INSTITUTE FOR STRUCTURE AND NUCLEAR ASTROPHYSICS

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Recoil Separator
Context and Key Design Concepts

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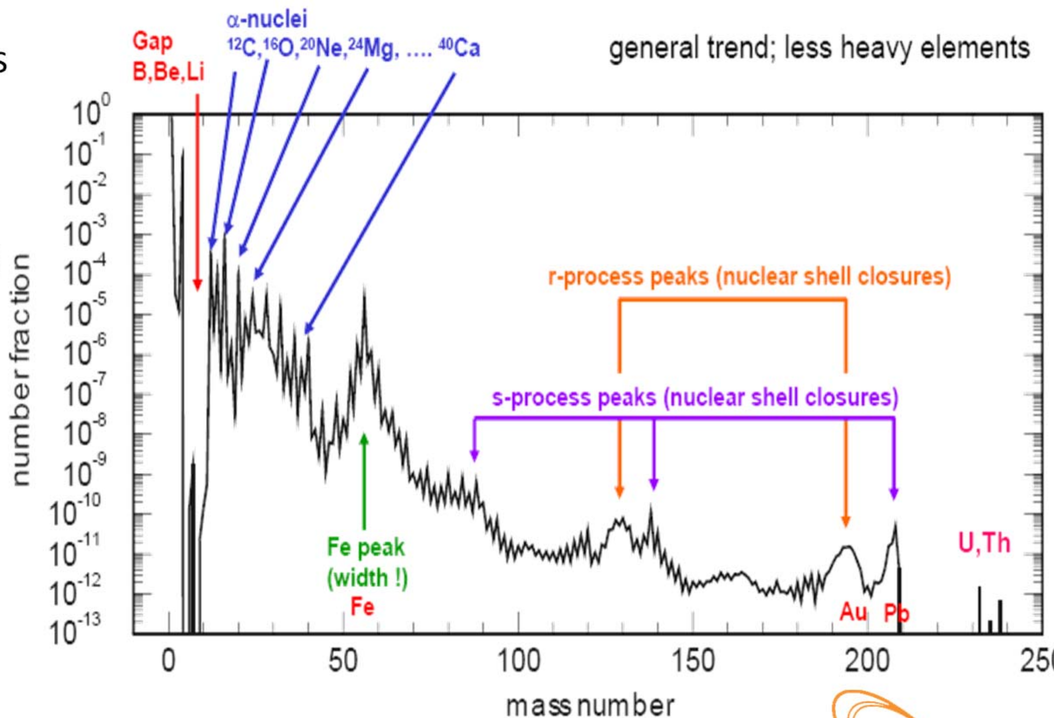
Goals

- Used formalism your learn from G. Berg and the properties of ions to define expectation on recoils separators for ion optics

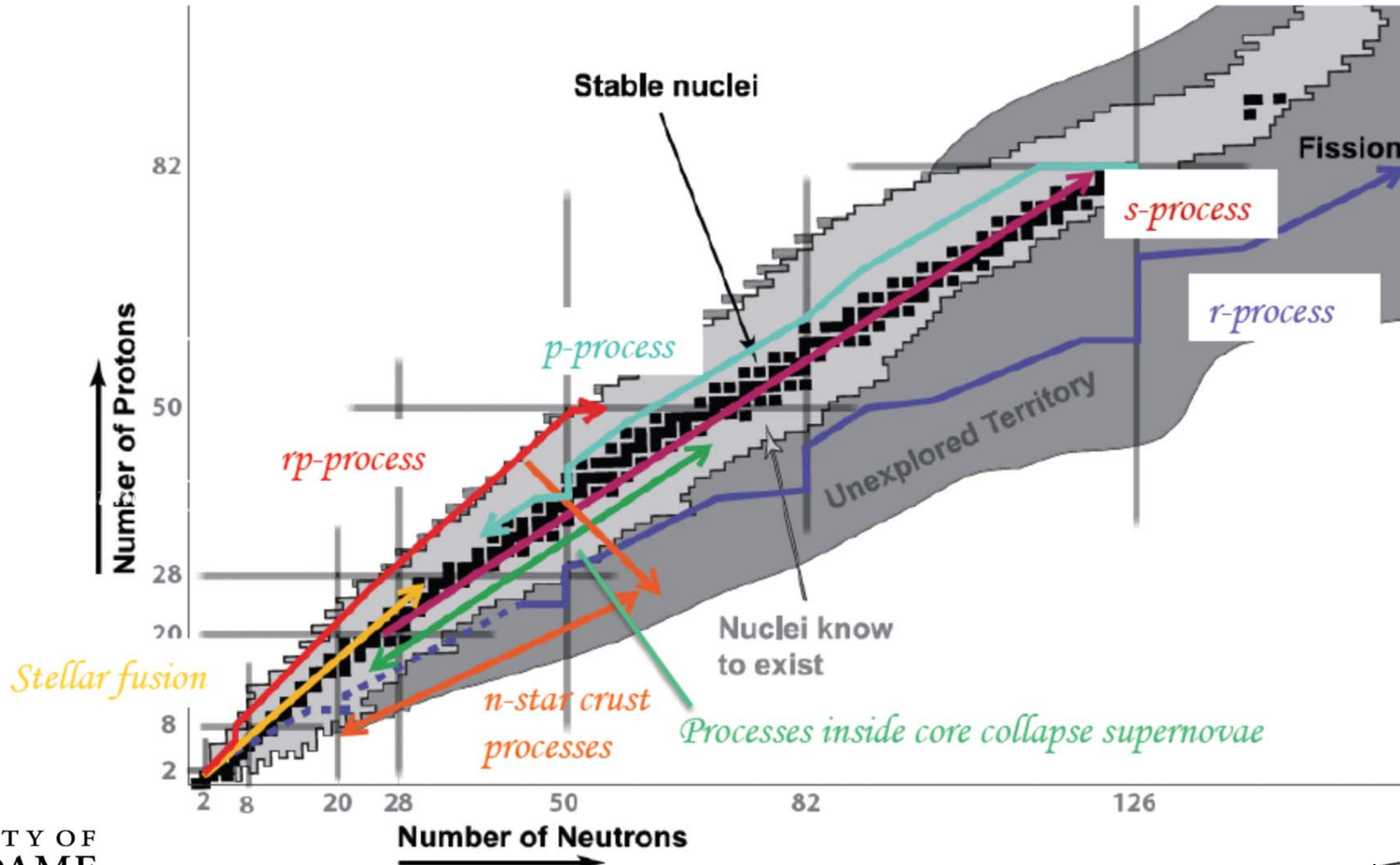
- By the end of the lecture you should be able to
  - Calculate kinematics properties of radiative capture reactions of astrophysical interest and decide whether the results fit (or not) in the acceptance of known recoil separators
  - Describe how to scale magnetic and electrostatic fields of a recoil separator from a known ion optic solution for a given reaction to apply it to another reaction
  - Define the concept of resolving power and mass resolution and explain both are useful in the context of recoil separators

Radiative Capture and Fusion Reactions

- First step in chemical evolution of our universe
  - Big Bang nucleosynthesis
  - 500 million years later first generation of stars
  - Present star generation
- Charged particle reactions generate the seed and the fuel for nucleosynthesis processes building the elemental and isotopic abundance distribution as observed

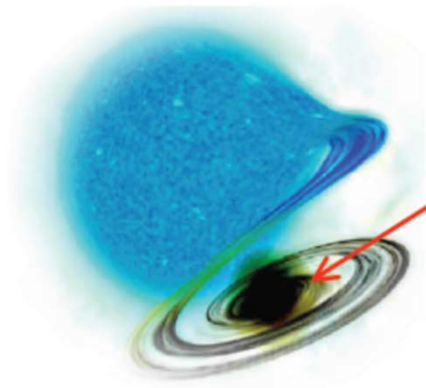


Stellar processes



From H. Schatz

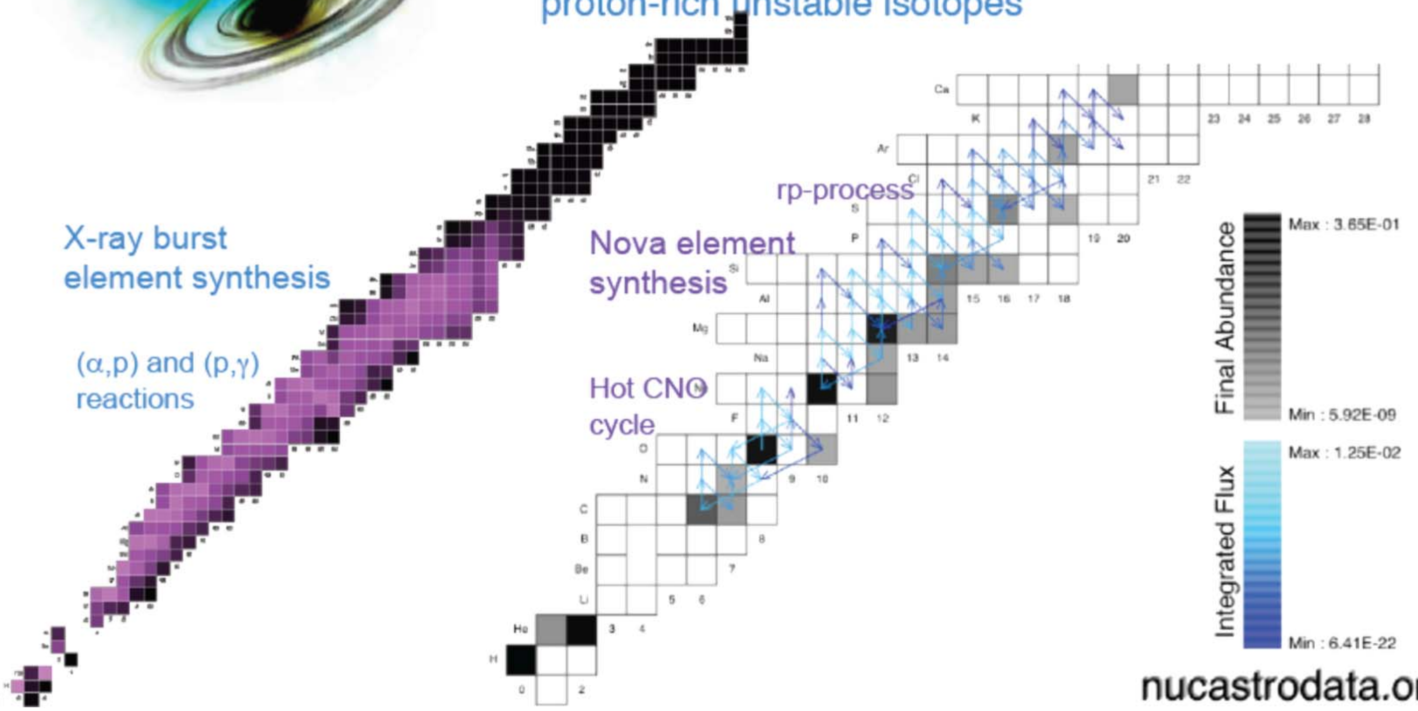
explosive nucleosynthesis - novae & X-ray bursts



