Making an Exotic Beam with MARS : Part 1

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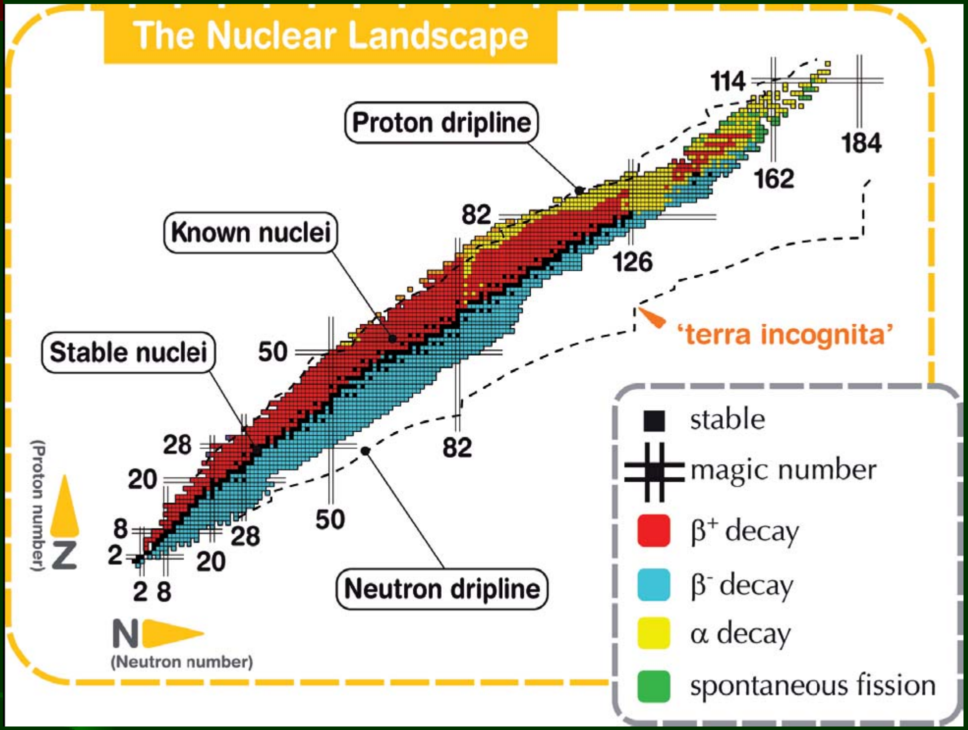
Overview

- Motivation: Why do we need to "make" an exotic beam?
- In-flight Production of exotic beams
  - Reaction Mechanisms
  - Why we need MARS?
- Review of charged particle motion in E and fields.
  - Concept of Magnetic Rigidity or "$B\rho$".
  - Concept of Velocity Filter → $v = E/B$.
- Particle Identification at the Focal Plane
  - Energy Loss in Materials – Bethe – Bloch Equation
  - Final Selection by the Slits
- Conclusion
- Example: Separation of ^{26}Si (Alex Spiridon)
- What we do for ^{20}Na (Alex Spiridon) ?

