INSTITUTE FOR STRUCTURE AND NUCLEAR ASTROPHYSICS

Recoil Separators for Nuclear Astrophysics

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SECAR

Radiative Captures Are Important …

Focus on (p,γ) and (α,γ) with A<65 in inverse kinematics
Stellar Reaction rate mostly dominated by resonances

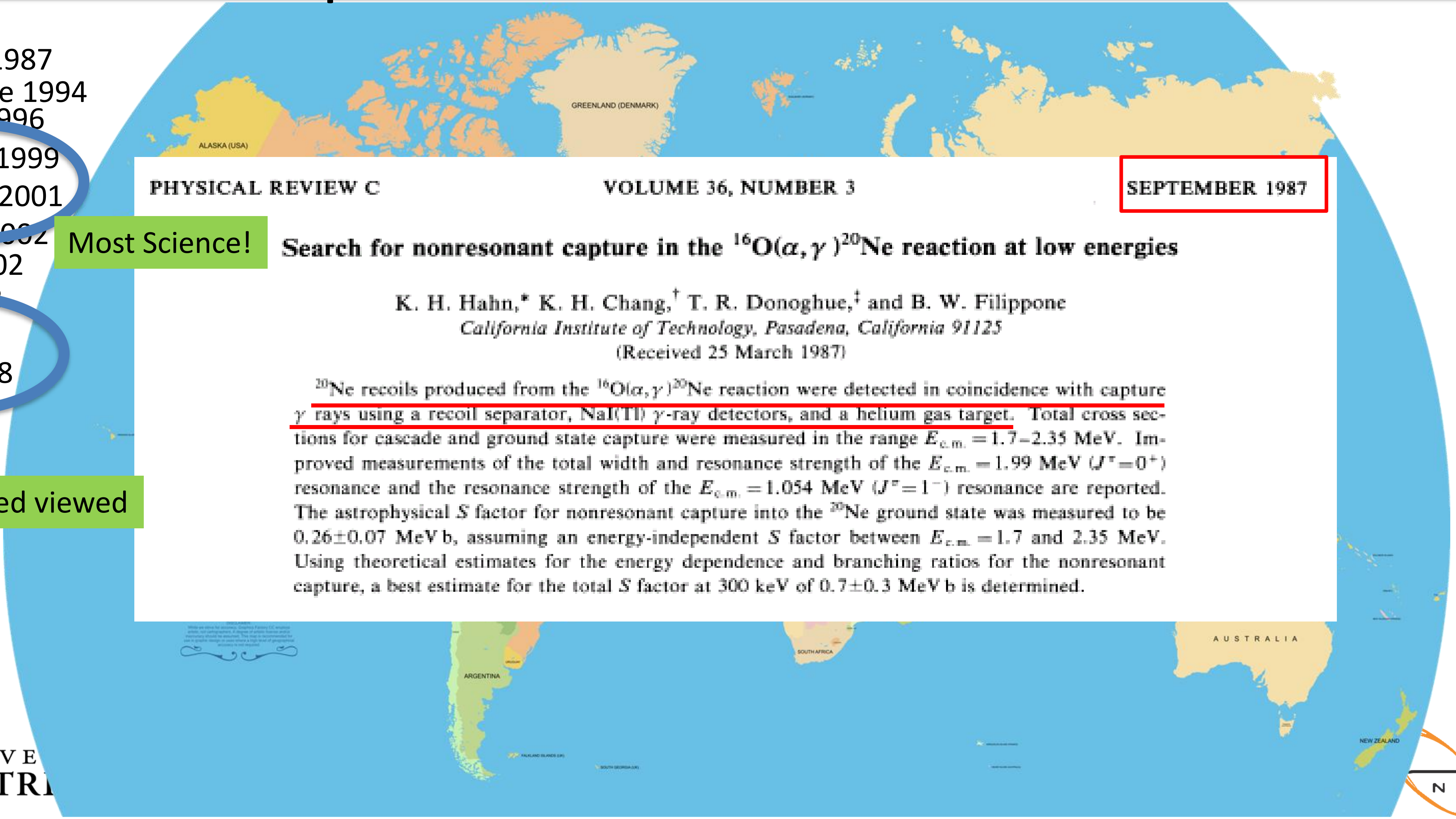
Ignoring higher masses and the highly critical (n, γ) is a choice not a statement!
"Storage" rings have emerged as a very competitive way to study those reactions and much more!
➔Talk by Carlo Bruno "Storage rings for nuclear astrophysics"

Recoil Separator Dedicated to Charge Particle Radiative Capture

Caltech 1987
Oak Ridge 1994
Naples 1996
TRIUMF 1999
Bochum 2001
Kyushu 2002
Tokyo 2002
LLN 2003
ND 2008
FRIB 2018

Most Science!

Biased viewed



PHYSICAL REVIEW C VOLUME 36, NUMBER 3 SEPTEMBER 1987

Search for nonresonant capture in the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction at low energies

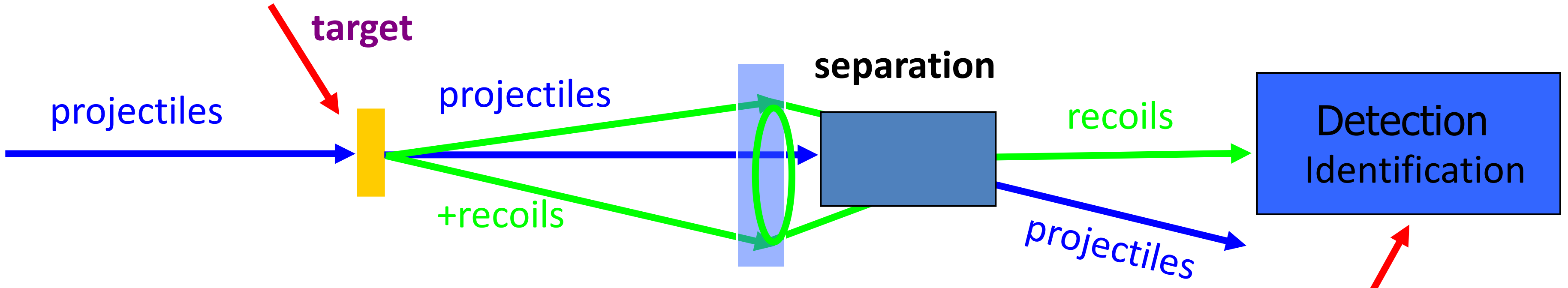
K. H. Hahn,* K. H. Chang,† T. R. Donoghue,‡ and B. W. Filippone
California Institute of Technology, Pasadena, California 91125
(Received 25 March 1987)

^{20}Ne recoils produced from the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction were detected in coincidence with capture γ rays using a recoil separator, NaI(Tl) γ-ray detectors, and a helium gas target. Total cross sections for cascade and ground state capture were measured in the range $E_{c.m.}=1.7$–2.35 MeV. Improved measurements of the total width and resonance strength of the $E_{c.m.}=1.99$ MeV ($J^{\pi}=0^{+}$) resonance and the resonance strength of the $E_{c.m.}=1.054$ MeV ($J^{\pi}=1^{-}$) resonance are reported. The astrophysical S factor for nonresonant capture into the ^{20}Ne ground state was measured to be 0.26 ± 0.07 MeV b, assuming an energy-independent S factor between $E_{c.m.}=1.7$ and 2.35 MeV. Using theoretical estimates for the energy dependence and branching ratios for the nonresonant capture, a best estimate for the total S factor at 300 keV of 0.7 ± 0.3 MeV b is determined.

Recoil Separator Principles

High efficiency
Reduced background for
γ spectroscopy

γ detector



focusing and charge selection

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

$$\vec{p}_{recoil} = \vec{p}_{beam} \pm \vec{p}_\gamma$$

Velocity/energy selection

Particle Identification Detector

If angular distribution is unknown → Separator must accept 100% of the angular opening for absolute cross section determination

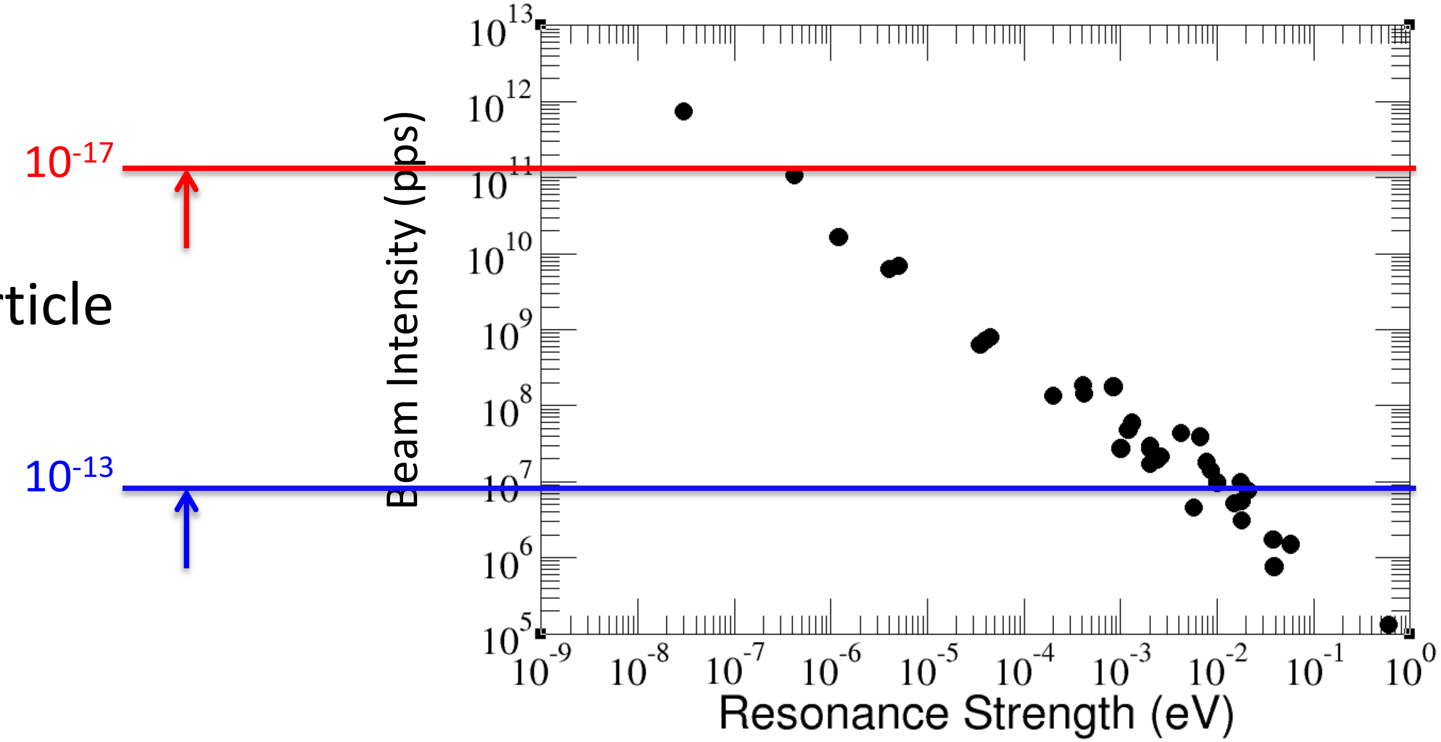
Drawing adapted from D. Schürmann

The Required Performances are Determined by Science

Aiming for a beam suppression Separator+ Particle Identification of less than 1 background event

This is defined as, one beam particle (mis-)interpreted as a recoil of interest per 10^{+x} beam particle on target

Typical astrophysical resonances
Minimum beam intensity for a 2-week measurement



St. George and SECAR: Experimental Goals

- St. George is designed to study (α,γ) reaction in inverse kinematics induced by “high-intensity” (10^{13} pps) stable beams
  - $\pm 40 mrad$ and $\frac{\Delta E}{E} < 7.5\%$ with 100% transmission of 1 charge state

- SECAR is designed to study (p,γ) and (α,γ) in inverse kinematics induced by beams from FRIB ReA3 accelerator (at most ~10^9 pps).
  - $\pm 25 mrad$ and $\frac{\Delta E}{E} < 3\%$ with 100% transmission of 1 charge state

Choose Your Own Adventure

- If you want to discuss some (ion) optics and address fewer details about recoil separators: **vote 1**
- If you want to skip ion optics discussion and address current recoil separator design and capabilities: **vote 2**

