Reactions - EBSS 2017 - ANL

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contents

- Why reactions?
- Basic features of reactions and experimental signatures
  - Basic nuclear potential scattering
  - Angular momentum
- Differential cross sections
- Reaction kinematics
- Forward vs inverse kinematics
  - (Some) experimental tools for inverse kinematics
- Reactions types and examples

Why study/learn about nuclear reactions?

1) To learn about nuclear structure, one often performs scattering experiments to populate excited states. To interpret the data and learn about structure, the reaction has to be understood well.
2) To directly measure cross sections (e.g. for astrophysics or for stewardship science).
3) To directly learn about the forces between nuclei.
4) To create rare isotopes
5) …

Note: Not all experiments require a detailed understanding or description of the reaction.

Extracting structure information from reaction studies

Reaction model (single particle cross section)

observable

$$\sigma^{if} = \sum_{j=J_f-J_i}^{j=J_f+J_i} S_j^{if} \sigma_{sp}$$

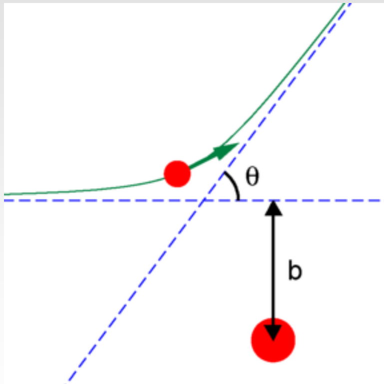
Structure model (spectroscopic factor)

- In order to extract the structure information we need to account reliably for the reaction part
- Can this be done without reaction theory?
  - Use multiple reactions to get to the same info
  - Calibrate with known structure inputs
- In general, a model for the reaction part is needed to extract the structure part

Basic reaction types

- Simple or direct reactions – I will focus on this mostly…
  - Usually peripheral (large impact parameter)
  - Involve mostly the valence/outer nucleons
  - Useful for probing single-particle properties
- Complex or central reactions
  - Central/head-on collisions (small impact parameter)
  - Involves all nucleons in nuclei
  - Probes statistical properties of nuclei (multi fragmentation or compound nucleus)

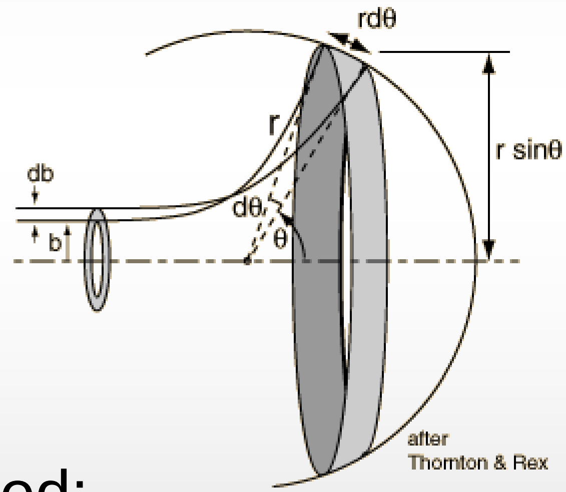
Impact parameter - b



There is a relation between impact parameter and scattering angle:

$$\theta = \pi - 2b \int_{r_{min}}^{\infty} \frac{dr}{r^2 \sqrt{1 - (b/r)^2 - 2U/mv^2}}$$

r_{min}: distance of closest approach
θ: scattering angle
U: potential $\rightarrow$ this is the interesting bit
m/v: mass/velocity of incoming particle



Since target nuclei are uniformly illuminated:
Probability(b)~bdb

Impact parameter - b

potential	Relationship between b and θ
Hard sphere U=0 (r>R) and U=∞ (r<R)	θ=0 if b>R b=Rcos(θ/2)
Coulomb potential $U = \frac{kZ_1Z_2e^2}{r}$	$b = \frac{Z_1Z_2ke^2}{2E_{kin}}\sqrt{\frac{1+\cos\theta}{1-\cos\theta}}$

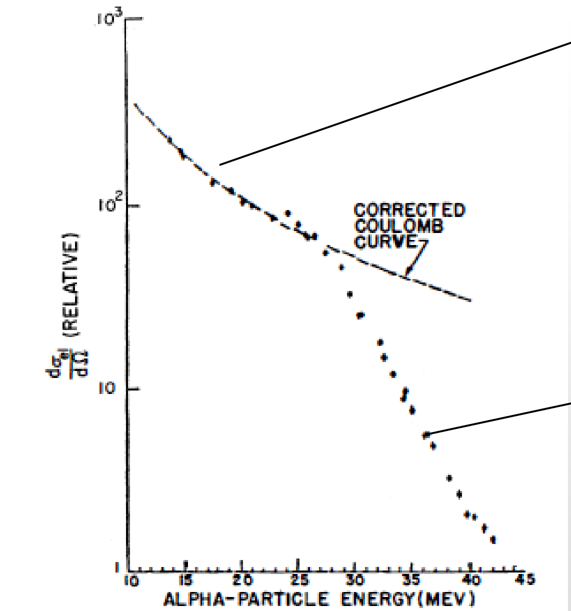


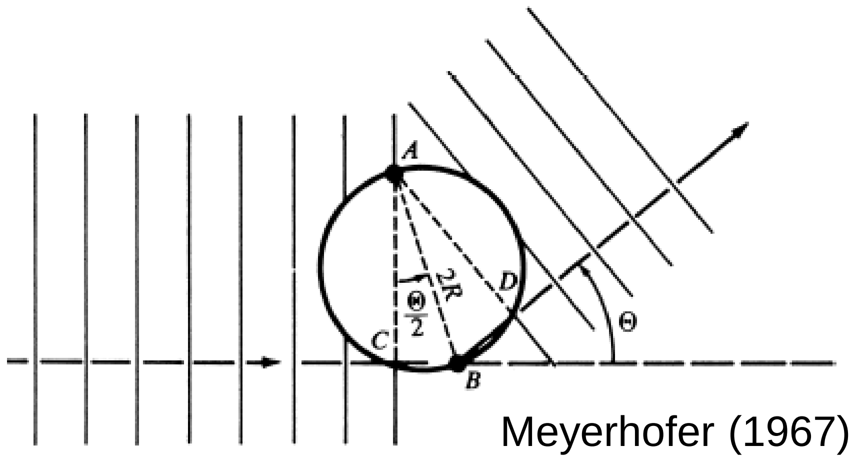
Fig. 5. Differential cross section for the elastic scattering of alpha particles by Pb at 60° as a function of the alpha-particle energy.

Rutherford scattering

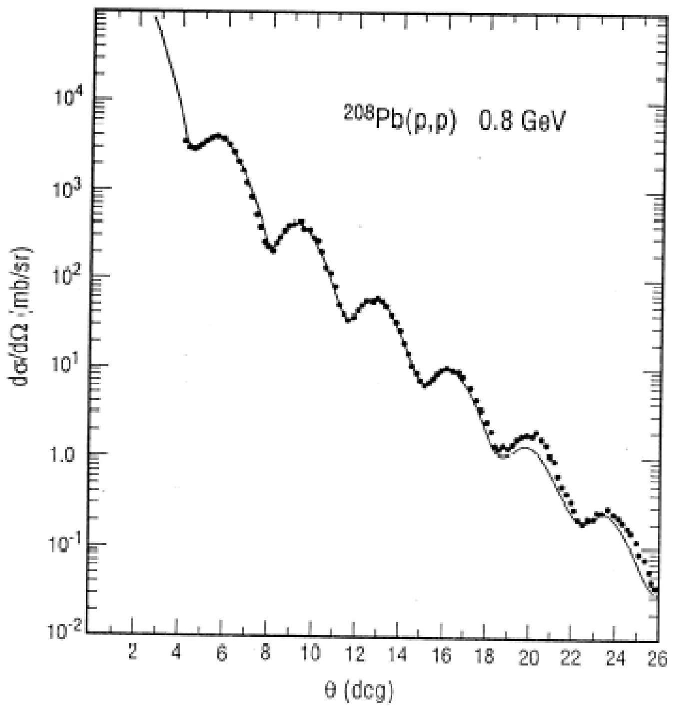
Effects of Nuclear potential

Eisberg, R. M. and Porter, C. E., Rev. Mod. Phys. 33, 190 (1961)

Diffraction in nuclear reactions



Meyerhofer (1967)



G.S. Blanpied et al. PRC 18, 1436 (1978)

Plane-wave scattering off a nucleus: consider scattering from points A and B

Fraunhofer diffraction pattern

CD+DB=nλ

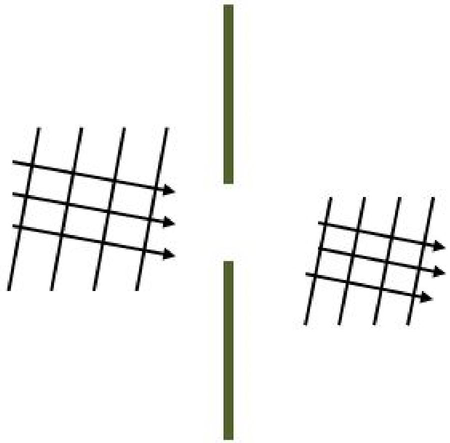
2*2Rsin(θ/2)=n λ

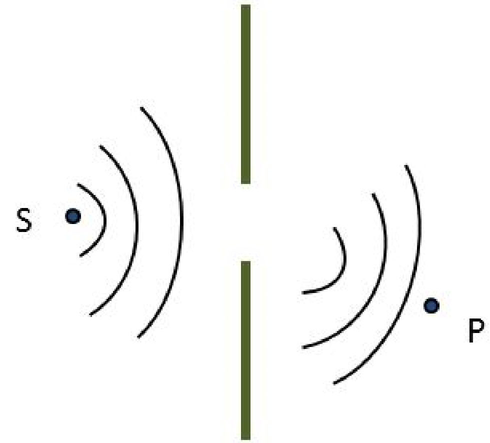
For 800 MeV protons:

λ=0.85 fm (λ=hc/E)

$\Delta\theta \approx 3.2^o$ (3.5^o) is measured

Fresnel *vs.* Fraunhofer diffraction





Fraunhofer:

both incident and diffracted waves may be considered to be planar (i.e. both S and P are far from the aperture)

Fresnel:

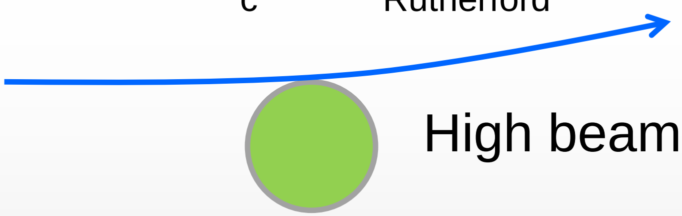
occurs when either S or P are close enough to the aperture that wavefront curvature is not negligible

Fresnel diffraction

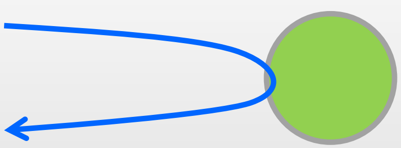
- If the Coulomb field is strong, the incoming wave becomes curved; particles scattered through a grazing angle θ_c appear to come from a virtual source at distance d from the scattering center ($d=b/\sin\theta_c$)

- θ_c : grazing angle, corresponds to the trajectory for which the two nuclei just touch each other R_a+R_b=distance of closest approach*

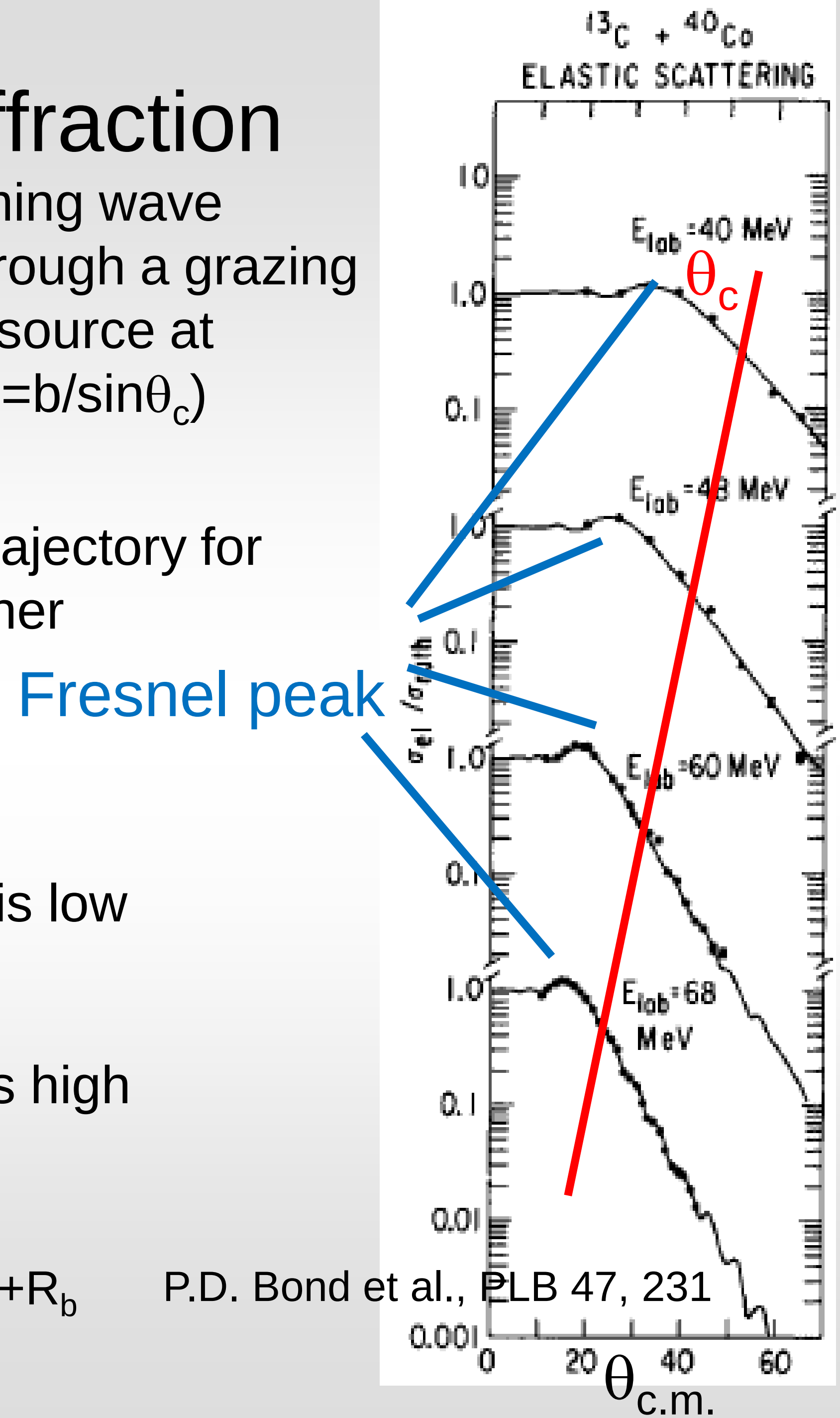
  At θ_c: $\sigma=\sigma_{Rutherford}/4$



High beam energy, θ_c is low



Low beam energy, θ_c is high

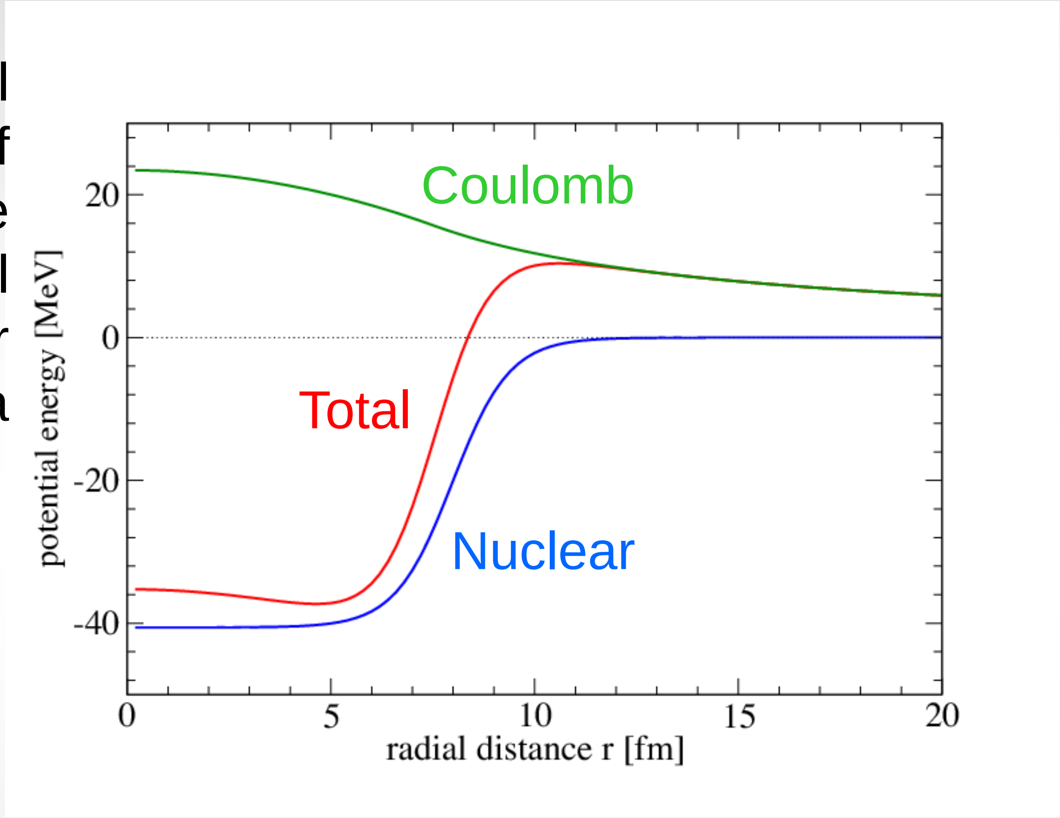


* It turns out it is actually slightly larger than R_a+R_b

P.D. Bond et al., PLB 47, 231

Coulomb & nuclear potentials

The combination of all contributions to the scattering of nuclei is modeled using a simple “optical” potential. It contains all the complexity of nuclear interactions and structure in a relatively simple form



General form:

$$U = V(r) + iW(r) + V_{so}(r) l \cdot s$$

V(r): real part – necessary to describe elastic scattering
W(r): imaginary part – describes to loss of flux to other channels – this is usually where the channel of interest contributes to.
$V_{so}(r)$: spin-orbit component – particularly important for polarization observables

Optical potential

The real and imaginary parts are generally assumed to have Woods-Saxon form:

$$U = \frac{-V_0}{1+e^{\frac{r-R_r}{a_r}}} + \frac{-iW_0}{1+e^{\frac{r-R_i}{a_i}}}$$

$R_{r,i}$: radius $a_{r,I}$: diffusiveness V_0, W_0: depth

Spin-orbit term: often a derivative of a Woods-Saxon shape

- In general, the calculation of the potentials based on nucleon-nucleon potentials is difficult, especially the imaginary part.
- Hence, the parameters are often determined from elastic scattering experiments – solutions are not necessarily unique
- Elastic scattering experiments are not so easy for unstable nuclei – why?

