Fundamentals of Experimental Techniques

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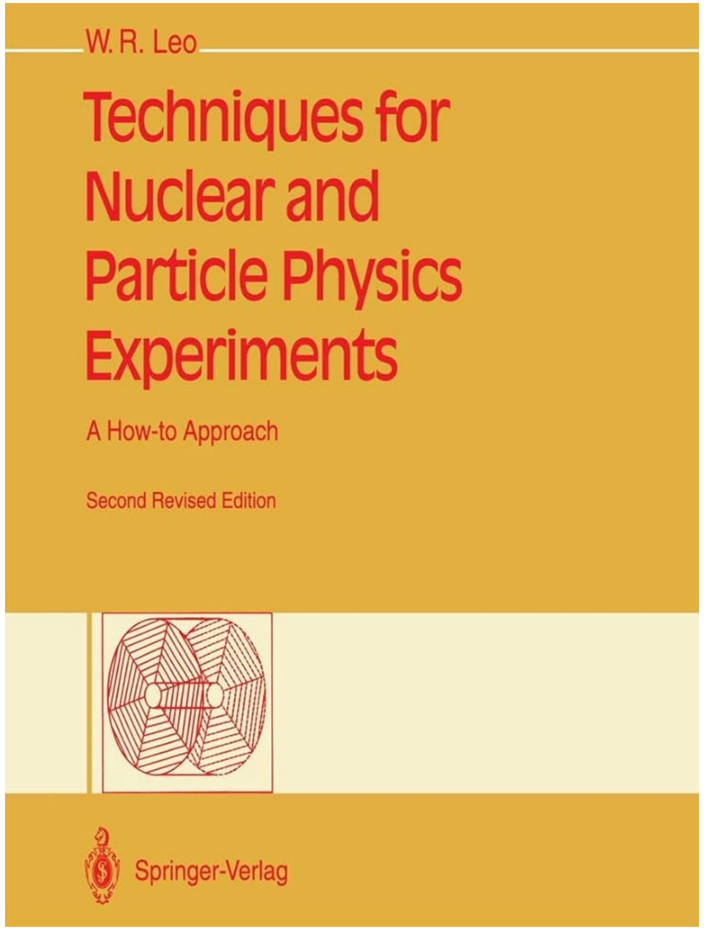
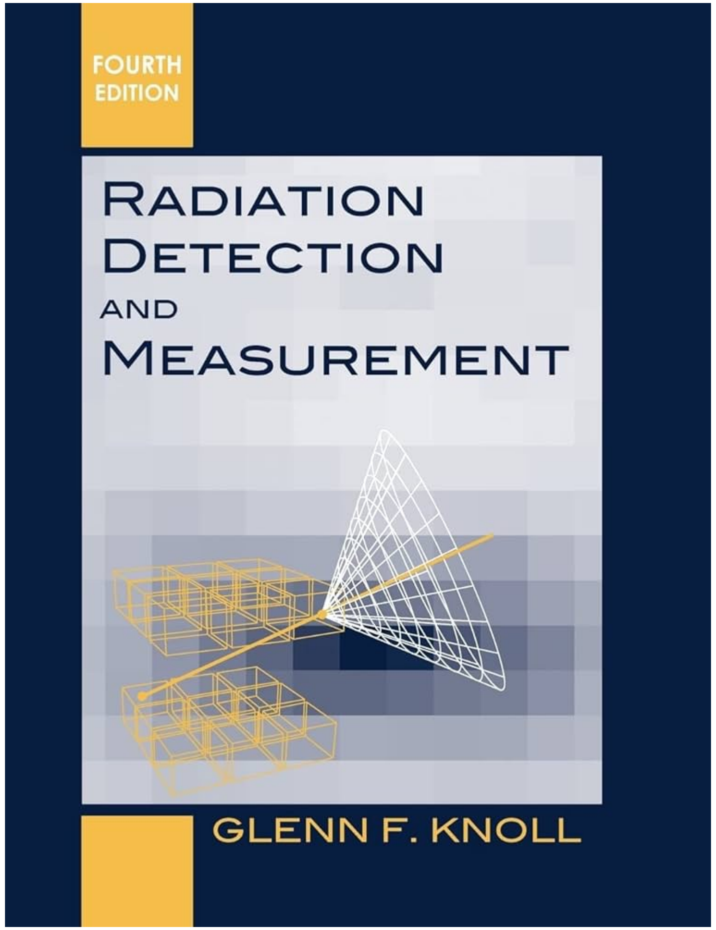
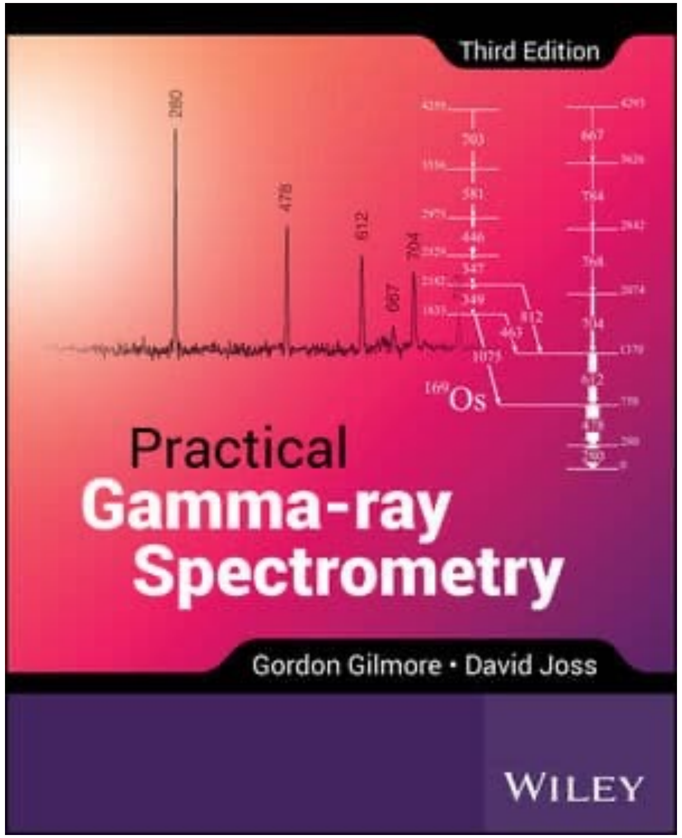
Ohio University

Exotic Beam Summer School
June 25, 2026

Resources for Experimental Nuclear Science







I want to do an experiment ☺

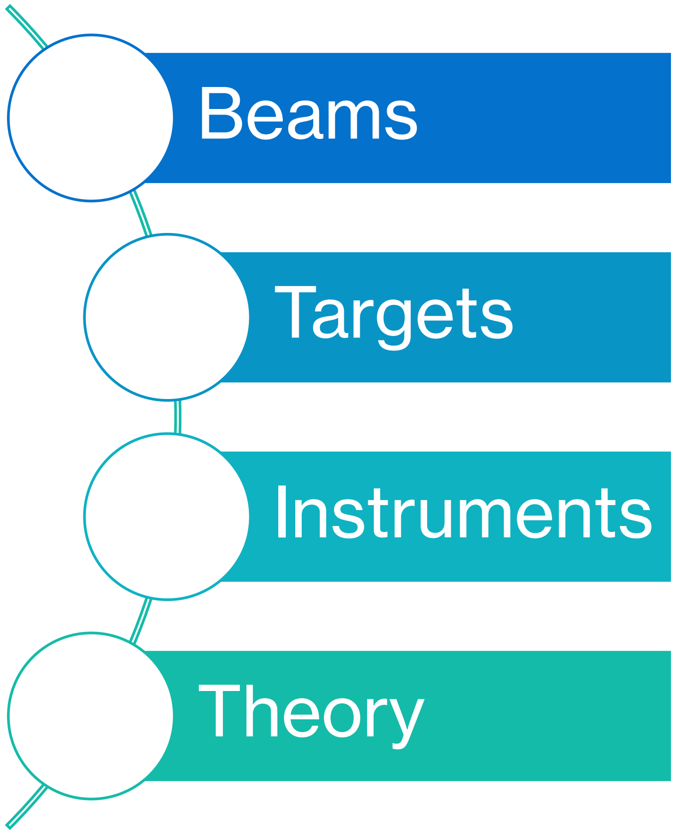
What do I need?

- Planning
- Detectors
- Money (Grant funding)
- Simulations
- Theory
- Motivations
- DAQ
- Beam & Targets
- People

*no particular order

The Recipe

- **Accelerator to provide the beam (reactors too)**
  - stable/radioactive, pure/cocktail, intensity
  - energies from keV to 100s MeV/A
- **A target***
  - solid/liquid/gaseous, density/thickness
  - active targets
- **Instruments**
  - HPGe detectors
  - Double-sided strip detectors (Si, Ge)
  - scintillators- magnetic spectrometers
  - gaseous detectors
  - ion traps
  - …
- **Theory**
  - interpretation of the data
  - motivate experiments to validate theories



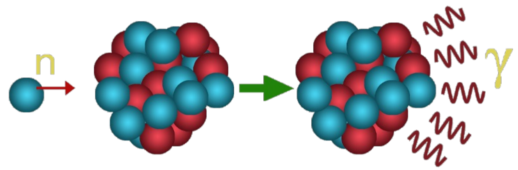
What do you want to measure?

Nuclear Properties
- Masses
- Half-lives
- Branching ratios
- Level densities
- Gamma-ray Strength Functions
- Decay Probabilities
- Decay Branching Ratios
- Isomers
- Fission
- ....

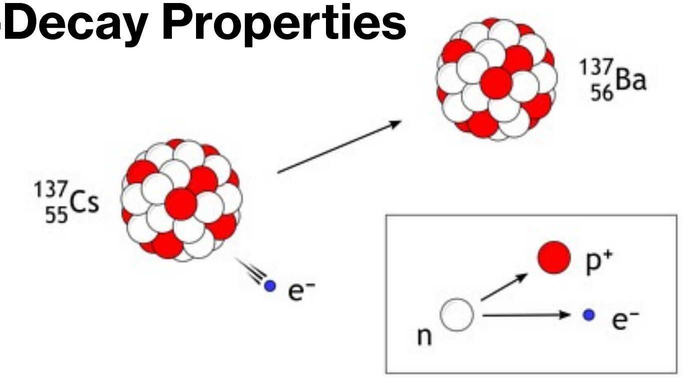
M. Mumpower

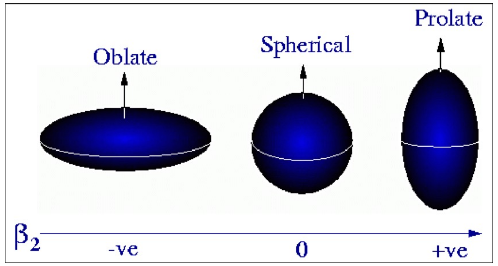
Nuclear Properties

Neutron-Capture Rates



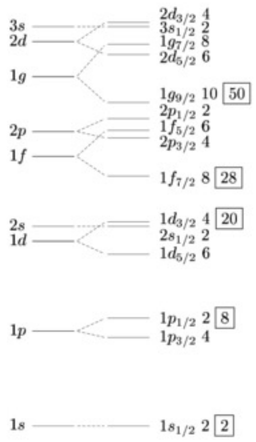
Beta-Decay Properties





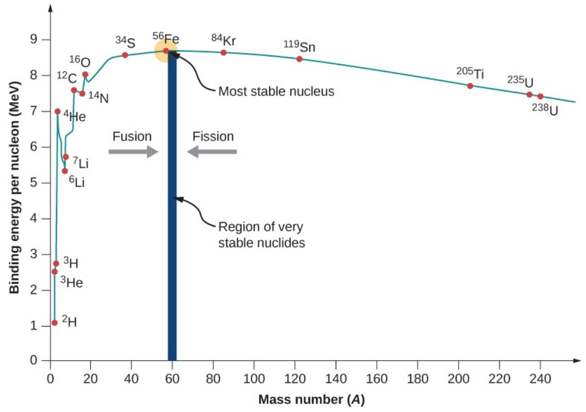
Nuclear Shapes

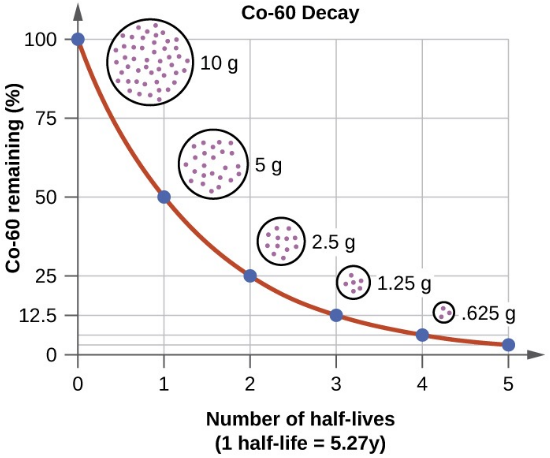
Mass



Level structure

Binding Energy

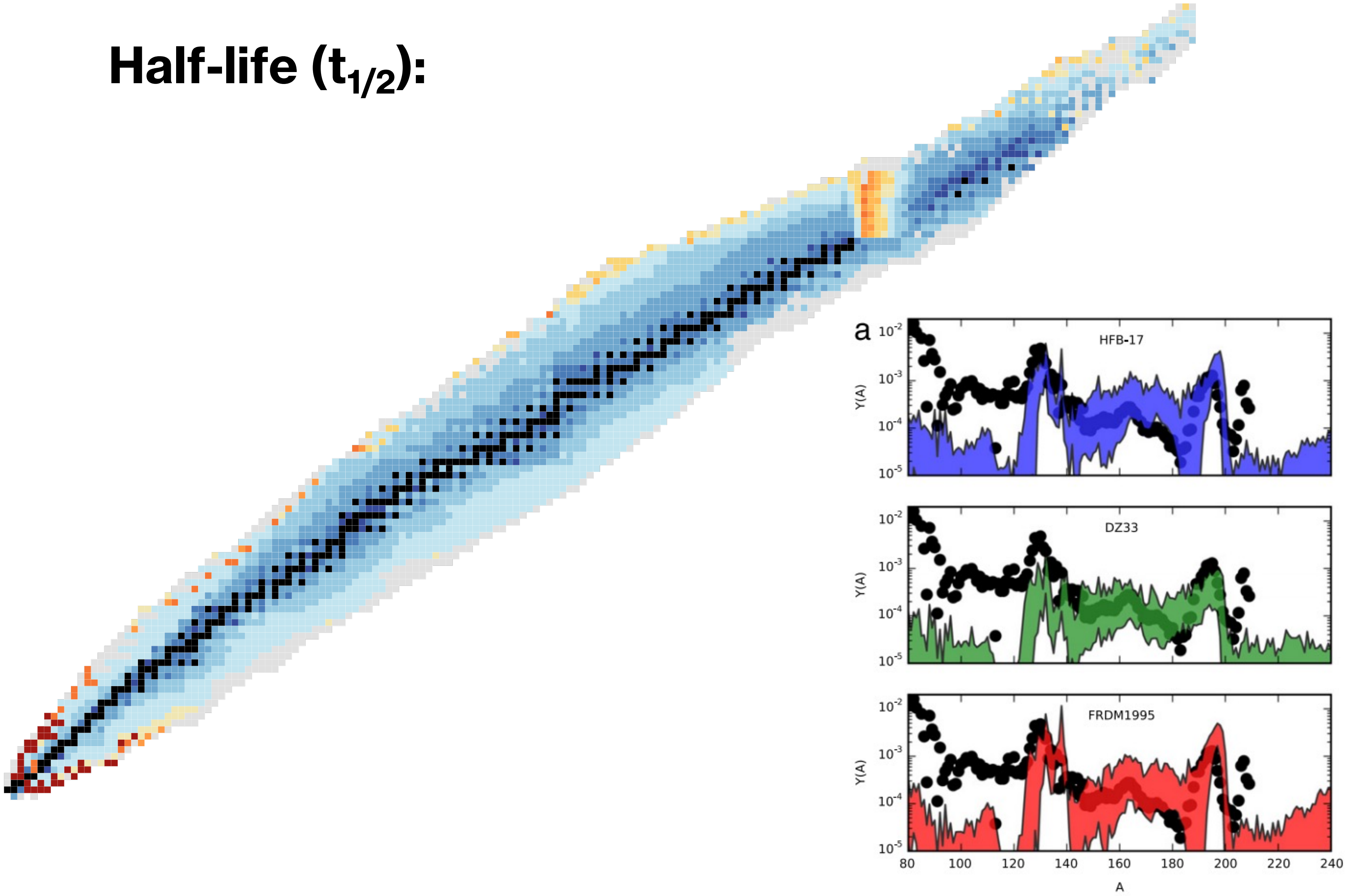




Half-life

Nuclear data: What do we know?

