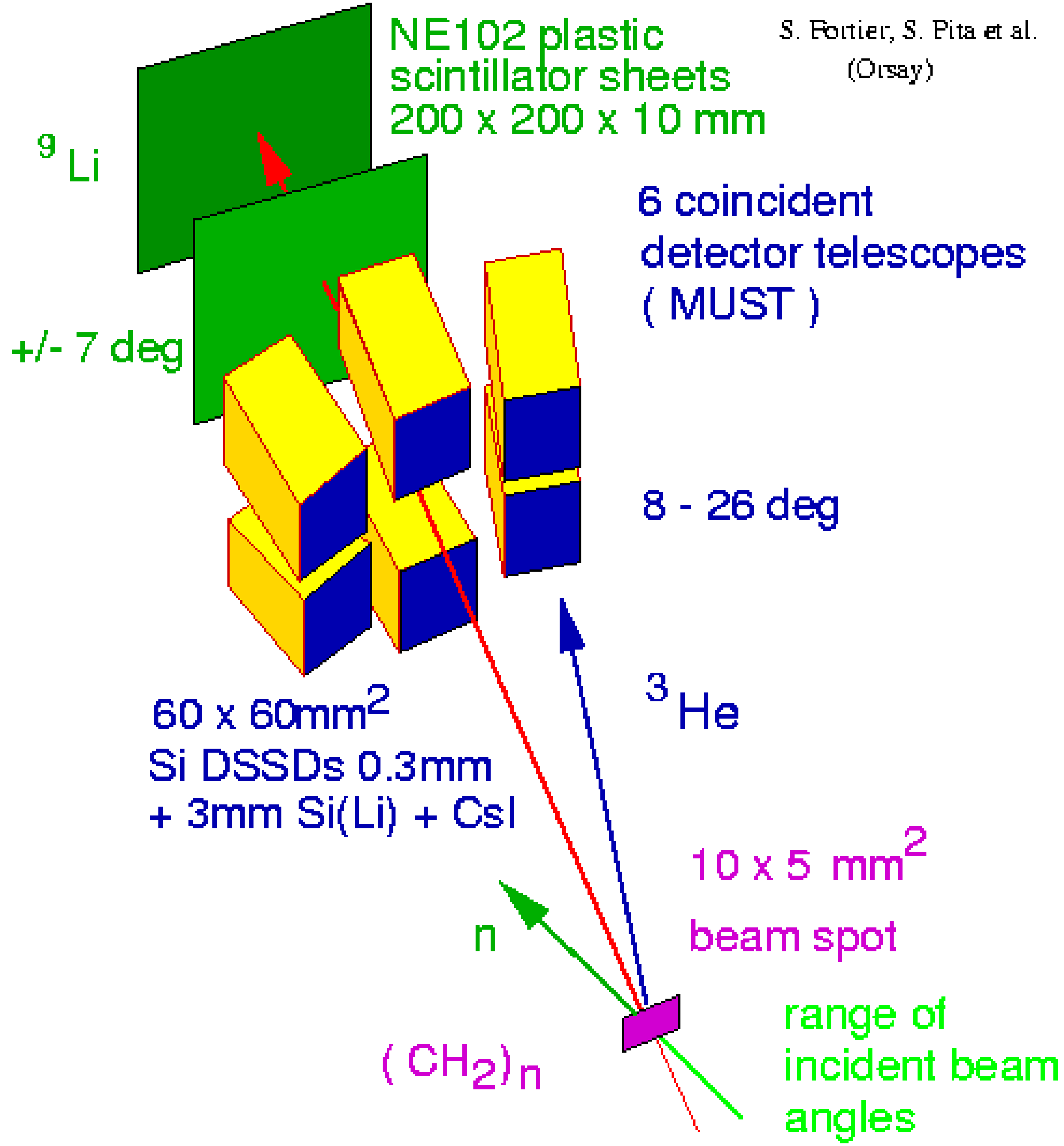
K. E. Rehm,[1] F. Borasi,[1] C. L. Jiang,[1] D. Ackermann,[1] I. Ahmad,[1] B. A. Brown,[2] F. Brumwell,[1] C. N. Davids,[1] P. Decrock,[1] S. M. Fischer,[1] J. Görres,[3] J. Greene,[1] G. Hackmann,[1] B. Harss,[1] D. Henderson,[1] W. Henning,[1] R. V. F. Janssens,[1] G. McMichael,[1] V. Nanal,[1] D. Nisius,[1] J. Nolen,[1] R. C. Pardo,[1] M. Paul,[4] P. Reiter,[1] J. P. Schiffer,[1] D. Seweryniak,[1] R. E. Segel,[5] M. Wiescher,[3] and A. H. Wuosmaa[1]







Inverse kinematics $^{11}Be(d,^{3}He)^{10}Li$



WHAT IS THE BEST IMPLEMENTATION FOR OPTIONS 2 AND 3 ?

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

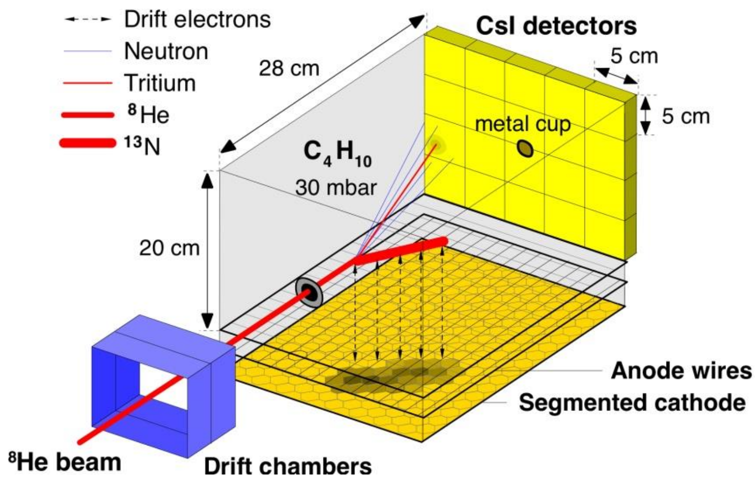
Several hundred keV is implicit, when tens would be required,
So the targets should be as thin as possible…

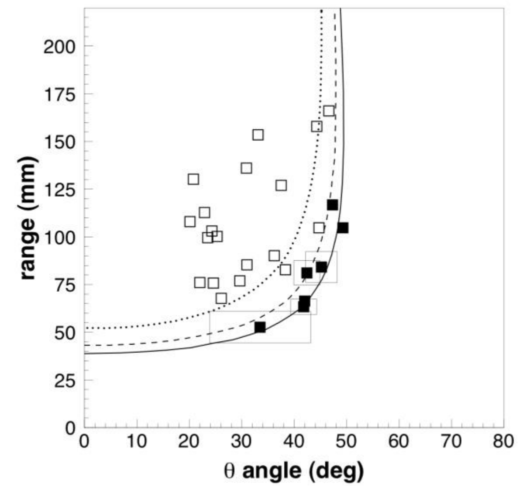
But RIBs, as well as being heavy compared to the deuteron target, are:
(a) Radioactive
(b) Weak

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

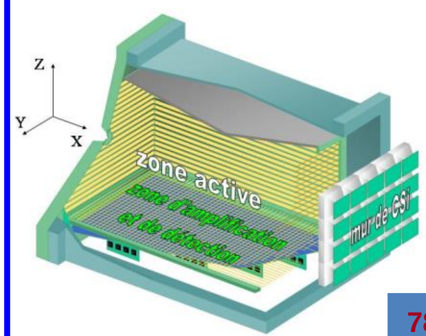
SOLUTIONS FOR BEAMS IN RANGE 10^2 to 10^4 pps USING TPC's