Example of systematizing OMP parameters

Nadasen et al. PRC 23, 1023 (1981)

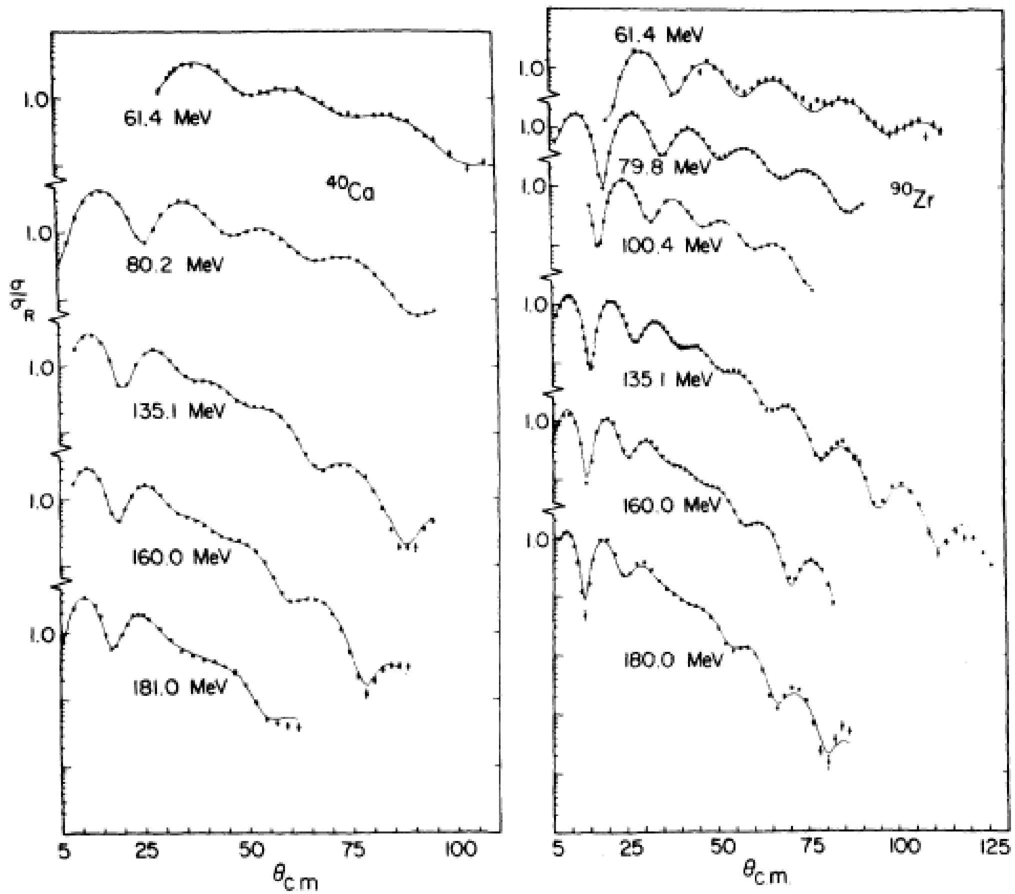
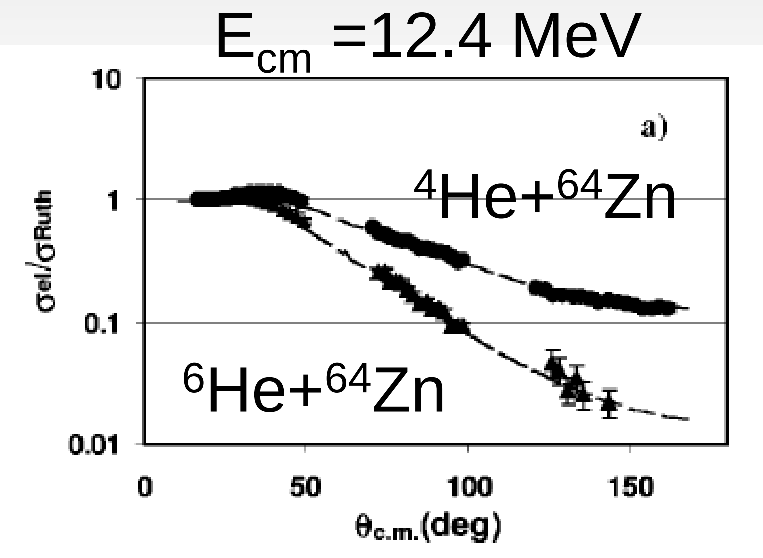


FIG. 2. Differential cross section angular distributions plotted as ratio-to-Rutherford for ^{40}Ca from 61.4 MeV to 181 MeV (61.4-MeV data from Ref. 7, 181-MeV data from Ref. 12); for ^{90}Zr from 61.4 MeV to 180 MeV (61.4-MeV data from Ref. 7, 100.4-MeV data from Ref. 8); and for ^{208}Pb from 61.4 to 182.4 MeV (61.4-MeV data from Ref. 7, 100.4-MeV data from Ref. 8). Relative errors are indicated where they exceed the size of the symbols (approximately ± 5%). The curves represent 10-parameter optical-model fits to the data.

Example: Elastic scattering of Halo nuclei

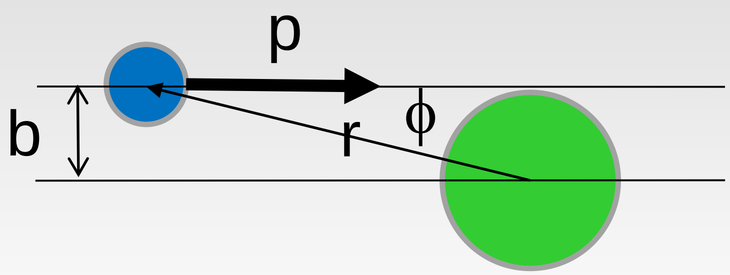
- For fixed E_{cm}: elastic scattering cross section for ^{6}He < ^{4}He: more flux is lost to non-elastic channels (break-up and transfer)
- Optical potential for ^{6}He has deeper imaginary potential with a larger radius and that is more diffuse



Di Pietro et al, PRC 69, 044613 (2004)

Reaction	$E_{c.m.}$(MeV)	V	r_0	a	W	r_i	a_i
^{4}He+^{64}Zn	12.4	123	1.2	0.43	20.4	1.05	0.43
^{6}He+^{64}Zn	12.4	104	1.2	0.6	38.9	1.2	0.85

Angular momentum



$L = \mathbf{r} \times \mathbf{p} = rp\sin\phi = bp$

Angular momentum is conserved for fixed b

Angular momentum transfer: $\Delta L = qb$ with $q = p_f - p_i$

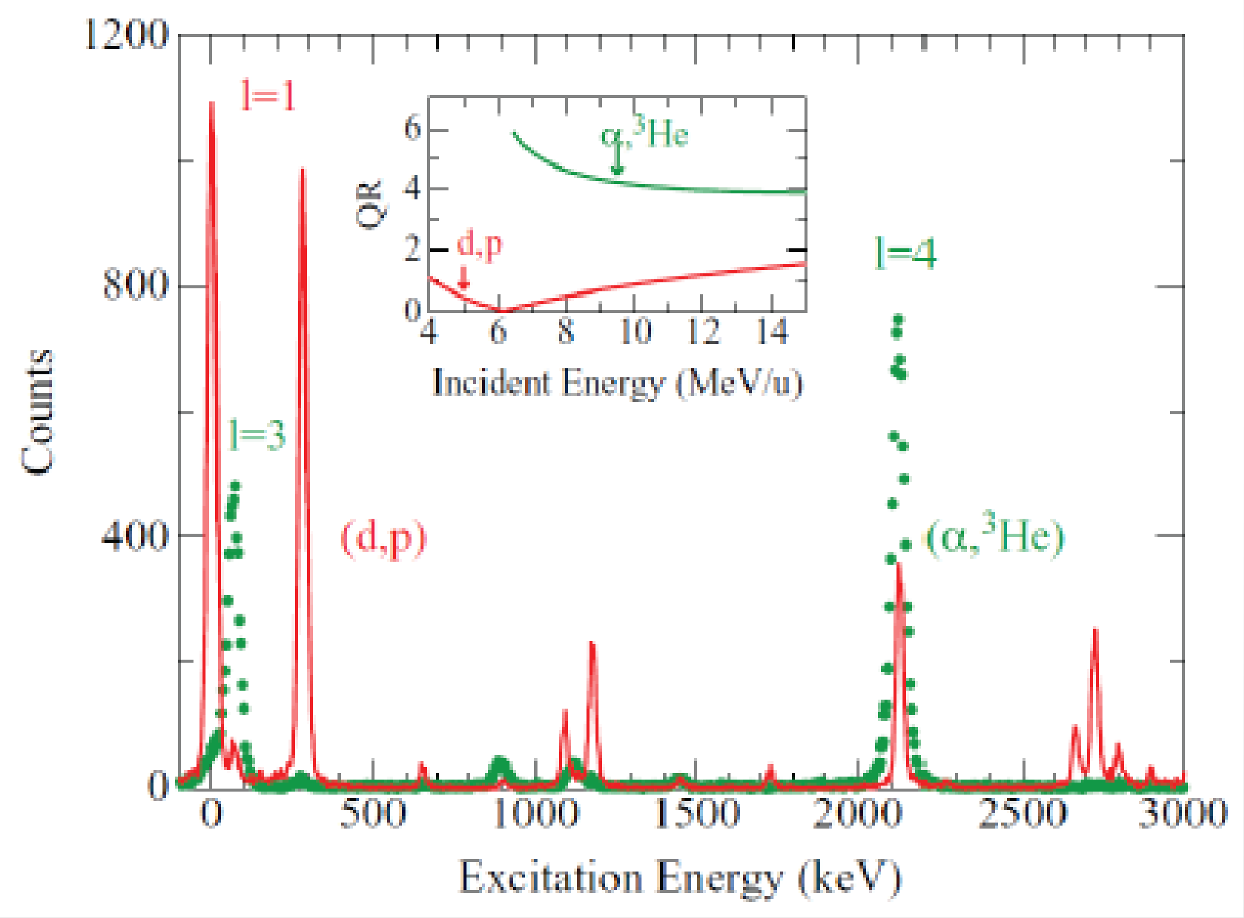
For reactions at the surface: $\Delta L \approx qR$

Momentum transfer q depends on:

- Reaction Q value
- Scattering angle
- Initial momentum

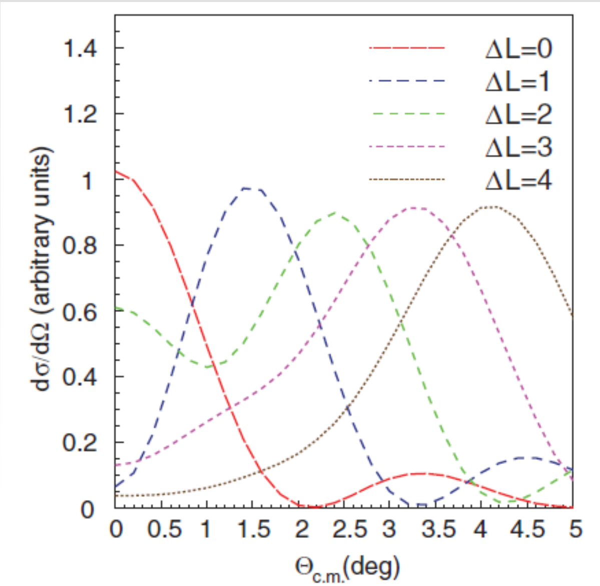
Momentum matching in transfer reactions

^{60}Ni(α,^{3}He): $Q_{g.s.}$= -12.8 MeV -> high momentum transfers
^{60}Ni(d,p): $Q_{g.s.}$= 5.6 MeV -> low momentum transfers

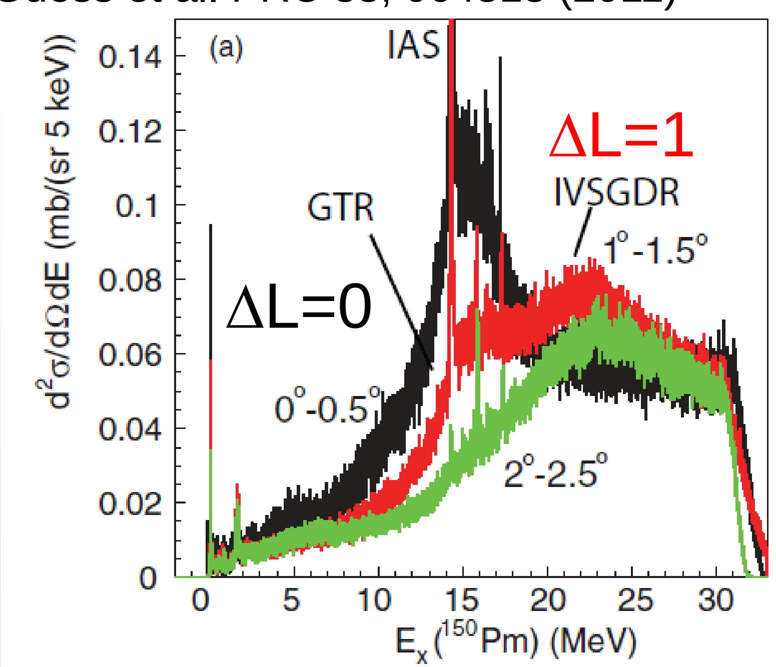


(example borrowed from C. Hoffman)

Angular momentum transfer and matching



Guess et al. PRC 83, 064318 (2011)



^{150}Nd(^{3}He,t) at 420 MeV

Q-value: -0.1 MeV

$R_{150Nd+3He}=1.2(A_{150}^{1/3}+A_3^{1/3}) \approx 8.1$ fm

$\theta=0^0$ q=0.001 1/fm $\Delta L=qR=0.008$

$\theta=1^0$ q=0.141 1/fm $\Delta L=qR=1.14$

$\theta=4^0$ q=0.563 1/fm $\Delta L=qR=4.56$

^{150}Nd(^{3}He,t) at 420 MeV

Q-value: -10 MeV

$R_{150Nd+3He}=1.2(A_{150}^{1/3}+A_3^{1/3}) \approx 8.1$ fm

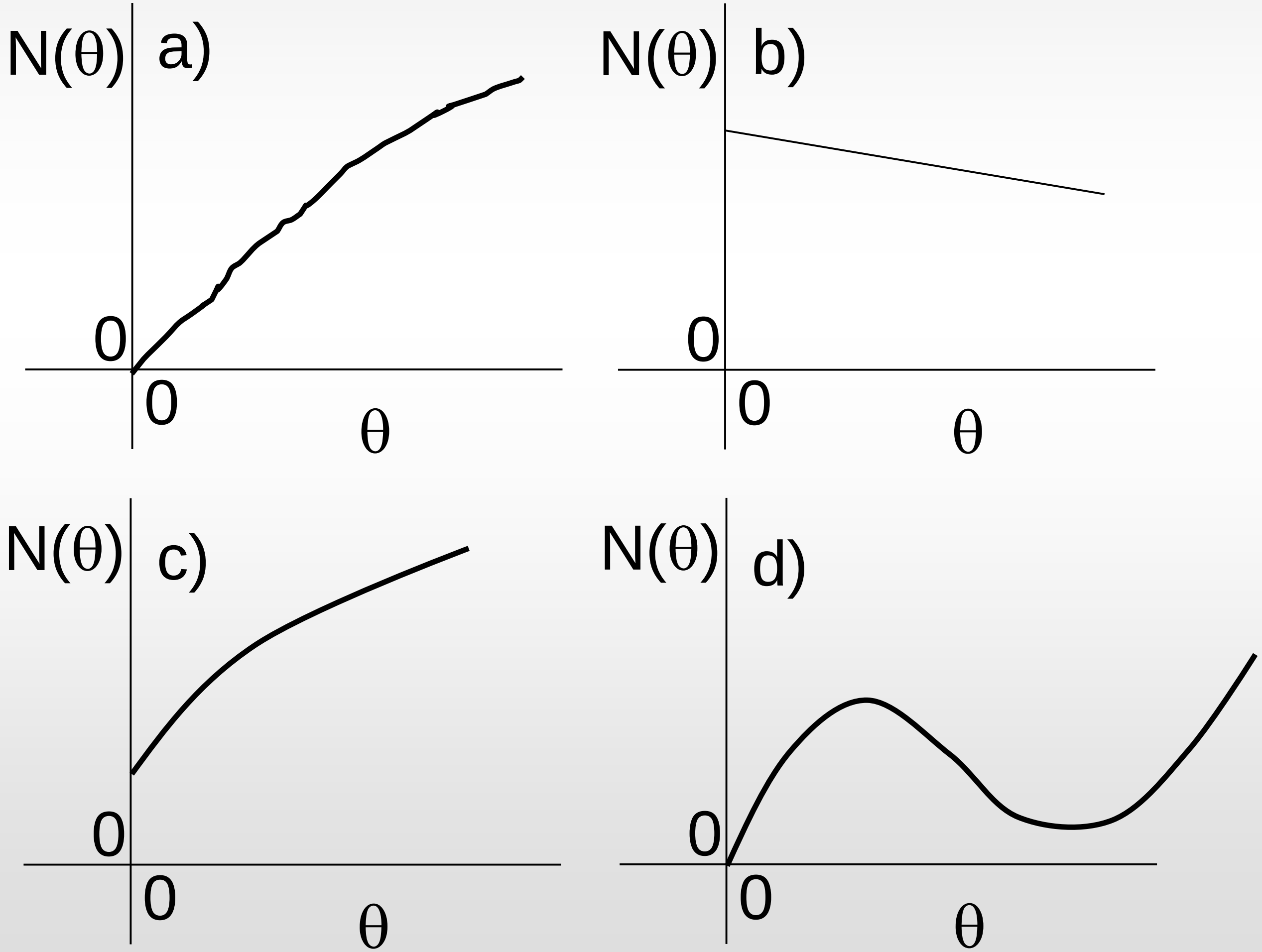
$\theta=0^0$ q=0.104 1/fm $\Delta L=qR=0.84$

$\theta=1^0$ q=0.175 1/fm $\Delta L=qR=1.42$

$\theta=4^0$ q=0.569 1/fm $\Delta L=qR=4.60$

Counting scattered particles

Which one(s) of the following curves depicting the number of events measured as a function of scattering angle cannot be realistic? You may assume that the angular resolution of the measurement is perfect.



Differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{N(\theta,\phi)}{N_{target} N_{beam} \epsilon d\Omega}$$

$N(\theta,\phi)$:number of particles scattered to scattering angle θ and azimuthal angle ϕ

N_{target}: number of target nuclei per unit of surface

N_{beam} : number of beam particles impinged on the target

$d\Omega$: solid angle covered by detector

ε: efficiency of the detector system

Units: $d\sigma/d\Omega$: mb/sr 1 b = 10^{-28} m^2 1mb = 10^{-27} cm^2

N_{target}: cm^{-2} = ρ(g/cm^3) x thickness(cm) x N_A / A*

N_{beam}: unitless

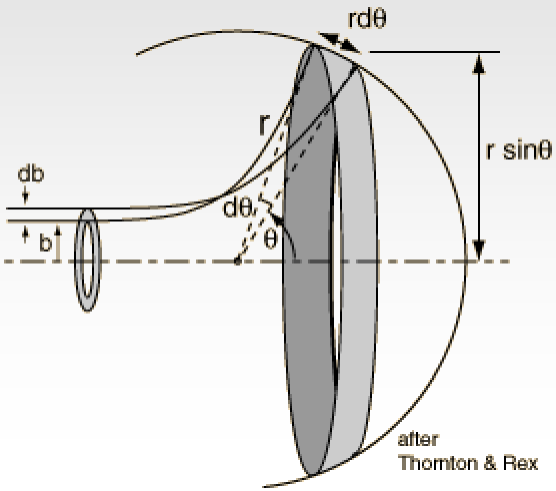
$d\Omega$: sr (simple geometry or simulation)

ε: unitless (simple measurement or simulation)

Why is it so hard to measure very accurate (~1%) absolute cross sections?

*: assumes mono-atomic target

Solid angle covered by a detector



$$d\Omega = sin\theta d\theta d\phi$$

θ: scattering angle
ϕ: azimuthal angle

if azimuthal angle covers 2π:

$$\int d\Omega = \int_0^{2\pi} \int_{\theta_1}^{\theta_2} sin\theta d\theta d\phi = 2\pi(cos\theta_1 - cos\theta_2)$$

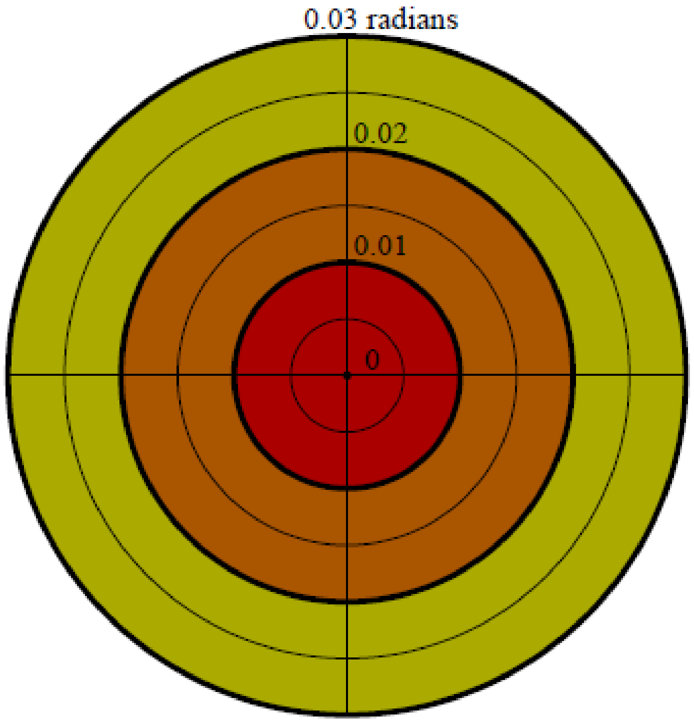
- At $\theta=0$ $\sin\theta=0$ $\rightarrow$ the solid angle at 0 degrees is 0
- If $\theta_1=0$ and $\theta_2=\pi$ $\rightarrow$ solid angle is 4π (whole sphere)
- Beware that usually differential cross sections are given in the center-of-mass and one needs to convert between c.o.m. and laboratory solid angles

Solid angle

$$\int d\Omega = \int_0^{2\pi} \int_{\theta_1}^{\theta_2} sin\theta d\theta d\phi = 2\pi(cos\theta_1 - cos\theta_2)$$

For fixed $d\theta$ and θ small,

$\Omega(0,d\theta) = 1/3\ \Omega(d\theta,2d\theta) = 1/5\ \Omega(2d\theta,3d\theta)$



Reaction kinematics (relativistic)

For details on the equations in the following slides refer to:

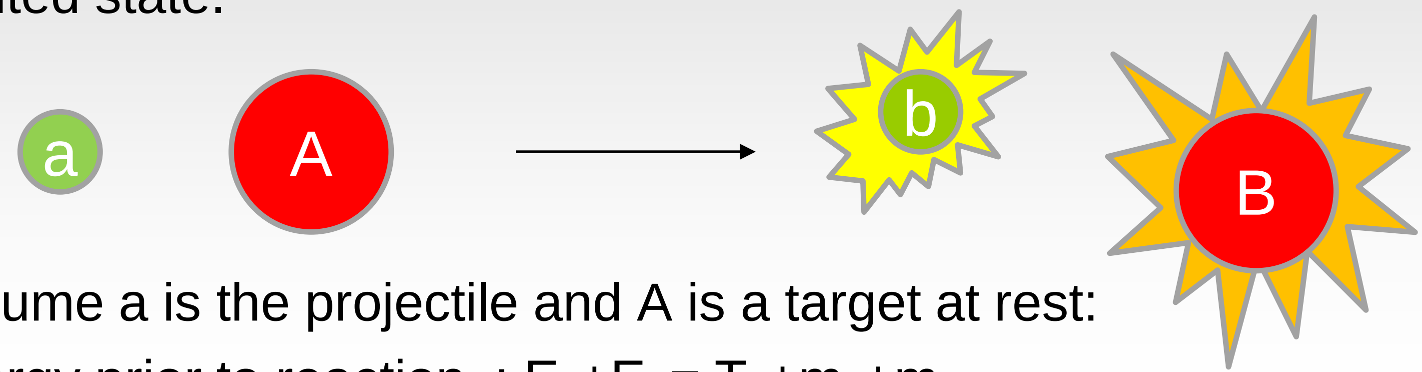
Relkin-english.pdf (relkin.pdf for the original German version)

catkin4.01.xlsm (based on catkin by Wilton Catford)

Available at: https://people.nscl.msu.edu/~zegers/ebss2017/

Two-body Reaction kinematics

Consider 2-body reaction: a+A $\rightarrow$ b+B; both B and b can be in an excited state.



Assume a is the projectile and A is a target at rest:

Energy prior to reaction : $E_a+E_A= T_a+m_a+m_A$

Energy after the reaction: $E_b+E_B=T_b+m_b+Ex_b+T_B+m_B+Ex_B$

T: kinetic energy, m: mass, Ex: excitation energy (c=1)

Ground state Q-value ($Ex_b=Ex_B=0$): $Q_{g.s.}=m_a+m_A-m_b-m_B$

Total Q-value: $Q=Q_{g.s.}- (Ex_b+Ex_B)$

Conservation of energy: $T_a+Q_{g.s.}=T_b+T_B+Ex_b+Ex_B$

Or: $Q=T_b+T_B-T_a$ typically, T_a is known, T_b is measured and T_B can be derived.

Center-of-mass system

In the center-of-mass system, the system as a whole is at rest:
$p_{a,cm}+p_{A,cm}=0$

$$E_{cm} = \sqrt{(E_a + E_A)^2 - (p_a + p_A)^2}$$

$$E_{a,A} = T_{a,A} + m_{a,A} \qquad p_{a,A}^2 = T_{a,A}^2 + 2T_{a,A}m_{a,A}$$

$$\beta_{cm} = \frac{p_a + p_A}{E_a + E_A} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\tan\theta_3 = \frac{\sin\theta_3^{cm}}{\gamma(\cos\theta_3^{cm} + \frac{\beta}{\beta_3^{cm}})} \qquad \tan\theta_4 = \frac{\sin\theta_4^{cm}}{\gamma(\cos\theta_4^{cm} + \frac{\beta}{\beta_4^{cm}})}$$

Angle transformations

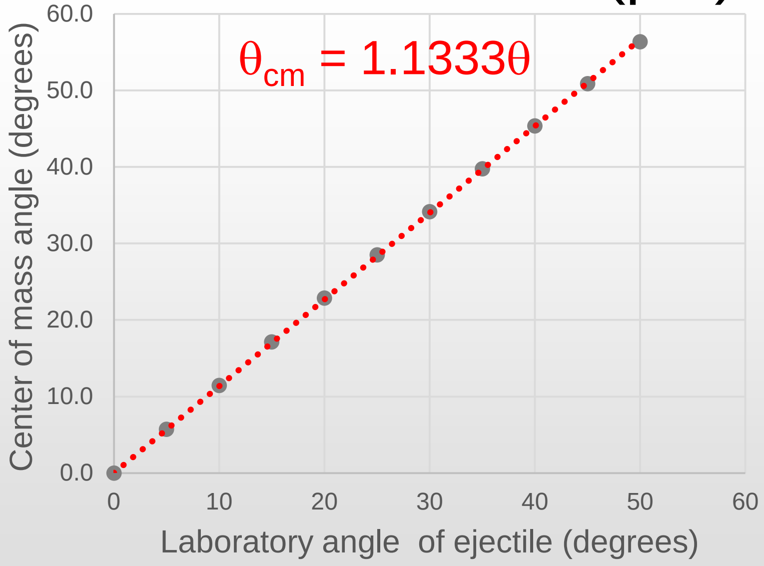
$$\tan\theta_3 = \frac{\sin\theta_3^{cm}}{\gamma(\cos\theta_3^{cm} + \frac{\beta}{\beta_3^{cm}})}$$

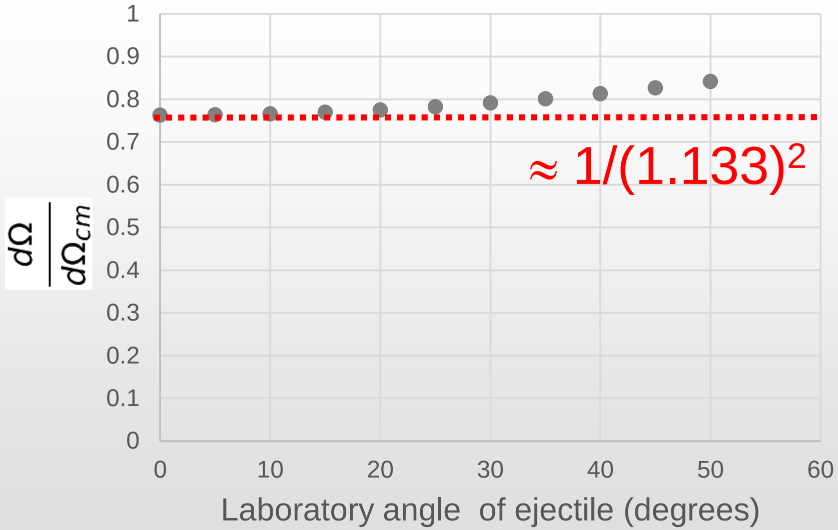
$$\tan\theta_4 = \frac{\sin\theta_4^{cm}}{\gamma(\cos\theta_4^{cm} + \frac{\beta}{\beta_4^{cm}})}$$

$$\frac{d\Omega}{d\Omega_{cm}} = \gamma \cdot \frac{1 + x\cos\theta_{cm}}{\sqrt{\sin^2\theta_{cm} + \gamma^2(\cos\theta_{cm} + x^2)^2}^{\,3}}$$