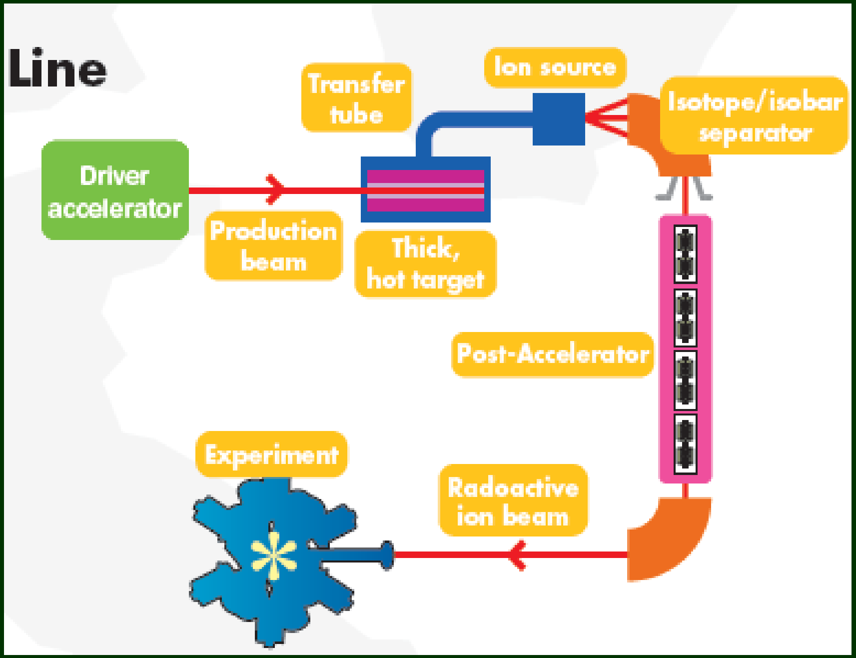
Motivation: Exotic Beam Studies



Must *MAKE* exotic beams via nuclear reactions!

- Would like to study exotic (radioactive, but particle stable) nuclei away from stability (Terra incognita regions).
- Most nuclear astrophysics processes that form heavy elements occur in reactions with exotic nuclei.
- Many exotic nuclei have short $T_{½}$ (less than 1 day), can not dig them out of the ground, can not make targets with them.

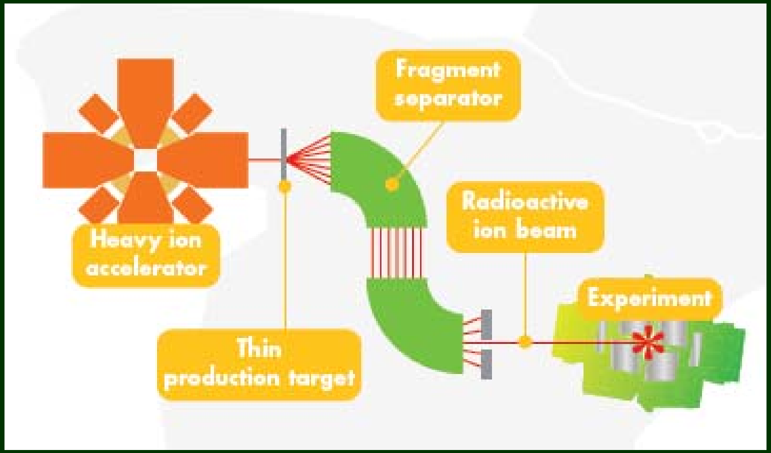
Methods of Exotic Beam Production (1)



ISOL – Isotope Separation On-Line

- Stop a light beam in a "thick" target, make exotic nuclei inside target.
- Separate exotic nuclei with chemistry – *limits beam types*
- Reaccelerate nuclei with a post-accelerator to experiments
- TAMU will use technique similar to this – (upgrade 2011).

Methods of Exotic Beam Production (2)