thermonuclear explosions on the surfaces of
white dwarf stars (novae)
neutron stars (X-ray bursts)

release 10^{45} ergs in visible, gamma rays, X-rays …

powered by [unmeasured] nuclear fusion reactions on proton-rich unstable isotopes



nucastrodata.org

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Slide from D. Bardayan

αp- and rp-process

- play crucial role in understanding the synthesis of heavy elements in x-ray bursts
- provides break out from CNO cycle
- enables rp-process

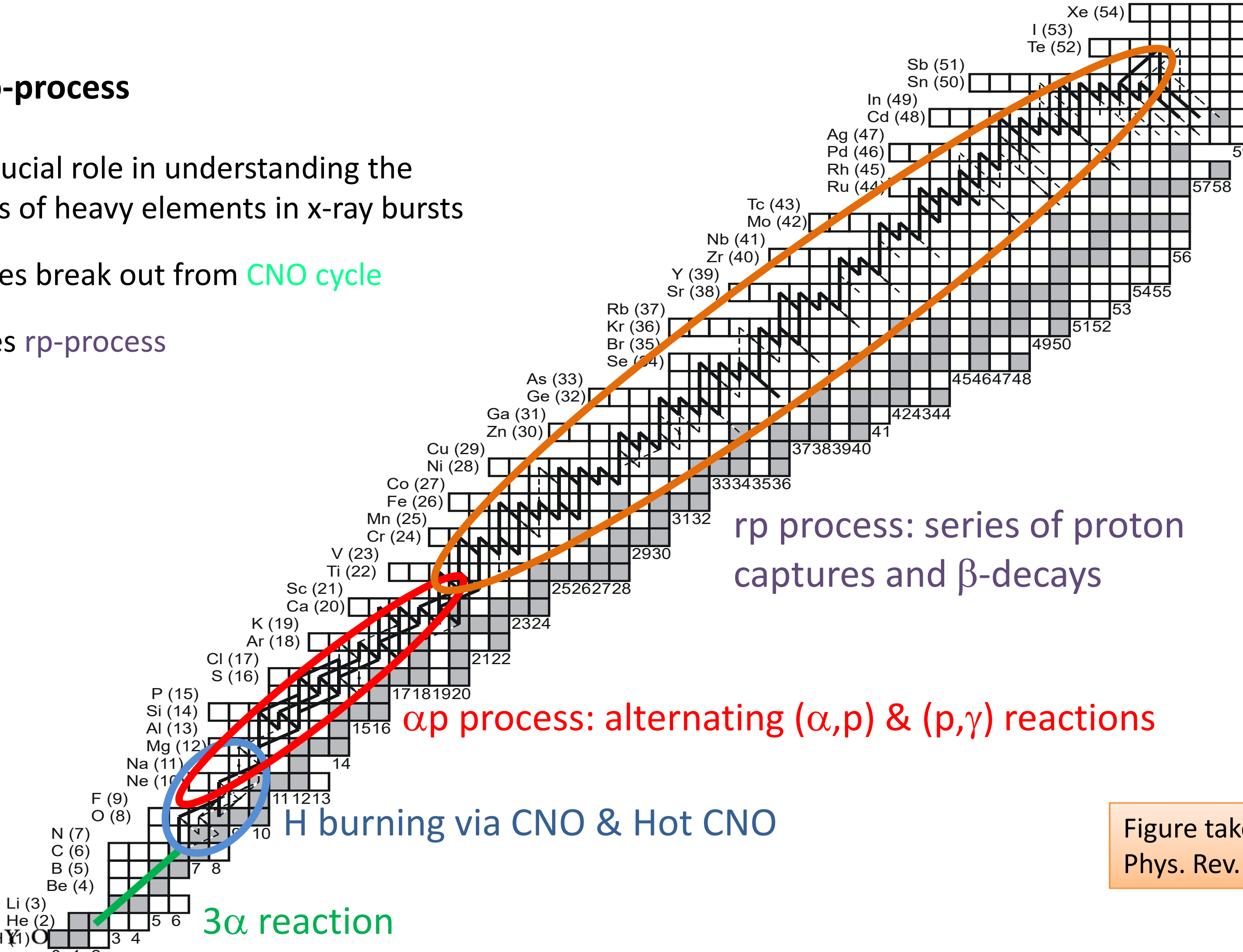

Figure taken from Schatz *et al.*, Phys. Rev. Lett. **68**, 3471 (2001)

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Slide from D. Bardayan

I S N A P

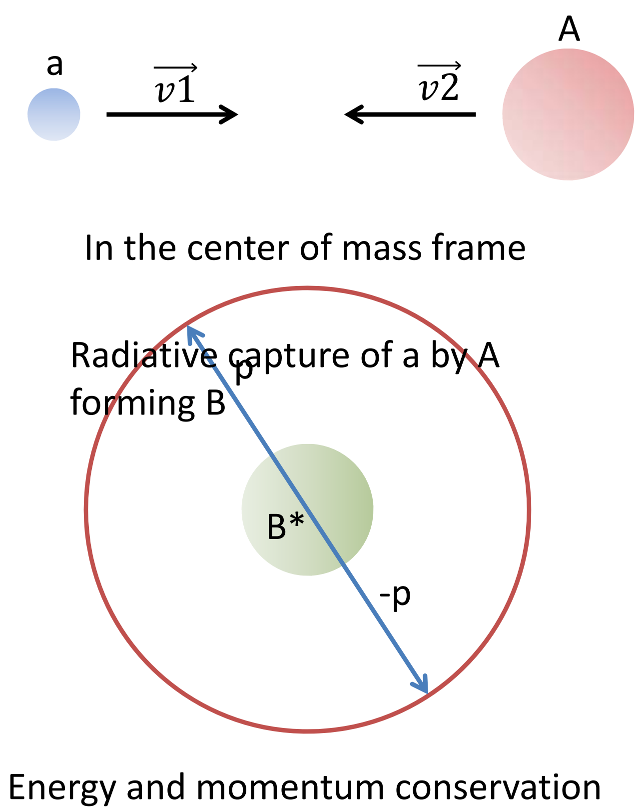
Inverse Kinematics/Recoil Detection?

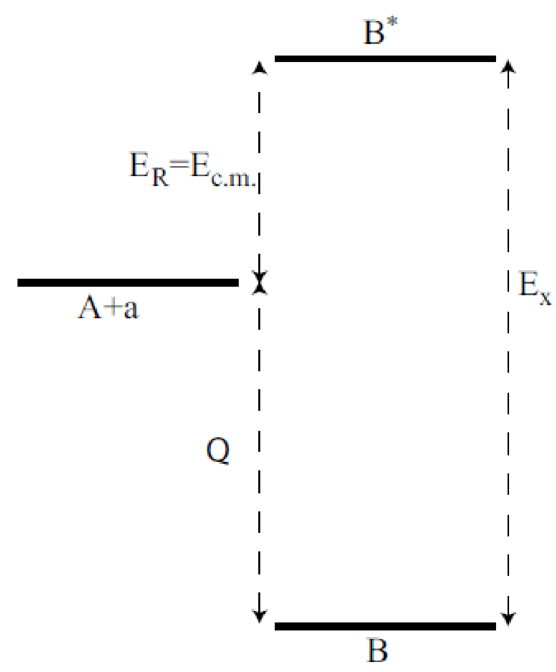
- Unstable isotope beams
- Detection of recoils decreases background

