Reaction Experiments with Exotic Beams

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Why Nuclear Reactions?

Nuclear reactions in general are used to:

1. Produce other nuclei:
*samples, sources, **new elements**, **isotopes for applications**, (**radioactive ion / rare isotope / exotic) beams***

choose your favorite expression

2. Study some properties of a nucleus of choice in a **reaction experiment** for:
nuclear structure, astrophysics, reaction mechanisms, stockpile stewardship,…

3. Study nuclear dynamics and nuclear matter equation of state

Outline of these lectures

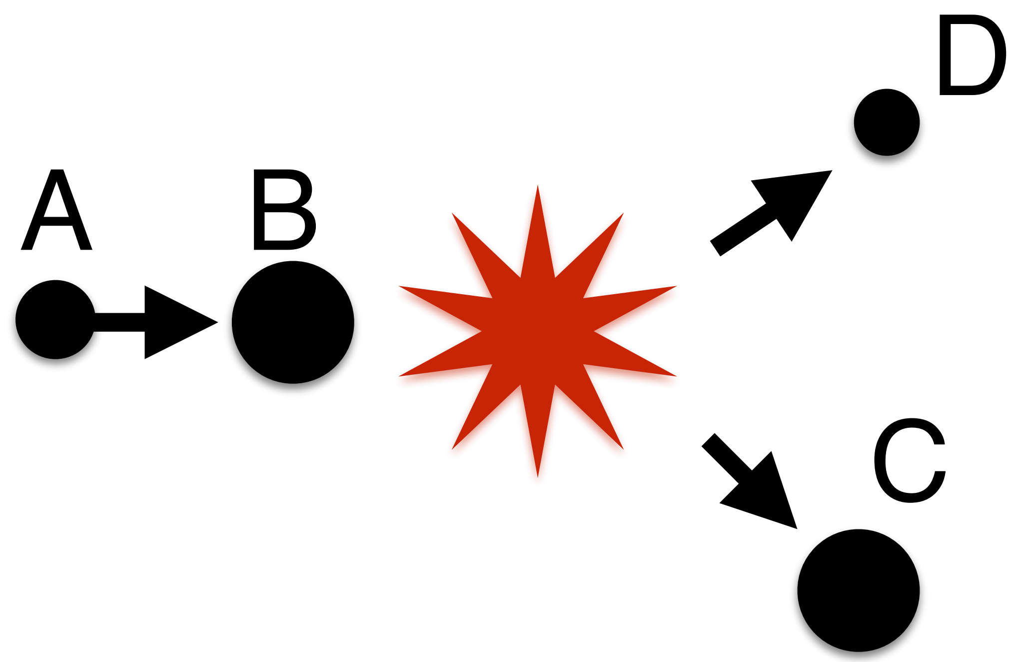
- few basics of reaction experiments
- different reaction types
- production of exotic beams for reaction experiments
- some experimental considerations
- examples reaction experiments with exotic beams

Some basic notations

projectile/beam target

A reaction: $A+B \rightarrow C+D$ *or* $B(A,D)C$

fragment/recoil residual/ejectile



Normal kinematics: $a+B \rightarrow C+d$; $B(a,d)C$, $M_{projectile} < M_{target}$

Inverse kinematics: $B+a \rightarrow d+C$; $a(B,C)d$, $M_{projectile} > M_{target}$

Conservation laws

Things that are considered conserved in nuclear reactions:

Energy

Linear momentum

Proton and neutron (baryon) number

Charge

Angular momentum

Parity

Isospin

Reaction Q-value

Reaction Q- value: amount of energy released in the reaction

$$Q = \sum_i ME_i - (\sum_f ME_f + E_f^*) = (M_{beam} + M_{target})c^2 - \sum_{products} (M_{product}c^2 + E_{excitation,product})$$

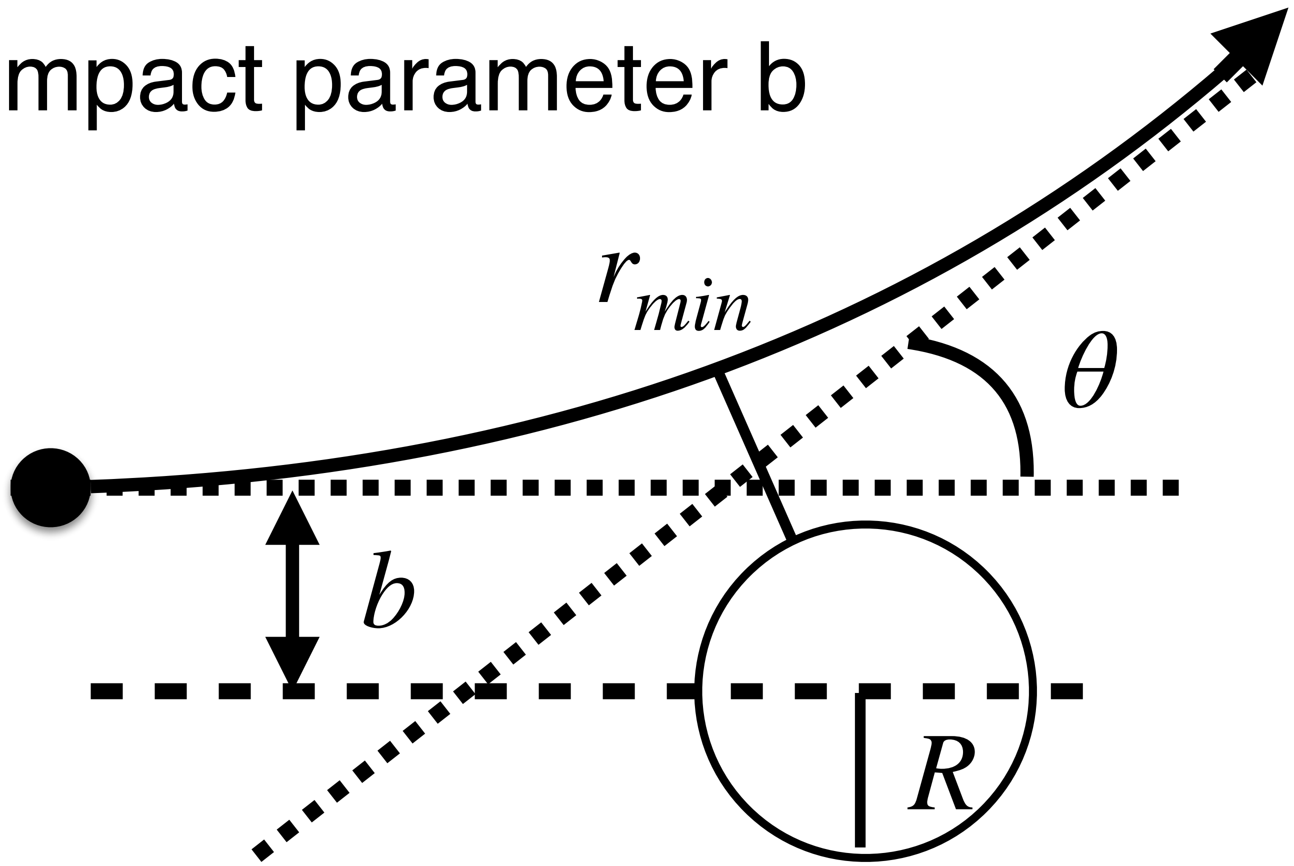
Most convenient to use mass excesses (ME) or binding energies (BE).
Evaluated values available e.g. through https://www-nds.iaea.org/amdc/
(various vintages of these evaluations are found through out codes, be careful if working on something very recent and code uses something older!)

Q < 0: endothermic reaction, requires energy input to make it work
Q > 0: exothermic reaction, energy is released, can occur if otherwise possible

Important to consider when choosing what reaction to use!
(reaction energy threshold, momentum matching, which states to populate, kinematics…)

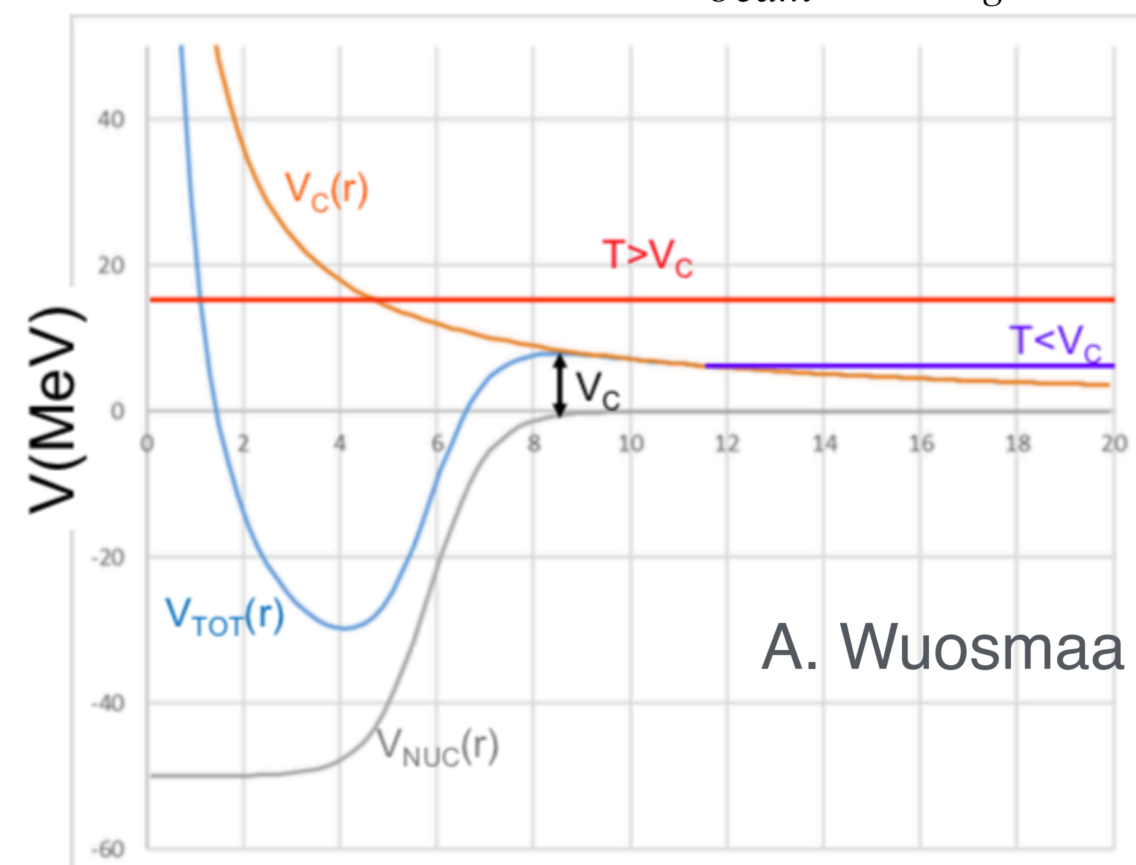
Few important parameters for reactions

Impact parameter b



Coulomb barrier height

$$V_c(MeV) \approx 1.44 \frac{Z_{beam} Z_{target}}{1.2(A_{beam}^{1/3} + A_{target}^{1/3})}$$



Classical deflection equation:

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

$\leftarrow$ $V_{tot}(r) = V_c(r) + V_{nuc}(r), E = mv^2/2$

$L = \vec{r} \times \vec{p} = rpsin\phi = bp$

L conserved for fixed b

$\Delta L = qb = (p_f - p_i)b \approx qR$ on surface

For experiment we can only choose:
Target, Beam, Energy, and Polarization

Types of Nuclear Reactions

- Elastic scattering: A+B→A+B
  (no energy exchange)
- Inelastic scattering: A+B→A+B*
  (energy exchange, no mass or charge exchange)
- Transfer of one or more nucleons x: (A=C+x)+B→C+(D=B+x)
  (mass and/or charge exchange)
- Breakup/knockout: A+B→B+C+D
  (projectile breaks due to interaction with the target)
- Compound nuclear reaction: A+B→C*→D+E
  (formation of a short lived intermediate nucleus)
- Radiative capture: A+B→C+γ
  (projectile captured by target, de-excitation via photon)
- Photo-disintegration: C+γ→A+B
  (inverse of radiative capture)
- Fission: A + B→C+D+ x neutrons
  (A typically neutron; B e.g. U, Pu; C,D heavy fragments)