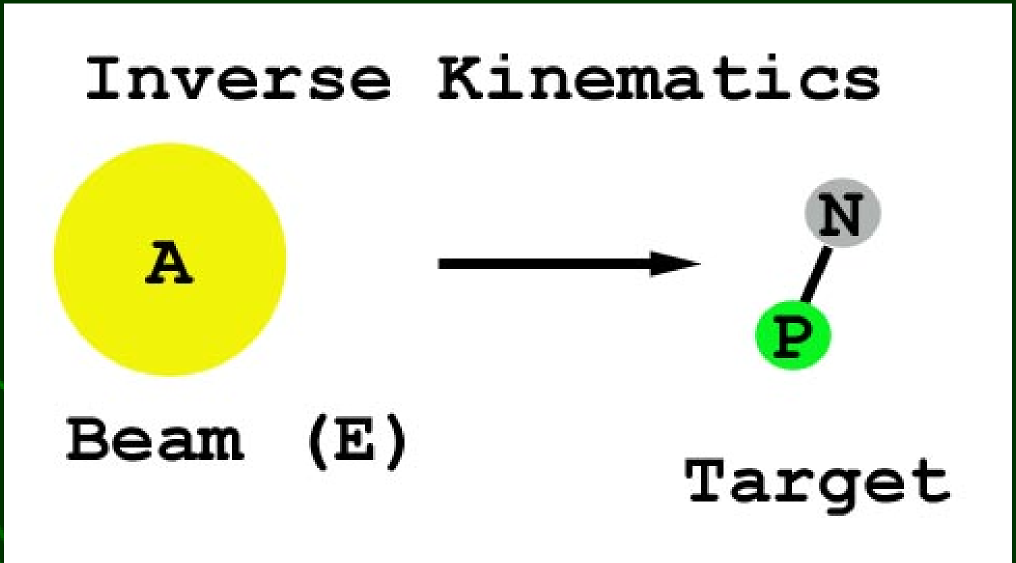


"In-flight" Technique – *MARS and others*

- Heavy-ion beam on a thin target of light nuclei, *e.g. H, He, Be, etc.* (Inverse Kinematics)
- In principle, can produce a beam of any isotope.
- Limitations:
  - Cross sections – decrease as you go further from stability.
  - Must work at high energy due to negative Q-values (E > 20 MeV/u)
  - Beams are often *not pure*! Must use *tricks* to obtain pure beam.

Inverse Kinematics

- Forward kinematics – light-ion beam on heavy mass target. *Most stable beam experiments done this way.*
- Inverse kinematics – heavy-ion beam on light mass target.
  - Get "forward focusing" of reaction products due to momentum conservation.
  - Heavy-ion product keeps most of the kinetic energy.



Reaction Mechanisms

- Different reaction types produce a nucleus of interest at different final energies.
- Use reaction-type that maximizes production of the exotic nucleus!
  - 1. *Transfer reaction* – Nucleon is transferred directly from target to beam or vise-versa. $E_{final} = E_{initial} + Q$.
  - *2. Fusion – Evaporation* – Form a “compound nucleus”, product “evaporates” nucleons as it de-excites → $v_{final} = v_{cm}$.
  - 3. Projectile Fragmentation (> 30 MeV/u) – nucleons “shaved” off of heavy-ion projectile → $v_{final} = v_{projectile}$.

Why do we need MARS?

- Can not pick and choose nuclei produced; can only choose initial reaction of beam + target.
- The most exotic nuclei (the furthest from stability) are often produced at the lowest rate → produce nuclei closer to stability at higher rates.
- Need a way to separate reaction products *we do want* from those *we don't want* and then make that into a beam → MARS!