Let's have a look at what is happening pass the target

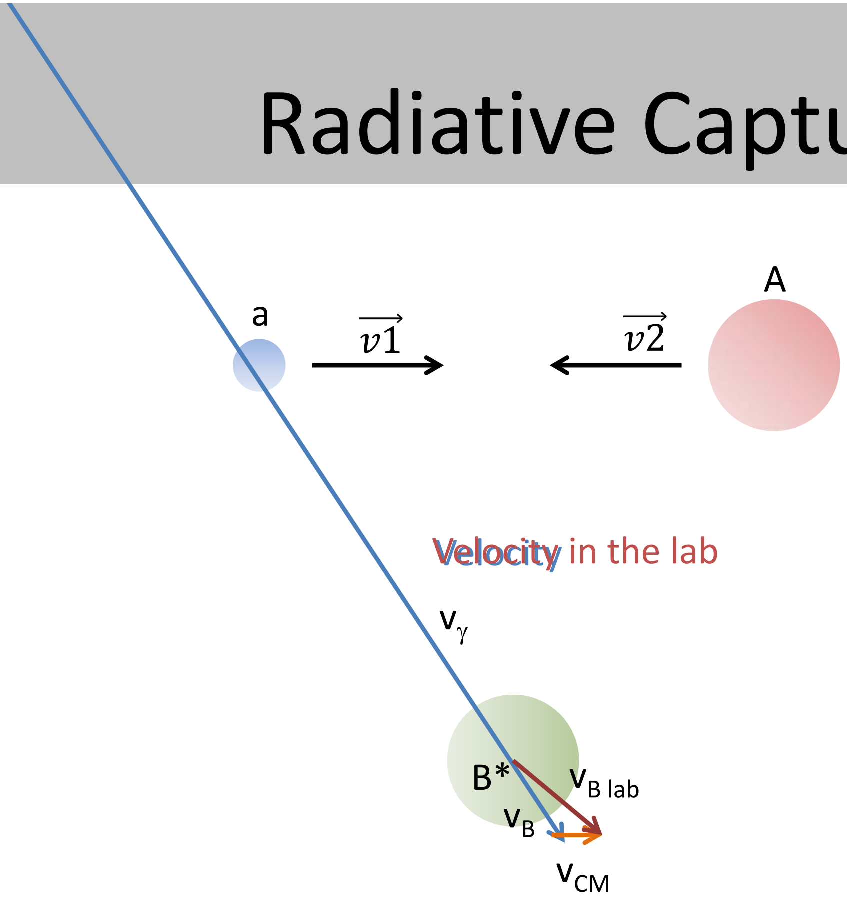
- Beam that did not interact continues
  - Some energy loss / straggling (can be calculated with standard tools)
- Recoil are emitted forward with calculable properties (kinematics)
- Atomic cross sections of capture and loss of electrons are large
  - Beam and recoil may have various charge states (calculation and measurements)

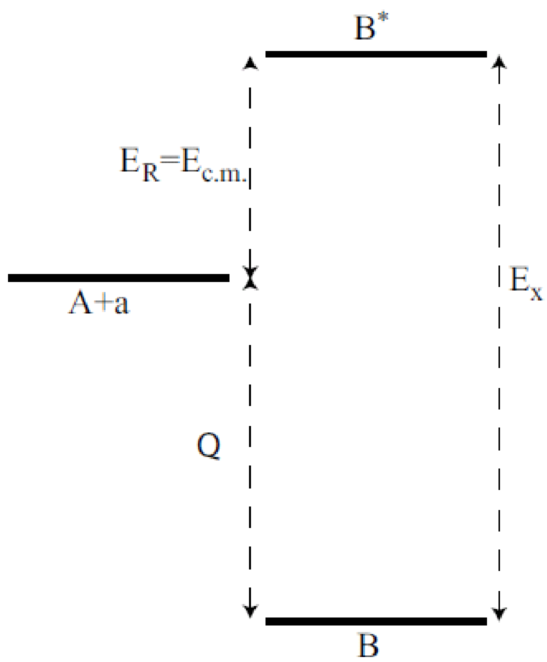
Radiative Capture Kinematics





Radiative Capture Kinematics





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Two-Body Kinematics Calculator and Plotter

This script generates plots and tables representing products of nuclear reactions, along with elastic and inelastic scattering processes u: kinetic energy of the projectile, any excitation energy of the products and select the desired output. The plots and tables created will be

Enter Isotopes (^{A}El) or Masses (AMU or MeV). Isotopes should be of form 1H, 4He, ^{16}O ... etc, case insensitive; *n*, *p*, *d*, *t*, *h*, *a*, *g*, *e* (or deuteron, triton, ^{3}He, alpha, gamma, electron and positron. Shorthand is also available for particles via pi+, pi-, pi0, rho+, rho-, rho0, by request. Isotope masses are taken from the table of atomic masses, mass.mas114, with Zm_e subtracted.

Please note: the notation has been changed so that m_1 has the kinetic energy. For an explanation of the calculations, see Relativistic Re

Projectile (m_1): 19Ne ◉ ^{A}El ○ AMU ○ MeV

Target (m_2): p ◉ ^{A}El ○ AMU ○ MeV

Ejectile (m_3): 20na ◉ ^{A}El ○ AMU ○ MeV

Recoil (m_4): g ◉ ^{A}El ○ AMU ○ MeV

Projectile Energy: 13 MeV ◉ kinetic ○ total

Ejectile Excitation Energy: MeV

Recoil Excitation Energy: MeV

Plot Abscissa (x-axis): ◉ θ_3 ○ θ_4 ○ θ_{3cm} ○ $\cos(\theta_{3cm})$ ○ E_3 ○ E_4 ○ v_3 ○ v_4 ○ $d\Omega_3/d\Omega_{cm}$ ○ $d\Omega_4/d\Omega_{cm}$

Plot Ordinate (y-axis): ○ θ_3 ○ θ_4 ○ θ_{3cm} ○ $\cos(\theta_{3cm})$ ◉ E_3 ○ E_4 ○ v_3 ○ v_4 ○ $d\Omega_3/d\Omega_{cm}$ ○ $d\Omega_4/d\Omega_{cm}$

Express angles in: ◉ degrees ○ radians

x min, x max:

y min, y max:

Plot Width: 900 pixels , Font Size: 21 pt

Number of Points: 100

Legend Font Size: 16 pt, Legend Vertical Displacement: 3 %

Output: ◉ display PNG image ○ generate EPS file ○ generate PDF file

CALCULATE

http://skisickness.com/2010/04/relativistic-kinematics-calculator/

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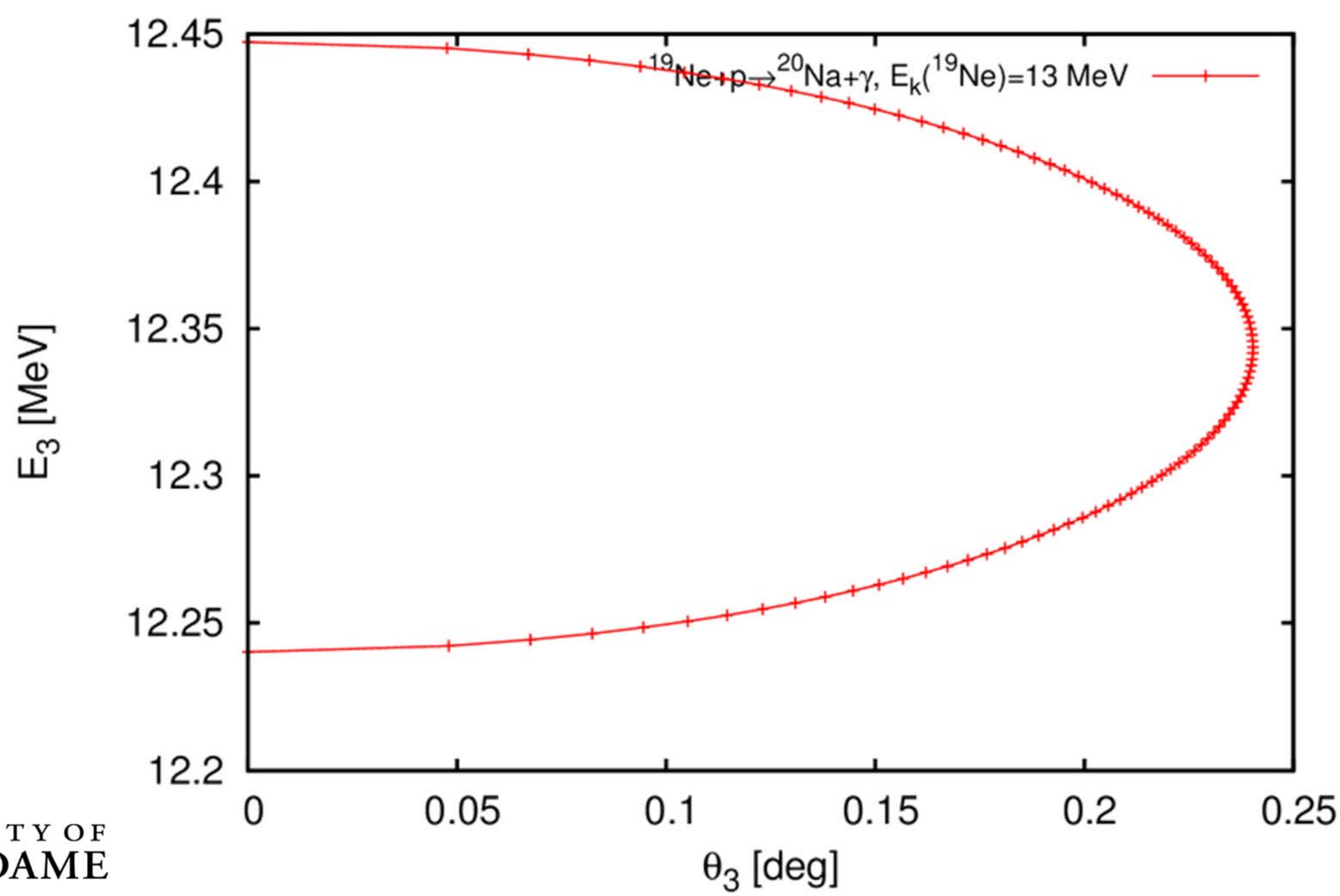
I S N A P

Reaction summary for ^{19}Ne+p→^{20}Na+γ, $E_k(^{19}\mathrm{Ne})$=13 MeV

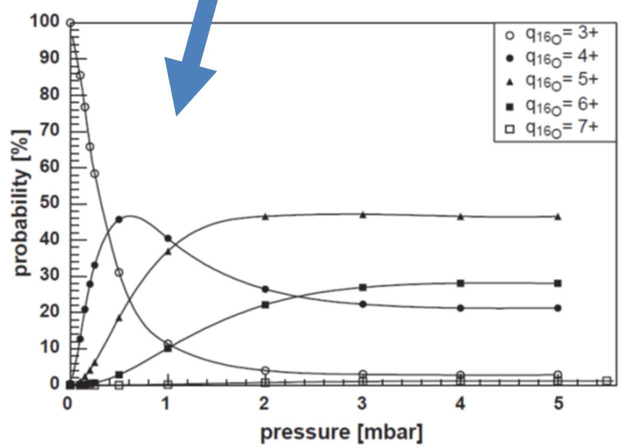
- The maximum ^{20}Na energy is 12.447 MeV. The minimum ^{20}Na energy is 12.24 MeV. The maximum ^{20}Na angle is 0.24 degrees.
- The maximum γ energy is 2.951 MeV. The minimum γ energy is 2.743 MeV.