Nuclear Reaction Timescale

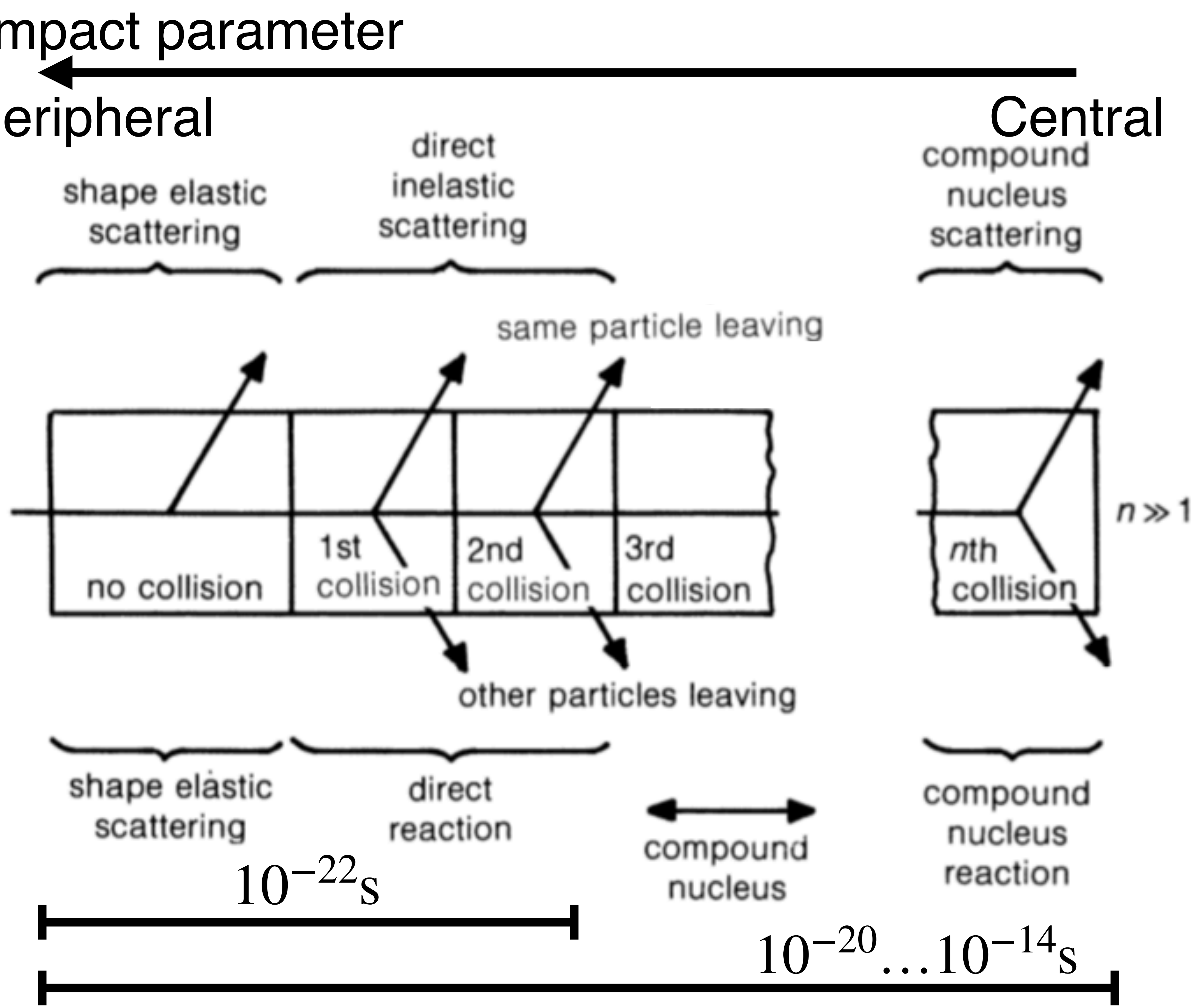
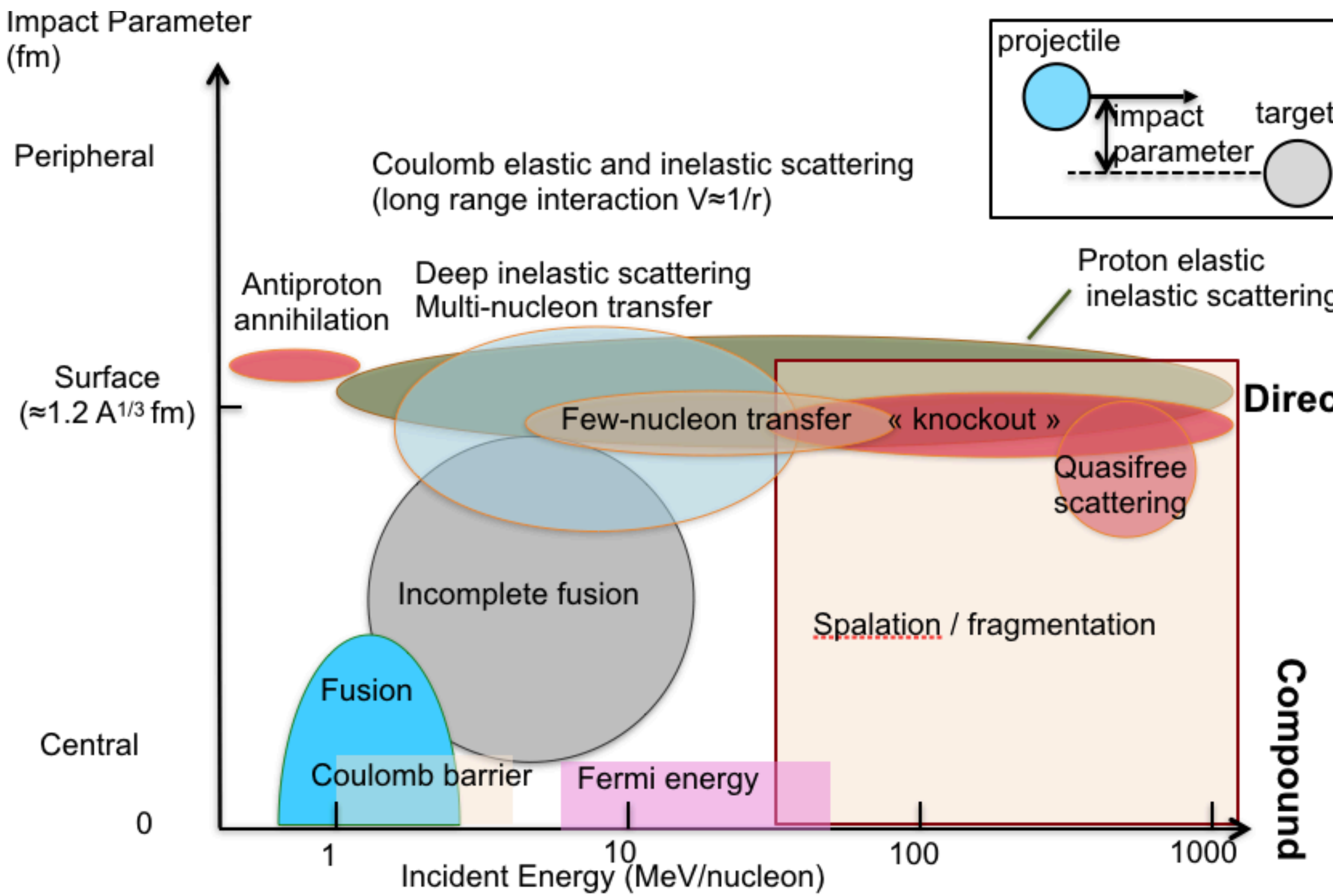


Image credit: R.J. Blin-Stoyle, Nuclear and particle physics

Reaction Types: Impact Parameter vs Energy



A. Obertelli / Euroschool on Exotic Beams 2016

What do we measure in a reaction experiment?

Our instruments measure **Energy** and **Time**
of the beam components, reaction products, γ/X-rays,…

→ *Particle identification (PID) of beam/products (dE/dx, ToF,…), Energy levels of the states involved,…*

We know the **positions and coverage** of our instruments relative to the beam and the target

→ *Kinematics, angular distributions,…*

We **count** the amount of these interactions with known **efficiencies**

→ *Probabilities of the reactions, cross sections, branching ratios,…*

One can **polarize** the beam or the target

→ *Spin orientation, spin dependence of reaction cross section*

See Tony Ahn's lectures for the techniques how

Cross sections

Most reaction experiments measure a cross section in some form (probability of a reaction taking place) e.g. some of these

$$\sigma \qquad \sigma(\theta) \qquad \sigma(E)$$

Integrated cross sections

$$\frac{d\sigma}{d\Omega} \qquad \frac{d\sigma}{dE} \qquad \frac{d^2\sigma}{dEd\Omega}$$

Differential cross sections

Shape and angular distribution of cross section:
→ information about reaction mechanism (theory!)
→ properties of residual nuclei: size, shape, spins and parities of levels,…

Energy dependence:
→ information about reaction mechanism (theory!)
→ identify resonances

Unit is “barn”: 1 barn = 10^{-24} cm^2, millibarn = 10^{-27} cm^2 very common

“Just for fun, some have referred to the microbarn as an outhouse, but you’ll probably never find that in a peer-reviewed publication.”
*S. Goldfarb & K. Anthony, Nature Physics **15**, 414 (2019).*

Who can get  into LaTeX?!

Differential cross section: Experiment meets Theory

This we can measure
at given angle and incident energy

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = C^2 S \left(\frac{d\sigma}{d\Omega}\right)_{theory}$$

This has the reaction model
from your favorite /most applicable
theoretical description

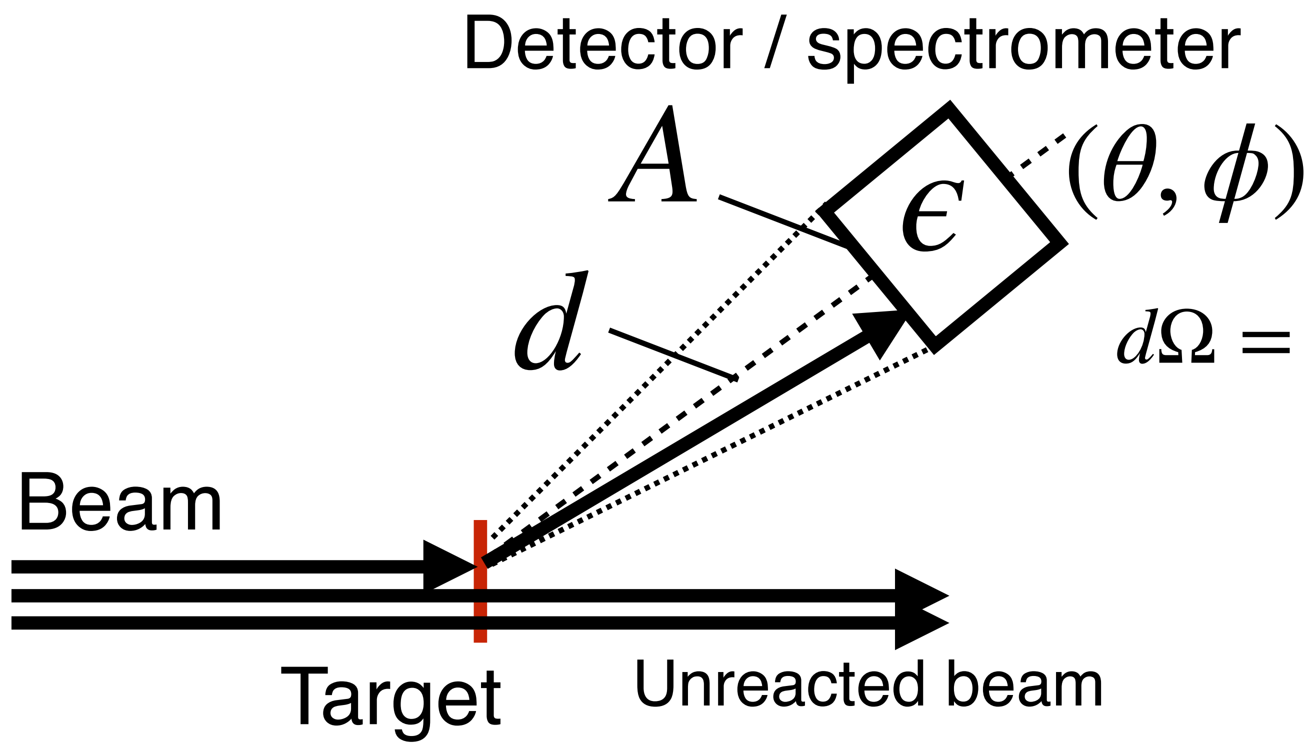
This has the nuclear structure:

