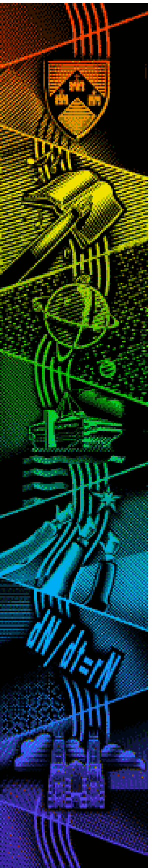


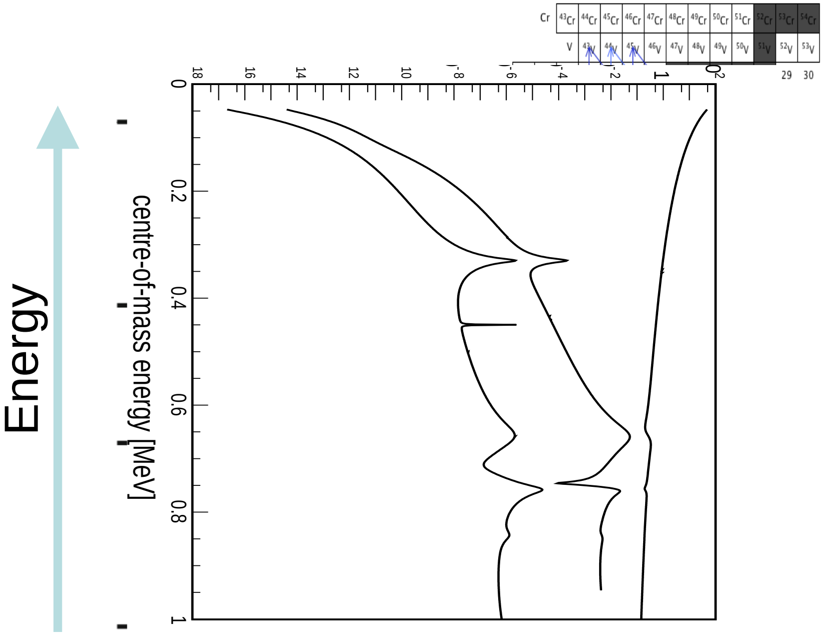
Recoil separators in astrophysics

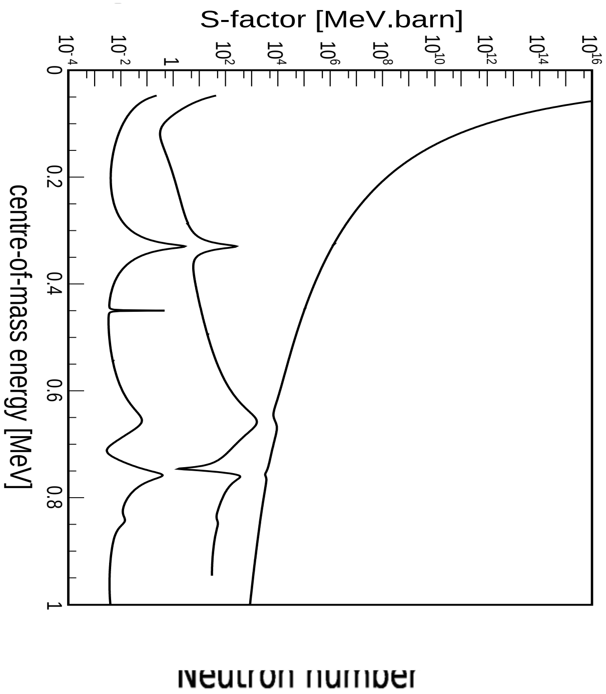
Alison Laird
The University of York

Outline

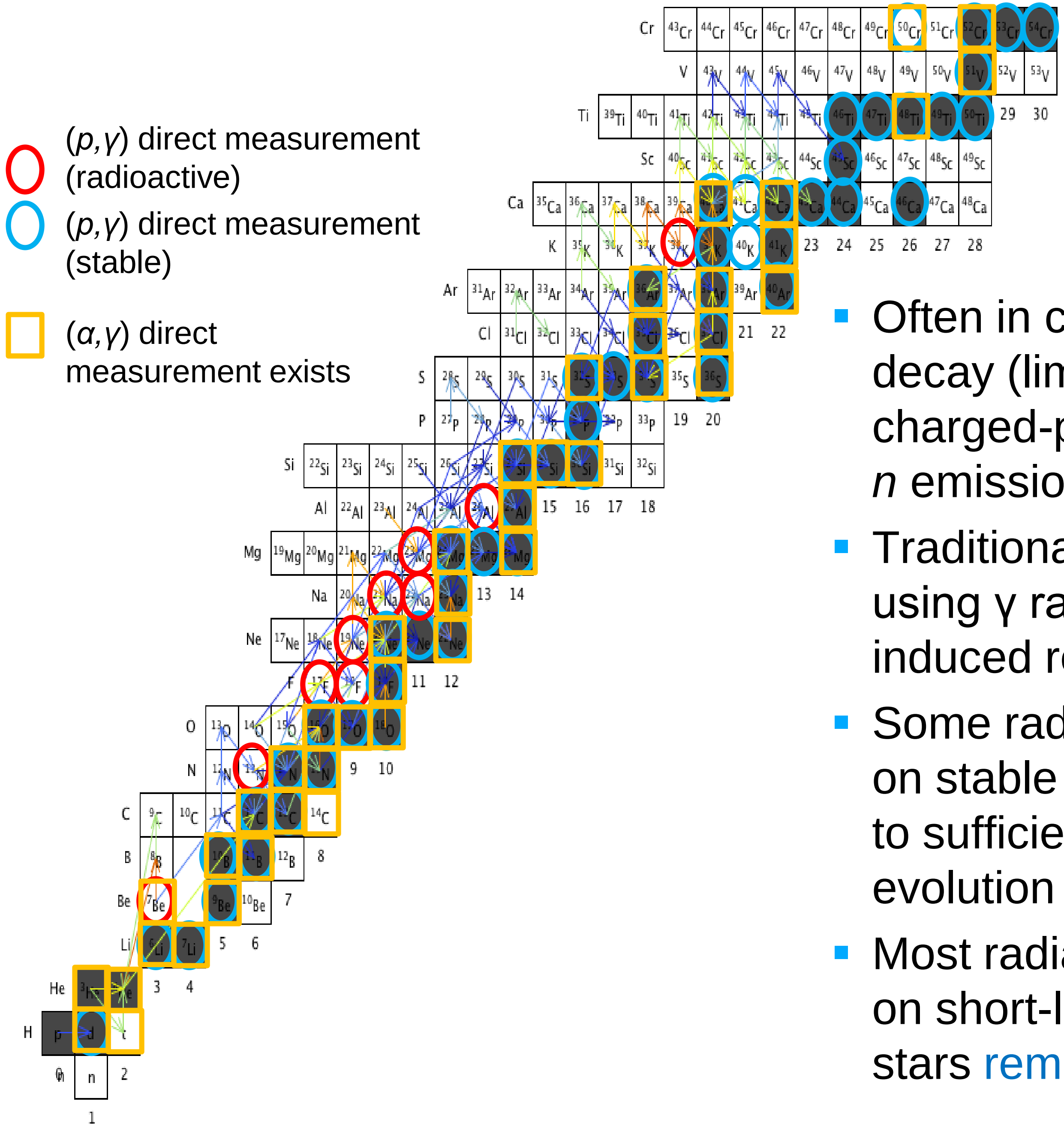
- Introduction
- Radiative capture in inverse kinematics
- DRAGON@TRIUMF
  - Separator
  - Gas target
  - BGO array
  - Focal plane detectors
- Data analysis
- Summary

Radiative capture





- Defined as any reaction A(b,γ)C whereby a bound state of the final nucleus is reached via emission of a photon (can be direct, or via particle-unbound states)
- Ubiquitous in astrophysics, from BBN (e.g. D(p,γ)^{3}He .. ^{3}He(α,γ)^{7}Be), to the pp-chain, to the CNO cycles, to explosive nucleosynthesis
- Radiative capture reactions are relatively *weak* due to the fine structure constant, but span a large range at applicable astrophysical energies: (range of cross sections) → intense beams, low background,…

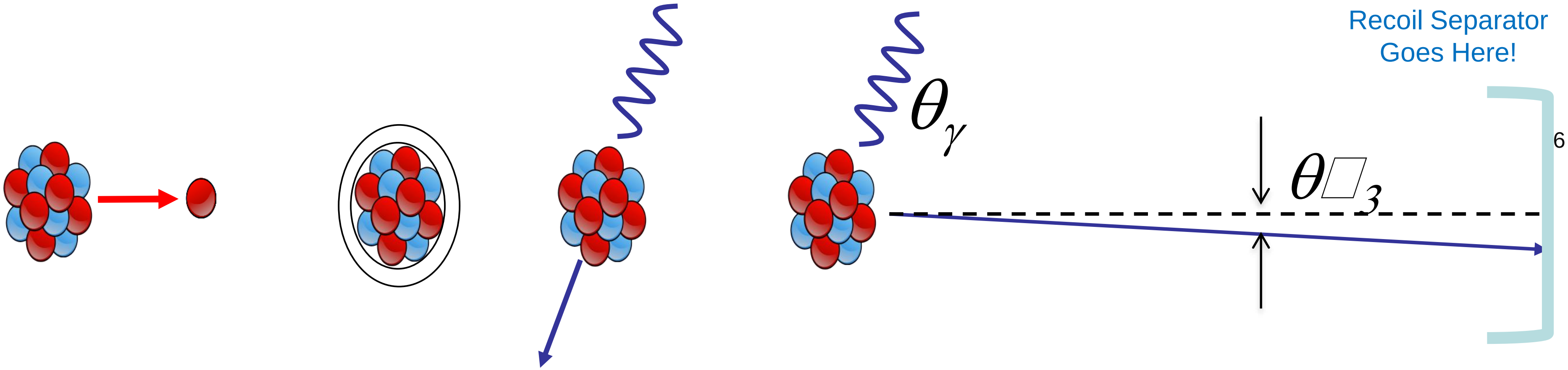


- Often in competition only with $\beta+$ decay (limiting our discussion to charged-particle induced), or *p, α, n* emission
- Traditionally have been studied using γ rays, via light particle induced reactions
- Some radiative capture reactions on stable nuclei remain unknown to sufficient precision for stellar evolution or astronomy
- Most radiative capture reactions on short-lived radioactive nuclei in stars remain unmeasured