KE_3 as a function of θ_3:



Charge State of Ion After Crossing Matter

- When ion cross matter they exchange electron with the medium
- If the medium thickness is sufficient the charge state distribution reaches an equilibrium



D. Schürmann et al.
NIMA531 428 (2004)

Fig. 2. Charge state distribution of ^{16}O ions ($q_{in} = 3^+, E_{lab} =$ 9.6 MeV) in ^{4}He gas as a function of ^{4}He pressure in the gas target cell. The curves through the data points are to guide the eye.

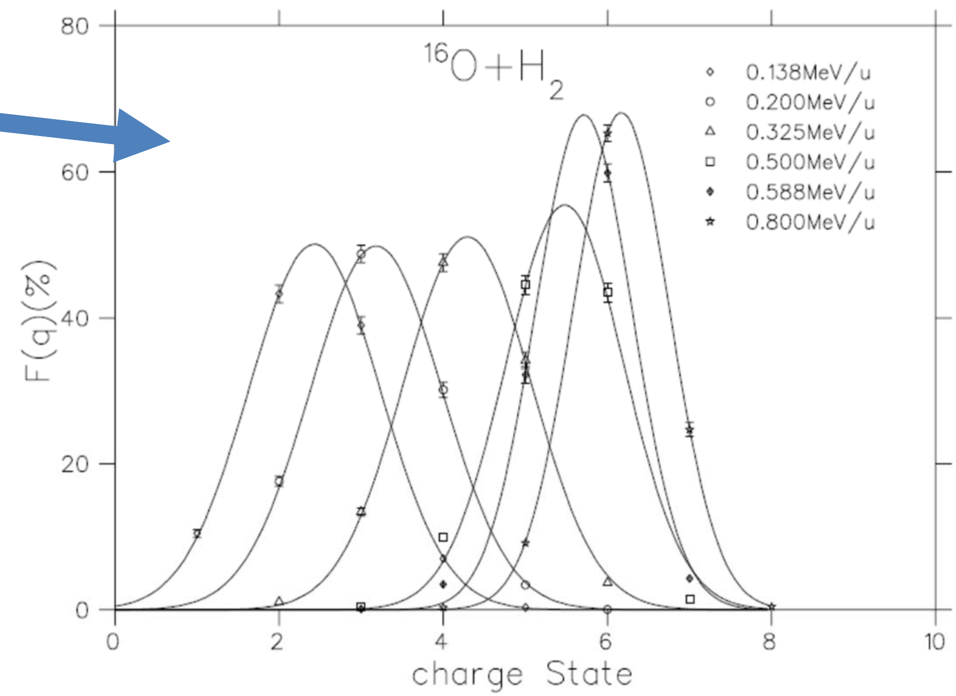


Figure 4.2: Equilibrium charge state distribution of ^{16}O beam passing through hydrogen gas target, with symbols representing the experimental data and line for Gaussian distribution.

CHARGE STATE STUDIES OF HEAVY IONS PASSING THROUGH GAS
Wenjie Liu

http://dragon.triumf.ca/docs/wenjiethesis.pdf

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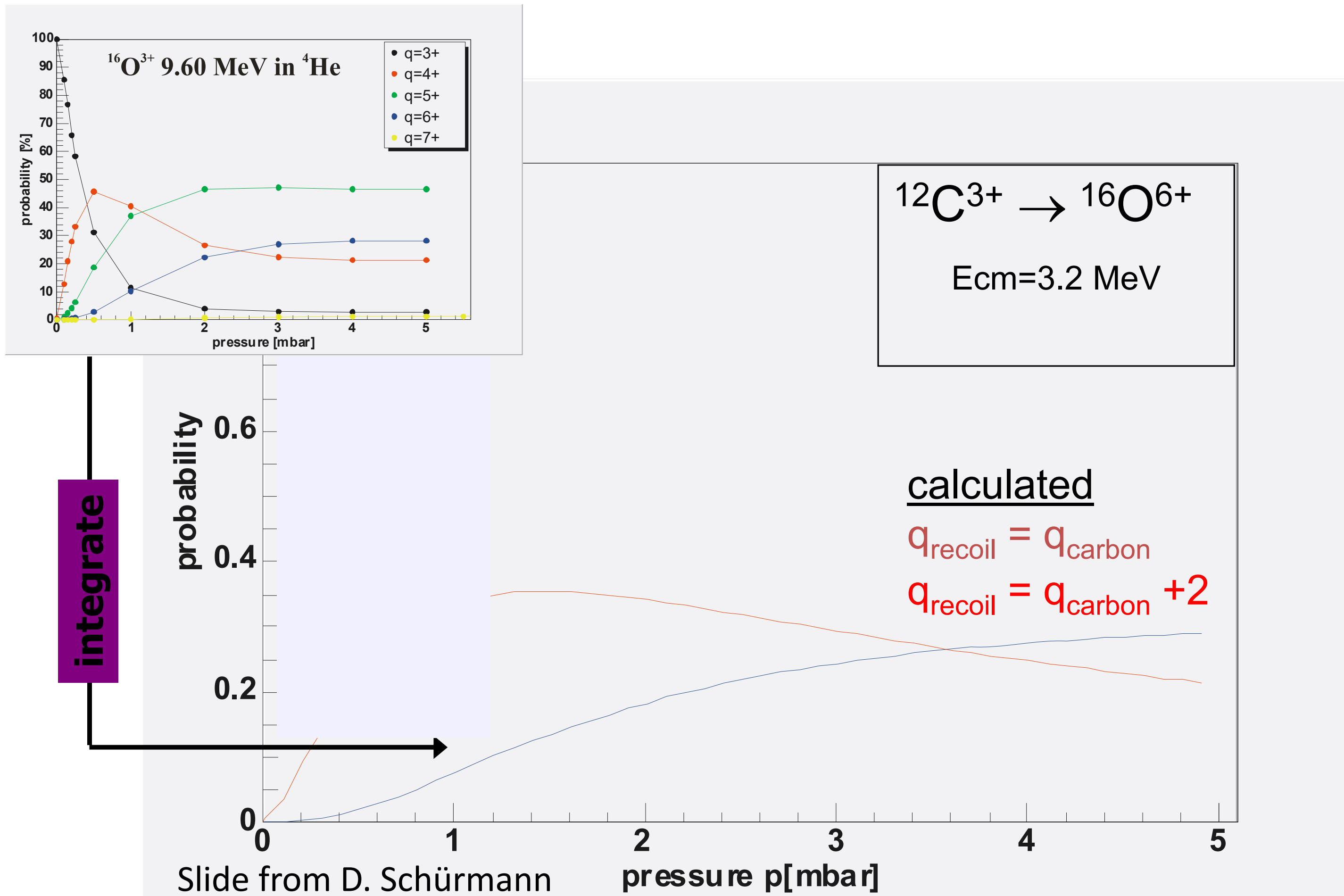
Charge State of Ion After Crossing Matter

When reaction take place things are more problematic

ERNA: Choose to use a stripper right after their gas target



Status

- In inverse kinematics we have:
  - Beam that did not interact
  - Recoil with, in average, the same momentum as the beam
  - Recoil with an momentum/energy distribution
  - Recoil with an angular opening that is larger than that of the beam
  - Beam and recoil with various charge state

Difficult to detect the recoils right after the target

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ELSEVIER

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms

Volume 204, May 2003, Pages 124–128

14th International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications

Recoil separators

Cary N. Davids

Phy

http

Recoil separators are devices which separate nuclear reaction products (recoils) leaving a target from the unreacted beam particles.

Abstract

Recoil separators operating in the vacuum mode play a key role in a number of current research areas, including searches for superheavy elements, the study of nuclei far from stability and nuclear astrophysics. I will review some of these facilities, and will discuss ideas for improving the selectivity and efficiency of these devices.