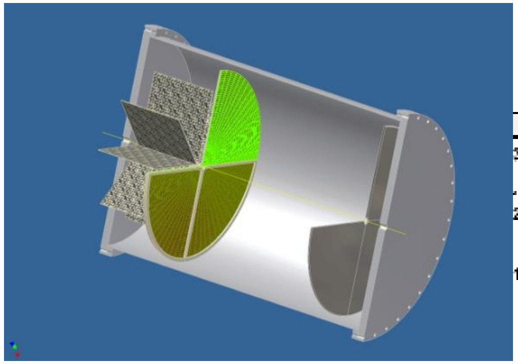




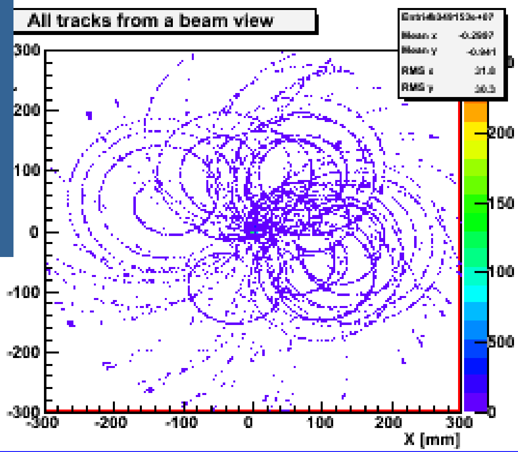
MAYA

Now in use at
GANIL/SPIRAL
TRIUMF





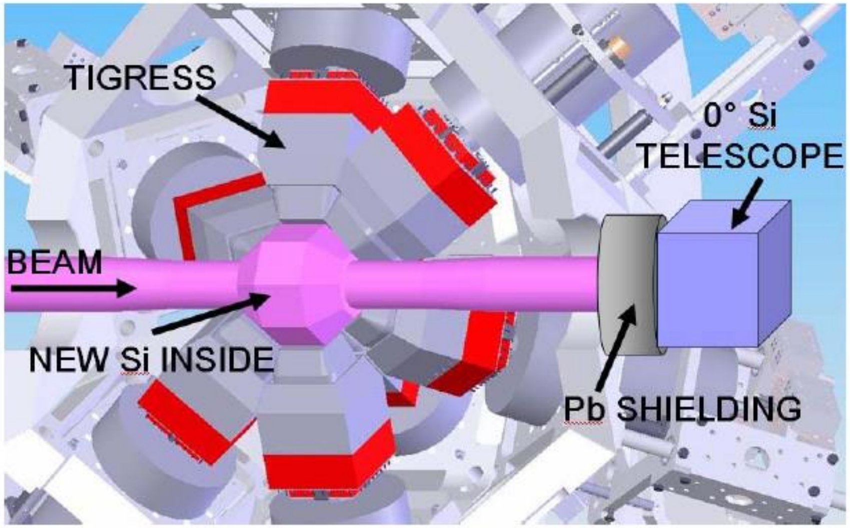
^{78}Ni(d,p)^{79}Ni at 10 A MeV

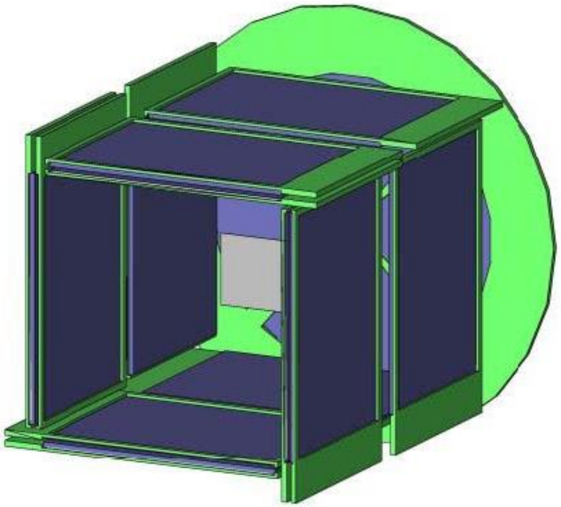


ACTAR

being designed
for future
SPIRAL2

SOLUTIONS FOR BEAMS IN RANGE 10^4 to 10^6 pps USING GAMMAS

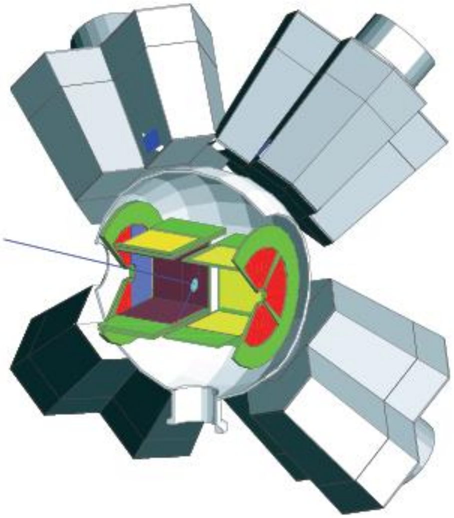


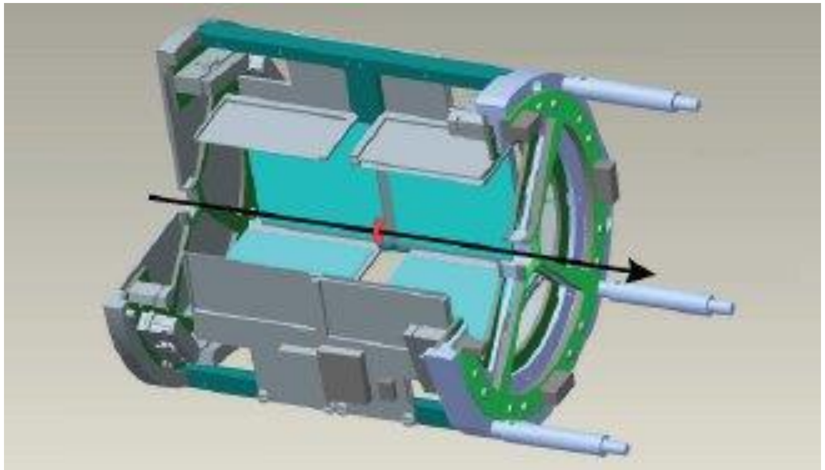


SHARC

TIGRESS
TRIUMF

TIGRESS COLLABORATION
York
Surrey



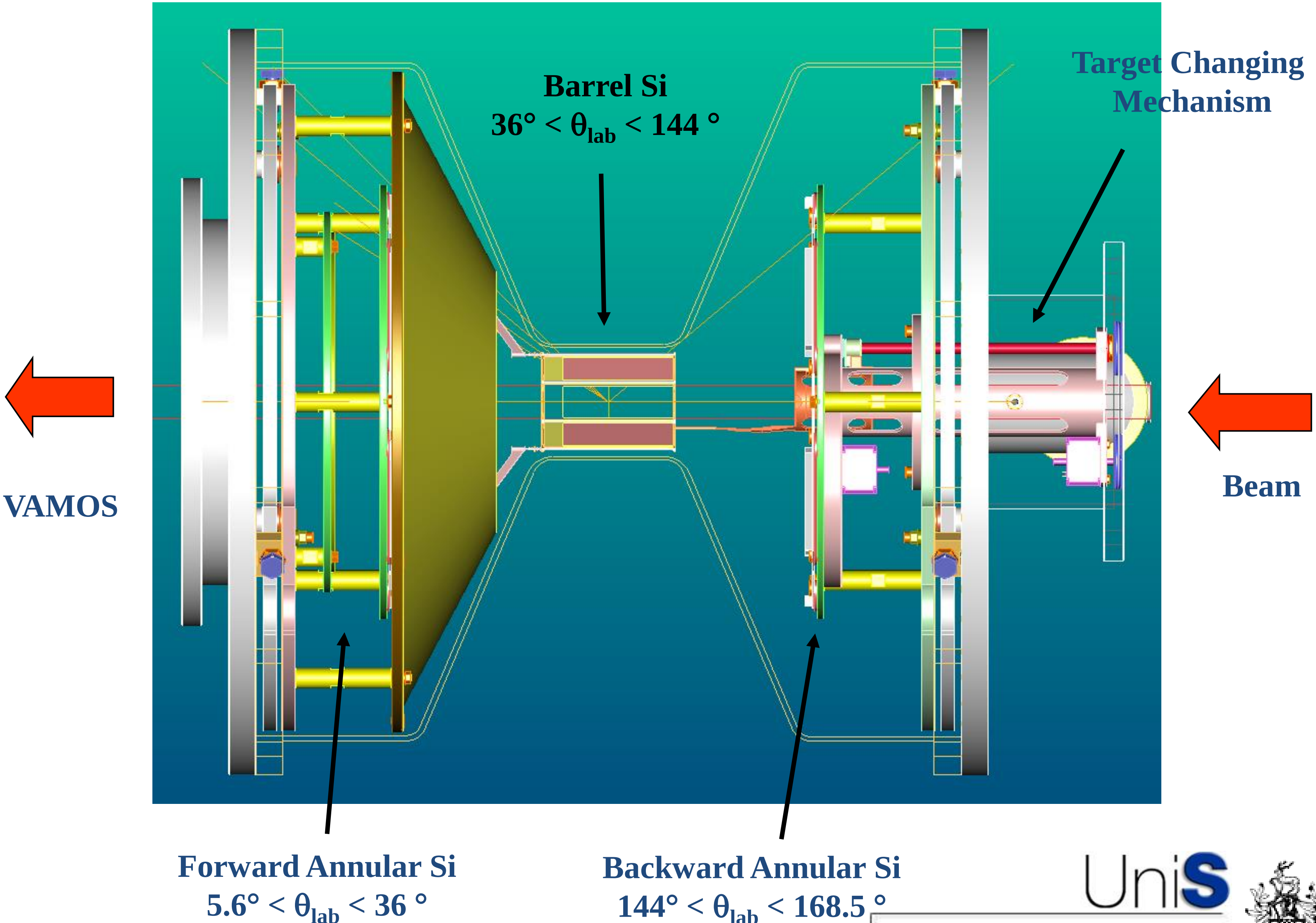


T-REX

MINIBALL
REX-ISOLDE

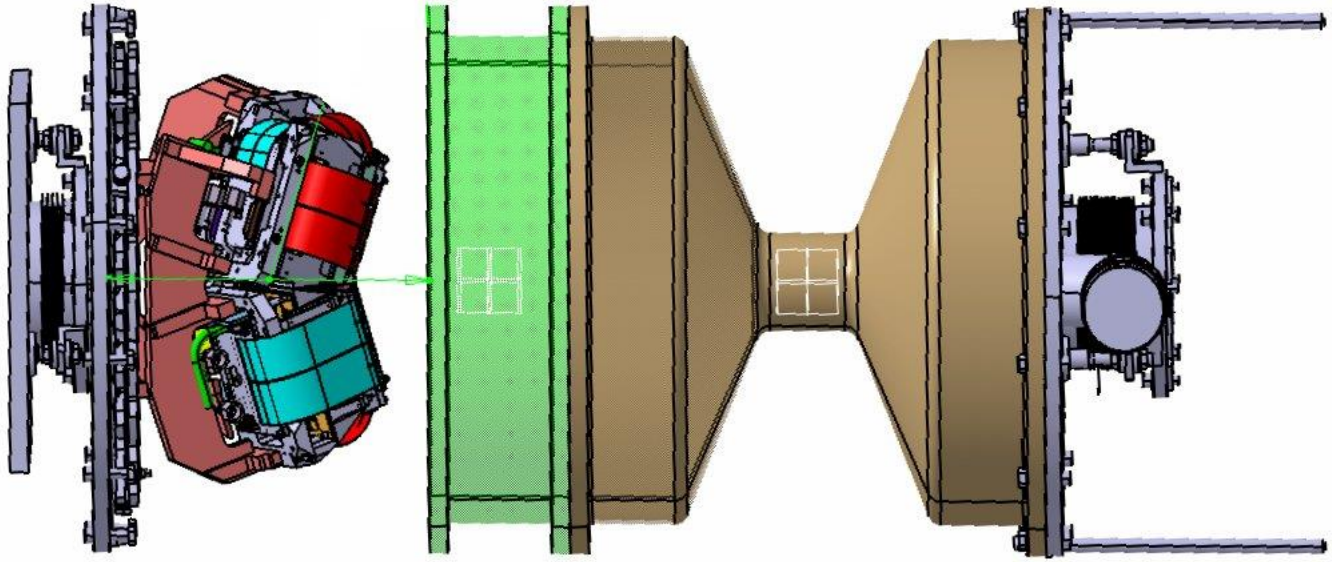
MINIBALL COLLABORATION