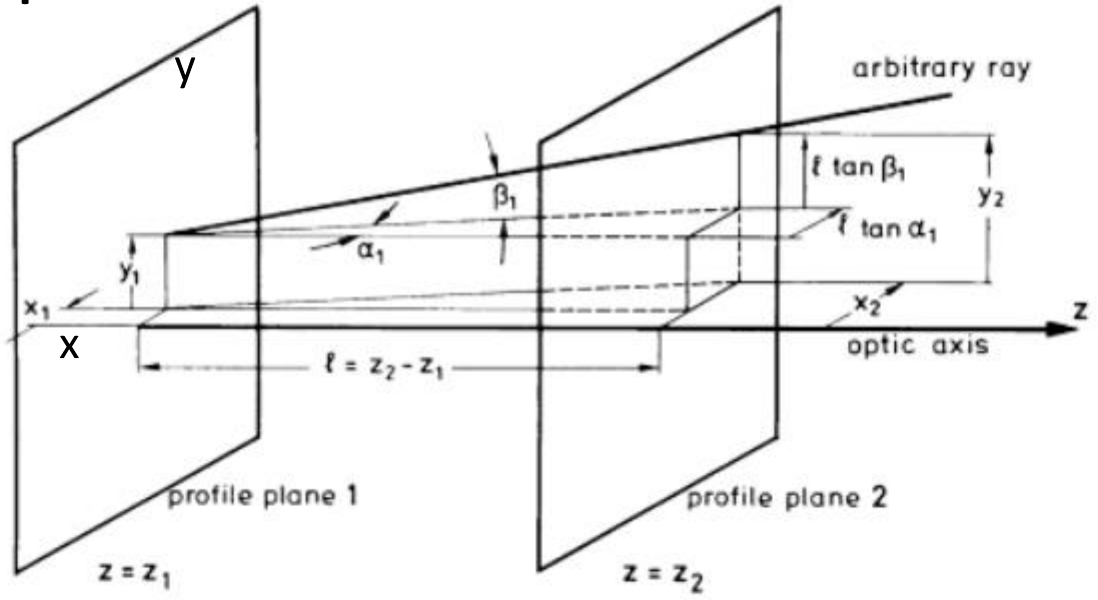
Cheat sheet: if vote 2, skip to slide 20

Straight Rays

- Z axis = Optics axis of a bundle of rays
- Deviation of rays from bundle
- Angular dependence

$$x(z_2) = x_1 + (z_2 - z_1)\tan(\alpha_1)$$
$$y(z_2) = y_1 + (z_2 - z_1)\tan(\beta_1)$$

$$\tan(\alpha(z)) = \tan(\alpha_1)$$
$$\tan(\beta(z)) = \tan(\beta_1)$$



Optics of Charged Particles
By Hermann Wollnik

Straight Rays

- Z axis = Optics axis of a bundle of rays
- Deviation of rays from bundle
- Angular dependence

$$x(z_2) = x_1 + (z_2 - z_1)\tan(\alpha_1) \qquad \tan(\alpha(z)) = \tan(\alpha_1)$$

$$y(z_2) = y_1 + (z_2 - z_1)\tan(\beta_1) \qquad \tan(\beta(z)) = \tan(\beta_1)$$

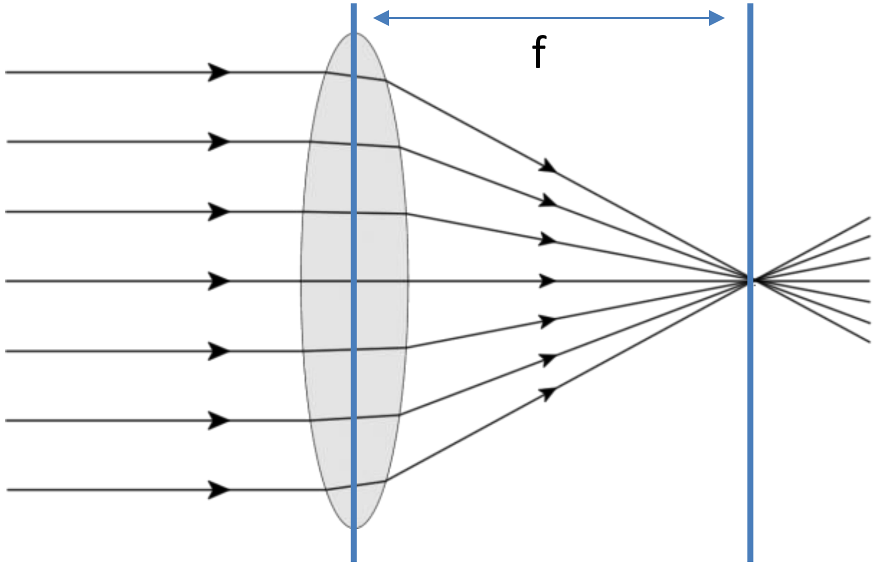
$$\begin{pmatrix} x_2 \\ \tan(\alpha_2) \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \tan(\alpha_1) \end{pmatrix}$$

$$\begin{pmatrix} y_2 \\ \tan(\beta_2) \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y_1 \\ \tan(\beta_1) \end{pmatrix}$$

Transfer matrix from one profile plane to another

In rotationally symmetric system
Both matrix are identical…

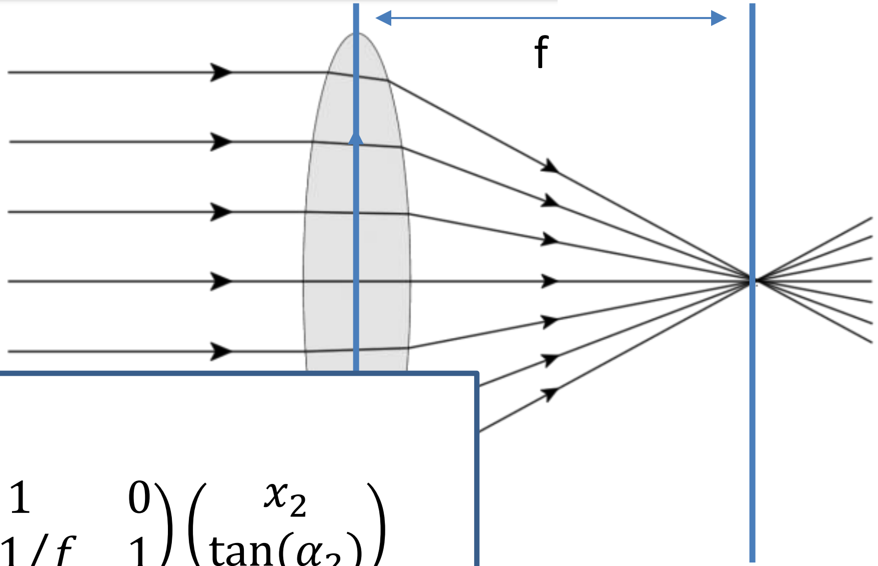
What is a Focal Point?



Rays that enter the system parallel to the optical axis are focused such that they pass through the "rear focal" point.

Any ray that passes through it will emerge from the system parallel to the optical axis.

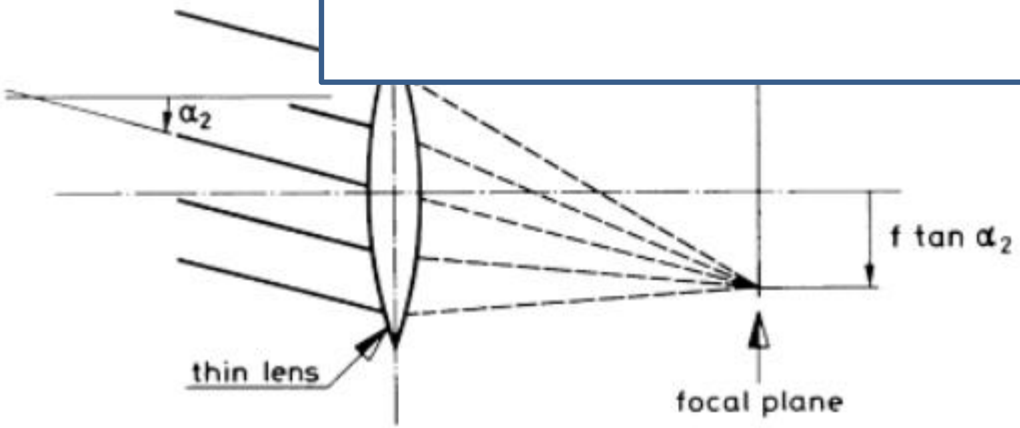
"Thin Lens"



- transfer from 2 to 3

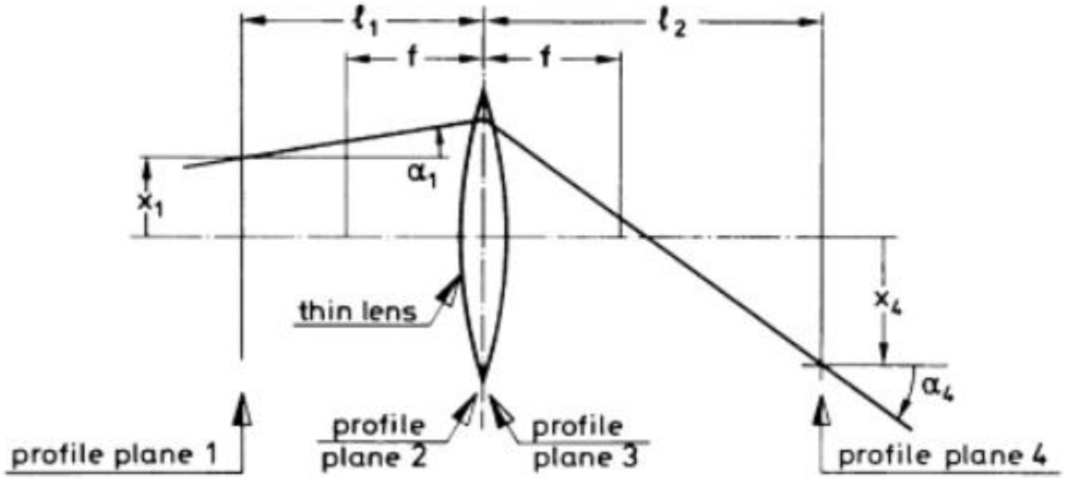
$$x_3 = x_2$$
$$\tan(\alpha_3) = -x_2/f$$

$$\begin{pmatrix} x_3 \\ \tan(\alpha_3) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} x_2 \\ \tan(\alpha_2) \end{pmatrix}$$



$$x_3 = x_2$$
$$\tan(\alpha_3) = \tan(\alpha_2) - x_2/f$$

Transport through…



$$\begin{pmatrix} x_4 \\ \tan(\alpha_4) \end{pmatrix} = \begin{pmatrix} 1 & l_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & l_1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \tan(\alpha_1) \end{pmatrix}$$

$$\begin{pmatrix} x_4 \\ \tan(\alpha_4) \end{pmatrix} = \begin{pmatrix} 1-(l_2/f) & l_1+l_2-(l_1 l_2/f) \\ -1/f & 1-(l_1/f) \end{pmatrix} \begin{pmatrix} x_1 \\ \tan(\alpha_1) \end{pmatrix}$$

How do we get a proper picture?

$$\begin{pmatrix} x_4 \\ \tan(\alpha_4) \end{pmatrix} = \begin{pmatrix} 1-(l_2/f) & l_1+l_2-(l_1l_2/f) \\ -1/f & 1-(l_1/f) \end{pmatrix} \begin{pmatrix} x_1 \\ \tan(\alpha_1) \end{pmatrix}$$

Independence of final ray position on initial angle

$$l_1 + l_2 - (l_1l_2/f) = 0$$
$$(1/l_1) + (1/l_2) = 1/f$$

Under that condition there is a *object-image* relation between profile planes 1 and 4

Additional Definitions

$$\begin{pmatrix} x_4 \\ \tan(\alpha_4) \end{pmatrix} = \begin{pmatrix} 1-(l_2/f) & 0 \\ -1/f & 1-(l_1/f) \end{pmatrix} \begin{pmatrix} x_1 \\ \tan(\alpha_1) \end{pmatrix}$$

$$\frac{x_4}{x_1} = M = 1 - \frac{l_2}{f} = (-\,l_2/l_1)$$

M is called the magnification

Notation change to allow for generalization

$$\begin{pmatrix} x(z) \\ \tan(\alpha(z)) \end{pmatrix} = \begin{pmatrix} (x_2|x_1) & (x_2|\tan(\alpha_1)) \\ (\tan(\alpha_1)|x_1)) & (\tan(\alpha_2)|\tan(\alpha_1)) \end{pmatrix} \begin{pmatrix} x_1 \\ \tan(\alpha_1) \end{pmatrix}$$

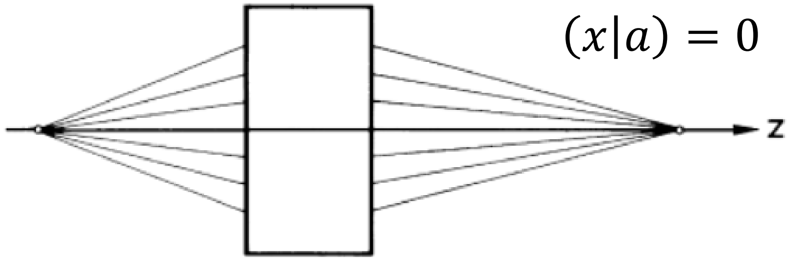
$$\begin{pmatrix} x(z) \\ a(z) \end{pmatrix} = \boxed{\begin{pmatrix} (x|x) & (x|a) \\ (a|x)) & (\mathrm{a}|a) \end{pmatrix}} \begin{pmatrix} x_1 \\ a_1 \end{pmatrix} \qquad \begin{matrix} a = v_x/c \simeq \tan(\alpha) \\ b = v_y/c \simeq \tan(\beta) \end{matrix}$$

Can be a simple drift or a very complex system.