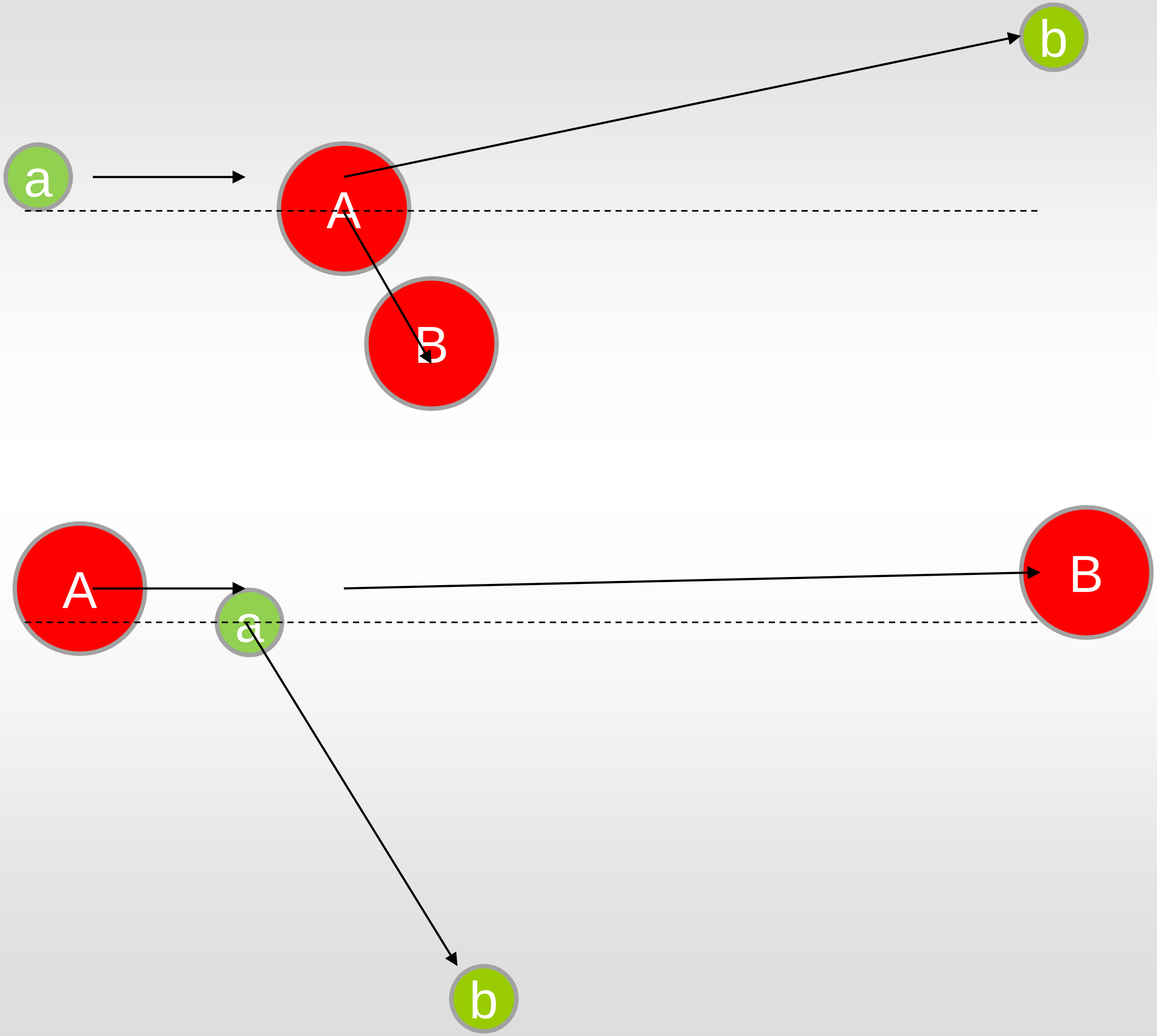
$$x = \frac{\beta}{\beta_{3,4}^{cm}}$$

$^{12}C(p,d)$ at 100 MeV



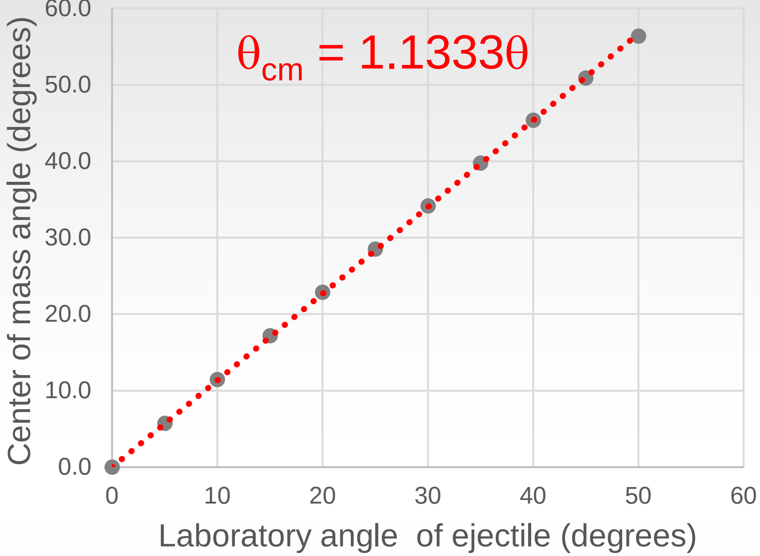


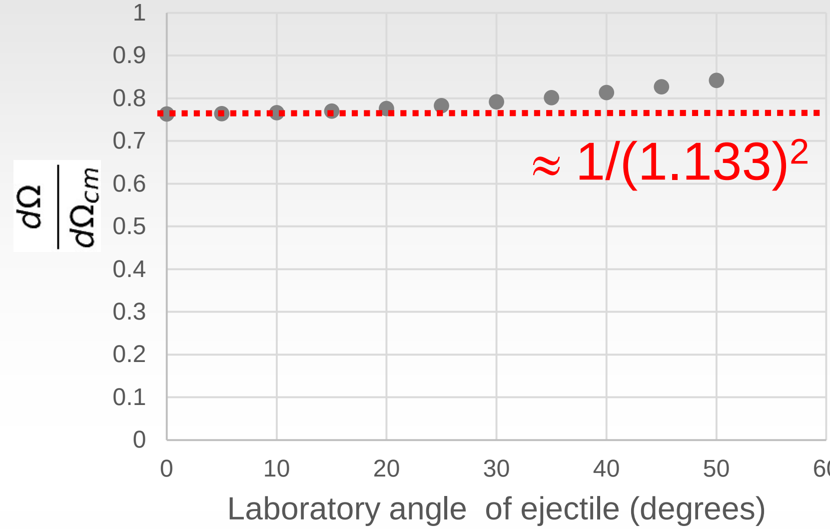
Forward and inverse kinematics



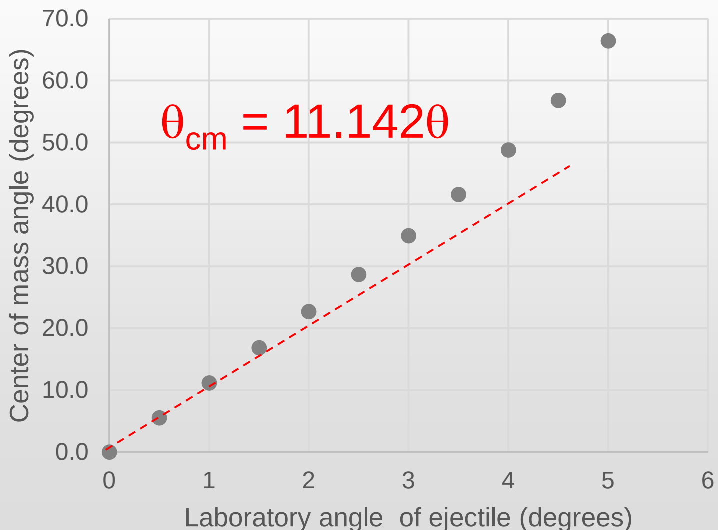
Forward & Inverse kinematics

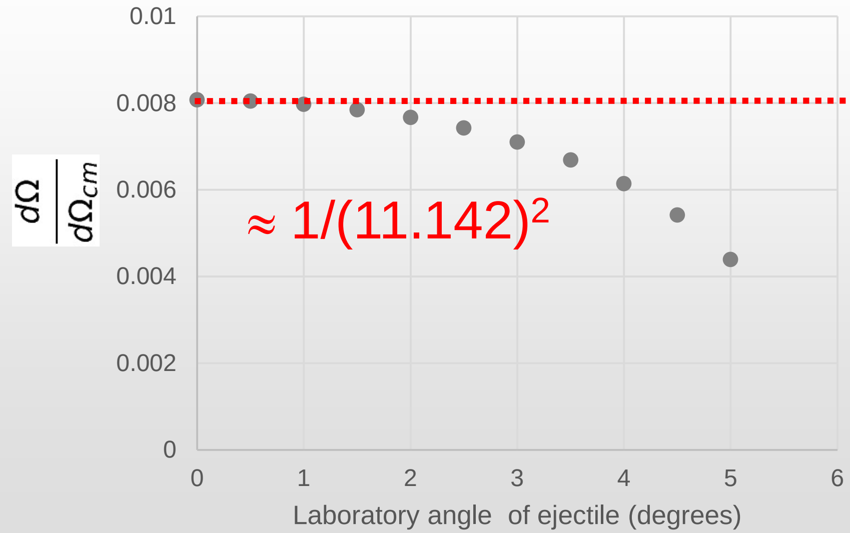
$^{12}C(p,d)$ at 100 MeV



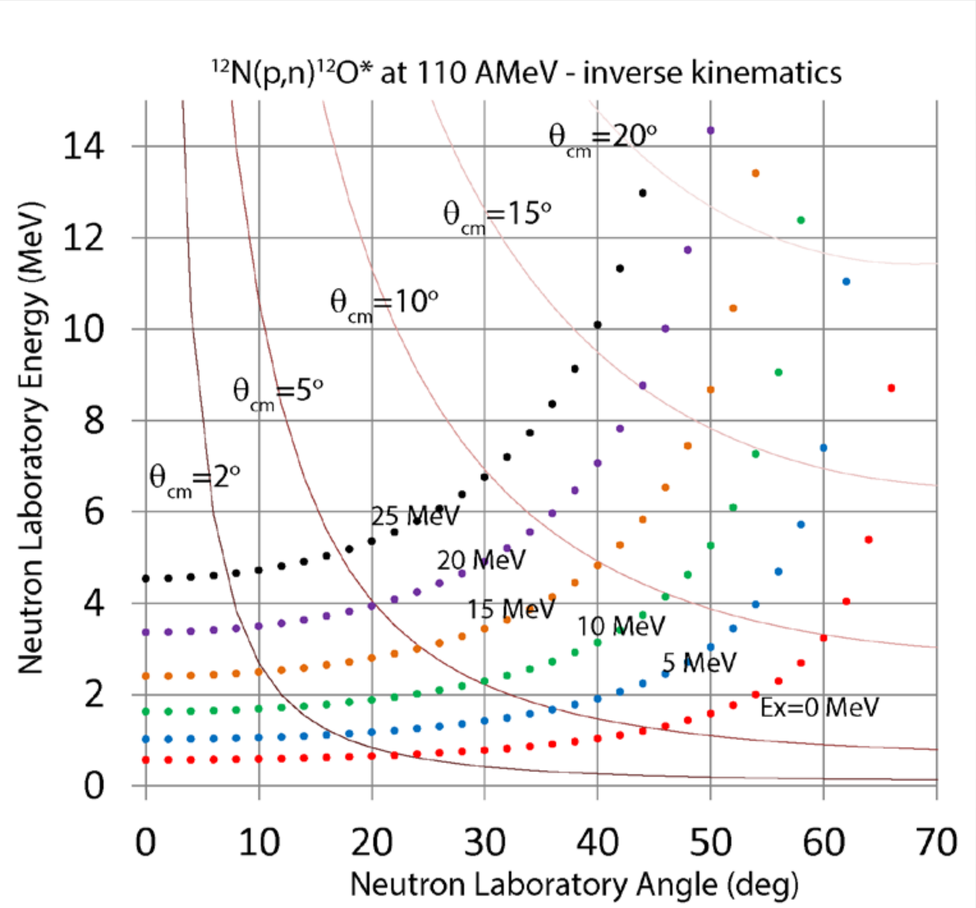


$p(^{12}C,^{11}C)$ at 100 MeV





Inverse kinematics - example



$^{12}N(p,n)^{12}O^*$ at 110 AMeV

In forward kinematics:

$\theta_n \approx \theta_{cm}$

$E_x \sim (E_p - E_n)$

In inverse kinematics, relationships between kinematical variables are more complicated

Missing mass

What is the excitation energy of B?

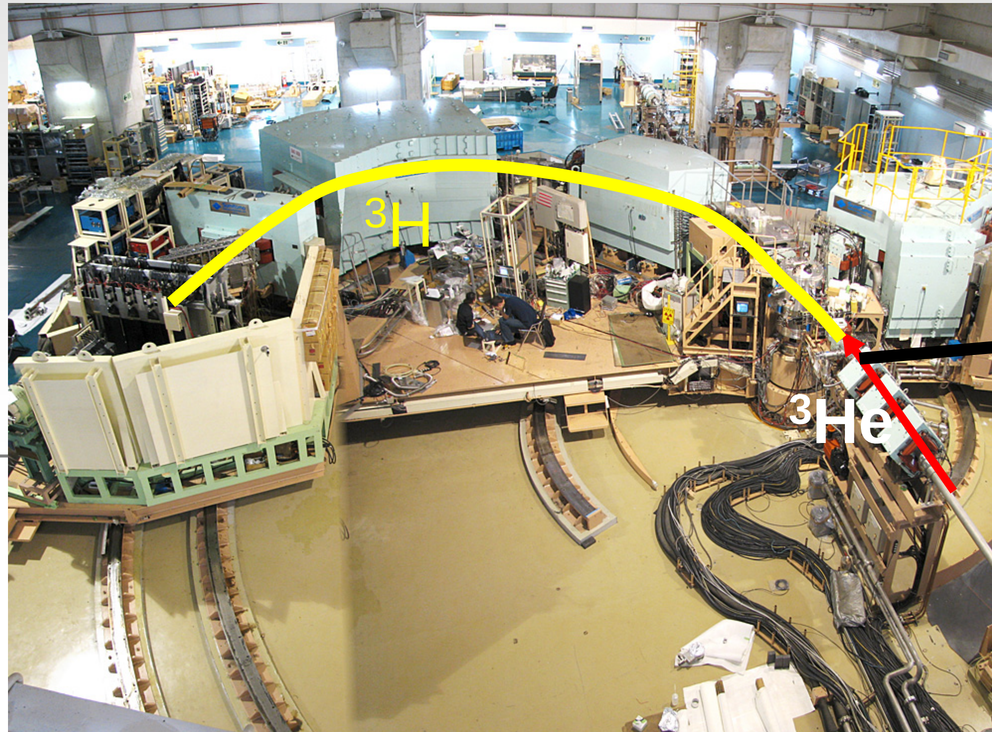
$$p_{miss} = \sqrt{(p_{a,x} - p_{b,x})^2 + (p_{a,y} - p_{b,y})^2 + (p_{a,z} - p_{b,z})^2}$$

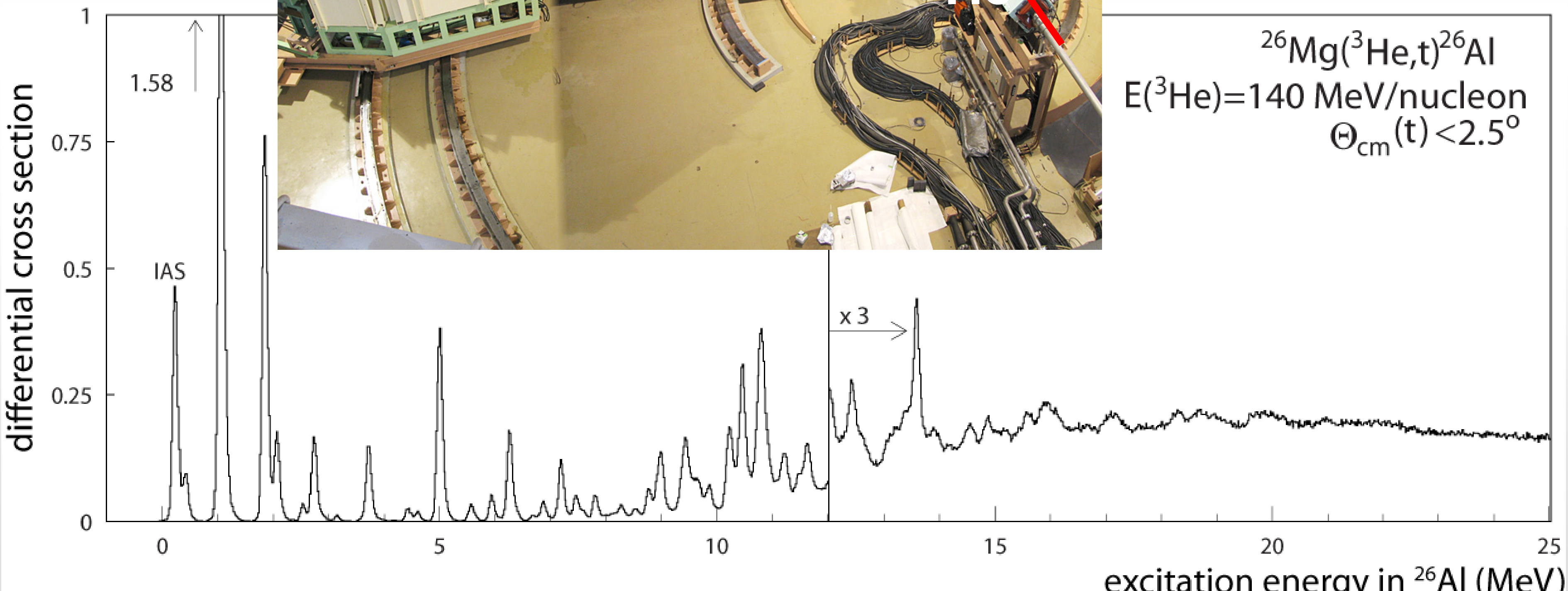
$$E_{miss} = m_a + T_a + m_A - \sqrt{p_b^2 + m_b^2}$$

$$m_{miss} = \sqrt{E_{miss}^2 - p_{miss}^2}$$

$$Ex_B = m_{miss} - m_B$$

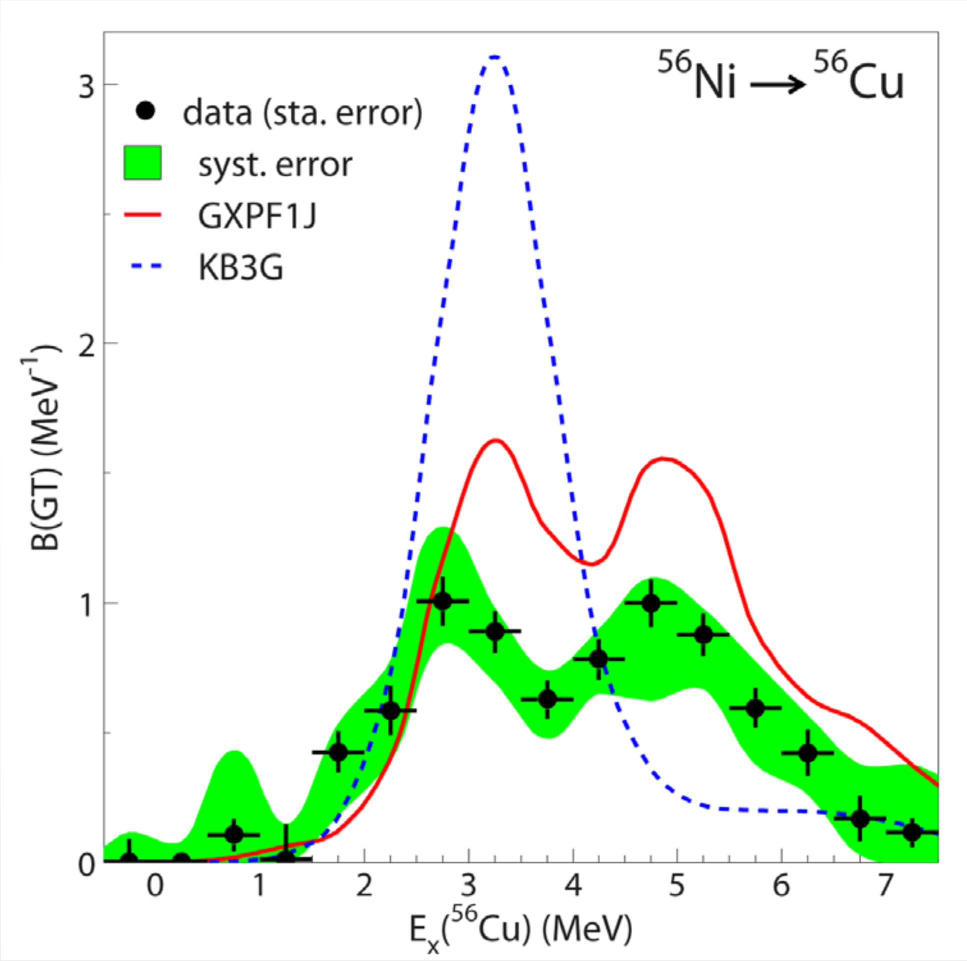
Example: $^{26}Mg(^{3}He,t)$ – measured the triton

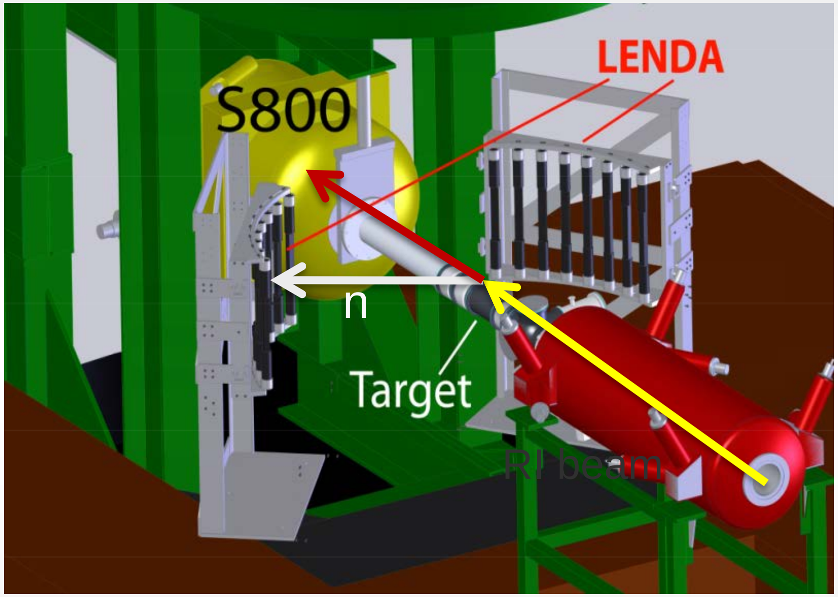




(p,n) in inverse kinematics

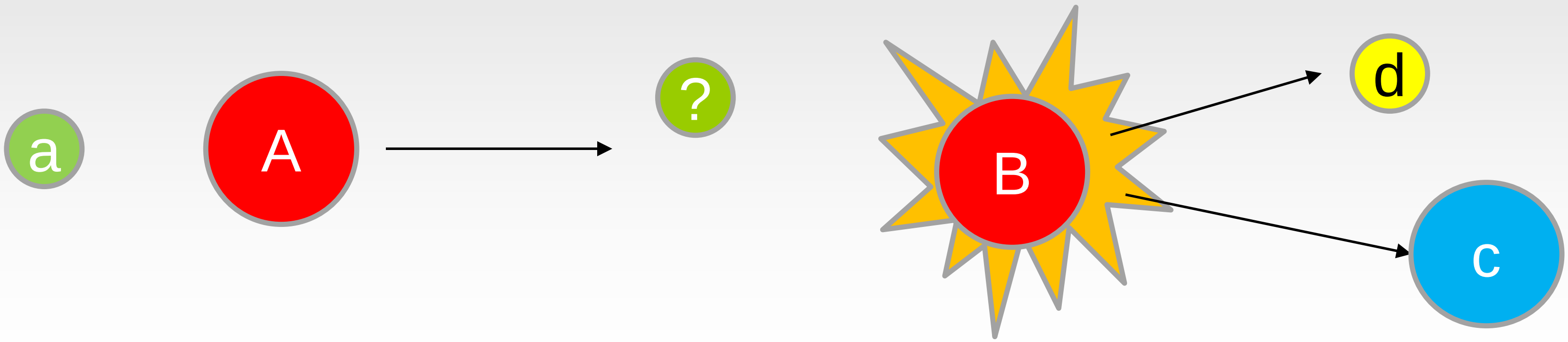
p(^{56}Ni,^{56}Cu*)n at 110 MeV/u





Invariant mass

What is the excitation energy of B?