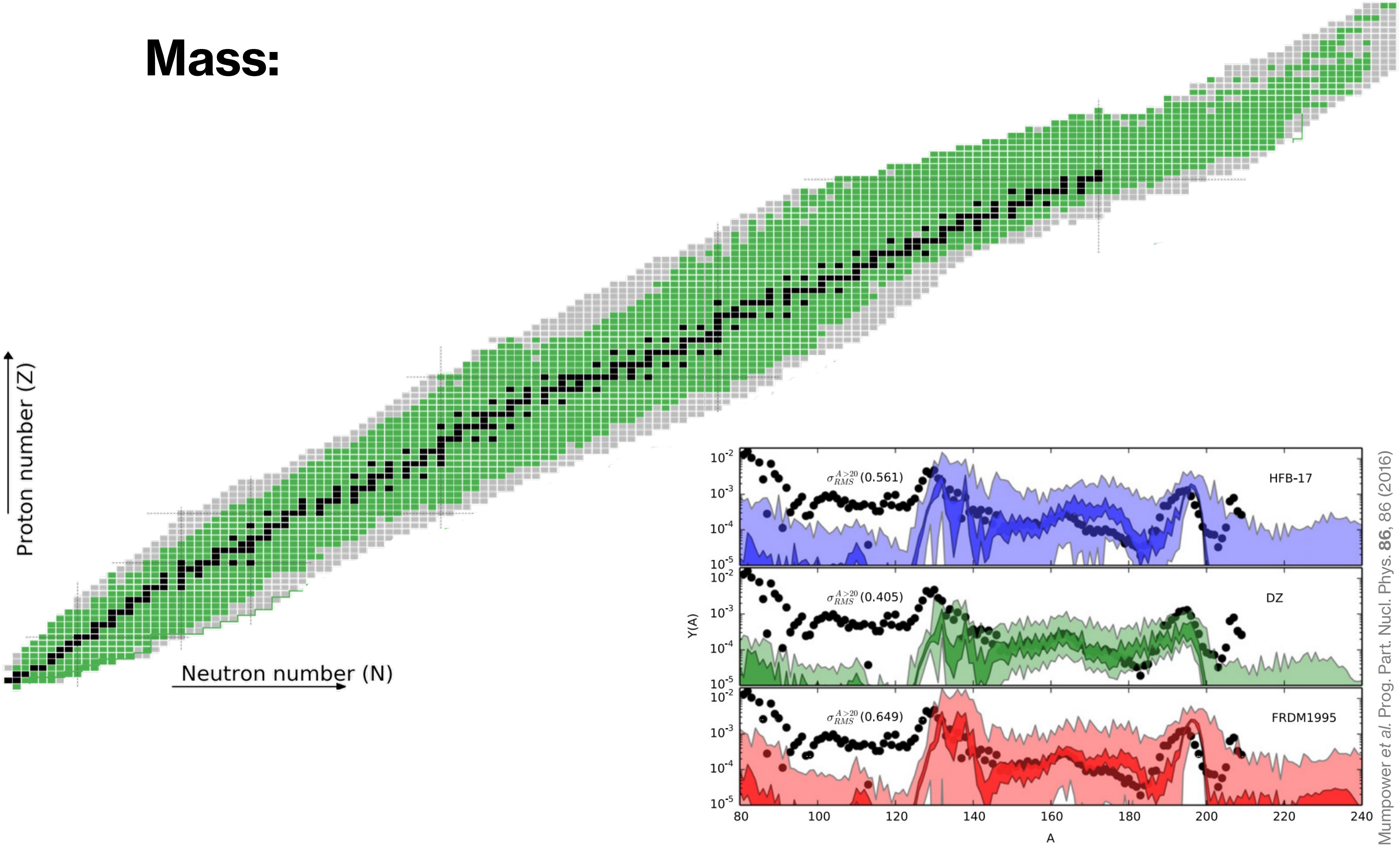
Half-life ($t_{1/2}$):



Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

Nuclear data: What do we know?

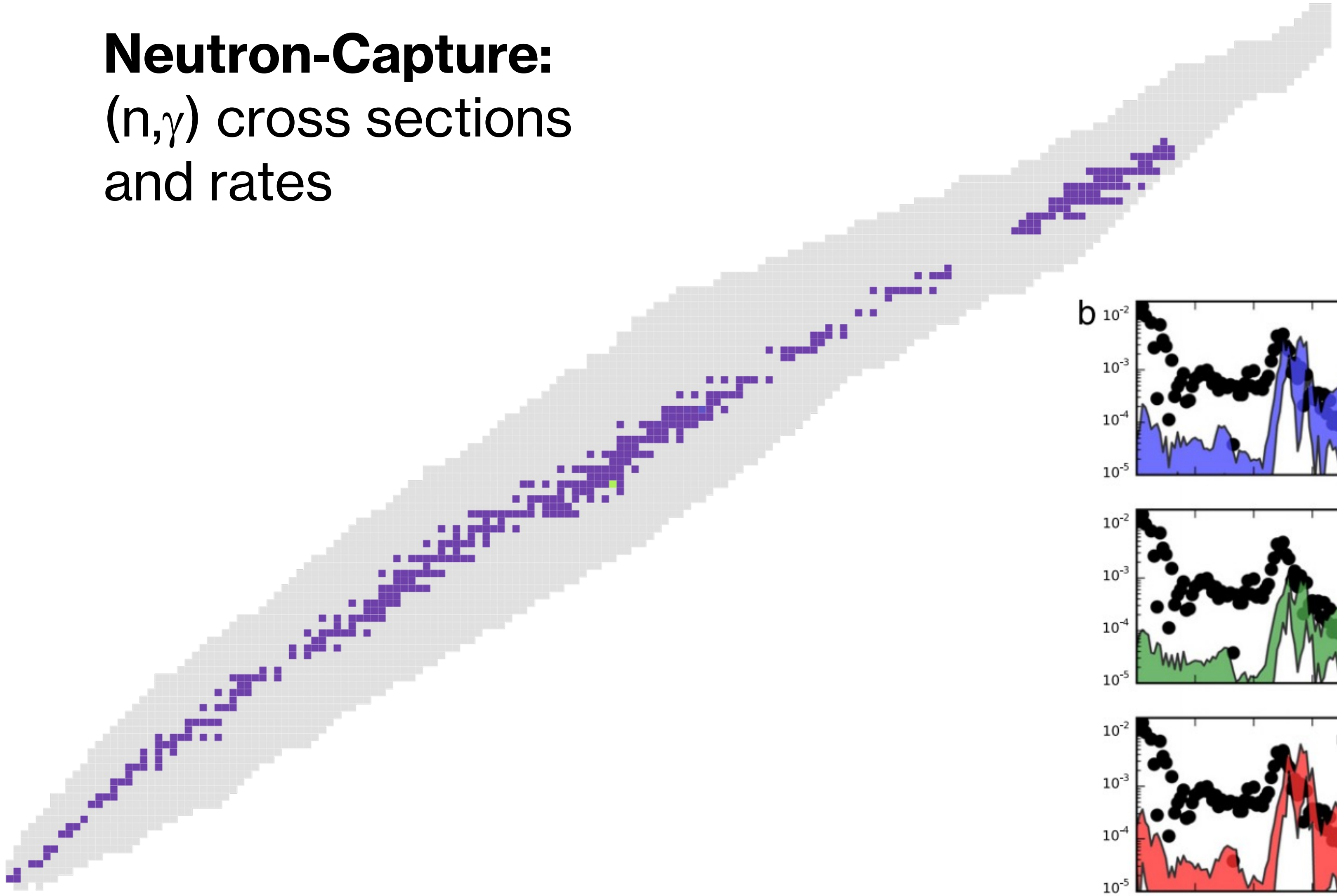
Mass:

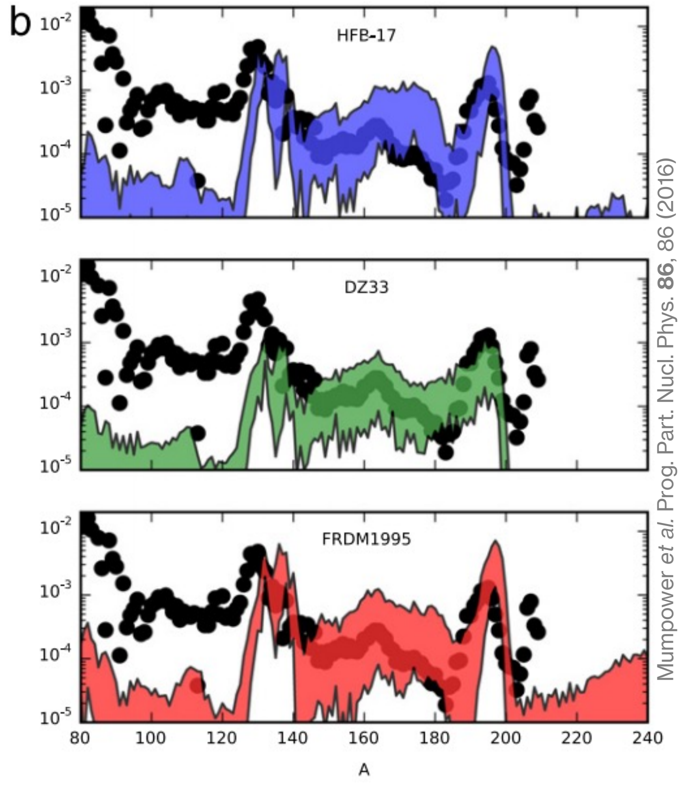


Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

Nuclear data: What do we know?

Neutron-Capture:
(n,γ) cross sections
and rates





Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

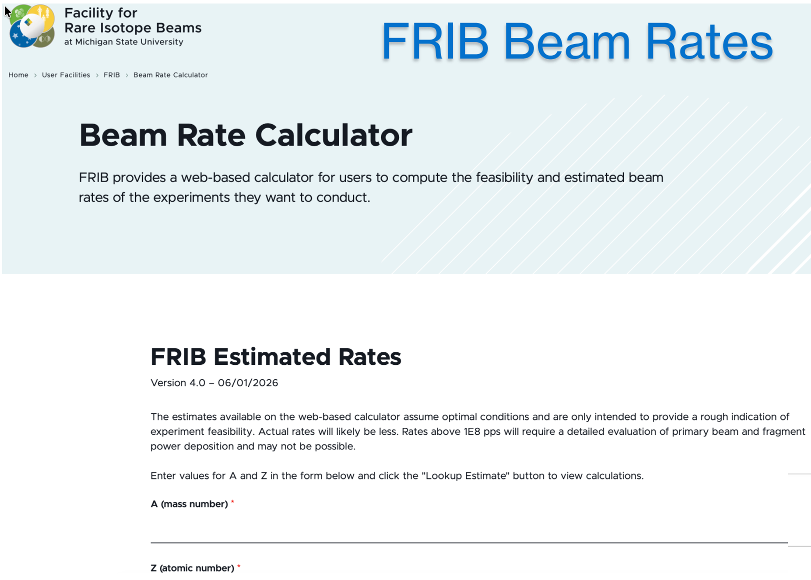
How do we measure nuclear properties/reactions?
Important Considerations

- Motivation
- What kind of beam, what energy
- Facility capabilities
- Beam rates
- Type of experiment (inverse vs. normal kinematics)
- Detector setup
- Availability of beam time

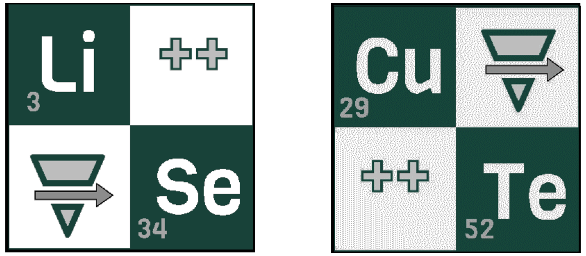
  PAC?

Beam Rates
Is your experiment feasible?

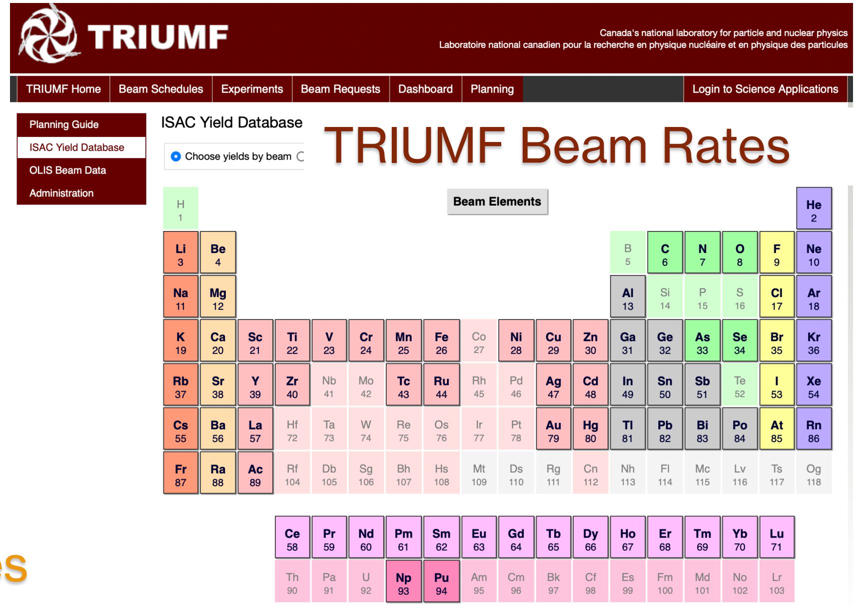
FRIB Beam Rates



https://frib.msu.edu/user-facilities/frib/calculator



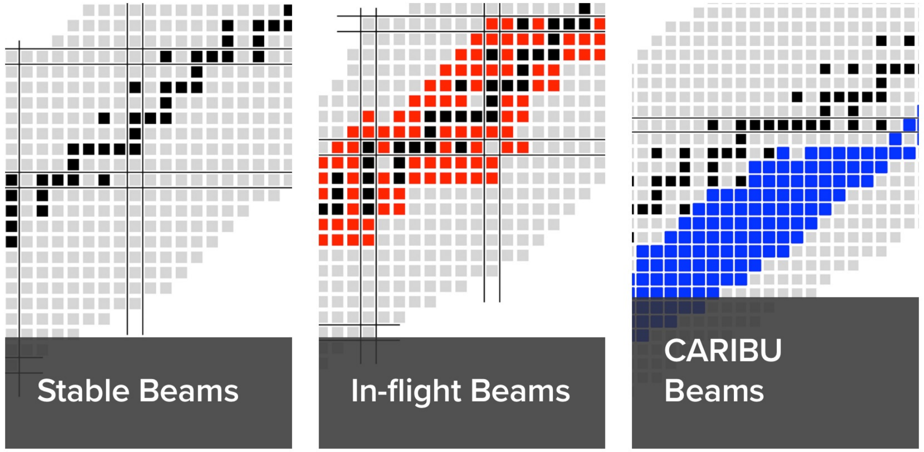
TRIUMF Beam Rates



https://mis.triumf.ca/science/planning/yield/beam

Argonne NATIONAL LABORATORY 80 1946–2026

ANL Beam Rates



https://www.anl.gov/atlas/available-beams

Beam rates often define the type of experiments you can do!

Where is the best place to measure it?
Facilities

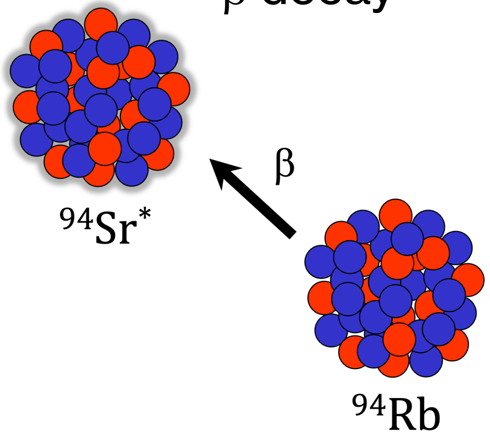
Reactions

- Coulomb excitation (low and high energy)
- (deep-)inelastic scattering, (multi-nucleon) transfer reactions, incomplete fusion
- fusion-evaporation
- target/beam fragmentation
- nucleon knockout

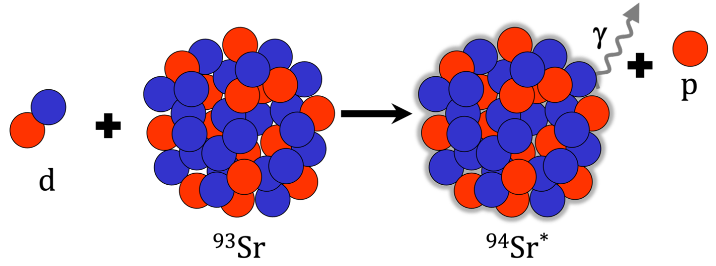
Decay

- alpha-decay
- beta-decay
- fission (spontaneous/induced)

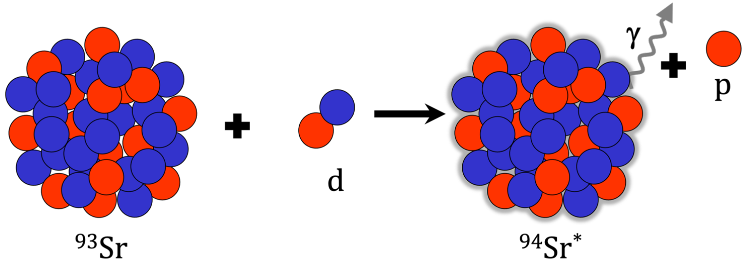
β decay



Normal Kinematics



Inverse Kinematics



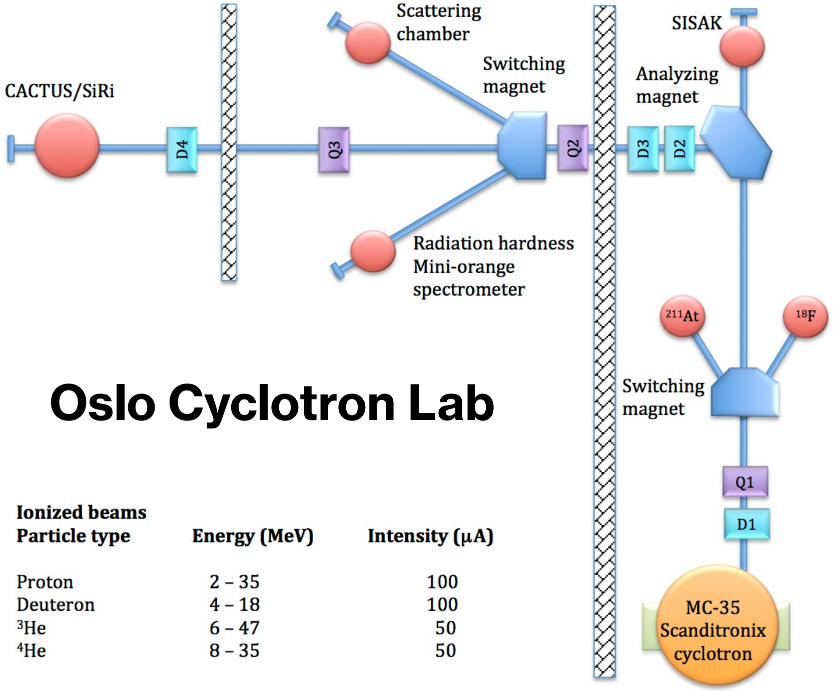
Where can you get stable beams?

