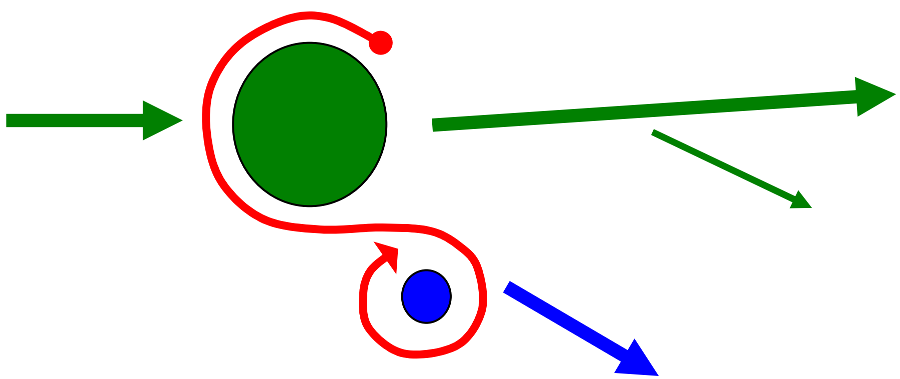
Transfer reactions in Inverse Kinematics
*
an experimental overview

Nucleon Transfer with Radioactive Beams



- focus on 10-30 MeV/A reactions
- kinematics are then generic
- a general array can be envisaged
- resolution issues are general
- three classes of solution/choice
- catalyst to discussion
- outline of TIARA array

- overview : Nucl Phys A701 (2002) 1c-6c
- overview : Acta Phys Pol 32B (2001) 1049-1060
- resolution : JSW et al NIM A396 (1997) 147-164

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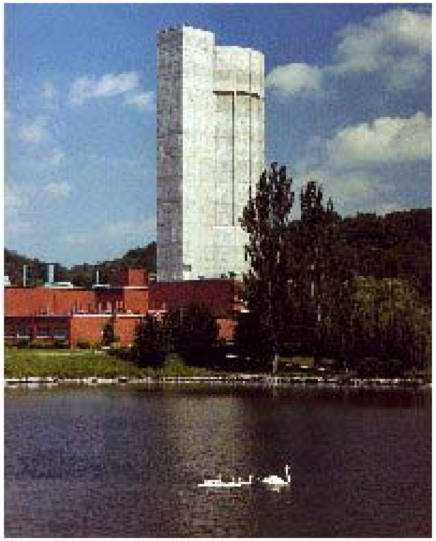
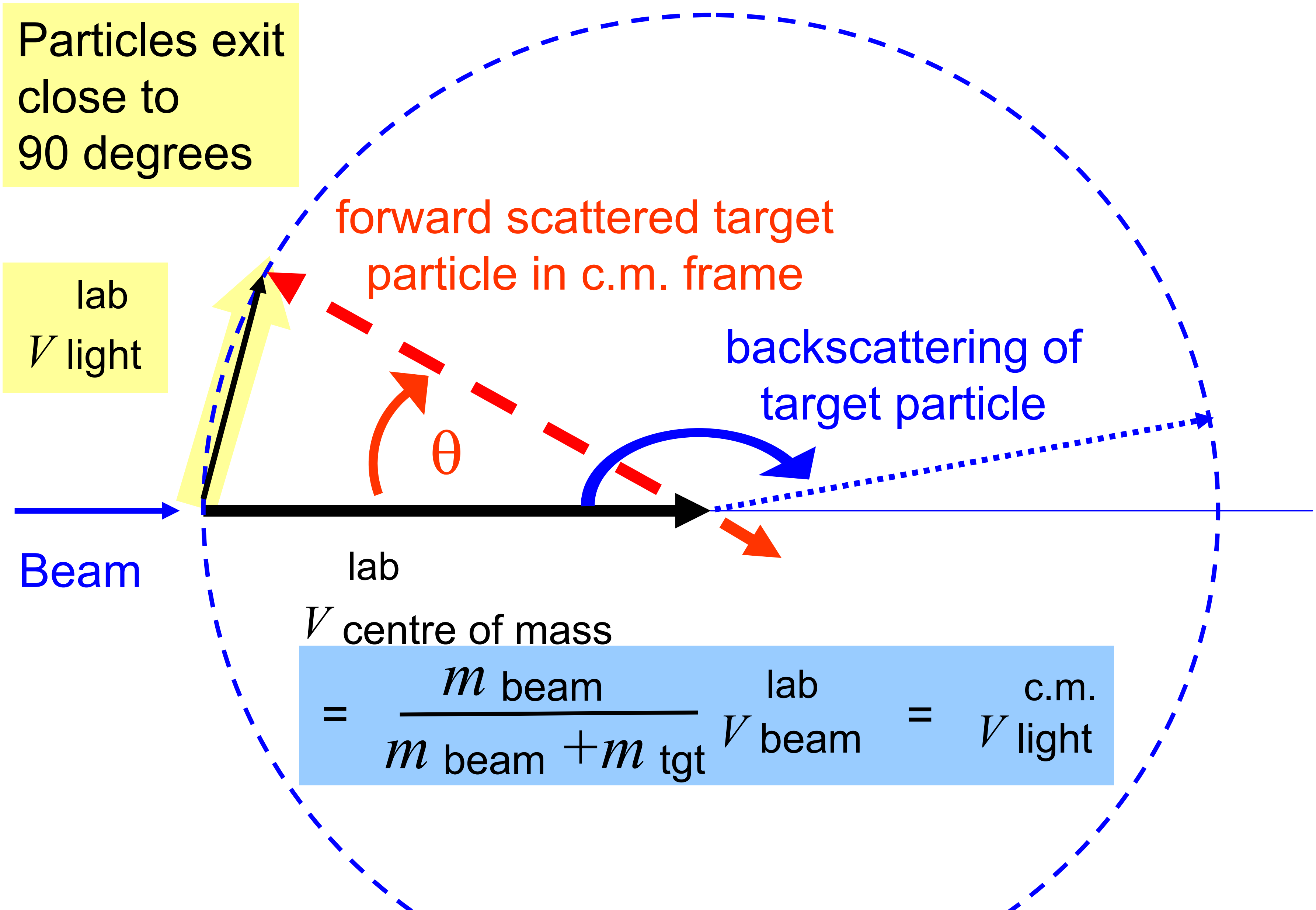
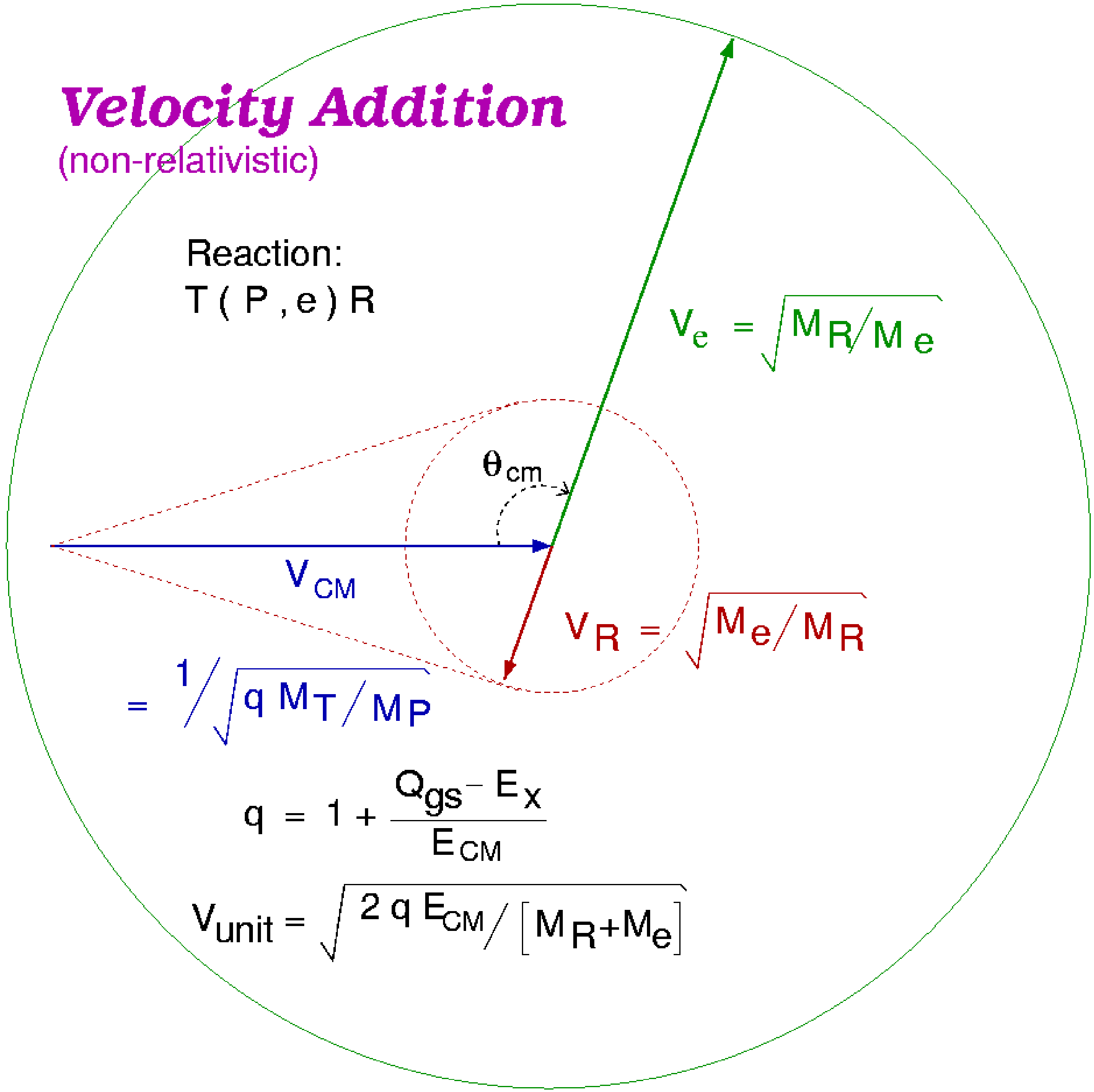
Oak Ridge TN
June 2002



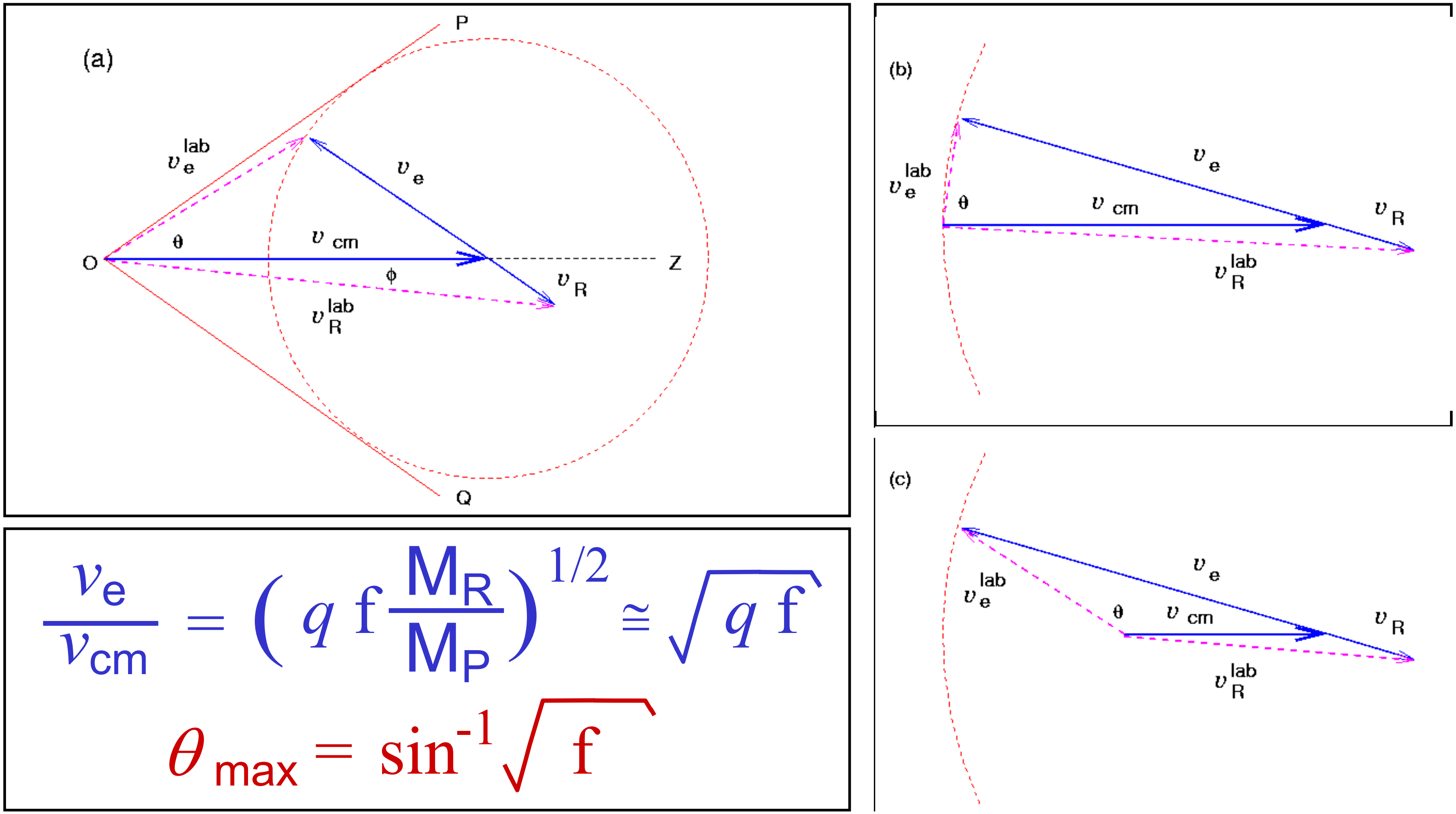
Velocity vector addition diagram




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

Inverse Kinematics

$q \cong 1 + Q_{tot} / (E/A)_{beam}$
f = 1/2 for (p,d), 2/3 for (d,t)