C^2: a statistical factor (Glebsch-Gordan coef.),
omitted in some texts

S: spectroscopic factor

Most common unit: mbarn/sr = 10^{-27} cm^2/sr   k  /sr?

How to measure: Differential cross section



$$d\Omega = \frac{A}{d^2} = \frac{\text{det . area}}{\text{distance}^2}[\text{sr}]$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{N_{Detected}(\theta, \phi)}{N_{Beam} \cdot N_{Target} \cdot \epsilon \cdot d\Omega}$$

Integrated counts from detector / spectrometer

Integrated beam particles

Non-overlapping target atoms in target per unit area [1/cm^2]
(careful with composite targets!)

Detector / spectrometer efficiency [unitless]
& solid angle / acceptance [sr]

About exotic beam reaction kinematics

Traditionally reaction experiments done with
light projectile on heavier stable target — *"normal kinematics"*

Most of the exotic beam reaction experiments done with
a projectile on typically much lighter target — *"inverse kinematics"*

→ Energy - angle systematics are quite different
and need to be careful in coordinate transformations
between the laboratory and center of mass frames

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{1+\gamma^2+2\gamma cos\theta_{cms}}{|1+\gamma cos\theta_{cms}|}\cdot\left(\frac{d\sigma}{d\Omega}\right)_{cms}, \gamma = v_{cms}/v_{ejectile}$$

Good reads on topic, e.g. :
W. Catford, LNP879, 67 (2014),
J.S. Winfield et al., NIM A 396, 147 (1997)

W. Catford, LNP879, 67 (2014)

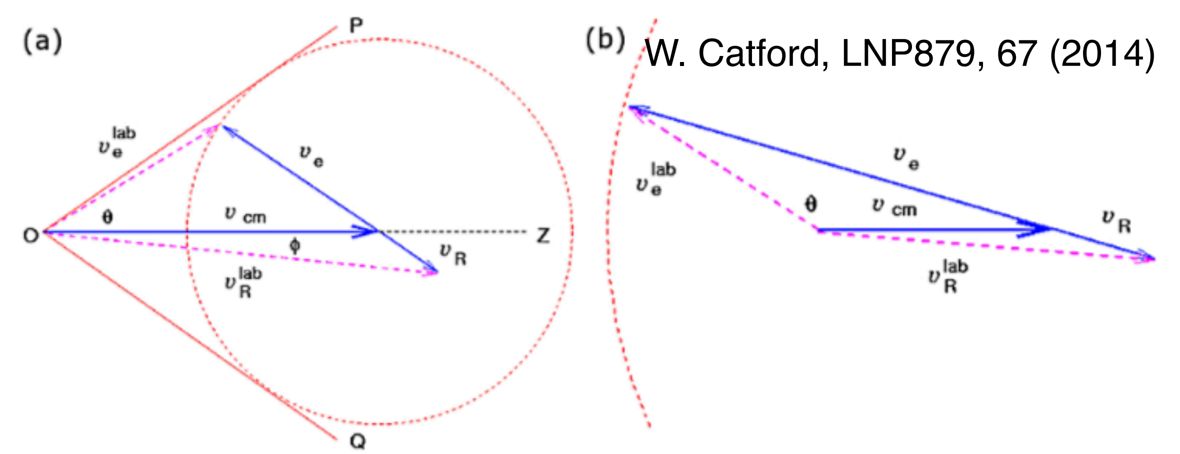


Fig. 3.10 Velocity addition diagrams (**a**) for a typical *pickup* reaction such as (p, d) or (d, t), and (**b**) for a typical *stripping* reaction such as (d, p). Certain assumptions about the beam energy and the reaction Q-value are described in the text

Reaction Kinematics: Useful Tools for Experimentalist

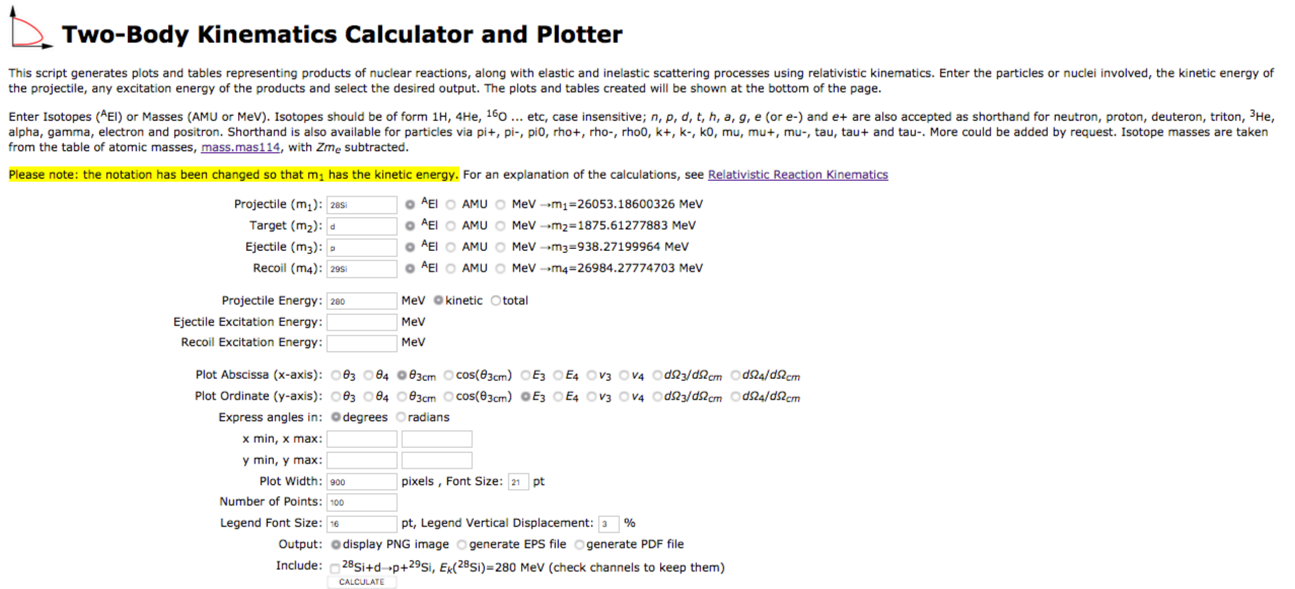
- LISE++ program by O. Tarasov et al.
  (includes a relativistic kinematics calculator)
  http://lise.nscl.msu.edu/lise.html
  O.Tarasov, D.Bazin, NIM B 266, 4657 (2008).
  D.Bazin, O.Tarasov, M.Lewitowicz, O.Sorlin, NIM A 482 307 (2002).

- CATKIN by W. Catford
  (Relativistic 2 body kinematics in Excel):
  http://personal.ph.surrey.ac.uk/~phs1wc/kinematics/

- Two-Body Kinematics Calculator and Plotter by S. Sjue:
  http://skisickness.com/2010/04/relativistic-kinematics-calculator/

- NPTOOL by A. Matta et al. (GEANT4/ROOT simulation / analysis framework, has e.g. kinematics plotting in ROOT command line)
  http://nptool.org/
  A. Matta et al., J. Phys. G 43, 045113 (2016).