This includes a lot …

The paper concentrates on devices for fusion/evaporation studies and concludes with a mention to dedicated devices for p and α radiative capture devices

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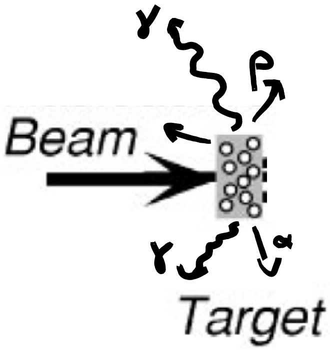
I S N A P

Basic Principles



Advantages? (in no particular order)

- Radioactive beam
- Identification of specific reaction channel using coincidence
- For radiative capture (p,γ) and (α,γ)
  - Charged particle detection → higher efficiency than γ detection (but regularly needs it)
  - Background reduction
  - Gas target → high intensity beam (for stable beam experiments)

Example $\alpha(^{44}Ti,p)^{47}V$

^{44}Ti observed in core collapse SN remnants

– Is used to determine distance/age of SN
– Destruction rate of ^{44}Ti critical

Sonzogni et al, PRL 84, 1651 (2000)

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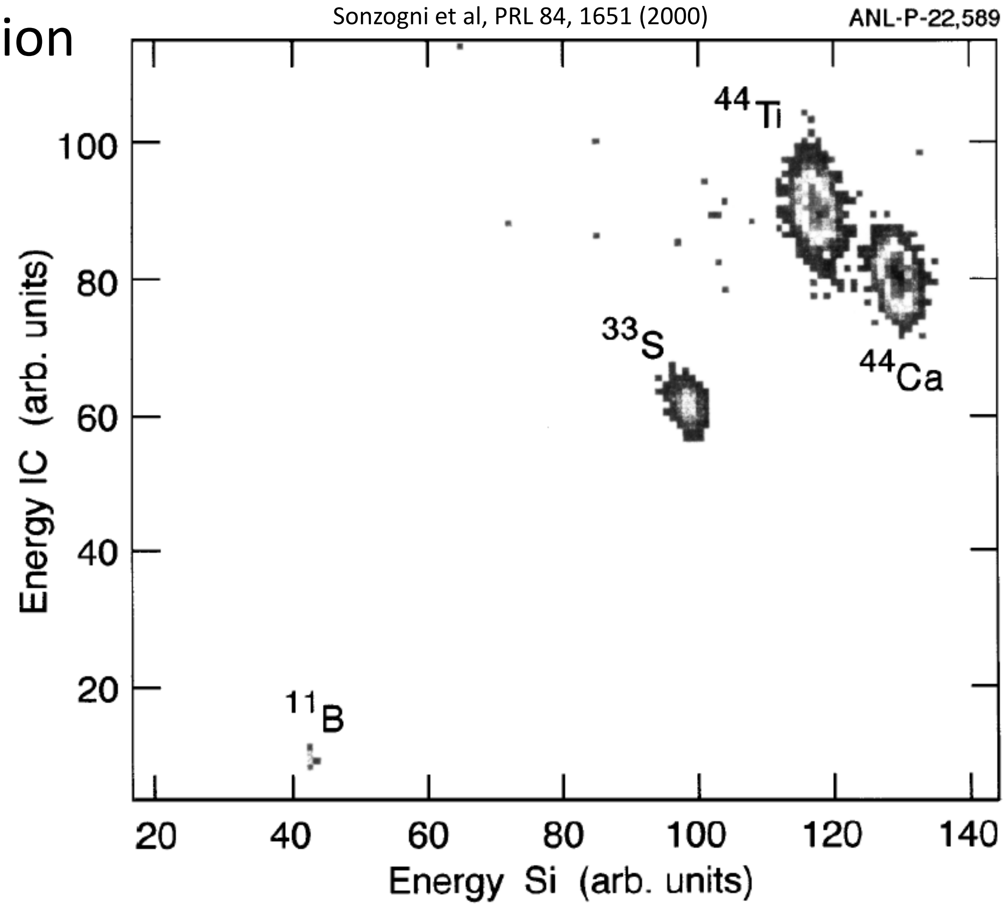
Example $^{44}Ti(\alpha,p)^{47}V$

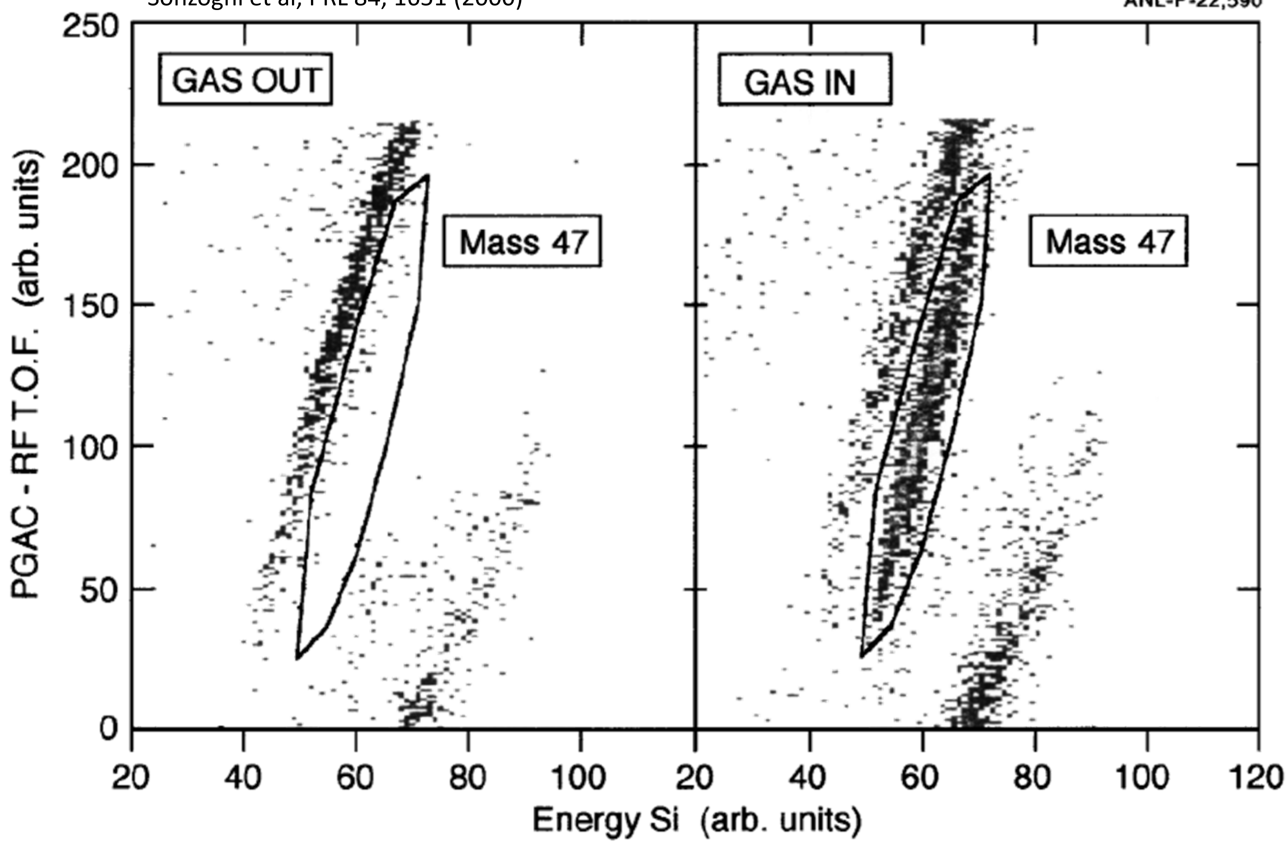
Beam contamination

Sonzogni et al, PRL 84, 1651 (2000)



Example $^{44}Ti(\alpha,p)^{47}V$

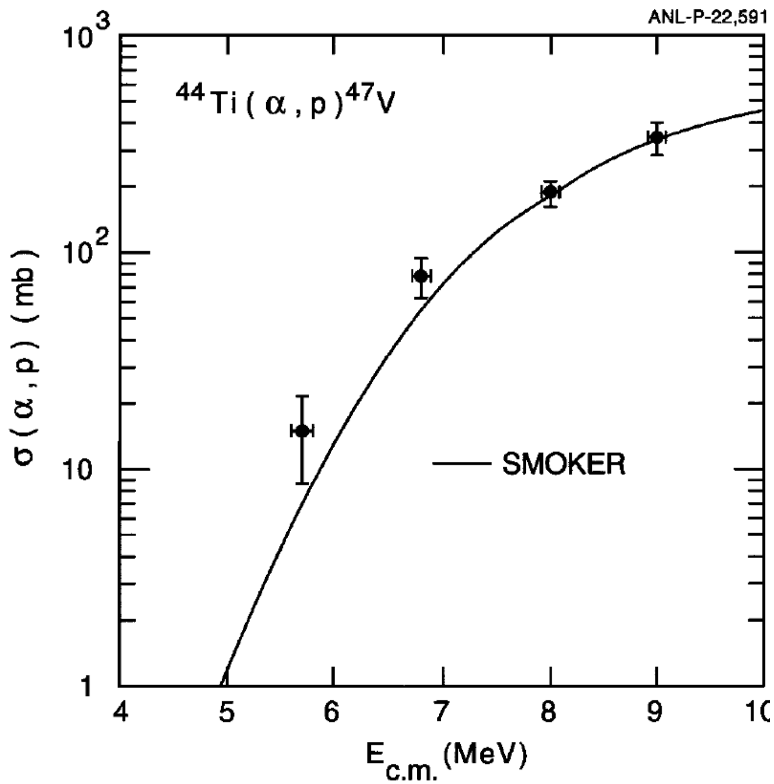
Sonzogni et al, PRL 84, 1651 (2000)



Subtraction of $^{44}Ca(\alpha,p)$ with pure 44Ca beam in a separate step

Example $^{44}Ti(\alpha,p)^{47}V$

Sonzogni et al, PRL 84, 1651 (2000)



Example $^{44}Ti(\alpha,p)^{47}V$

Lessons learned?