Munich
Leuven

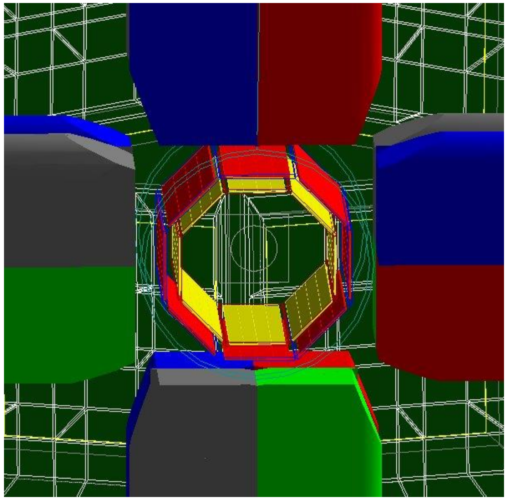
ORRUBA OAK RIDGE

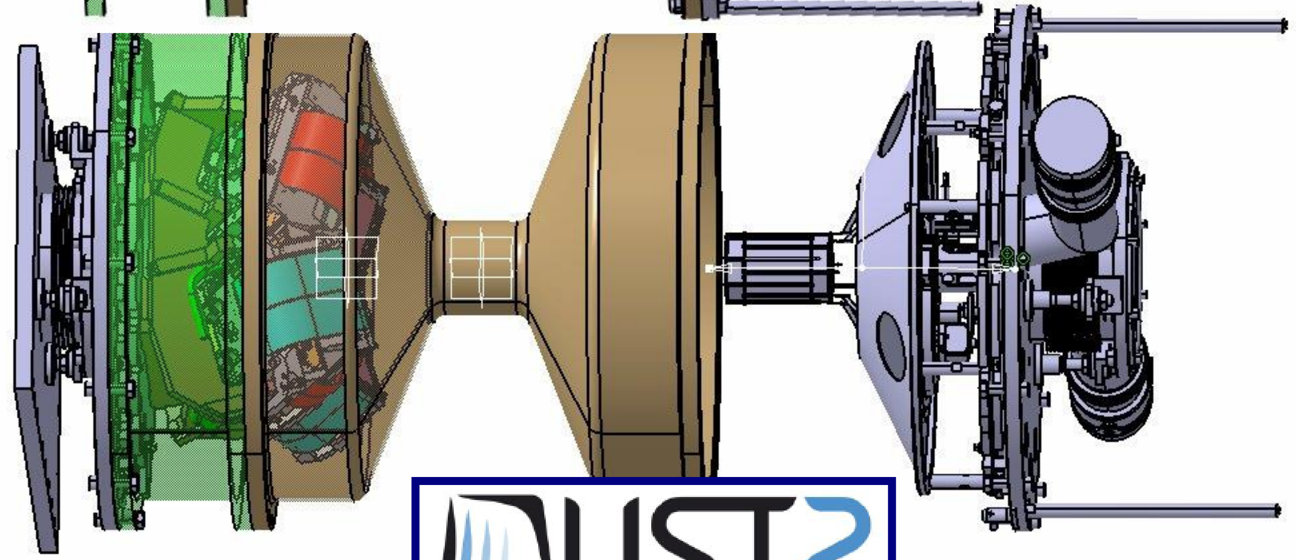


UniS
University of Surrey

SOLUTIONS FOR BEAMS IN RANGE 10^6 to 10^9 pps USING GAMMAS



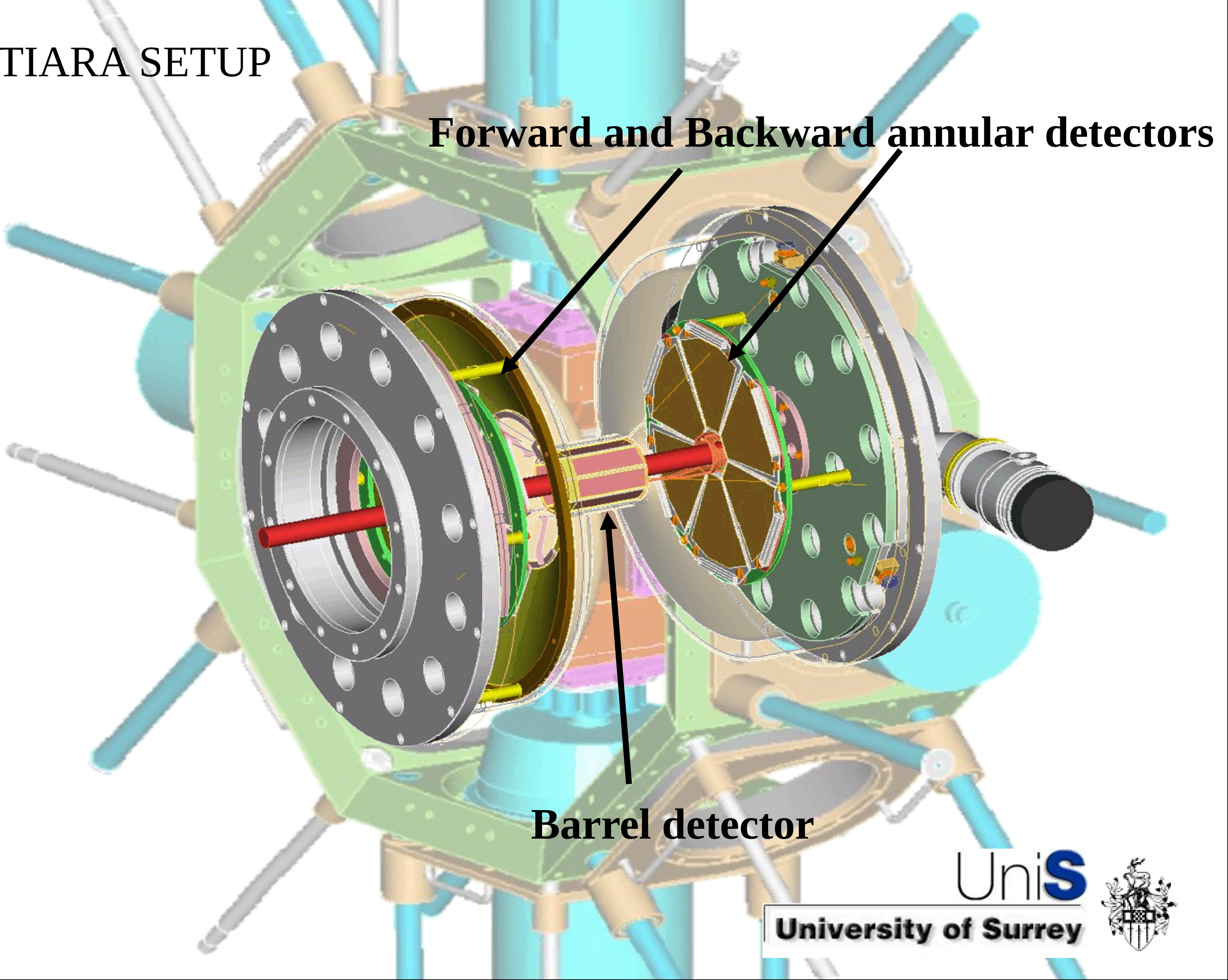




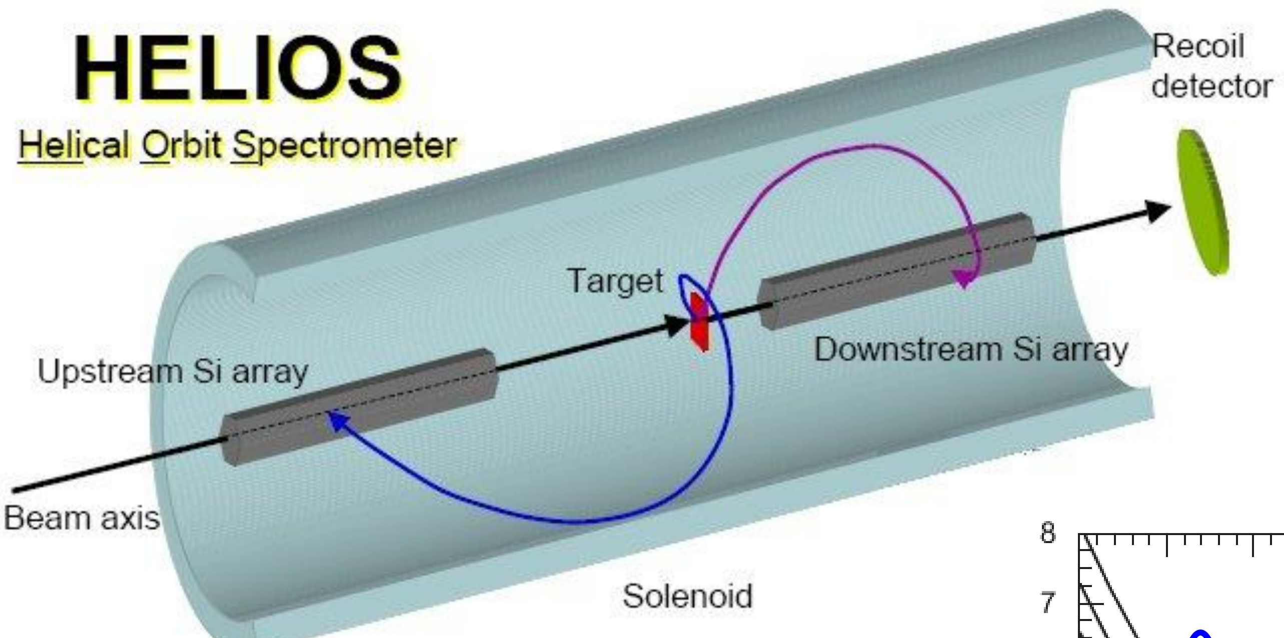
MUST2

TIARA

TIARA SETUP

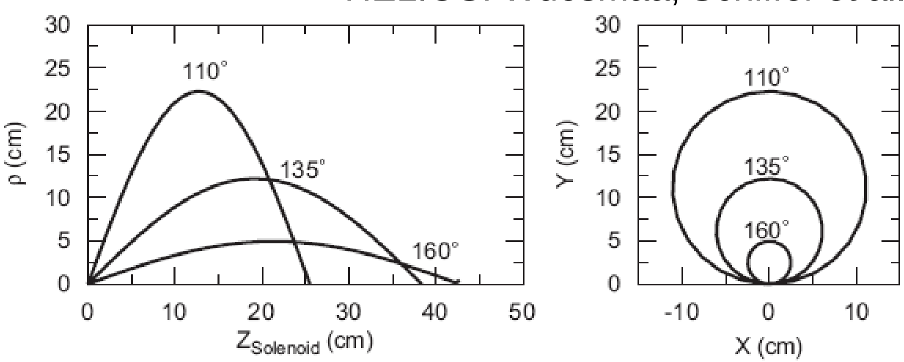

Forward and Backward annular detectors
Barrel detector
UniS
University of Surrey

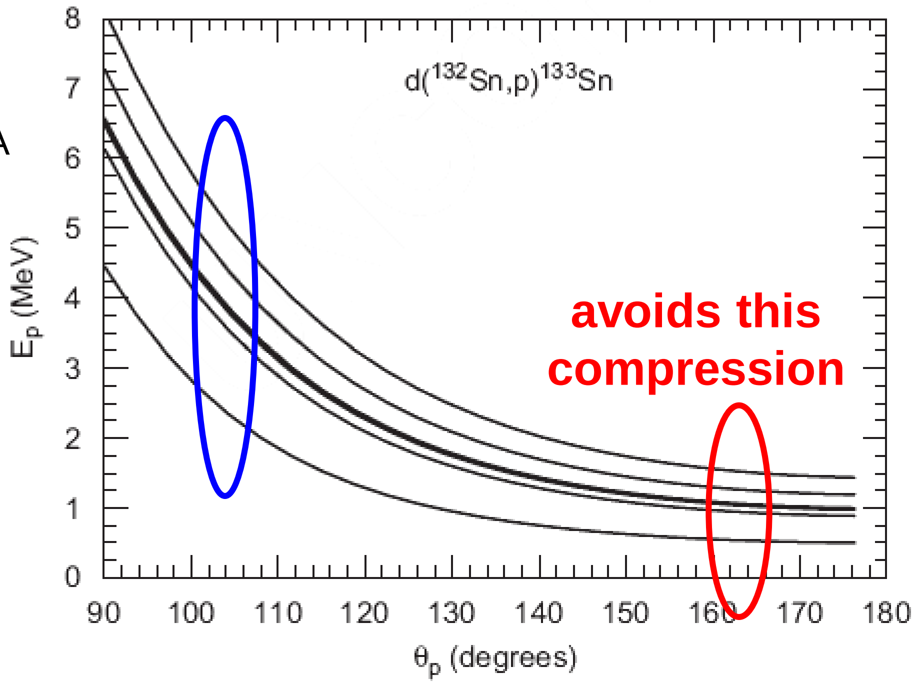
NOVEL SOLENOID FOR 4π DETECTION to DECOMPRESS KINEMATICS



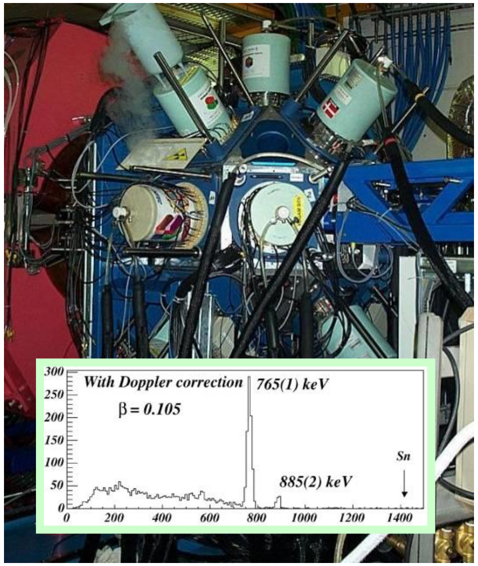
Actual solenoid – from MRI