Example: E_3 vs θ_{3cm} line for d(^{28}Si,p)^{29}Si @10MeV/u

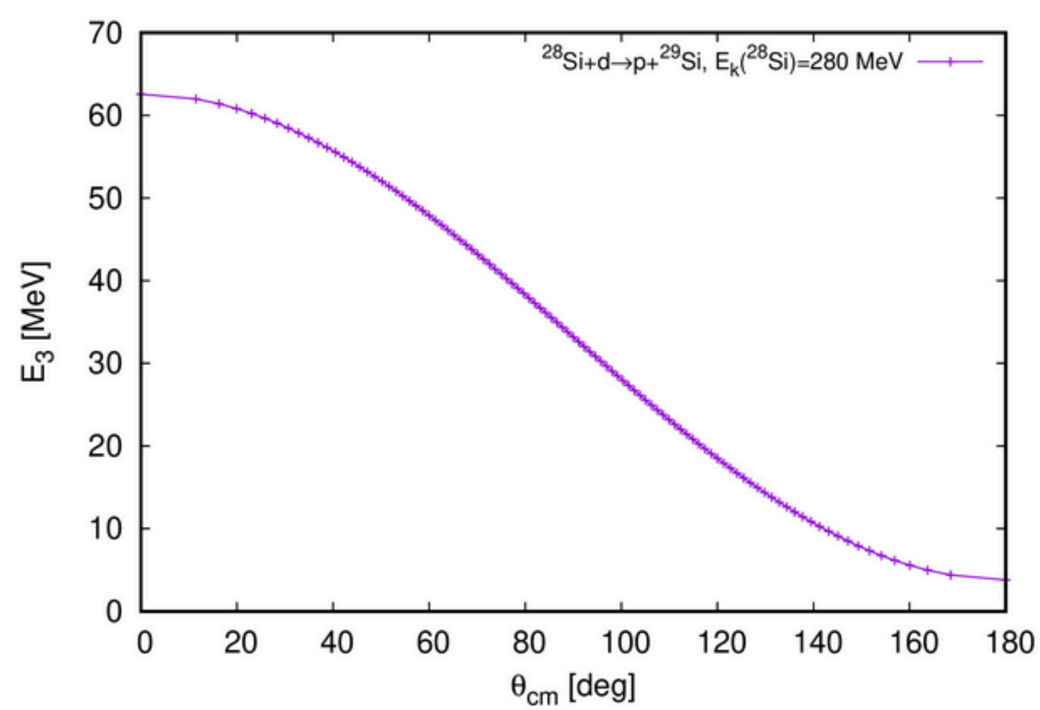


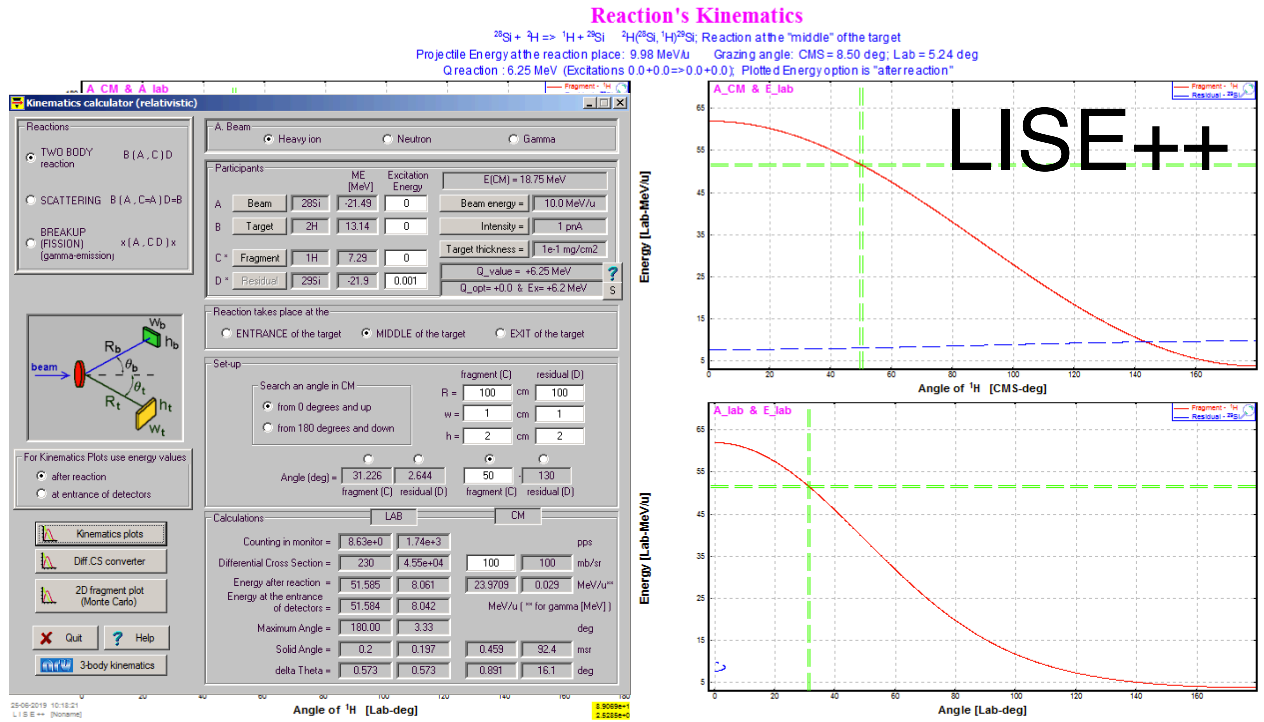
Two-Body Kinematics (webpage)

Reaction summary for ^{28}Si+d→p+^{29}Si, E_k(^{28}Si)=280 MeV

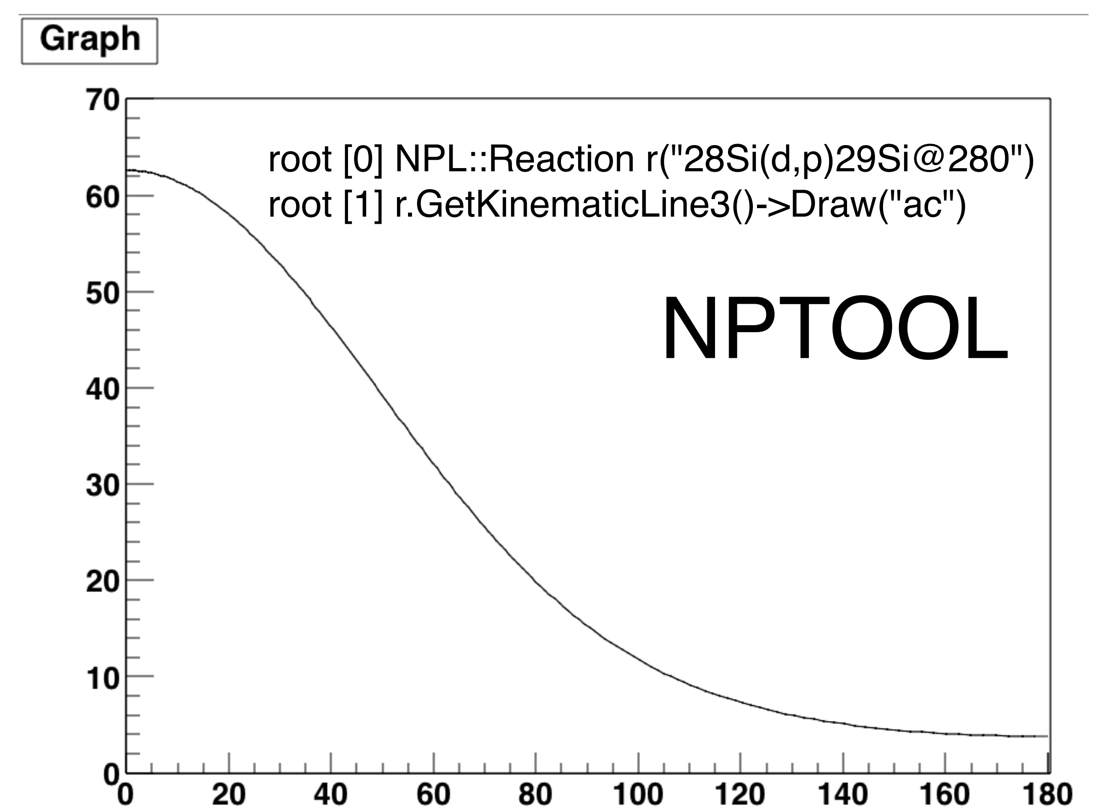
- The maximum p energy is 62.577 MeV. The minimum p energy is 3.802 MeV.
- The maximum ^{29}Si energy is 282.447 MeV. The minimum ^{29}Si energy is 223.672 MeV. The maximum ^{29}Si angle is 3.32 degrees.

KE_3 as a function of θ_{cm}:





LISE++



NPTOOL

Be careful with how different programs expect inputs to get consistent results!

Some experimental considerations

- Production of Exotic Beams
- Intensity needs for Reaction Experiments
- Systematic uncertainties

Units of beam intensities

Typical notation for intensity (or flux) of exotic beams:
particles per second, pps, 1/s, Hz, ^{A}X/s

Primary beams are measured as electric current, A (C/s), typically *nA, µA, mA* (better to use ***e****nA*, ***e****µA*, ***e****mA*)

Often also "particle current", expressed in "particle A"
p*nA*, ***p****µA* (take out the beam charge state)

$$I_{particle} = \frac{I_{electric}}{charge\ state}$$

$$Intensity = \frac{I_{electric}}{beam\ charge} = \frac{I}{q \cdot e}, \left[\frac{C/s}{C} = \frac{1}{s}\right]$$

q: beam charge state,
e = elementary charge = $1.602 \cdot 10^{-19}$ C

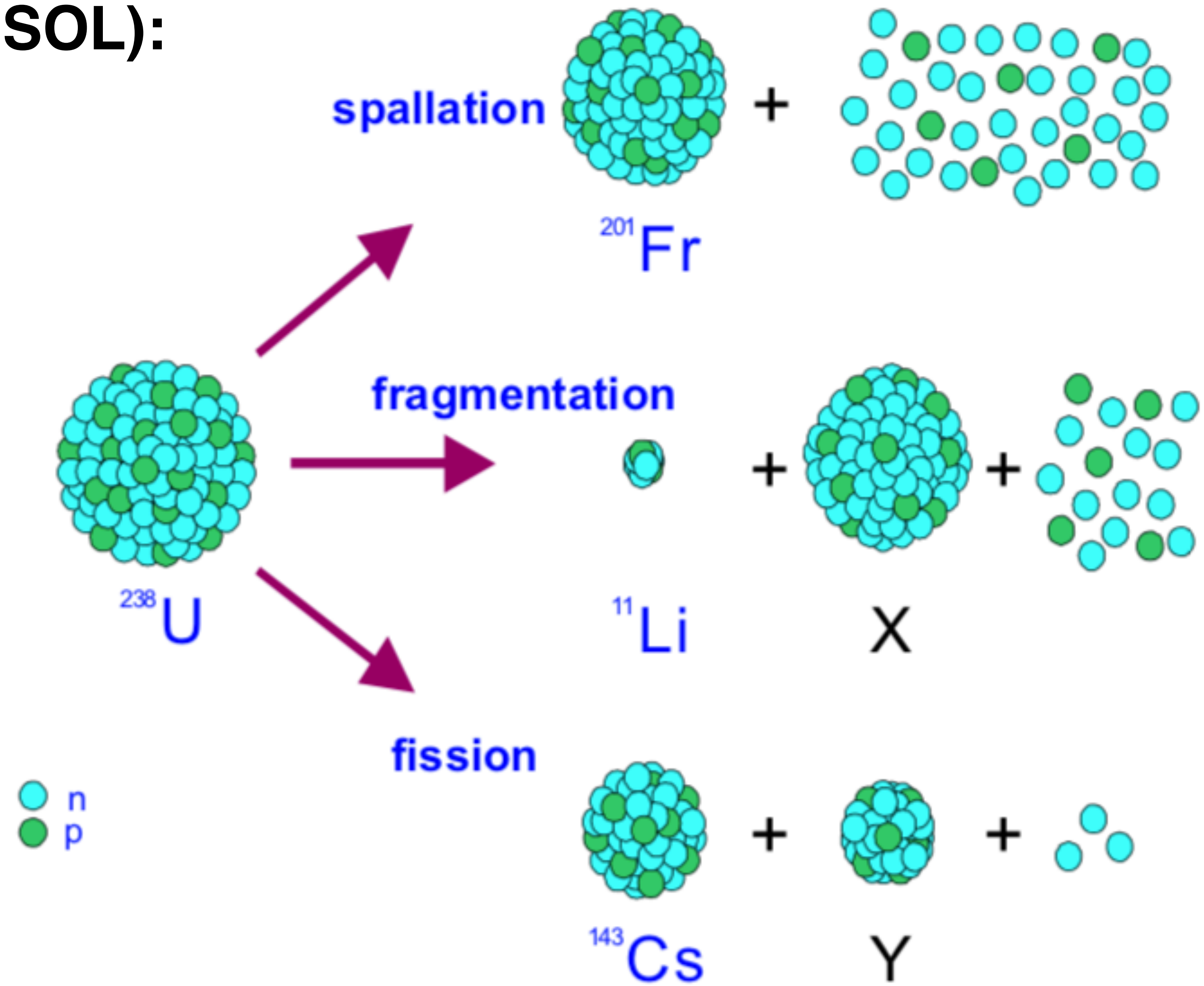
→Integrated current (total charge) gives total amount of incident particles

Most common production reactions

Isotope Separation On-Line (ISOL):
High energy, high power
p/e-/γ beam
on heavy target