- Beam contamination contributes signals
- Particle identification detection is critical
  - Detector design is a talk on its own
- The job of the separator is to reduce amount of beam in focal plane detector
- Not shown:
  - A single charge state is selected

Focus on Radiative Capture Studies

Direct studies of (p,γ) and (α,γ) reactions
in
Inverse kinematics (heavy beam on light target)

(indirect studies are critical)

Detection of the recoils

Coincidence with gamma-ray
critical for rejection
can provide cascade information

Critical quantities:

$$\overrightarrow{p_b} = \overrightarrow{p_R} + \Sigma\overrightarrow{p_{\gamma_i}}$$

$$\theta_{max} = \arctan(\frac{E_\gamma/c}{\sqrt{2m_b E_b}})$$

Charge state distribution of recoils

$\Delta M/M$

Beam Rejection

Transmission of the recoils

Energy acceptance
Angular acceptance

Transmission Requirements

From: PoS(ENAS 6)058

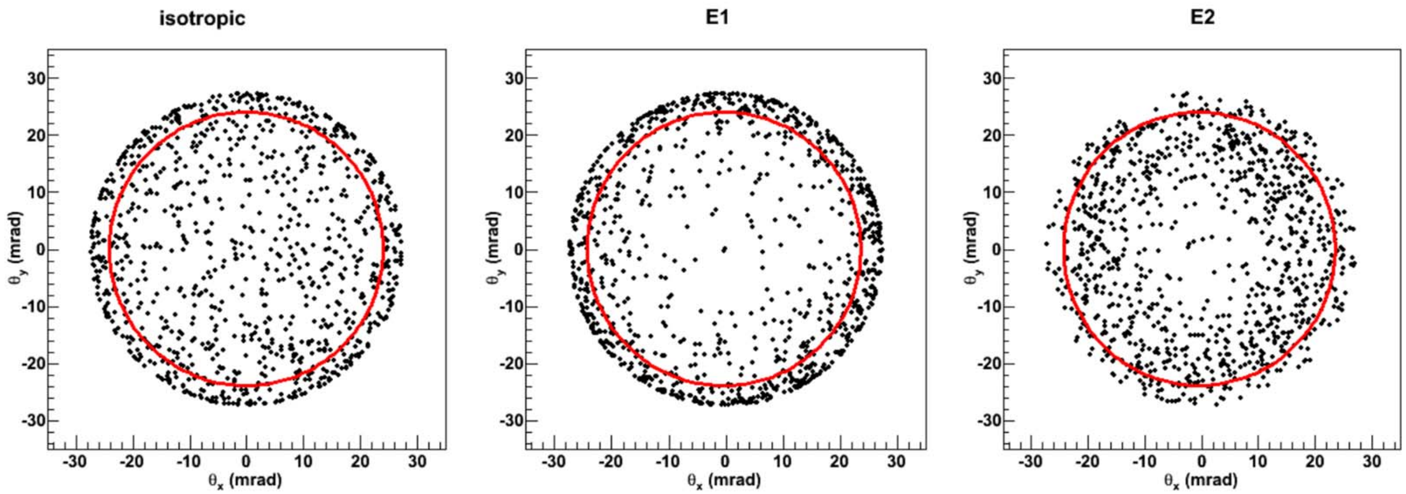


Figure 1 Distribution of recoils in the θ_x, θ_y space for $^{12}C(\alpha,\gamma)^{16}O$ ground state transition at E = 1.0 MeV. For different γ-ray angular distributions. Left: isotropic. Center: $\sin^2\theta$. Right: $\sin^2\theta\cos^2\theta$. For reference, a circle shows an angular acceptance of 24 mrad. See text for details.

For absolute cross section, full transmission of the selected charge state is needed

Attempt at FMA to study $^{13}C(p,\gamma)^{14}N$ and $^{18}O(p,\gamma)^{19}F$ and $^{18}F(p,\gamma)^{19}Ne$ but limited in transmission

Rejection Requirements

Total Rejection = Separator rejection * Detector rejection

For background <1

the Total Rejection needed must be better than:

Reaction rate (recoil/incident ion)

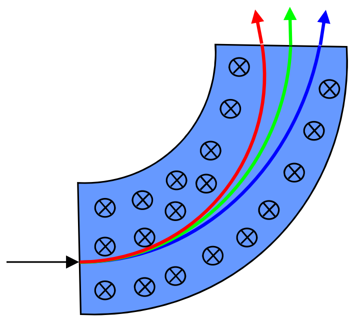
* 10^{-3} (rejection provided by particle ID detector)

* 1/#of recoil to reach statistical significant measurement

Measured rejection at DRAGON between 10^{-9} and 10^{-15}

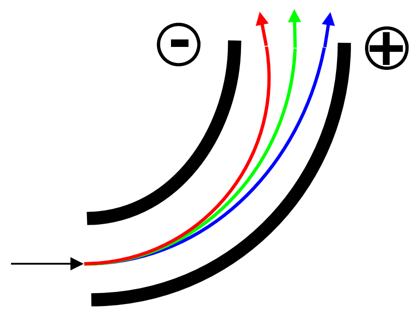
Separation Principle: E&M 101

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$



magnetic dipole

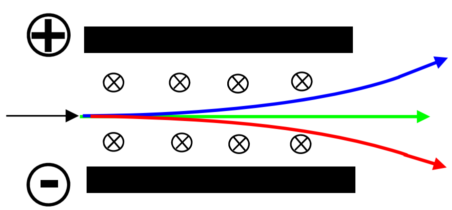
$$\frac{p}{q} = B\rho$$



electric dipole

$$\frac{2E}{q} = U\rho$$

U is the electric field



Wien filter

$$v_0 = \frac{U}{B}$$

Combination of two elements

Dipole magnet cancels either E/Q or velocity dispersion to achieve M/Q dispersion

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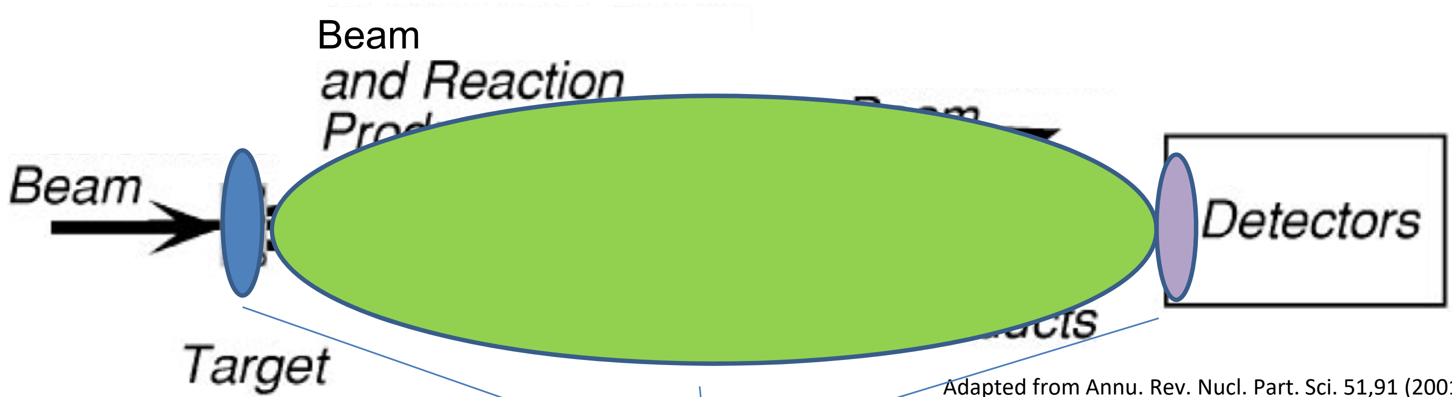
Drawings from D. Schürmann

ISNAP

Ion Optics Description

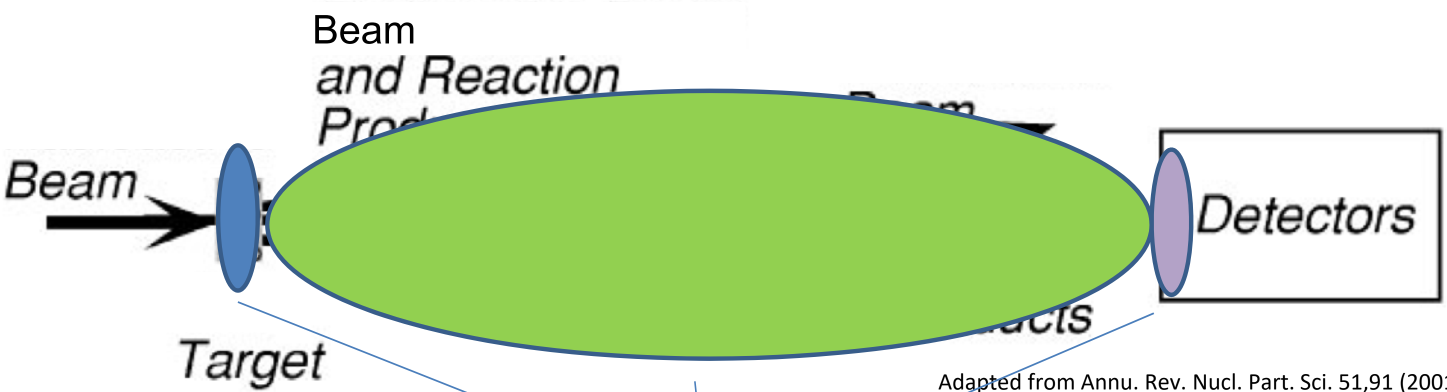


Adapted from Annu. Rev. Nucl. Part. Sci. 51,91 (2001)

$$\begin{pmatrix} x(z) \\ a(z) \\ y(z) \\ b(z) \\ d_i(z) \end{pmatrix} = (Transfer\ Matrix) \begin{pmatrix} x(z=0) \\ a(z=0) \\ y(z=0) \\ b(z=0) \\ d_i(z=0) \end{pmatrix}$$

$$d_i = \frac{\Delta p}{p_0}, \frac{\Delta E}{E_0}, \frac{\Delta Q}{Q_0}, \frac{\Delta m}{m_0}$$

Ion Optics Description



Adapted from Annu. Rev. Nucl. Part. Sci. 51,91 (2001)

$$\begin{pmatrix} x(z) \\ a(z) \\ d_i(z) \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) & (x|d) \\ (a|x) & (a|a) & (a|d) \\ (d|x) & (d|a) & (d|d) \end{pmatrix} \begin{pmatrix} x_0 \\ a_0 \\ d_{i0} \end{pmatrix}$$

$$d_i = \frac{\Delta p}{p_0}, \frac{\Delta E}{E_0}, \frac{\Delta Q}{Q_0}, \frac{\Delta m}{m_0}$$

How do we characterize beam rejection?