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

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

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

Reaction Q-values in MeV

Z

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												

= 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

N

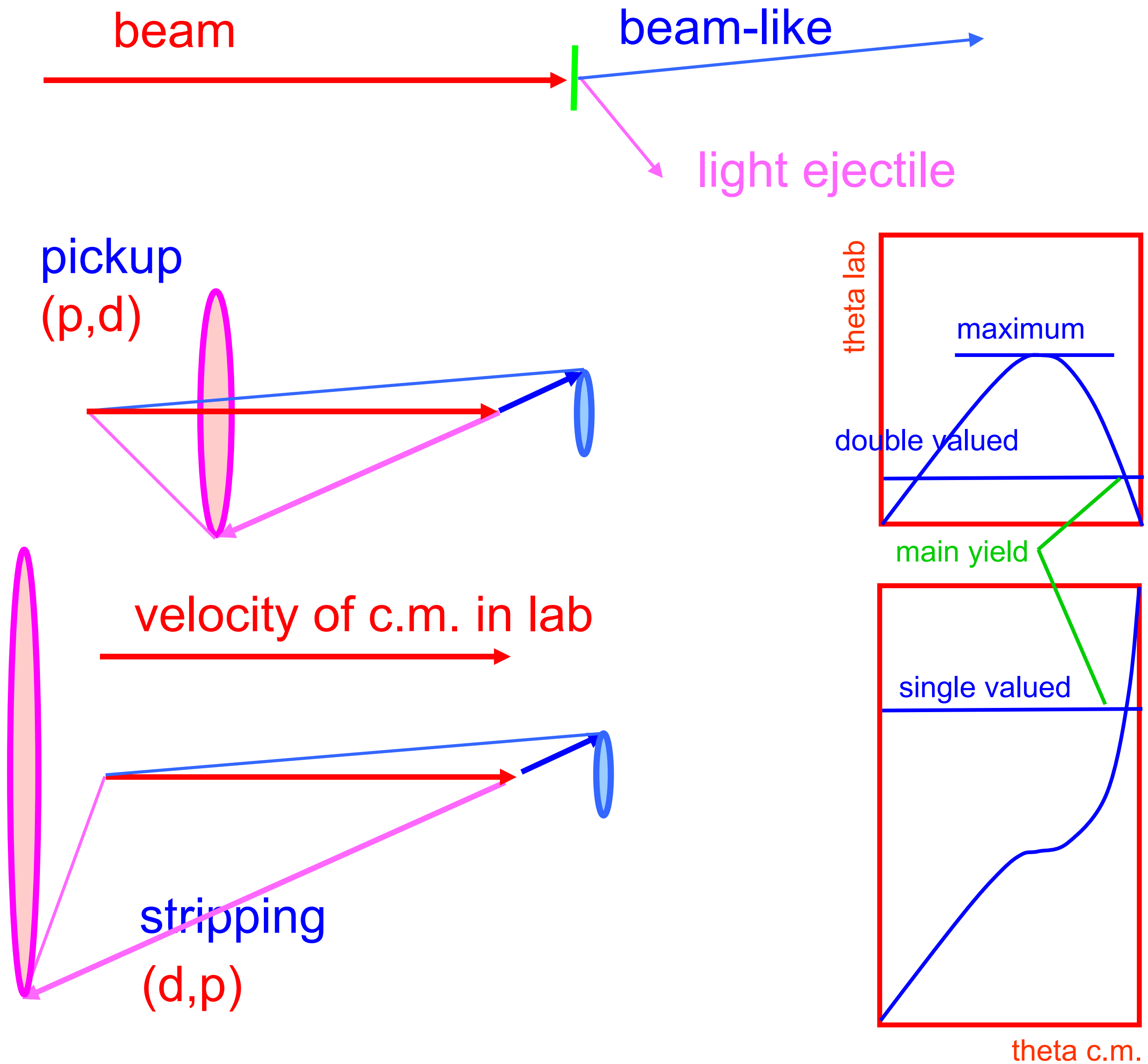
Ne					15 60.3	16 5.4	17 4.0	18 1.6	19 -0.9	20 -7.4	21 -7.5	22 -9.8	23 -9.8	24 -11.1	25 -11.6	26 -12.3	27 -13.1	28 -17.1	29 -16.4	30 -18.4
F				13 75.0	14 8.7	15 7.0	16 6.0	17 4.9	18 -0.1	19 -2.5	20 -5.1	21 -5.6	22 -7.0	23 -7.9	24 -8.6	25 -9.6	26 -16.7	27 -14.1	28 -15.6	N=20
O				12 5.4	13 4.0	14 0.9	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												

= stable

Reaction Q-value in MeV

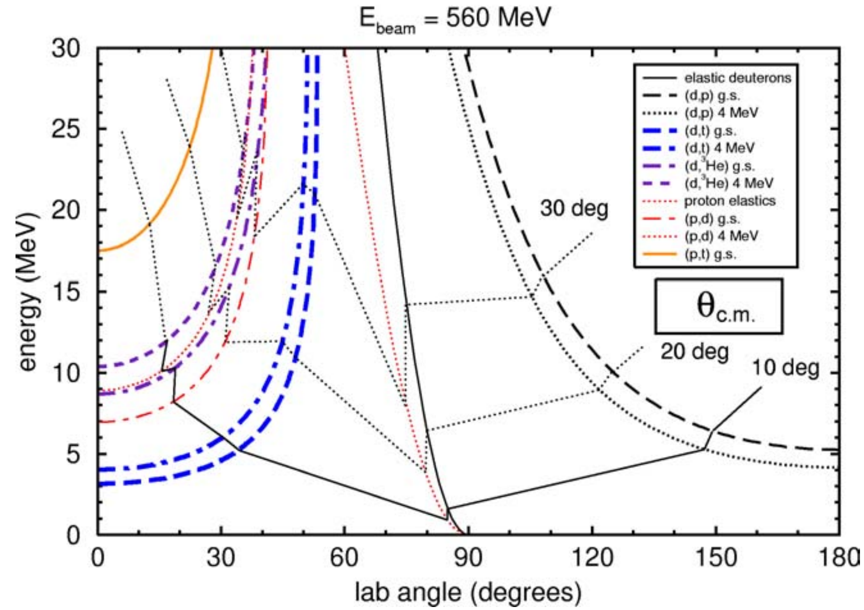
(d , ^{3}He) : refer to cell of TARGET

Kinematics of nucleon transfer in inverse kinematics

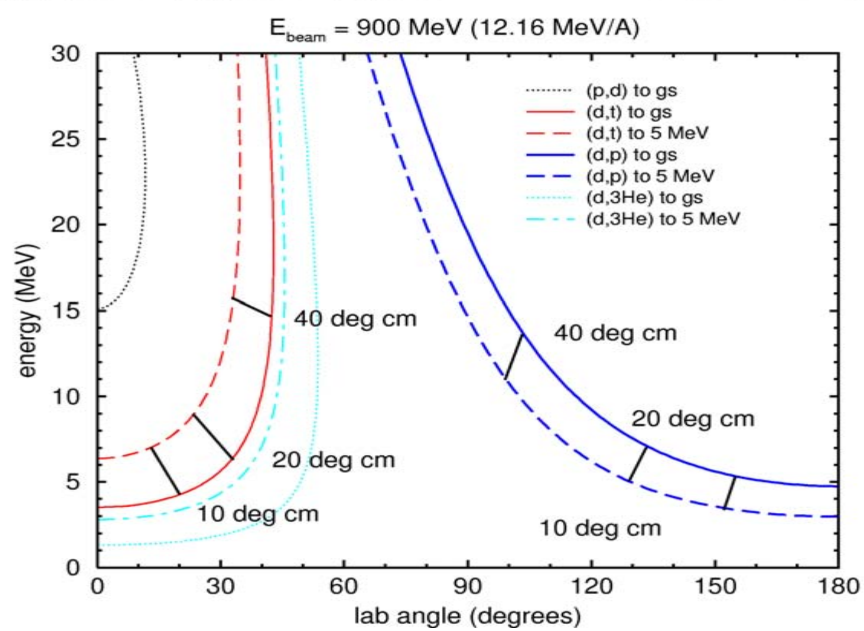


The general form of the kinematic diagrams is determined by the light particle masses, and has little dependence on the beam mass or velocity

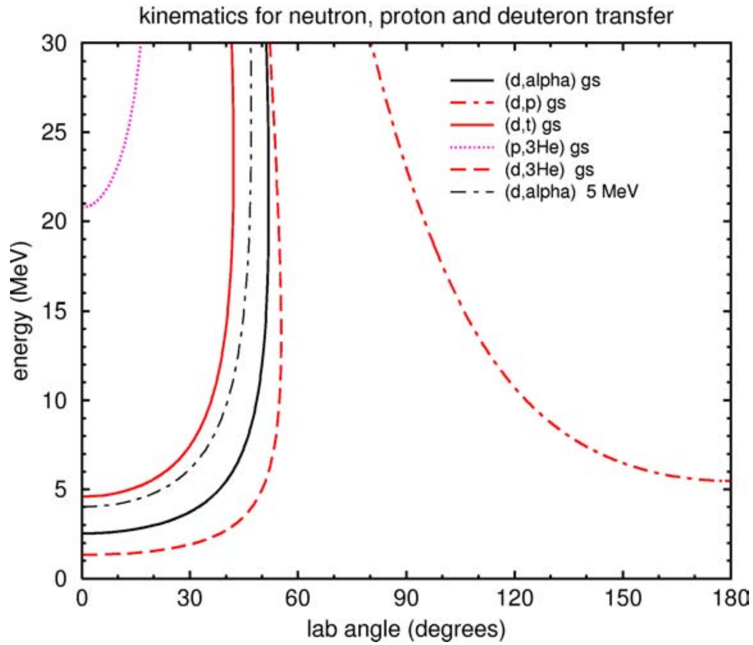
^{16}C incident on ^{2}H at 35 MeV/u



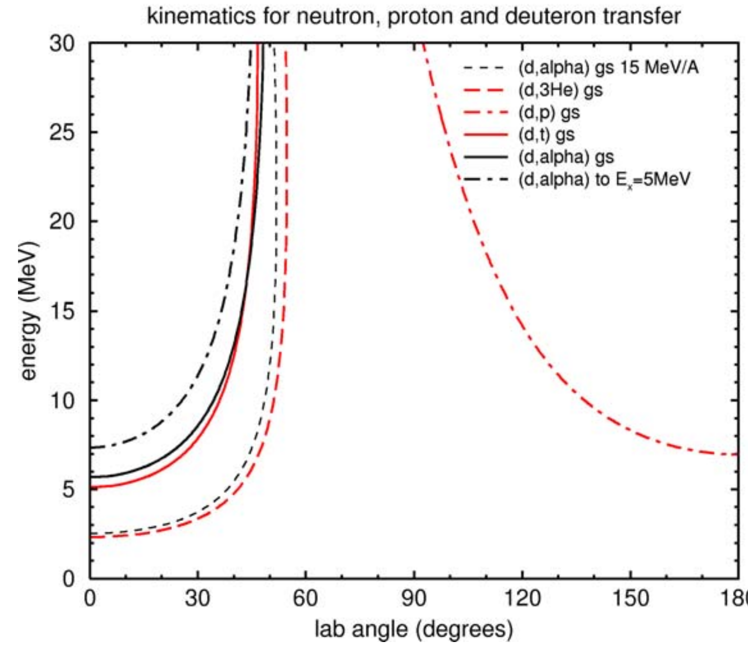
(p,d) and (d,t) and (d,p) on ^{74}Kr in inverse kinematics