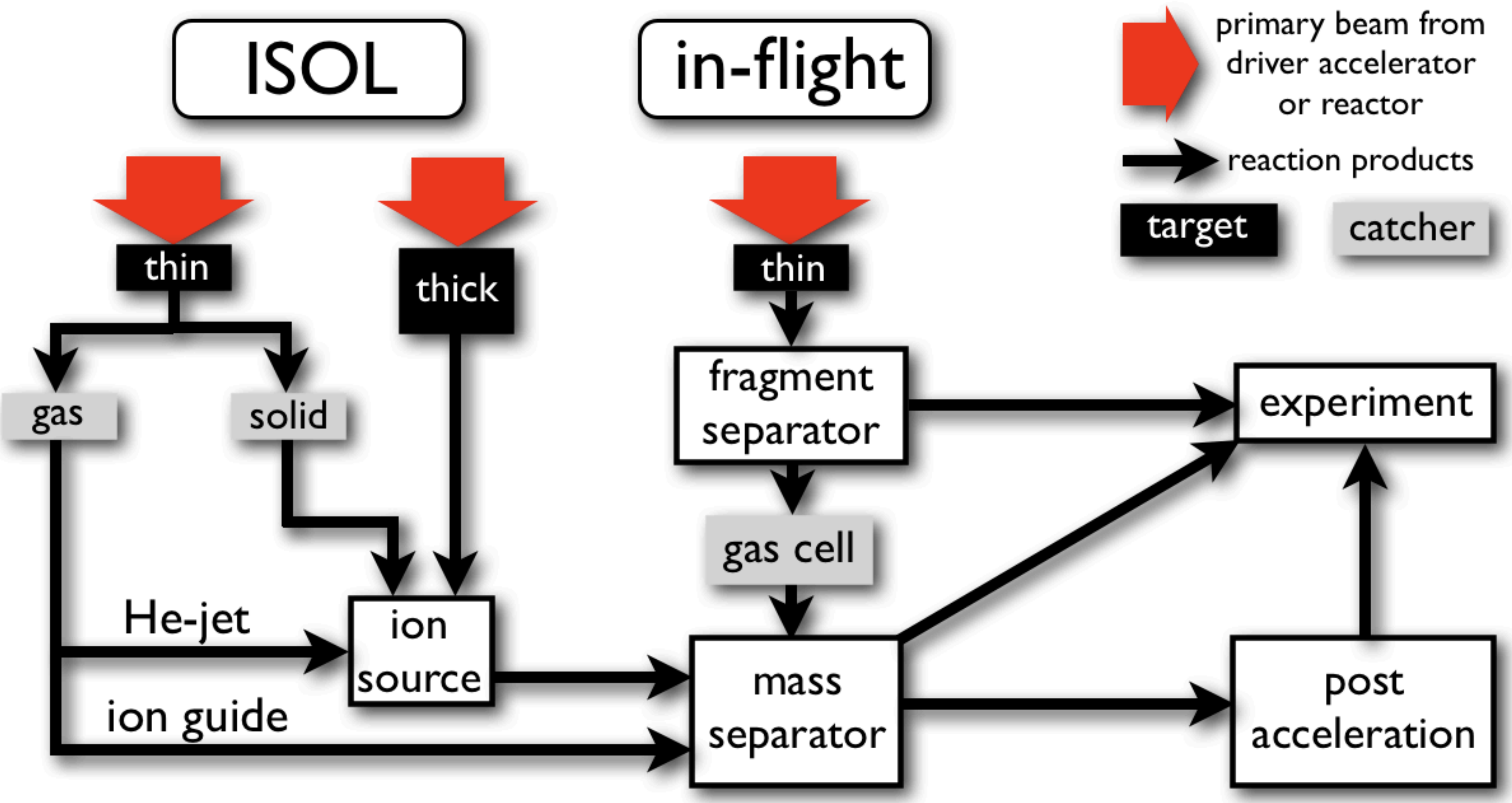
In-flight:
High energy, high power
heavy ion beam
on typically a Be target

High energy: ~100 MeV…1 GeV/u
High power: up to MWatts!
(1 MeV * 1 μA = 1W)



At lower energies (both ISOL and in-flight):
Fusion evaporation, few nucleon transfer, deep-inelastic / multi-nucleon transfer

Production of Exotic Beams



Main features of ISOL and in-flight

Isotope Separation On-Line:
- *thick target, thin target+ solid catcher* → slow release of products (up to seconds), chemically selective, need to ionize products
- *thin target or source + gas catcher* → faster ∝ 0.1…10 ms, products extracted typically as 1+ ion/molecule, chemically nonselective, but less efficient than thick catcher
- mass separator, charge state booster before reacceleration
  → typically beam with little to none impurities
- most common post-accelerator is tandem / linac
  → present facilities have availability of few MeV/u, soon up to ~10 MeV/u
  → good quality beam after post-acceleration

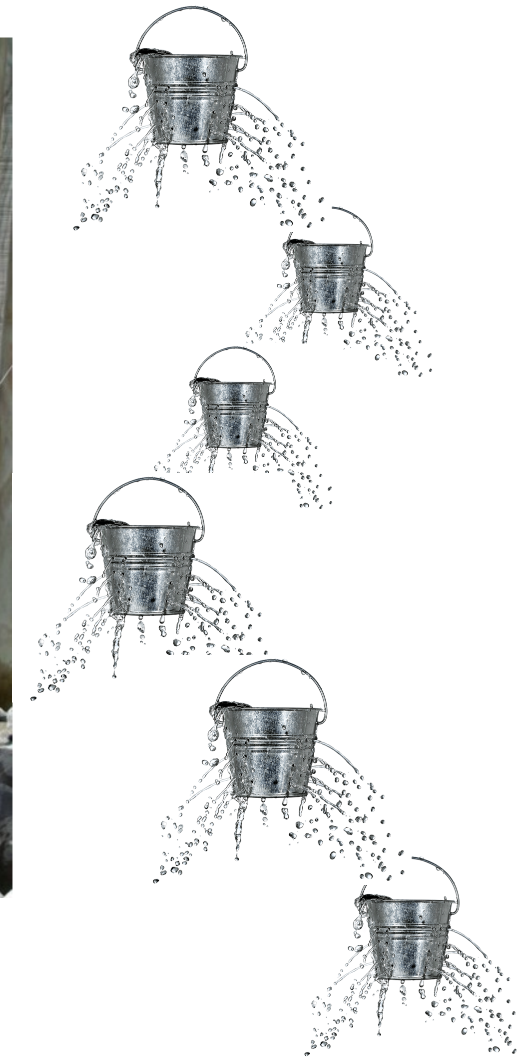
In-flight:
- products emerge from target with similar energy as the primary beam (up to GeV/u)
  → fast, depends on separator/spectrometer flight time, typical few μs
- chemically nonselective (can produce whatever reaction allows)
- efficient (products very forward focused towards the separator)
- secondary beam has typically considerable amount of impurities, energy/momentum spread, emittance
- tradeoffs between secondary beam energy, intensity, quality (can't have it all!)
  → for better beam quality need gas catcher, charge state booster, post-accelerator: energies available few MeV/u, soon up to ~10 MeV/u

Exotic Beam Intensity

Intensity of an Exotic Beam delivered to an experiment:

$$I = \sigma \cdot F \cdot N \cdot \epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3 \cdot \epsilon_4 \cdot \epsilon_5 \cdot \epsilon_6 \cdot \epsilon_7 \qquad \text{[1/s, pps]}$$

σ : production cross section [cm^2]
F : primary-beam intensity [1/s]
N: number production target nuclei [1/cm^2]
ε_1: product release and transfer efficiency
ε_2: ion-source efficiency
ε_3: efficiency due to radioactive decay losses
ε_4: fragment separator efficiency
ε_5: gas cell efficiency
ε_6: mass separator efficiency
ε_7: post-acceleration efficiency



ISOL production part: ε_1-ε_3
Fragment separator: ε_4
Reaccelerated beams: ε_5-ε_7

Exotic beam intensity requirement for an experiment?

How many counts per angle and how many incident energies are needed?

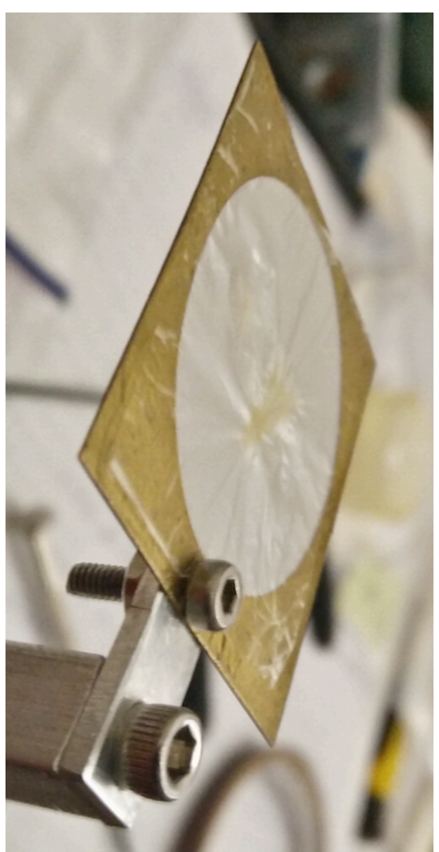
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{N_{Detected}(\theta,\phi)}{N_{Beam}\cdot N_{Target}\cdot \epsilon \cdot d\Omega}$$

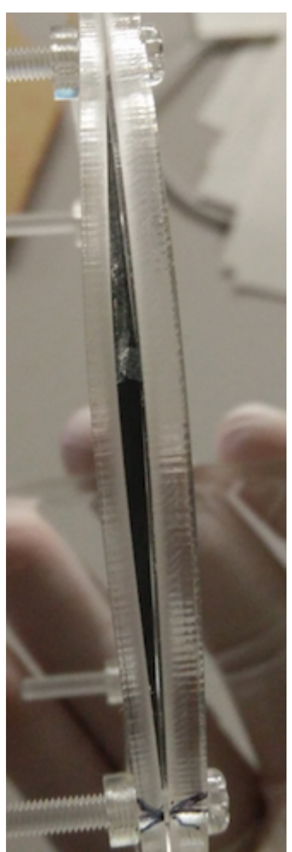
$$N_{beam} = \int_{beamtime} I dt; \quad I = \sigma \cdot F \cdot N \cdot \epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3 \cdot \epsilon_4 \cdot \epsilon_5 \cdot \epsilon_6 \cdot \epsilon_7$$

$$N_{target} = \delta \cdot \frac{N_A}{M} = d \cdot \rho \cdot \frac{N_A}{M}$$

δ: mass/unit area [g/cm2], d: thickness [cm],
ρ: density [g/cm3], M: molar mass [g/mol],
N_A: Avogadro's number [1/mol]

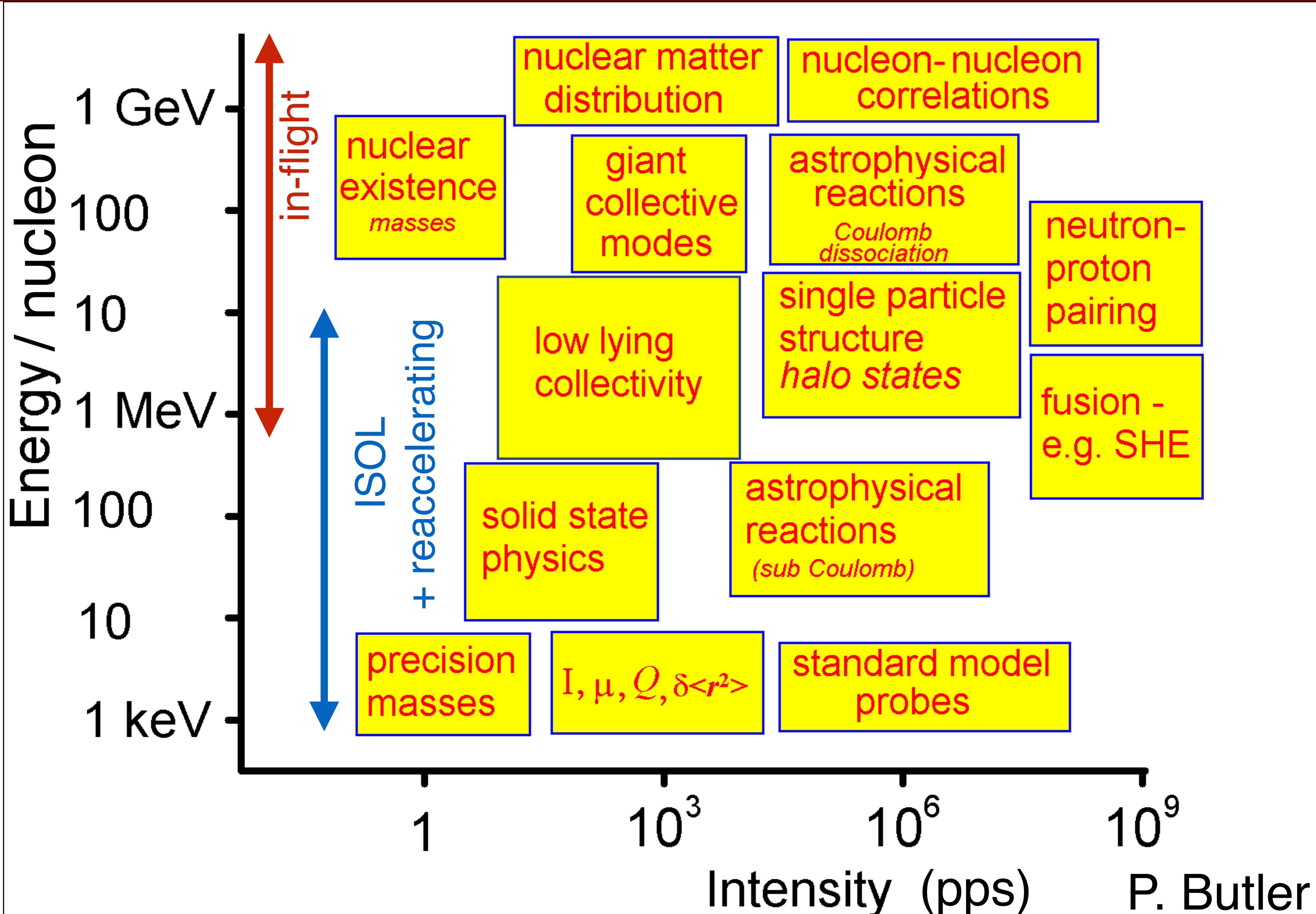
ε: detection efficiency — needs to be optimized
dΩ: solid angle — maximize coverage