Examples

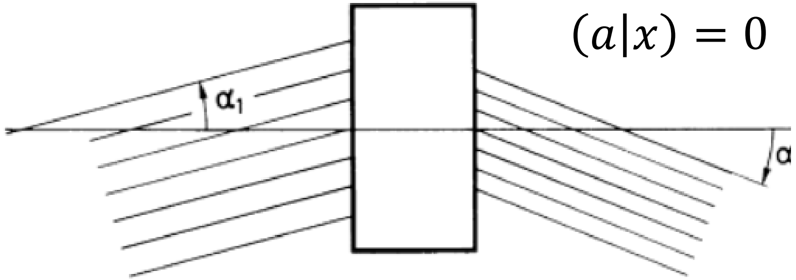
$$\begin{pmatrix} x(z) \\ a(z) \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) \\ (a|x)) & (\mathrm{a}|a) \end{pmatrix} \begin{pmatrix} x_1 \\ a_1 \end{pmatrix}$$

$(x|a) = 0$



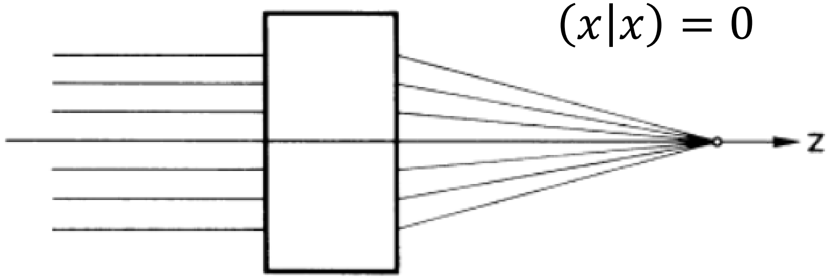
(a)

$(a|x) = 0$



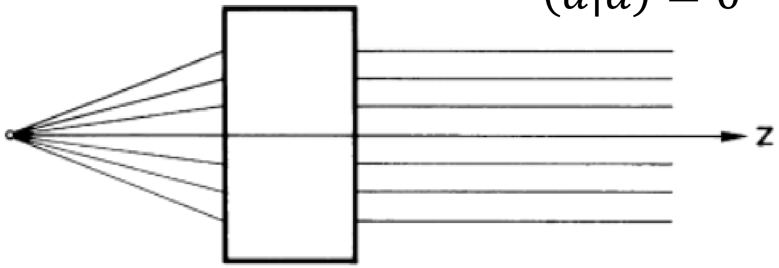
(b)

$(x|x) = 0$



(c)

$(a|a) = 0$



(d)

What constraints on which matrix element needs to explain the plots?

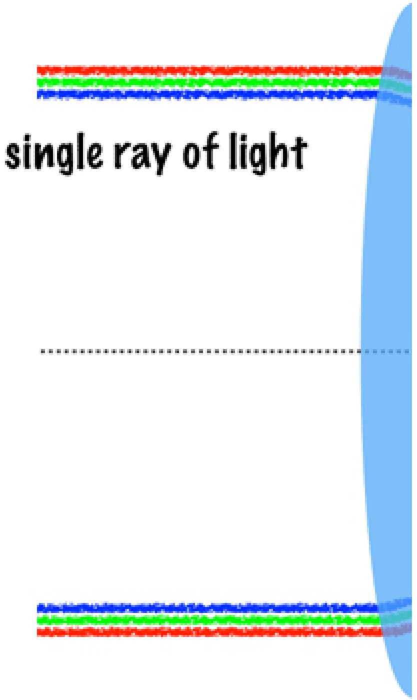
Optics of Charged Particles
By Hermann Wollnik

Charged Particle Optics

- Same idea
- $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
- In uniform magnetic fields charged particles have a circular motion
  - $mv^2/R = qvB$
  - $B\rho = p/q$ Magnetic Rigidity
- Equivalent for Electric field
  - $E\rho = 2K/q$ Electric Rigidity

Approximation

The Color Twist



d could represent any variable
They could be more
Actually, most transport code
Use at least 6 dimensions.

$$\begin{pmatrix} x(z) \\ a(z) \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) \\ (a|x)) & (\mathrm{a}|a) \end{pmatrix} \begin{pmatrix} x_1 \\ a_1 \end{pmatrix}$$

$$\begin{pmatrix} x(z) \\ a(z) \\ d(z) \end{pmatrix} = \begin{pmatrix} (x|x) & (x|a) & (x|d) \\ (a|x) & (a|a) & (a|d) \\ (d|x) & (d|a) & (d|d) \end{pmatrix} \begin{pmatrix} x_1 \\ a_1 \\ d_1 \end{pmatrix}$$

Design Philosophy:
Ion Optics Optimization Approach St. George and SECAR

Key Design parameters:

- Ratio: $\Delta M/M$ to reject e.g. $^{14}N(p,\gamma)^{15}O$ $\Delta M/M=1/15$
- Angular acceptance: Target effects to be included
- Momentum or energy acceptance

First order – Description of horizontal plane

$$x_1 = x_0(x|x) + \cancel{a_0(x|a)} + \cancel{\frac{\delta E}{E}(x|\delta E)} + \frac{\delta M}{M}(x|\delta m) + \cancel{\frac{\delta q}{q}(x|\delta q)}$$

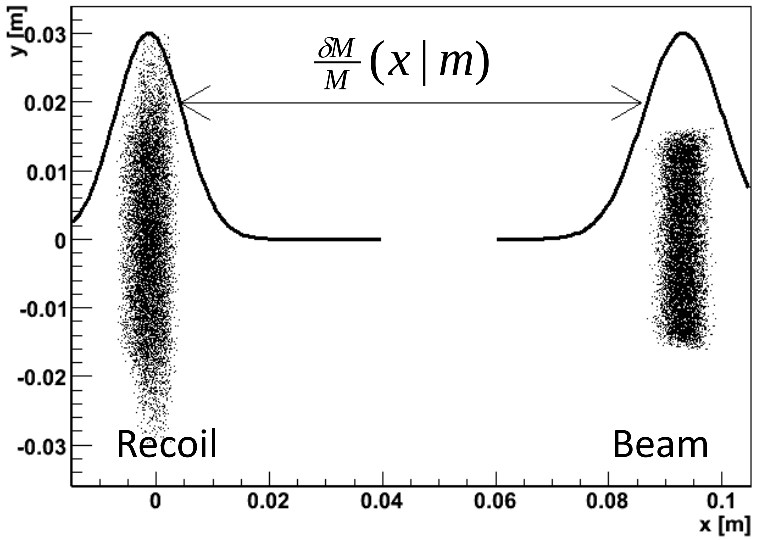
Magnification

=0 we want a focus

=0 we want an achromatic focus

Define Mass separation:

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



Minimum theoretical mass separation achieved when the two blobs touch: $\frac{\Delta M}{M}(x|\delta m) = 2x_0(x|x)$

Good on paper but in real life???
For SECAR, expectation of $\Delta M/M = 1/65$
To achieve this for a theoretical separation of $\sim 10^{-17}$
Assuming Gaussian shape: $\frac{\Delta M}{M} \simeq \frac{1}{800}$ is needed

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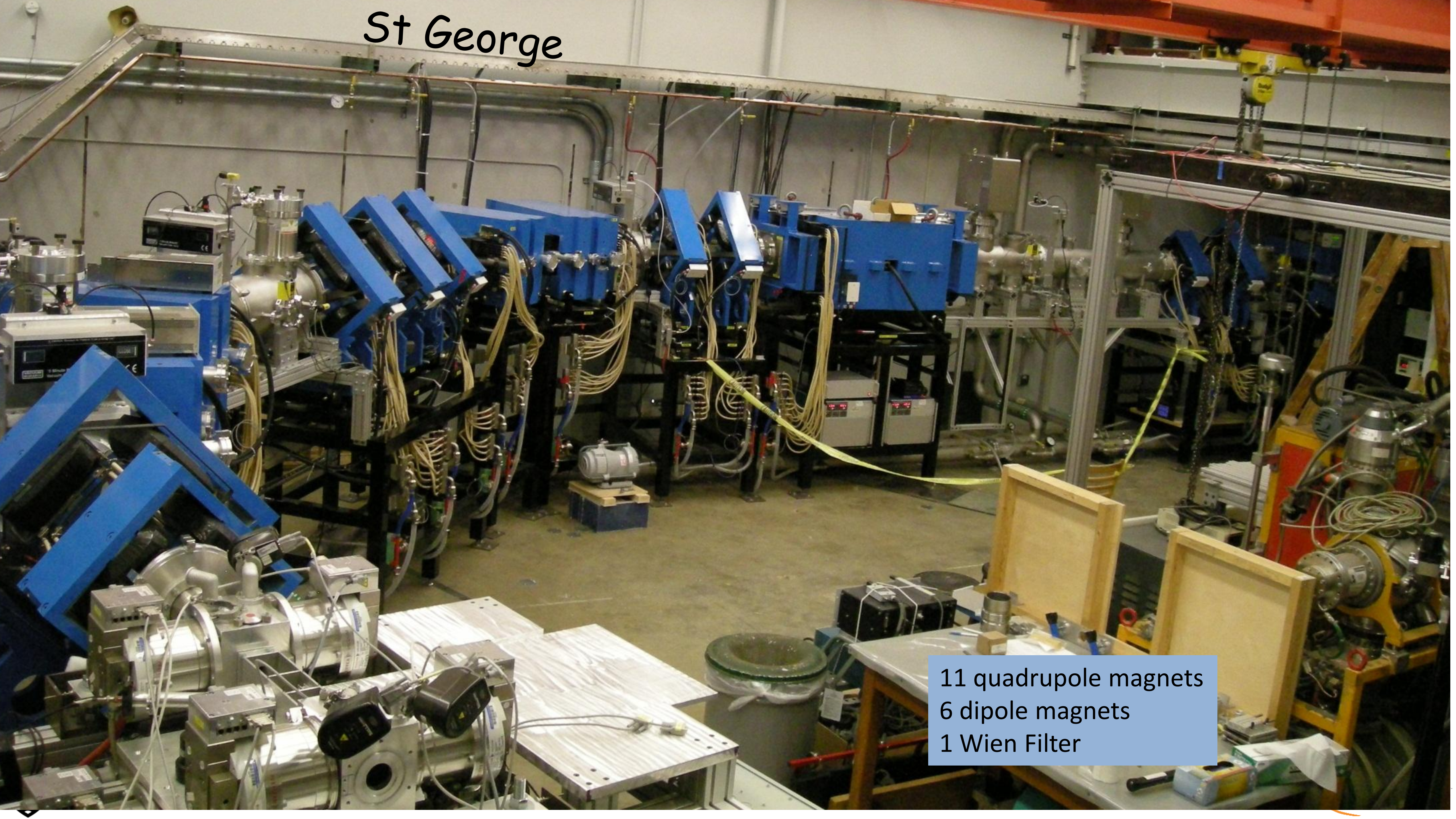
I S N A P