Inverse Kinematics

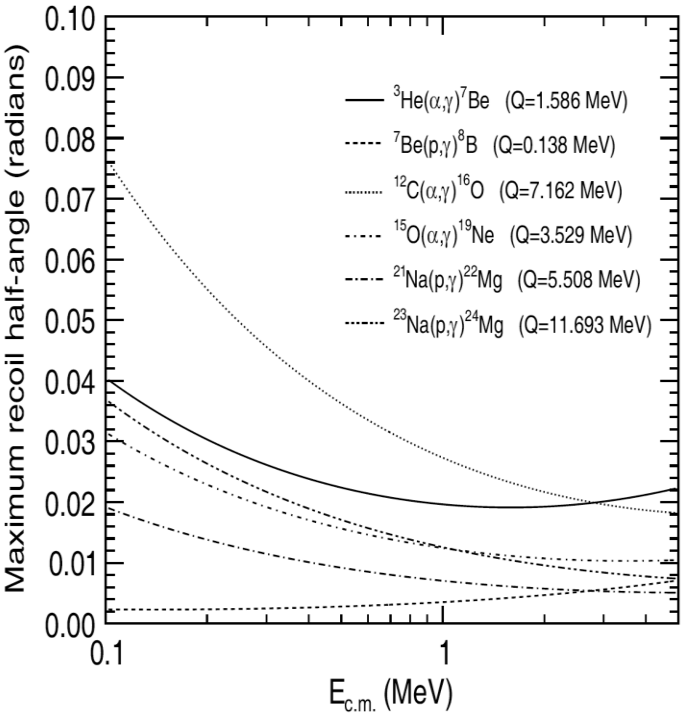
- Necessary due to not being able to make short-lived radioactive targets
- Detect recoiling product nucleus: forward focused, 100% efficiency
- Becomes problem of separating **rare** reaction products from **abundant** beam

  → zero-degree electromagnetic separator
- Additional advantages:
  - –Target either H_2 or He: gaseous at stp → windowless (jet,extended), purified etc…
  - –Still detect gamma rays (tag)
  - –Particle ID on reaction products



Recoil Separator
Goes Here!

- **Maximum** possible **recoil angle** when E_γ is maximized for $E_\gamma = Q+E_{c.m.}$
- AND emission perpendicular to beam axis **(θ©=π/2)**



Reactions per incident ion

Stopping power

$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

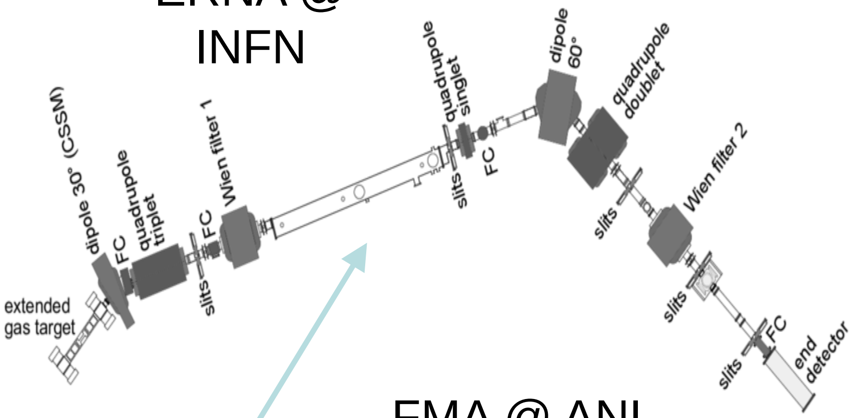
Stellar reaction rate over isolated, narrow resonance:

$$N_A < \sigma\nu >= 1.54 \times 10^{11}(\mu T_9)^{-3/2}\omega\gamma \exp(-11.605\frac{E_R}{T_9})$$

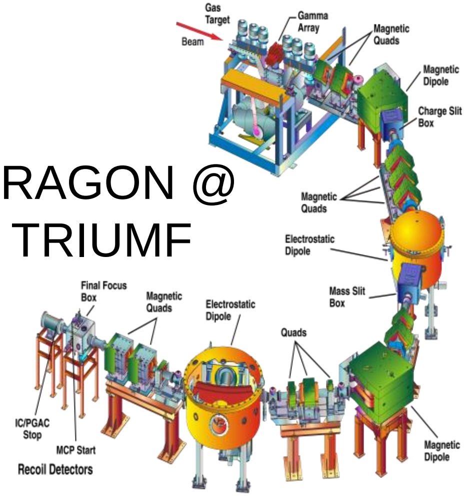
+ Caltech
NABONA @ Napoli
ARES @ LLN
DRS @ ORNL

“Recoil Separators”

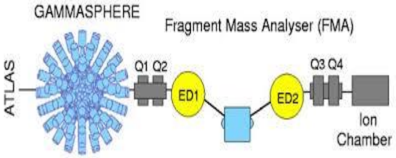
ERNA @ INFN

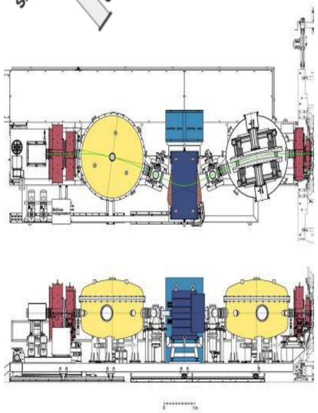


DRAGON @ TRIUMF

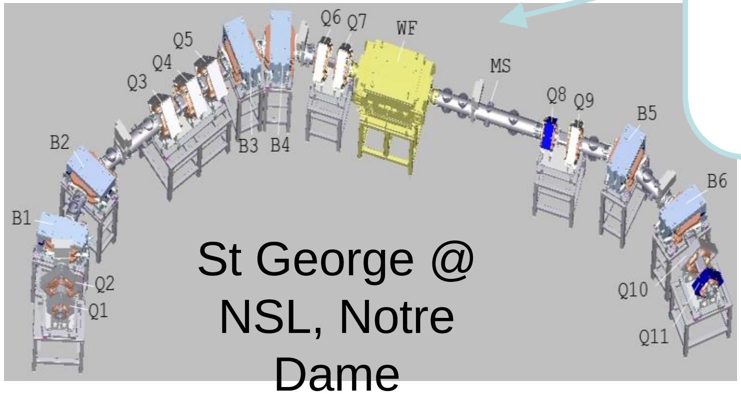


FMA @ ANL,
EMMA @ TRIUMF

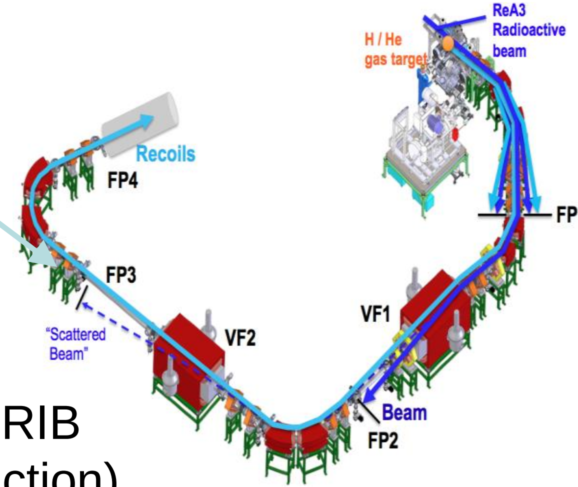




Wien Filters
0°
transmission
velocity
selection



St George @ NSL, Notre Dame



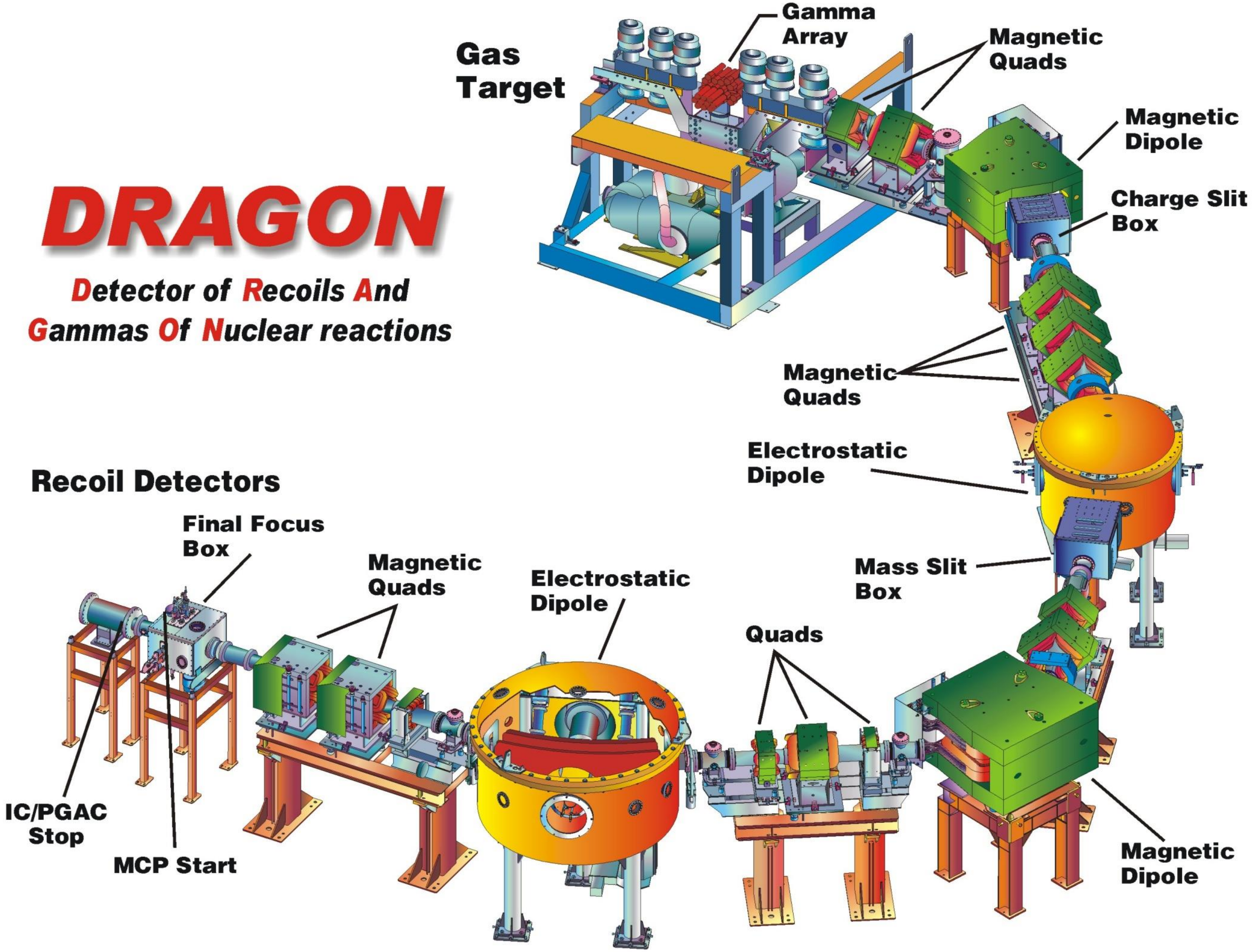
SECAR @ FRIB (under construction)