Association for Research at University Nuclear Accelerators

Plus others like ANL’s ATLAS facility, iThemba in South Africa, Oslo Cyclotron Lab in Norway, ++

Stable Beam Production

- Linear, Tandem, Cyclotron
- Usually normal kinematics with light ion beams



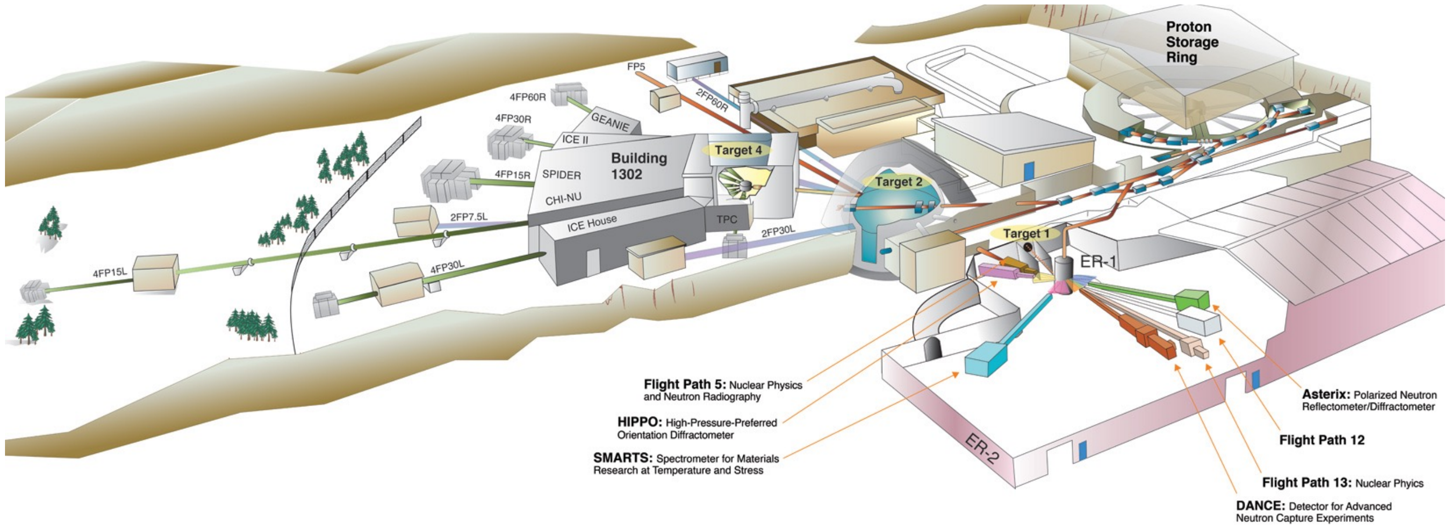
Oslo Cyclotron Lab

Ionized beams Particle type	Energy (MeV)	Intensity (μA)
Proton	2 – 35	100
Deuteron	4 – 18	100
^{3}He	6 – 47	50
^{4}He	8 – 35	50

John Fox Lab (FSU)

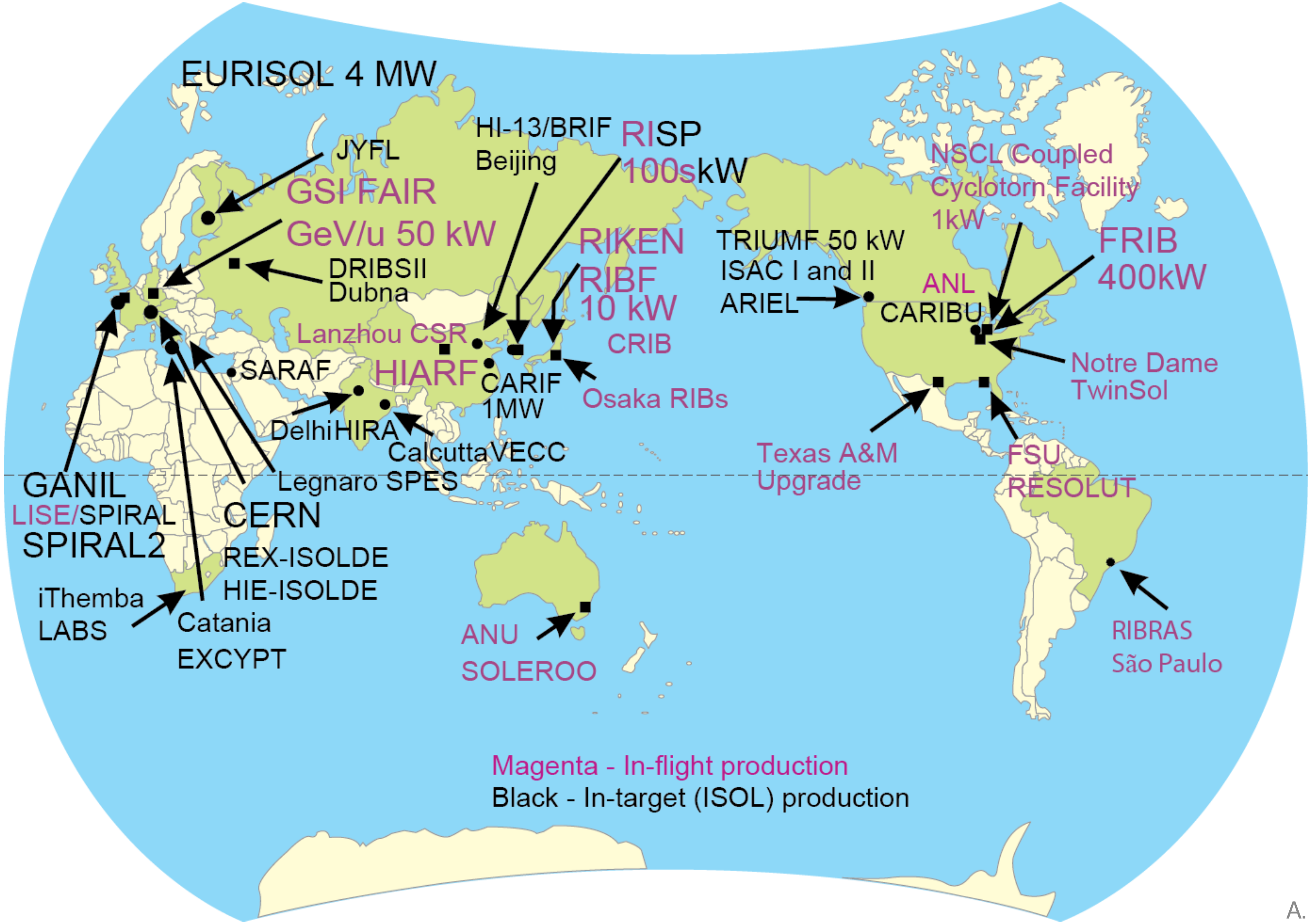
Neutron Beam Facilities

- **Time-of-Flight**: e.g. n_TOF@CERN, LANSCE@ Los Alamos, etc.
  - High energy protons on heavy target, broad energy distribution, pulsed beam.



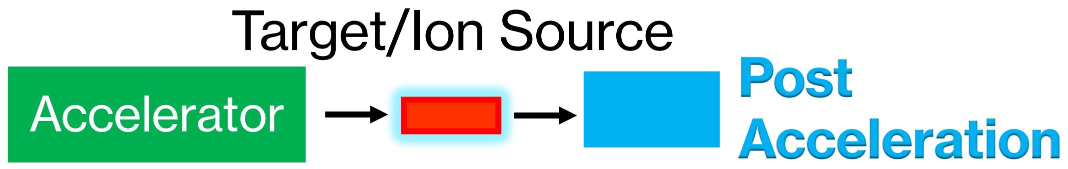
- **Reaction-based, quasi-monoenergetic**: Any low energy facility (e.g. OU)
  - $^{2}H(^{2}H,n)^{3}He$ – Q= 3.3 MeV - E_n= 2.5 MeV
  - $^{3}H(^{2}H,n)^{4}He$ – Q= 17.6 MeV - E_n = 14.1 MeV
  - Broad spectrum too: $^{7}Li(p,n)^{7}Be$, …

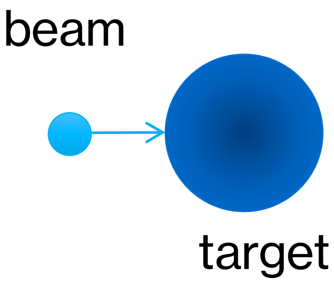
Where can you get radioactive ion *exotic* beams?



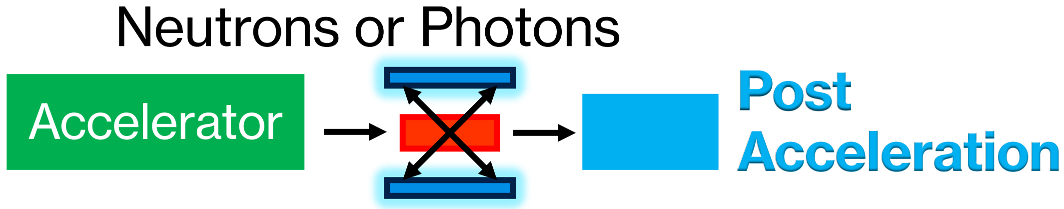
Rare Isotope Beam Production

- Isotope Separation On-Line and fragmentation by light ions

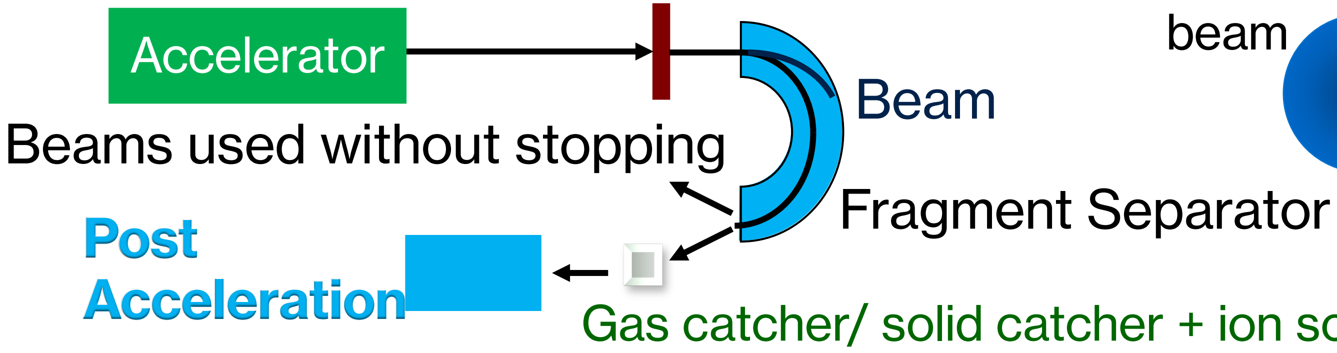


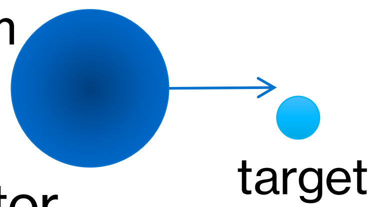


- Neutron induced fission (2-step target)



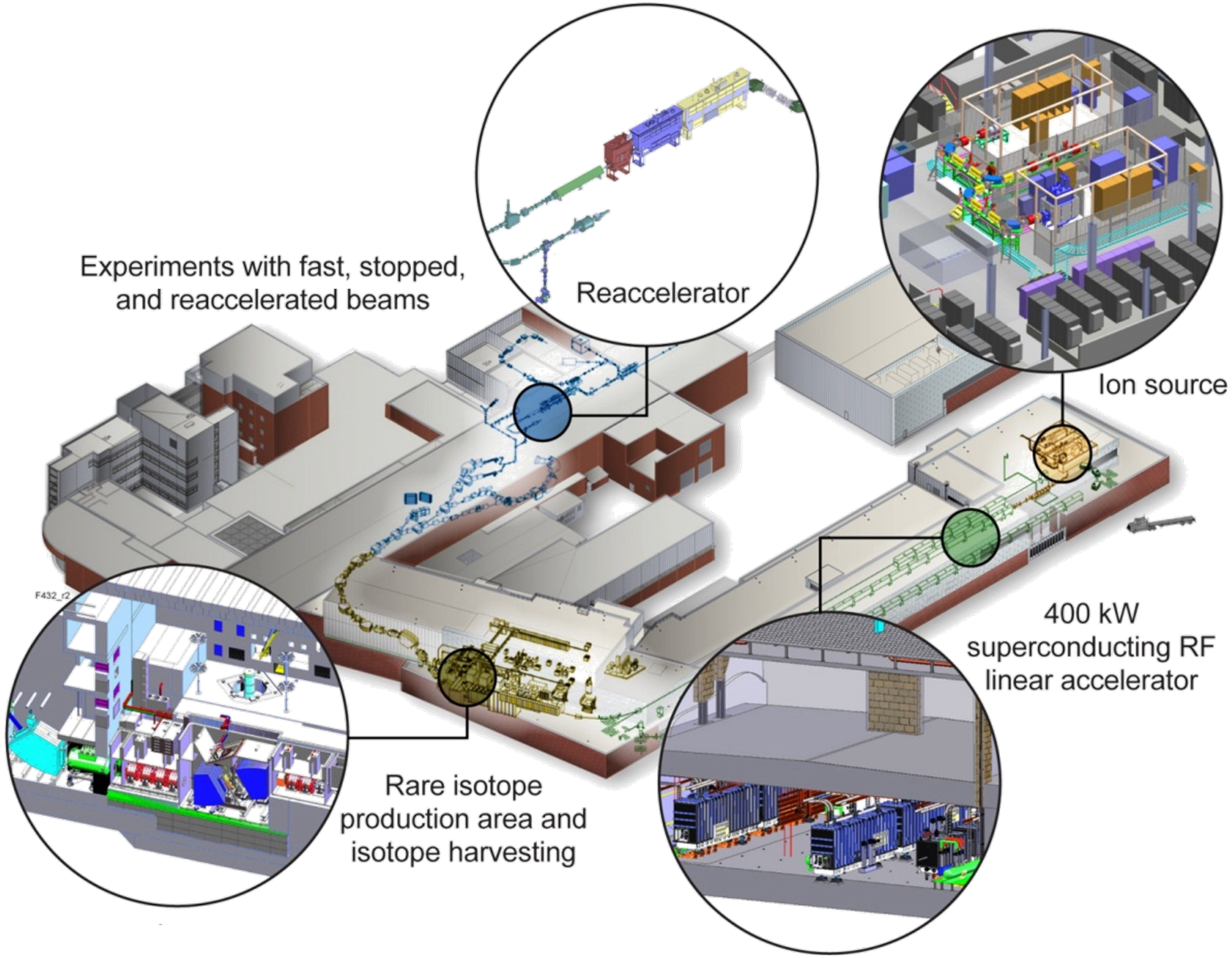
- In-flight Separation following projectile fragmentation/fission