Separator Design Choices: St. George and SECAR

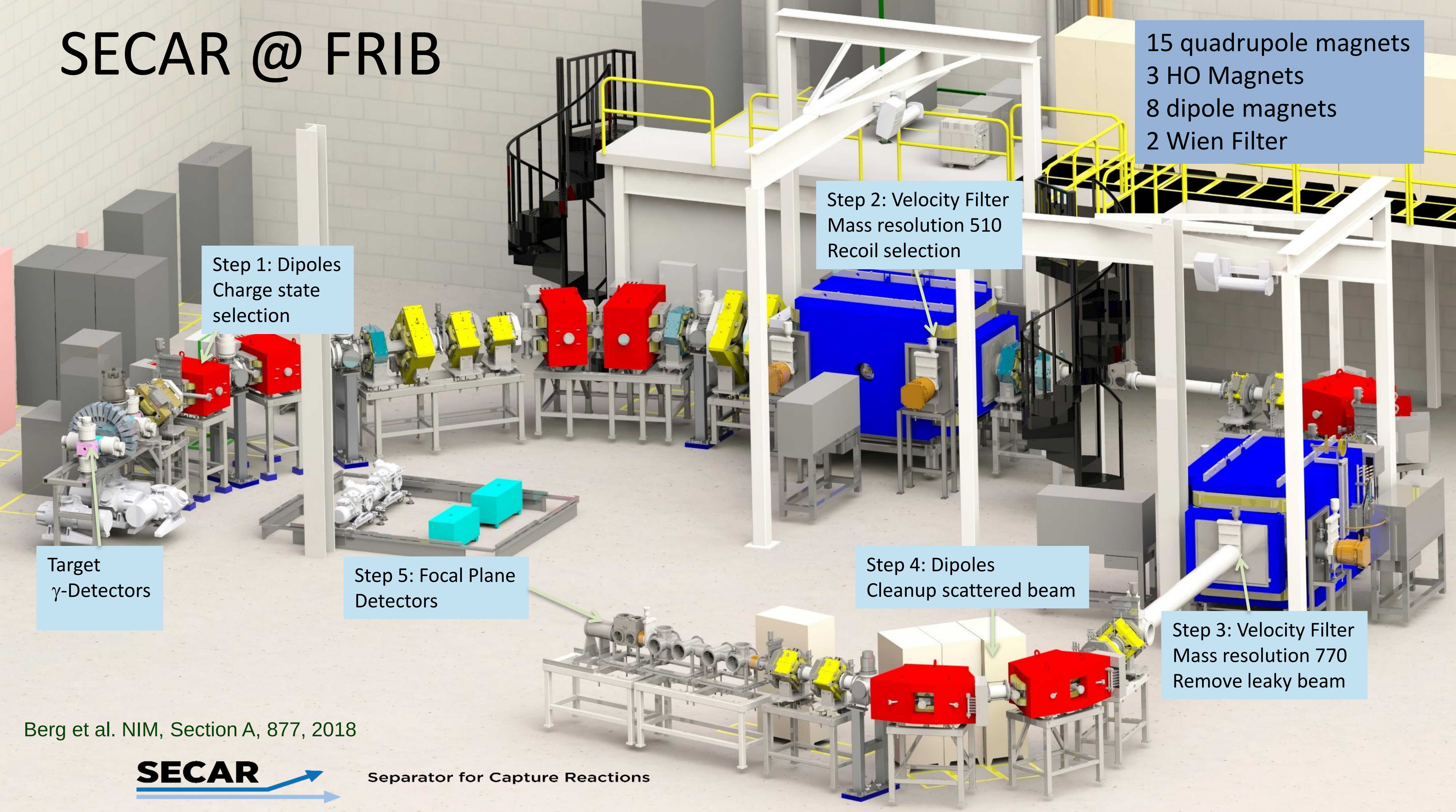
- “Low emittance” beam
- Point like gas jet target (+extended for SECAR)
  - HIPPO (10^{17} at/cm^2)
  - JENSA (10^{19} at/cm^2)
- Mass separation using Wien filter(s) (velocity filters)
- One charge state selection
- “Clean-up” section -> Momentum selection
- Particle identification detection system

St George



11 quadrupole magnets
6 dipole magnets
1 Wien Filter

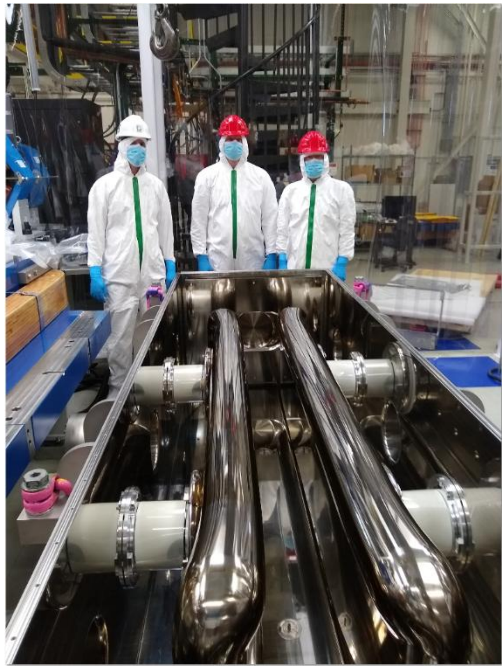
SECAR @ FRIB



Berg et al. NIM, Section A, 877, 2018

SECAR Separator for Capture Reactions

SECAR @ FRIB



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SECAR

Separator for Capture Reactions

Commissioning of the System(s)

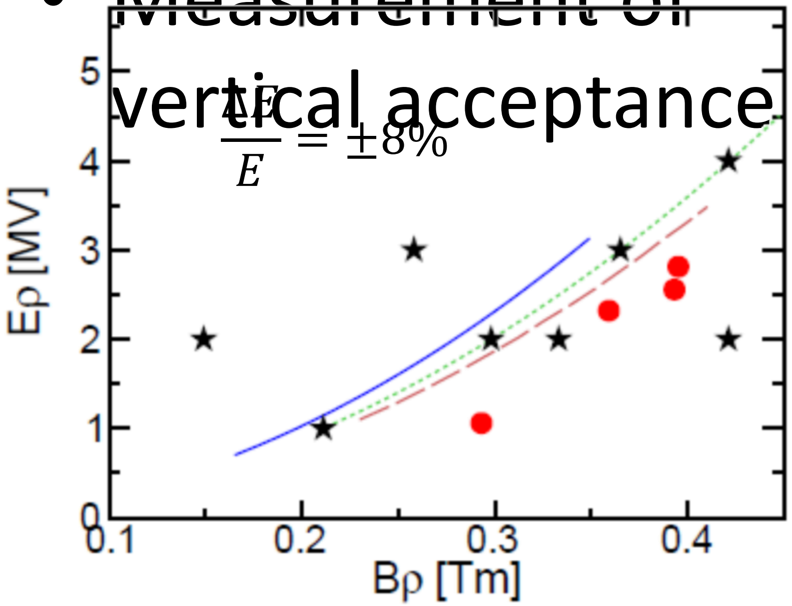
- Acceptance
- Experiments to reproduce known information
- Solve unexpected issue(s)

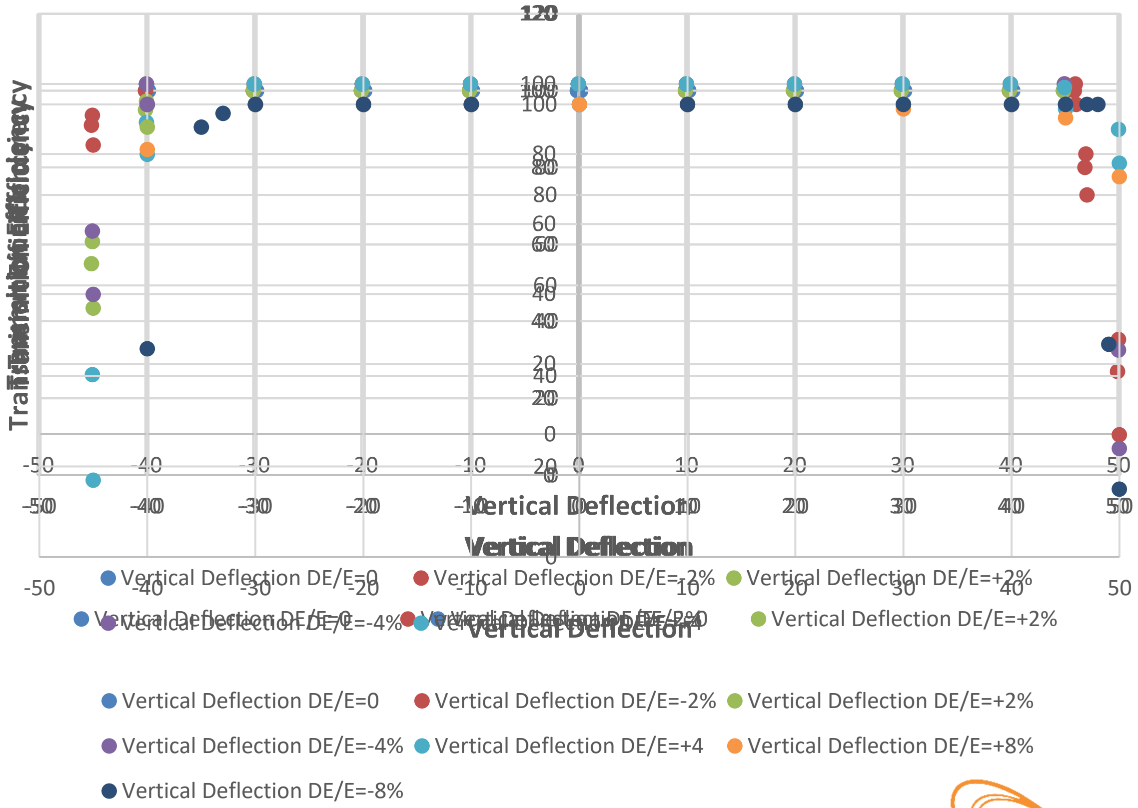
St. George: Yield Calculations

- Experimental Yield:
  - $Y(E) = \frac{N_{recoil}(E)}{f(q)T\epsilon(E)N_{beam}}$
    - T the separator recoils transmission
    - $f(q)$ the charge state fraction
    - $\epsilon(E)$ the detection system efficiency

St. George Acceptance Measurements

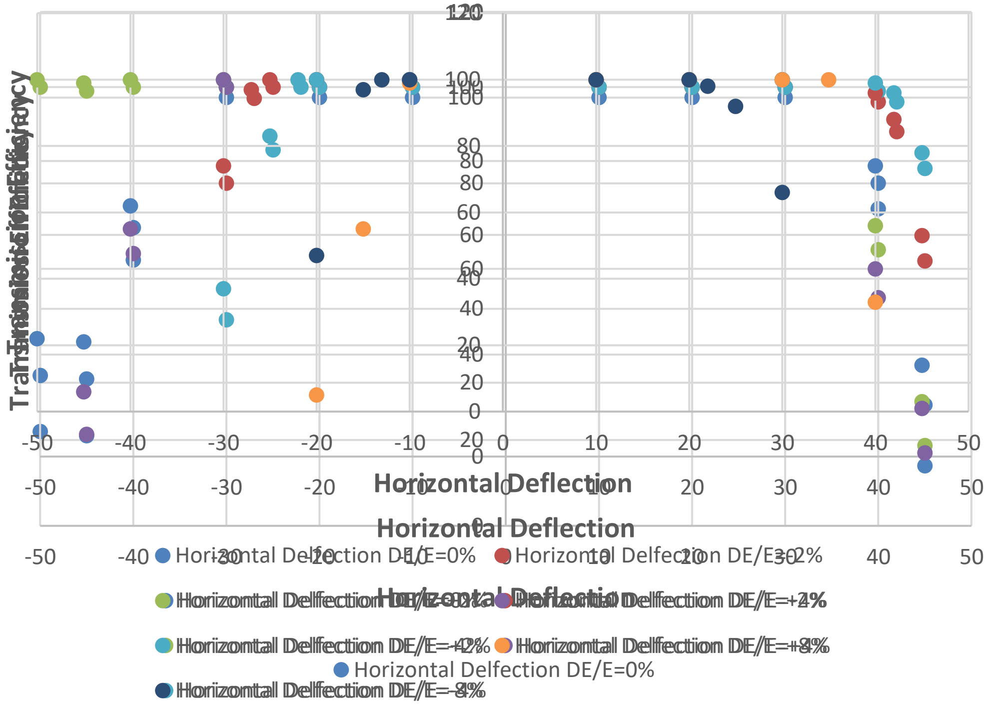
- Measurement of energy acceptance
- Measurement of vertical acceptance