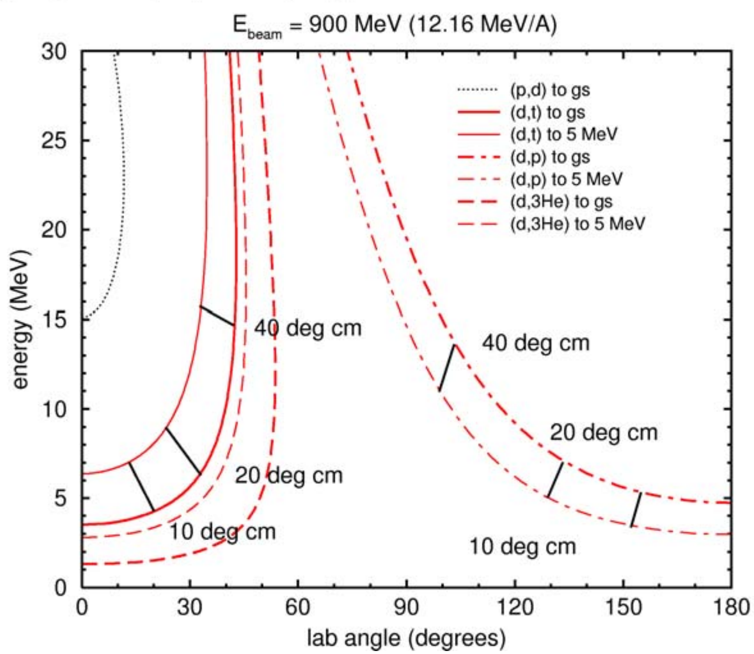
^{72}Kr at 15 MeV/A on p and d targets



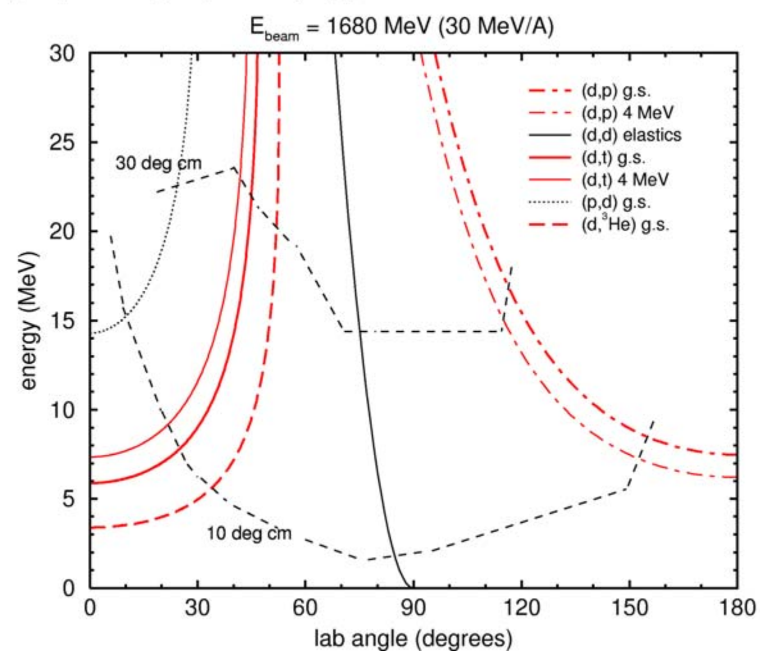
^{72}Kr at 25 MeV/A on d target



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



(p,d) and (d,t) and (d,p) on ^{56}Ni in inverse kinematics



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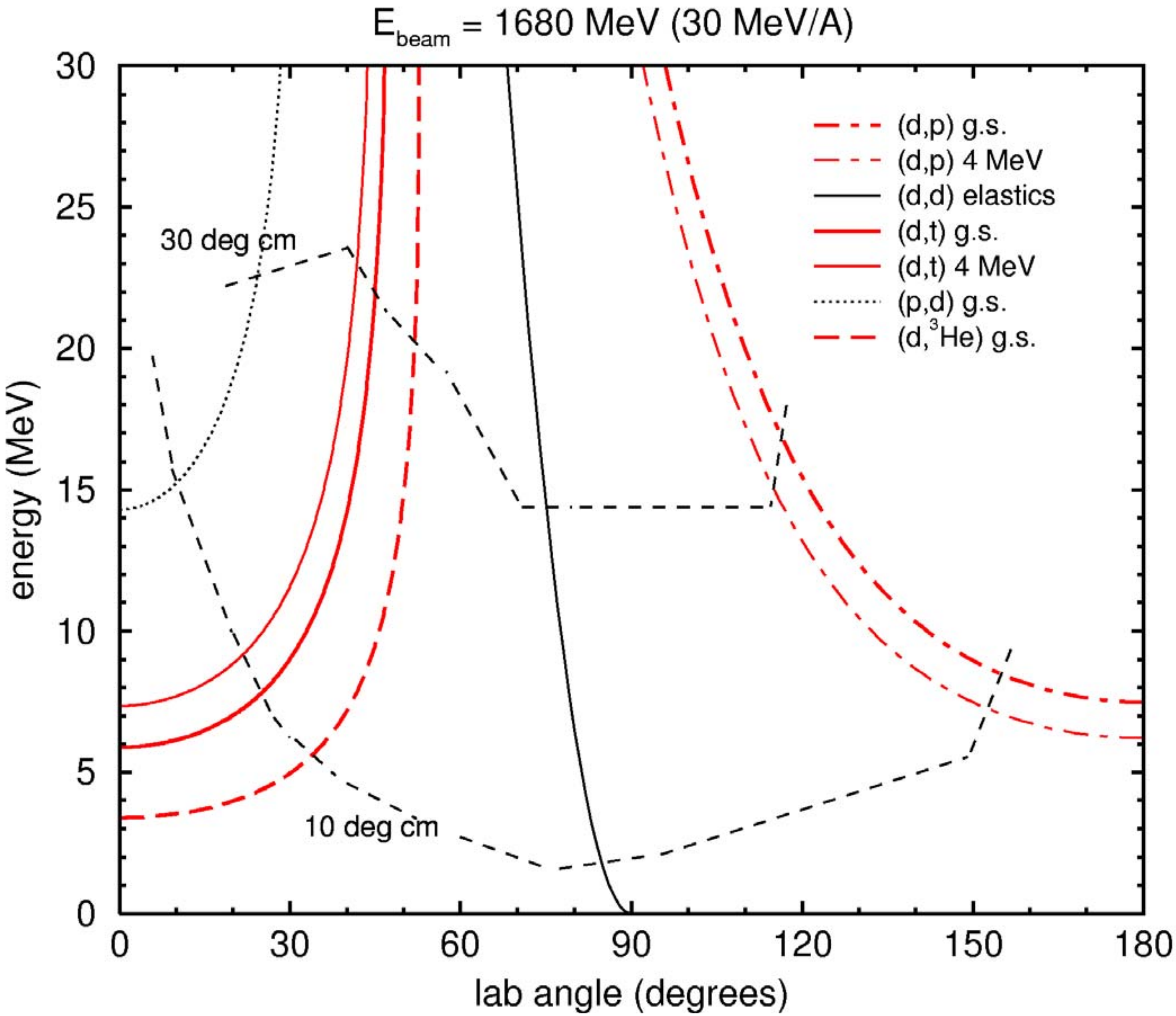
(p,d) and (d,t) and (d,p) on ^{56}Ni in inverse kinematics



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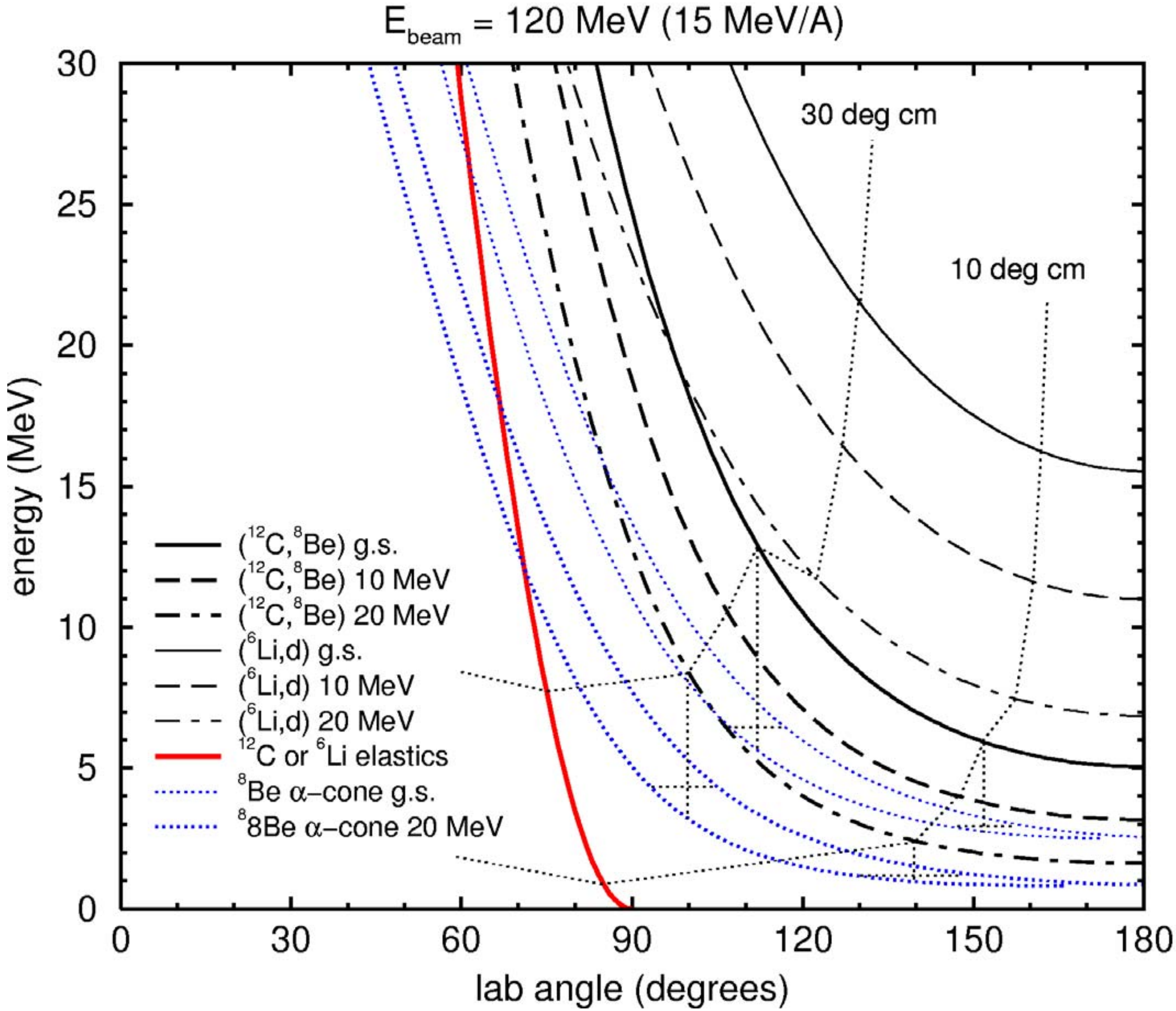
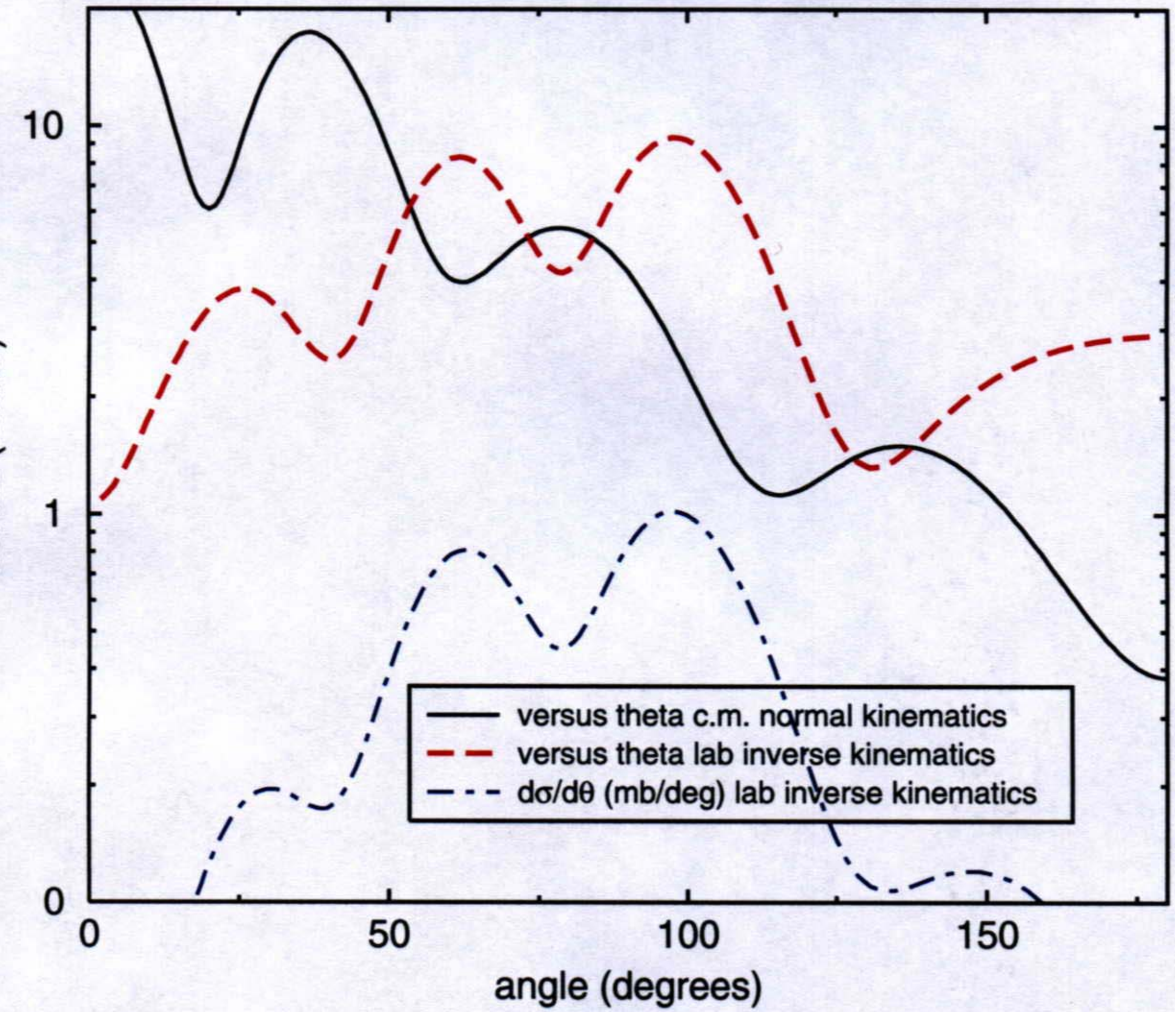
(^{12}C,^{8}Be) and (^{6}Li,d) on ^{8}He in inverse kinematics