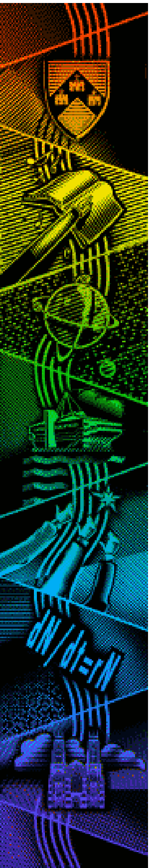
Detector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear reactions

The DRAGON recoil separator

DRAGON

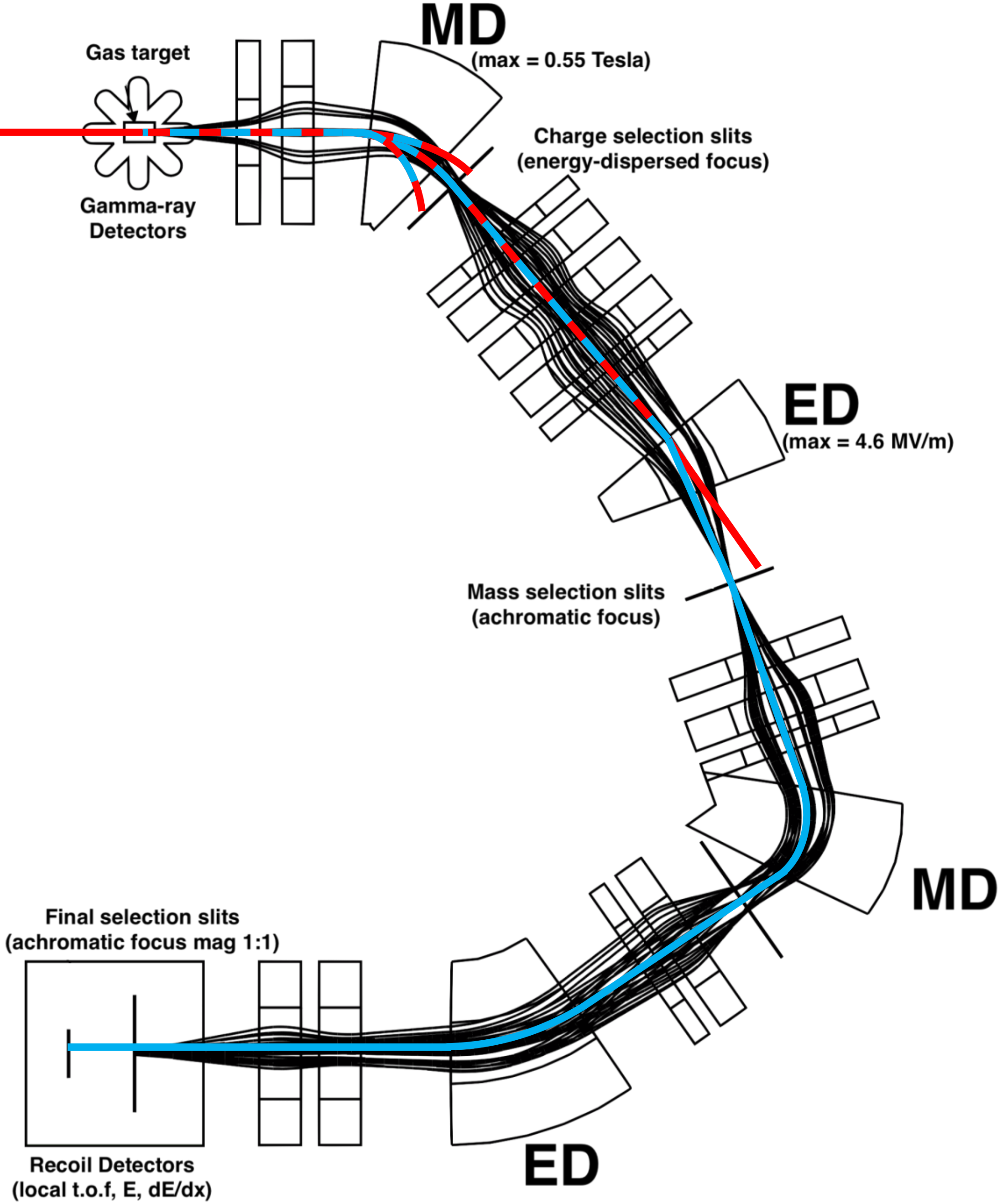
Detector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear reactions

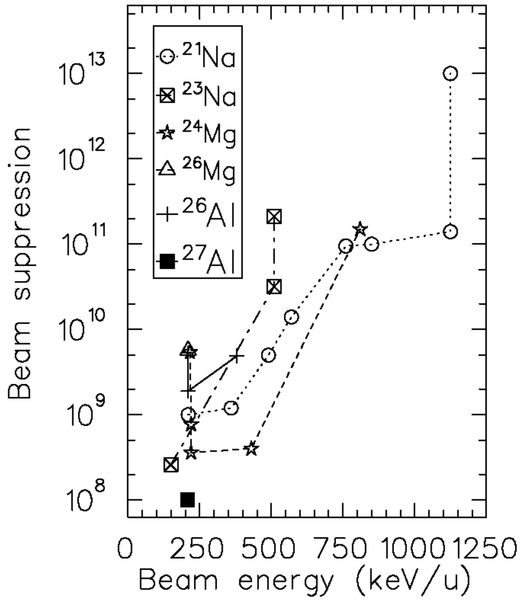


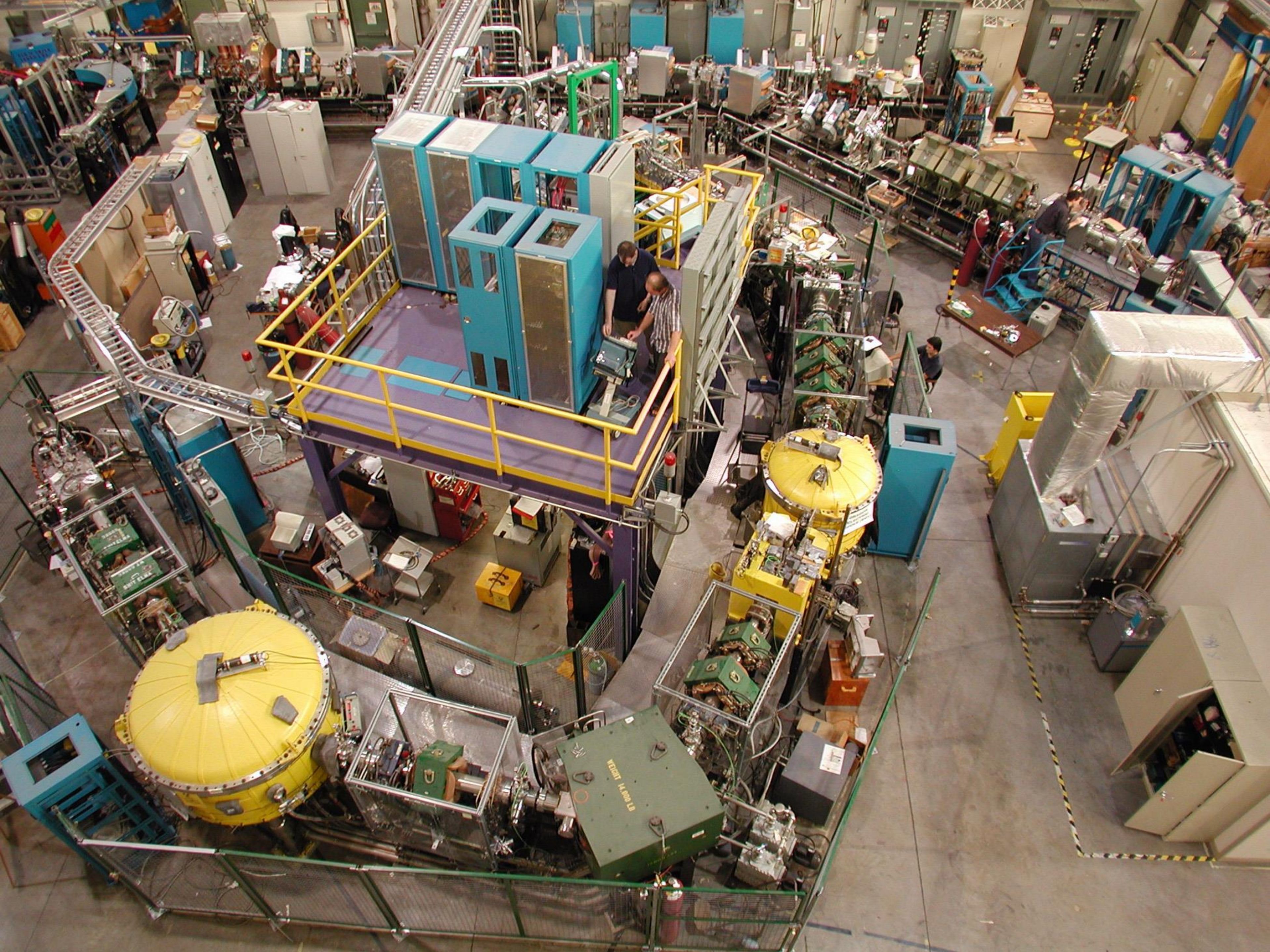


— beam

— recoils






WEIGHT 14,000 LB

DRAGON

- DRAGON designed for mass < 30
- Differentially pumped windowless hydrogen or helium gas target
- Suppression ~ $10^{-12} – 10^{-15}$
- Acceptance around 20 mrad
- Existing magnets/dipoles field limits
  - MD1 ~ 5500 G (could go higher but at limit of NMR probe)
  - ED1 ~ 200 kV (rated to 300 kV)

- Lowest beam intensity ~ 10^6 pps
- Highest beam intensty ~ few 10^{12} pps
- Lowest mass reaction studied $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$
- Highest mass reaction studied $^{76}\text{Se}(\alpha,\gamma)^{80}\text{Kr}$
  - Required additional ‘charge state booster’