St. George Acceptance Measurements

- Measurement of energy and horizontal acceptance



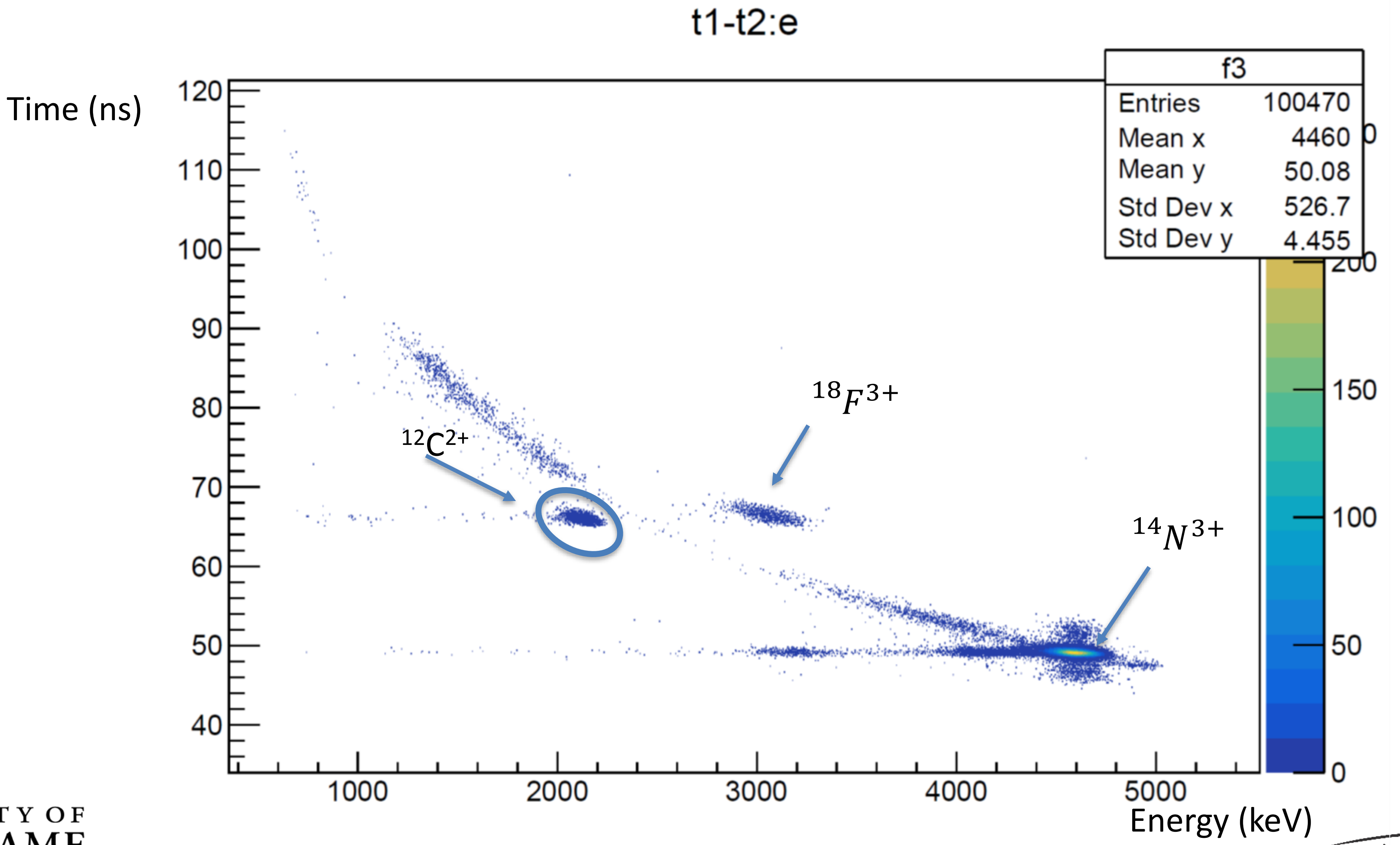
Need optimization!

However, at +/-20mrad and DE/E<+/-4%
Science is possible

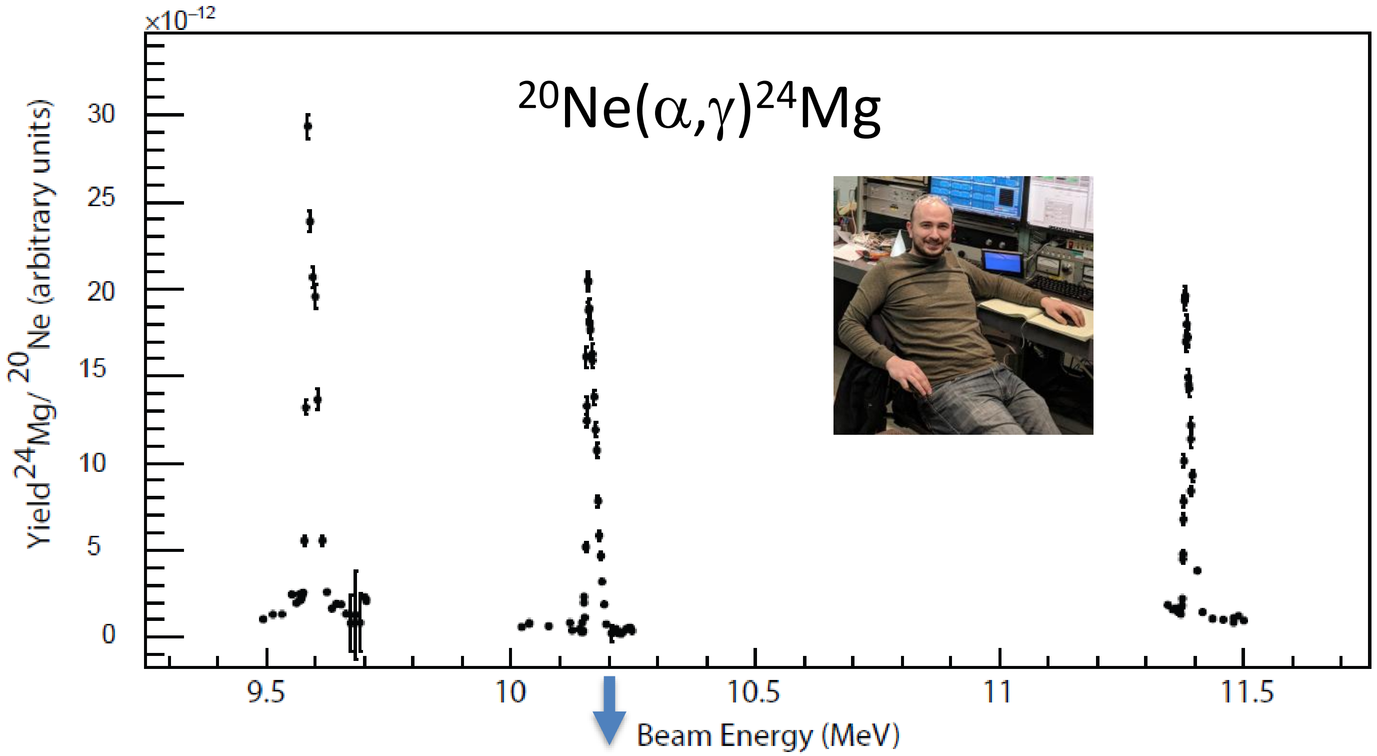
St. George Commissioning Experiments

- Goal: Demonstrate that we can reproduce existing results
- Selected reactions: $^{14}N(\alpha,\gamma)^{18}F$ and $^{20}Ne(\alpha,\gamma)^{24}Mg$
- Advantages
  - Well studied at "high energy" $E_{CM} \approx 1 - 2\ MeV$
    - High cross section ~10-20 minutes measurement needed with ~10pnA beam
  - There are remaining interesting questions at low energy
    - Helium burning and AGB stars for $^{14}N+\alpha$
    - Neon burning for $^{20}Ne+\alpha$
  - Most abundant charge state (average charge state) is accessible

St. George Example: $^{14}N(\alpha,\gamma)^{18}F$

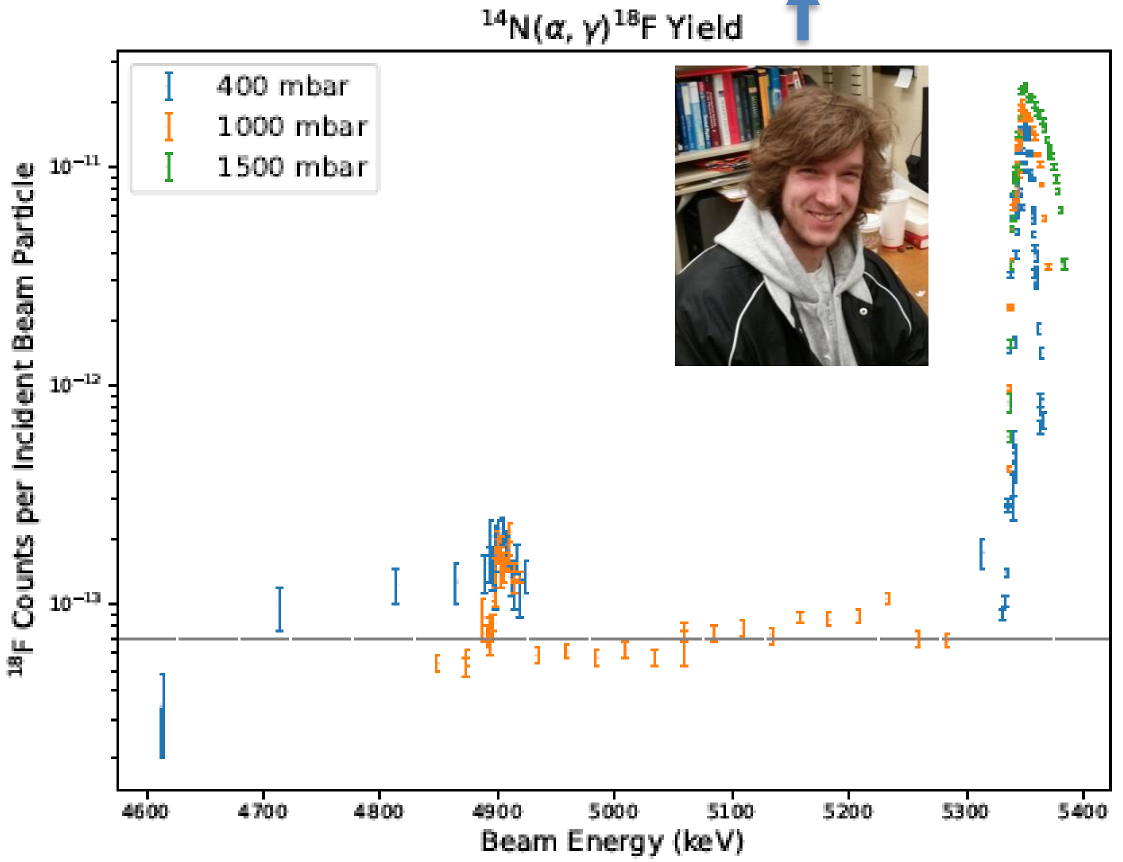


St. George Commissioning Results



Energy (CM)	$\omega\gamma$(this work)	$\omega\gamma$ (literature)*
$1606\ keV$	$2.0 \pm 0.3\ eV$	$2.2 \pm 0.3\ eV$
$1703\ keV$	1.7 ± 0.3 eV	$1.5 \pm 0.2\ eV$
$1909\ keV$	$1.5 \pm 0.3\ eV$	$1.7 \pm 0.2\ eV$

Energy (CM)	$\omega\gamma$ (this work)	$\omega\gamma$(literature)*
$1088\ keV$	$6 \pm 1 meV$	$7 \pm 1 meV$
$1189\ keV$	$1.2 \pm 0.1 eV$	$1.3 \pm 0.1\ eV$



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*: NACRE Compilation 1999

SECAR: Machine Learning for Tune Optimization

- Standard Approach
  - Canonical ion optics, scaled to rigidity
  - Experience
- Two goals
  - Find new magnetic field tunes that will optimize SECAR for different experimental conditions
    - For reactions other then radiative captures
      - Wien filter(s) off
    - Too high electric rigidity, need different E/B ratio in Wien filters
  - Reduce actual tuning time