$$p_{tot} = \sqrt{(p_{c,x} + p_{d,x})^2 + (p_{c,y} + p_{d,y})^2 + (p_{c,z} + p_{d,z})^2}$$

$$E_{tot} = E_c + E_d = \sqrt{p_c^2 + m_c^2} + \sqrt{p_d^2 + m_d^2}$$

$$m_{inv} = \sqrt{E_{tot}^2 - p_{tot}^2}$$

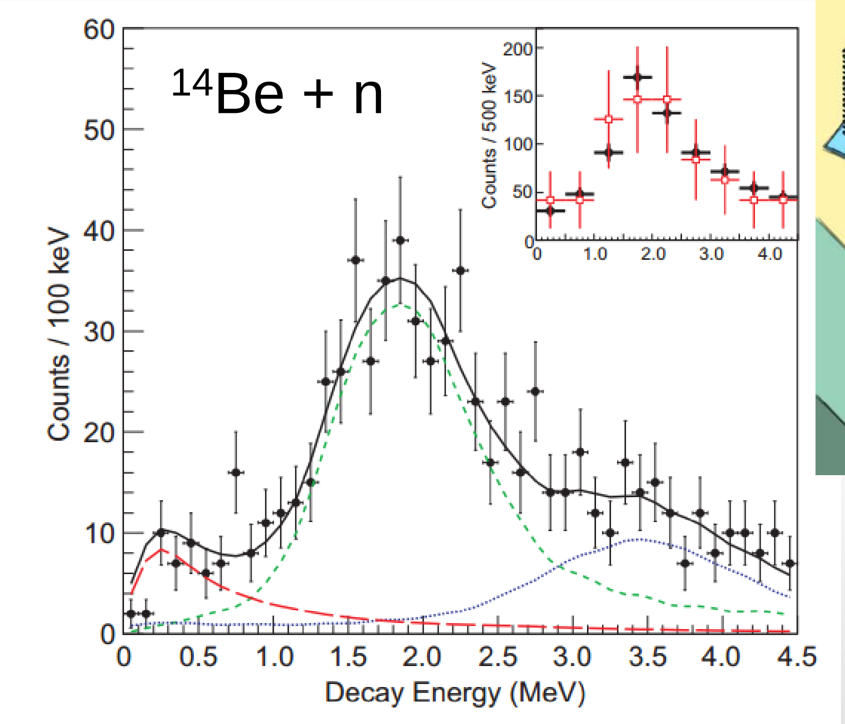
$$E_{decay} = M_{inv} - M_c - M_d$$

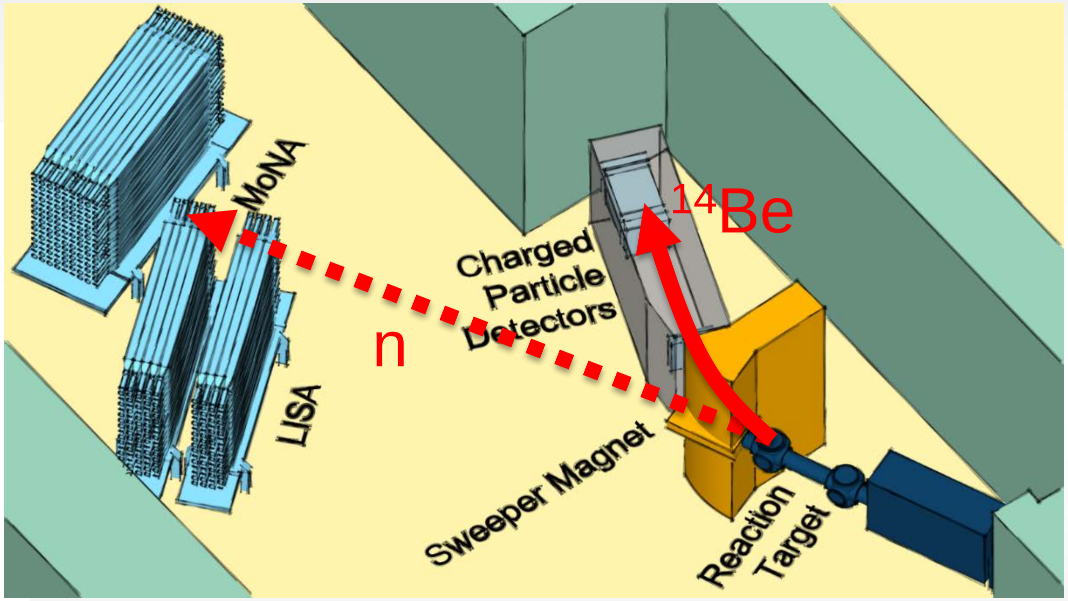
$$Ex_B = M_{inv} - M_B$$

Requires M_B to be known

Example: ^{15}Be

^{14}Be(d,p)^{15}Be → ^{14}Be + n

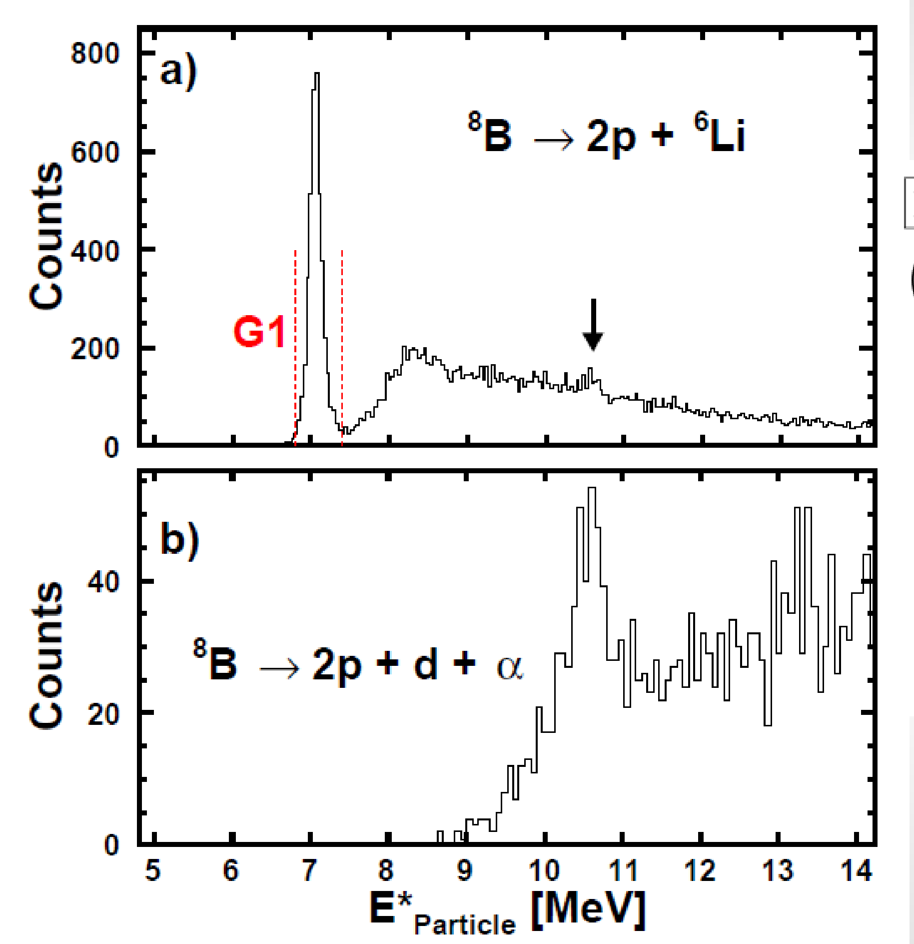


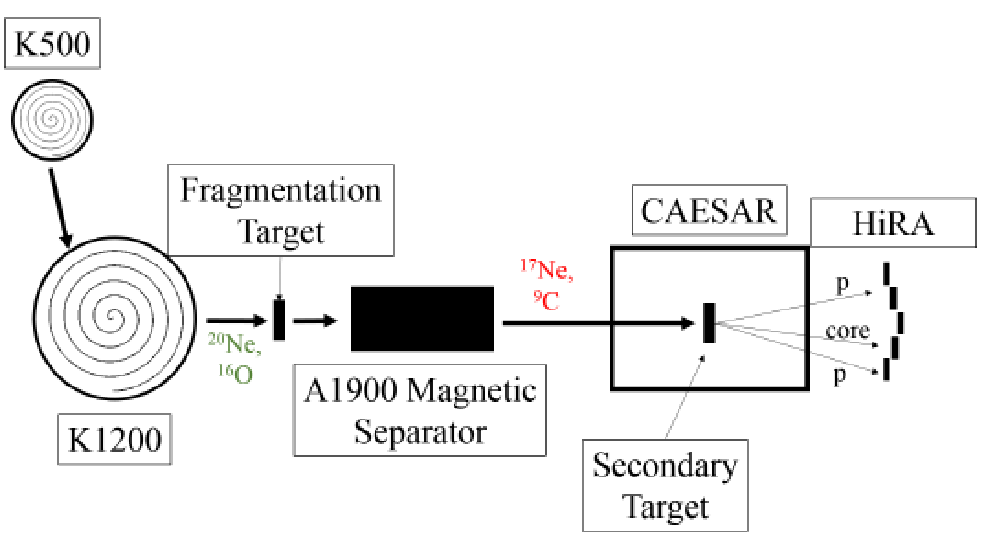


Snyder et al. PRC Rapid 2013

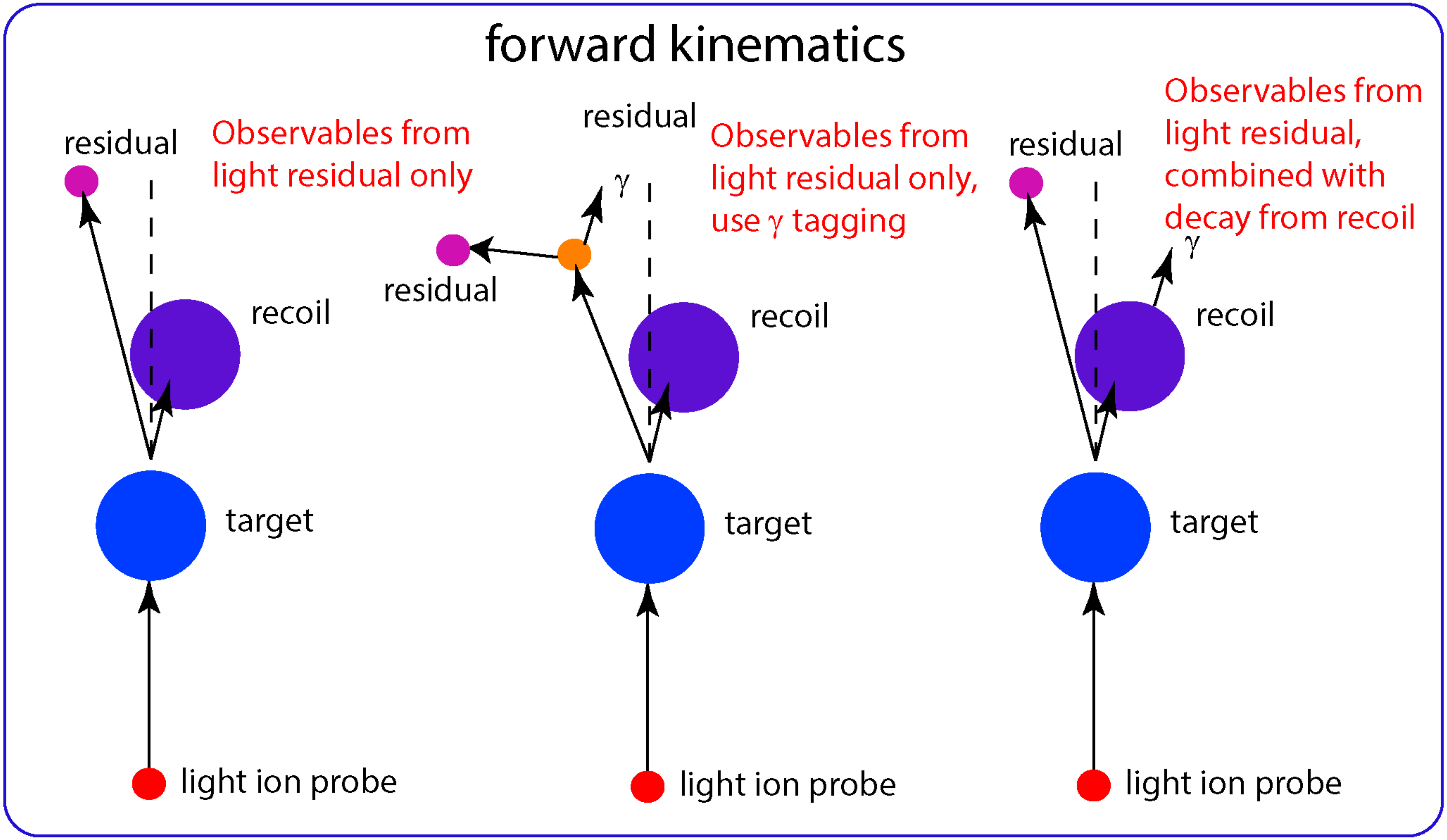
Another example

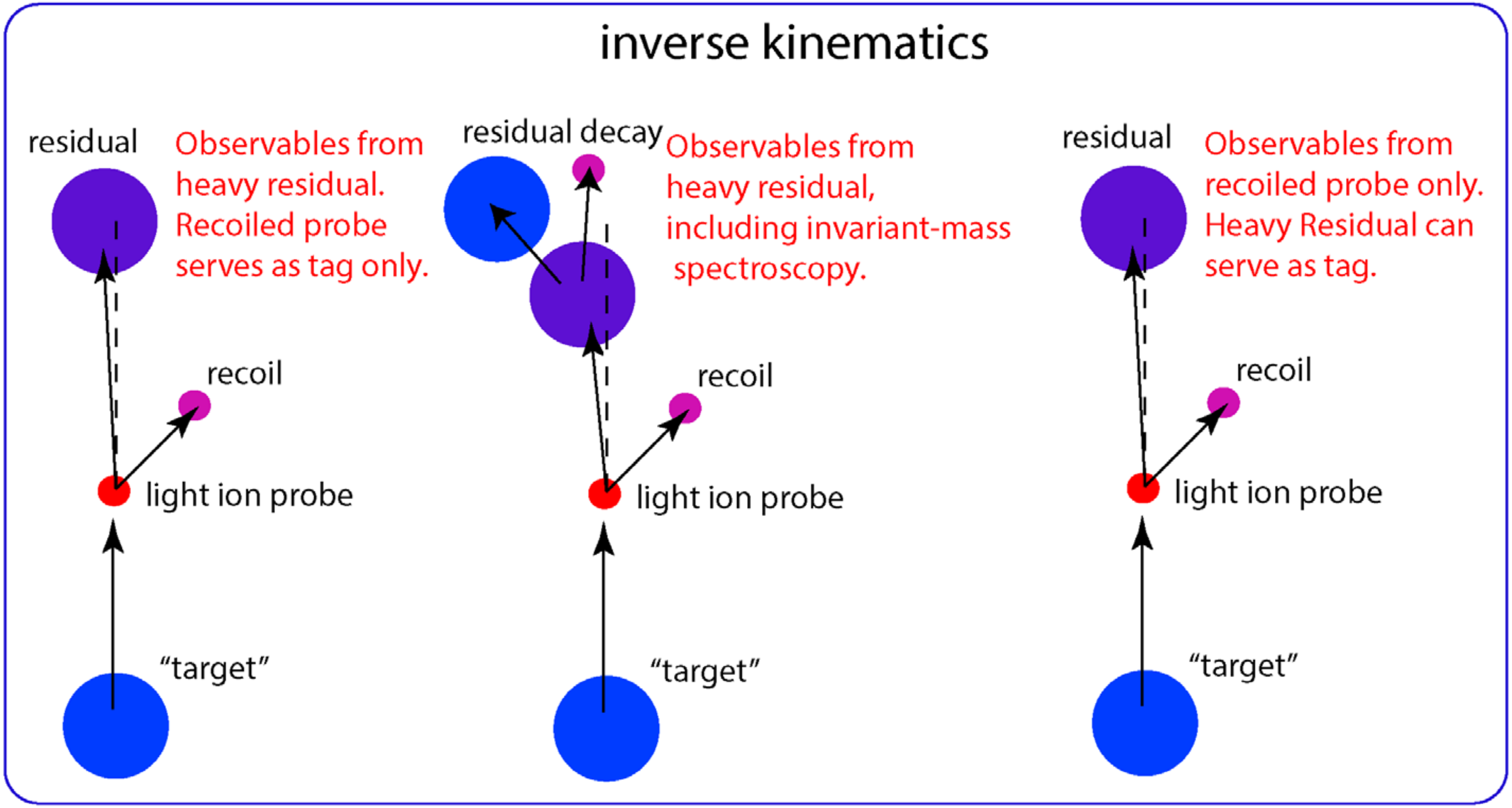
Invariant mass spectroscopy of ^{8}B





Thesis of K. Brown, WU (2016)


forward kinematics
residual
Observables from
light residual only
recoil
target
light ion probe
residual
γ
residual
Observables from
light residual only,
use γ tagging
recoil
target
light ion probe
residual
Observables from
light residual,
combined with
decay from recoil
γ
recoil
target
light ion probe


inverse kinematics
residual
Observables from heavy residual. Recoiled probe serves as tag only.
recoil
light ion probe
"target"
residual decay
Observables from heavy residual, including invariant-mass spectroscopy.
recoil
light ion probe
"target"
residual
Observables from recoiled probe only. Heavy Residual can serve as tag.
recoil
light ion probe
"target"

Why are reaction experiments in inverse kinematics with rare isotope beams so difficult?

- Low beam intensities and cocktail beams
- Impure/Thick reaction targets (resolution) – recoil particles get stuck in target
- Forward kinematic focusing of ejectile – resolutions, rates, contaminants
- Complex kinematical analysis – difficult to rely on two-body (missing mass) analysis
- Doppler reconstruction of particles/gamma’s emitted in flight
- …

More knowledge/assumptions on reaction theory is likely required…

Advantages of inverse kinematics?

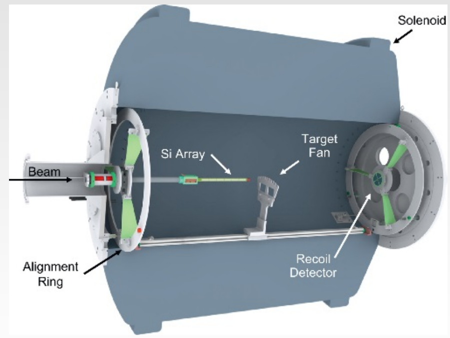
- Low beam intensities and cocktail beams
- Forward kinematic focusing of ejectile
- Kinematics can be beneficial in certain cases
- Doppler reconstruction of particles/gamma’s emitted in flight – opportunities for lifetime studies
- …

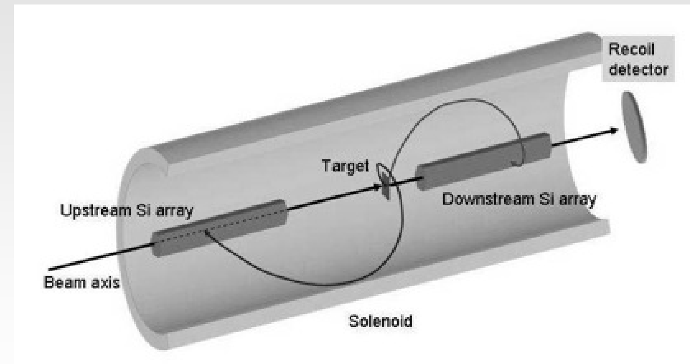
Development of new detector systems for studying nuclear reactions in inverse kinematics with rare isotope beams has been a huge effort by the low-energy nuclear physics community – investment in detector systems are very worthwhile since beam time is expensive and in short supply!