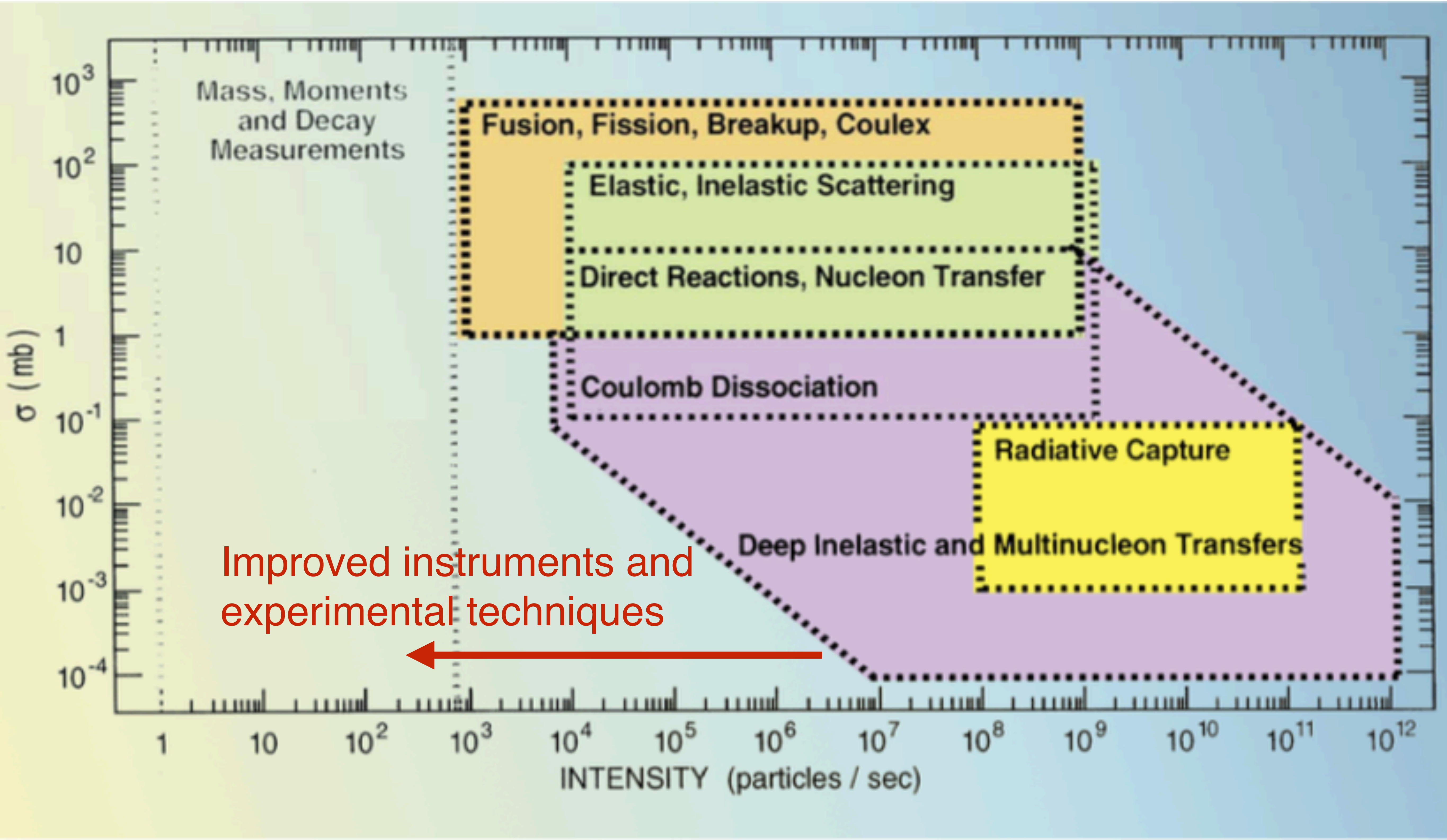


How thick target can be used?

Exotic Beam Physics Reach



Intensity requirements for reaction experiments



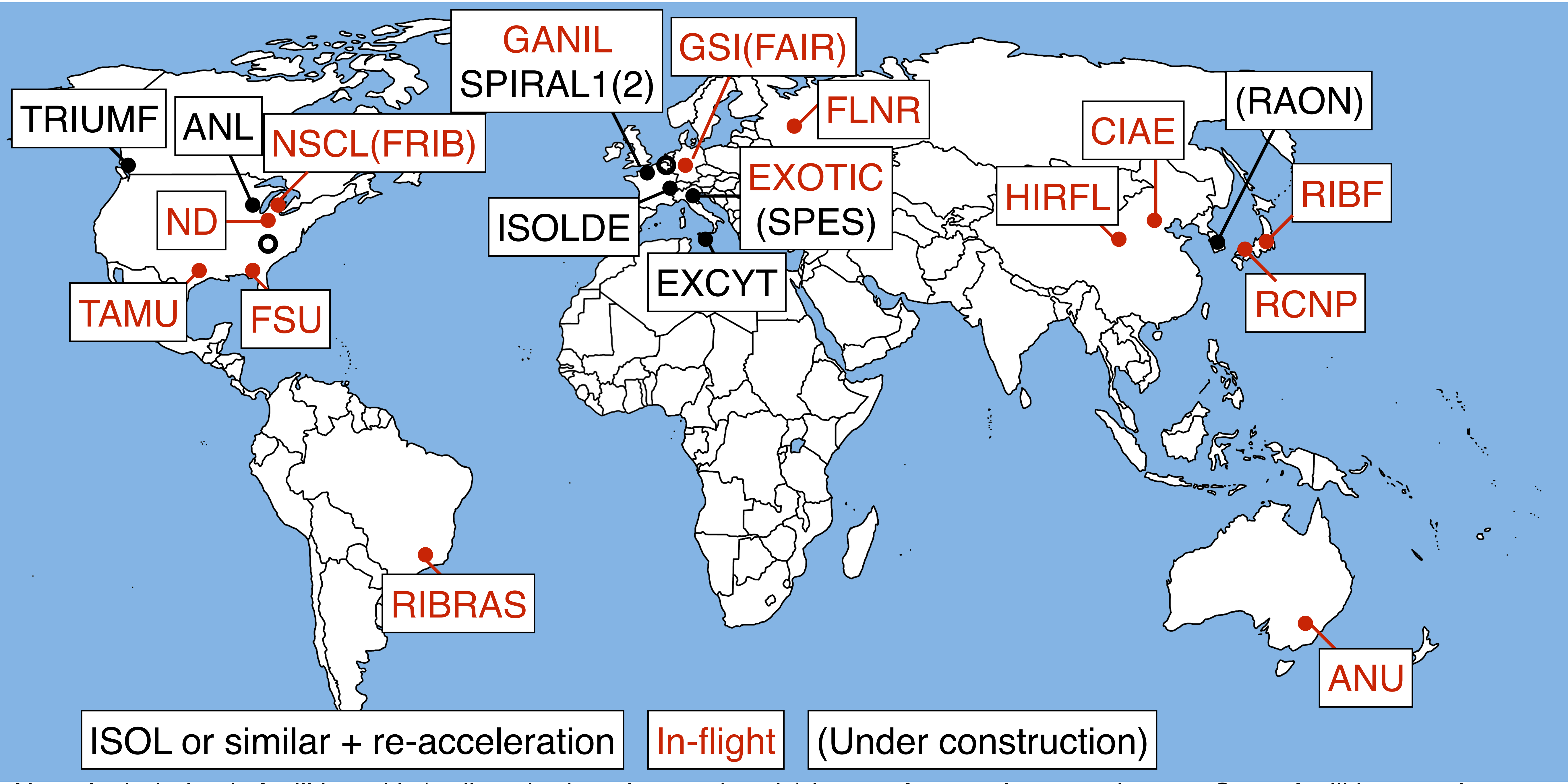
Example: Requirements for transfers in inverse kinematics

K Wimmer 2018 *J. Phys. G: Nucl. Part. Phys.* **45** 033002

Type of experiment	I (pps)	d (mg cm^{-2})	$\sigma(E_{exc})$ (keV)
Fragmentation beams:			
Ejectile detection in spectrometer	10^4	20	700
Silicon detector array for recoil	10^4	10	600
Post-accelerated beams:			
Silicon detector array for recoil	5×10^4	0.5	400
For high intensity beams	10^6	0.1	200
With γ-ray detection	10^5	1.0	1
Magnetic spectrometer for recoil	5×10^4	0.1	100
Active targets	10^3	10	100

Where do you want to do your experiment?

Facilities providing exotic beam for reactions



Note: Included only facilities with (radioactive/rare isotope/exotic) beams for reaction experiments. Some facilities may have more than one way to make beams! There are a lot of other existing facilities with stable beams or very low-energy (keV) exotic beams.