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

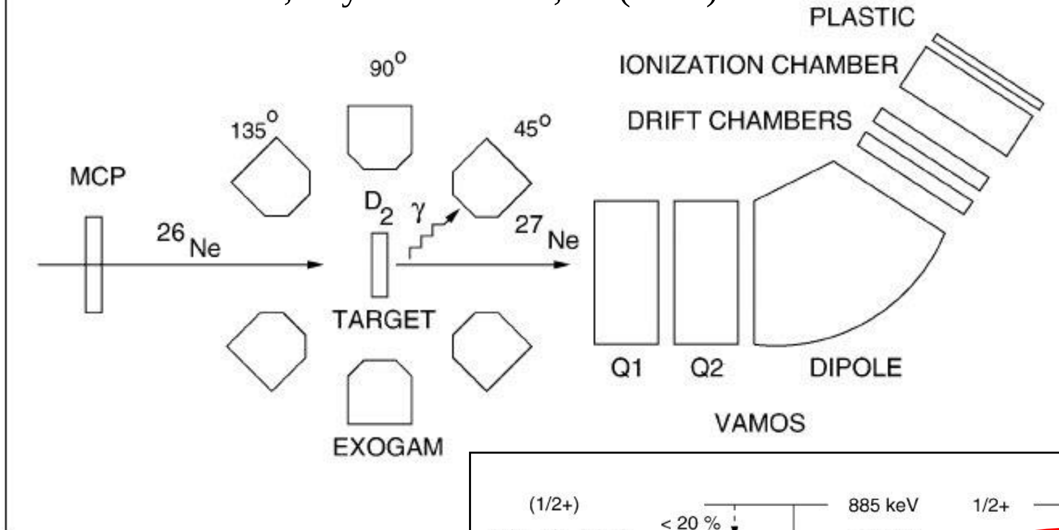


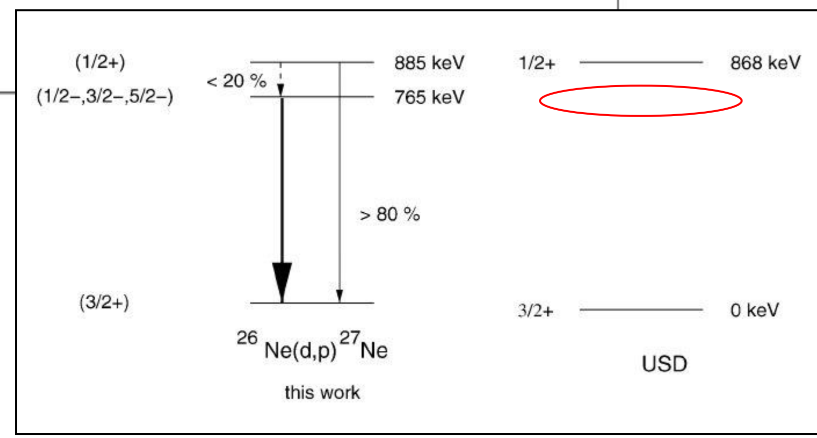


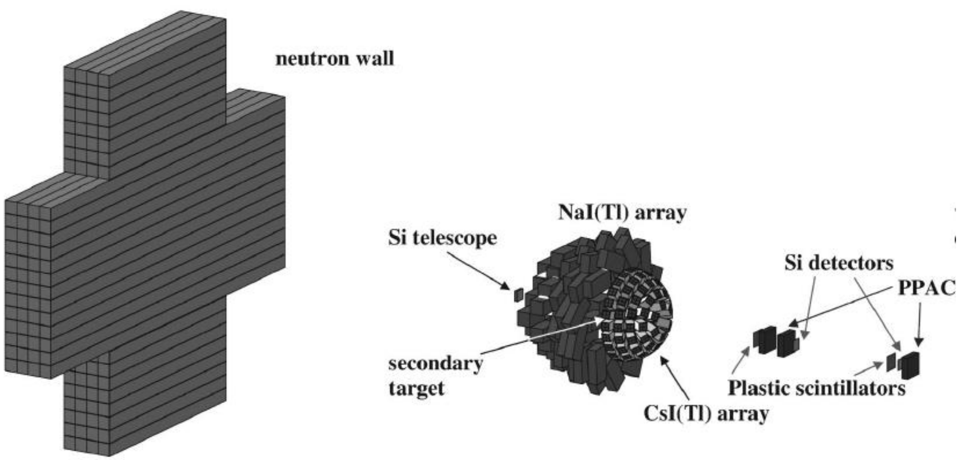
FROZEN TARGETS and not detecting the LIGHT PARTICLE



A. Obertelli *et al.*, Phys. Lett. **B633**, 33 (2006).







Also:

Elekes et al PRL 98 (2007) 102502

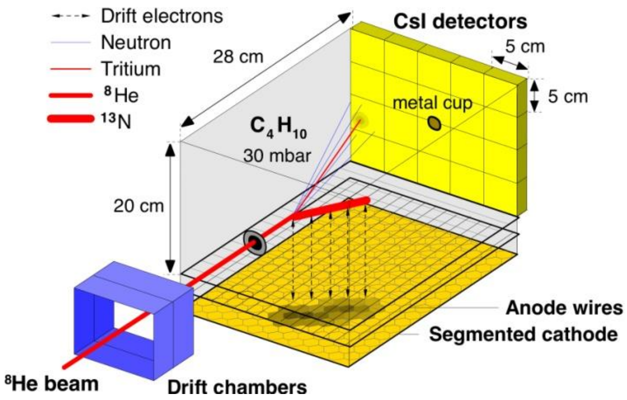
^{22}O(d,p) to n-unbound ^{23}O SP states

And helium:

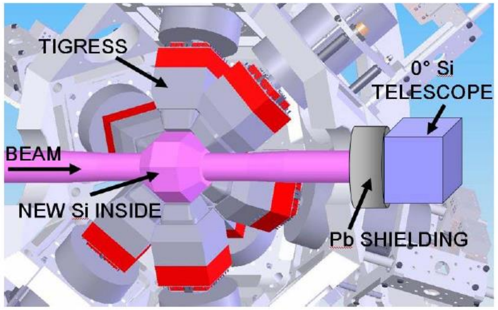
Especially (α,^{3}He) etc. at RIKEN

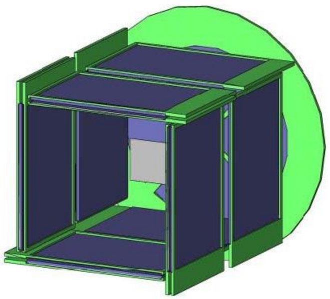
Experimental approaches largely depend on the beam intensity and resolution:

Below 10^4 pps MAYA, ACTAR…

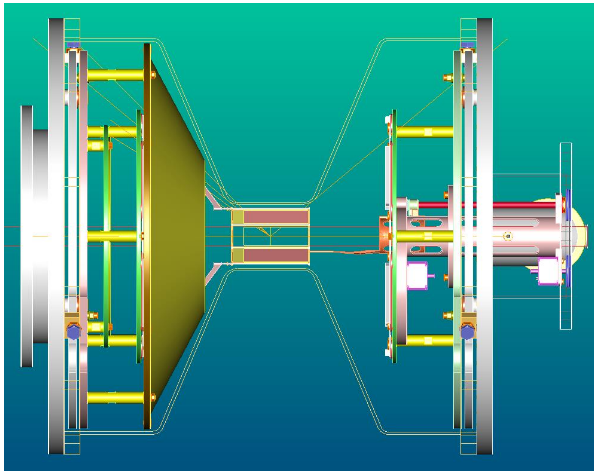


Below 10^6 pps SHARC, T-REX…



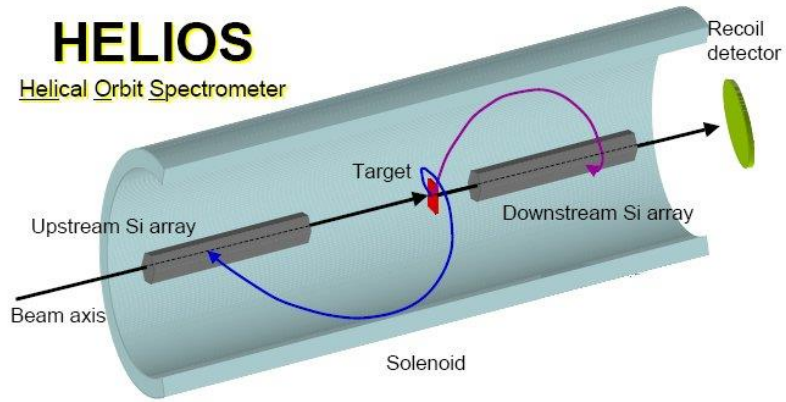


Up to 10^9 pps TIARA or alternatively…



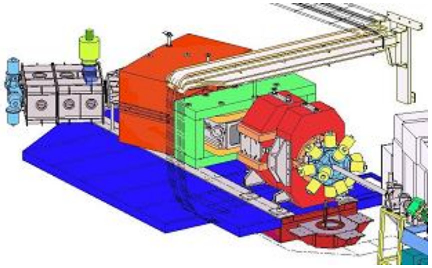
TIARA

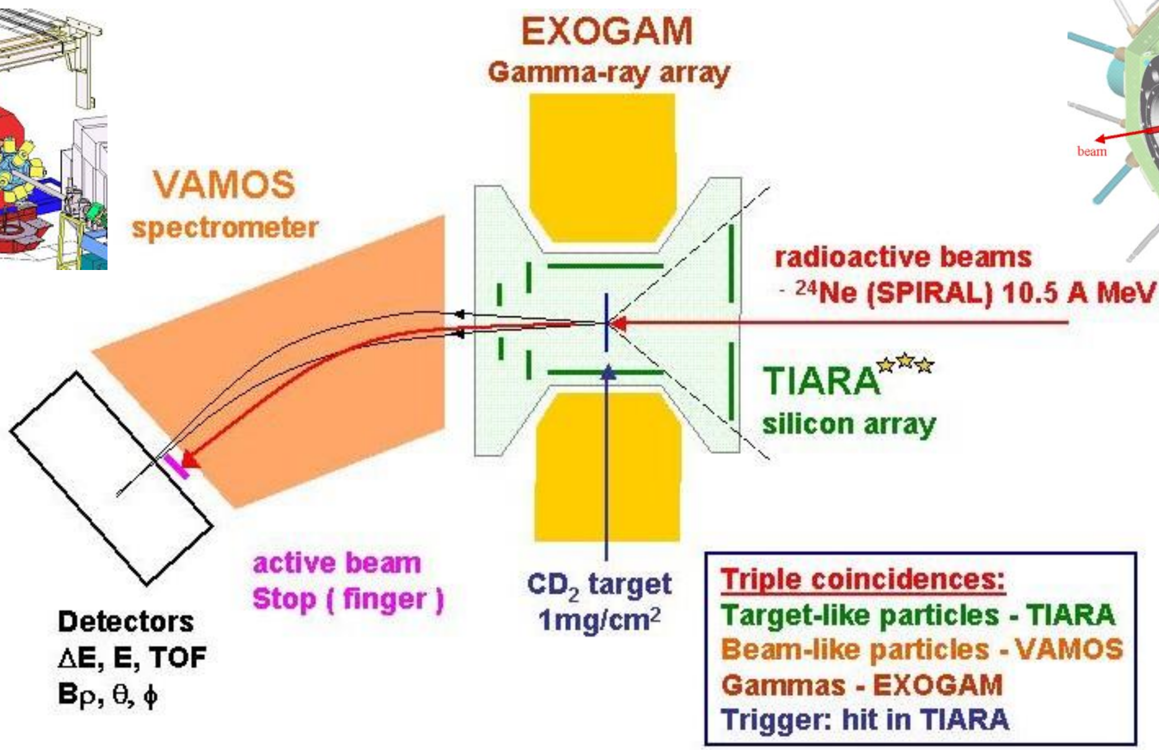
A solenoid device…

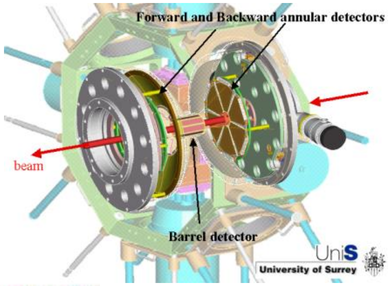


OUR EXPERIMENT TO STUDY ^{25}Ne $d_{3/2}$

^{24}Ne(d,pγ) N=16 replaces broken N=20







Schematic of the TIARA setup. A beam of 10^5 pps of ^{24}Ne at 10.5A MeV was provided from SPIRAL, limited to 8π mm.mrad to give a beam spot size of 1.5-2.0 mm. The target was 1.0 mg/cm^2 of $(CD_2)_n$ plastic. The TIARA array covered 90% of 4π with active silicon.

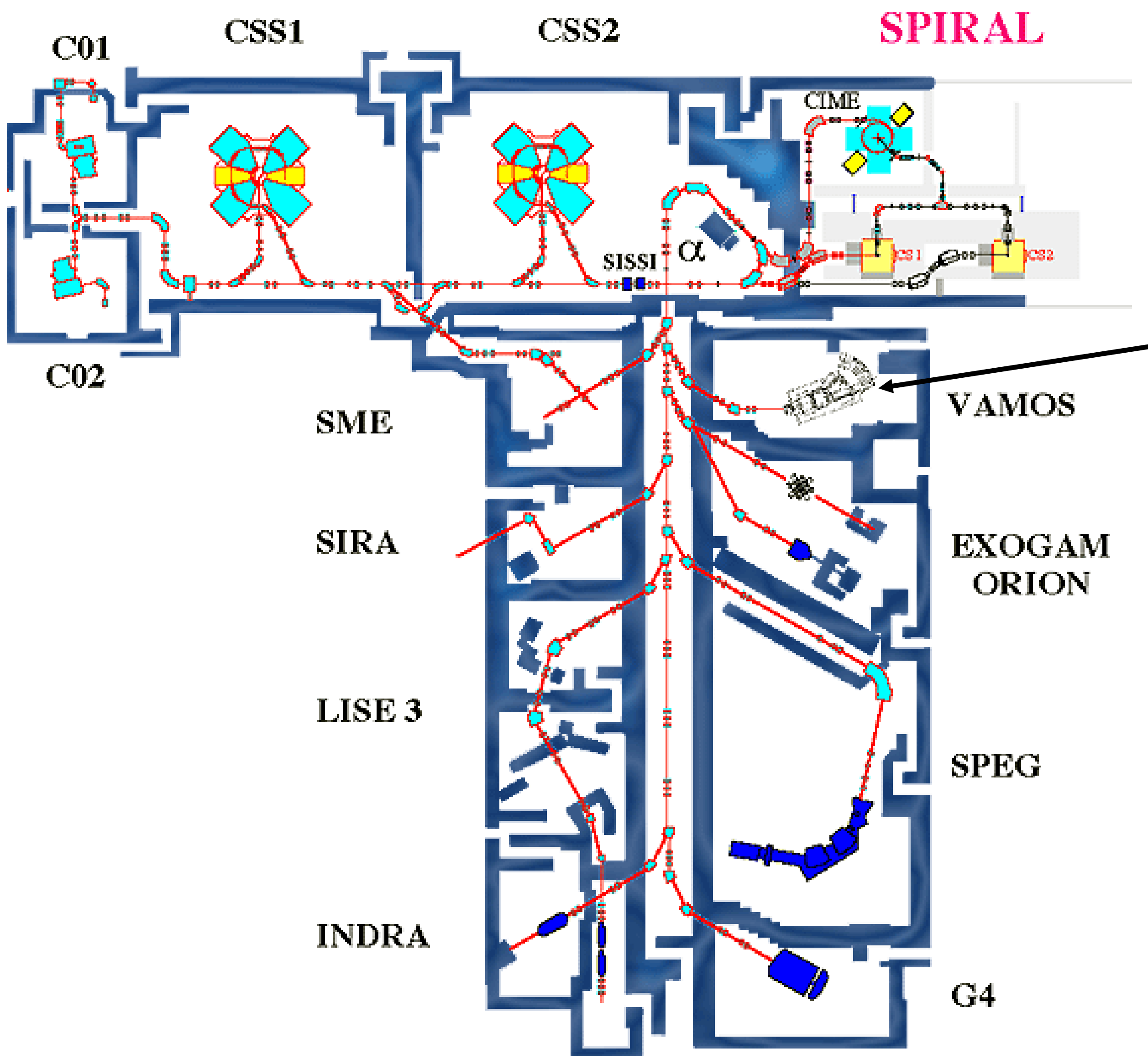
W.N. Catford *et al.*, Eur. Phys. J. **A25**, Suppl. 1, 245 (2005).