Bayesian Optimization for Beam Tuning

SECAR
SEparator for CApture Reactions

From Fernando Montes

1. Need beam on axis at target. If beam is not on axis, quadrupoles steer beam on viewer

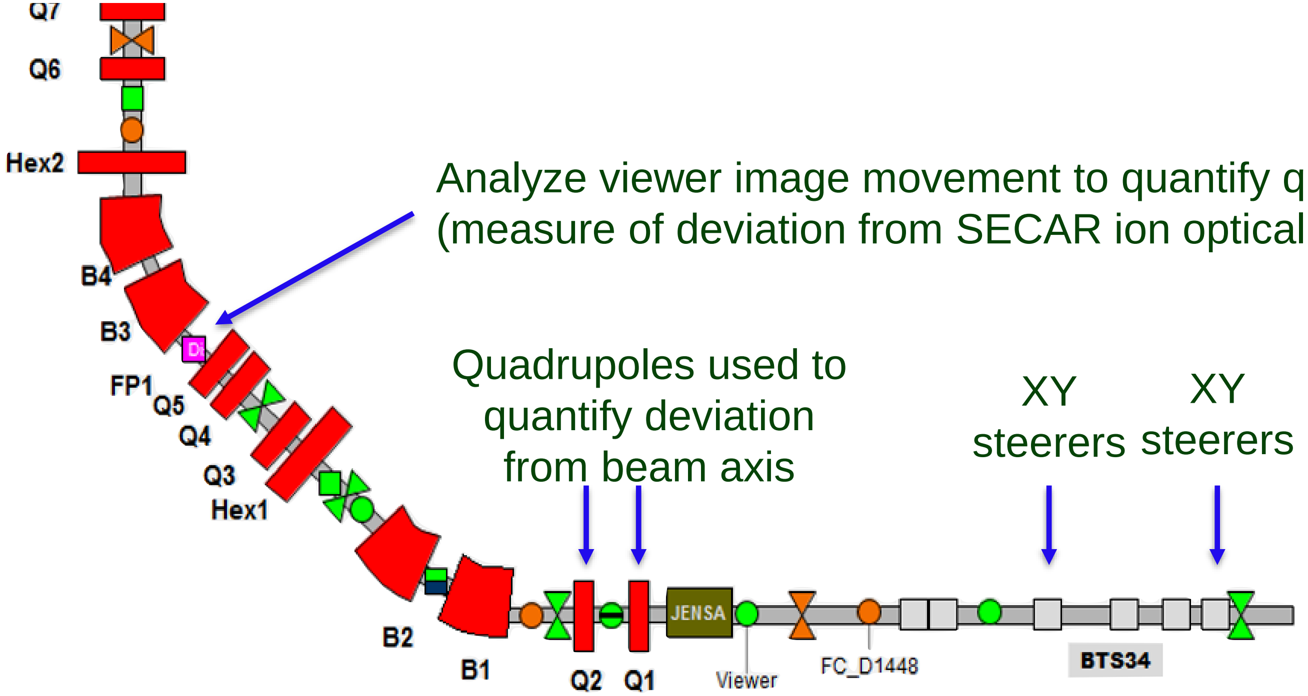
2. Obtain steerer settings that correct angle and location at target

Analyze viewer image movement to quantify quadrupole steering (measure of deviation from SECAR ion optical axis)

Quadrupoles used to quantify deviation from beam axis

XY steerers

XY steerers



Bayesian Optimization for Beam Tuning

- Implemented through the Python GPy library and the associated GPyOpt tool, with the PyEpics library for controls

Algorithm

1: Randomly select initial steerer settings and evaluate average steering function f at viewer
2: **while** criterion not met **do**
3: Compute $x^* = \text{argmin}\ (\text{LCB}(x))$
4: Set steerer settings to new x^*
5: Evaluate f to get average beam movement at viewer
6: Add new observation to set of samples
7: Set x^* to the final tune

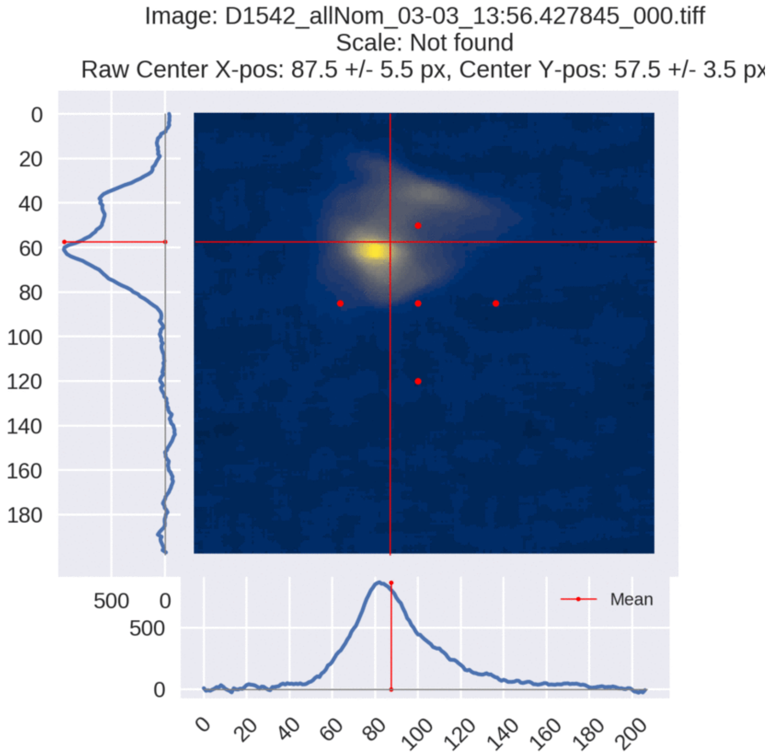
From Fernando Montes

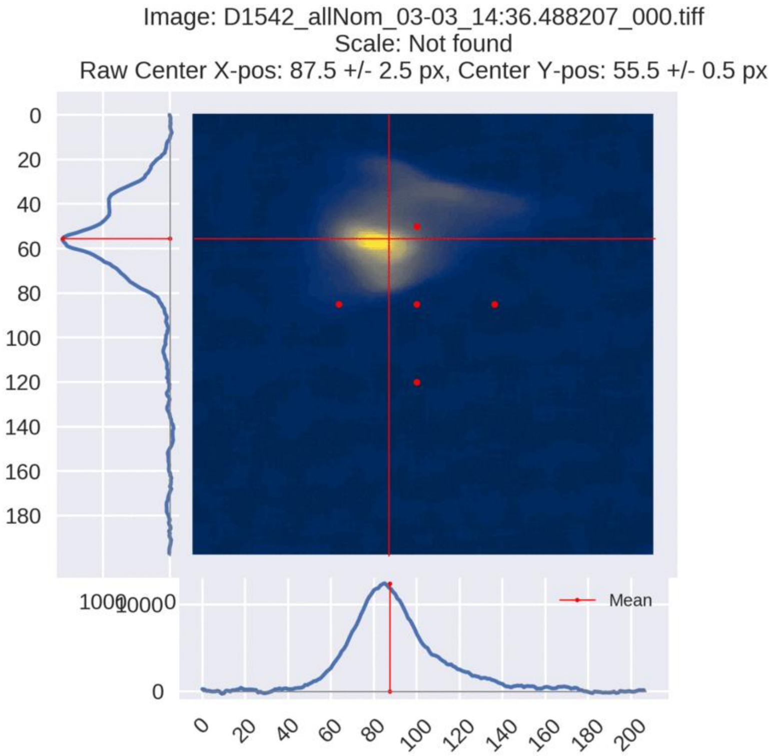
Miskovich et. al., PRAB 25, 044601 (2022)

Bayesian Optimization for Beam Tuning

SECAR
SEparator for CApture Reactions

From Fernando Montes





Steering Before:

~ 21 px / 7 mm

Steering After:

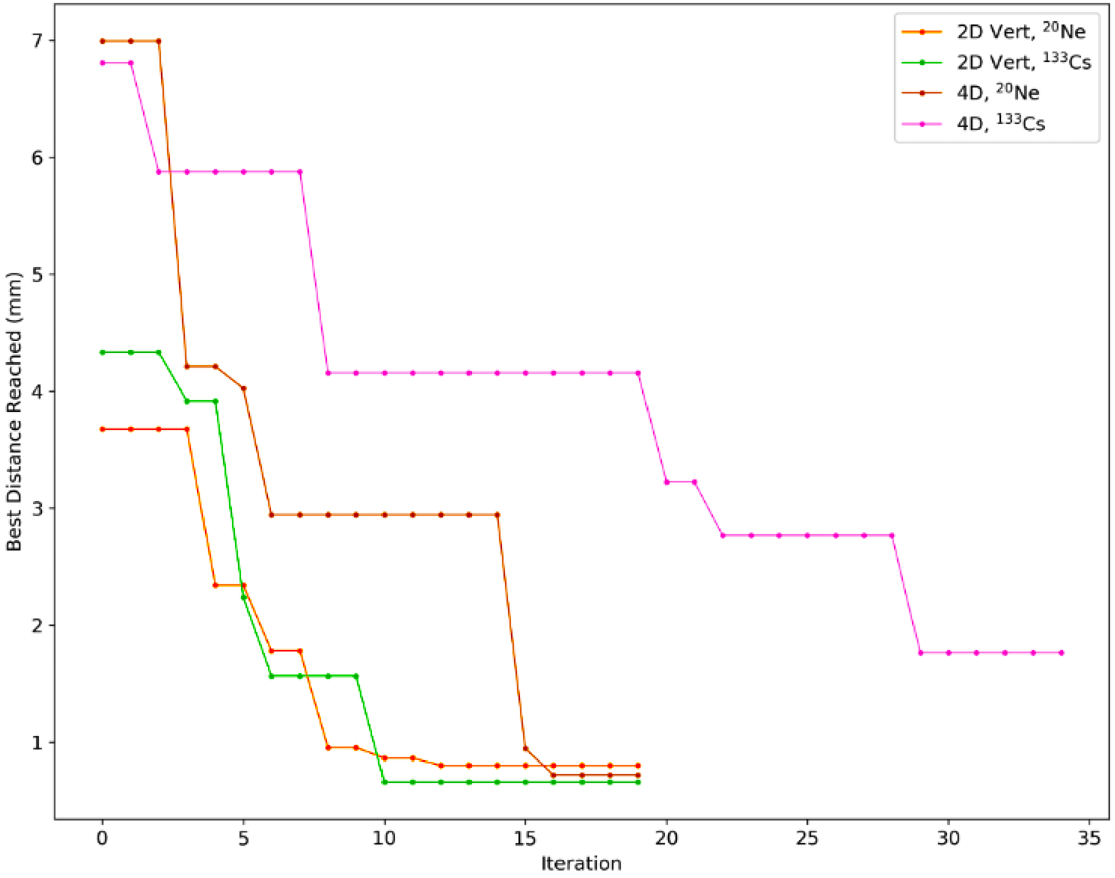
~ 2 px / 0.6 mm

Bayesian Optimization for Beam Tuning

SECAR
SEparator for CApture Reactions

From Fernando Montes

- 15-35 iterations
- 5-30 min per tune
- ~84% faster than **initial** manual tuning
- Removes human bias
- Reproducible
- Can use any viewer/quads combination to adjust along beamline

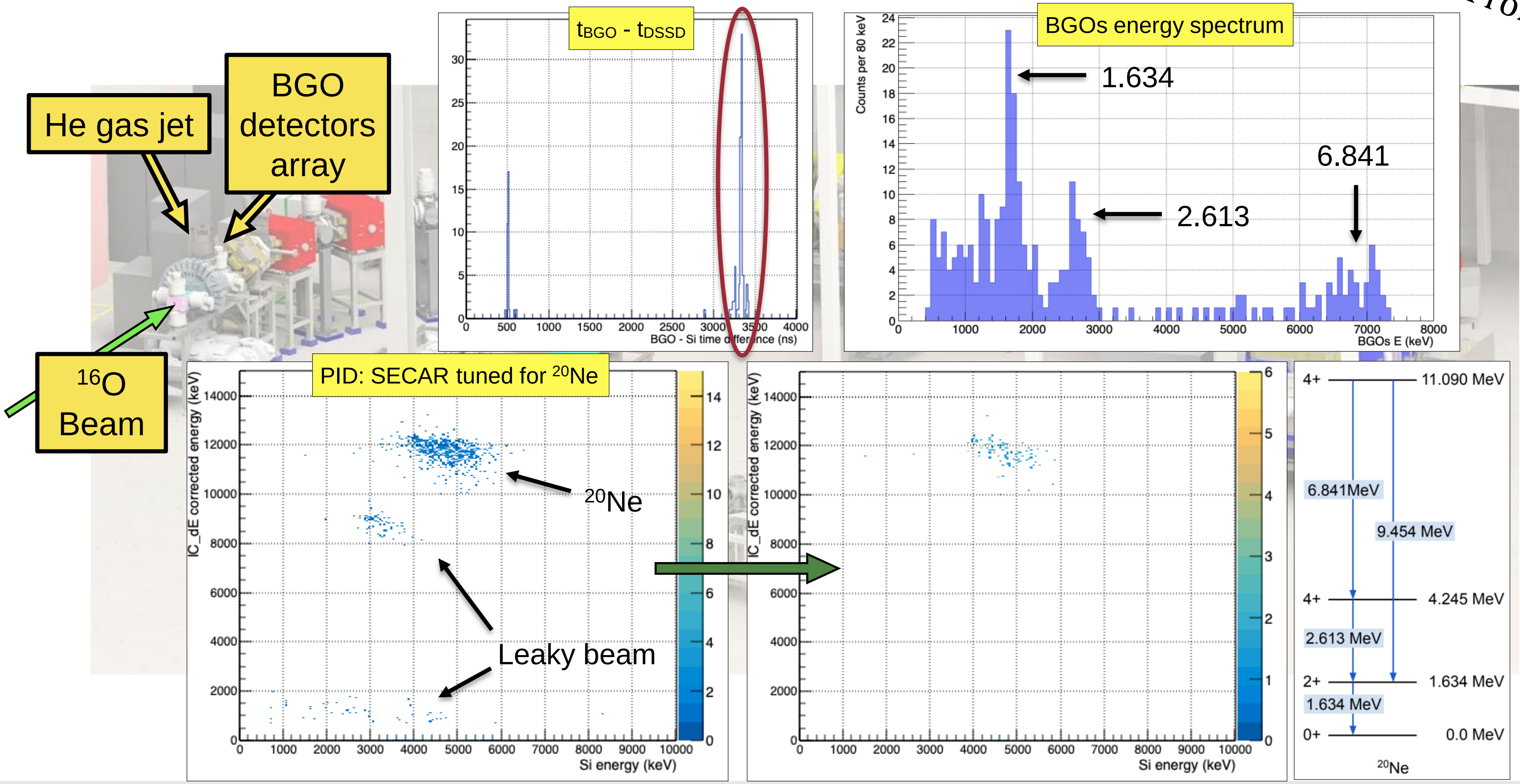


Commissioning of SECAR: (α,γ)