Resolving Power

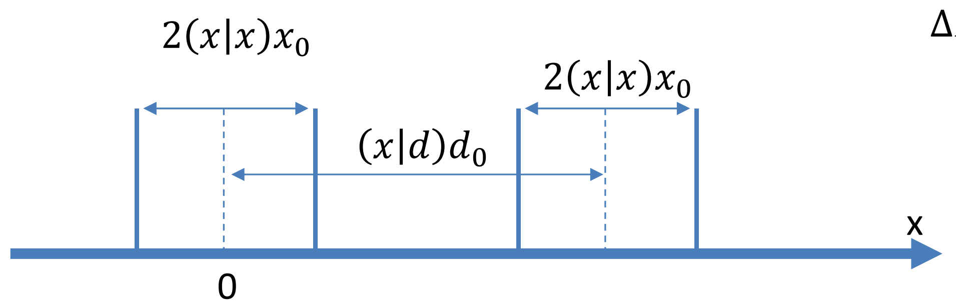
$$\begin{pmatrix} x(z) \\ a(z) \\ d(z) \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) & (x|d) \\ (a|x) & (a|a) & (a|d) \\ (d|x) & (d|a) & (d|d) \end{pmatrix} \begin{pmatrix} x_0 \\ a_0 \\ d_0 \end{pmatrix}$$

Your favorite spectrometer/separator

$$x(z) = (x|x)x_0 + \cancel{(x|a)}a_0 + (x|d)d_0$$

Maximum half size of your target

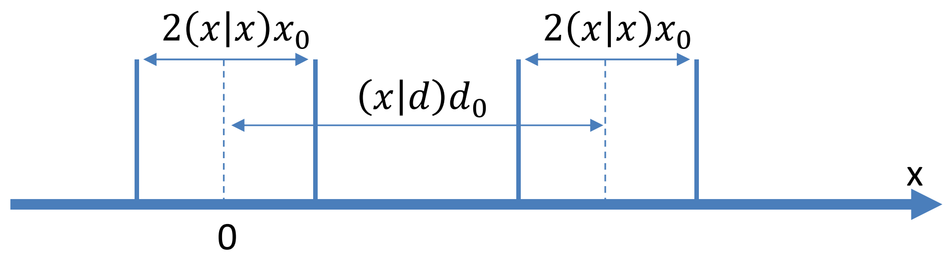
d : $\Delta p/p_0$, $\Delta m/m_0$, $\Delta E/E_0$ or $\Delta Q/Q_0$



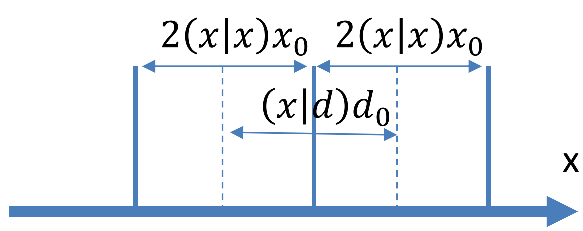
Resolving Power

$$x(z) = (x|x)x_0 + (x|a)a_0 + (x|d)d_0$$

Half size of your target



The resolving power is the inverse value of d_0 that still provide a separation

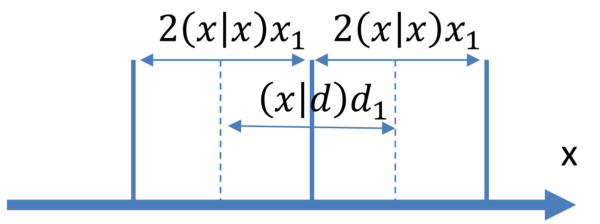


$$(x|d)d_0 = 2(x|x)x_0$$

$$1/d_0 = \frac{(x|d)}{2(x|x)x_0}$$

Resolving Power

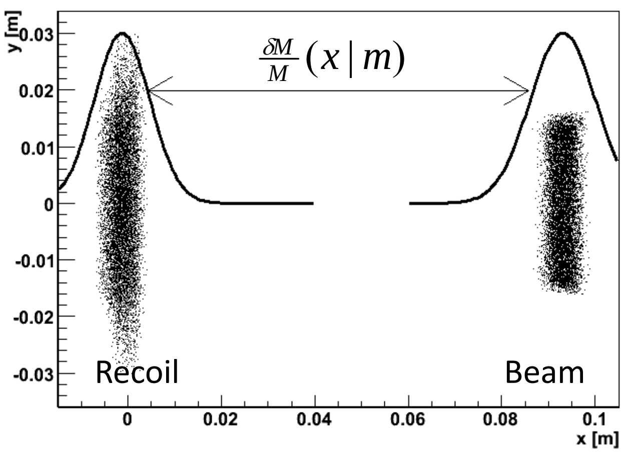
The resolving power is the inverse value of d_1 that still provide a separation



$$(x|d)d_1 = 2(x|x)x_1$$

$$1/d_1 = \frac{(x|d)}{2(x|x)x_1}$$

$^{18}O(\alpha,\gamma)^{22}Ne$ @ 2. MeV



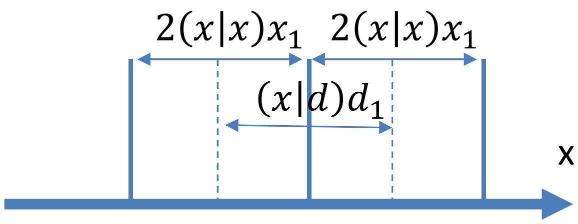
$$(x|\,dm/m) = 0.52 \text{ m/\%}$$

$$M = (x|x) = 1$$

$$R = 1/d_1 = \frac{0.52}{2 \times 1 \times 0.0015} = 173$$

Resolving Power->Mass Resolution

The resolving power is the inverse value of d_1 that still provide a separation

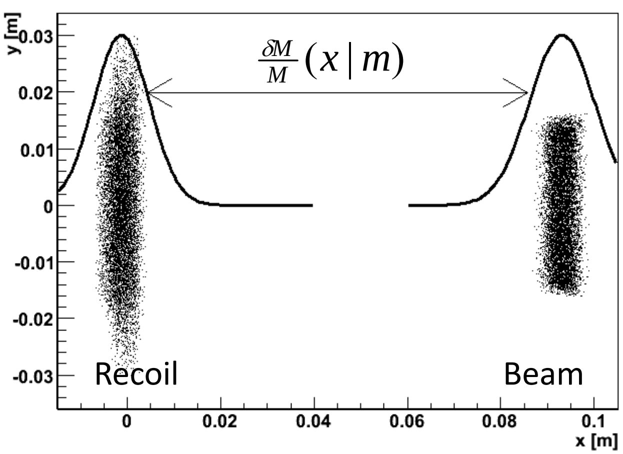


$$(x|d)d_1 = 2(x|x)x_1$$

$$1/d_1 = \frac{(x|d)}{2(x|x)x_1}$$

Width of beam/recoil spot

$^{18}O(\alpha,\gamma)^{22}Ne$ @ 2. MeV



$$(x|\,dm/m) = 0.52 \text{ m/\%}$$

$$M = (x|x) = 1$$

$$R = 1/d_1 = \frac{0.52}{2 \times 1 \times 0.0015} = 173$$

Replacing the first order spot size by realistic size calculated from higher order will deliver more a realistic concept:

MASS RESOLUTION

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Pros/Cons?

Limitation of the Described Approach?

Not actually a “square” beam/recoil spatial distribution

Beam is **many** order of magnitudes more intense than recoils

Advantages?