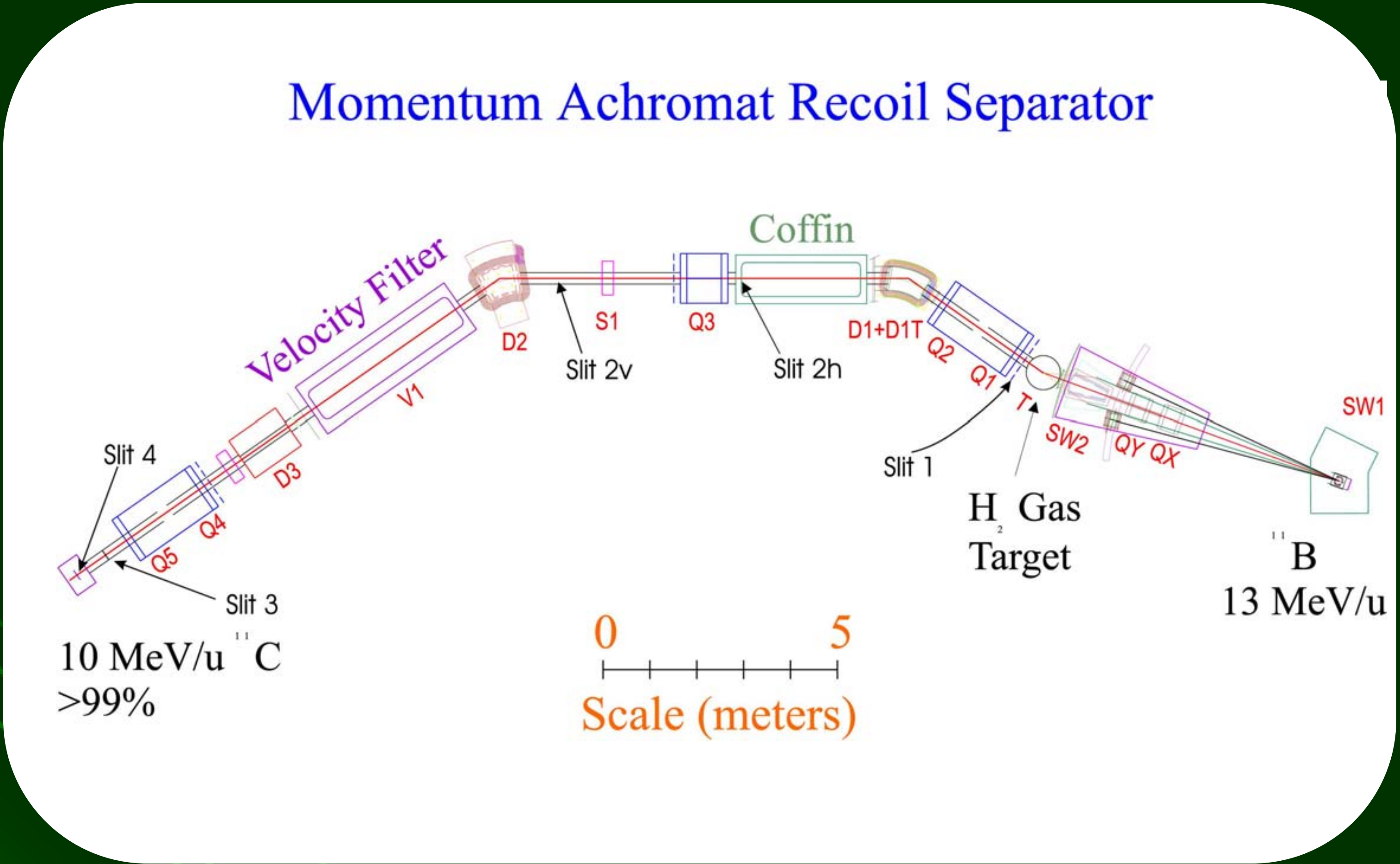
MARS

- MARS → *Momentum Achromat Recoil Separator*.
- Separates Reaction Products in two ways:
  - *Magnetic Rigidity* Selection – ("Brho")
  - *Velocity* Selection – (Velocity or "Wien" Filter)
- Block out unwanted ions by closing position "slits" along the way.

R.E. Tribble et al. – Nucl. Instr. and Meth. A285, Pg. 441 (1989).

R.E. Tribble et al. – Nucl. Instr. and Meth. B56/57, Pg. 956 (1991).

Overview of MARS



- More details in talk by Alex S.

Magnetic Rigidity - Basics

- A charged particle (ion) in a magnetic field moves in a circle according to the Lorentz force.