SECAR
SEparator for CApture Reactions

Measurement of a known resonance in $^{16}O(\alpha,\gamma)^{20}Ne$ reaction at E_{CM} = 6.36 MeV.

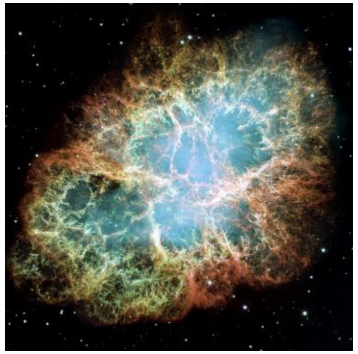
From Ruchi Garg



SECAR: Experiments Beam Rate Limited →Alternative Use

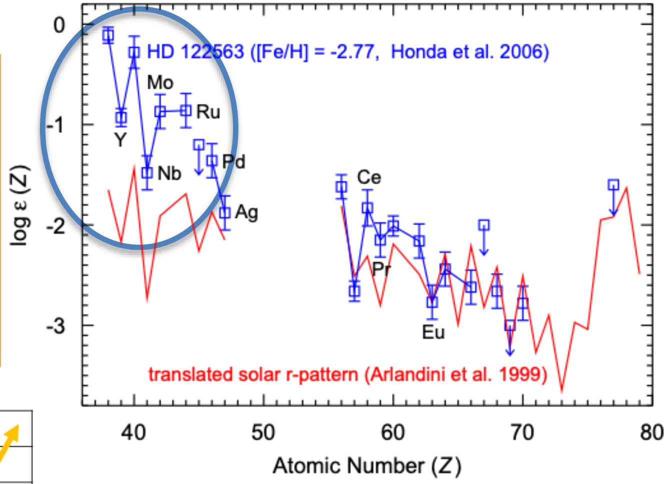
- How can we use the separator while the beam intensity is increased?
  - (p,n) and (α,n) reaction studies ← New SECAR tune
  - Neutron detectors at the JENSA gas target

Weak r-process: n-rich ν-driven winds in Core-Collapse Supernovae



J. Hester and A. Loll, NASA, ESA

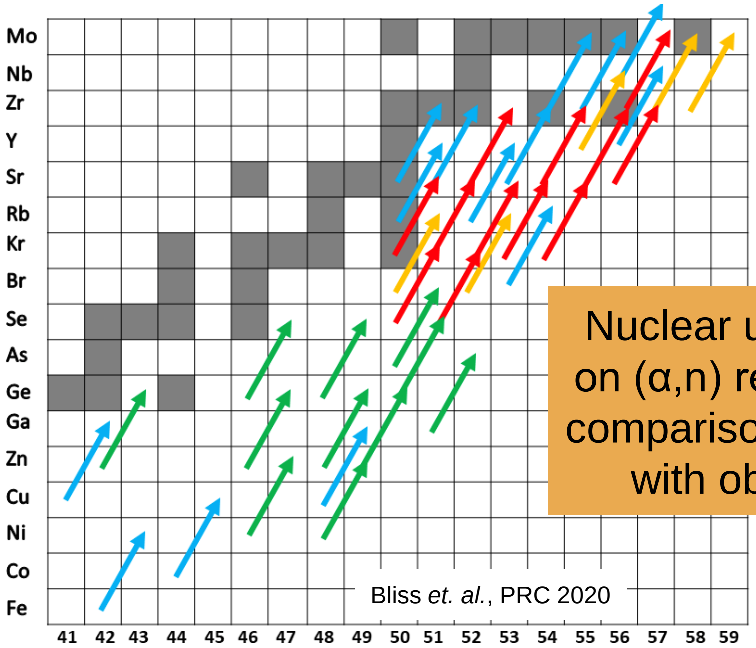
Weak r-process may explain the metal-poor stars with large Z = 38 - 47 abundances.



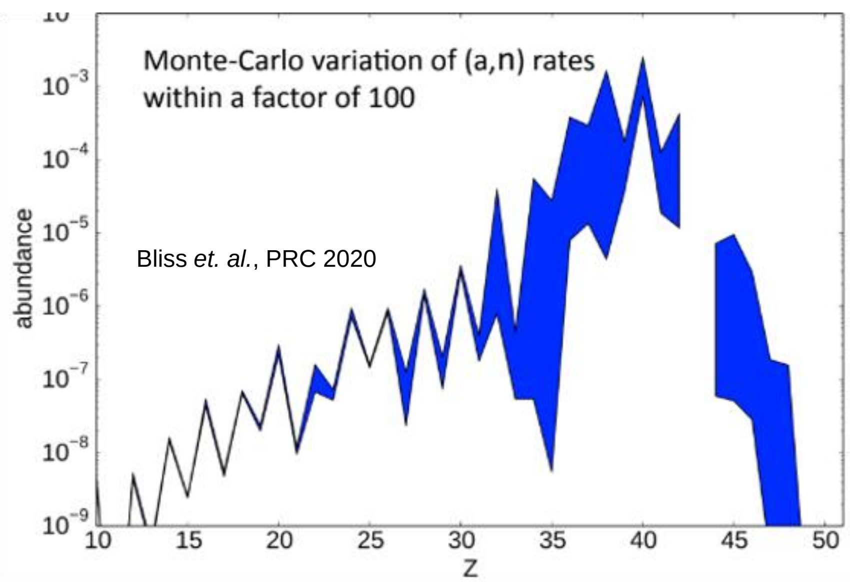
From Ruchi Garg

SECAR large acceptance allows for (α,n) reactions.

Already performed ^{86}Kr(α,n)^{88,89}Sr measurement, Feb 2022.



Nuclear uncertainties on (α,n) reactions limit comparisons of models with observation



$^{86}Kr(\alpha,n)^{89}Sr$ and $^{86}Kr(\alpha,2n)^{88}Sr$

SECAR
SEparator for CApture Reactions

Important to the weak r-process.

Sensitivity study by Bliss *et. al.* [PRC 2020] showed $^{86}Kr(\alpha,n)^{88,89}Sr$ to affect elements Z = 38-42, 44, 45, & 47.

SECAR configuration:
JENSA gas jet target
LENDA + Liquid Scintillators
IC + DSSD recoil detectors

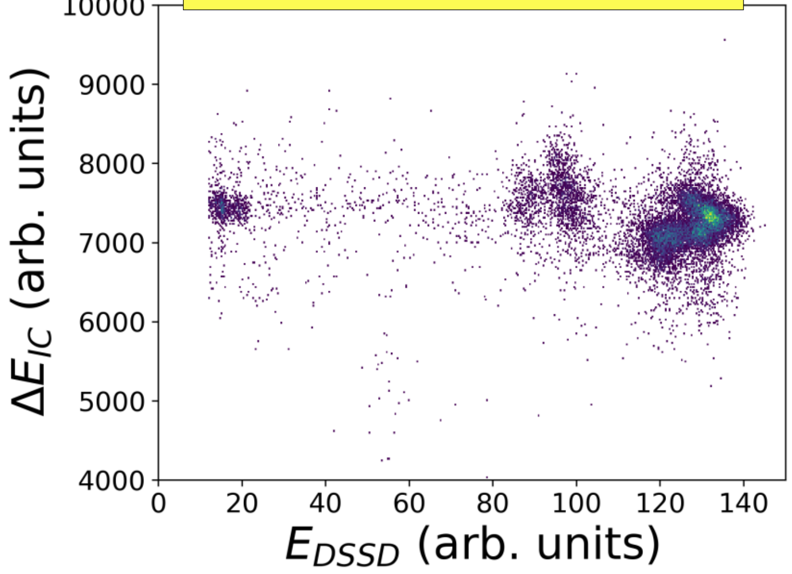
From Ruchi Garg

Led by:
Ohio University
Z. Meisel (P.I.)
C. Marshall (Postdoc.)
Michigan State University
F. Montes (P.I.)

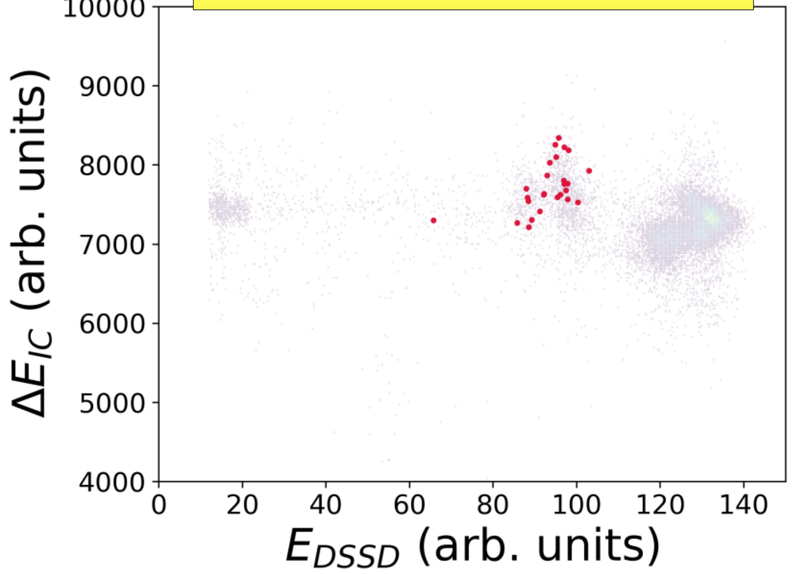
Plots by C. Marshall

Beam = ^{86}Kr 26+, 3 MeV/u

PID: SECAR tuned for ^{88}Sr 28+



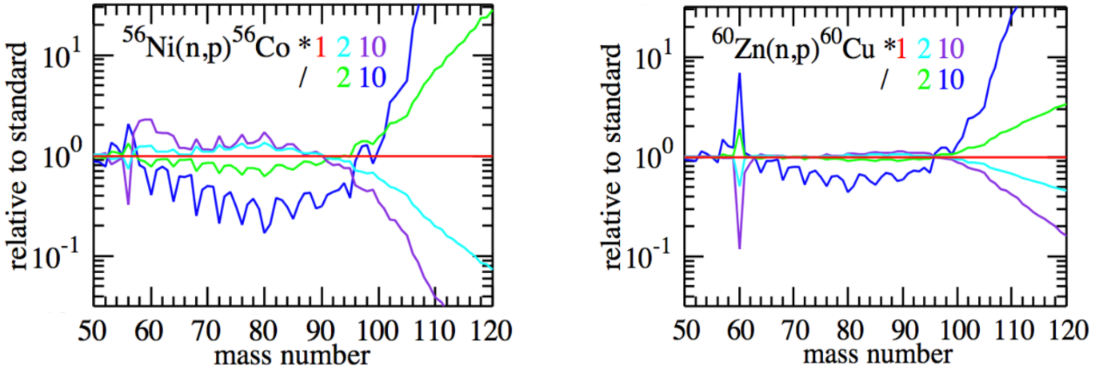
Gated on neutrons > 2 MeV



νp-process: p-rich ν-driven winds in Core-Collapse Supernovae

From Pelagia Tsintari
Georgios Perdikakis

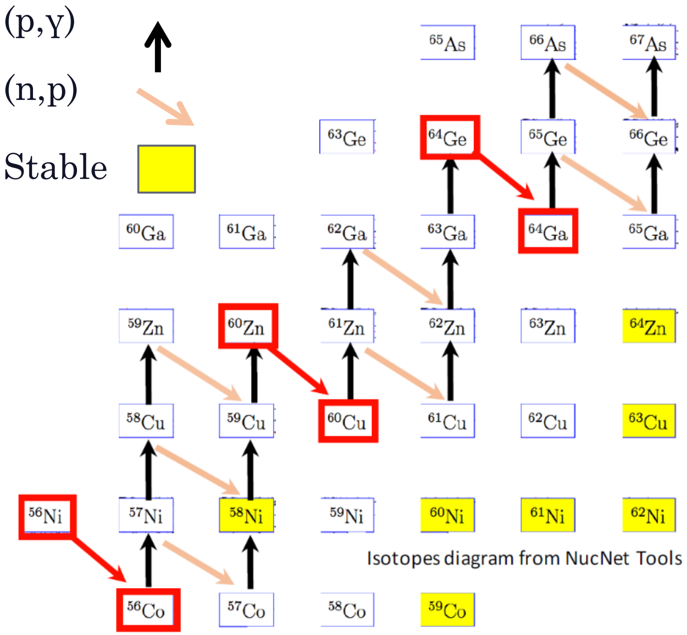
S. Wanajo et al. *The Astrophysical Journal* 729(1):46 (2011)



The reaction chain of the vp – process starts at ^{56}Ni and is initiated from the neutrons created by the neutrino winds.