DWBA ZR: $^{94}Sr(d,p)^{95}Sr^{*}(1.0 MeV; s_{1/2})$ at 4.894 MeV/u

Adiabatic deuteron potential (B–G) and Perey proton potential



Calculations of E_x resolution from particle detection

beamlike particle detected

light 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

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

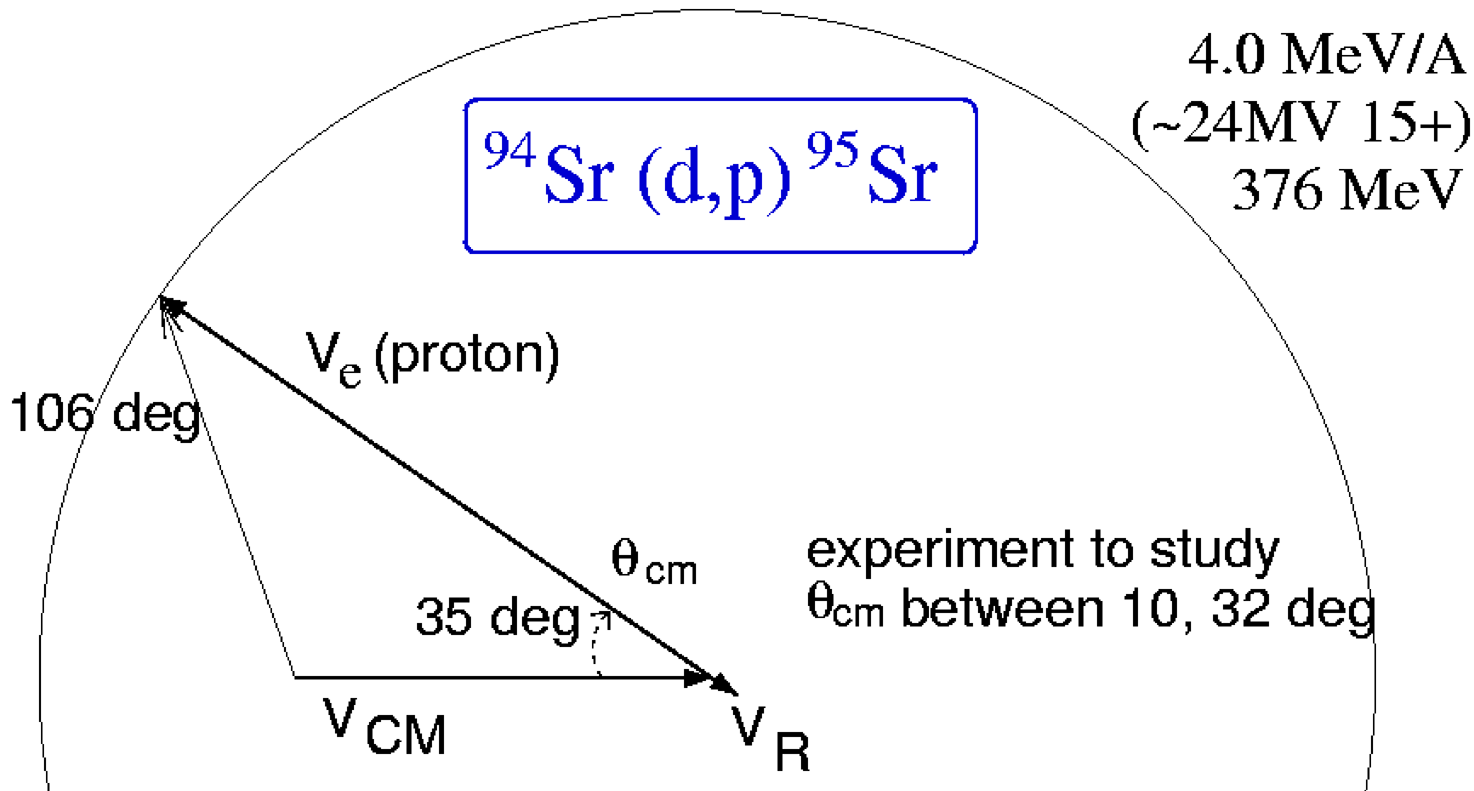
Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, d)^{11}Be	30	19.0°	136	74	114	96	649	685
p(^{12}Be, d)^{11}Be	15	17.8°	66	72	55	89	984	995
p(^{77}Kr, d)^{76}Kr	30	15.0°	124	55	64	63	186	249
p(^{77}Kr, d)^{76}Kr	10	6.0°	26	24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

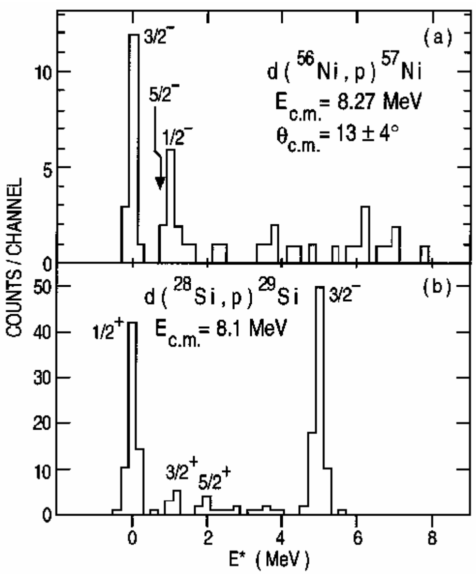
Better to detect light particle (target thickness lilmits resolution)

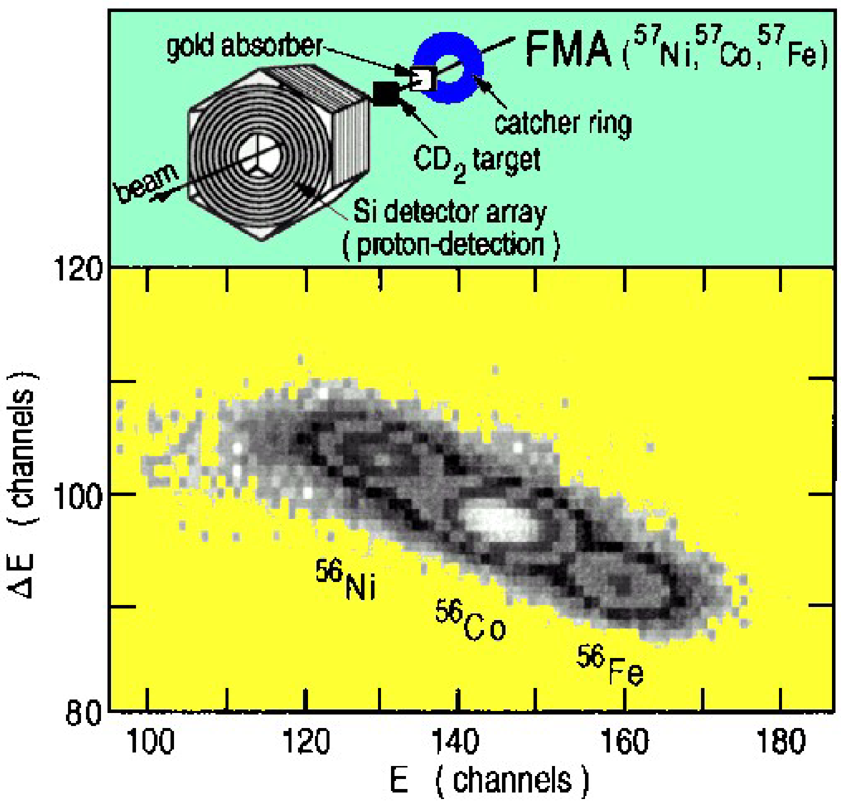


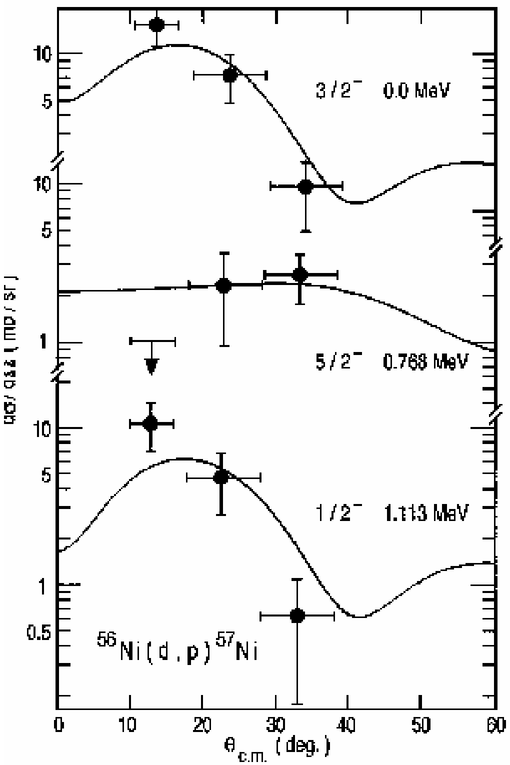
θ_{lab}	θ_{cm}	E_{proton}	0.2 deg $\Delta\theta$	35 keV E_{res}	ENRGY STRAG	MULT/ SCATT	DIFF'L DE/DX TARG	TOTAL IN QUAD	DE(Ex) /DE(Ep)
112	32	3.33	23	50	19	56	393	401	-1.43
154	10	1.58	7	87	21	23	389	400	-2.53

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

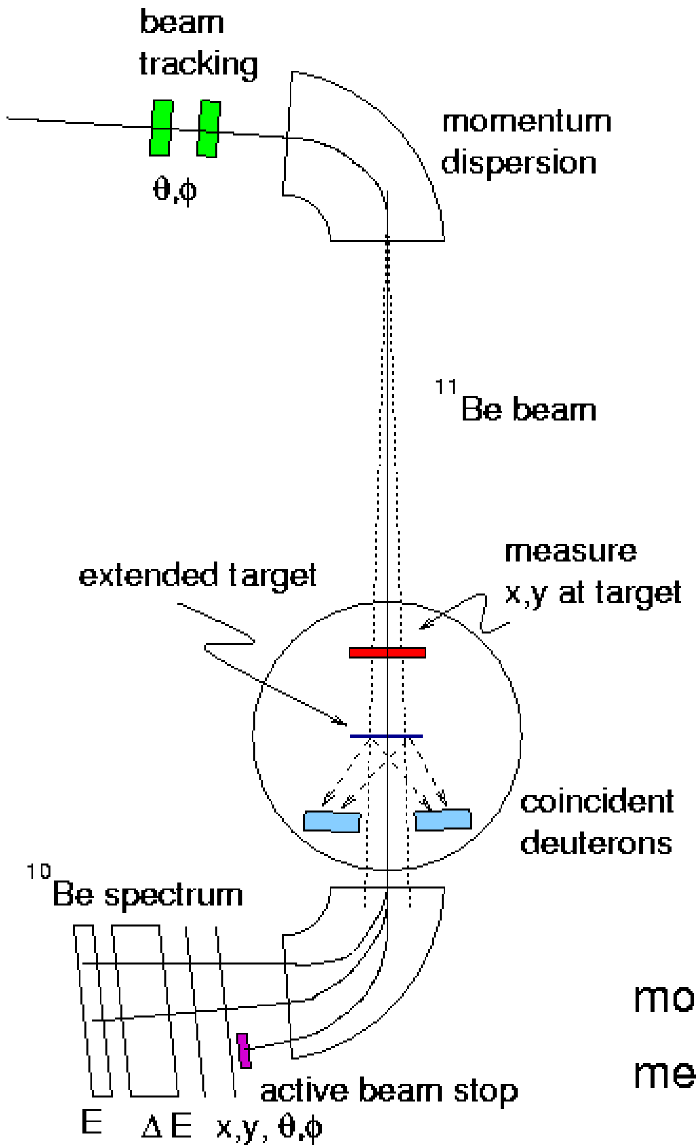
K. E. Rehm,[1] F. Borasi,[1] C. L. Jiang,[1] D. Ackermann,[1] I. Ahmad,[1] B. A. Brown,[2] F. Brumwell,[1] C. N. Davids,[1] P. Decrock,[1] S. M. Fischer,[1] J. Görres,[3] J. Greene,[1] G. Hackmann,[1] B. Harss,[1] D. Henderson,[1] W. Henning,[1] R. V. F. Janssens,[1] G. McMichael,[1] V. Nanal,[1] D. 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]