Reaction Experiment Uncertainties

Statistical **uncertainties:**
Mostly just how many counts one can get!
For Poisson statistics: $\propto \sqrt{N}$
(assuming counting time separated independent events)

See e.g. IEEE Trans. Nucl. Sci. 43, 2501 (1996)
uncertainty of Gaussian peak centroid:

$$var(x_0) = \frac{\sigma^2}{A}$$

Systematic **uncertainties:**

Beam related:

- Energy/momentum spread
- Angular spread
- Time spread

Target related:

- Target thickness, uniformity
- Target composition
- Target orientation

Detector related:

- Detector distance
- Detector orientation
- Detector efficiency

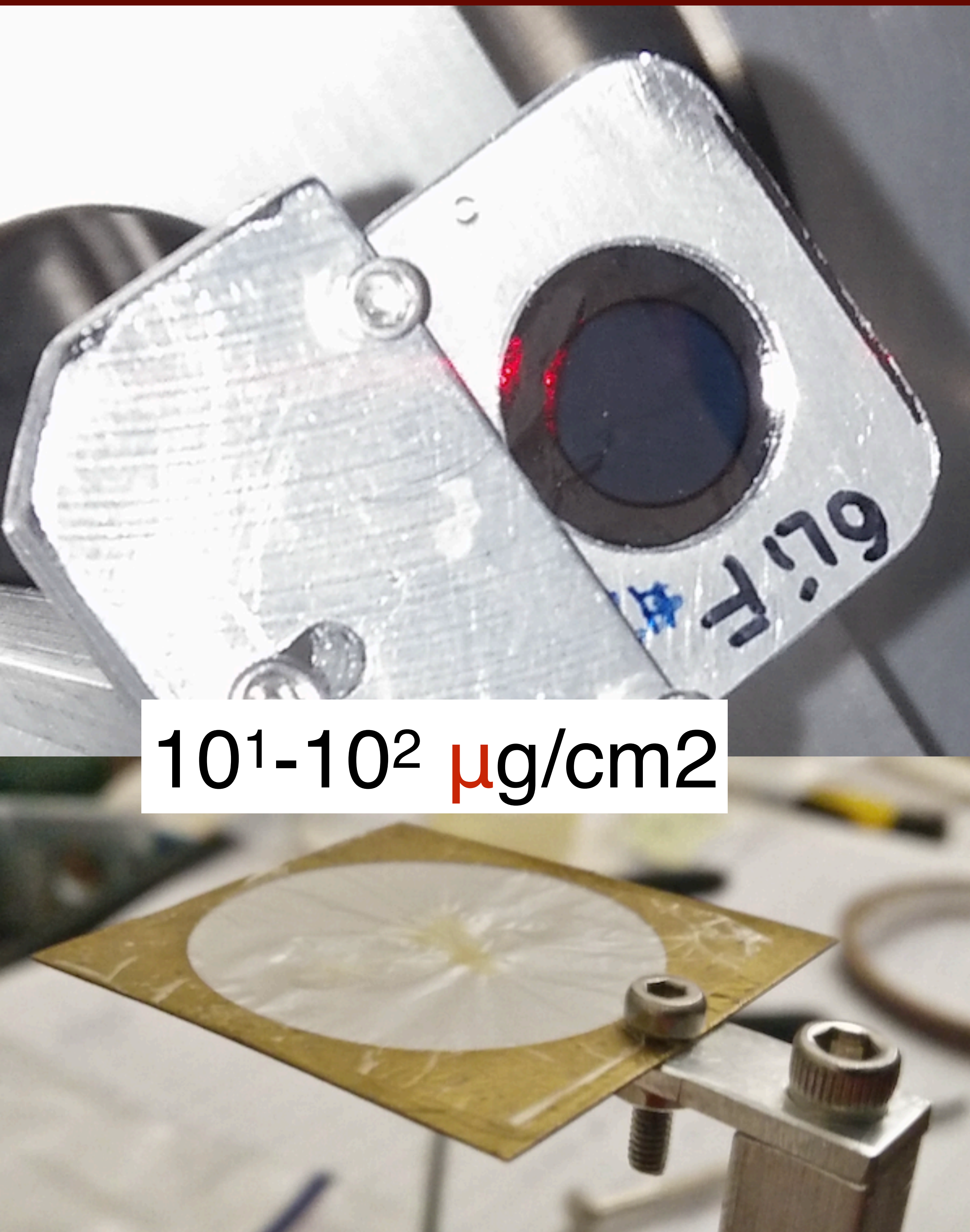
Beam characterization, tracking, …

Target characterization, background measurements, alignment, …

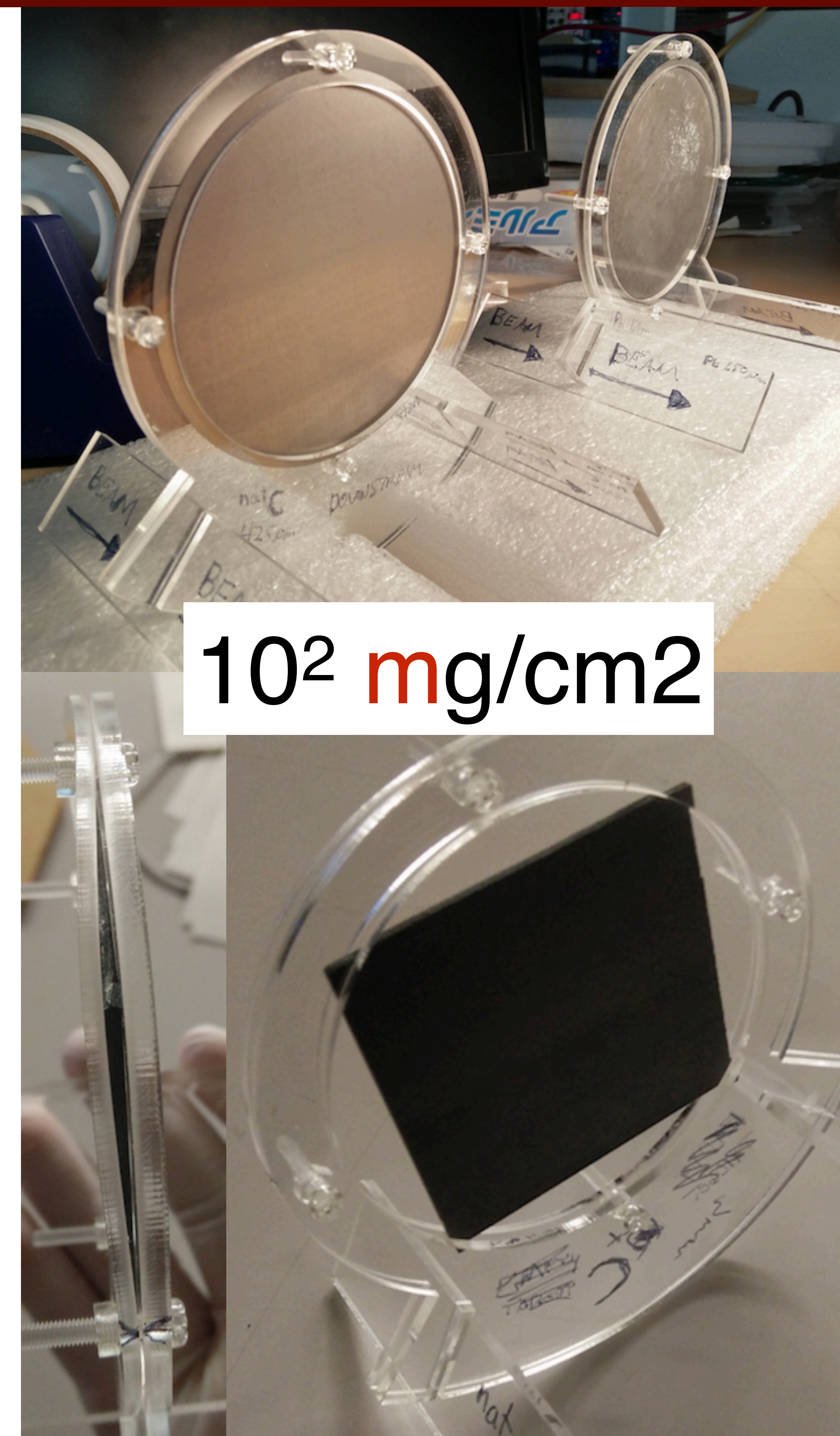
Understanding the instruments, simulations, alignment, …

… and much much more, all specific for a given experiment!