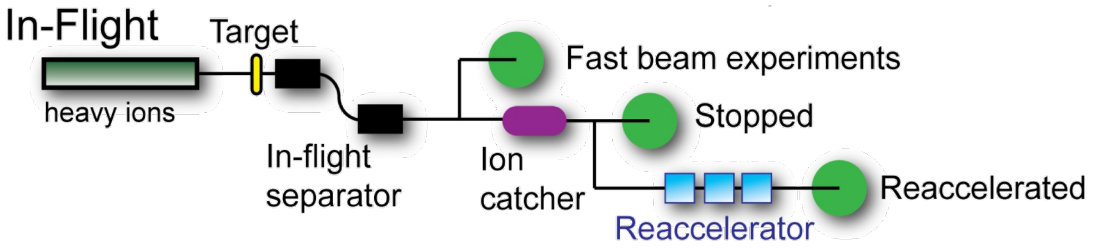




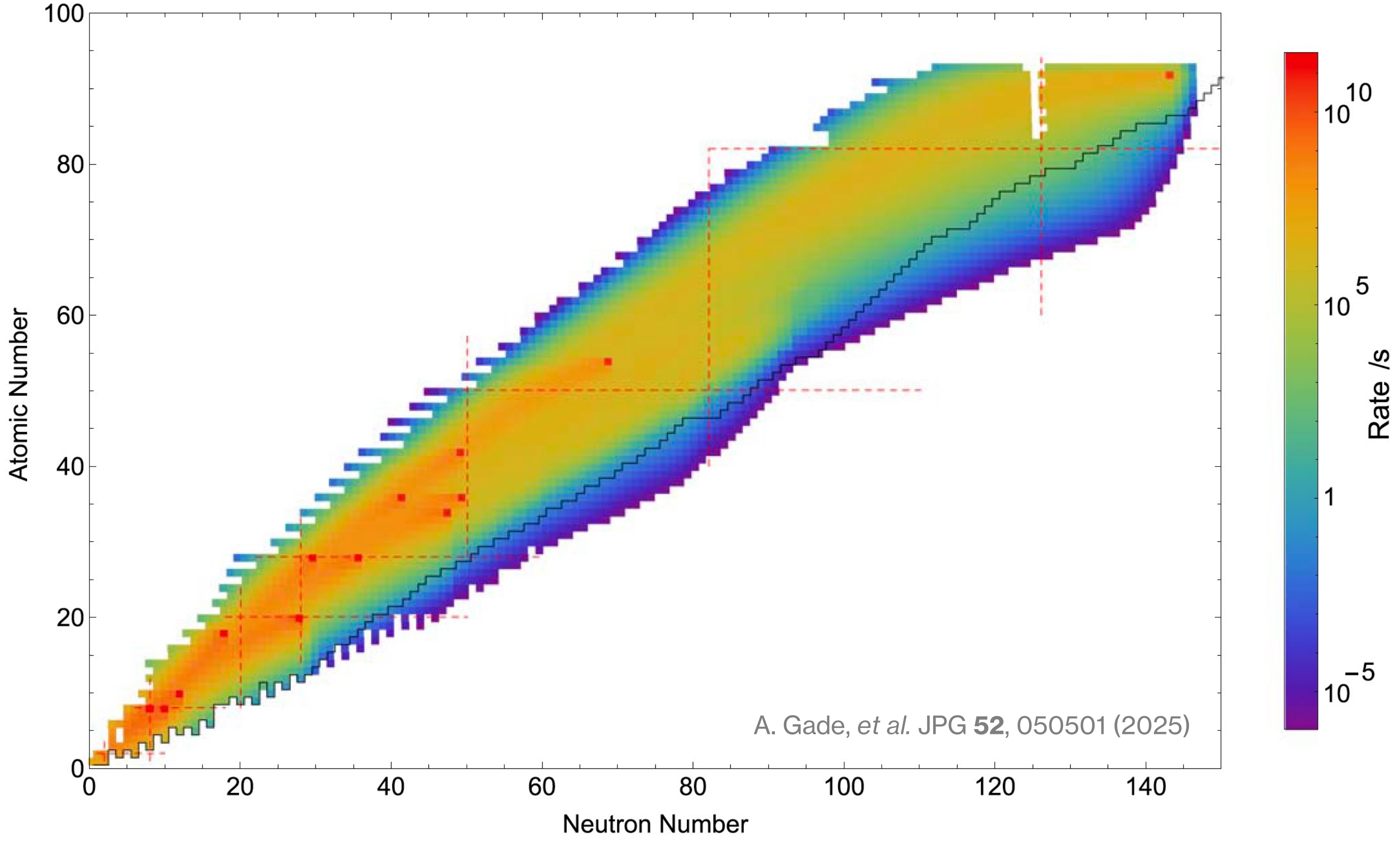
Slide courtesy of Brad Sherrill

Facility for Rare Isotope Beams

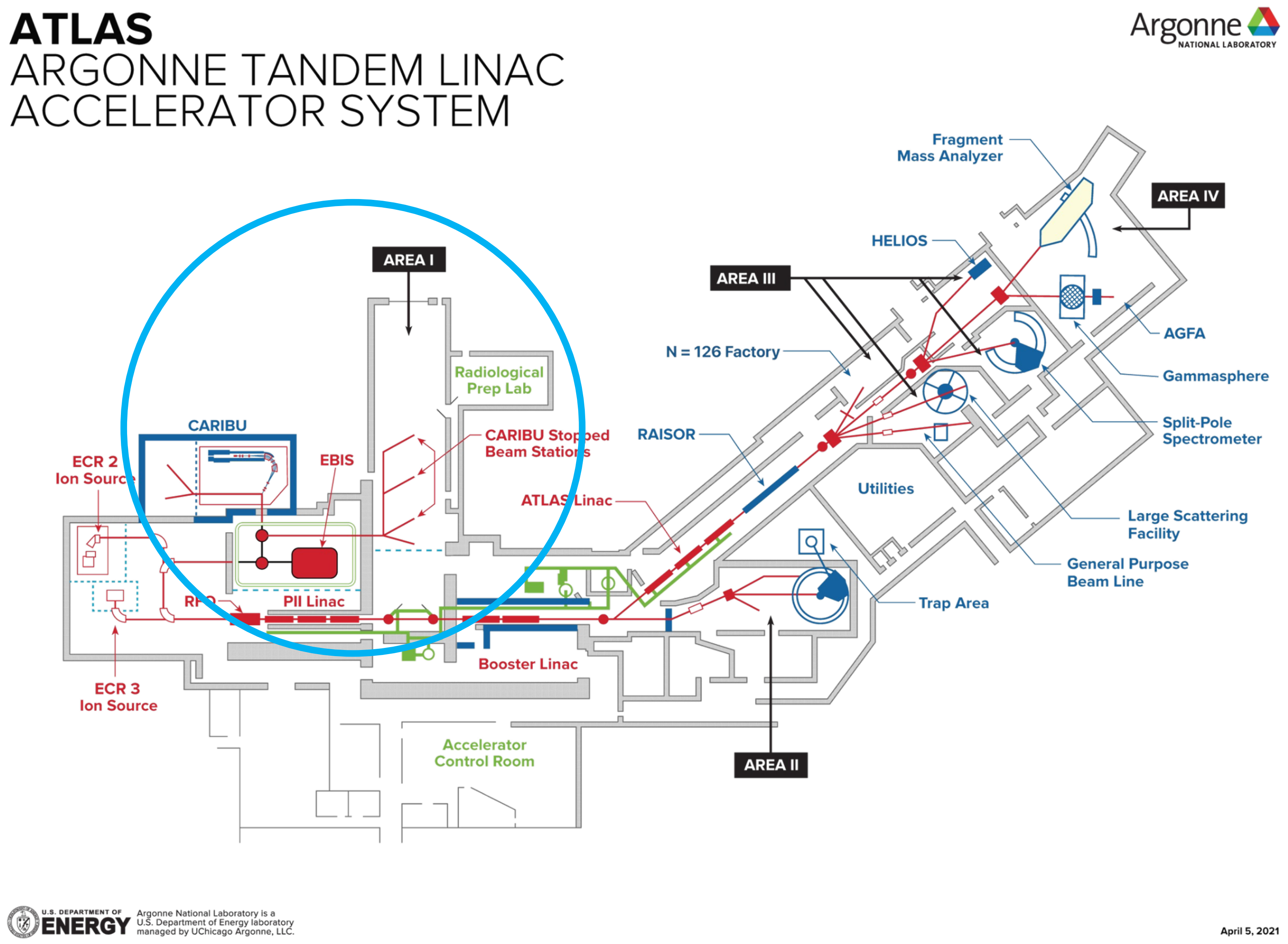




FRIB Beam Rates

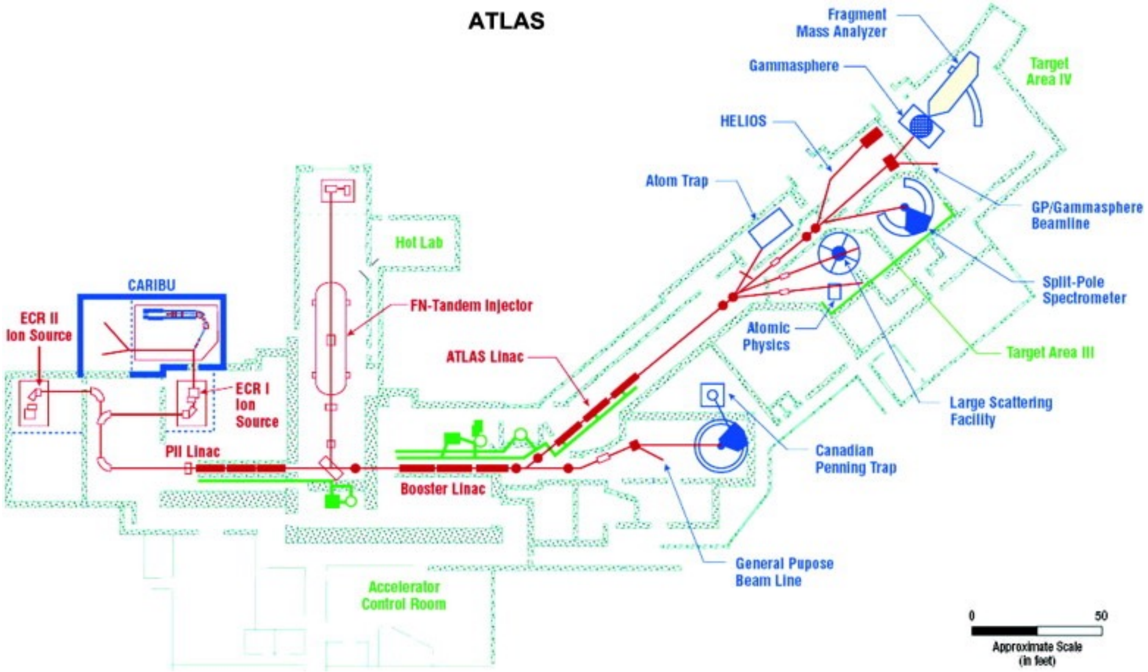


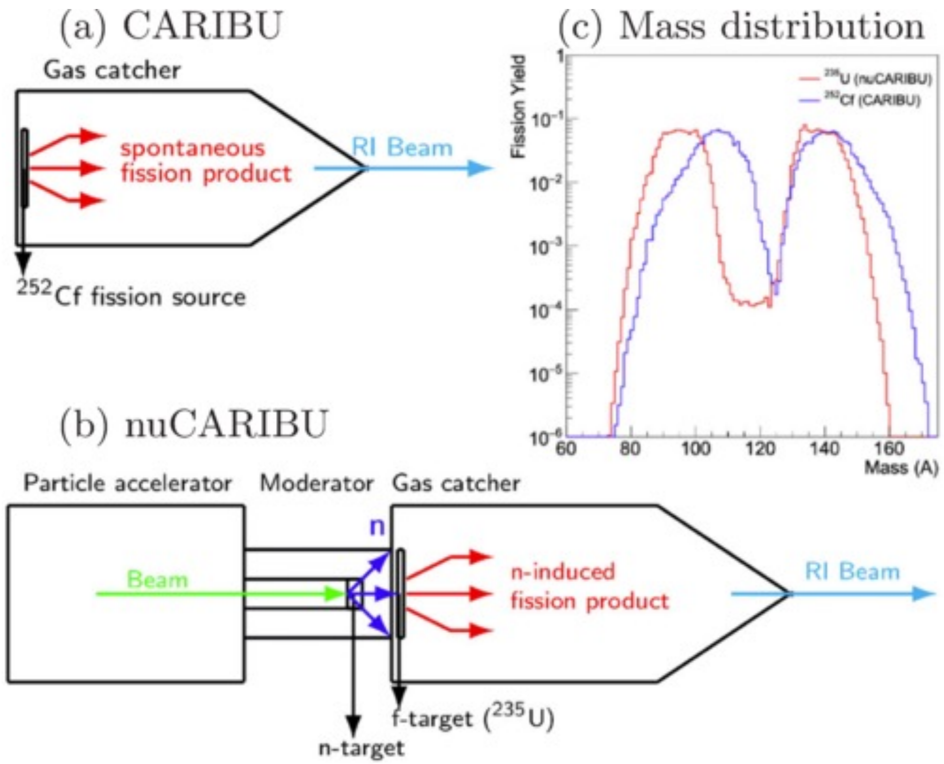
Argonne National Lab: ATLAS + nuCARIBU



Fission-fragment accelerator

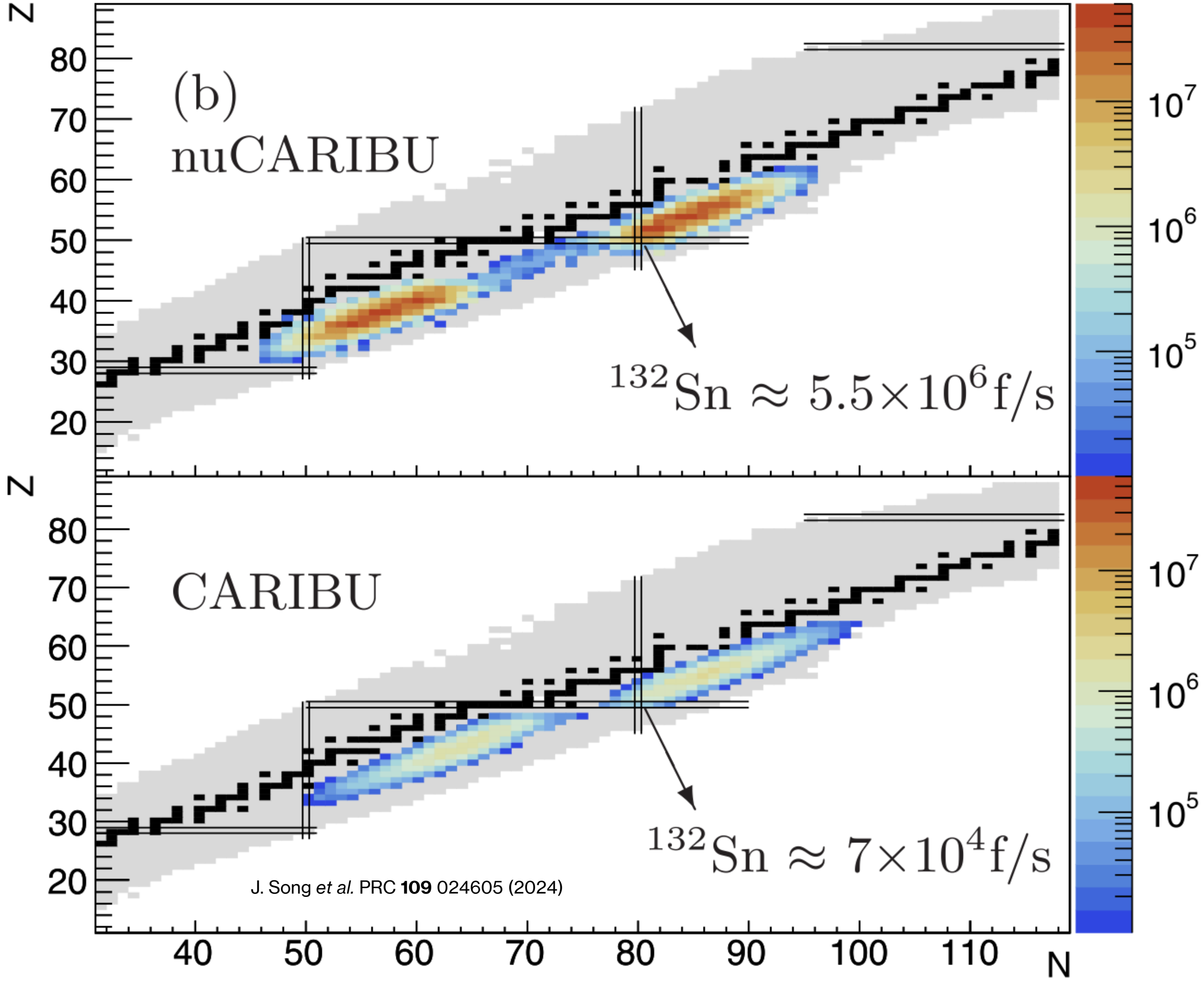
- Turns a source of neutron-rich isotopes, such as a spontaneous fission source (CARIBU) or neutron-induced fission (nuCARIBU), into a low-energy beam using a gas catcher and charge breeder





https://doi.org/10.1103/PhysRevC.109.024605

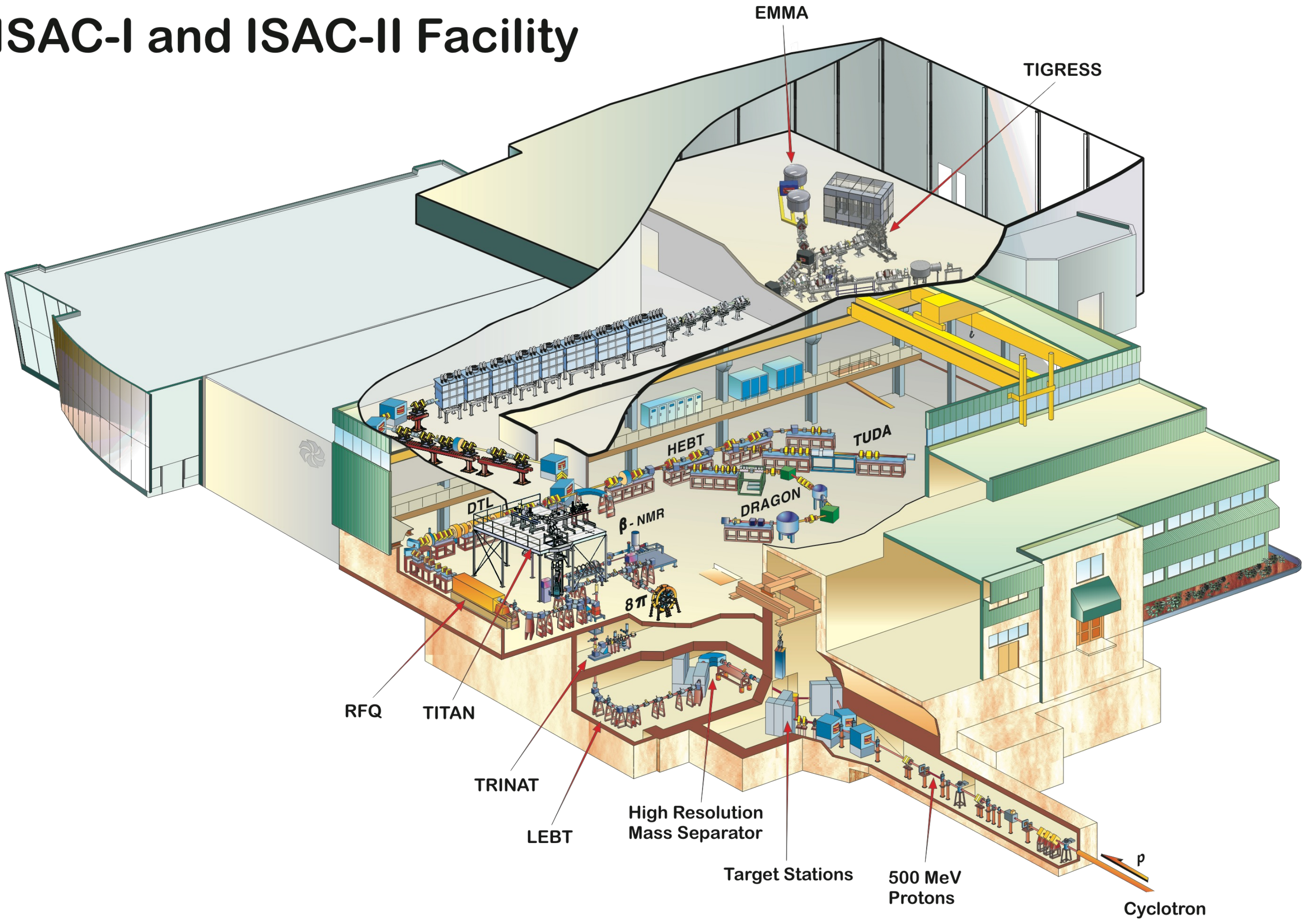
nuCARIBU Beam Rates



J. Song *et al.* PRC **109** 024605 (2024)

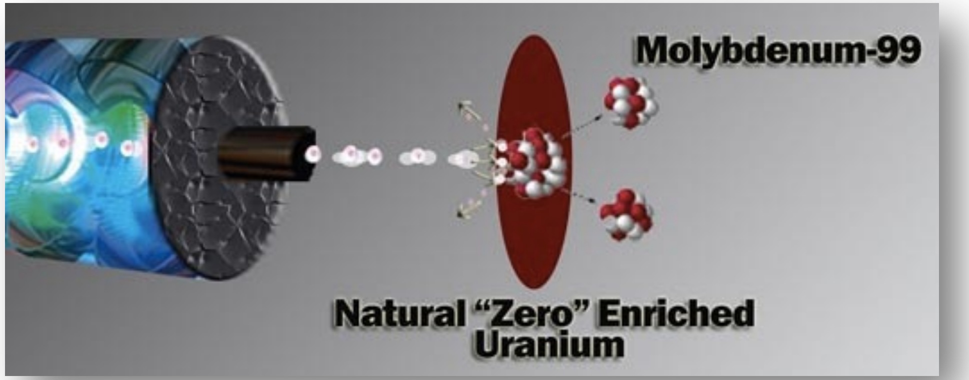
TRIUMF

ISAC-I and ISAC-II Facility



- TRIUMF is home to the world's largest cyclotron – accelerates H- to 520 MeV, extracts as proton beam
- ISOL Facility
- Proton beam is sent into target hall, and interacts with thick targets (materials such as UC)