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



beam energy resolution 2.0-3.0 MeV

angular spread ±1 °

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

microchannel plate

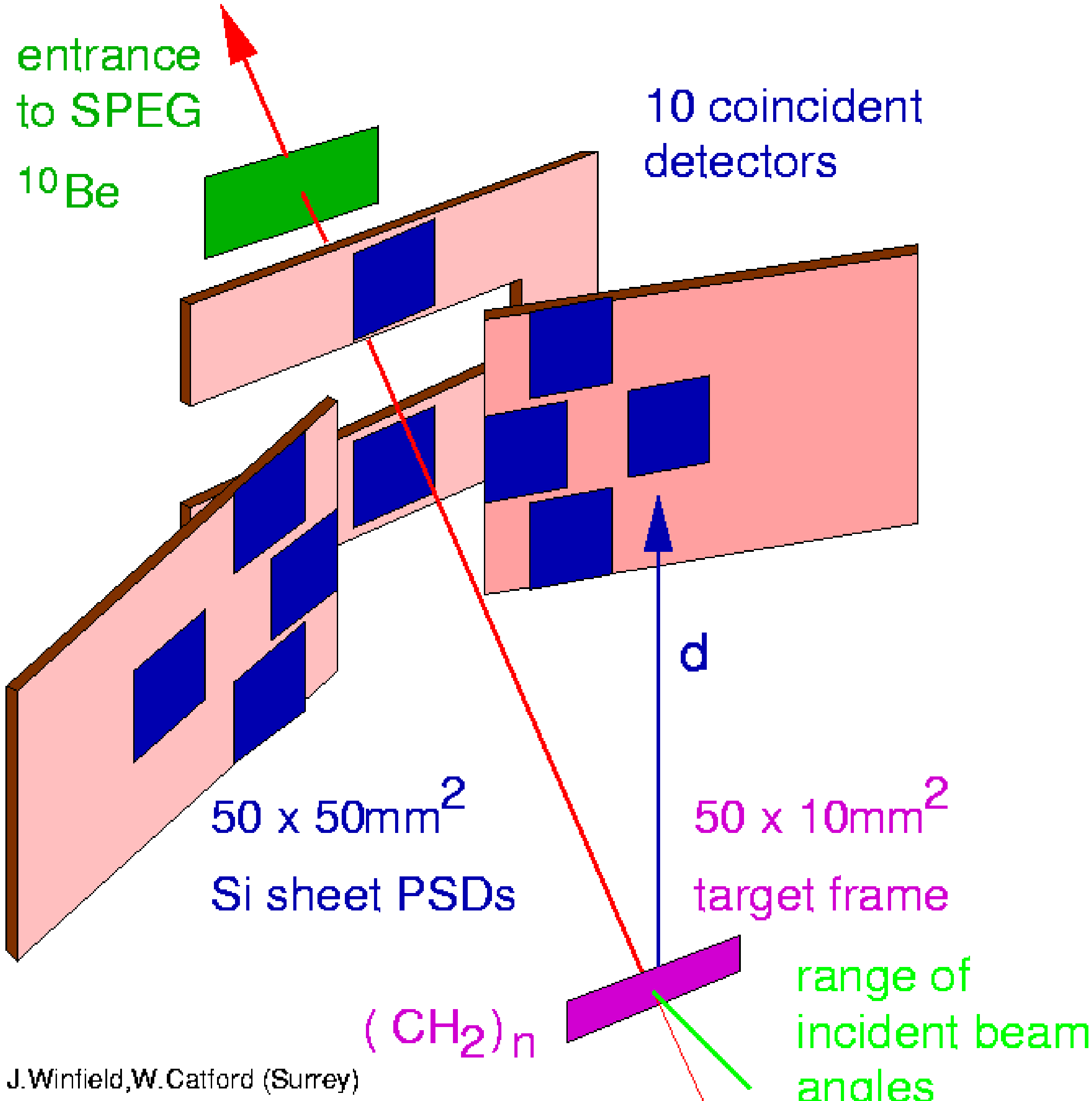
polythene target

ten Silicon PSD's

momentum analysis

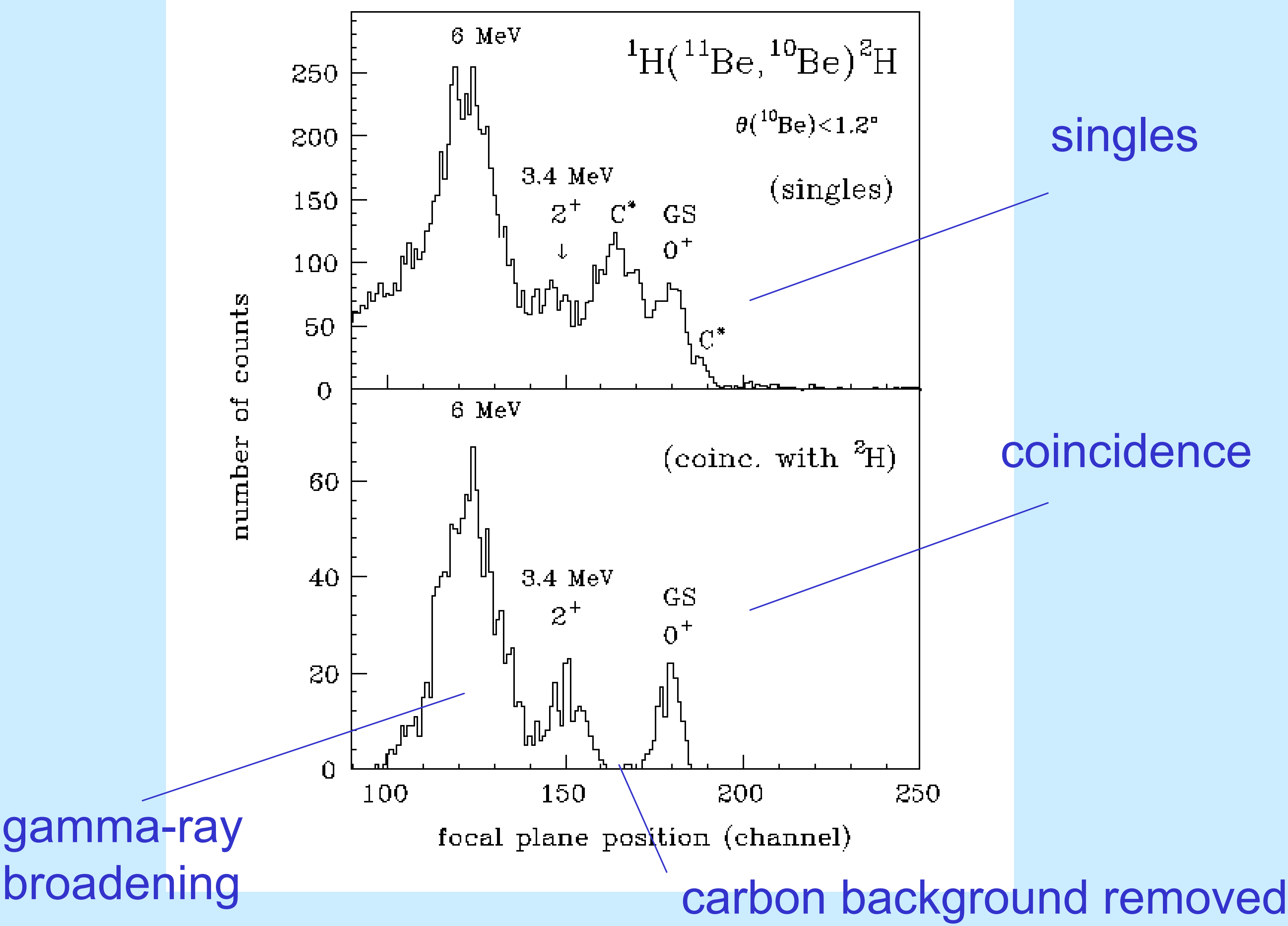
measure reaction angle

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

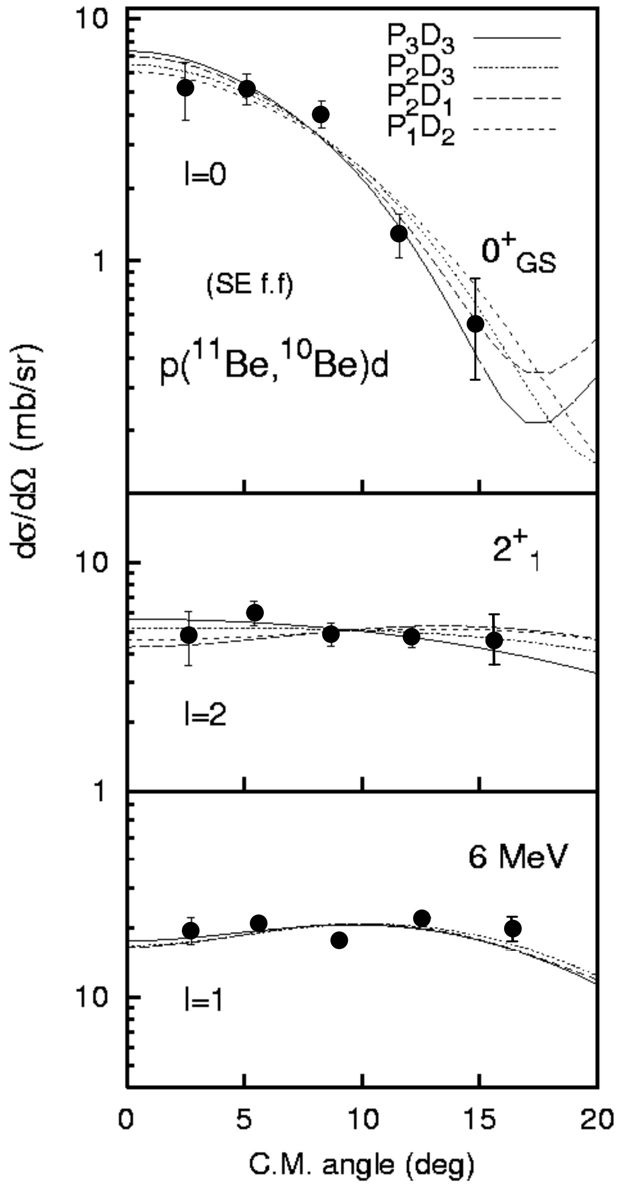


J.Winfield,W.Catford (Surrey)

Focal plane spectrum from SPEG magnetic spectrometer



Separation Energy form factor | Vibrational form factor



0^+ 2^+

α^2 β^2

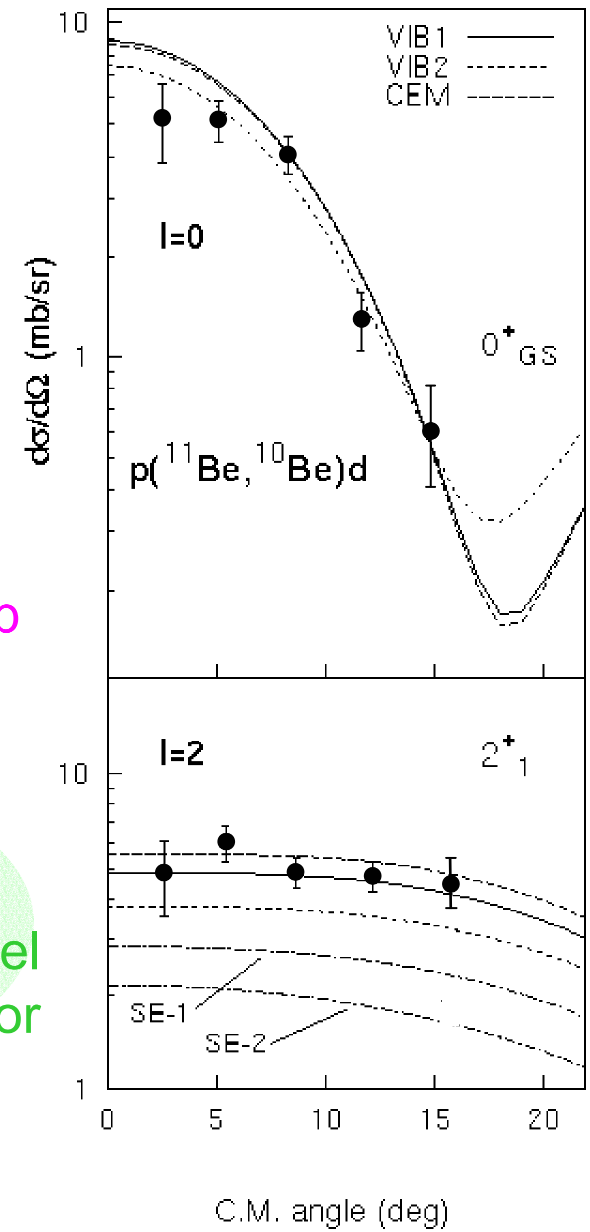
~~0.49 0.51~~

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

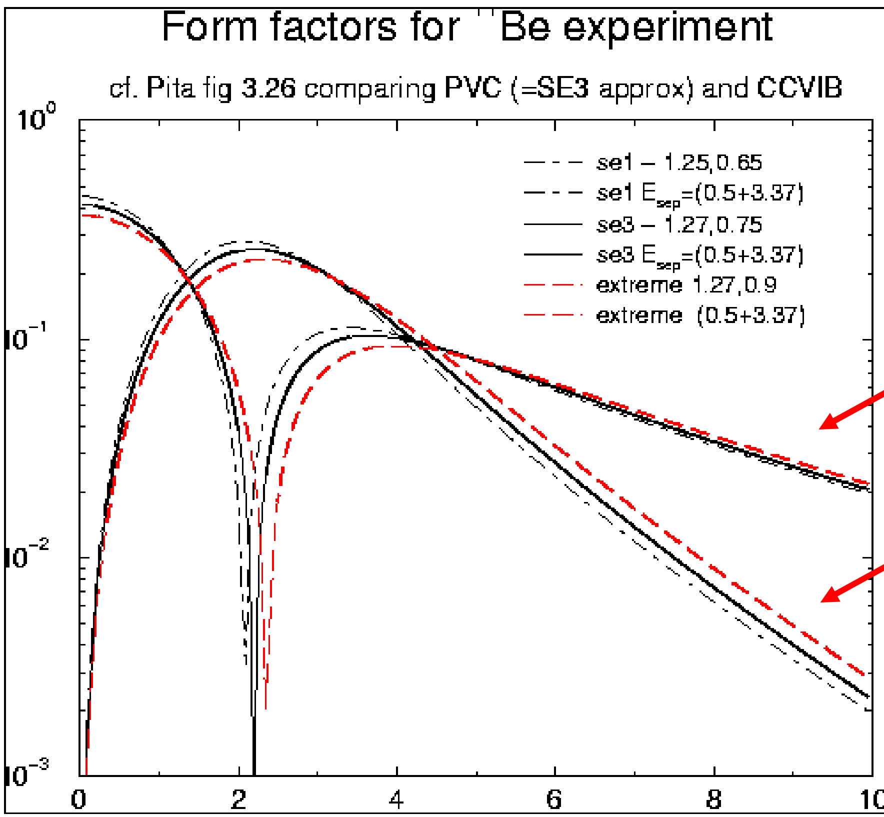
0.84 0.16

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

{ 0.74 0.19
Shell model }



Radial form factor for the transferred nucleon (in ^{11}Be)