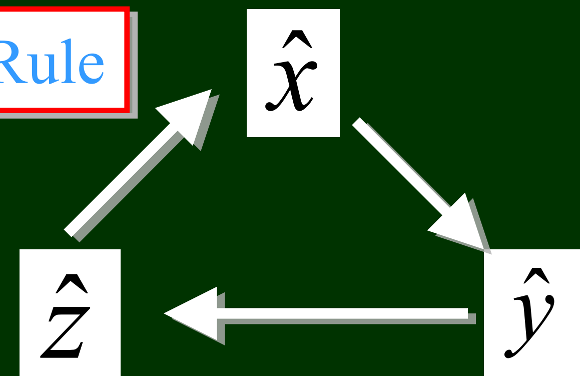
$$F_{centripetal} = F_{Magnetic}$$

$$\frac{Mv^2}{\rho} = q(\vec{v} \times \vec{B})$$

$$\frac{Mv^2}{\rho} = qvB$$

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

"Right-Hand" Rule

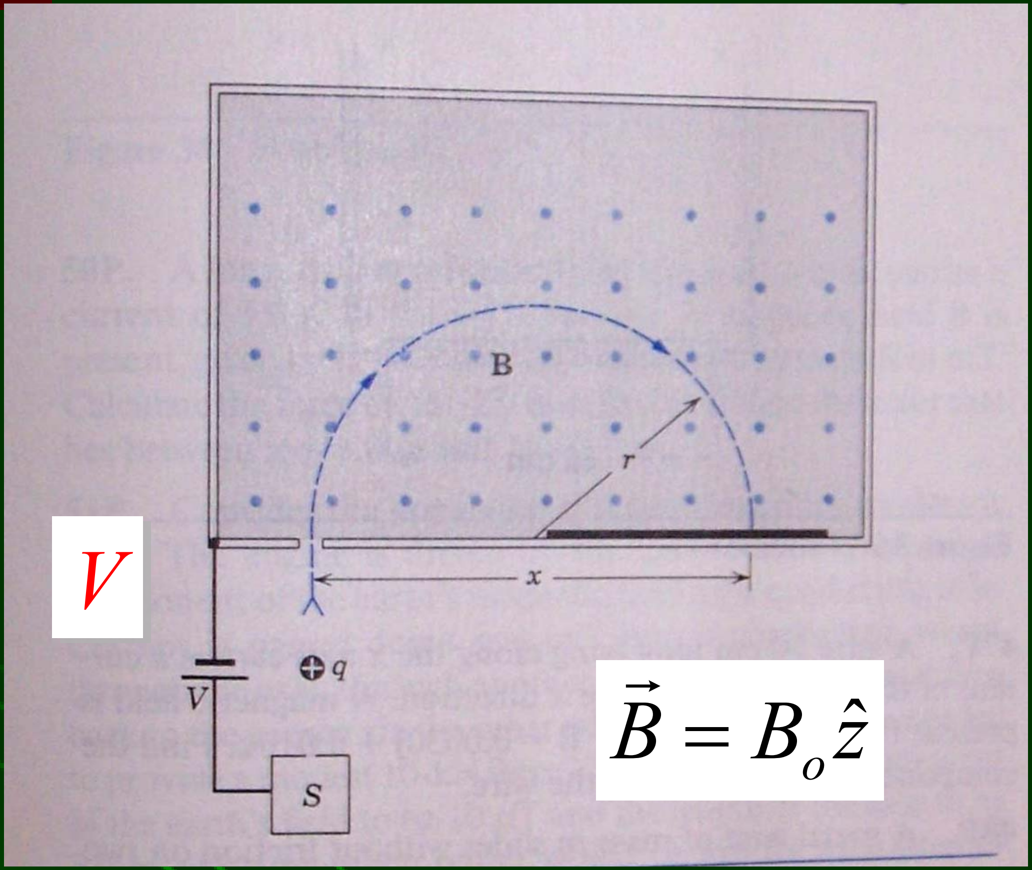


← Definition of Magnetic Rigidity!

***For a magnetic separator, *Bρ* = constant – provides selection in p/q!**

*** Magnetic Fields (static) do no Work! (ΔE = 0)**

Example – "Simple" Mass Separator



V

$$\vec{B} = B_o \hat{z}$$

(1) $$\frac{mv}{q} = B\rho$$

$$\frac{1}{2}mv^2 = qV$$

(2) $$v^2 = \frac{2qV}{m}$$

(3) $$x = 2\rho$$

Mass separation condition: this case

$$\Rightarrow \sqrt{2V\frac{m}{q}} = B\rho$$

Halliday and Resnick, *Fundamentals of Physics 3rd edition (1988)*

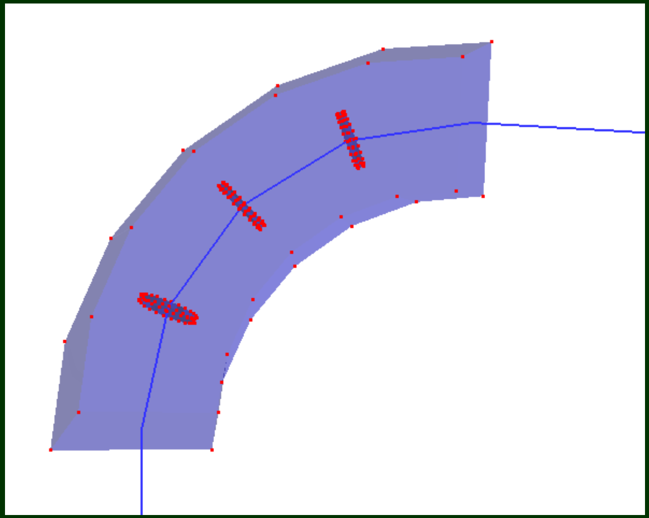
$B\rho$ – constant B

$$\Rightarrow \sqrt{2V\frac{m}{q}} = B\rho$$

$$\frac{Mv^2}{\rho} = q(\vec{v} \times \vec{B})$$

- Particle Mass m and charge $+q$ curves to right (+x direction) with radius ρ.
- Particle Mass *2m and* charge $+q$ curves to right (+x direction) with radius $\rho\sqrt{2}$. Separated in position!
- Particles Mass *2m* and charge $+2q$ (and nm and $+nq$) curve to right with same radius $\rho \rightarrow$ can not be separated in position!