On the horizon: Photo-fission production



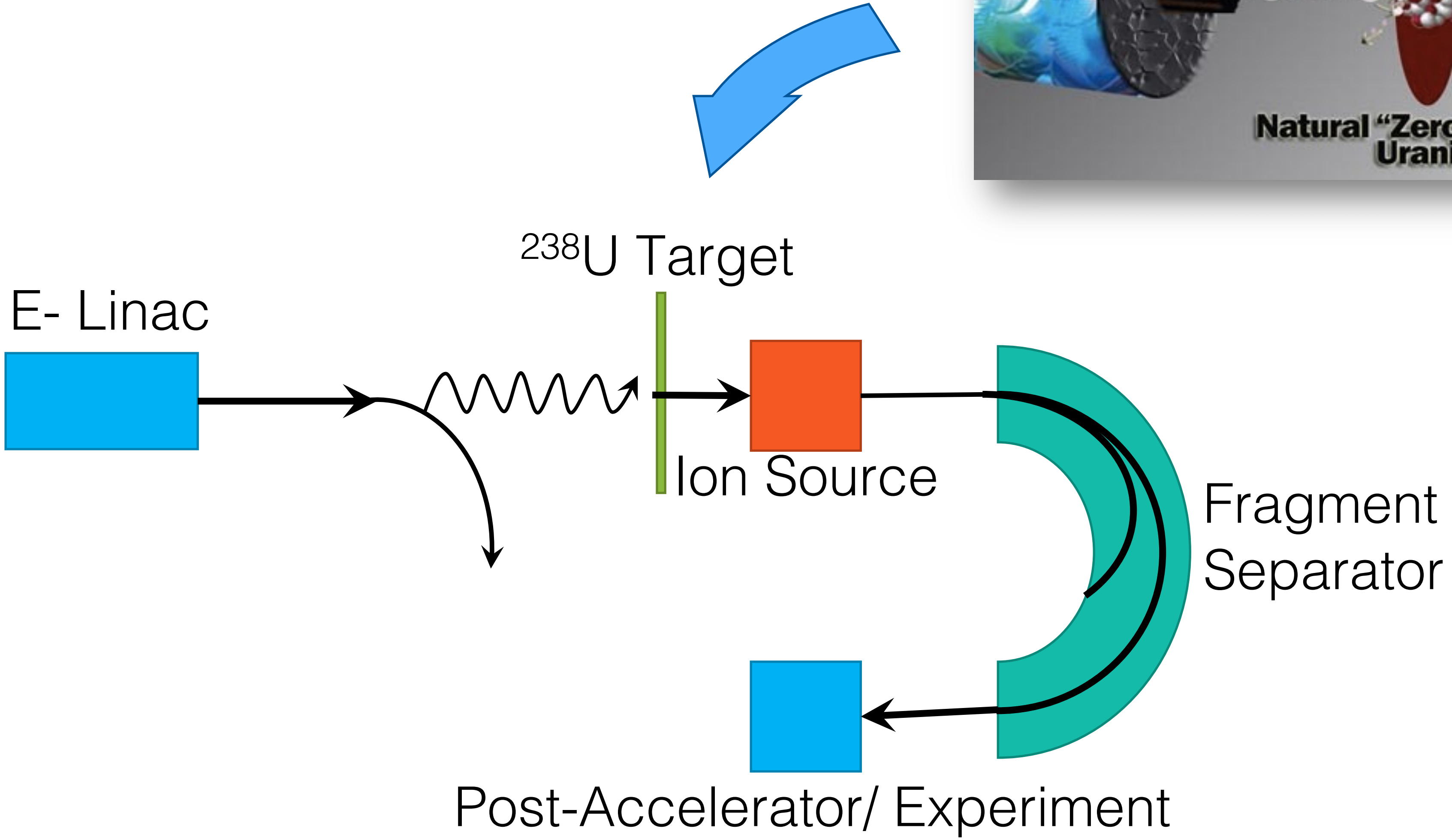
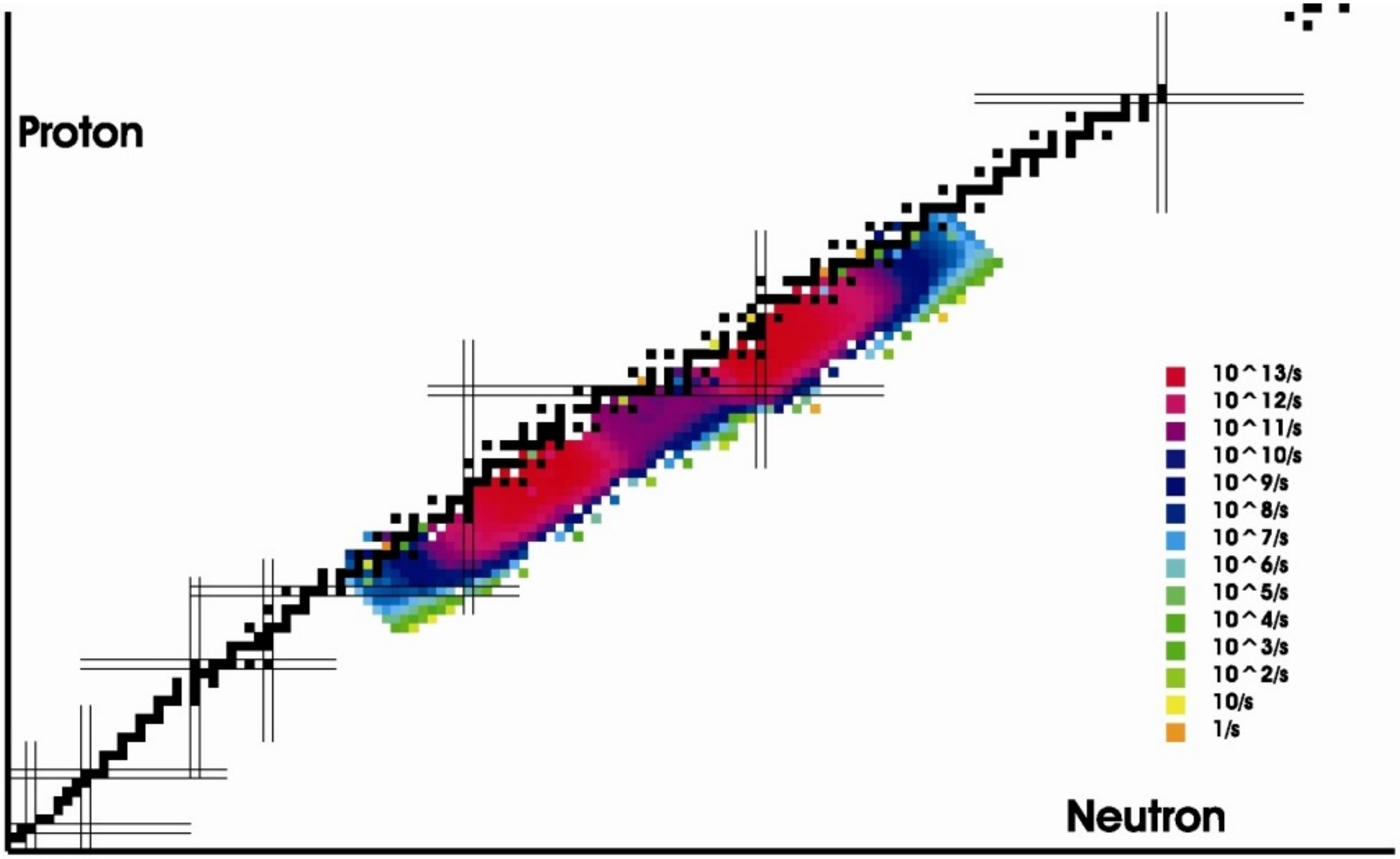


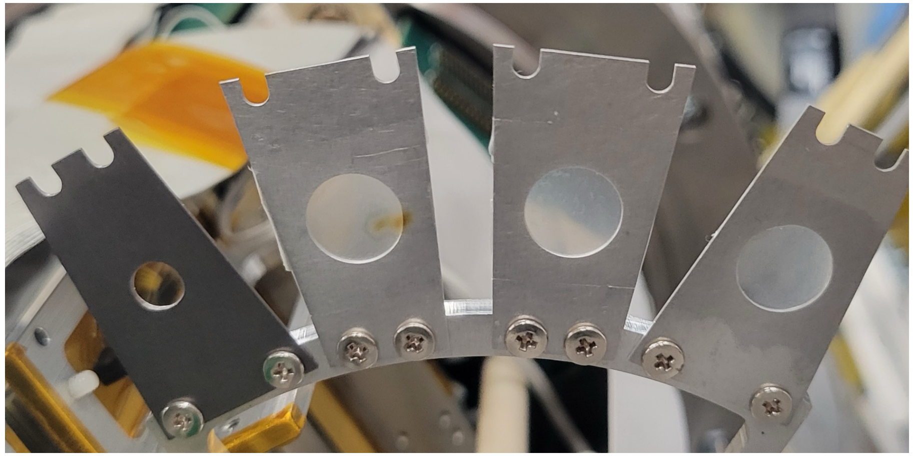
Photo-fission facility: ARIEL @ TRIUMF

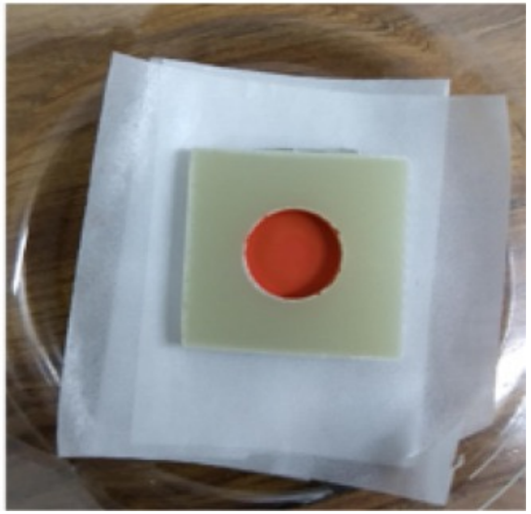


ARIEL: www.triumf.ca/ariel

Targets

CD$_2$ targets, one slightly burned by beam





Solid Mercury targets

https://doi.org/10.1016/j.nima.2022.167087

JENSA Gas Target, ORNL @ FRIB
Jet Experiments for Nuclear Structure and Astrophysics

^{100}Mo targets 💰🤑

How can we measure?
General Characteristics of Detectors

- **What we want to measure:**
  - → energy, velocity, momentum, mass
  - → time
  - → position
  - → cross section
  - → correlations (angular, feeding)

- **What we actually measure:**
  - → charge or light (pulse)
  - → time (from a defined clock)
  - → segment ID (pixel hit)
  - → number
  - → true/false logic gates

- **We then want to infer (with theory):**
  - → spin/parity
  - → angular momentum transfer
  - → spectroscopic factors
  - → reaction rates

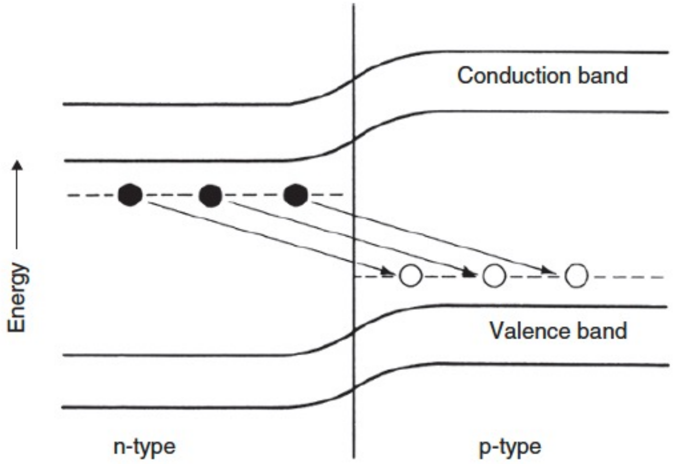
- **Things we can optimize:**
  - → resolution
  - → efficiency
  - → rate capability
  - → selectivity

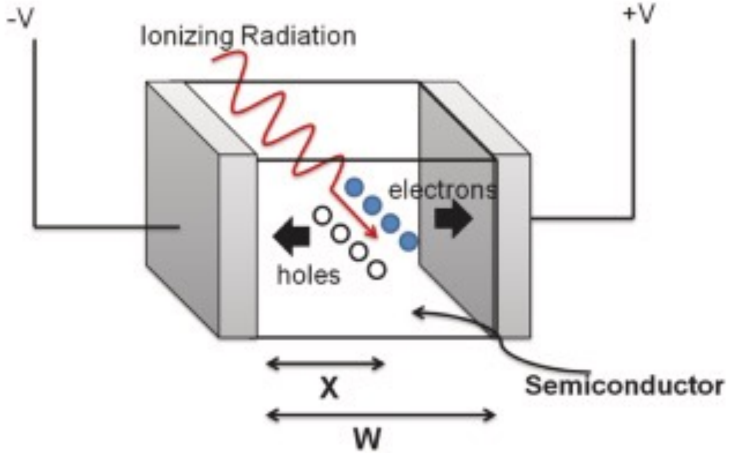
General Characteristics of Detectors

- We need a device that will convert incoming radiation into a signal that we can measure
- Generally, there are three classes of detectors
  - **Semi-conductor detectors**: ionization (electron-hole pairs) collected into current or charge signal
  - **Scintillation detectors**: deexcitation (photons), converted to electrons via a photocathode/photodiode and collected into current or charge signal
  - **Gas-filled detectors**: ionization (electron-ion pairs) collected into current or charge signal

Semi-Conductor Detectors

- Also known as “solid-state” detectors
- Silicon, Germanium = semi-conductors
- “intrinsic” semiconductors are rare and hard to produce in large quantities, so we want to dope the semiconductor to tailor its response to our needs
- *n-type*: donor electrons from doping (pentavalent dopant in the case of silicon), lie very close to conduction band, net effect is to create far more conduction electrons than holes
- *p-type*: donor holes (or “acceptors”) from doping (trivalent dopant in the case of silicon), lie very close to valence band, net effect is to create more conduction holes as the charge carrier
- incoming radiation creates electron-hole pairs along track (roughly 3 eV per pair), these charge carriers are migrated through the material with an applied electric field and the current signal, proportional to energy, is read out from electrical contacts



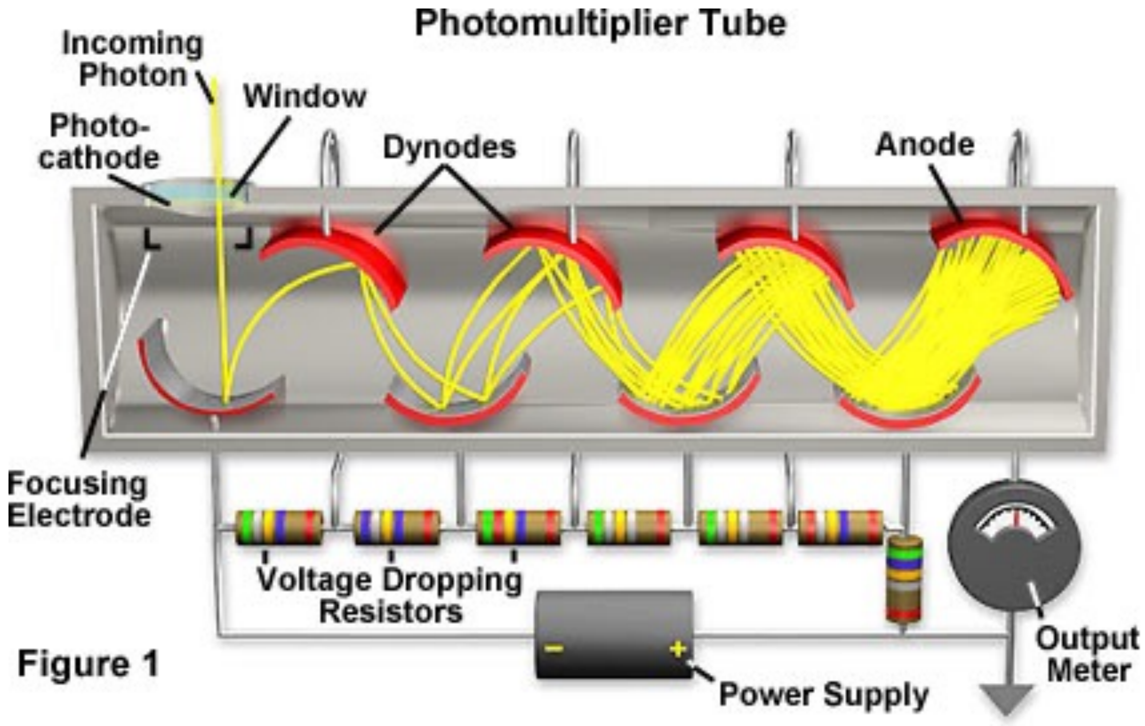


Scintillation Detectors

- A scintillation detector consists of a scintillating material, coupled to a light guide, and a photo detector.
- Two types: organic and inorganic
  - Differ by how light is produced
- **Inorganic scintillators**: NaI (Tl), CsI (Tl), BGO – $Bi_4Ge_3O_{12}$, BaF_2, ...
  - Scintillation properties are different depending on the crystal
  - Scintillation mechanism is usually due to the band structure of the crystal (band gaps ~ 5-10 eV)
- **Organic scintillators**: plastics (e.g. benzene C_6H_6, stilbene, naphtalen, NE-213)
  - Scintillation mechanism is due to the transition of electrons between molecular orbitals

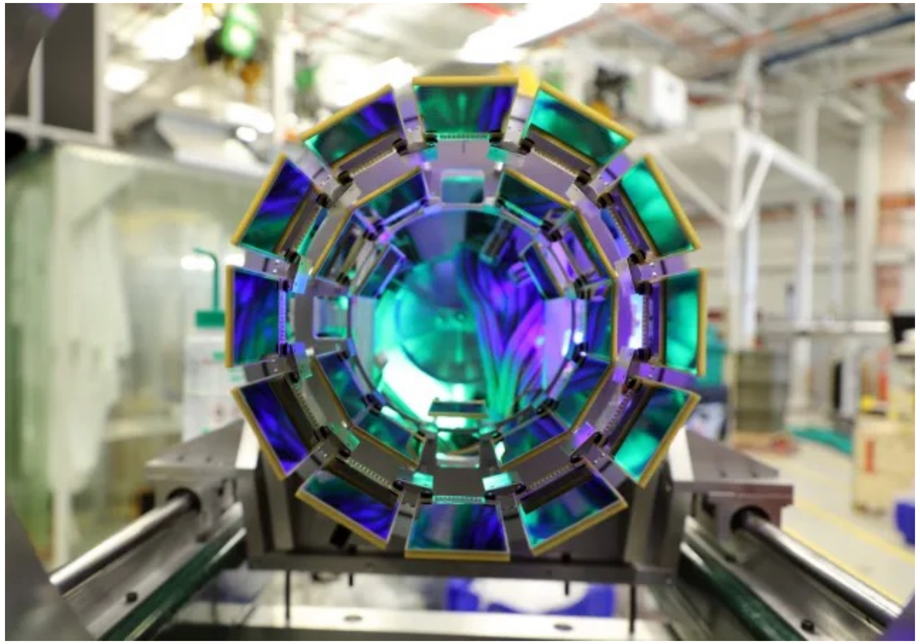
Scintillation Detectors

- Regardless of organic vs. inorganic, light pulses need to be converted into measurable signals.
- This is done using a photoelectric material (photo-cathode) to generate electrons from incident photons
- Because just a few photons are "detectable," the signals are small, so we need electron multiplication (gain)