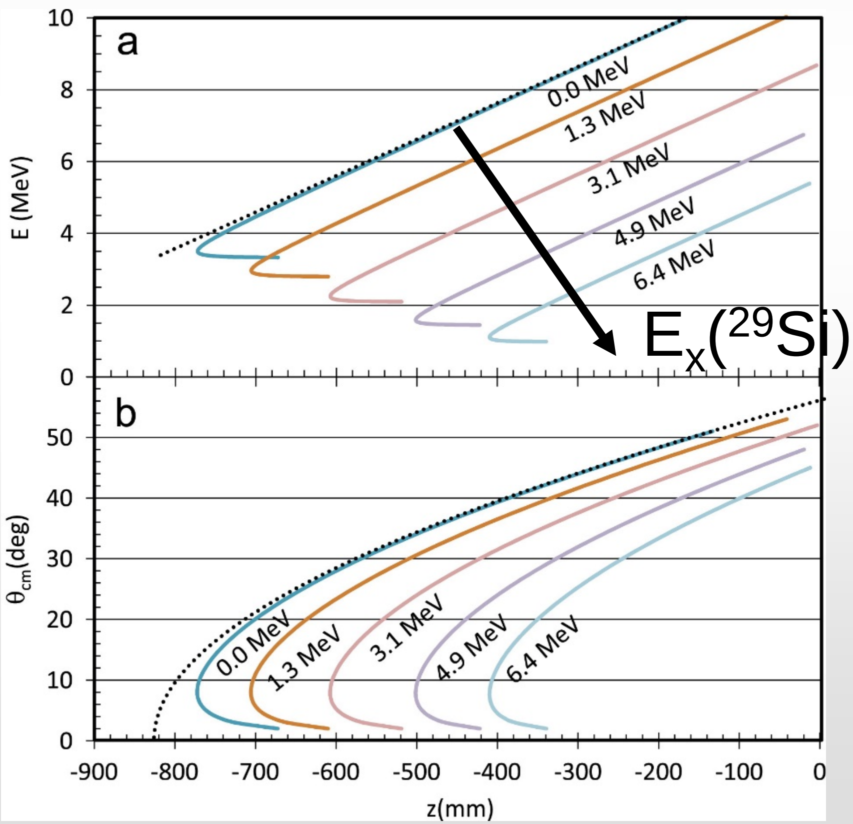
Special tools for reaction studies in inverse kinematics

Helios Helical Orbit Spectrometer

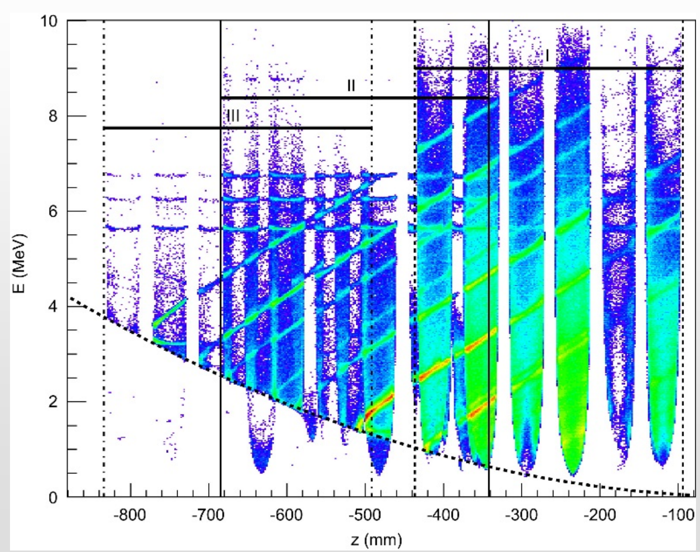
$d(^{28}Si,p)^{29}Si$ at 6 MeV/u





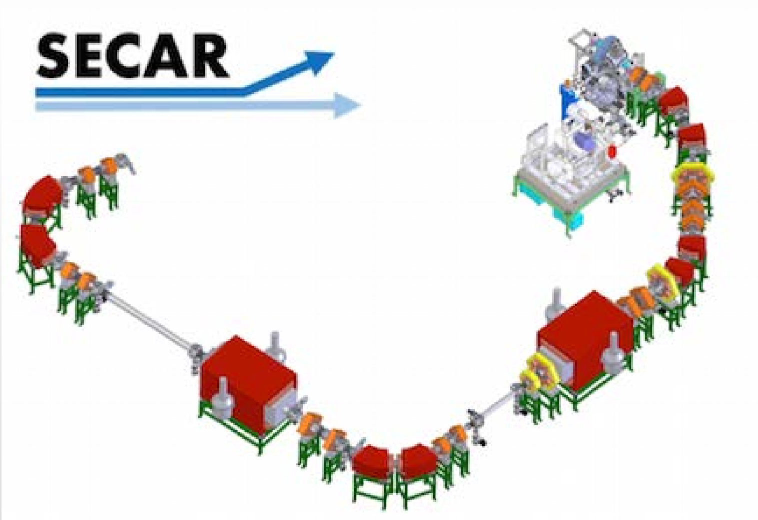


Lighthall et al, NIMA 622, 97 (2010)



Special tools for reaction studies in inverse kinematics

JENSA Gas-jet target – windowless Gas target (e.g. H, ^{2}He, ^{3}He, ^{4}He) for low-energy reactions in astrophysics $\sim 10^{19}$ atoms/cm^2 can be achieved.
1 mg/cm^2 H_2 target: 6×10^{20} atoms/cm^2

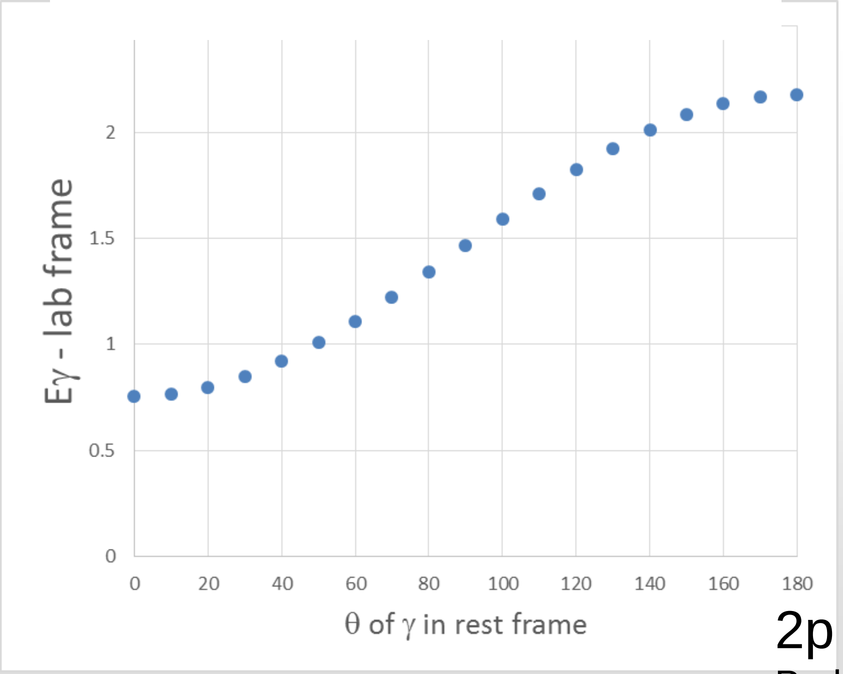


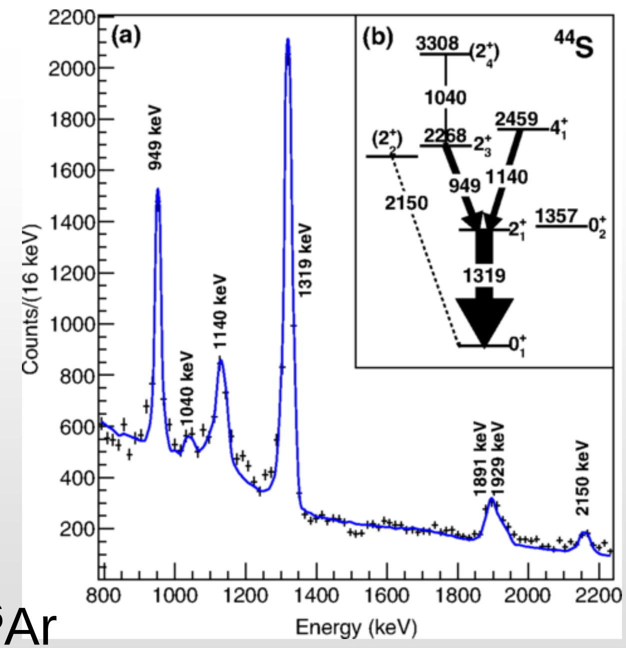
Separator for Capture Reactions (SECAR) – under construction experimental device for studying capture reactions on unstable nuclei for X-ray bursts/Novae, Supernovae and Supermassive stars

Special tools for reaction studies in inverse kinematics, e.g.

Gretina: Gamma-Ray Energy Tracking In-beam Nuclear Array provides good angular resolution for gamma rays emitted in flight.

$$E_\gamma = \frac{E_{\gamma,lab}\,(1-\beta\cos\theta)}{1-\beta^2}$$





2p knockout from ^{46}Ar

Parker et al, PRL 118, 052501 (2017)

Active Targets

- Detector gas serves as target as well
- Relatively thick targets can be made
- Beam loses energy in gas: reactions at several energies can be measured
- Recoils have no "invisible" energy loss

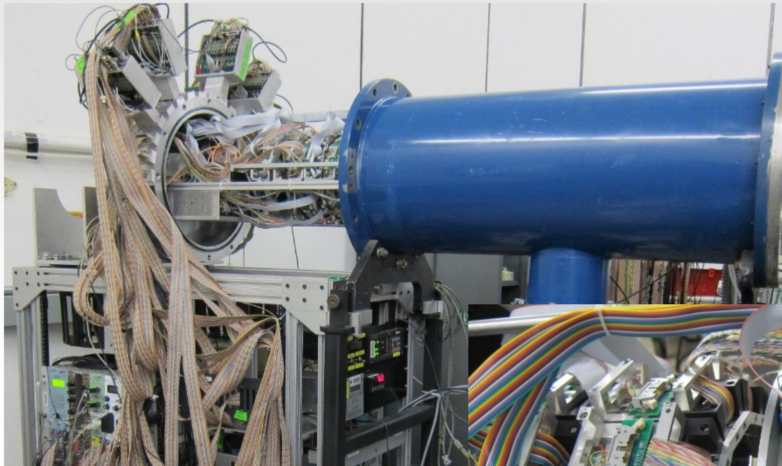
Table 1: Active Targets in operation or being constructed.

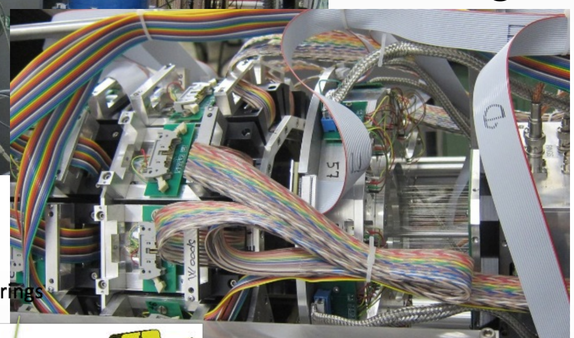
Name	Lab	gas ampl.	Volume [cm^3]	pressure [atm]	Energy [MeV/n]	elec tronics	Number of chan.	sta tus[a]	ref
Ikar	GSI	NA	$60 \cdot 20^2\pi$	10	700	FADC	6*3	O	[5]
Maya	GANIL	wire	$30 \cdot 28.3^2$	0.02-2	2-60	gassiplex	1024	O	[6]
ACTAR	GANIL	μmegas	20^3	0.01-3	2-60	GET	16000	C,P	[7]
MSTPC	various	wires/ GEM	$70 \cdot 15 \cdot 20$	<0.3	0.5-5	FADC	128	O	[8] [9, 10]
CAT	CNS	GEM	$10 \cdot 10 \cdot 25$	0.2-1	100-200	FADC	400	T	[11]
MAIKo	RNCP	μ-PIC	14^3	0.4-1	10-100	FADC	2×256	T	[12]
pAT-TPC	MSU	μmegas	$50 \cdot 12.5^2\pi$	0.01-1	1-10	GET	256	T,O	[13]
AT-TPC	FRIB	μmegas	$100 \cdot 25^2\pi$	0.01-1	1-100	GET	10240	O	[14]
TACTIC	TRIUMF	GEM	$24 \cdot 10^2\pi$	0.25-1	1-10	FADC	48	T	[15]
ANASEN	FSU/ LSU	wires	$43 \cdot 10^2\pi$	0.1-1	1-10	ASIC	512	O	[16]
MINOS	IRFU	μmegas	6000	0.01-3	>120	feminos	5000	O	[17]
O-TPC	TUNL	grid	$21 \cdot 30^2$	0.1	γ10	optical CCD	$2048 \cdot 2048$ pixels	O	[18]

[a] O: operational, C: under construction, P: Project, T: test device

S. Beceiro-Novo PPNP 84, 124 (2015)

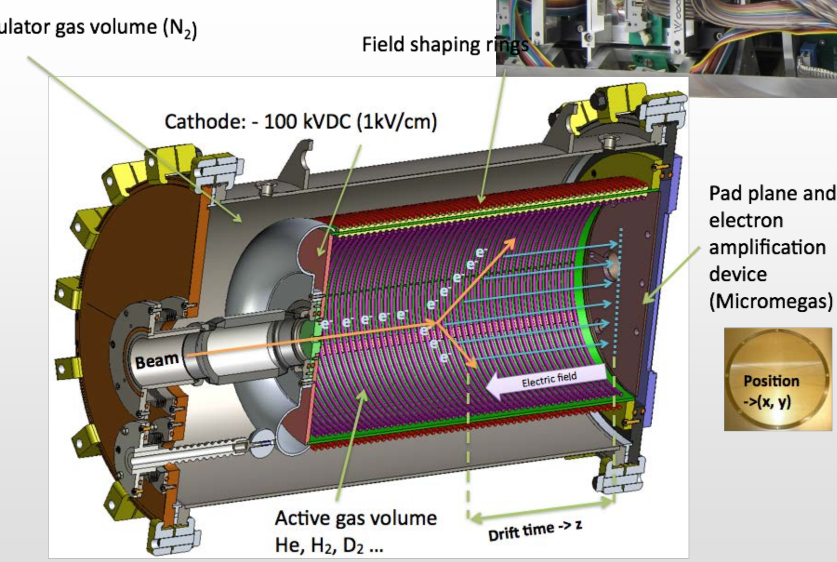
Some active target systems



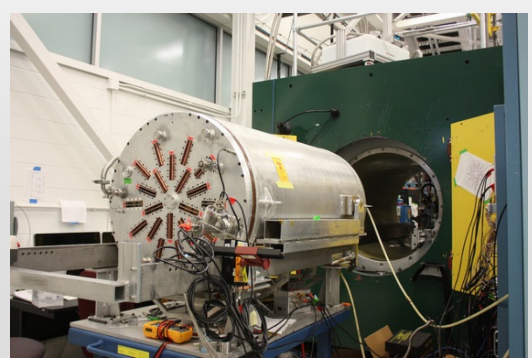


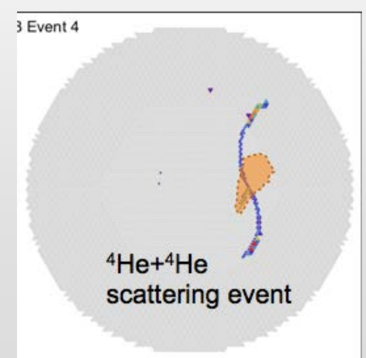
ANASEN (FSU/LSU)

layers of vertex proportional counter, multi-strip Silicon and CsI detectors surround the gas



Active Target-Time Projection Chamber (MSU) – imaging of tracks





…and many others…

Basic reaction types

- Simple or direct reactions
  - Usually peripheral (large impact parameter)
  - Involve mostly the valence/outer nucleons
  - Useful for probing single-particle properties
- Complex or central reactions
  - Central/head-on collisions (small impact parameter)
  - Involves all nucleons in nuclei
  - Probes statistical properties of nuclei (multi fragmentation or compound nucleus)

Direct reactions

- Momentum transferred between target and projectile is usually small compared to initial momentum
- Associated with large impact parameters
- Timescale is short ($<10^{-22}$ s – time for projectile to traverse through the nucleus
- Beam energy is typically in excess of 20 MeV
- Reactions proceed predominantly through a single step
- Final states have a memory of the initial states
- Angular distributions tend to be forward peaked

Direct reactions

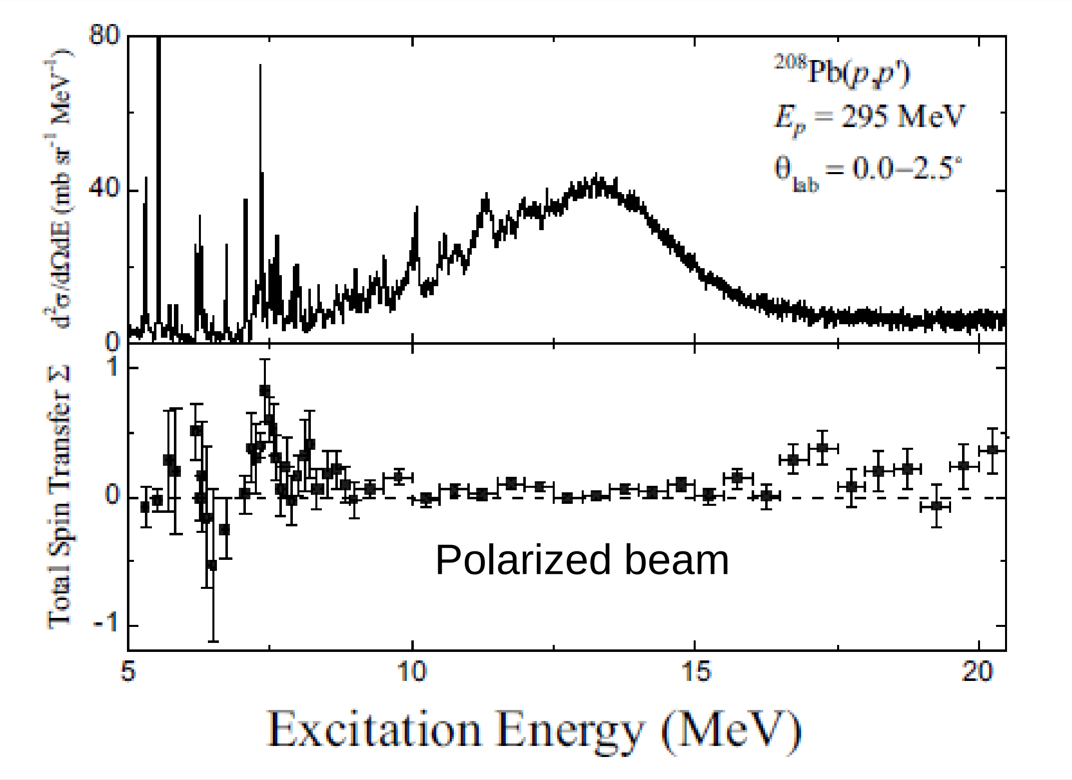
Reaction	Use/Motivation (sampled!)
Elastic scattering, e.g. $^{58}Ni(p,p)^{58}Ni(g.s.)$	Extract optical potentials, radii, density distributions
Inelastic scattering, e.g. $^{58}Ni(p,p')^{58}Ni^{*}$	Extract information about electromagnetic and nuclear transitions, deformations, level schemes
Transfer reactions, e.g. $^{58}Ni(d,p)^{57}Ni^{*}$	Shell structure – spin, parity, spectroscopic factors
Two-nucleon transfer, e.g. $^{58}Ni(t,p)^{56}Ni^{*}$	Two-nucleon correlations, pairing
Knock-out reactions, e.g. $^{58}Ni(^{9}Be,X)^{57}Ni$	Shell-structure - spin, parity, spectroscopic factors
Breakup reactions, e.g. $^{14}Be(^{12}C,X)^{12}Be+2n$	Halos, states in the continuum
Charge-exchange reactions, e.g. $^{58}Ni(t,^{3}He)^{58}Co^{*}$	Isovector transitions, structure, Gamow-Teller strengths, astrophysics
….	