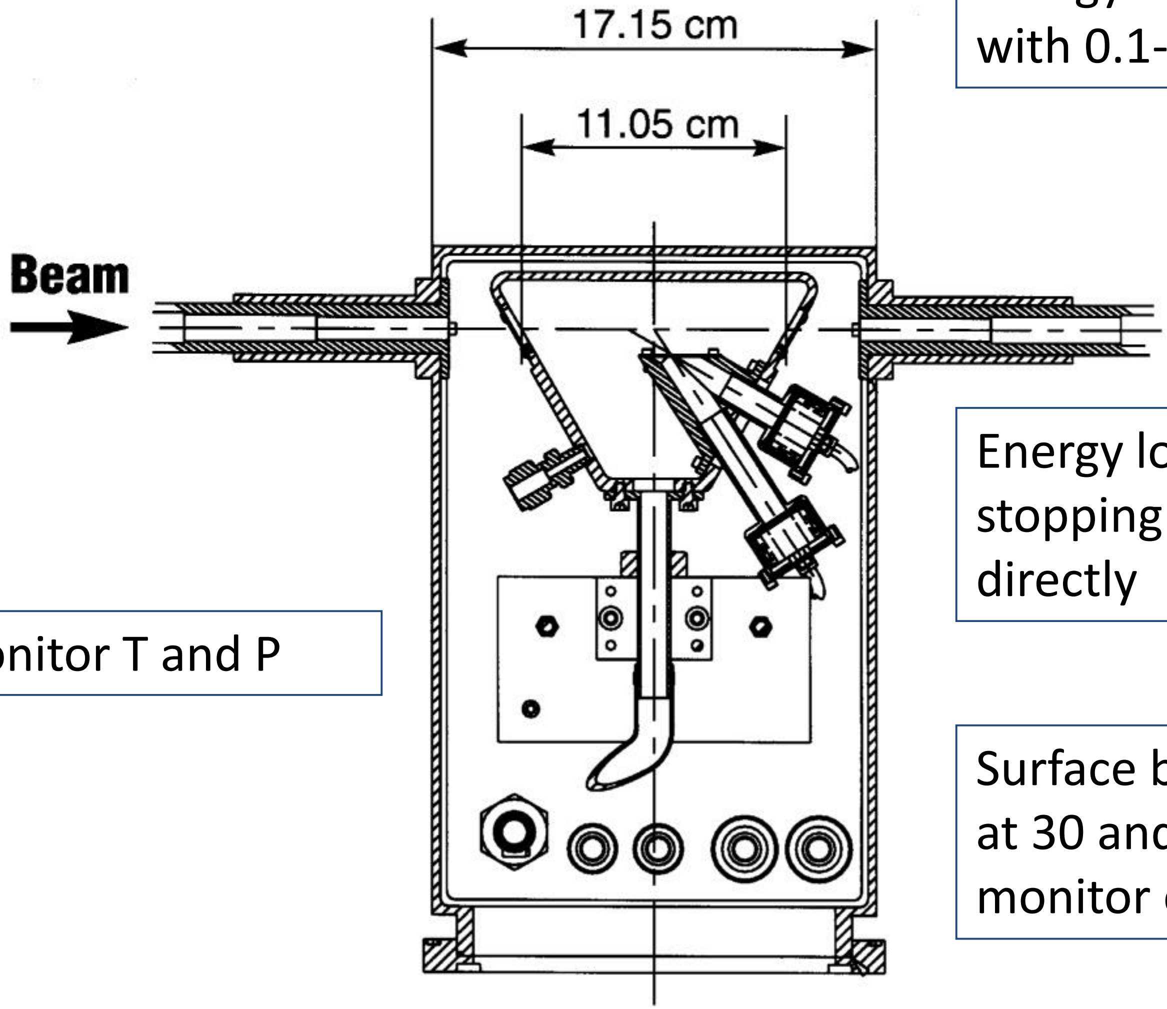
DRAGON gas target

Windowless, differentially pumped, recirculating **gas target** (H_2 or He)

1-10 mbar (pumping constraints) → $\lesssim 6 \times 10^{18}$ at/cm^2 H_2

LN_2 cooled zeolite cleaning trap

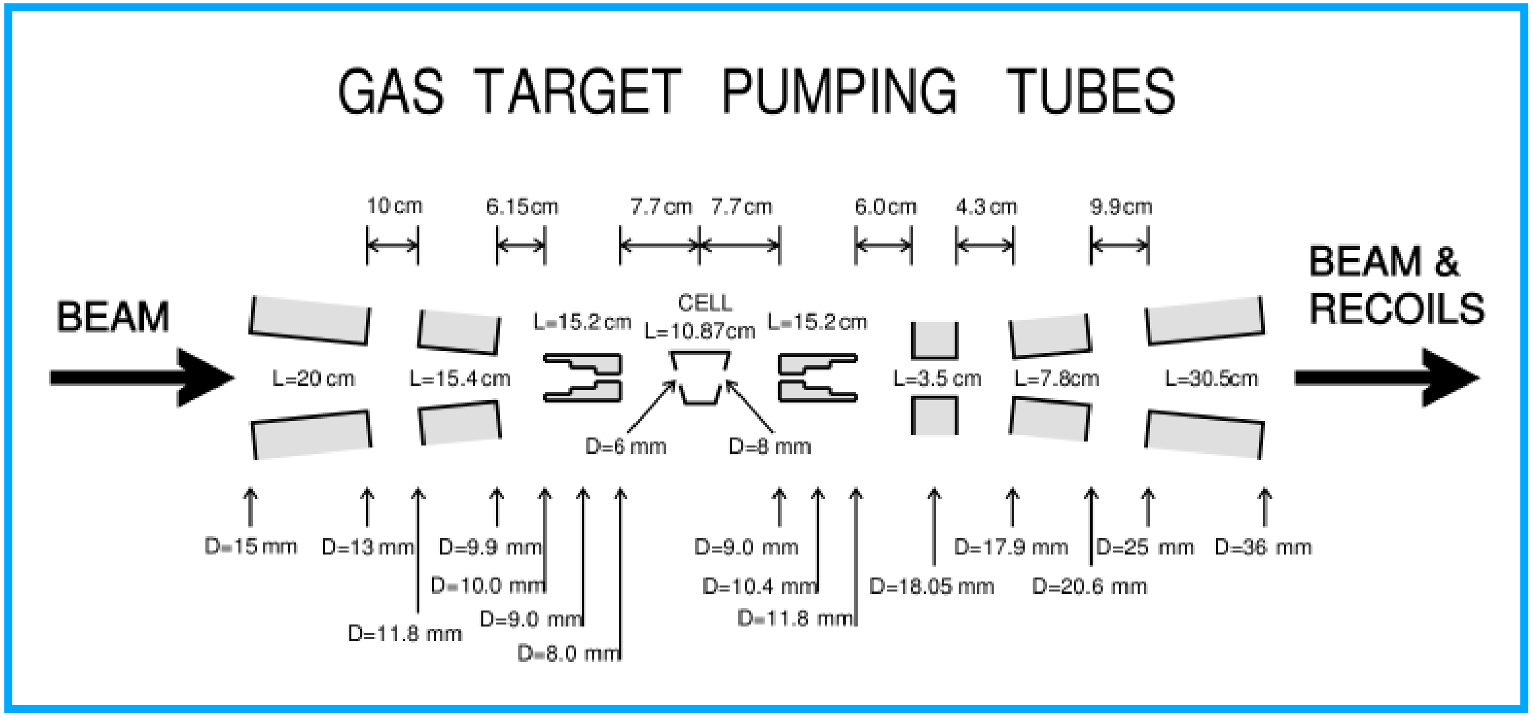
Energy can be measured with 0.1-0.2 % accuracy



Energy loss & therefore stopping power measured directly

Monitor T and P

Surface barrier detectors at 30 and 57 deg. to monitor elastic scattering.



Large pressure drop to ~3×10^{-6} Torr

DRAGON gas target – DON'TS!

We learned the hard way…

- **Pumping <u>Xenon</u> resulted in <u>catastrophic failure</u> of 6 turbo pumps!**
- **High atomic weight → noble gases generate large quantities of heat when striking the rotor**
- **Low specific thermal capacity → little heat transfer to stator or housing**

→ High rotor temperatures!

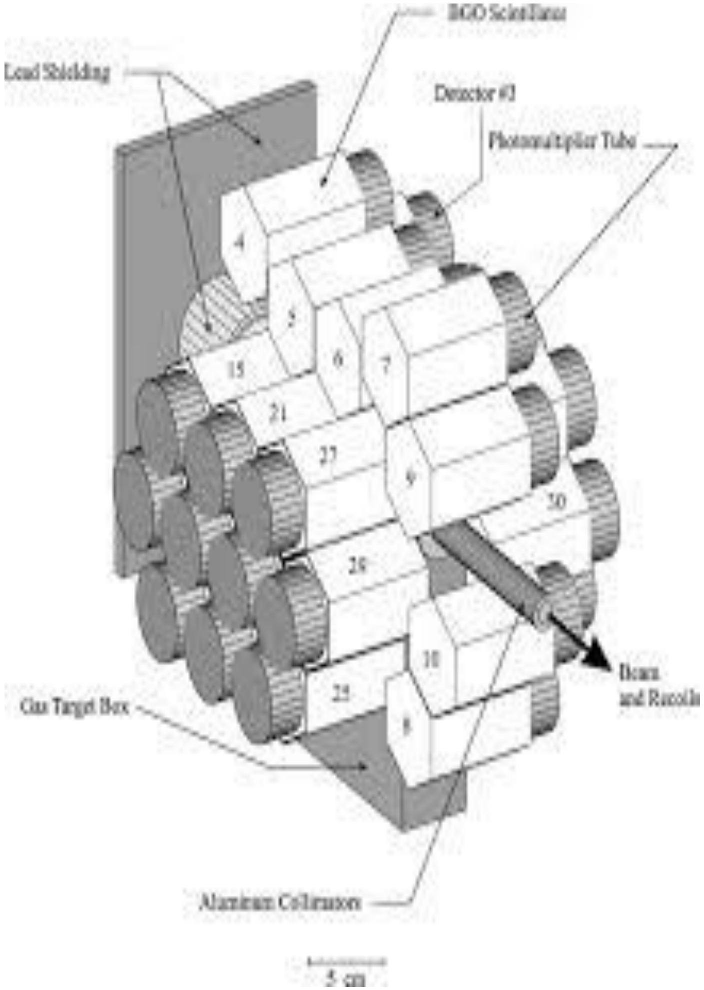
DRAGON BGO array

DRAGON BGO array

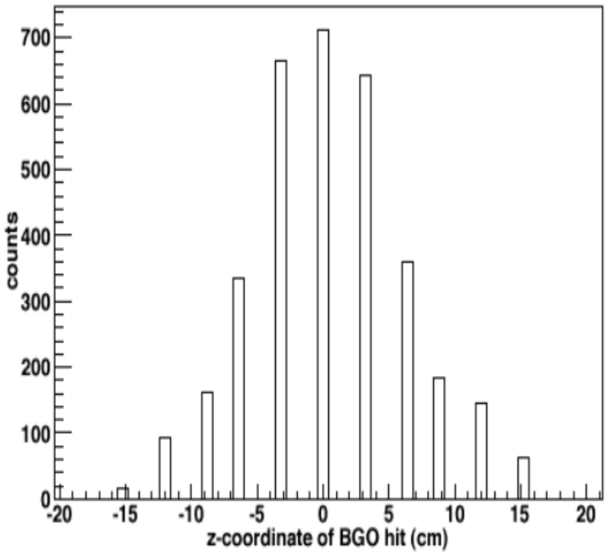
- **BGO** ($Bi_4Ge_3O_{12}$) array (30 detectors)
- High γ-ray detection efficiency (40 to 80%, depending on multiplicity & energy)
- Combined with TOF → **low random** coincidence rate!
- **Caveat:**
  - Rely on **simulation** for detection efficiency