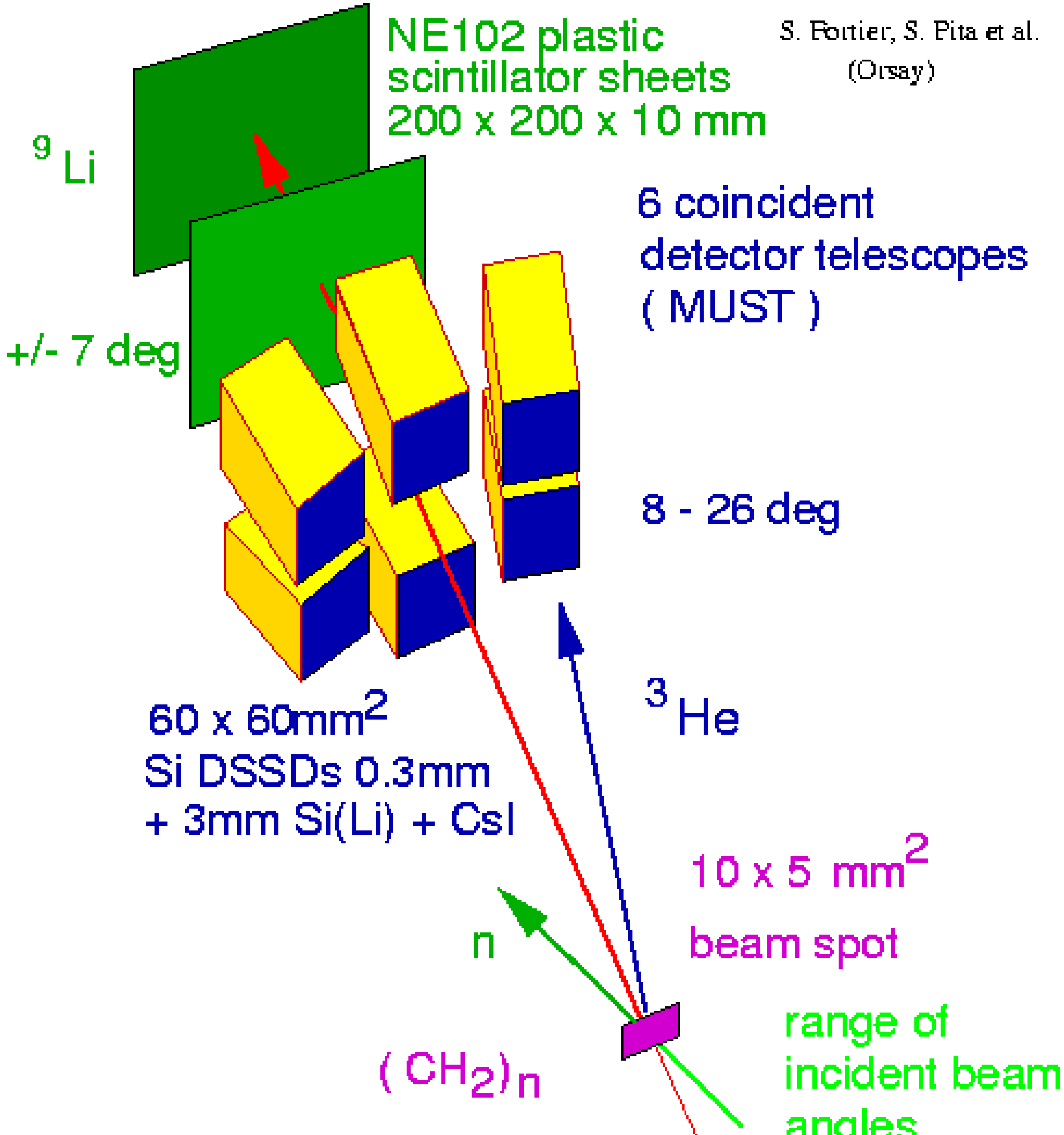
s-wave bound state wfn

d-wave bound state wfn

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

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

S. Fortier, S. Pita et al. (Orsay)



Excitation energy spectra from the Orsay experiment

S. Fortier,
S. Pita et al.,
(2000)

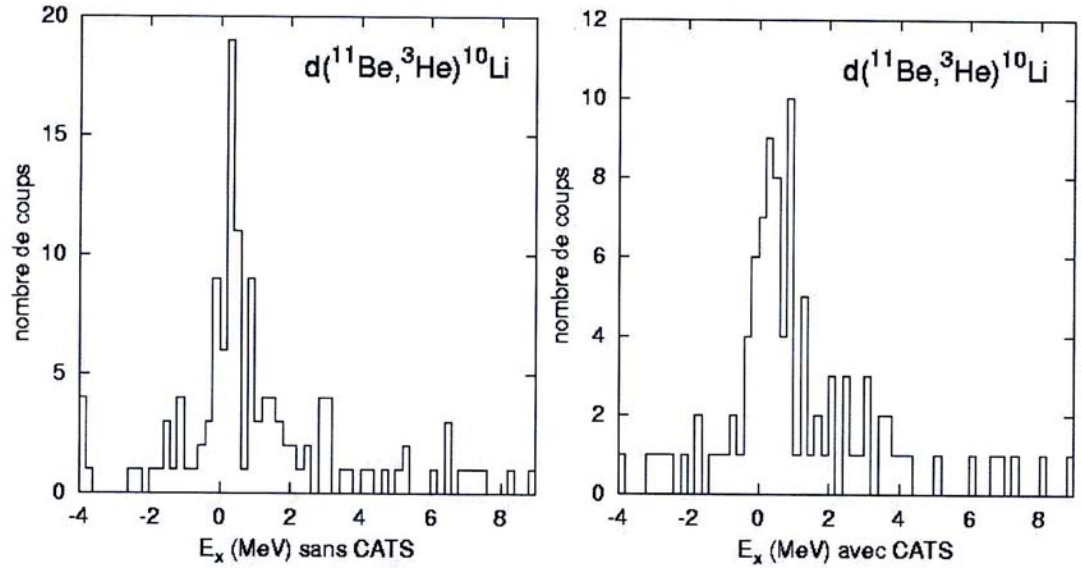


Figure 4.16: spectres en énergie du ^{10}Li, obtenus sans CATS (gauche) et avec CATS (droite)

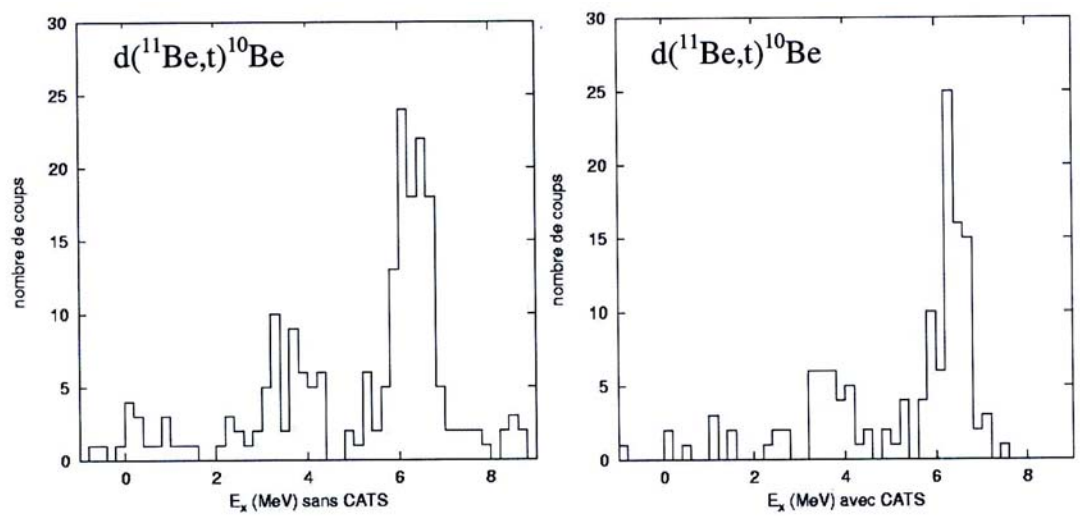
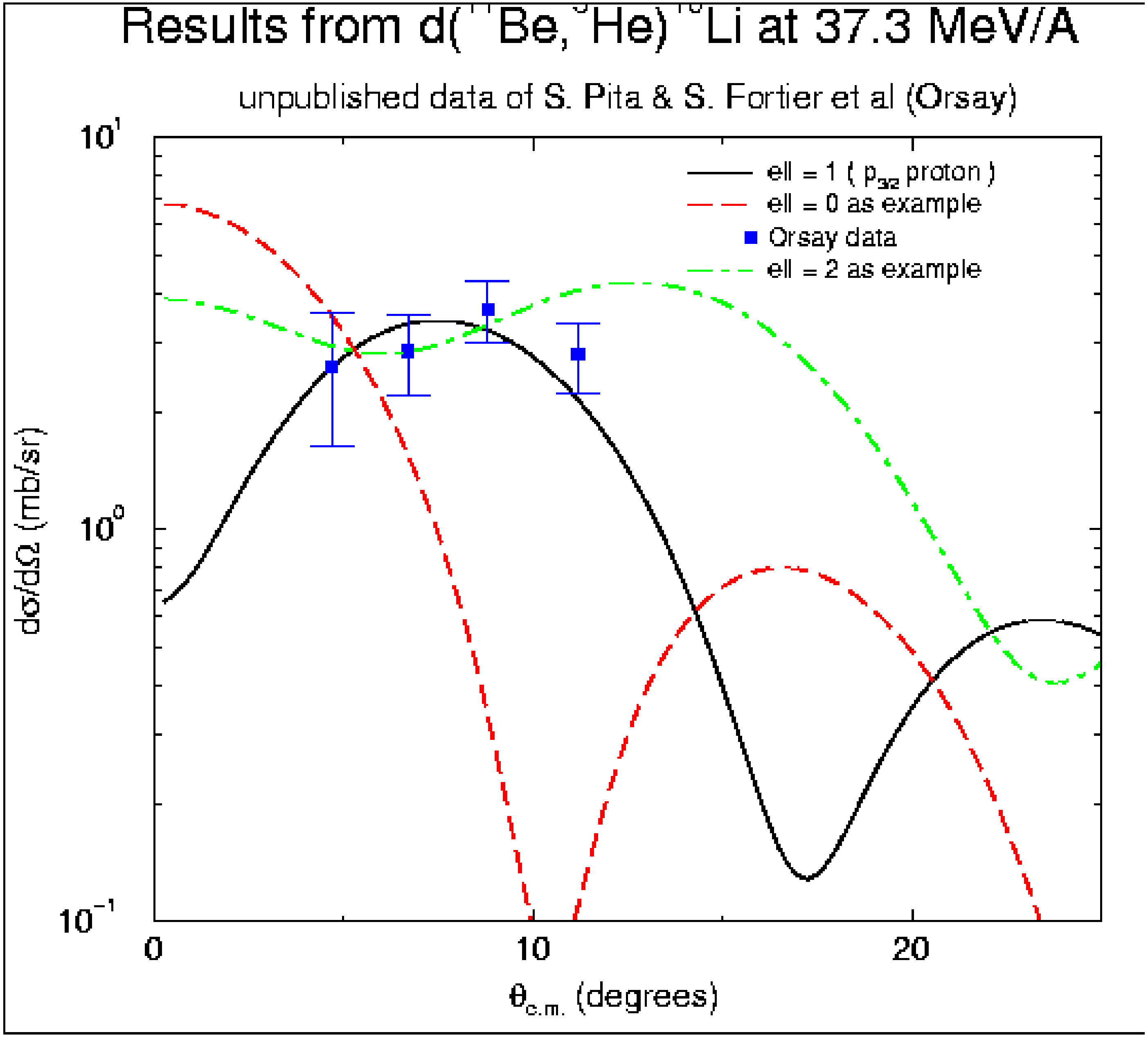
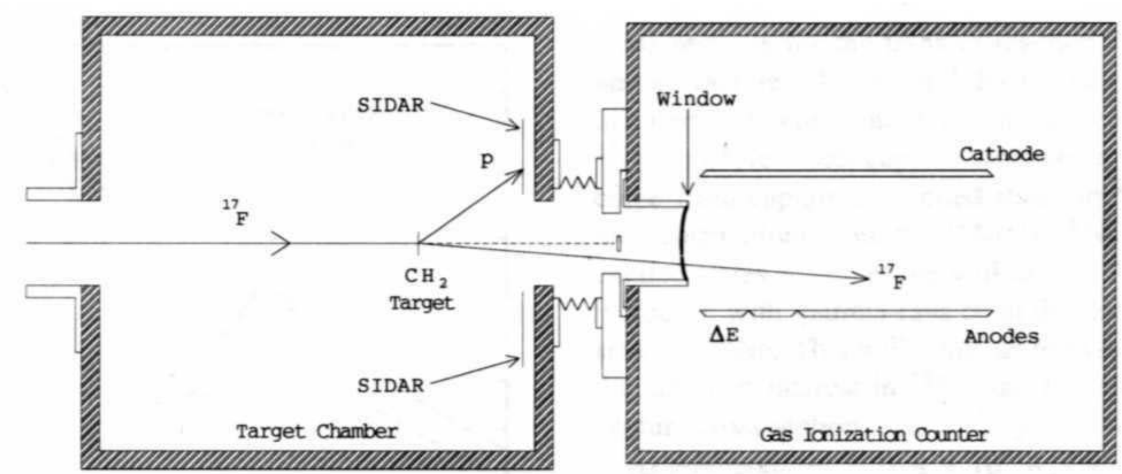


Figure 4.17: spectres d'énergie d'excitation du ^{10}Be obtenus sans (gauche) et avec (droite) les détecteurs CATS.