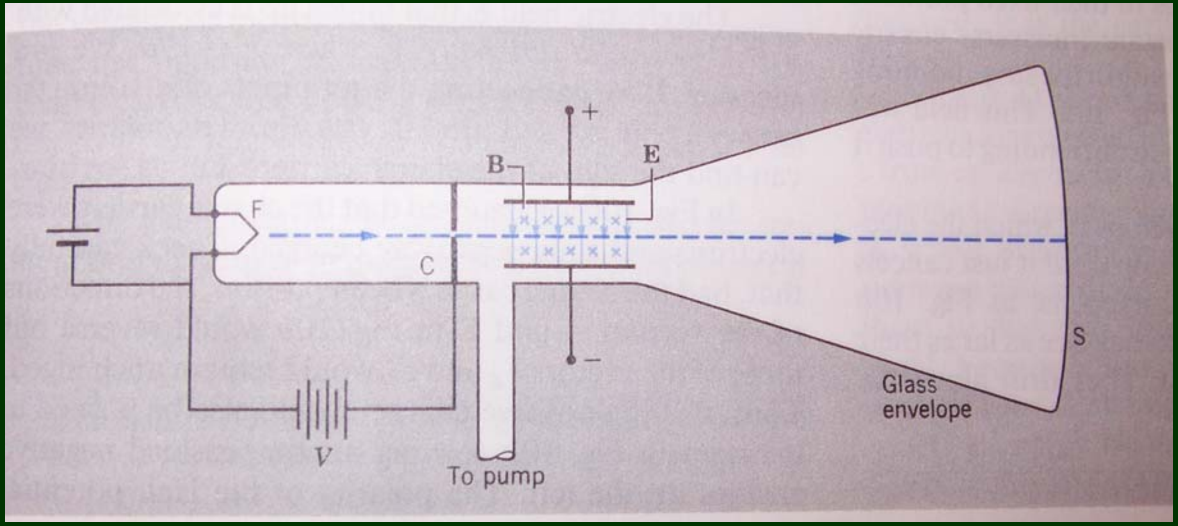
$B\rho$ – constant B and ρ



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

- Magnet has fixed ρ and *opening gap*.
- Once B is set, only particles with proper mv/q (± *opening gap*) get through magnet, others hit walls (bending radius too large or too small).
- Particles with higher mv/q – more "rigid"
- Particles with lower mv/q – less "rigid"
- Adjusting B field for reaction product of interest in mv/q allows it to pass, others can be blocked with slits, etc.

Velocity ("Wien") Filter



$$\vec{E}(-\hat{y}) \perp \vec{B}(\hat{x})$$

$$\Sigma\vec{F} = 0 \Rightarrow qE = qvB$$

$$v = \frac{E}{B}$$

- For a particle moving along the z-axis, E-field deflects downward (- y) and B-field (+ x) deflects upward (+y).
- Particle must be traveling at proper velocity to remain undeflected (forces balance).
- How does this help isotope selection ?

Halliday and Resnick, *Fundamentals of Physics 3rd edition (1988)*

Change "y" position as q/m

- Suppose only *E-field* :

$$\vec{E} = qE_0(-\hat{y})$$

$$\vec{F} = m\vec{a} = q\vec{E}$$

$$\vec{a} = \frac{qE_0}{m}(-\hat{y})$$

- Equations of Motion:

$$Z = vt$$

$$y = \frac{1}{2}\vec{a}t^2$$

$$y = \frac{qEZ^2}{2mv^2}(-\hat{y})$$

Change "y" position as q/m

- Now add in $v = E_0/B_0$:

Amount of Deflection →

$$y = \frac{q}{m}\frac{B_0^{\,2} Z^2}{2E_0}$$

If $v < E_0/B_0$ → $\vec{F}_{\vec{E}} > \vec{F}_{\vec{B}} \Rightarrow -\hat{y}$ deflection

If $v > E_0/B_0$ → $\vec{F}_{\vec{E}} < \vec{F}_{\vec{B}} \Rightarrow +\hat{y}$ deflection