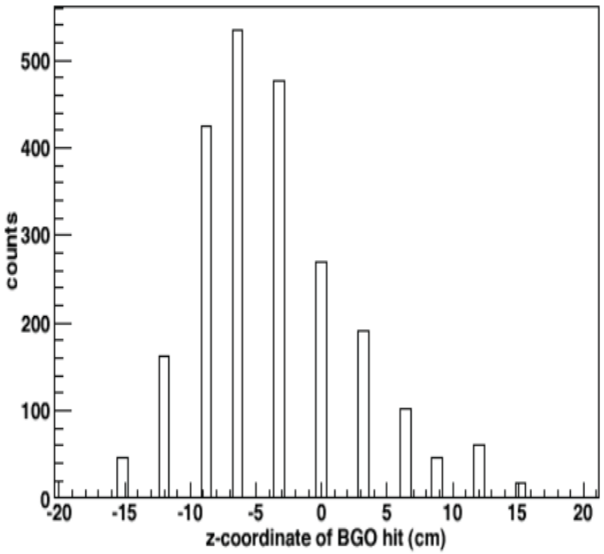
  → dominates syst. error of the experiment!

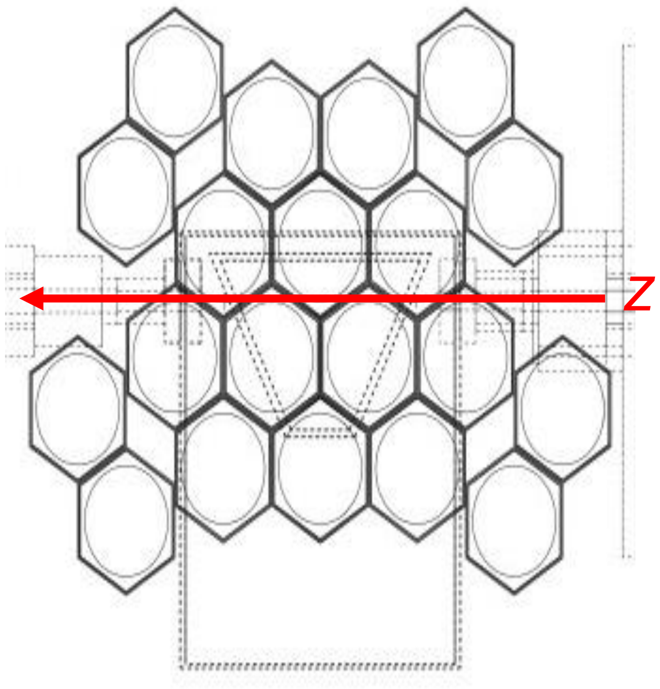
  - Limited γ-ray energy resolution (FWHM ~9%)
- **Segmented** BGO array along beam axis → Information about location of reaction
- BGO hit pattern → **resonance energy** (0.5%)



BGO “Hit pattern” Method

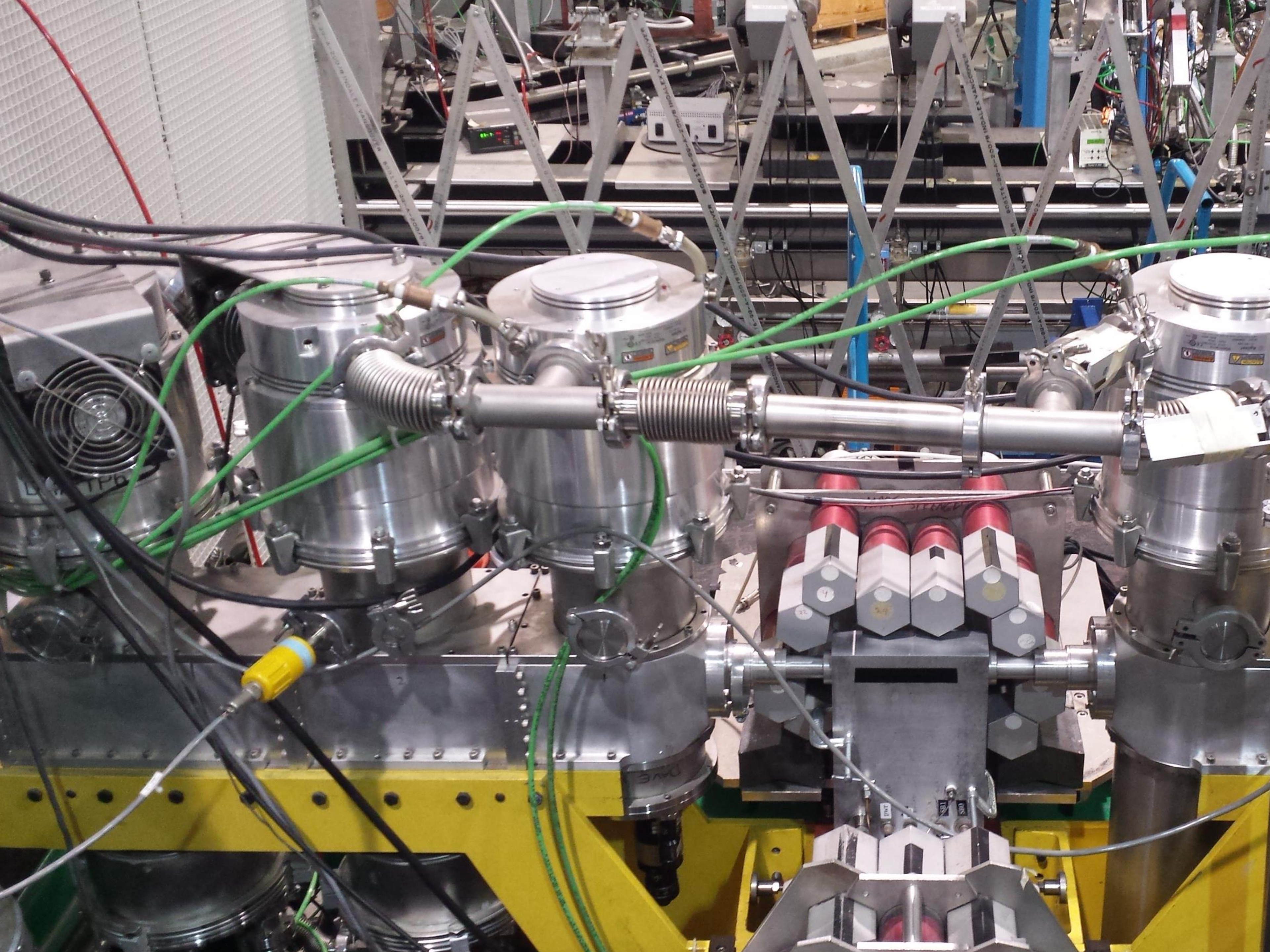




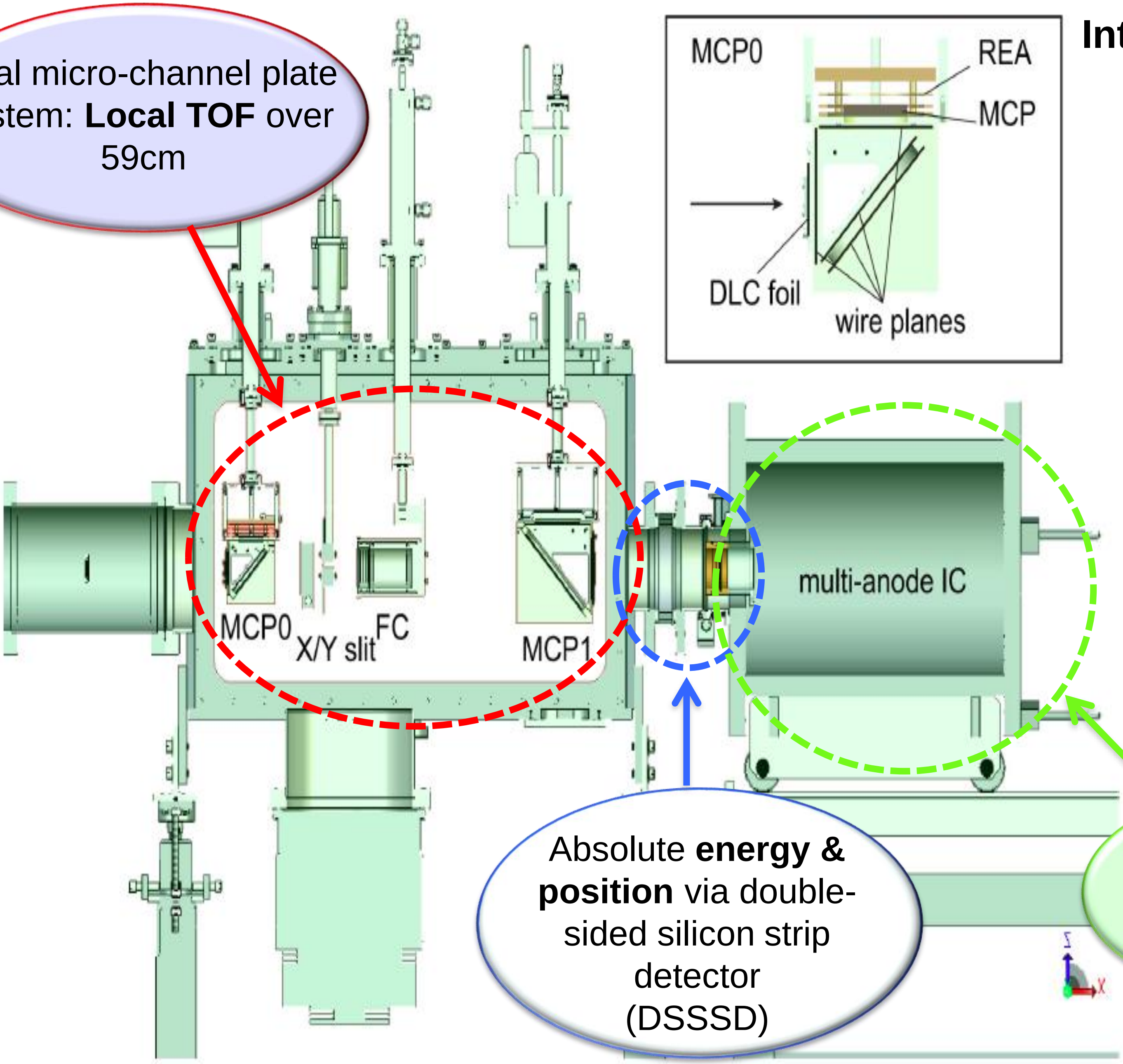


Use BGO crystal z-coordinate to extract resonance position within extended gas target …..but needs sufficient statistics