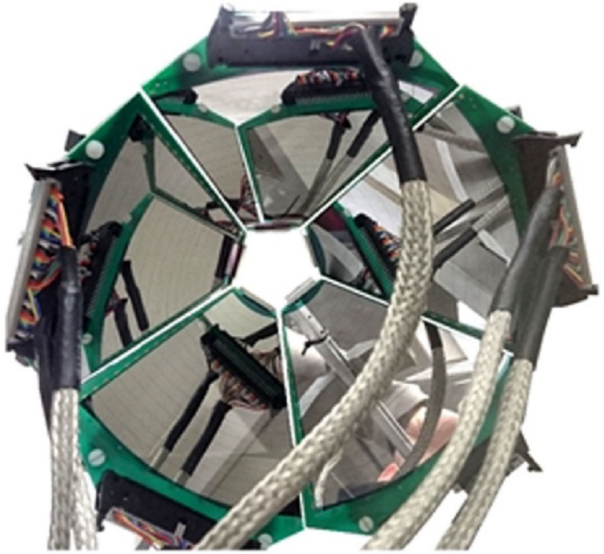
Charged Particle Detection

- Mostly semi-conductors and usually silicon, but other examples exist.
- Typically, very high detection efficiency
- Usually coupled to gamma-ray arrays



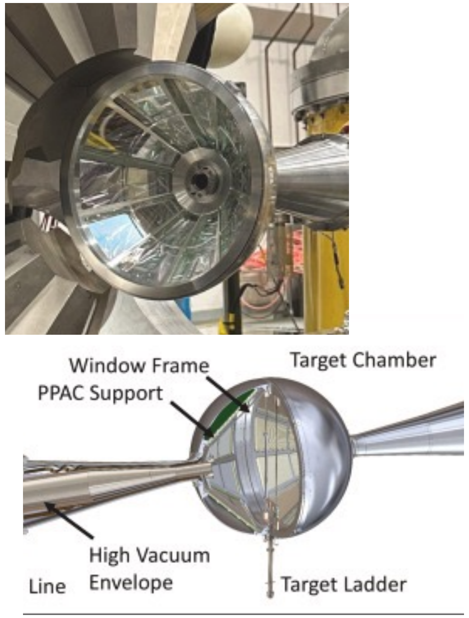
S.D. Pain *et al.*, NIMB **261** (2007)

ORRUBA



P. Adsley *et al* *JINST* **12** T02004 (2017)

CAKE @ iThemba



D. Rhodes *et al* *NIMA* **1089** 171563 (2026)

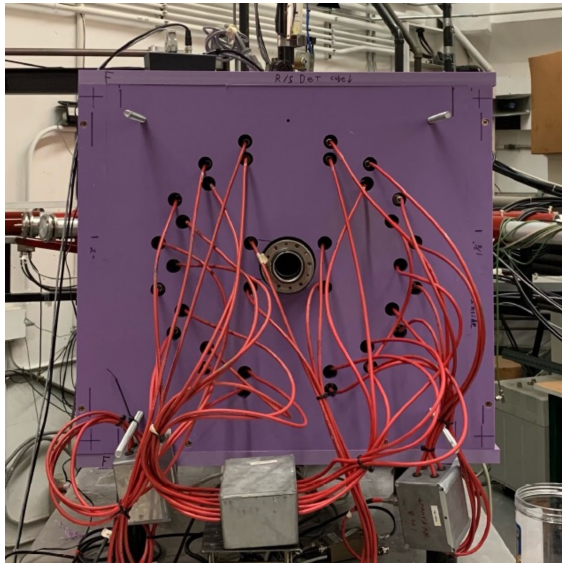
CHICOX

Neutron Detection

B. Luther *et al* *NIMA* **505**, 33 (2003)

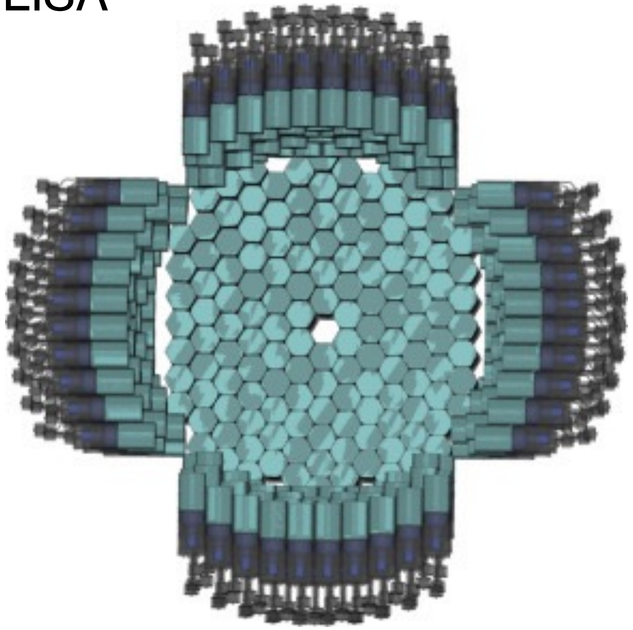
MoNA-LISA

- Typically, scintillator detectors or gas-filled



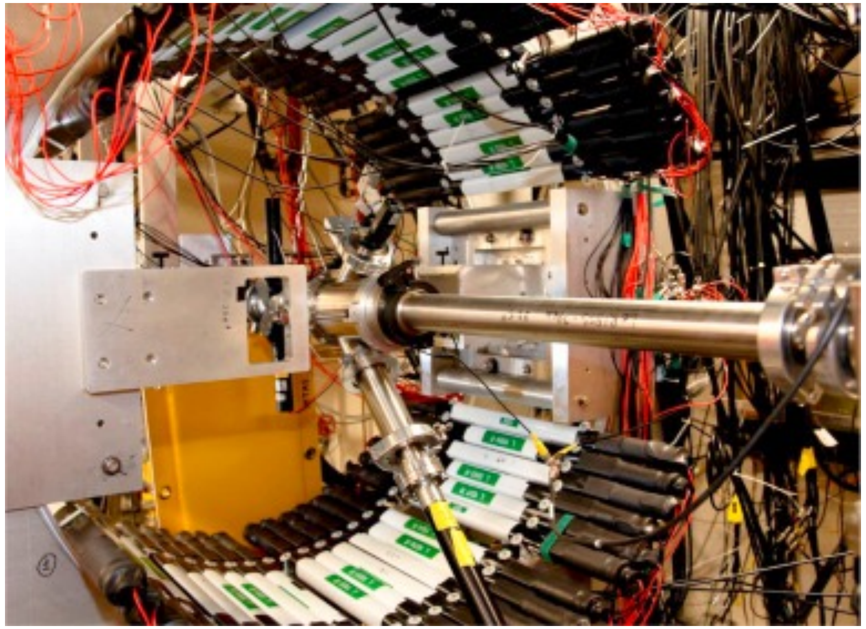
K. Brandenburg *et al* *JINST* **17** P05004 (2022)

HeBGB



J.J. Valiente-Dobón *et al* *NIMA* **927** 81 (2019)

NEDA



W. A. Peters *et al* *NIMA* **836** 122 (2016)

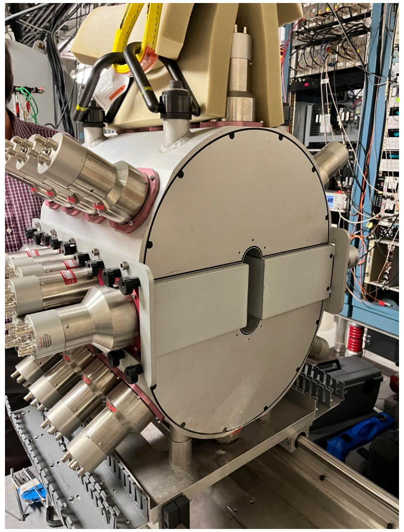
VANDLE

Gamma-Ray Detection

- Several types: semi-conductors (HPGe), scintillators (NaI, LaBr, CeBr, …)

S. Akkoyun *et al* NIMA **668**, 26 (2012)

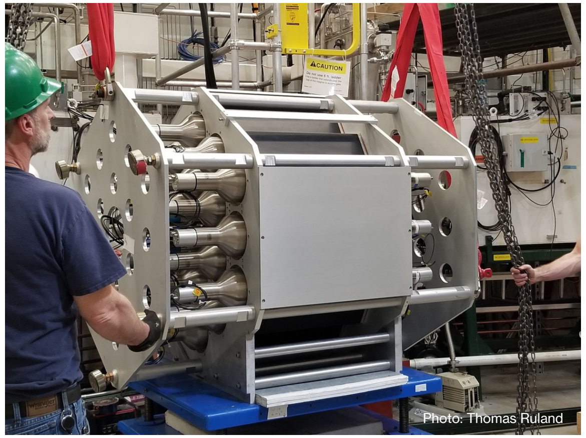
AGATA



E. K. Ronning *et al* NIMA **1082**, 170930 (2026)

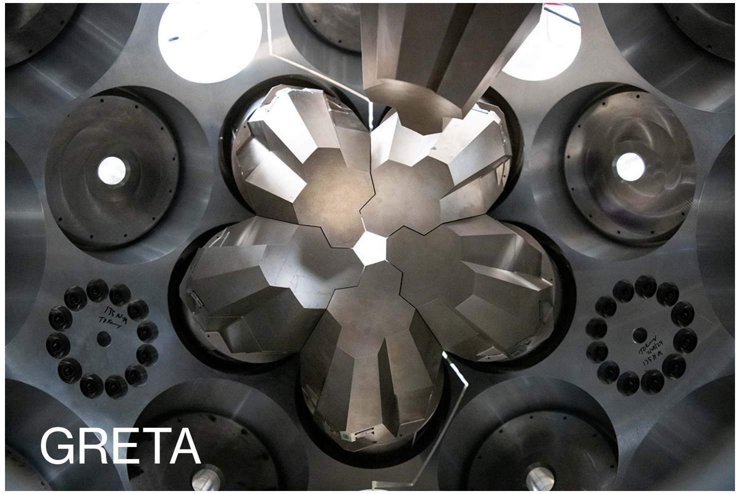
SuN++

MTAS



B. C. Rasco *et al* NIMA **788**, 137 (2015)

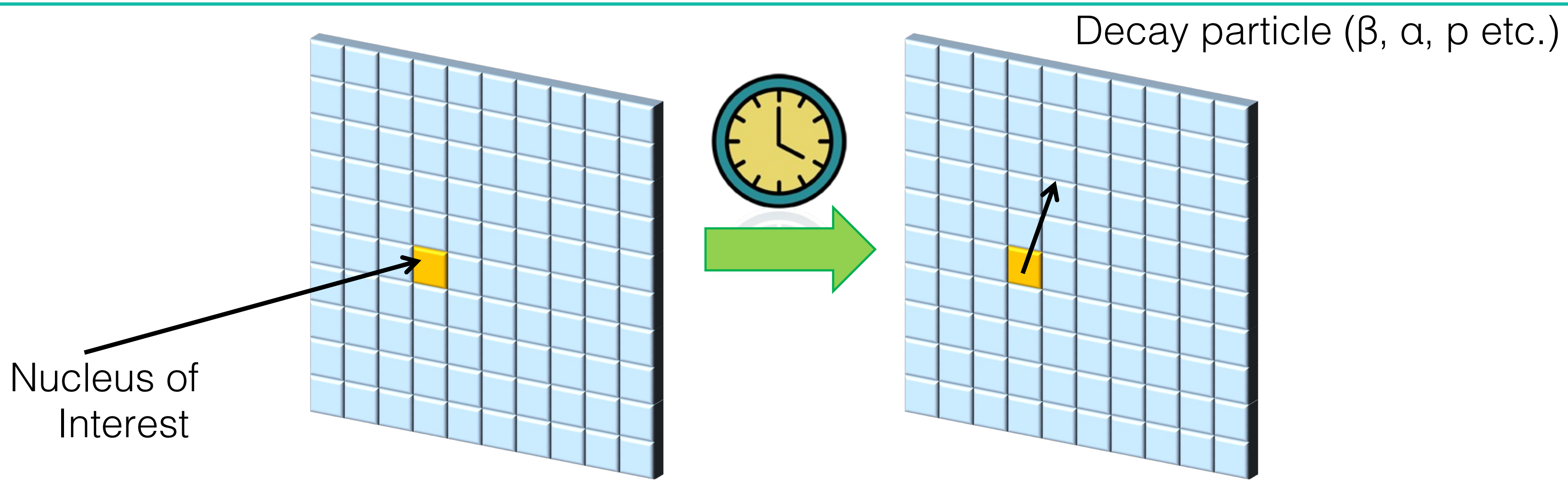
Couple to charged particle arrays!



M.A. Deleplanque *et al* NIMA **430**, 292 (1999)

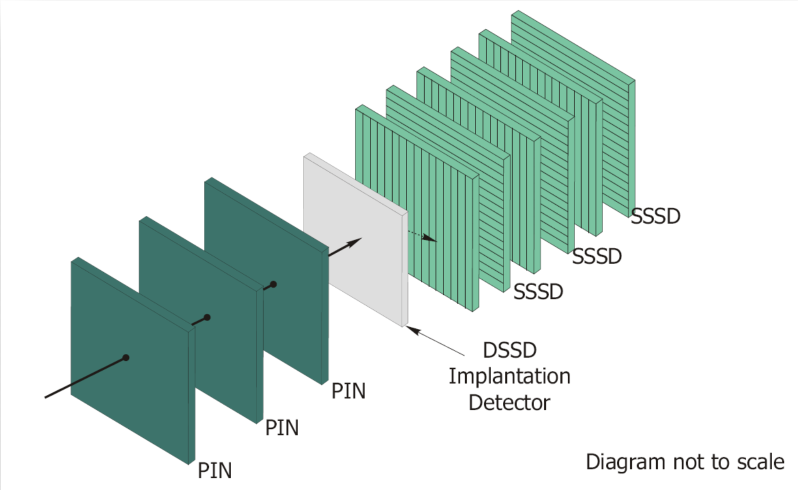
M. Heil *et al* NIMA **459**, 229 (2001)

Decay

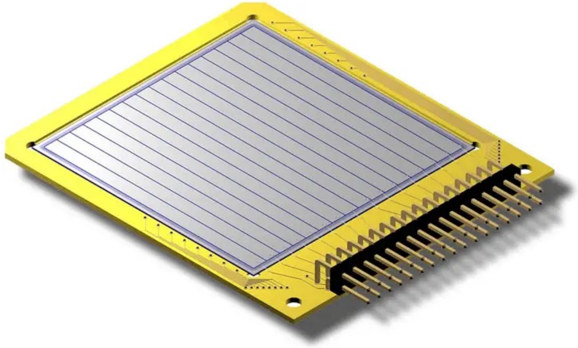


- How do you detect a decay event?
- There are several ways, but the most common is the use of dual gain semi-conductor detectors (usually Si). Observe beam implantation followed by decay corresponding to the half-life of the parent.

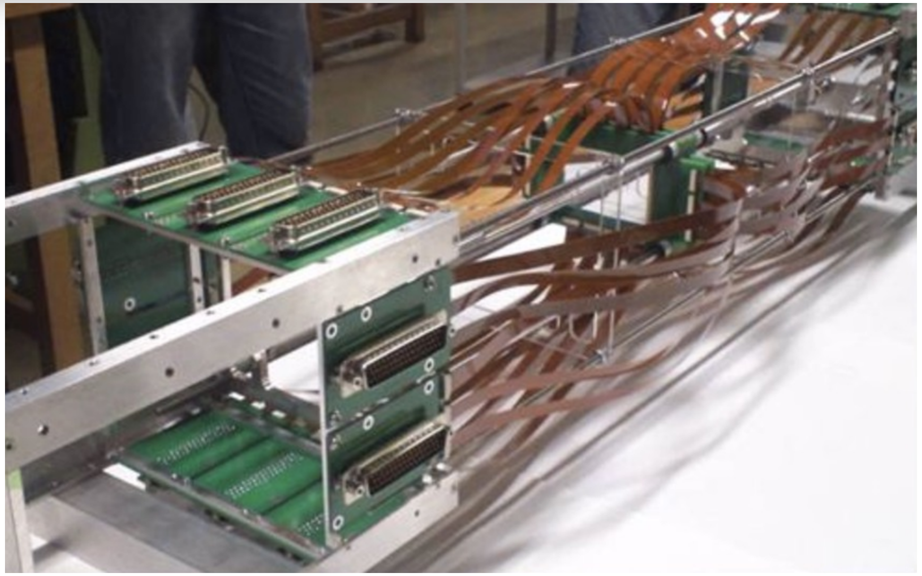
Implantation β-decay Spectroscopy Arrays



BCS at NSCL/FRIB



WAS3ABI for EURICA at RIBF (RIKEN)

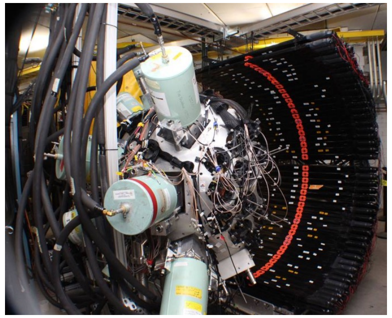


Beta-Decay Properties

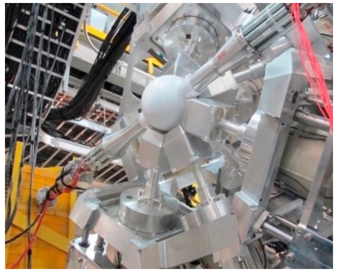
β-decay information is important for neutron-capture nucleosynthesis

- **Half-lives**
- β-delayed neutron emission probabilities
- β-decay feeding intensities