Inelastic scattering

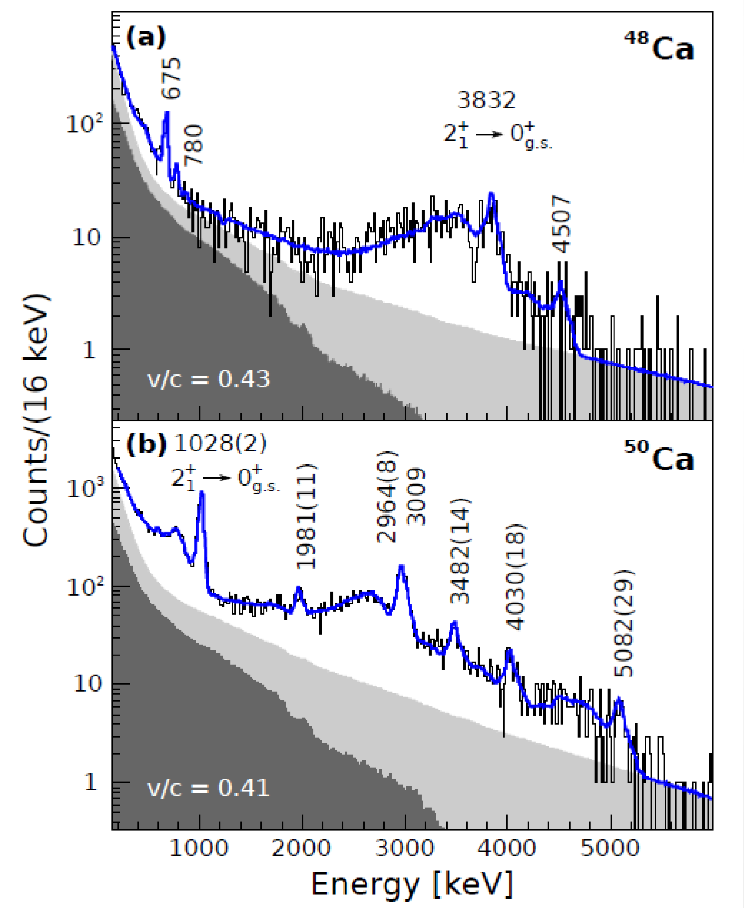
^{208}Pb(p,p') at 295 MeV at forward c.o.m. angles:

- Response is dominated by E1 (dipole) transitions which are excited through Coulomb excitation (no spin transferred)
- Nuclear excitations present, primarily through M1 excitations (spin transferred)

Inverse kinematics (p.p') at ~95 MeV/u – low-lying study transitions as a means for understanding shell-evolution

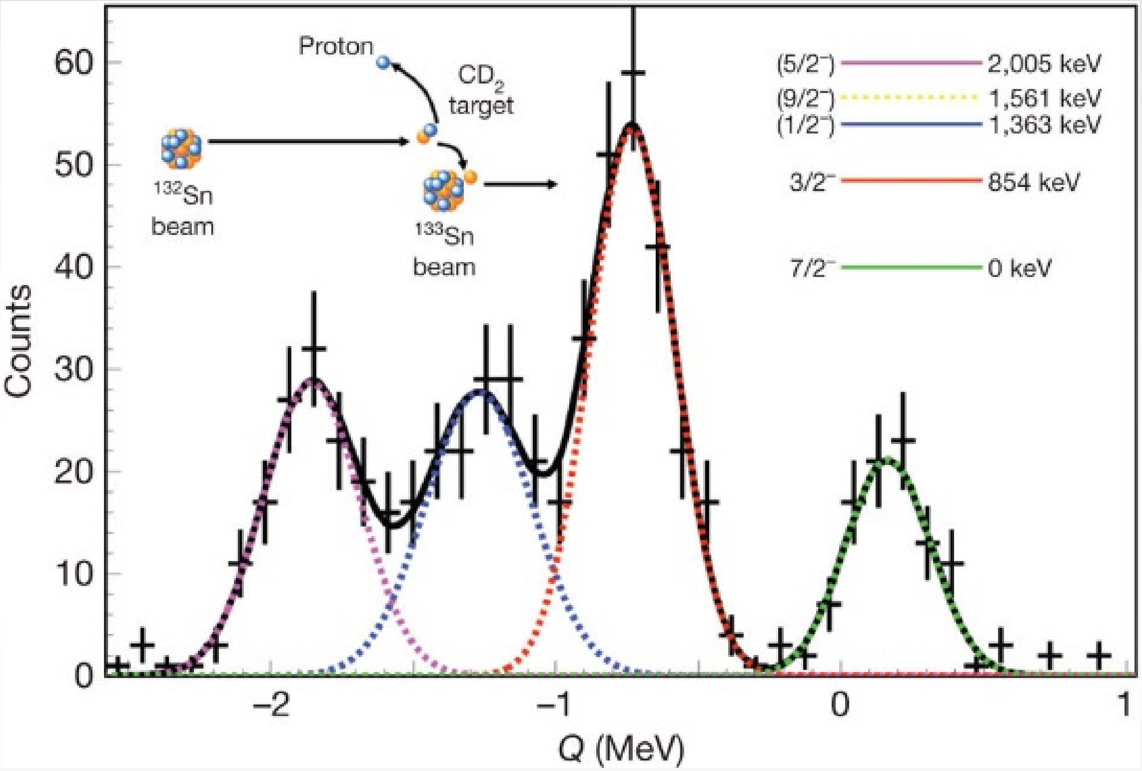


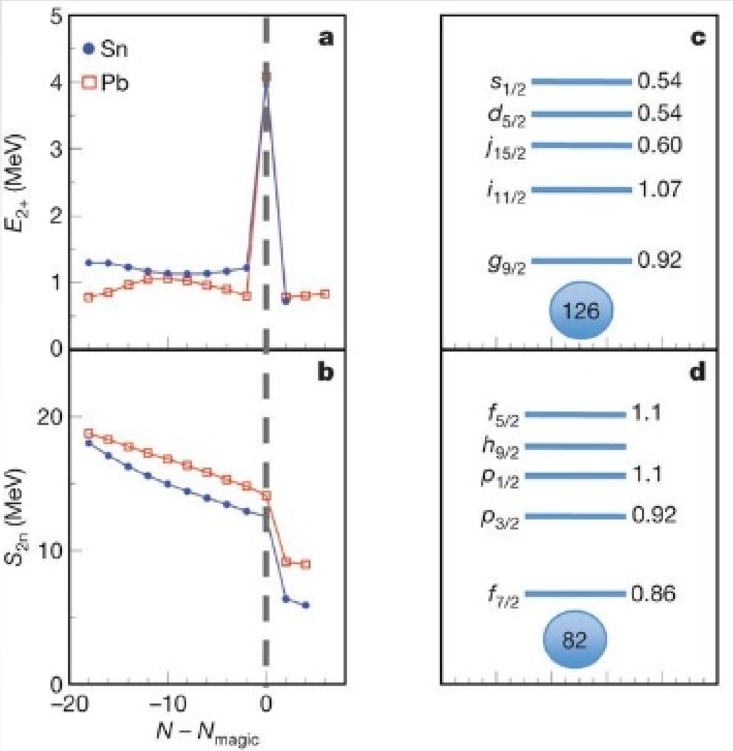
Tamii et al., EPJA 50, 28 (2014)



Riley et al., PRC 90, 011305 (2014)

Transfer reactions



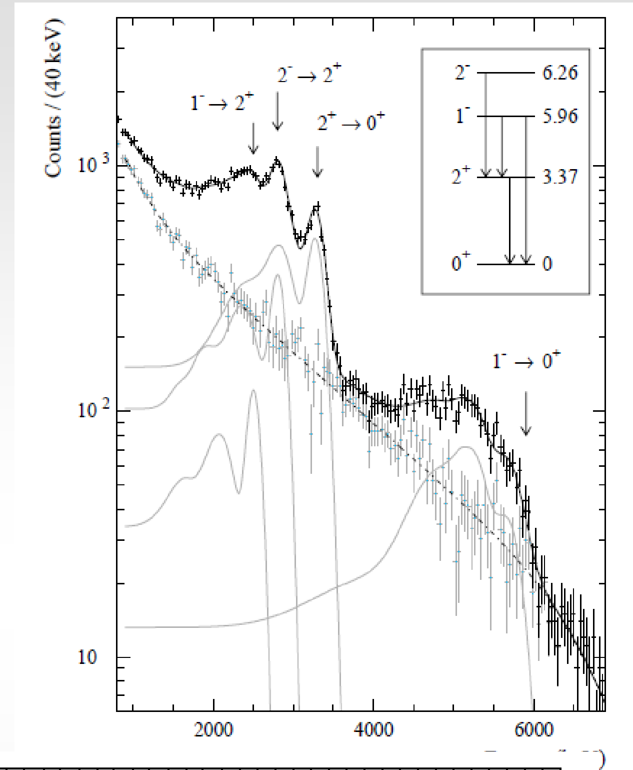


d(^{132}Sn,^{133}Sn)p reaction – revealing the structure of double-magic ^{132}Sn
The spectroscopic strength is contained in a few single-particle states, rather than being very fragmented.

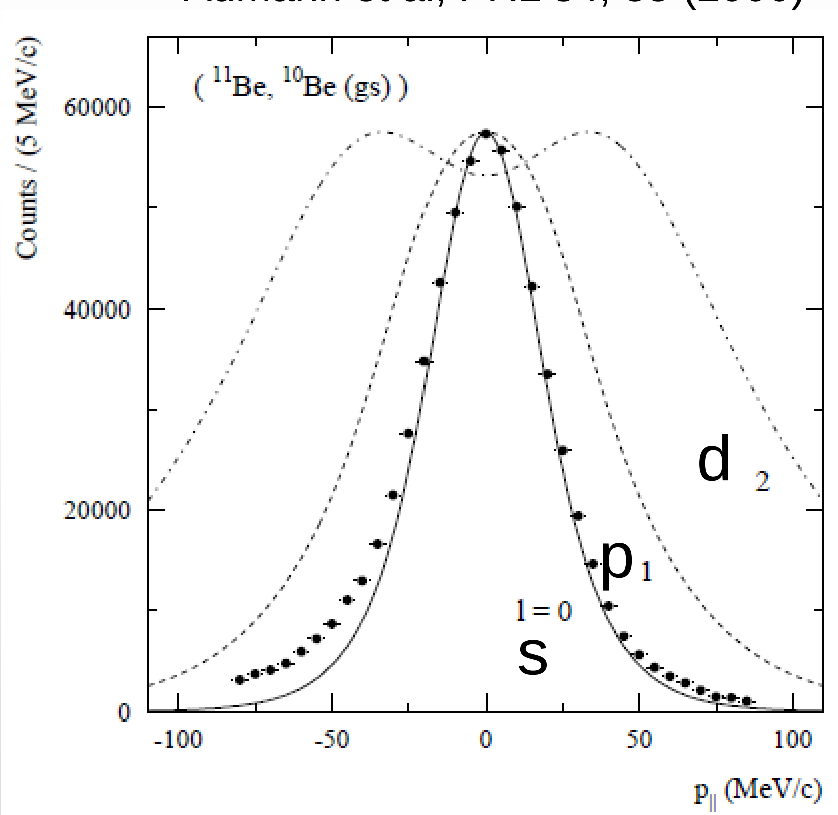
Jones et al., Nature 465, 454 (2010)

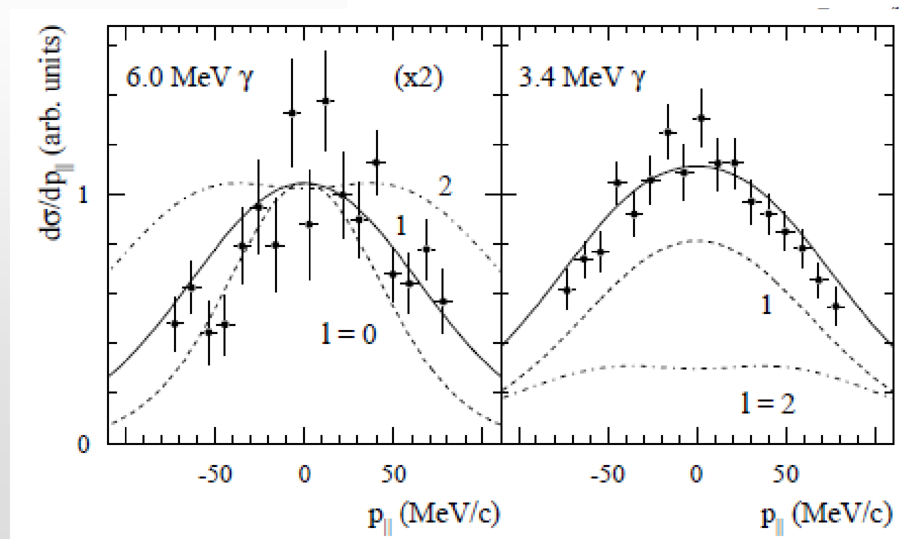
Knock-out reactions

Momentum distribution of residual determines the angular momentum of the knocked-out nucleon, e.g. in (^{11}Be,^{10}Be) 1-neutron knock-out below.
γ-tagging is used to look at the nature of excited states

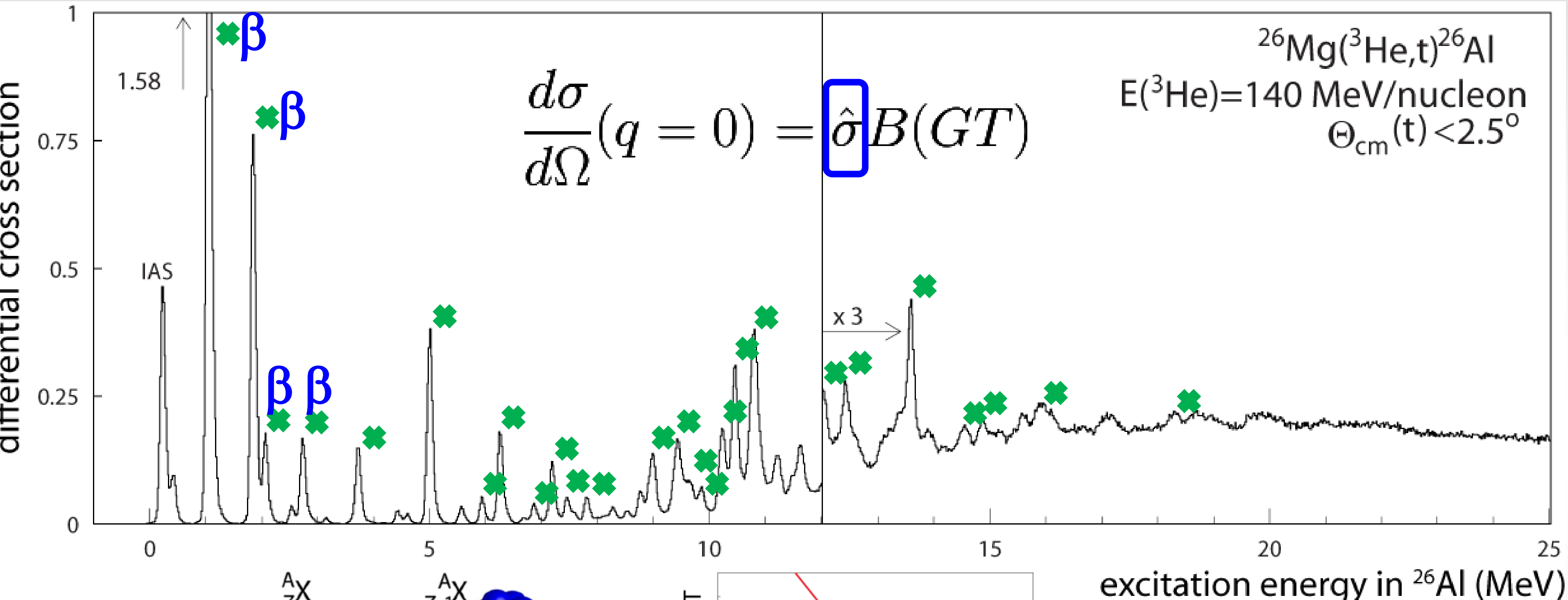


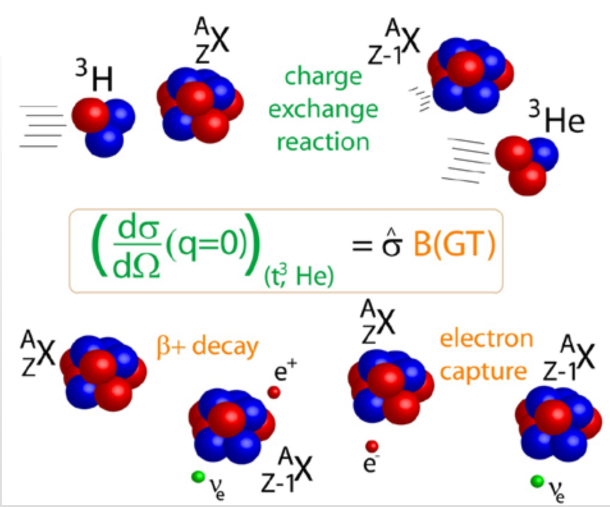
Aumann et al, PRL 84, 35 (2000)

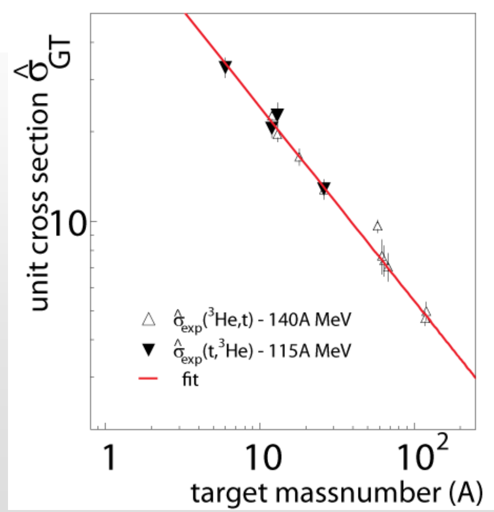




Extracting Gamow-Teller transition strength from charge-exchange data







β-decay data can be used to calibrate the unit cross section – allows for model-independent extraction of strength

R.Z. et al., Phys. Rev. C. 74, 024309 (2006)

Central collisions

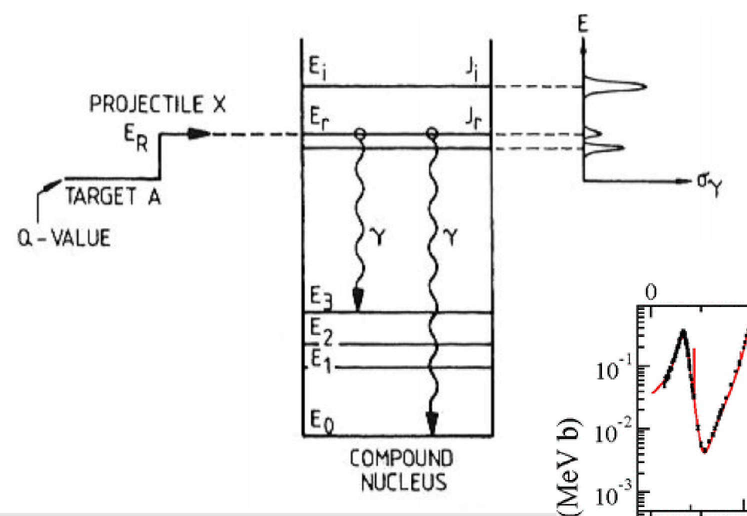
- Associated with a small impact parameters
- Involve many nucleons of the projectile and target
- Studied at low and high energies
- Reactions involve several/many steps
- Final states have no memory of initial channels/properties
- Timescales tend to be longer
- Angular distributions tend to be flatter