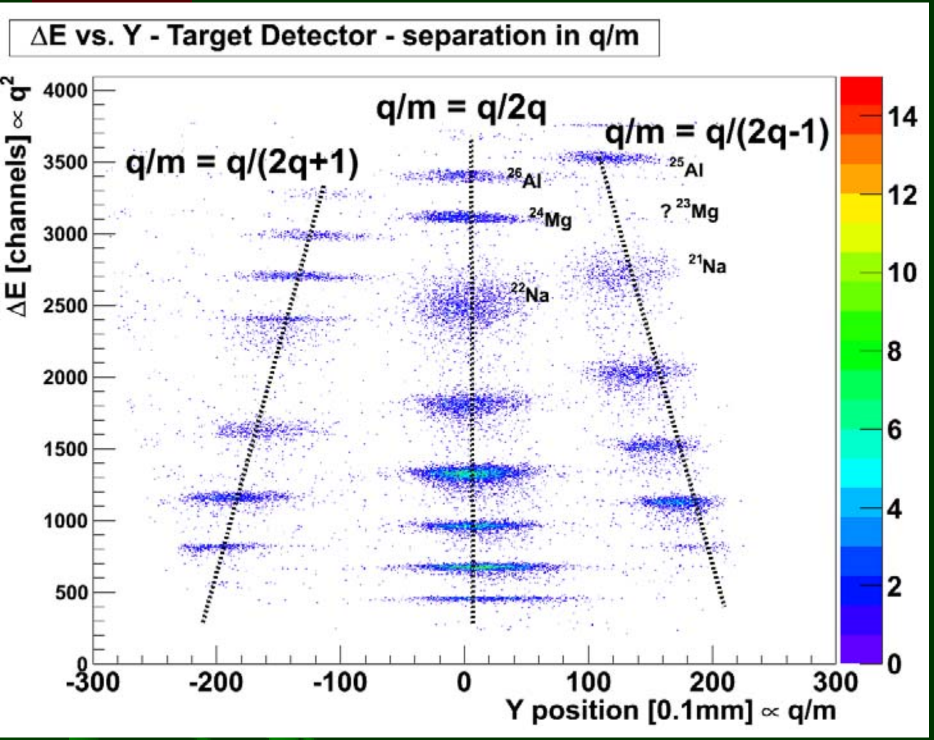
- Ions with different q/m are separated in "y"!
- Allows Particle Identification (PID) in focal plane (with energy loss in detector).