Results from d(11Be,3He)10Li at 37.3 MeV/A
unpublished data of S. Pita & S. Fortier et al (Orsay)
ell = 1 (p3/2 proton)
ell = 0 as example
Orsay data
ell = 2 as example
dσ/dΩ (mb/sr)
10^1
10^0
10^-1
0
10
20
θc.m. (degrees)

Resonance scattering at ORNL: $^{18}F\ (p,\alpha)\ ^{15}O$

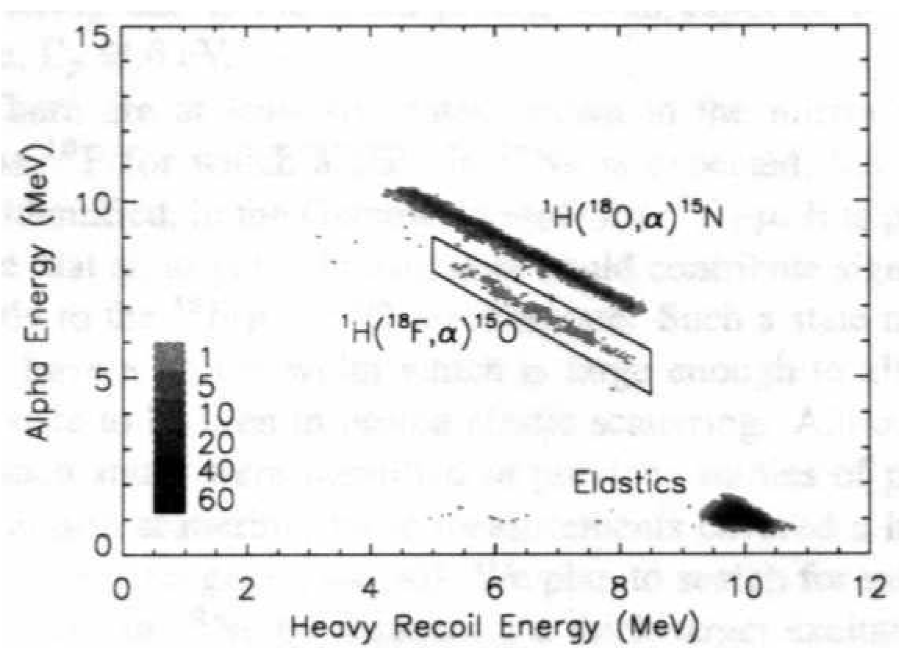


E_{beam} = 0.65 MeV/A

θ_{lab} (Si) = 15 - 45 °

Q = + 2.88 MeV

q = 5.563 $\gg$ 1



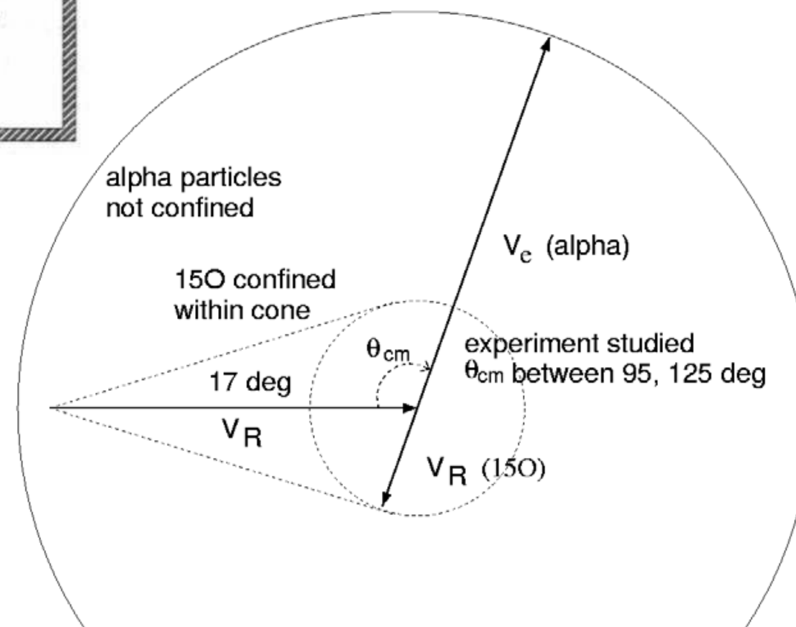


Diagram actually similar to
generic (d,p) diagram
(Note: low E/A compared to Q)

Angle and energy of light particle crucial for 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

Proof of Principle using weak ^{36}S beam and inverse ^{36}S(d,p)^{37}S

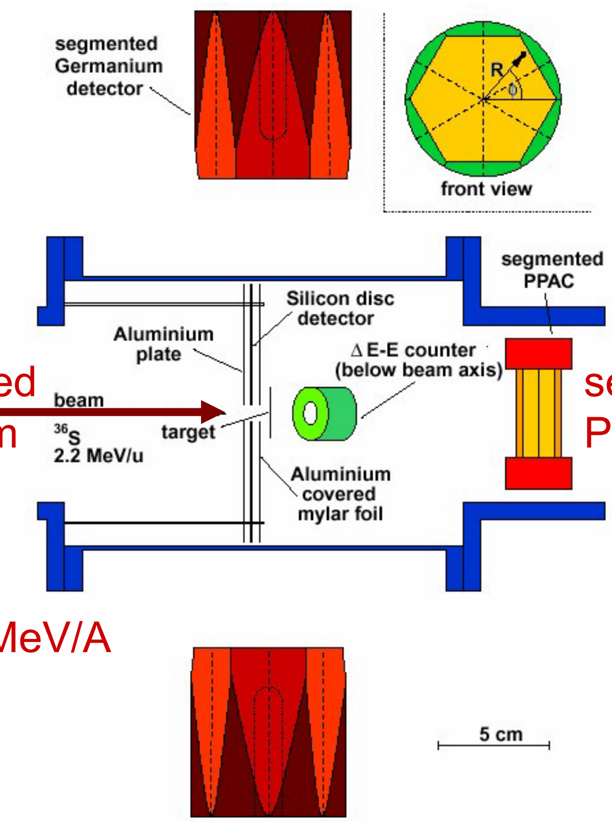
C. Grund *et al.* (Heidelberg/Darmstadt)
Eur. Phys. J. A10 (2001) 85

segmented Ge

pulsed beam

10^6 pps

2.2 MeV/A



segmented PPAC

segmented Ge

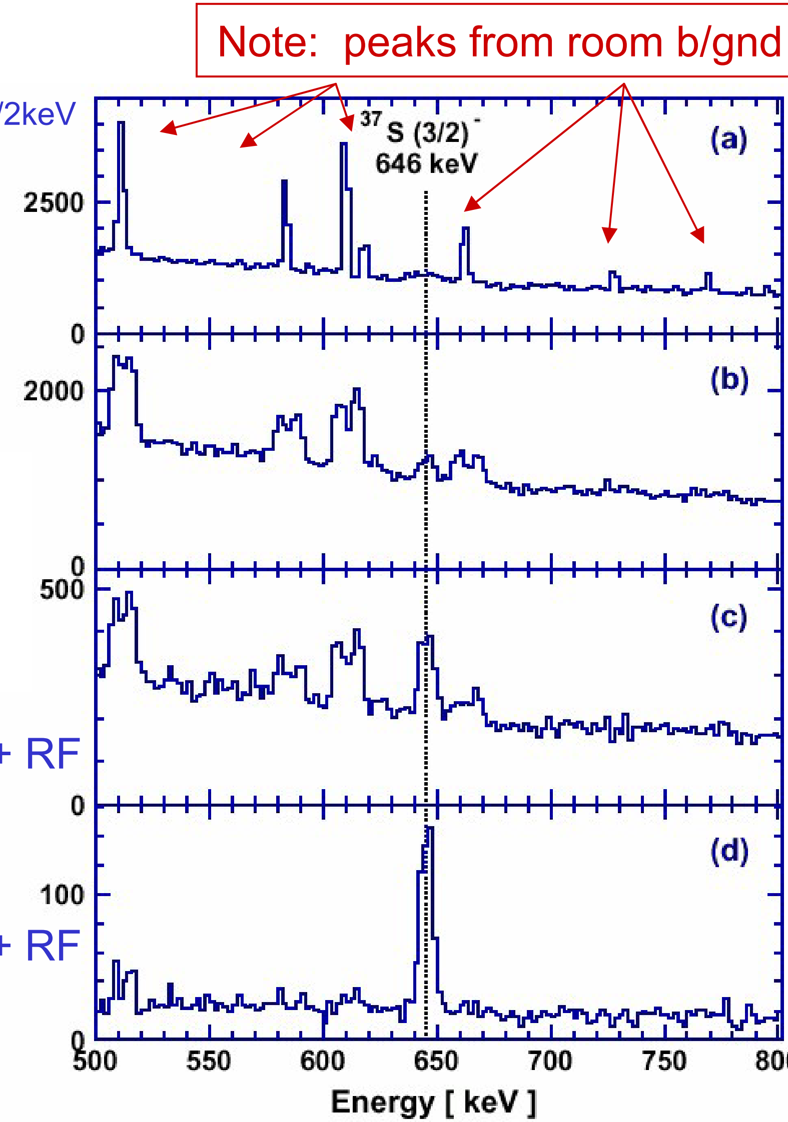
counts/2keV

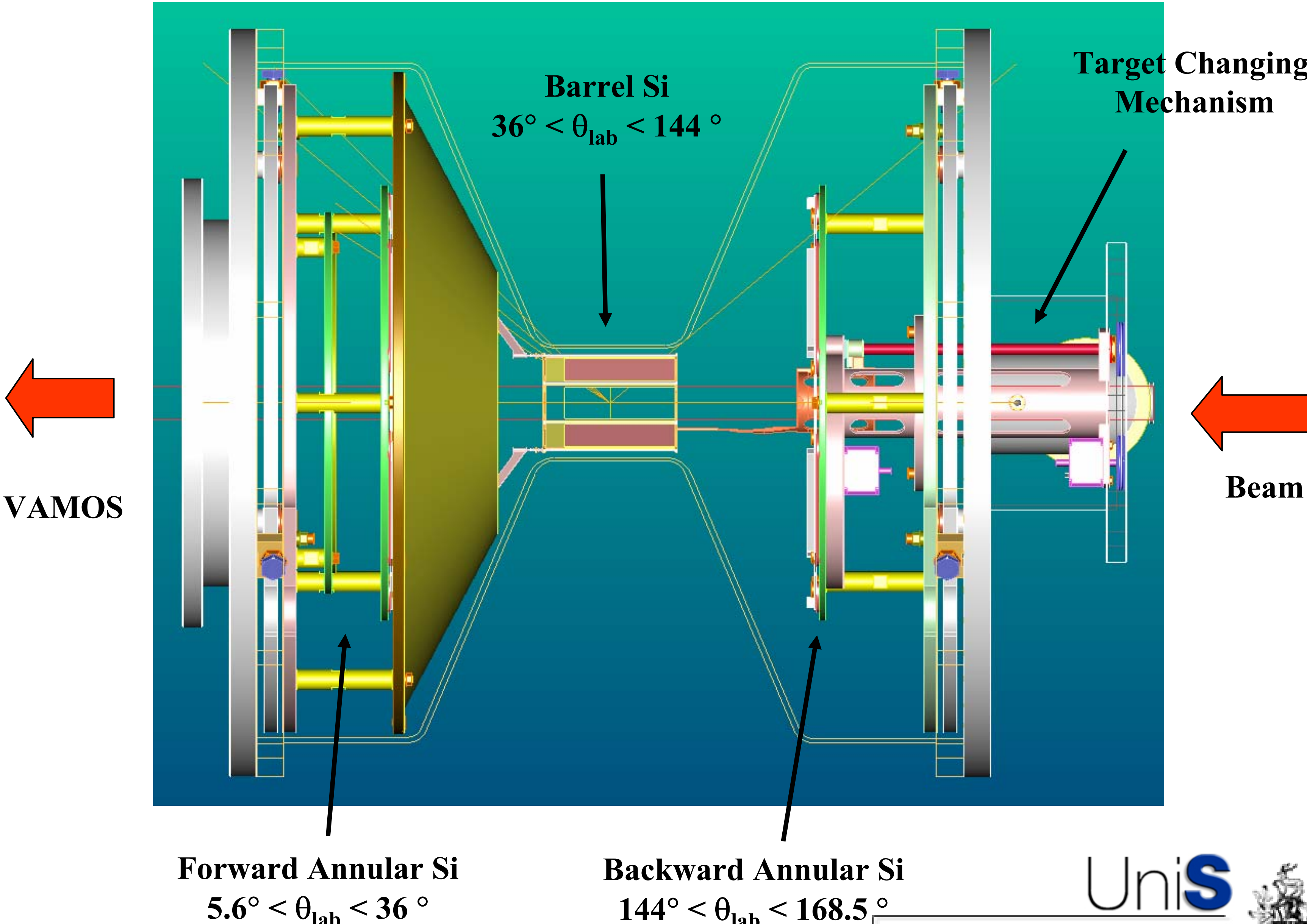
singles

singles + Doppler

singles + Doppler + RF

singles + Doppler + RF + PPAC





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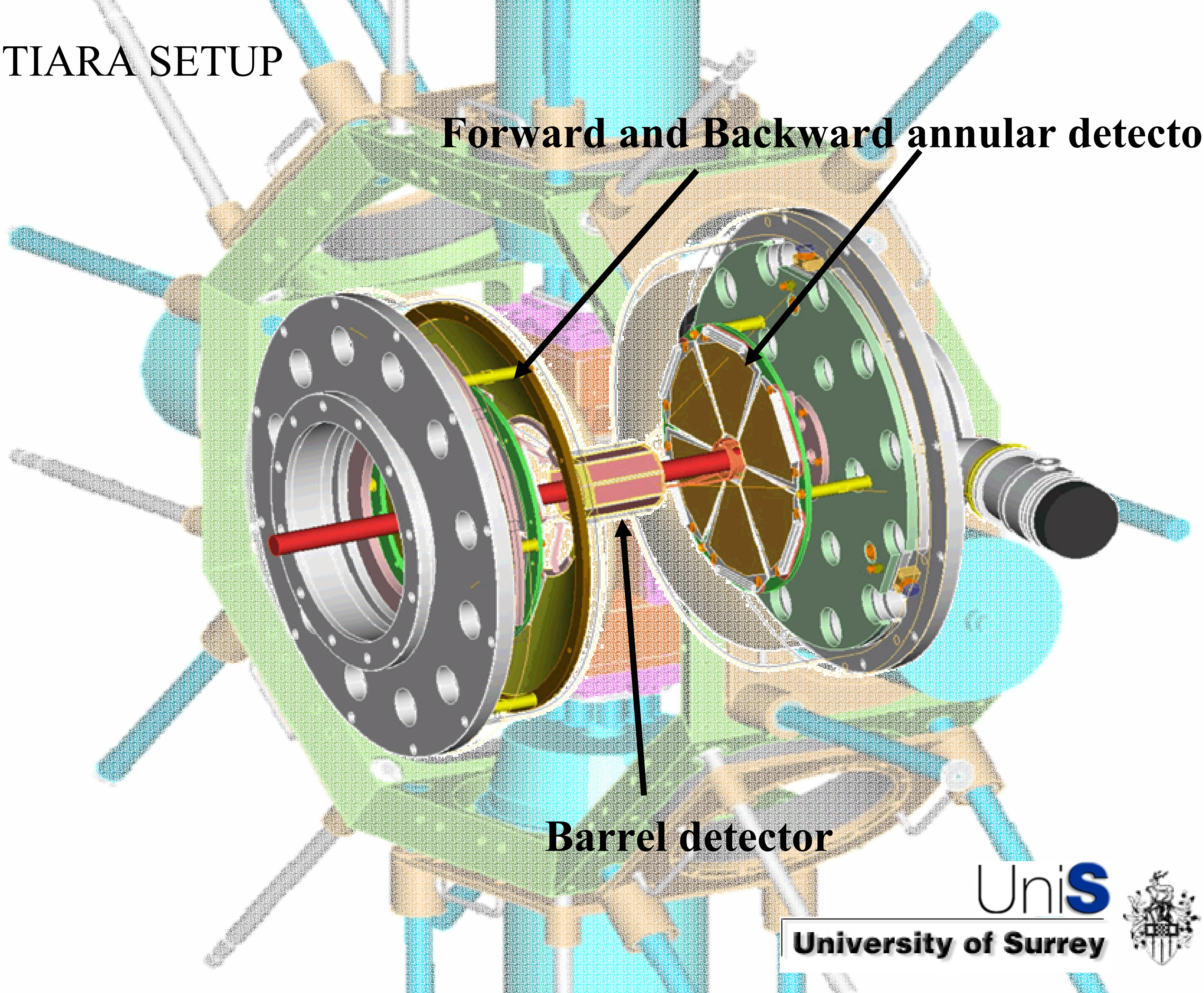
TIARA SETUP