UPGRADE to LaBr would allow method using timing (BGO timing too slow)



Focal plane detectors –
particle detection and identification



Dual micro-channel plate system: **Local TOF** over 59cm

Interchangeable end detectors IC or DSSSD (Depending on reaction)

- Particle ID
- Local TOF
- ΔE/E, Total E

Absolute **energy & position** via double-sided silicon strip detector (DSSSD)

ΔE-E in ionization chamber for **Z-identification**

^{18}F(p,γ)^{19}Ne - Event identification

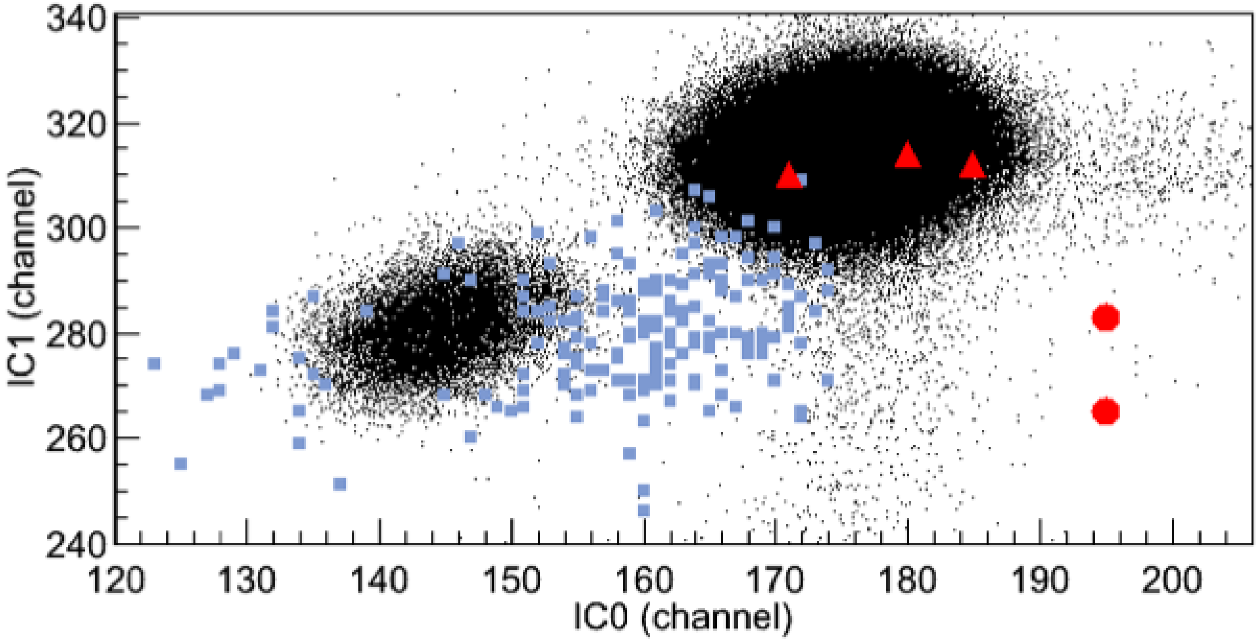


FIG. 1. Energy loss vs. energy loss plot obtained from the first two anodes in the IC. The attenuated beam run is shown in black and two well-separated loci are clearly visible signifying the presence of both ^{18}F and ^{18}O. Circles (triangles), both red online, correspond to observed ^{19}Ne (^{18}F) events when the separator was tuned to recoils. Squares (blue online) correspond to ^{19}F recoils during the separate ^{18}O beam run.

Beam intensity ~ 10^6 pps – too low for reliable FC reading.

Normalisation using elastic scattering.

$^{58}Ni(p,\gamma)^{59}Cu$ measurement

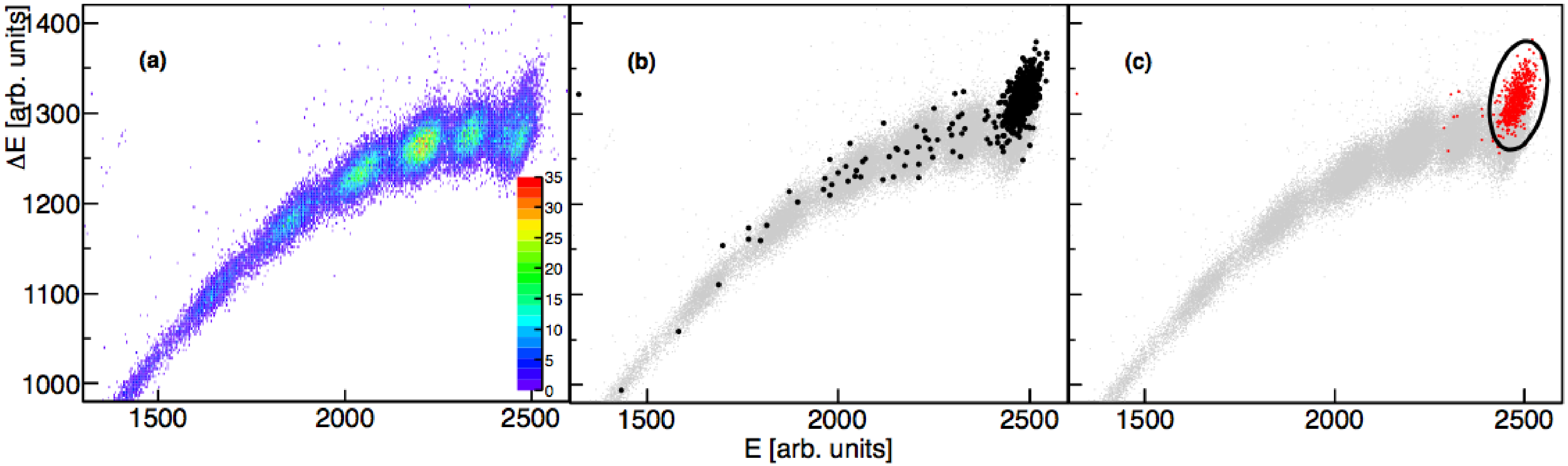
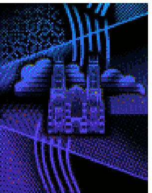


Fig. 2. Energy loss vs. total energy for (a) singles, (b) recoils coincident with γ-rays (black circles) and (c) recoils coincident with γ-rays with additional condition on separator and MCP time-of-flight (red squares). In panels (b) and (c) the shaded area denotes the singles histogram plotted for reference. Black contour denotes the range of true events.