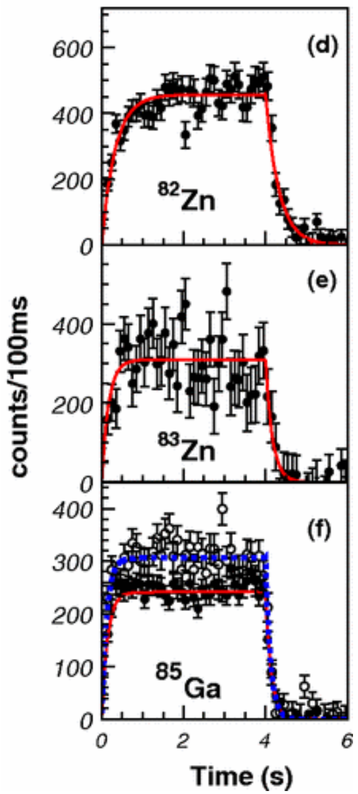
FDSi at FRIB

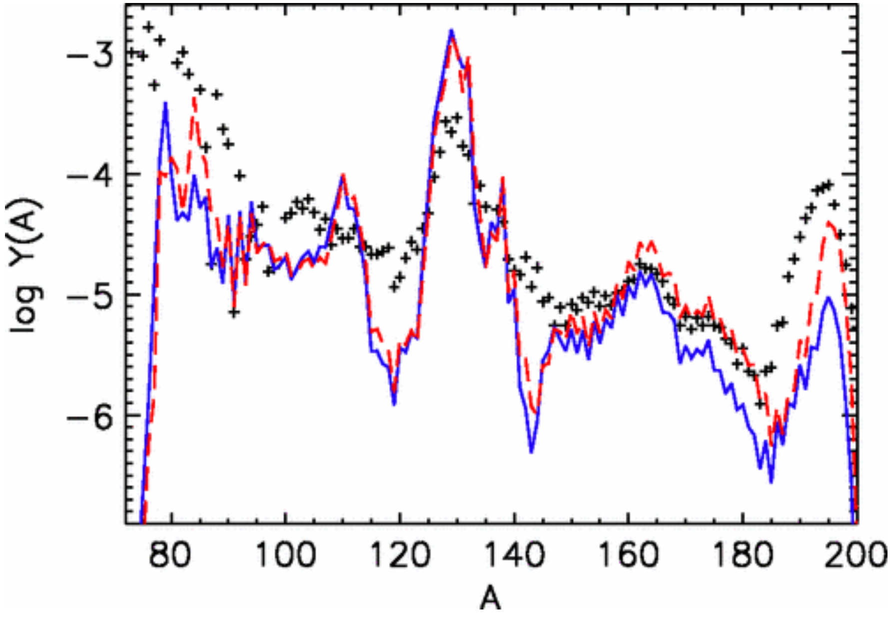


GRIFFIN at TRIUMF

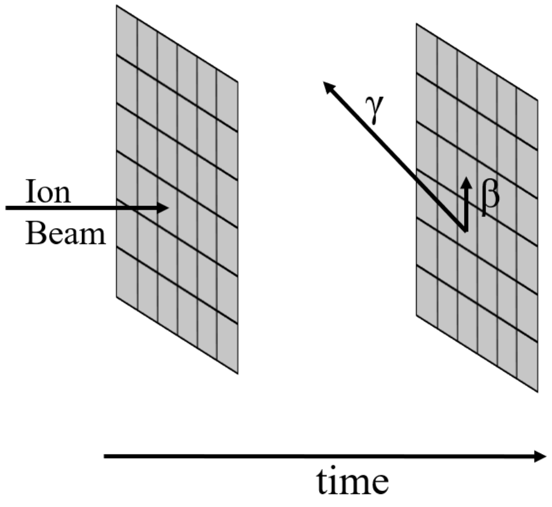


Garnsworthy, *et al.* NIM-A **918**, 2019





M. Madurga, Phys. Rev. Lett. **109**, 112501 (2012)

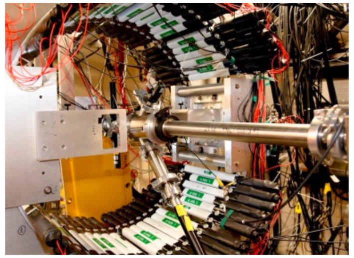


Beta-Decay Properties

β-decay information is important for neutron-capture nucleosynthesis

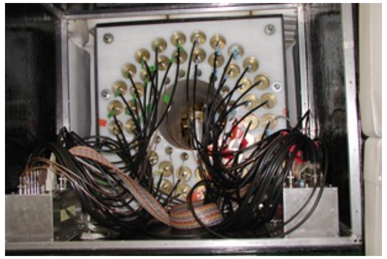
- Half-lives
- **β-delayed neutron emission probabilities**
- β-decay feeding intensities

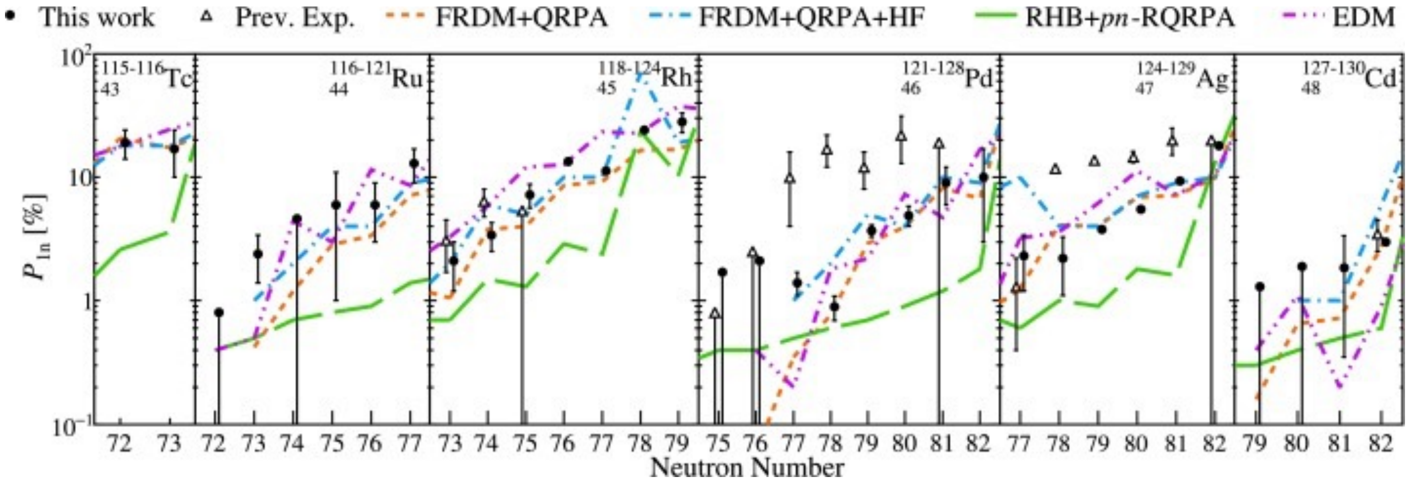
VANDLE at UTK



Peters, *et al.* NIM-A **816**, 2016, pages 122-133

NERO at FRIB



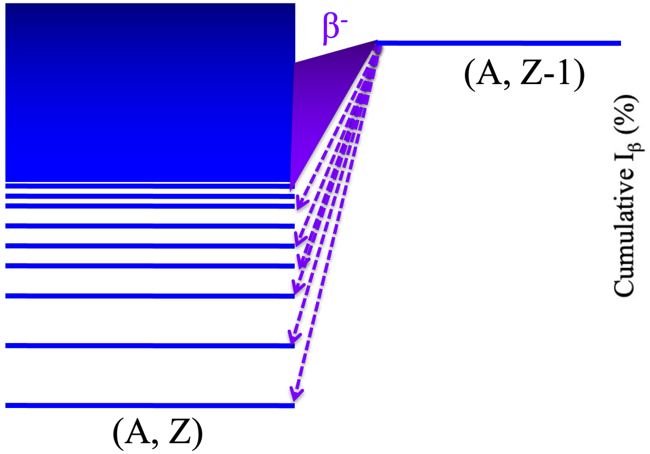


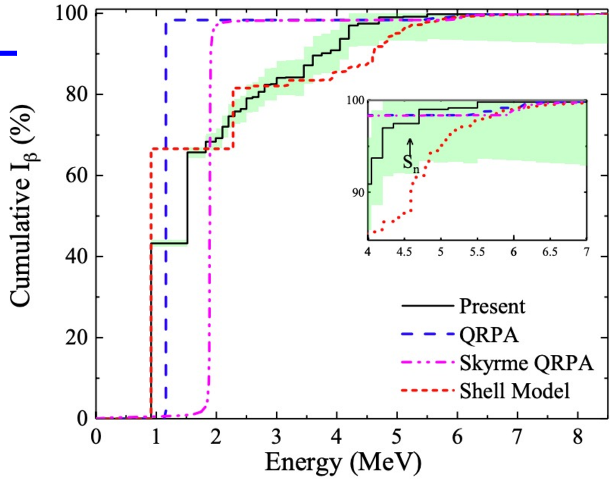
O. Hall, Phys. Lett. B **816**, 136266 (2021)

Beta-Decay Properties

β-decay information is important for neutron capture nucleosynthesis

- Half-lives
- β-delayed neutron emission probabilities
- **β-decay feeding intensities**





(a) Cumulative I_β results for ^{69}Co decay.

Lyons *et al.* PRC **100**, 025806 (2019)

MTAS at ORNL

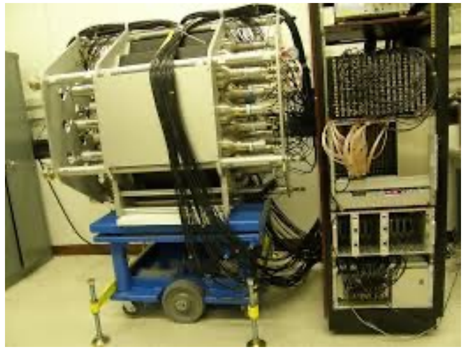
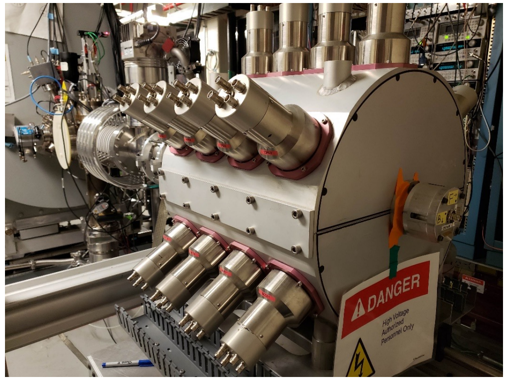


Photo from M. Karny

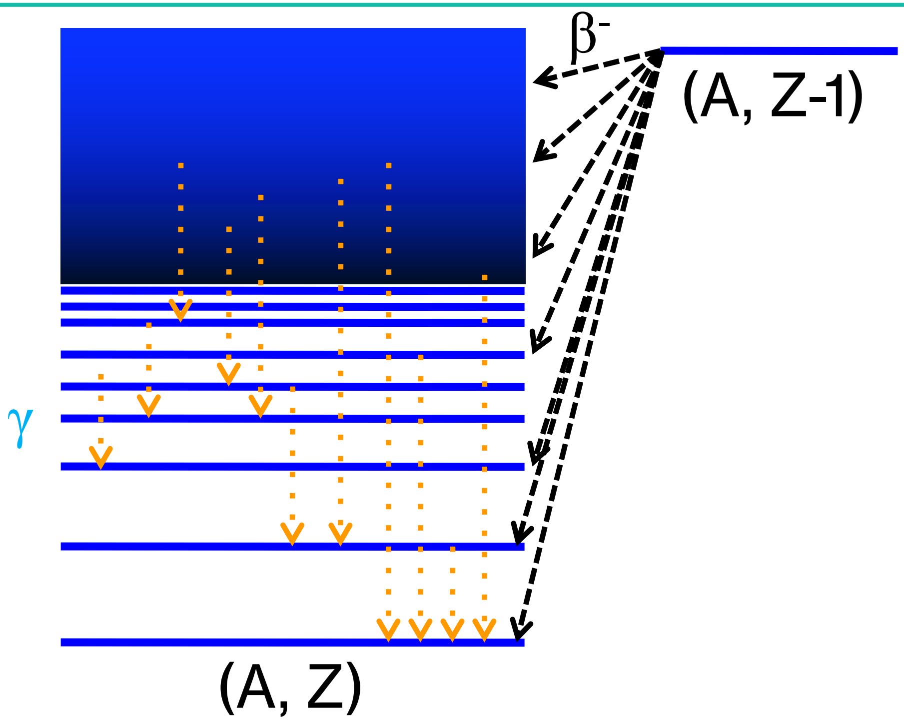
SuN at FRIB



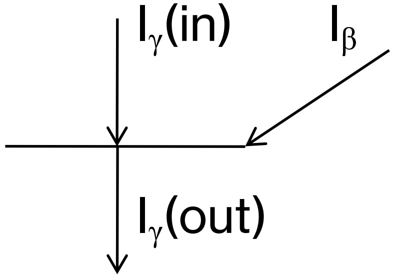
Total Absorption Spectroscopy

The Pandemonium Effect

John Milton's "Paradise Lost



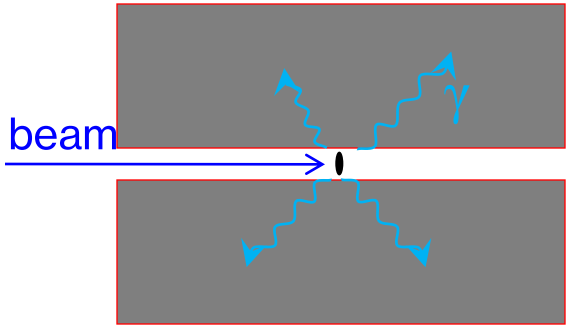
Small size – low efficiency detector



$I_\beta = I_\gamma(out) - I_\gamma(in)$

J.C. Hardy et al., PLB ***71*** 307 (1977)

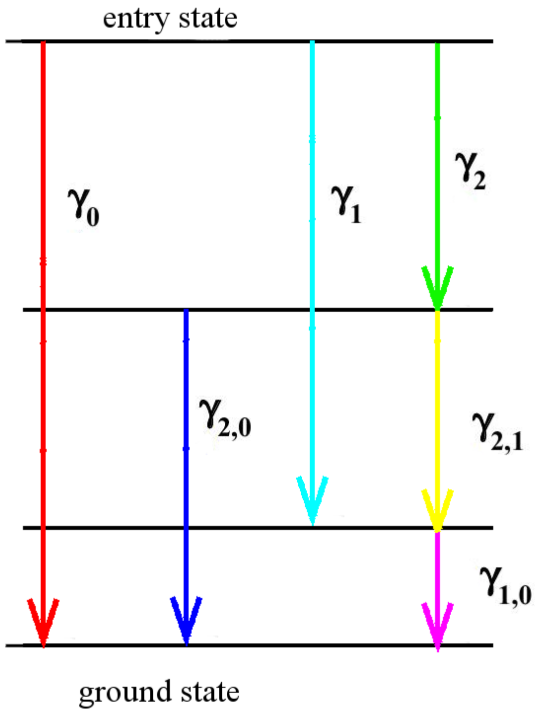
Large size - high efficiency detector



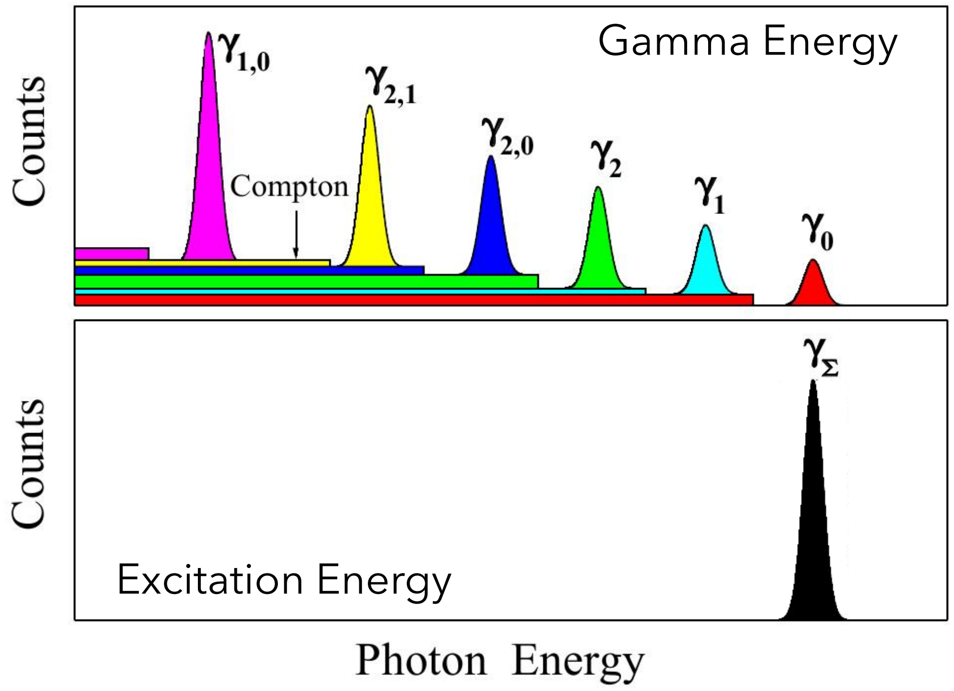
$E_x = E_{\gamma1} + E_{\gamma2} + E_{\gamma3} + E_{\gamma4} + \ldots$