TIARA SPIRAL

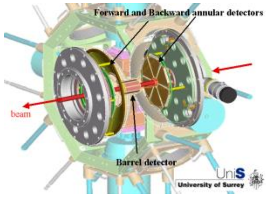
GANIL

GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

LABORATOIRE COMMUN DSM/CEA-IN2P3/CNRS



TIARA★★★



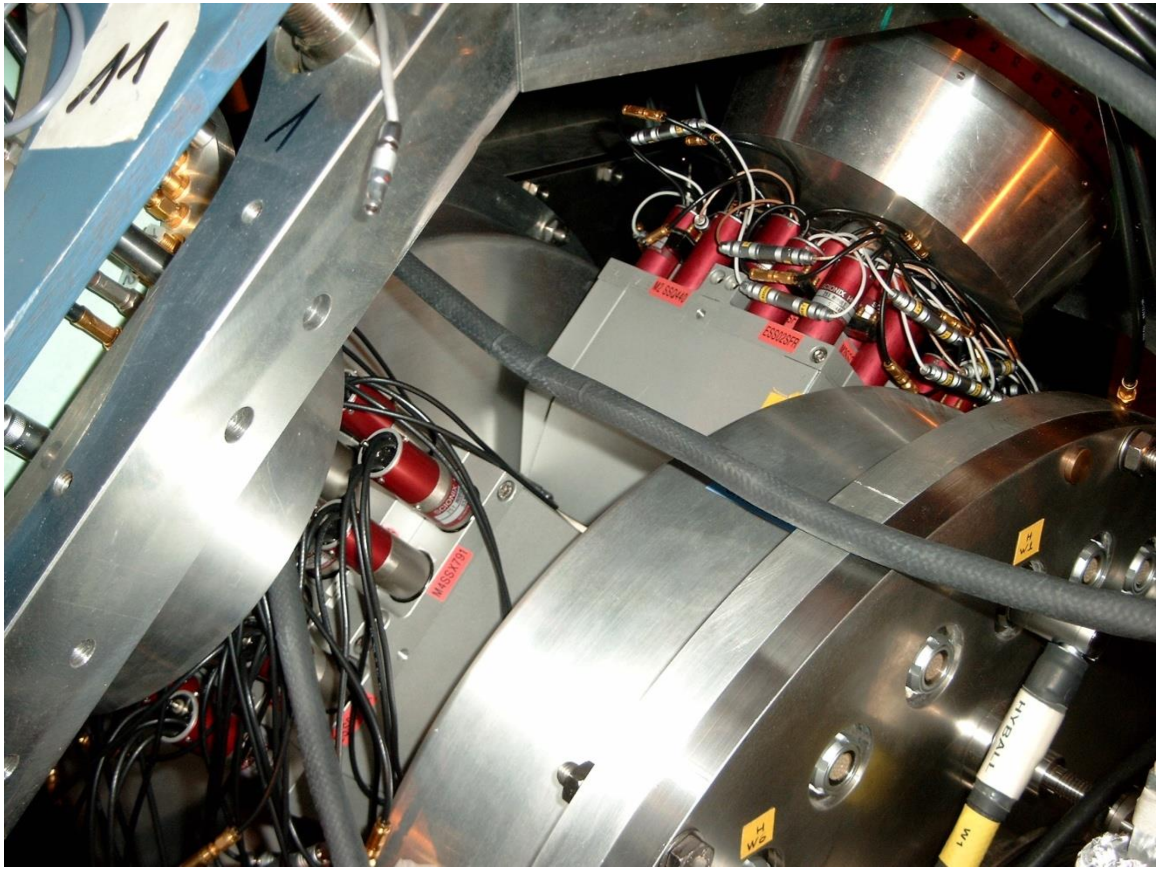
$^{24}Ne + d$

$\rightarrow {}^{25}Ne + p$

τ = 3.38 min

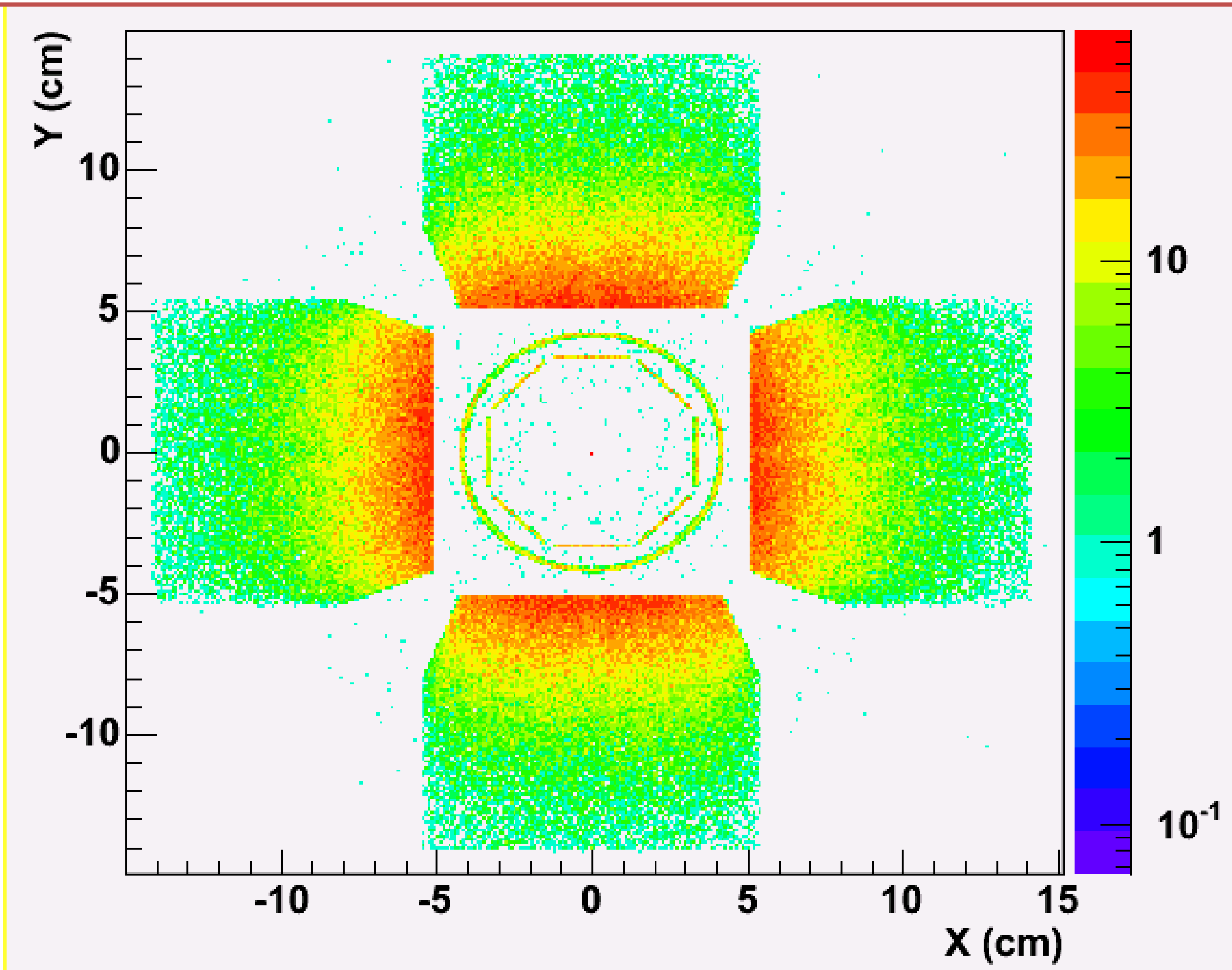
100,000 pps

EXOGAM + TIARA



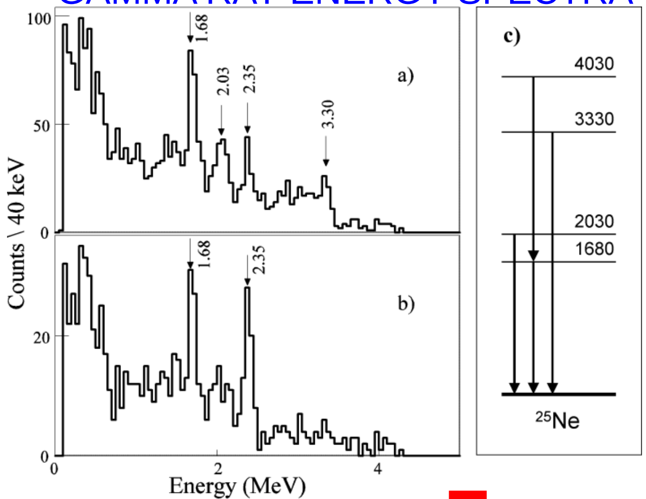
TIARA

Geant simulation: first interaction point for E(gamma) = 2.05 MeV



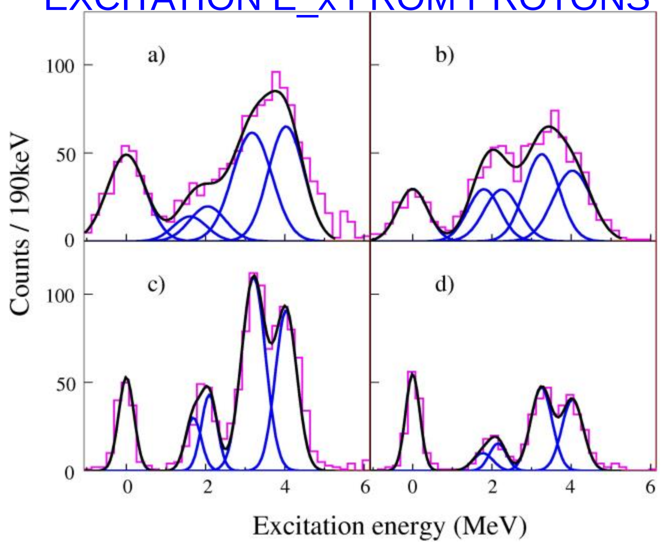
Results from the experiment to study ^{25}Ne