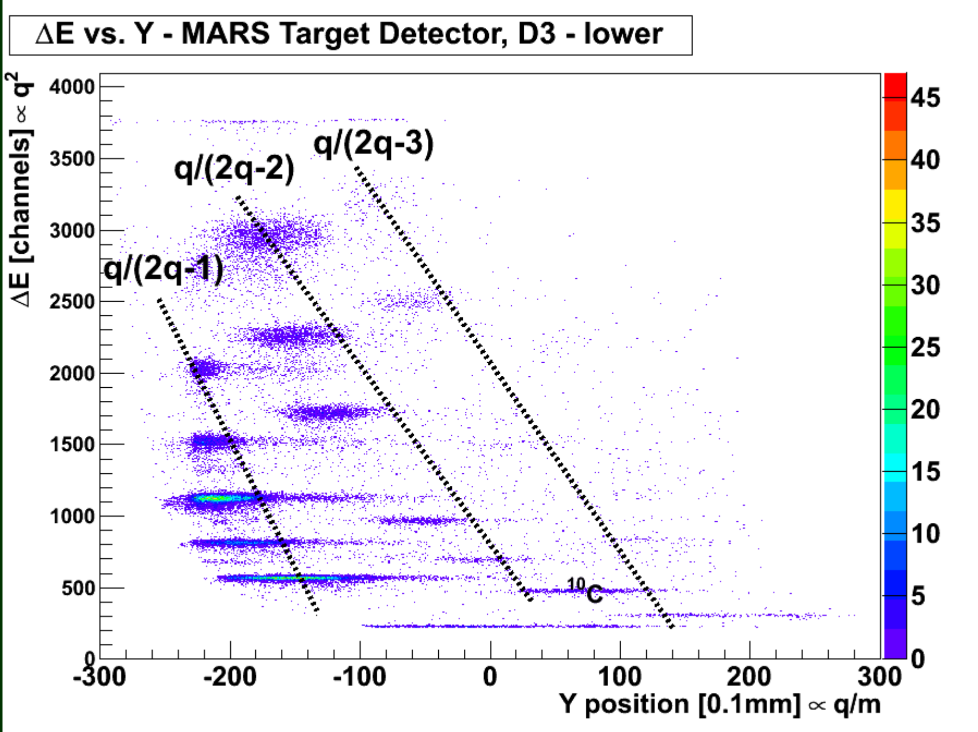
Energy Loss in Target Detector

$$-\frac{dE}{dx} \propto \frac{q^2}{v^2}$$

- Bethe-Bloch formula – energy loss in material (silicon detector) proportional to square of (q/v) – independent of mass.
- Energy-loss in materials can be calculated with programs (e.g. SRIM/TRIM, LISE)
- If "v" is similar for all ions after velocity filter, then $-dE/dx \rightarrow q^2$.

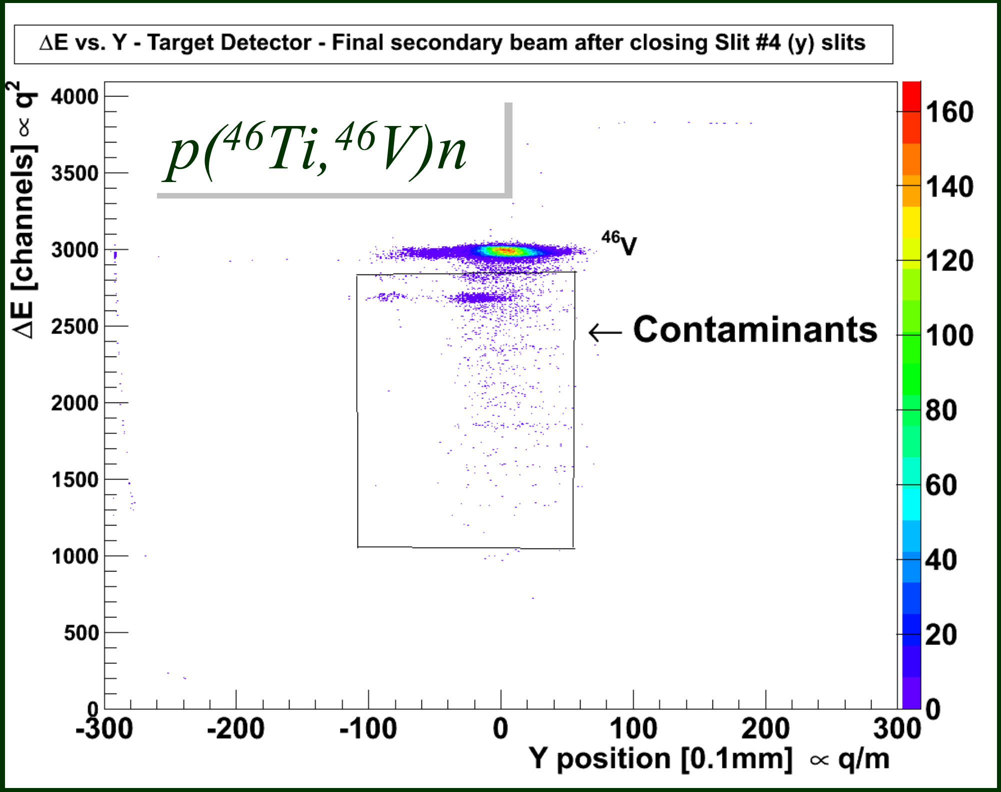
Particle Identification – $^{24}Mg + ^{9}Be$





- Particles separated on "y" axis by energy loss.
- Particles separated on "x" axis by position in "y".
- For different q/m, particles are in different hyperbolas.

Final Selection by the Slits



- Center ion of interest (secondary beam) in "y" by matching *Bρ* of D3 to *velocity v* selected by velocity filter – See Alex's talk.
- Block out other ions by closing vertical ("*y*") slits in front of target detector.

Conclusion

- Can make an exotic beam to study nuclei far from stability with reactions in Inverse Kinematics
- Can make a secondary beam of an isotope of interest by separation in p/q (magnetic rigidity) and q/m (velocity filter).
- Limitations :
  - Must be able to conduct experiments with higher energy beams or degrade energy of beam to desired energy.
  - Beams with very similar or equal $B\rho$ can not be separated in position (need energy loss technique).

Questions ?