Example: Target thickness / uniformity

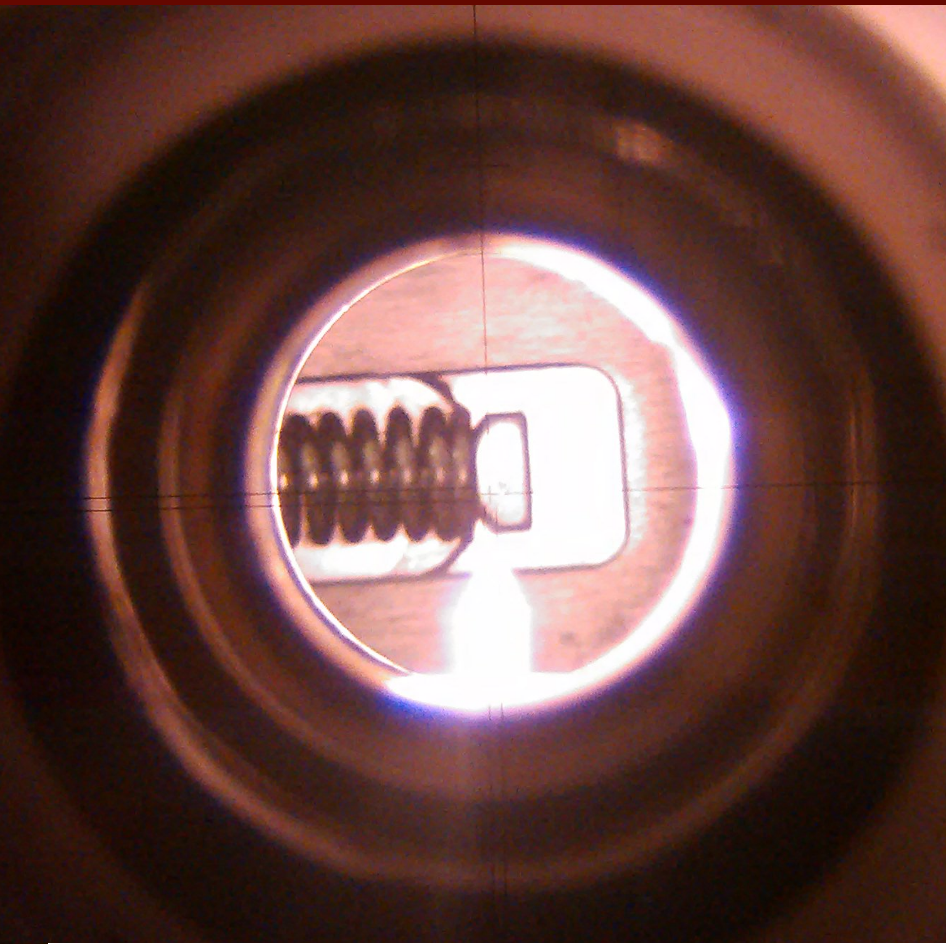


10^1-10^2 μg/cm2



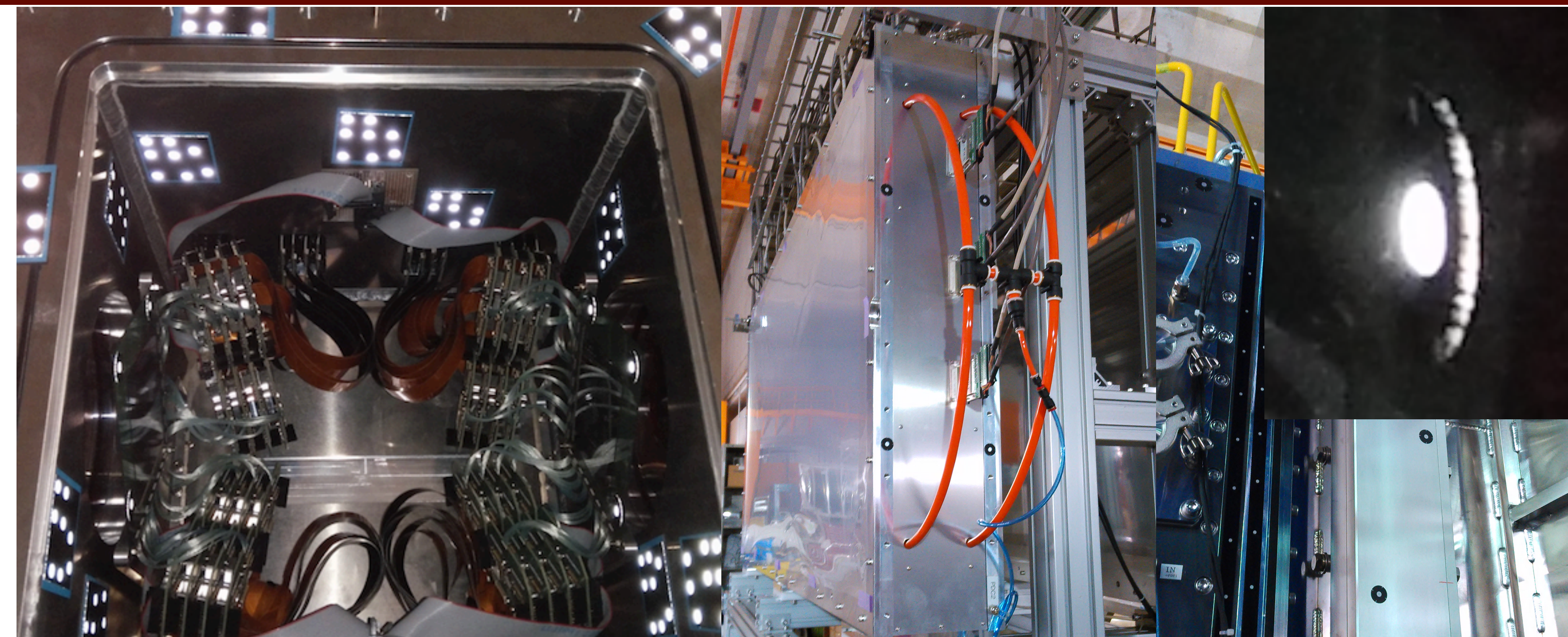
10^2 mg/cm2

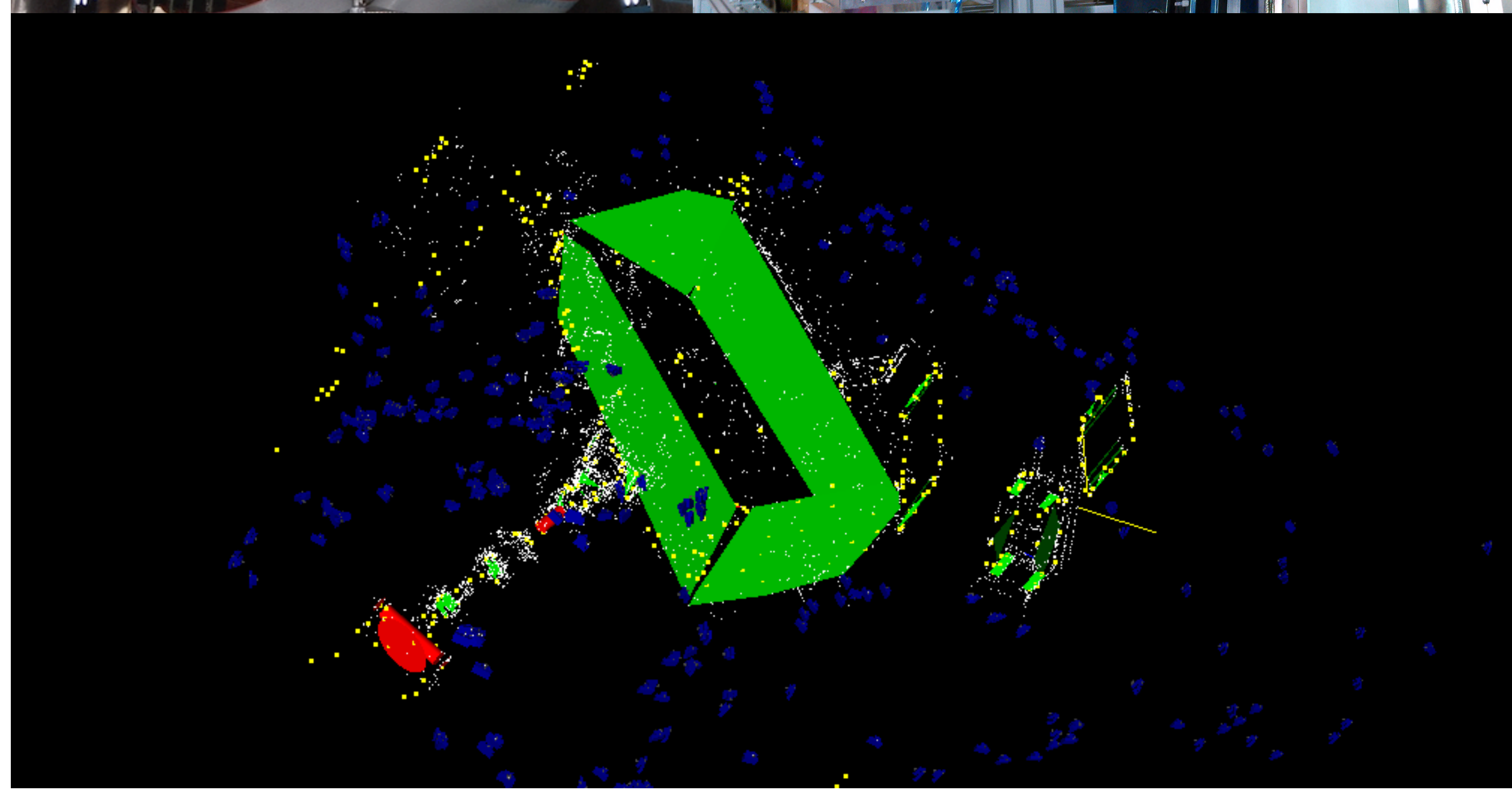
Example: Setup alignment



Transit: < 0.1 mm over few tens of m (on single axis)

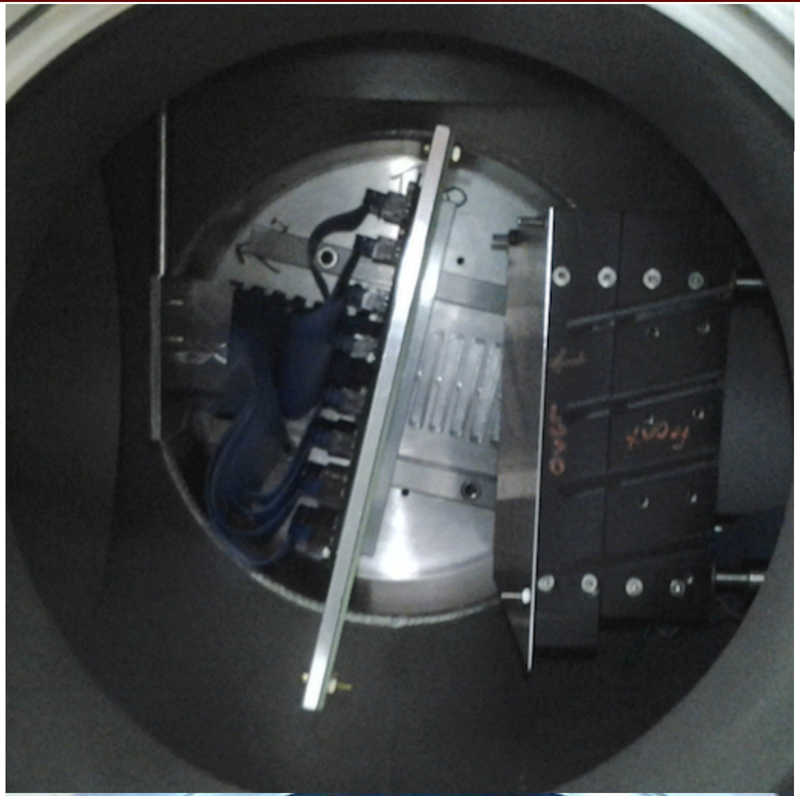
In not so distant future:
Reconstruct setup in 3D with < 1 mm precision from photos taken with an app?

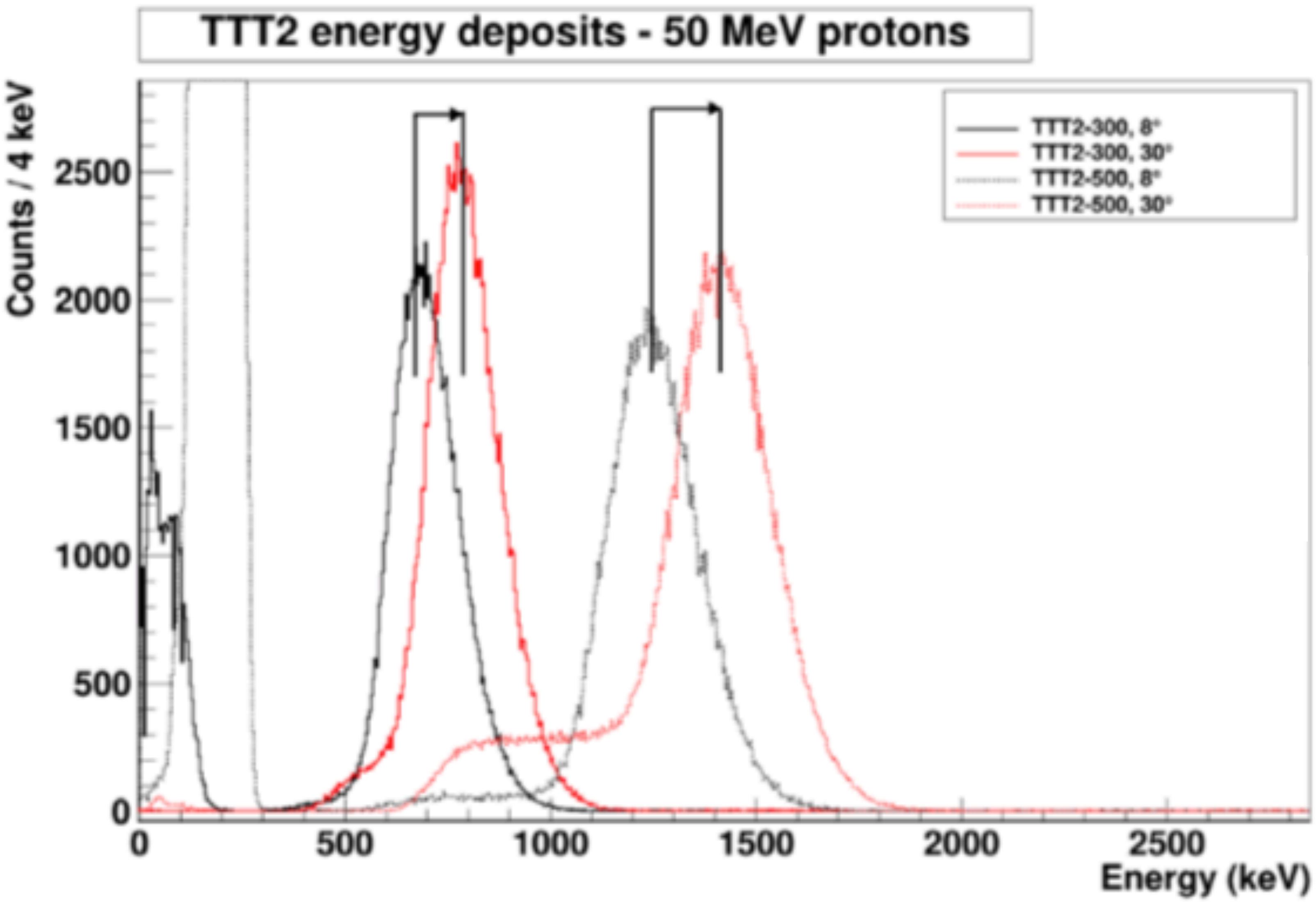




Reconstruction from images with markers:
< 1 mm precision throughout experimental hall

Example: Detector orientation





Know thy instruments!

Summary lecture 1

- few basics of reaction experiments

- different reaction types

- production of exotic beams and intensity requirements for reaction experiments

- some experimental considerations

Lecture 2: Examples of reaction experiments with different approaches