We can study of (n,p) reactions of interest via measuring the time reverse (p,n) reactions

$$p + \bar{\nu}_e \rightarrow n + e^+$$



Isotopes diagram from NucNet Tools

Sequence of (n,p), (p,γ) reactions drive nucleosynthesis to heavier elements.

The $^{58}Fe(p,n)^{58}Co$ reaction

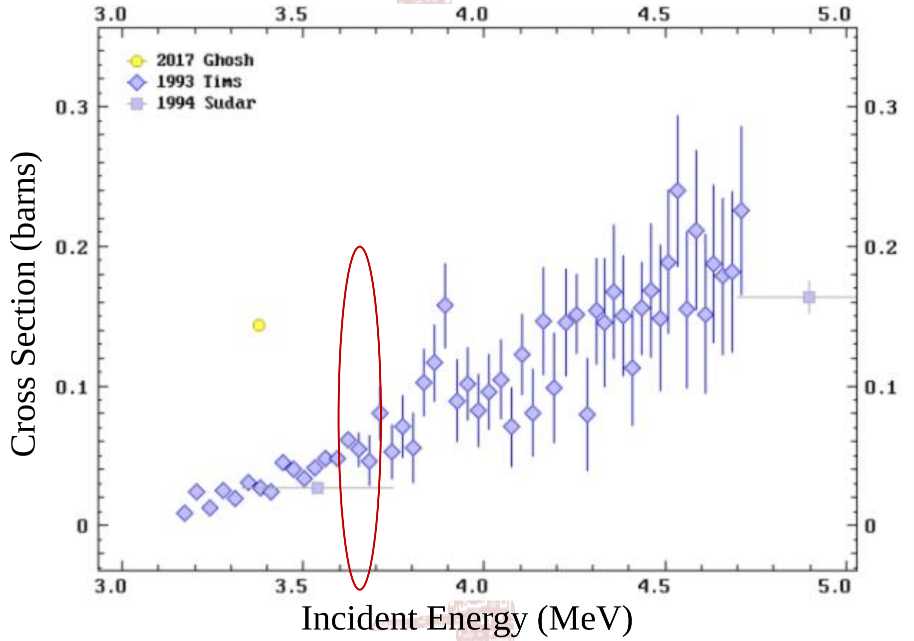
From Pelagia Tsintari
Georgios Perdikakis

- ^{58}Co belongs to the "Fe-peak" elements and its creation takes place at the final reactions of the silicon burning chain in massive stars

- $^{58}Fe(p,n)$ - Q - value = -3.09 MeV,
  Coulomb barrier = 3.9 MeV

- Previous measurements were done using the activation method

- **A $^{58}Fe^{21+}$ beam accelerated at 3.785 MeV/u impinged on a thin (0.391 mg/cm^2) polyethylene (CH_2) foil**



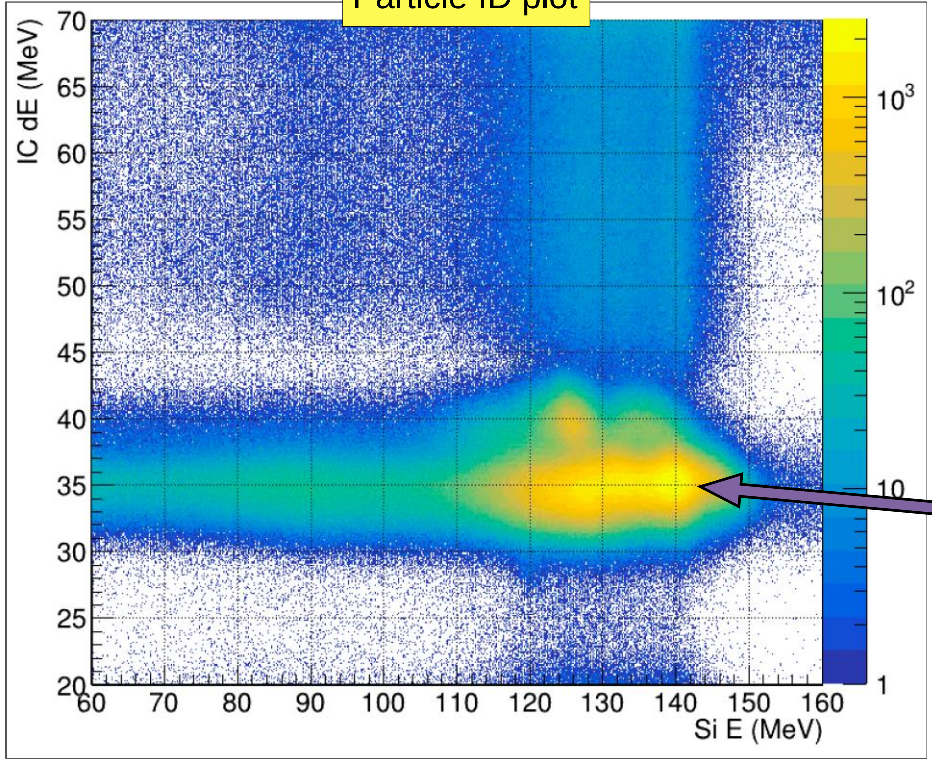
Beam energy at the center of the target foil is ~ 3.65 MeV/u

Commissioning of SECAR: (p,n)

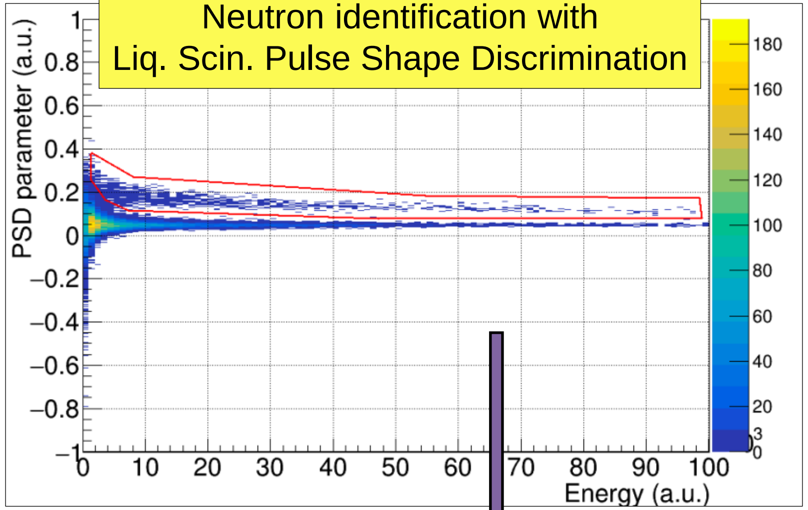
SEparator for CApture Reactions

Measurement of the known $^{58}Fe(p,n)^{58}Co$ reaction cross section

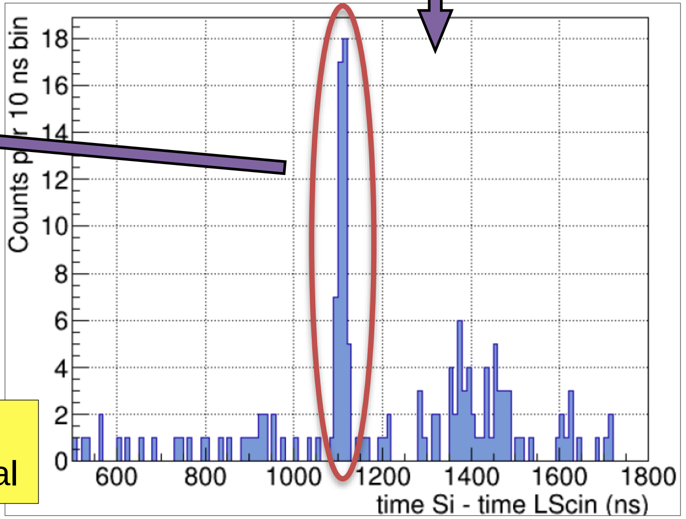
Particle ID plot



Neutron identification with Liq. Scin. Pulse Shape Discrimination



From Ruchi Garg
Pelagia Tsintari
Georgios Perdikakis



Time difference between Liq. Scin. and DSSD signal

SECAR
Separator for CApture Reactions

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Machine learning enabled measurements of astrophysical (p, n) reactions with the SECAR recoil separator

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Hide

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Exp

FRIB

Summary

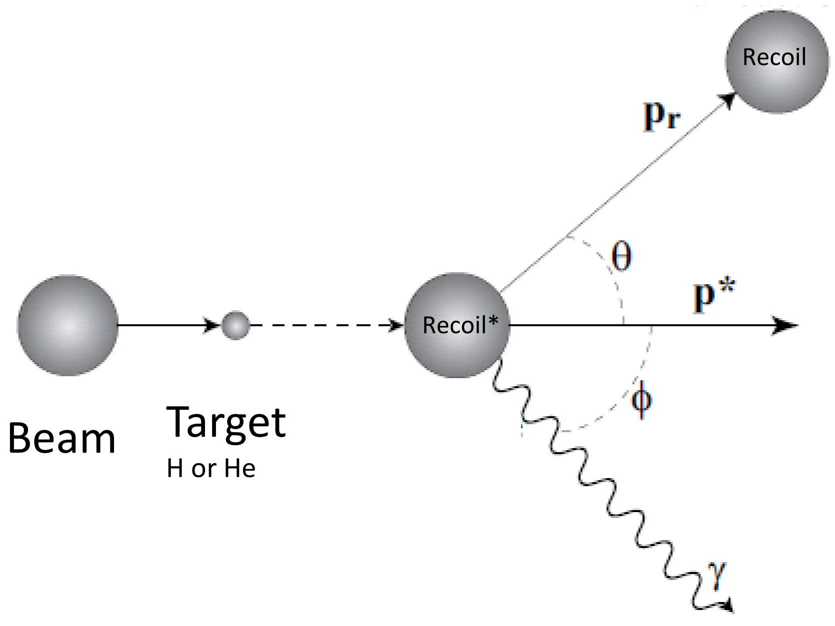
- Radiative capture reactions play crucial roles in stellar nucleosynthesis
- Direct measurements are hard
- The St. George recoil separator at Notre Dame is now studying (α,γ) reactions of astrophysical interest
  - Need help to figure out ways to estimate charge state fraction (let's chat at the coffee breaks if you are curious)
- SECAR at FRIB is commissioned and ready to performed PAC approved experiments
  - Already used to study (α,n) and (p,n) reactions
  - Leading the way in ML for optimization of ion optic design and beam tuning procedure

Radiative Capture in Inverse Kinematics

- Heavy ion beam on light target (H or He)
- Compound Nuclei/Product of Reaction/Recoil decays by gamma emission
- Boosted forward
- From conservation of momentum

$$\vec{p}_{beam} = \vec{p}_{recoil} + \vec{p}_{\gamma's}$$ and

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



- The beam and the recoils are moving forward in a narrow aperture cone defined by the q-value+ center of mass energy
  - Too much beam for direct recoil detection