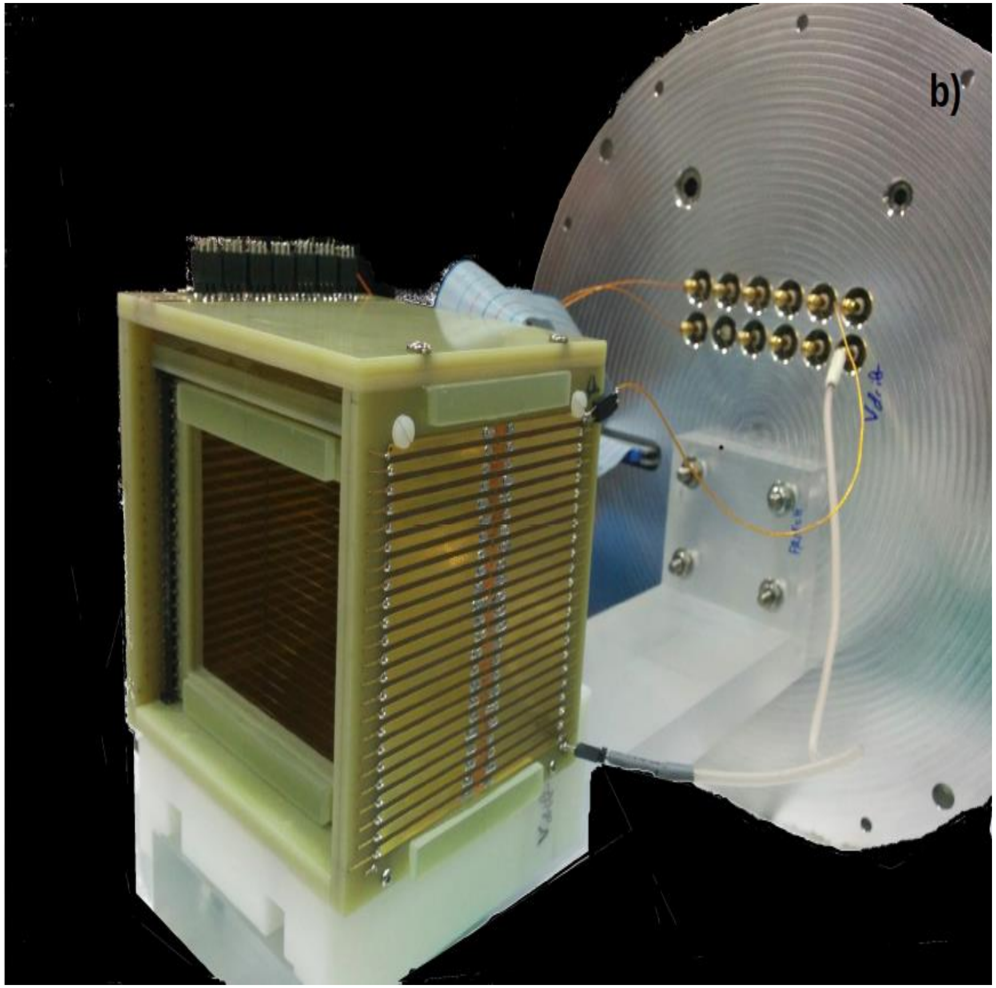


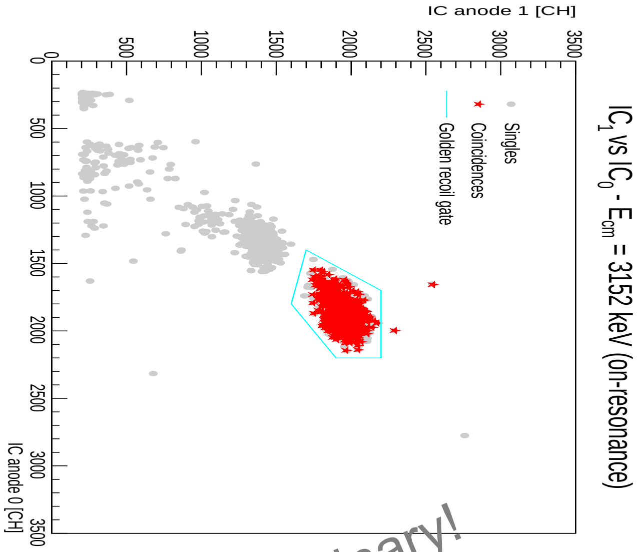
Resonance strength = 0.303(65) eV

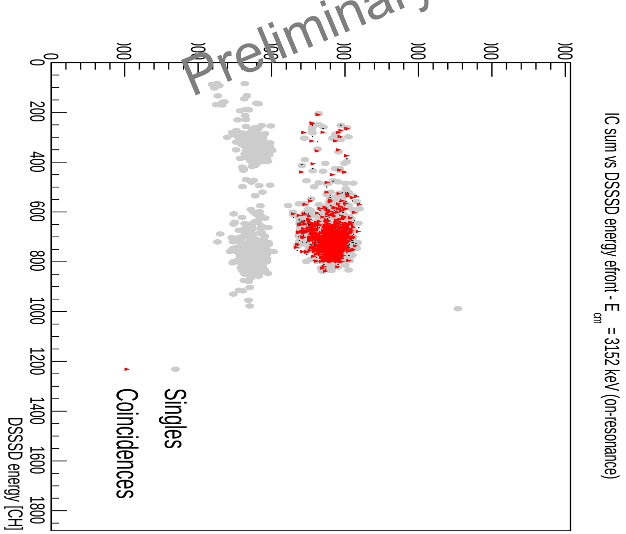
A. Simon et al., Ep. J.

Hybrid detector

Combine properties of IC (ΔE) and DSSSD (operation, position sensitivity & resolution) in hybrid detector







Data analysis

Data analysis

To extract a cross section or resonance strength, we need to know:

Corrected yield -

- charge state fraction – measured or formula based on previous DRAGON data
- gas target transmission efficiency – measured using Faraday Cups
- separator transmission efficiency – GEANT simulation
- focal plane detector efficiences - measured
- DAQ deadtime - measured
- BGO efficiency, if running coincidences – GEANT simulation based on data

Beam normalisation

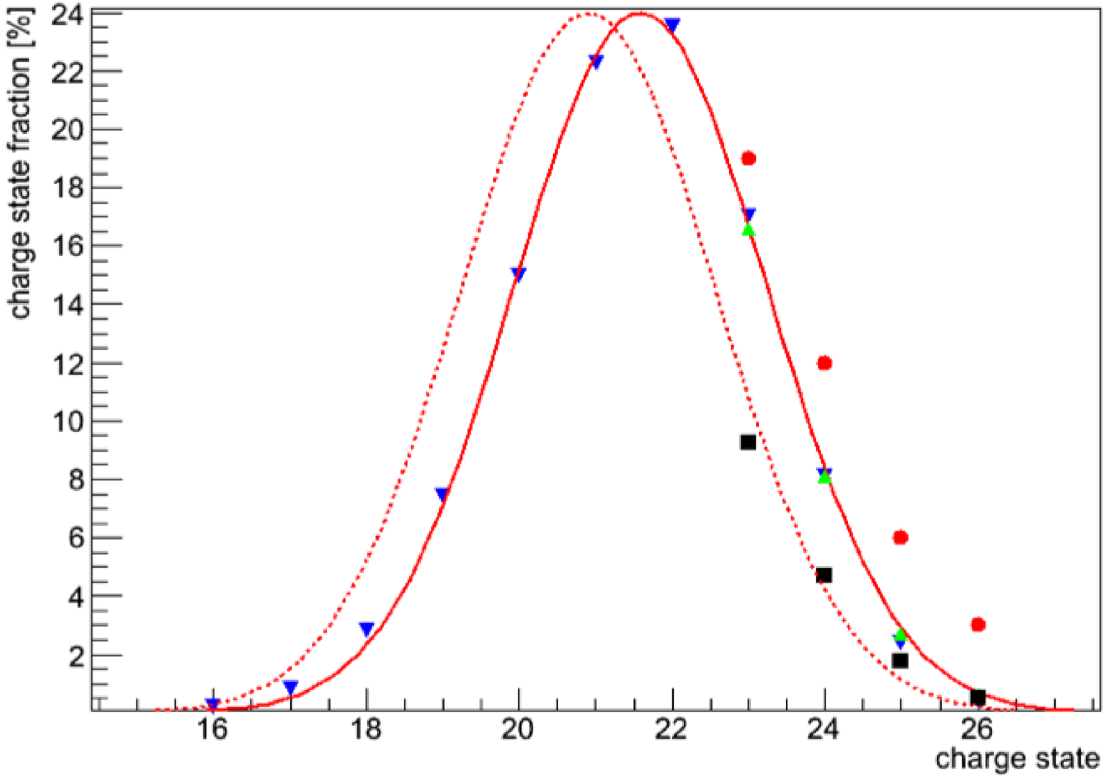
- Intensity measured in Faraday cups before and after every run
- Relative changes in intensity from elastic scattering rate in target

Stopping power – SRIM code shows 20-50% deviation from experiment

- measure energy loss across target - using MD1 with and without gas
- know effective length of target – extensive studies using sources and known resonances

^{84}Kr charge state distribution measurement

Courtesy of Anna Simon



Blue triangles – my Sayer code
Green triangles – TUDA CSD code
Red circles – DRAGON Sayer code
Black squares – measured data

My Sayer code agrees with TUDA CSD → I'm going to use it for other ions.

Solid red line – Gaussian fit to my Sayer code
Dashed red line – the fit shifted to match the experimental results (the same area under curve and sigma, just varied the centroid)

Useful tools: rossum

•Automated running

- runs started and stopped automatically every hour
- key parameters recorded and saved into data stream
- between each run, all Faraday cup readings taken
- warnings by text and email
- allows remote running with stable beam – no night shifts!

Summary

DRAGON designed to study **nuclear reactions** relevant for nuclear astrophysics in **inverse kinematics**

“Strengths”

- Gas target (variable gas & pressure)
  - → enables radioactive beam exp.
- High beam suppression
- Location (access to beams)
- γ-coincidence measurements
- Variable end-detector system
- TOF (local & separator)
- RF Timing
- Beam Diagnostics
- Stopping power measured

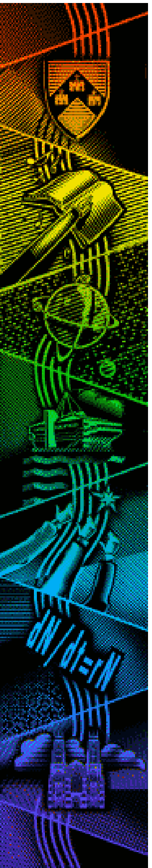
“Weaknesses”

- Limited rigidity

→ Limitations for higher masses

- Simulation required for detection efficiency
- Limited γ-energy resolution w BGO array
- Limited angular acceptance
- Due to extended target, separator transmission can depend on resonance position in gas target

Successful DRAGON programme for over 15 years



Reaction	Motivation	Intensity (s^{-1})	Purity (beam:cont.)
$^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$	1.275 MeV line emission in ONe novae	5×10^{9}	100%
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	Helium burning in red giants	3×10^{11} to 1×10^{12}	
$^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
$^{12}\mathrm{C}(^{12}\mathrm{C},\gamma)^{24}\mathrm{Mg}$	Nuclear cluster models	3×10^{11}	
$^{40}\mathrm{Ca}(\alpha,\gamma)^{44}\mathrm{Ti}$	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 – 200:1
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	1.275 MeV line emission in ONe novae	5×10^{7}	1:20 – 1:1,000
$^{17}\mathrm{O}(\alpha,\gamma)^{21}\mathrm{Ne}$	Neutron poison in massive stars	1×10^{12}	
$^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$	511 keV line emission in ONe novae	2×10^{6}	100:1
$^{33}\mathrm{S}(p,\gamma)^{34}\mathrm{Cl}$	S isotopic ratios in nova grains	1×10^{10}	
$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$	Stellar helium burning	1×10^{12}	
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	Explosive hydrogen burning in novae	1×10^{12}	
$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$	Solar neutrino spectrum	5×10^{11}	
$^{58}\mathrm{Ni}(p,\gamma)^{59}\mathrm{Cu}$	High mass tests (p-process, XRB)	6×10^{9}	
$^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	SNII contribution to galactic ^{26}Al	2×10^{5}	1:10,000
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$	Ca/K/Ar production in novae	2×10^{7}	1:1
$^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$	^{19}F abundance in nova ejecta	2×10^{7}	1:1 to 4:1
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	NeNa cycle; explosive H burning in classical novae	2×10^{12}	
$^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$	ν-p process		1:200 to 1:1000

Thank you for your attention

DRAGON core collaboration

Barry Davids, Dave Hutcheon, Chris Ruiz (TRIUMF)
Brian Fulton, Alison Laird (York)
Gavin Lotay (Surrey)
Uwe Greife (Colorado School of Mines)
Ahmed Hussein (UNBC)
Alan Chen (McMaster)

Thanks to Annika Lennarz and and Chris Ruiz for slides.