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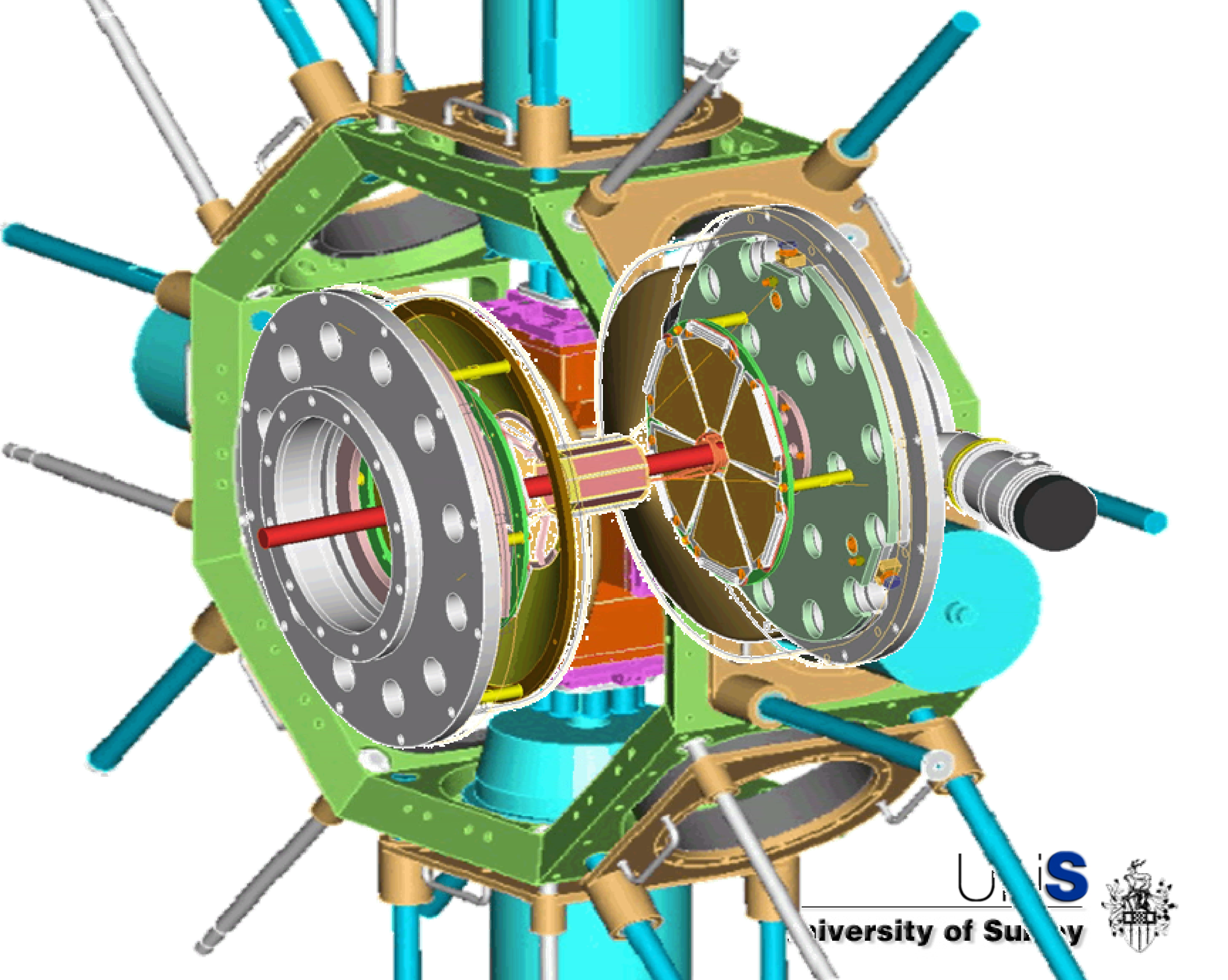
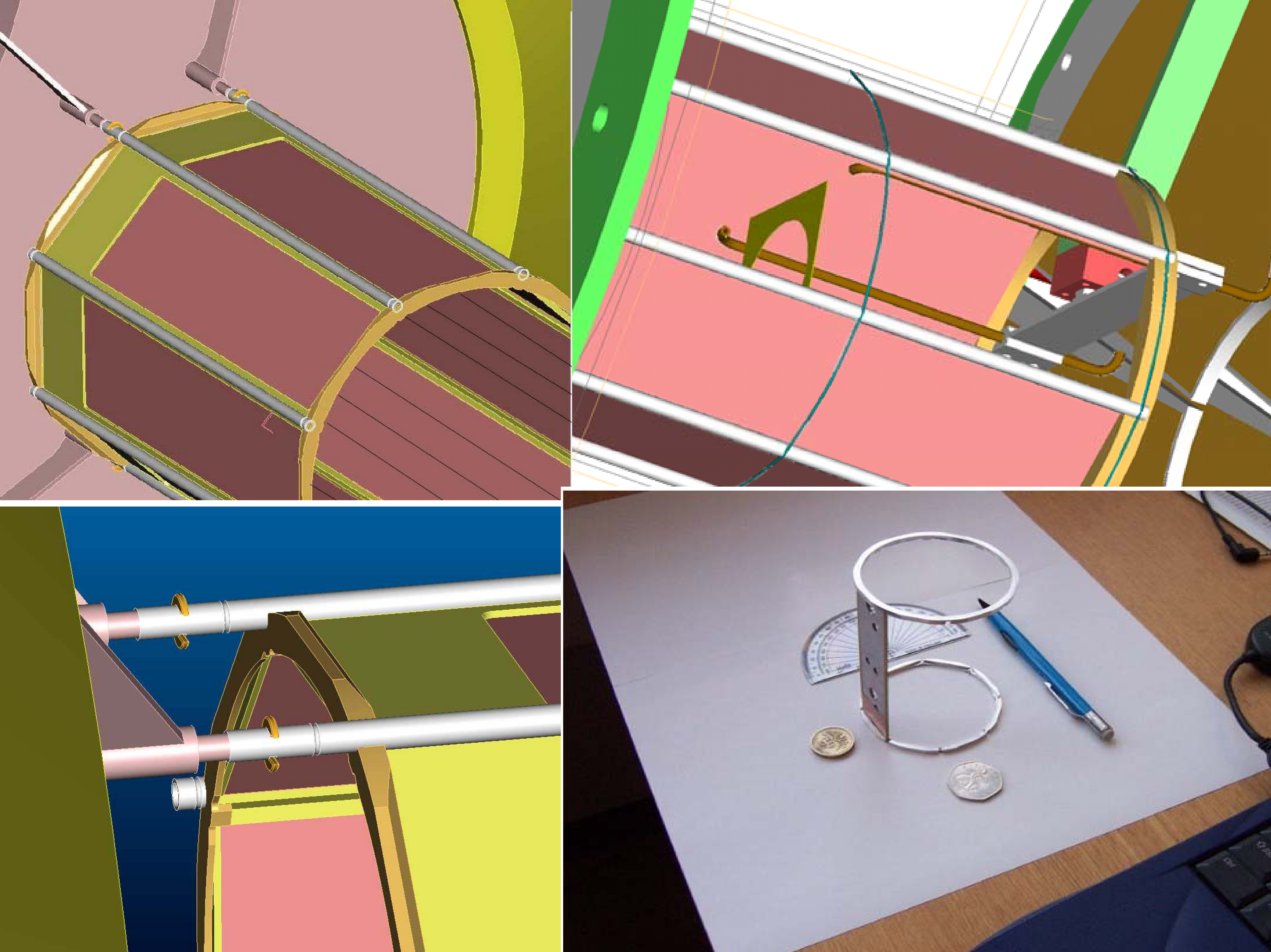
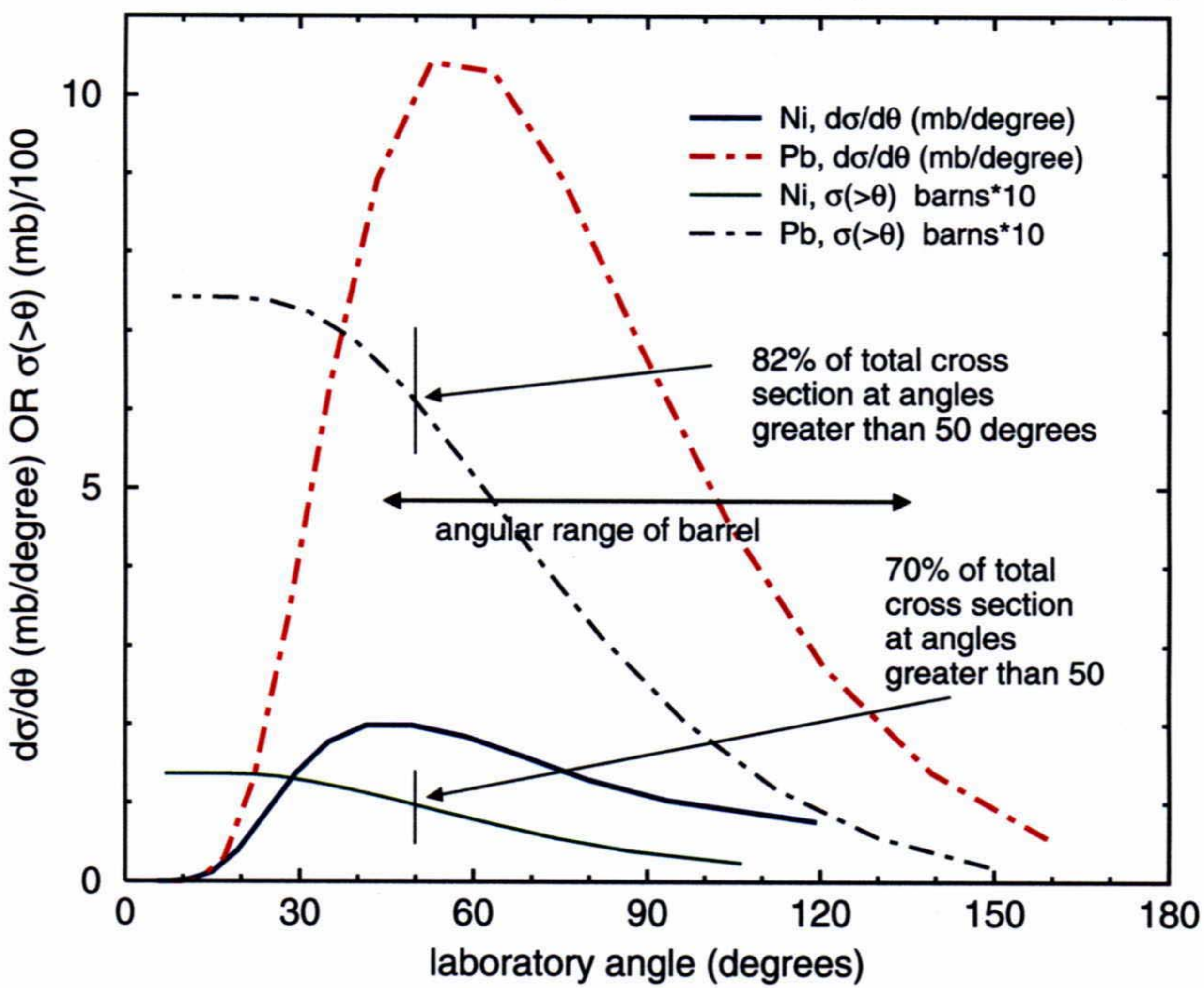


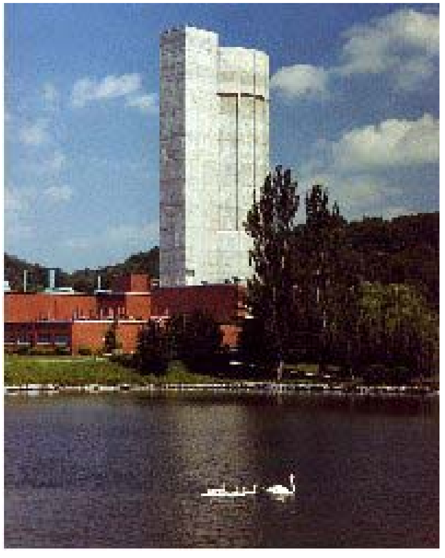


Coulex of ^{46}Ar (2^+; 1.577 MeV) , Ni & Pb targets

B(E2)=196 e^2fm^4; safe energies of 90 MeV (Ni) and 155 MeV (Pb)



OUTLOOK



Oak Ridge TN
June 2002

Experimentally proven

- inverse kinematics manageable
- gamma-ray detection often desirable

Reactions on p and d targets

- identify angular momentum and E_X
- then, measure spectroscopic factors

Alpha 2-nucleon transfer

- $(d,^{6}Li)$ or $(^{12}C,^{8}Be)$ or $(^{6}Li,d)$ possible
- (t,p) or $(^{9}Be,^{7}Be)$ or $(^{10}B,^{8}B)$ possible

Experimental challenges

- pushing beyond 35-40 deg in (p,d) etc.
- stopping all particles & detecting gammas
- low energy thresholds for particles
- detection of beam-like particle (identify Z)
- scattered beam particles are radioactive