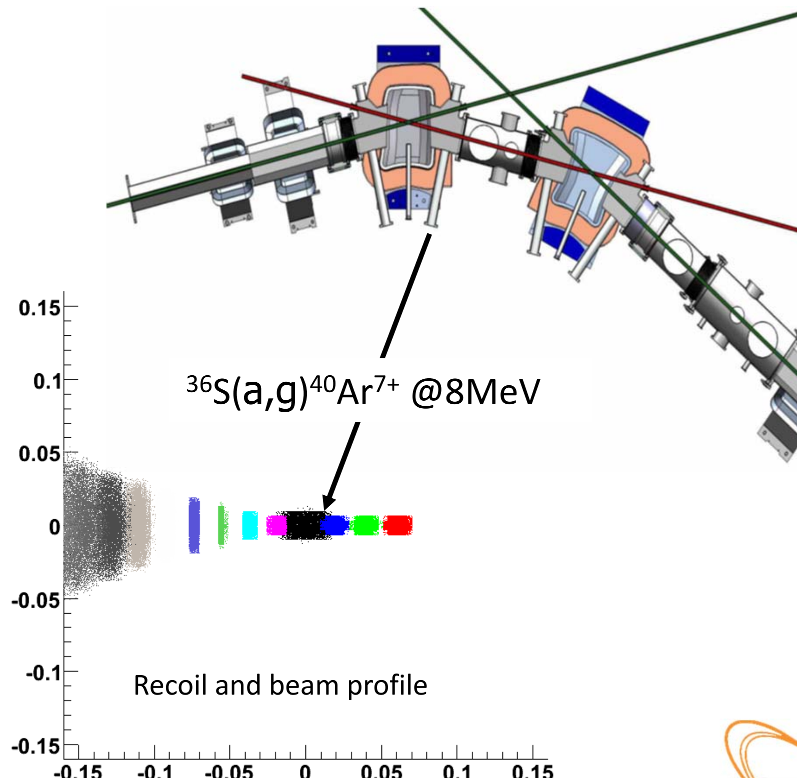
As long as calculations are made for worse acceptance scenario the ion optics solution is fully scalable

Useable (even if not realistic) quantities to optimize

Charge Selection Stage

$$x(z) = (x|x)x_0 + (x|a)a_0 + (x|\Delta E)\frac{\Delta E}{E_0} + (x|\Delta M)\frac{\Delta M}{M} + (x|q)\frac{\Delta Q}{Q_0}$$

- Multiple charge state after gas target
  - RMS total efficiency is charge state dependent
  - Selection of the most abundant one (~40%)
  - Clean rejection of the other beam/recoil charge state
- Charge selection can be a source of background:
  - $\Delta Q/Q_0$ can be large
    → selection in two steps



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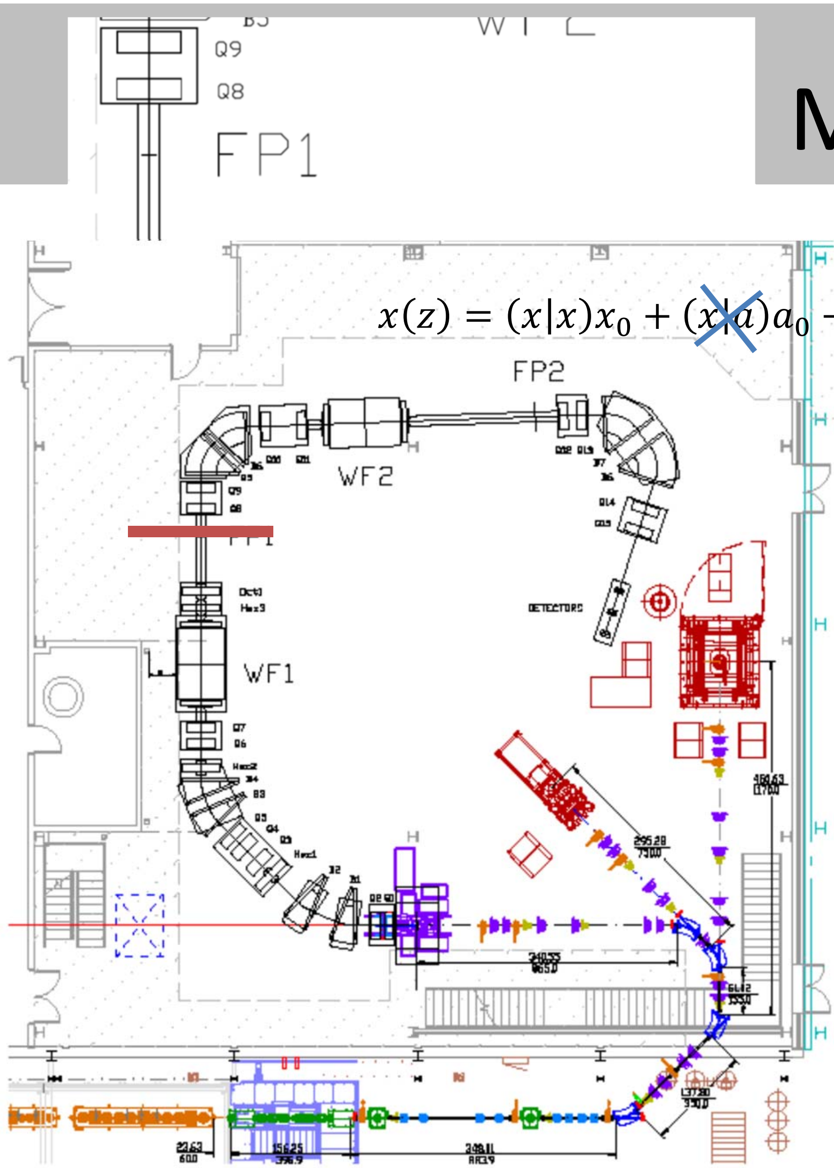
Mass Selection Stage



$$x(z) = (x|x)x_0 + \cancel{(x|a)}a_0 + \cancel{(x|E)}\frac{\Delta E}{E_0} + (x|q)\frac{\Delta Q}{Q_0} + (x|m)\frac{\Delta M}{M_0}$$

Maximize

First stage:
Resolving power: 750
Mass resolution: **520**

St. George

Acceptance:	Resolving power:
θ= ±40mrad ΔE= ±7.4% A<40 Bρ<=0.65 Tm	~120

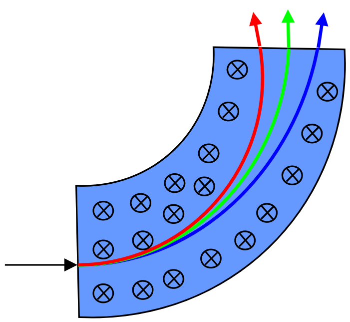
Scaling Optics Elements

The ion optic solution obtained for the design of a separator is usually provided for the worse case scenario

The largest angular and energy spread, the highest mass…

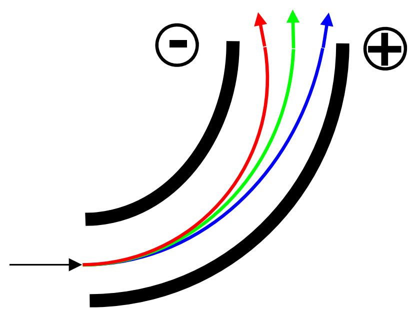
To extract the specific magnetic and electric field for a given reaction, the "tune" can be scaled.

In the St. George COSY file the variable QF is doing it for you as long as you provide new input in config.txt



magnetic dipole

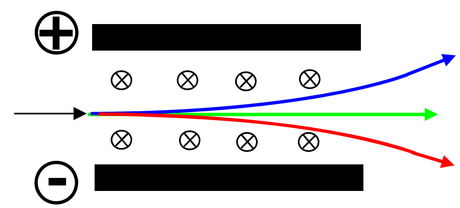
$$\frac{p}{q} = B\rho$$



electric dipole

$$\frac{2E}{q} = U\rho$$

U is the electric field



Wien filter

$$v_0 = \frac{U}{B}$$

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Drawings from D. Schürmann

ISNAP

Experiment Efficiency

- The efficiency of a measurement with a recoil separator is

$$\epsilon = \boldsymbol{Transmission} \ * \boldsymbol{charge\ state\ fraction} \ * \boldsymbol{detecton\ efficiency}$$

  - Goal transmission to 100% for a single charge state

COSY IN 8 DIMENSIONS

How to Calculate the Impact of E,M,Q Differences on Ion Optics

- OV 1 3 0
  - Gets you a calculation for the first 6 coordinates

1.867722	0.6545035	0.000000	0.000000	-0.4182102E-01	100000
-0.1830194E-01	0.5289980	0.000000	0.000000	0.5697954E-02	010000
0.000000	0.000000	10.71432	3.370834	0.000000	001000
0.000000	0.000000	-0.7206330	-0.1333854	0.000000	000100
0.000000	0.000000	0.000000	0.000000	1.000000	000010
0.9876789E-02	0.2585257E-01	0.000000	0.000000	3.063536	000001

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I S N A P

How to Calculate the Impact of E,M,Q Differences on Ion Optics

- OV 1 3 2
- RP ENERGY MASS*PARA(1) CHARGE*PARA(2)
  - Gets you a calculation for the first 8 coordinates

1.867722	0.6545035	0.000000	0.000000	-0.4182102E-01	10000000
-0.1830194E-01	0.5289980	0.000000	0.000000	0.5697954E-02	01000000
0.000000	0.000000	10.71432	3.370834	0.000000	00100000
0.000000	0.000000	-0.7206330	-0.1333854	0.000000	00010000
0.000000	0.000000	0.000000	0.000000	1.000000	00001000
0.9876789E-02	0.2585257E-01	0.000000	0.000000	3.063536	00000100
-0.5240240	-0.2233728	0.000000	0.000000	-3.480441	00000010
0.5141472	0.1975202	0.000000	0.000000	0.4169052	00000001

How to Calculate the Impact of E,M,Q Differences on Ion Optics

1.867722	0.6545035	0.000000	0.000000	-0.4182102E-01	10000000
-0.1830194E-01	0.5289980	0.000000	0.000000	0.5697954E-02	01000000
0.000000	0.000000	10.71432	3.370834	0.000000	00100000
0.000000	0.000000	-0.7206330	-0.1333854	0.000000	00010000
0.000000	0.000000	0.000000	0.000000	1.000000	00001000
0.9876789E-02	0.2585257E-01	0.000000	0.000000	3.063536	00000100
-0.5240240	-0.2233728	0.000000	0.000000	-3.480441	00000010
0.5141472	0.1975202	0.000000	0.000000	0.4169052	00000001

- Five columns because the energy/mass and charge state of the particles are assumed to not change as they move through the system