Central collision - examples

Reaction	Use/Motivation
Compound nuclear reaction (fusion-evaporation, fusion-fission,… reactions) $A+a \rightarrow C^{*} \rightarrow B+b_1+b_2+\ldots$	Nuclear structure, astrophysical reactions, applications
Deep inelastic scattering (some Z,A equilibration between parts of nuclei)	Structure studies, high angular momentum transfers
Heavy-ion collisions/multi-fragmentation	Equation of state studies
…	

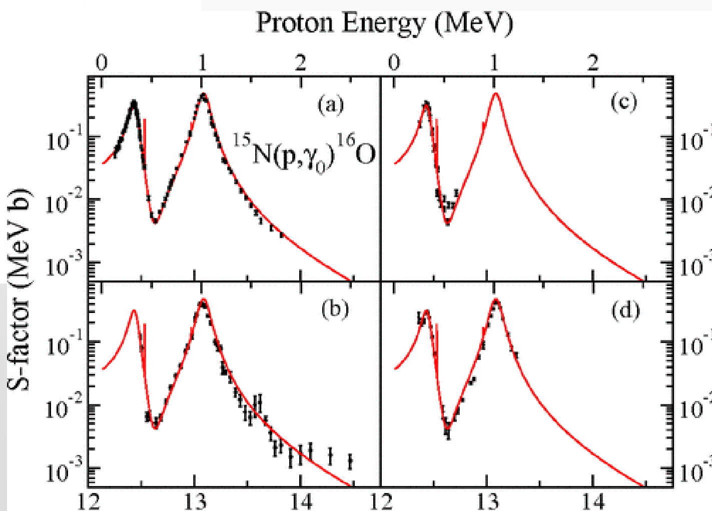
Compound nuclear reactions

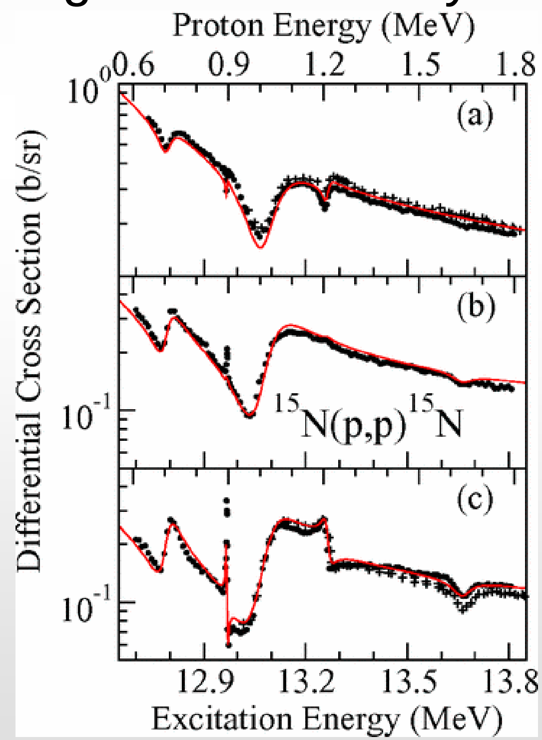
- Reactions at low energies: nuclei form a compound of the projectile and target (note that direct contributions to the cross section can contribute as well, but with very different angular distributions
- Sharp resonances at low excitation energies are observed, which are associated with the formation of a long-lived states of the compound system. The resonances decay by gamma and or particle emission
- At high excitation energies, the level density is very high and the decay becomes statistical in natures



$^{15}N(p,p)^{15}N$

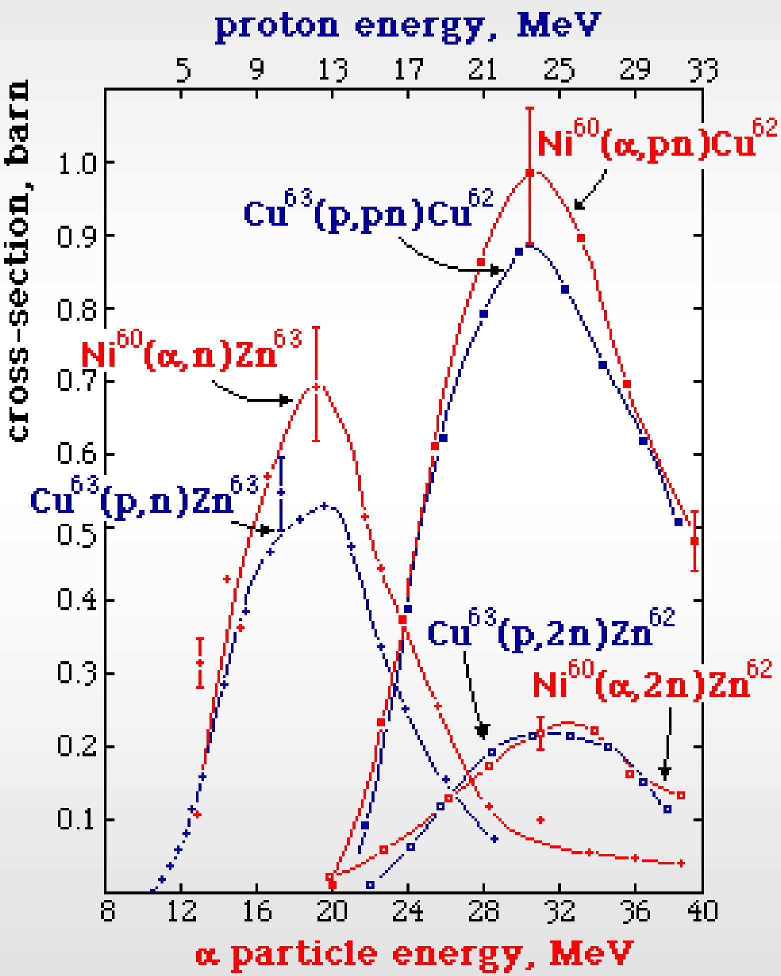
$^{15}N(p,\gamma)^{16}O$

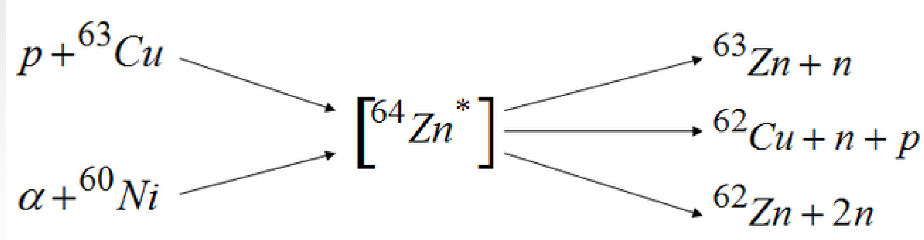




deBoer et al.,
PRC 87, 015802, 2013

Reaction has no "memory"



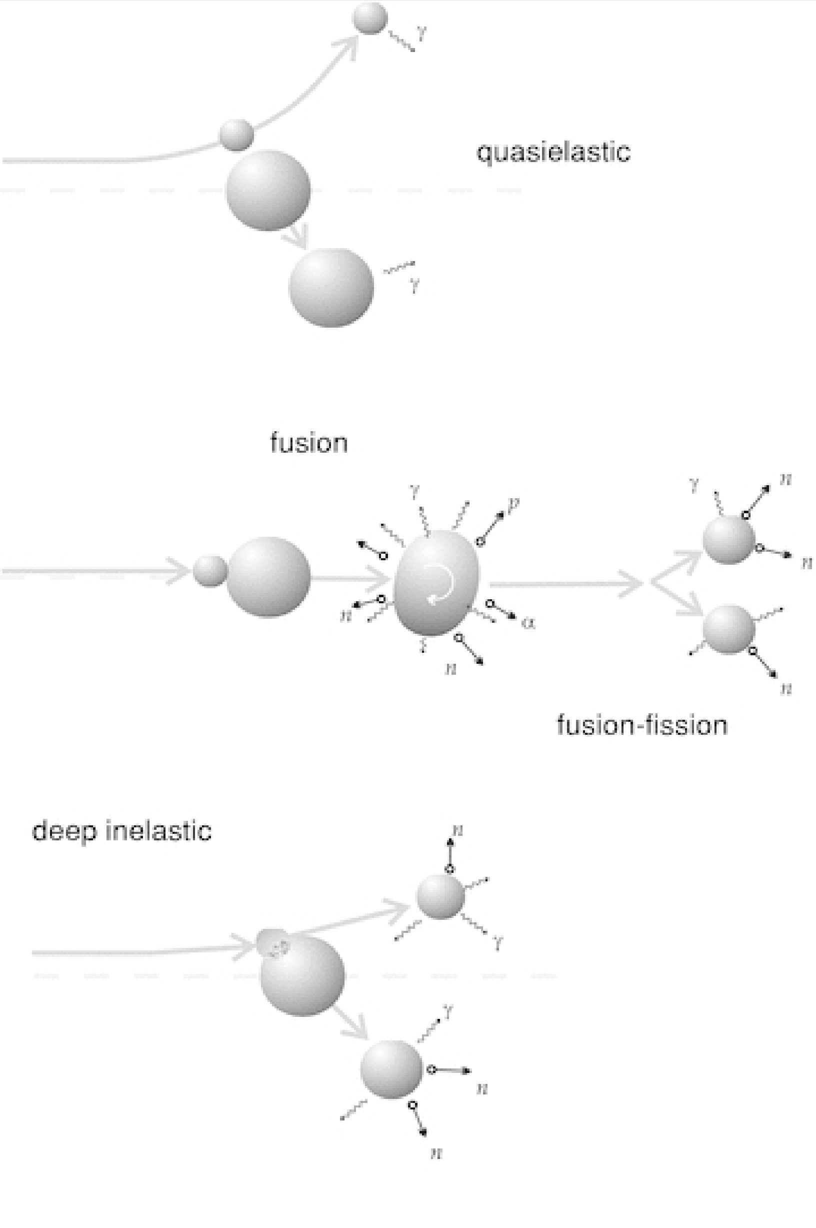


$$a + X \to [C^*] \to Y + b$$

S. Goshal PR 80, 939 (1950)

Deep inelastic scattering

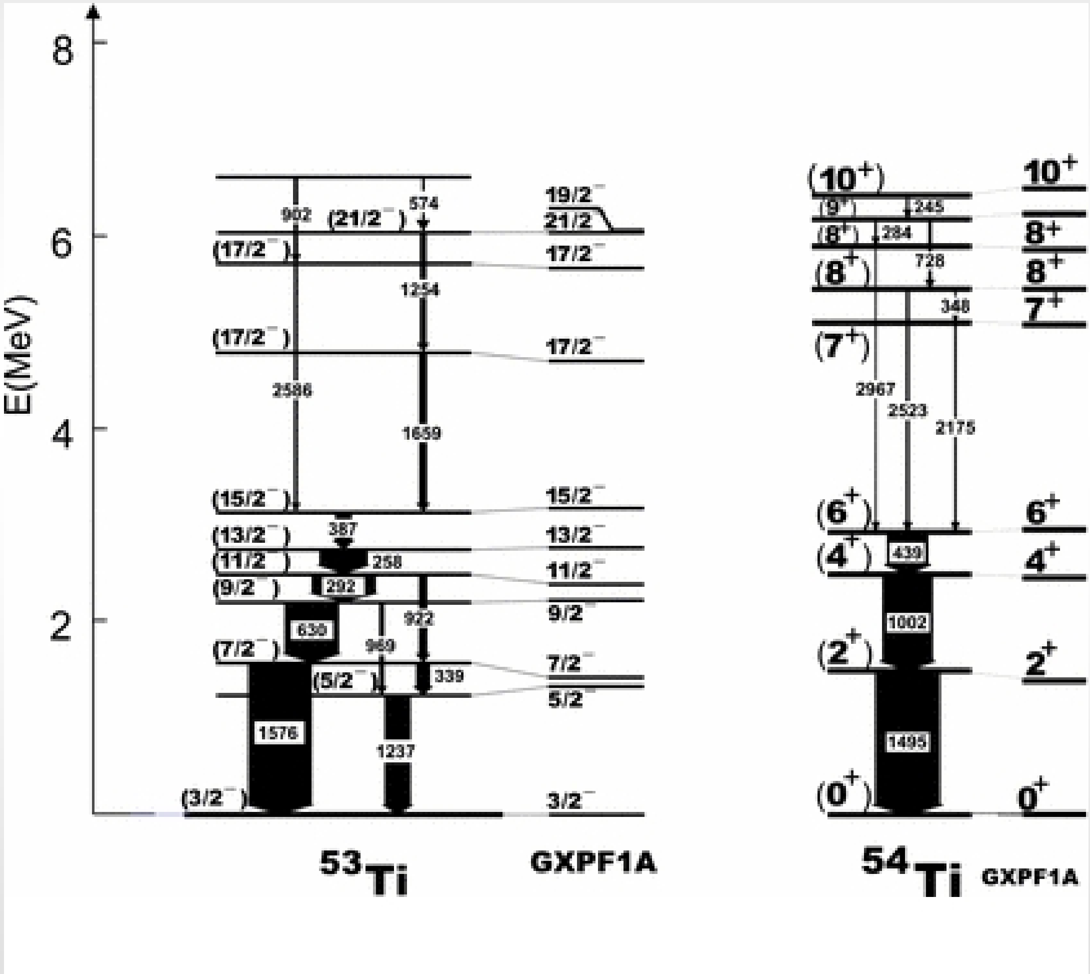
- Impact parameter in between grazing and head-on collisions; E>10 MeV/u
- Projectile and target exchange significant amount of nucleons and energy and make a partially fused complex
- Is very useful for populating high angular-momentum states
- Experiments e.g. with ATLAS and Gamma-sphere at ANL



R Broda 2006 J. Phys. G: Nucl. Part. Phys. 32 R151

Deep Inelastic scattering

^{48}Ca beam on ^{208}Pb and ^{238}U targets



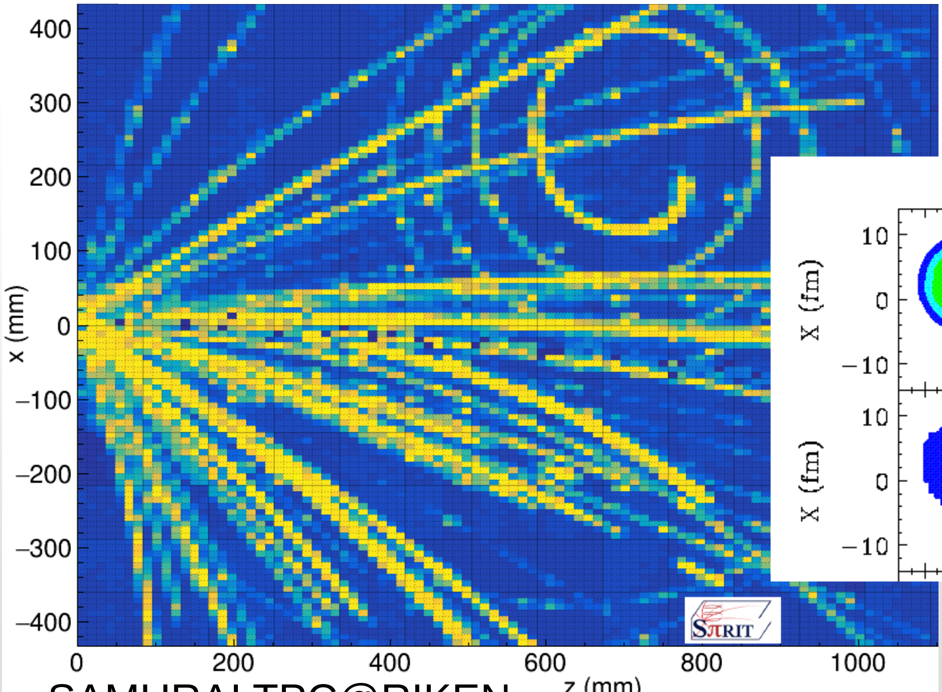
Fornal B et al 2005
Phys. Rev. C **72** 044315

Janssens R V F et al 2002
Phys. Lett. B **546** 55

Heavy-ion collisions and equation of state studies

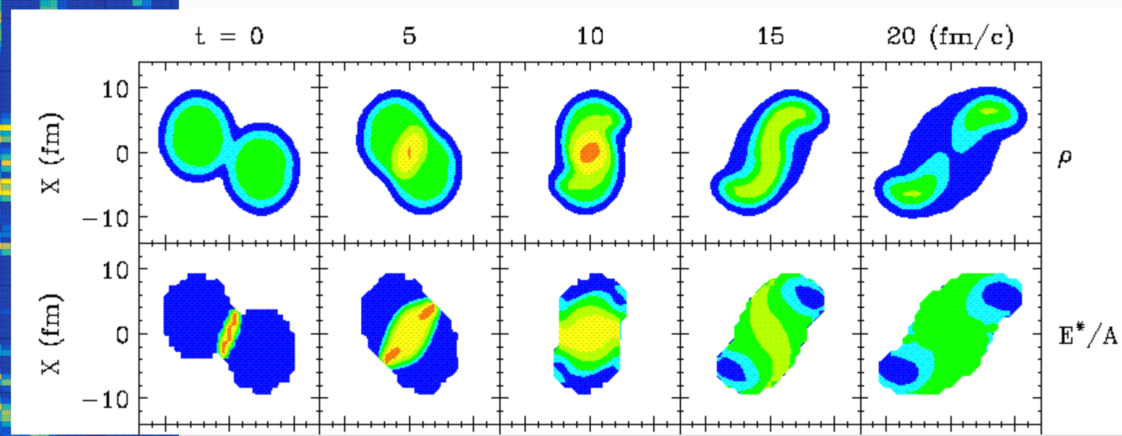
- Heavy-ion collisions at energies of 50-250 MeV/u (and beyond, e.g. at RHIC!) are used to create hot regions of varying temperature and density from which the emission of fragments is studied
- The fragment distributions provide information about the EoS (how does nuclear matter behave as a function of temperature/energy, pressure and density)

$^{132}Sn+^{124}Sn$ collisions @270 AMeV



SAMURAI TPC@RIKEN

- Experiments typically contain various detector systems to measure charged and neutral particles



Shi et al, PRC 64, 031001, 2001

Conclusions

- There are a wide variety of reactions and probes to study and understand the properties of nuclei and their interaction
- Many new experimental tools have been created to make full use of the opportunities provided by the availability of rare isotope beams even if the basic reaction types or techniques were developed in the past
- Interplay between theoretical and experimental efforts is critical to make progress
- Performing experiments with rare isotope beams and analyzing the data comes with challenges and opportunities – you play an important role in shaping the future program!