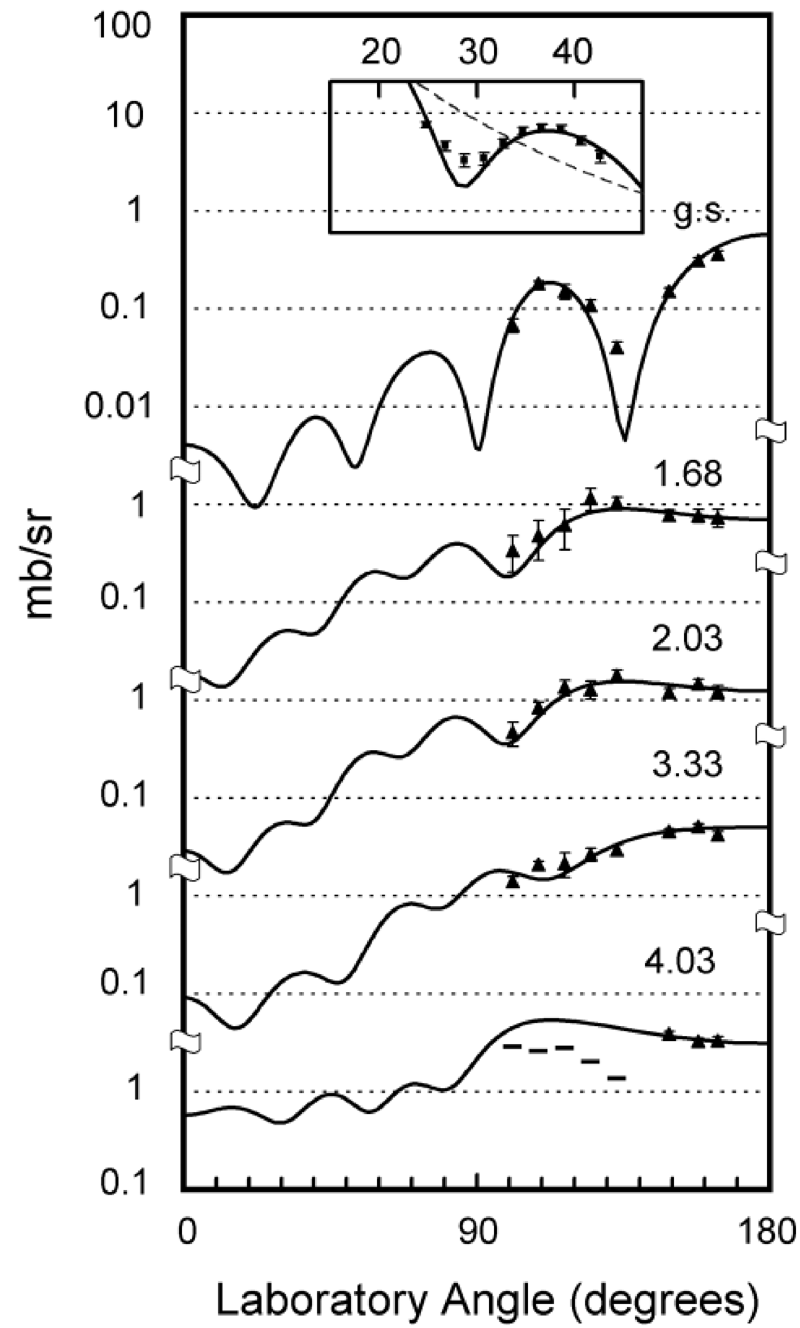
GAMMA RAY ENERGY SPECTRA



FIX E_x

EXCITATION E_x FROM PROTONS

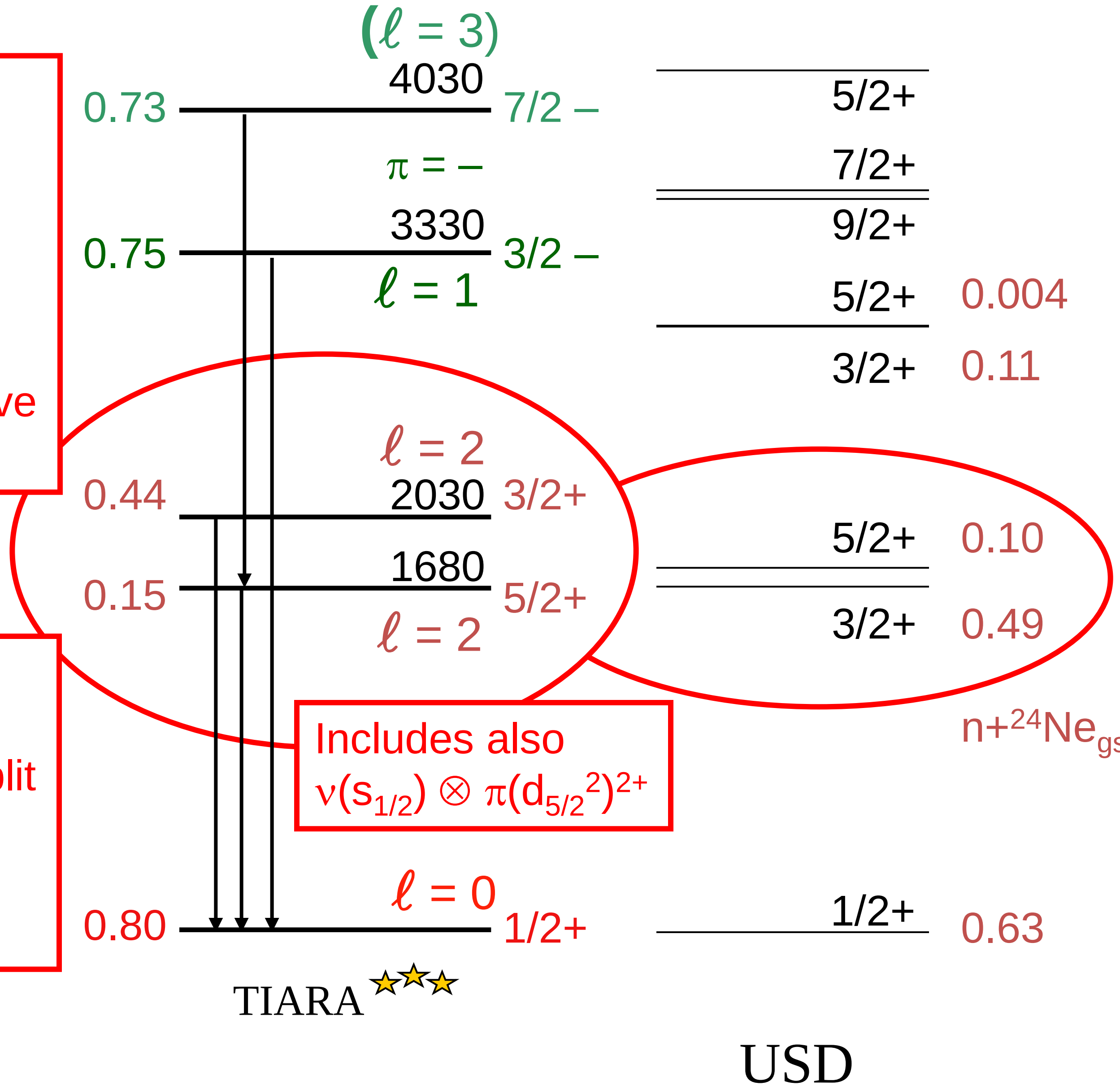




SOME RESULTS and PERSPECTIVES

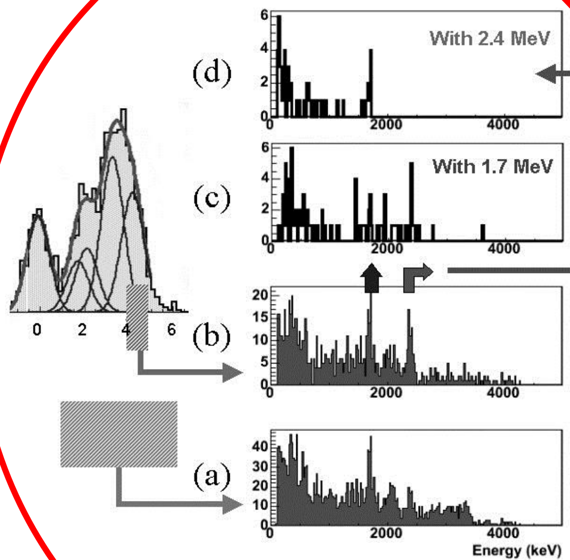
In ^{25}Ne the $3/2^+$ state was far from a pure SP state due to other couplings at higher energies, but it was clear enough in its ID and could be used to compare with its SM partner to improve the USD interaction