John D’Auria
1939-2017
TISOL → ISAC
DRAGON

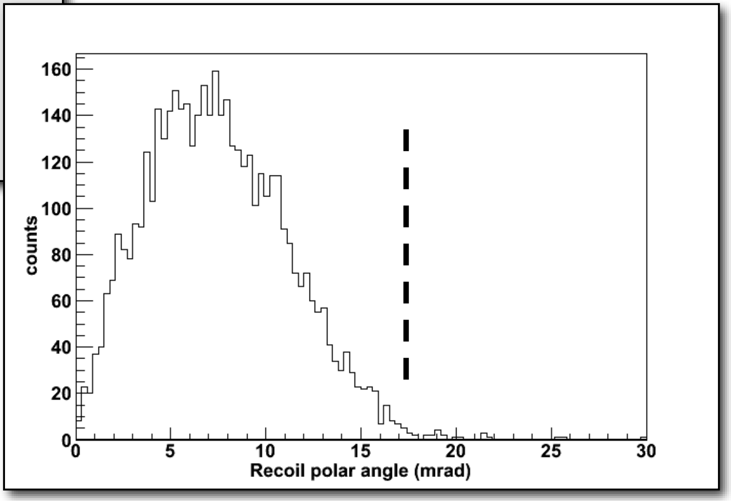
Radiative capture in inverse kinematics

- Radionuclei that can't be made into a target
  - accelerate them, make H or He target.
- Gaseous H_2 or He target
- Detect recoils in coincidence with γ rays
- Measure stopping powers directly (required for $\omega\gamma$)
- Change target thickness easily
- Can make target 'extended'
  - (sensitivity to resonance position ⇒ resonance energy)
- Target does not degrade over time
- Target elastic scattering for normalization

$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T_9)^{-3/2}\omega\gamma\exp\left(-11.605\frac{E_R}{T_9}\right)$$

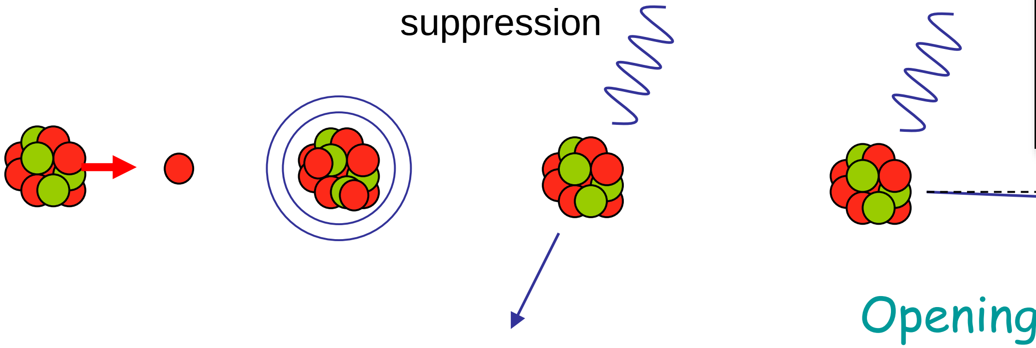
Thick target yield function in inverse kinematics

$$Y(\infty)=\frac{\lambda^2}{2}\frac{M+m}{m}\frac{1}{\epsilon}\omega\gamma$$



Max recoil angle ⇐ kinematics & decay scheme

Need recoil separator with full acceptance *and* high beam suppression



Opening angle and therefore detection efficiency depend on energy.

Separator beam suppression

- **High** intrinsic **beam suppression:** 10^8 to 10^{13} (proton capture)
- Depends on **beam energy & emittance**
- $>10^{14}$ raw suppression demonstrated for ^{3}He(α,γ)^{7}Be
- **Coincidence measurement** with prompt γ-rays & PID cuts & TOF

  → **suppression factor** of ~10^{15} for p-capture & ~$5\text{x}10^{17}$ for α-capture

*Beam suppression is **NOT** described by a single number, but determined by mass & charge difference, decay mode, energy, detectors, etc…*

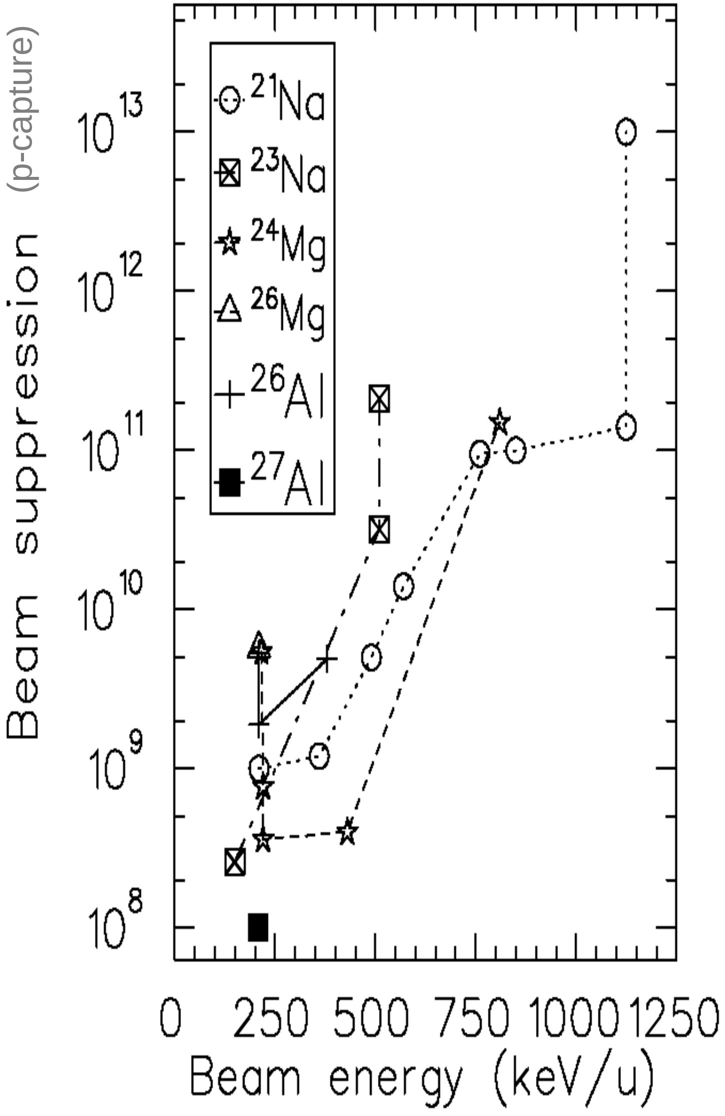


Figure from D. Hutcheon et al. NIMRB 266 (2008)

Event identification

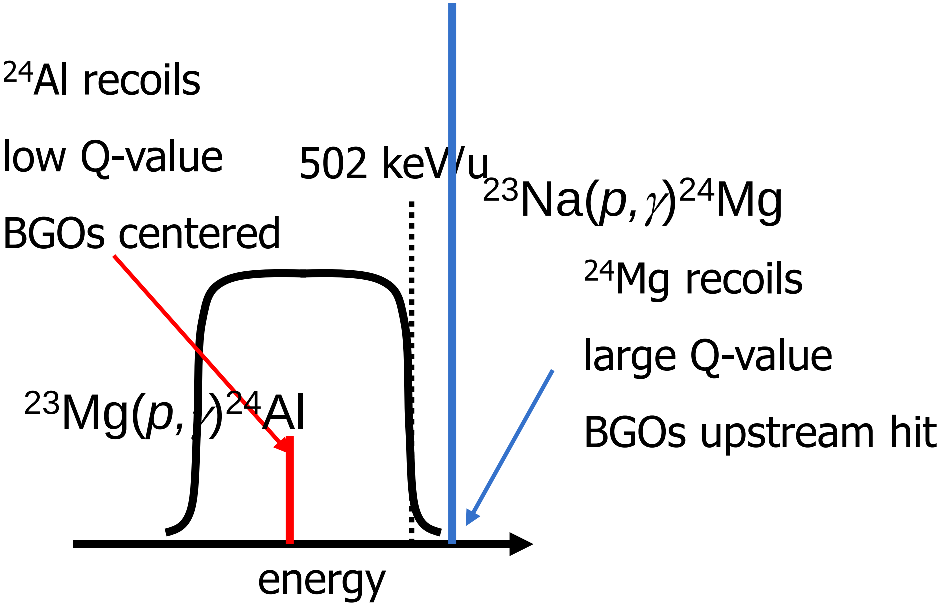
- Energy / energy loss at focal plane
- MCP local time of flight
- RF timing

- BGO coincidences
  - Separator time of flight
  - BGO energy

Particle ID: dealing with contaminants, background

- ISOL beams may contain **isobaric contaminants**
- Tradeoff between ΔM/M of mass separator to transmission (beam intensity)

ΔE-E & BGO distr. allows separation of isobars
& isobaric reactions



^{24}Al recoils
low Q-value
BGOs centered

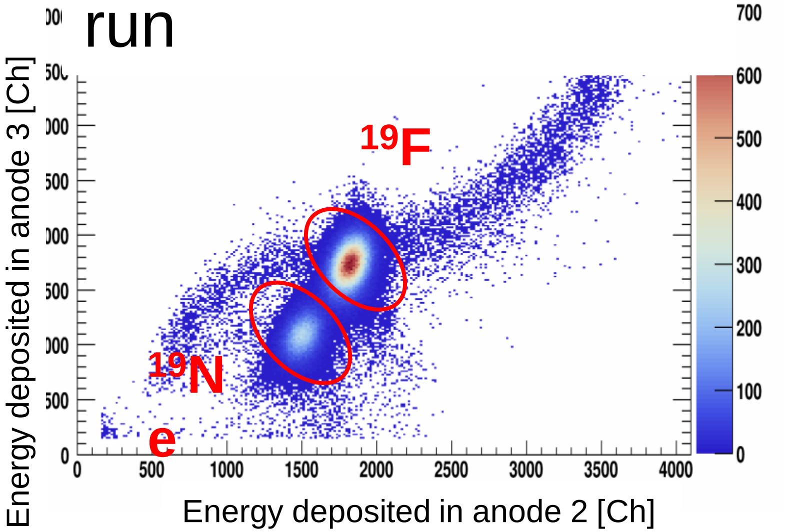
502 keV/u

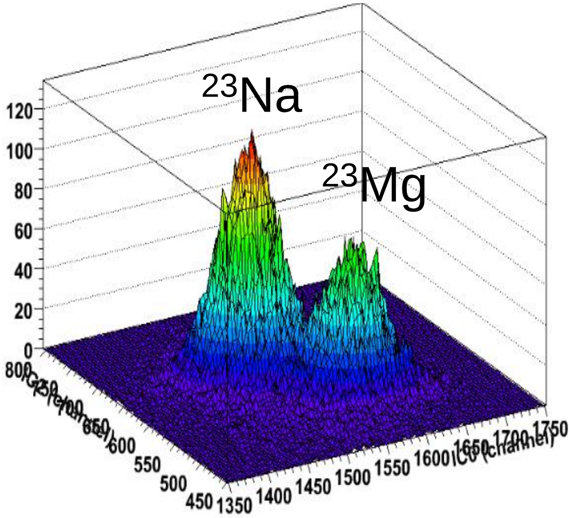
^{23}Na(p,γ)^{24}Mg

^{24}Mg recoils
large Q-value
BGOs upstream hit

^{23}Mg(p,γ)^{24}Al

Attenuated beam run





ΔE vs E (ionization chamber)