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

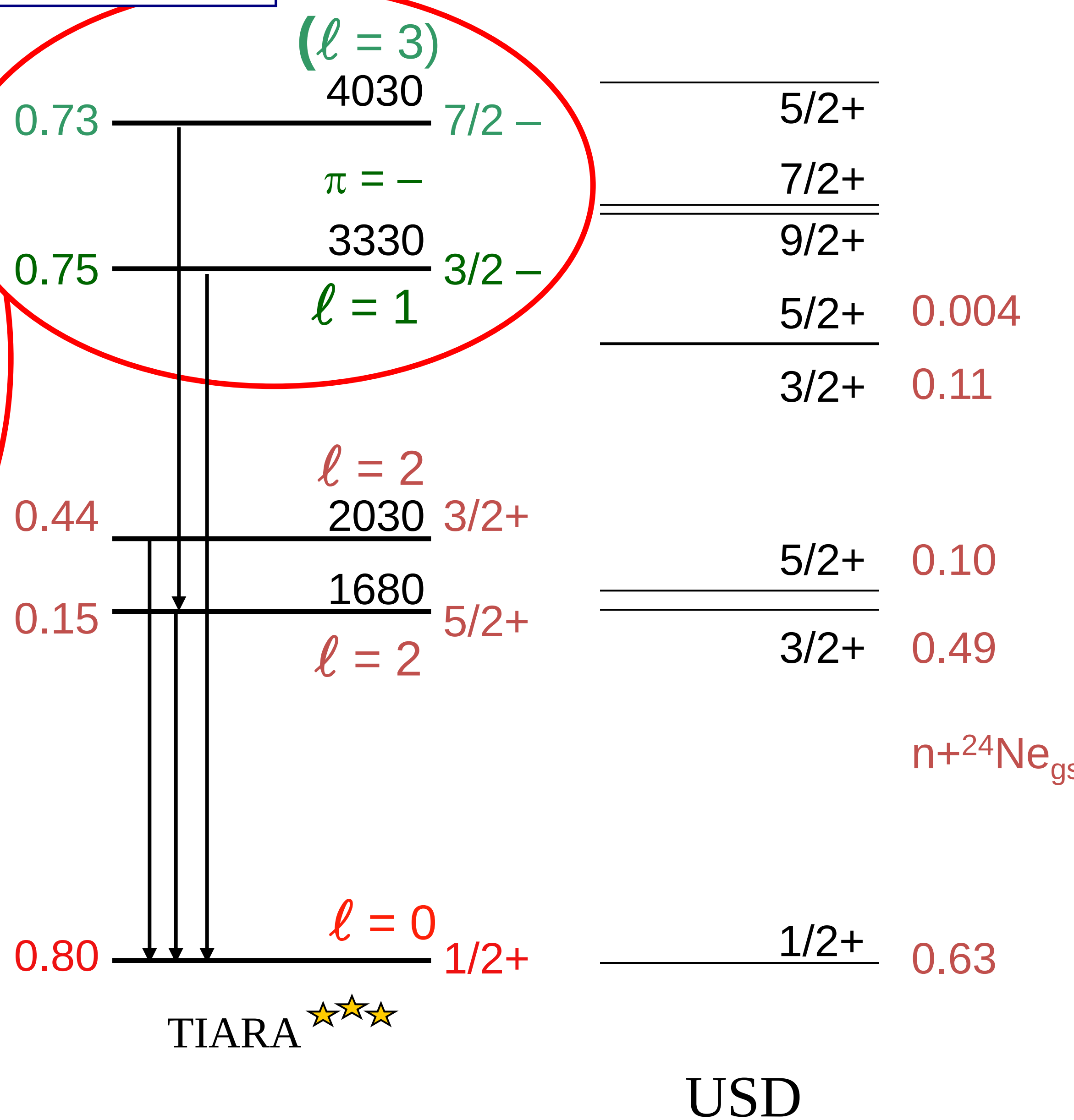


WILTON CATFORD JUNE 2008

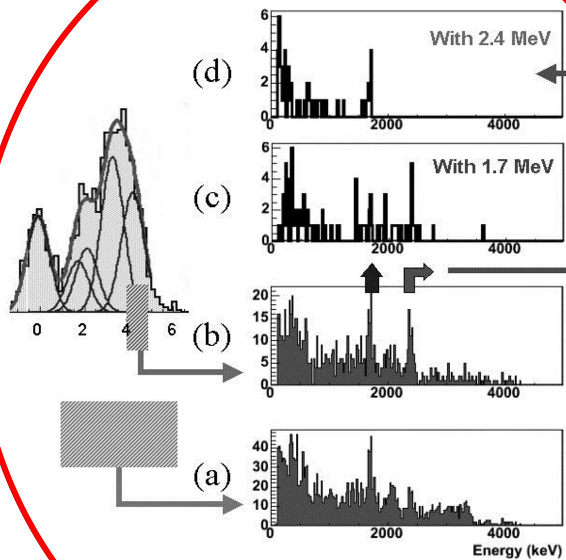
E. SOME RESULTS and PERSPECTIVES



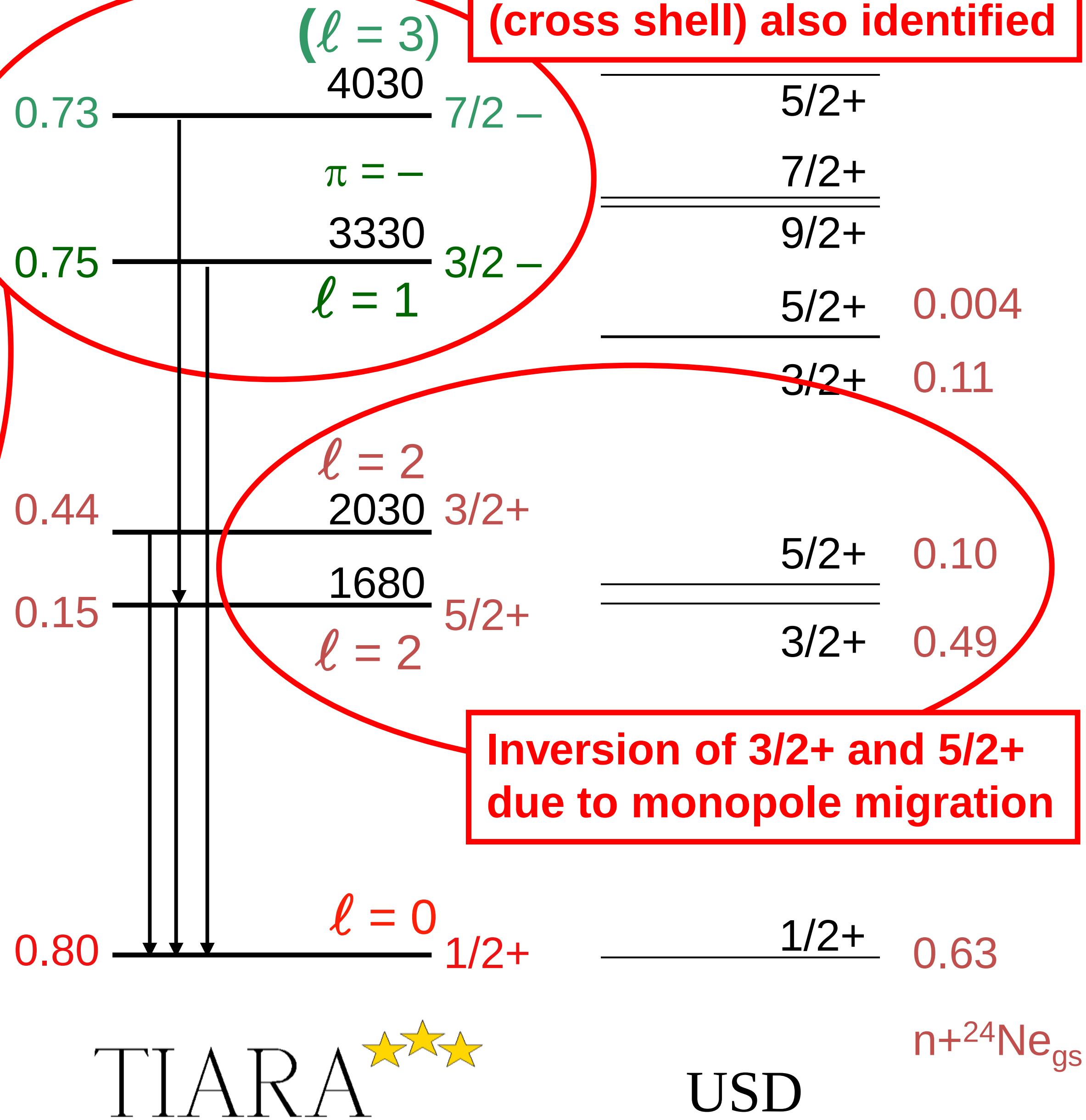
In ^{25}Ne we used gamma-gamma coincidences to distinguish spins and go beyond orbital AM



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

Physics outcomes for ^{25}Ne study:

COZMIN TIMIS and WNC, SURREY

Identified lowest lying 3/2+ and 5/2+ excited states

Showed that 3/2+ is significantly raised due to monopole shift,
Supporting N=16 emerging as a shell gap

Identified lowest negative parity intruder states as 3/2– and 7/2–

Measured relative energy of negative parity intruder states,
Supporting N=20 disappearance as a shell gap, and also
Supporting N=28 disappearance as a shell gap

Provided quantitative input to measuring magnitude of monopole shift

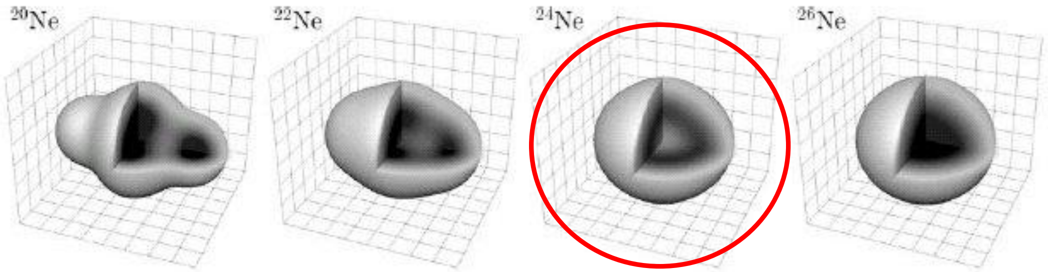


Fig. 12. Intrinsic single-particle density distribution $\rho(\mathbf{x})$ for different neon isotopes (cf. Fig. 11).

Roth, Neff et al., NPA 745 (2004) 3-33

We proceed from here by

- removing more protons from d5/2 – that is, looking at oxygen, namely **^{21}O**

… there are important anomalies to resolve, regarding the ν(d3/2) energy

- also looking at the more exotic neon isotopes – namely **^{27}Ne**, N=17

Oxygen 23 by (d,p) at 600 pps

PRL **98**, 102502 (2007) PHYSICAL REV

Elekes et al

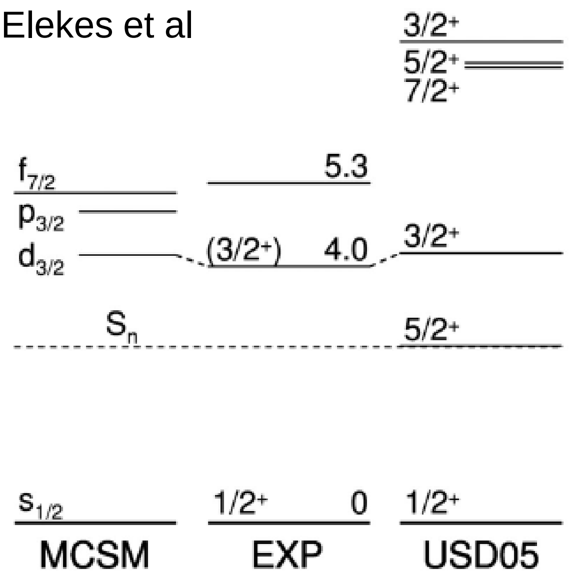


FIG. 4. Excited states of ^{23}O observed in the present experiment in comparison with the shell model calculation using the USD05 [11,12] interaction and the effective single particle energies taken from the Monte Carlo shell model (MCSM) calculation based on the SDPF-M interaction [15].

Oxygen 25 by ^{26}F – p at 20 pps

PRL **100**, 152502 (2008)

Hoffman et al

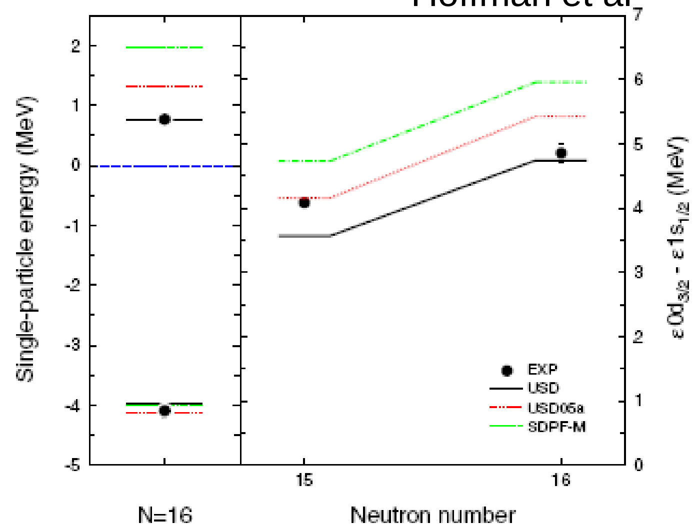


FIG. 3 (color online). The experimental (data points) and theoretical [13–15] (lines) single-particle energies (SPE) for the $\nu 1s_{1/2}$ and $\nu 0d_{3/2}$ orbitals at $N = 16$ are shown on the left. The difference between these SPEs is shown for $Z = 8$, $N = 15$ [12] and 16, giving the $N = 16$ shell gap size. Errors are shown if they are larger than the symbol size.

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 ^1H in the ^2H target allowed (p,d) measurements also

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