Total Absorption Spectrometers

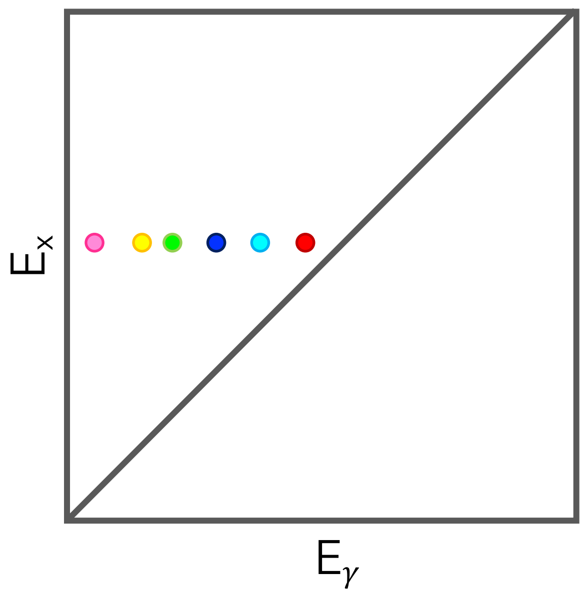
Cartoon Decay Scheme



Energy Spectrum



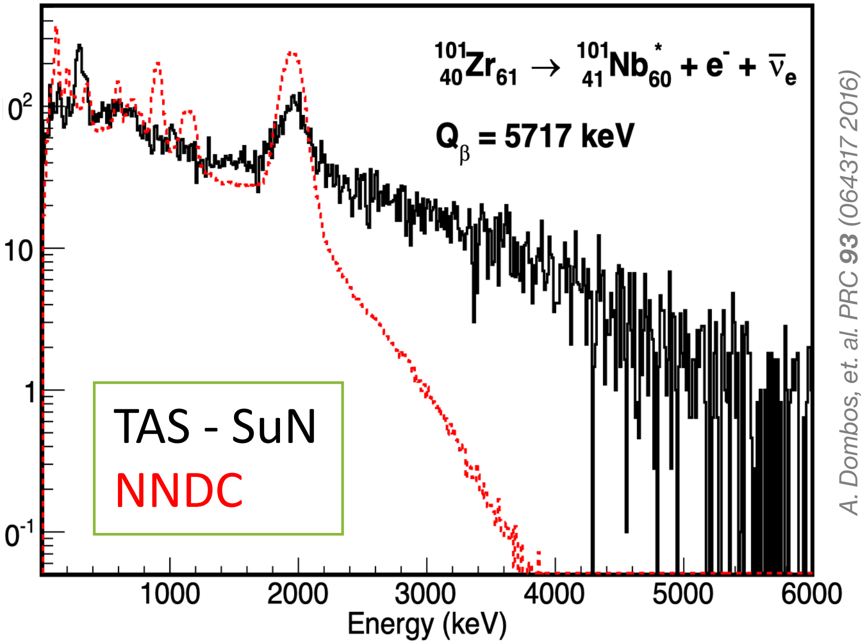
E_x-E_γ Matrix



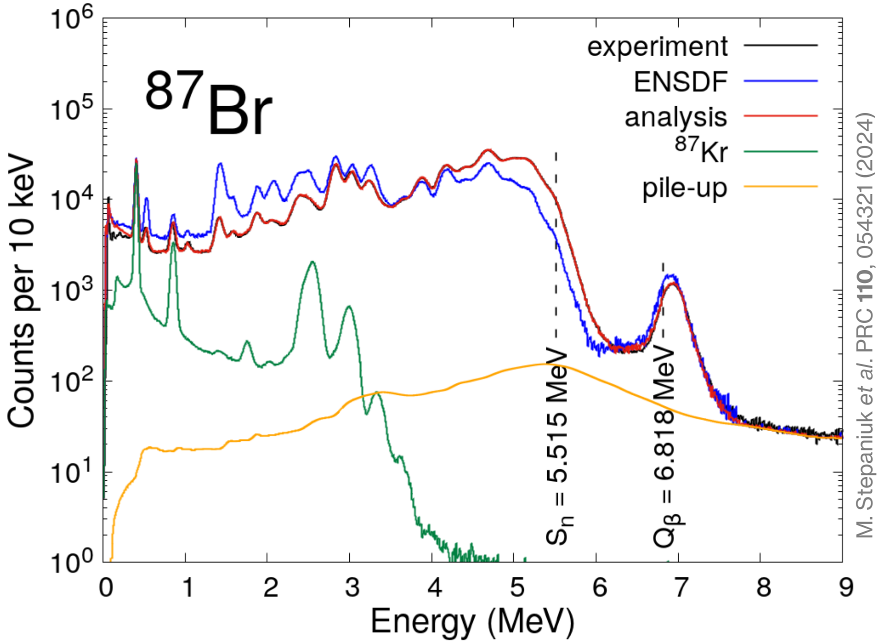
Total Absorption Spectroscopy
Pandemonium in Action

100Nb 1.4 s β⁻=100%	101Nb 7.2 s β⁻=100%	102Nb 4.3 s β⁻=100%	103Nb 1.36 s β⁻=100% β⁻n ?
99Zr 2.1 s β⁻=100%	100Zr 7.1 s β⁻=100%	101Zr 2.32 s β⁻=100%	102Zr 2.01 s β⁻=100%
98Y 548 ms β⁻=100% β⁻n=0.33%	99Y 1.483 s β⁻=100% β⁻n=1.77%	100Y 729 ms β⁻=100% β⁻n=1.11%	101Y 429 ms β⁻=100% β⁻n=1.88%

^{101}Zr β decay



^{87}Br β decay



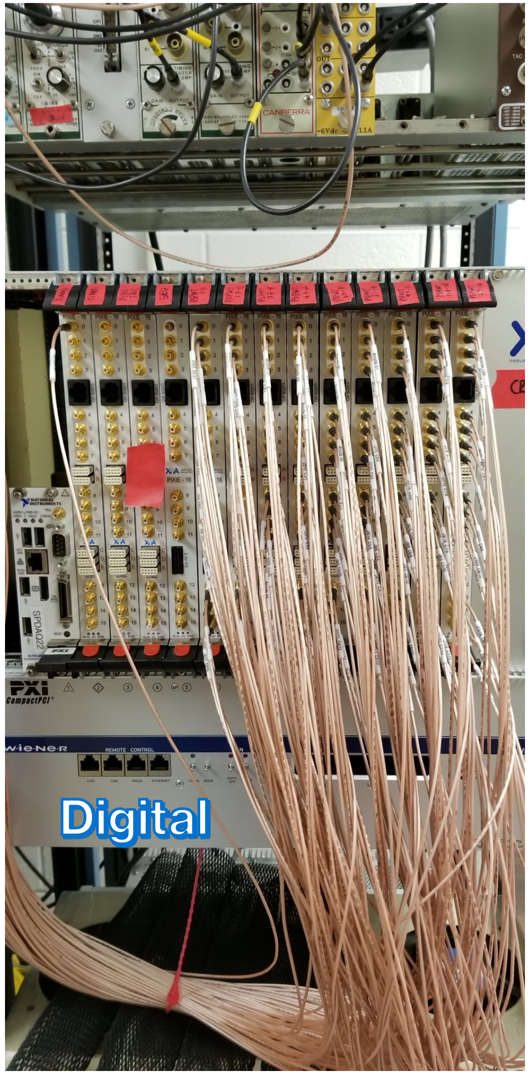
86Kr STABLE 17.279%	87Kr 76.09 min β⁻=100%	88Kr 2.803 h β⁻=100%	89Kr 3.147 min β⁻=100%
85Br 2.94 min β⁻=100%	86Br 55.1 s β⁻=100%	87Br 55.68 s β⁻=100% β⁻n=2.6%	88Br 16.34 s β⁻=100% β⁻n=6.62%
84Se 3.3 min β⁻=100%	85Se 32.9 s β⁻=100%	86Se 14.3 s β⁻=100%	87Se 5.51 s β⁻=100% β⁻n=0.36%

MTAS

Data Acquisition and Electronics

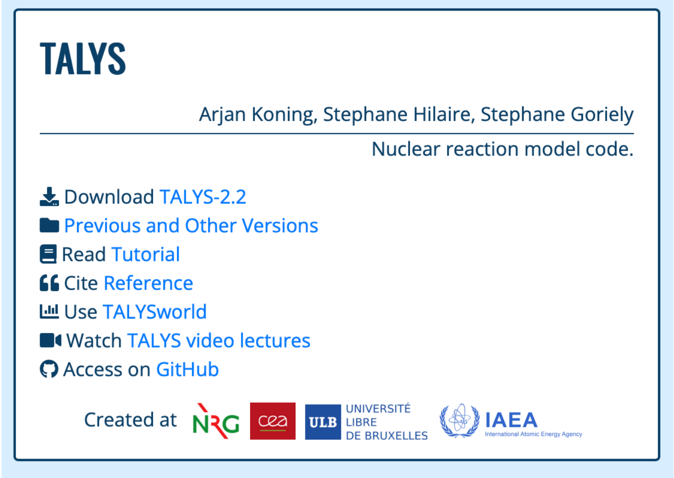
- How do we get signals from the detector to the DAQ?
- This differs slightly based on whether we are using an analog or digital data acquisition system – not because the basic premise differs, but just the order of operations:
  - analog DAQ: signal → shaping → discrimination → logic → event recording
  - digital DAQ: signal → some filtering → event recording → more filtering → logic

Signals can be processed by standard NIM (Nuclear Instrumentation Modules) or VME (versa module Europa) electronics (for example)



Theory

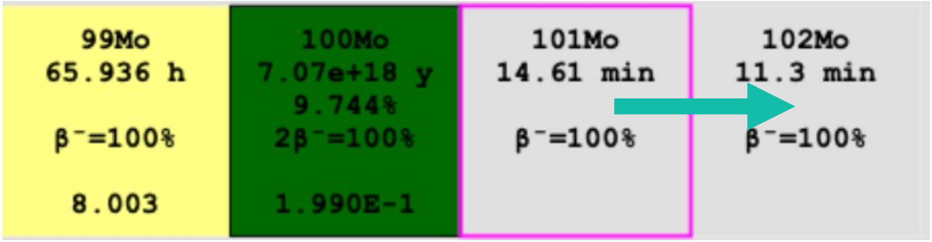
- Direct Reactions
  - FRESCO (Ian Thompson, LLNL)
    - BFRESCO (BAND collaboration, Bayesian)
    - SFRESCO (Chi-Square searches added)
  - TWOFNR
- Compound Reactions
  - TALYS or EMPIRE
  - TALYSWorld (online)
  - There are A LOT of adjustable parameters. DANGER!
- Codes for decay vary a bit depending on what you want to calculate
  - β-decay properties can be calculated using QRPA (Quasiparticle Random Phase Approximation)



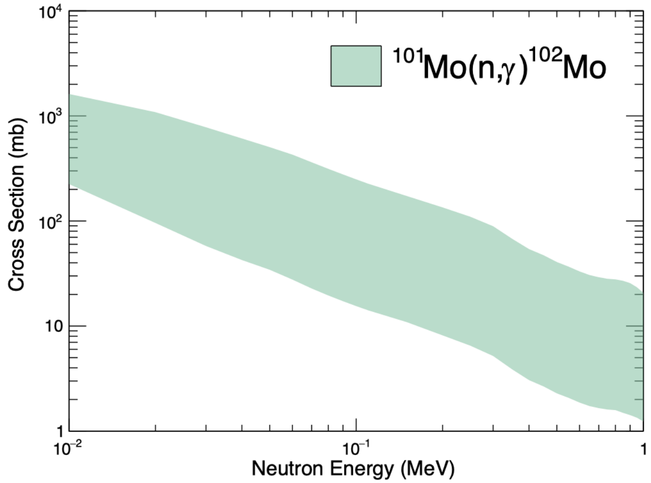
https://fribtheoryalliance.org/content/Resources/codes.php?title=Computer%20codes

A Practical Example: $^{101}Mo(n,\gamma)^{102}Mo$

Motivation: *i-process* ☺, no direct measurements



Current (n,γ) estimates:



How do I measure this?

- $^{101}Mo(d,p\gamma)^{102}Mo$
- ^{102}Nb β-decay
- ...

What are the beam rates at nuCARIBU?

- ^{101}Mo beam rate:

101Mo	101	42	59	14.6 m	9.2E+03

- ^{102}Nb beam rate:

102Nb	102	41	61	1.3 s	7.8E+04

Beam rates at FRIB are ~10^7 pps for both

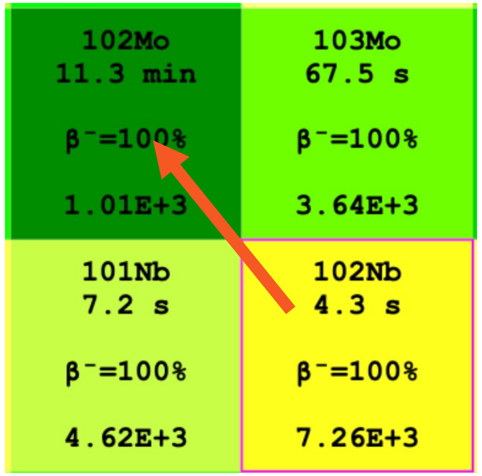
A Practical Example: $^{101}Mo(n,\gamma)^{102}Mo$

^{102}Nb β-decay is our choice

Method: The β-Oslo Method

Can this method be applied?

^{102}Nb Q_β = 7263 (9) keV ✓
^{102}Mo S_n = 8112 (8) keV
Predicted NLD: 10^5 levels/MeV at S_n



Facility: nuCARIBU at ANL

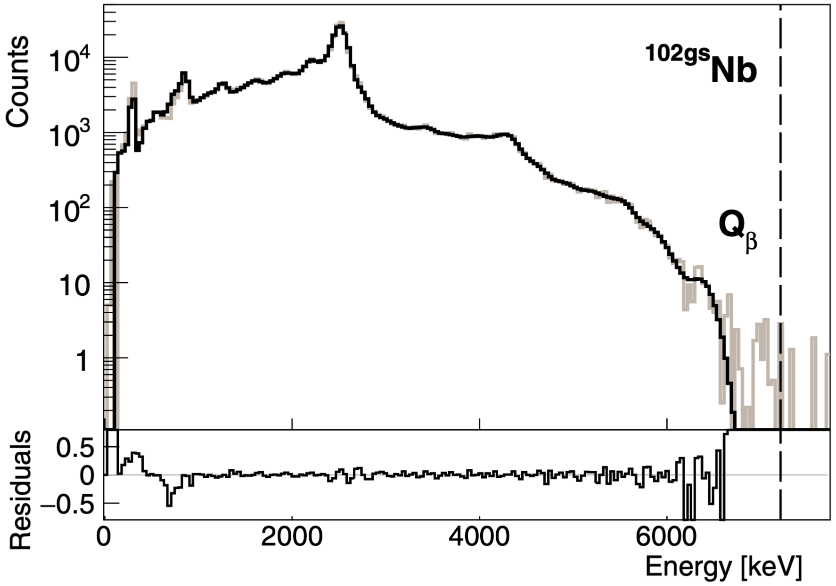
Detection system: TAS detector (SuN + tape station SuNTAN)

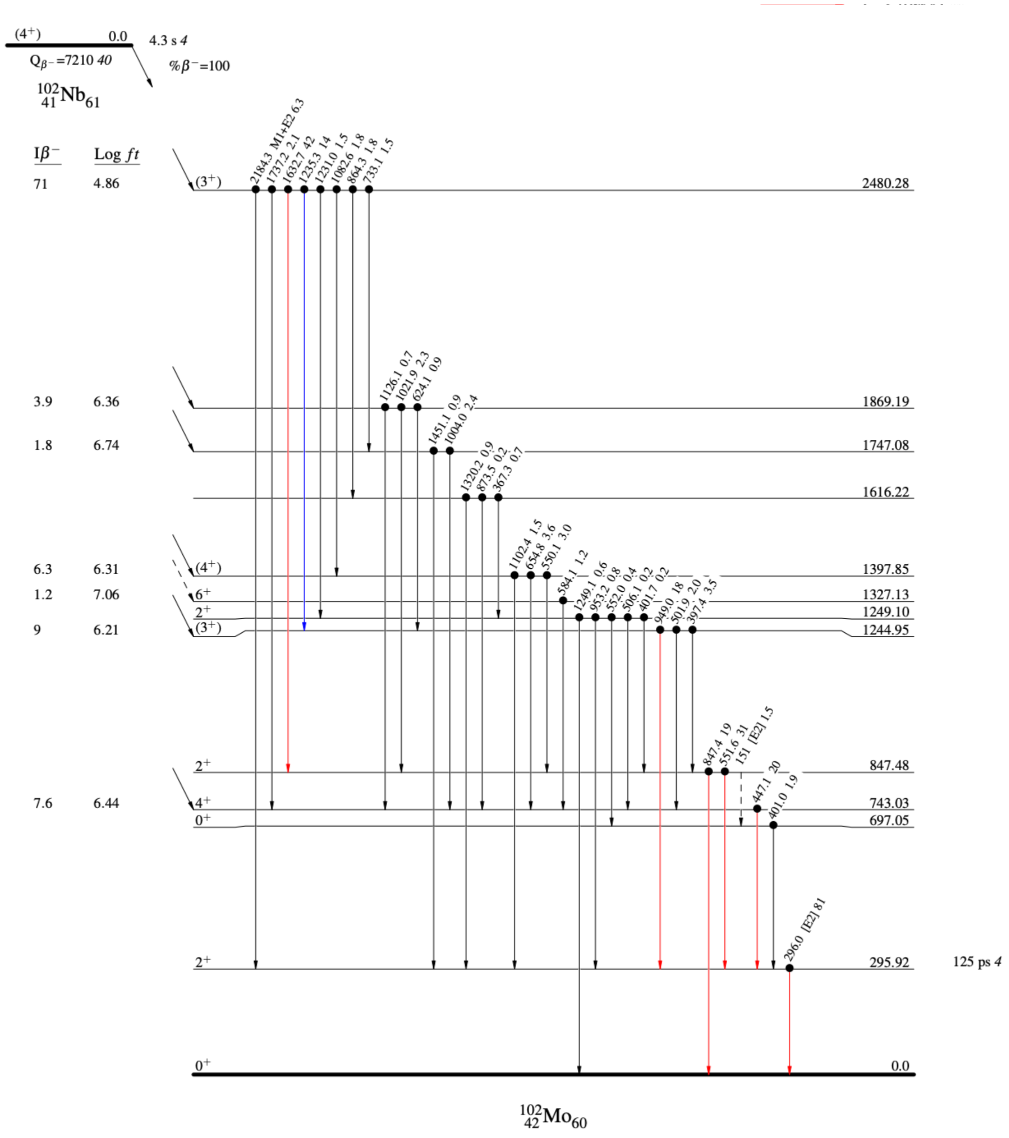
How long do I need to run? Time for some math!

Beam rate: 78,000 pps
Assumptions:
transmission to the detector is 50%, decay feeding to continuum,
β detector efficiency 30%, SuN summing efficiency 30%, other losses*

Previous Nuclear Data

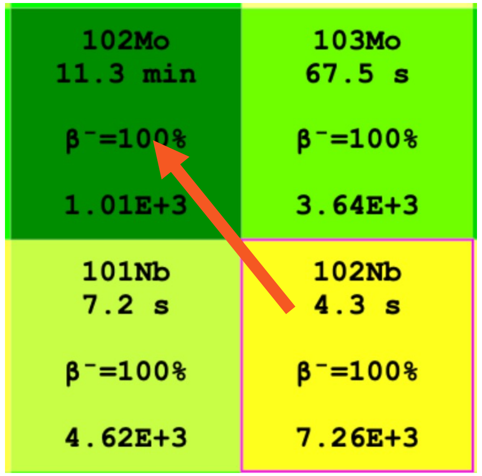
- Check ENSDF and XUNDL
- Decay Scheme previously measured using high-resolution spectroscopy
  - Can use this as a starting point
- TAS already measured with DTAS
  - V. Guadilla *et al.* PRC **100**, 024311 (2019)





A Practical Example: ^{101}Mo(n,γ)^{102}Mo

^{102}Nb β-decay is our choice



Method: The β-Oslo Method

Can this method be applied?

^{102}Nb Q_β = 7263 (9) keV ✓
^{102}Mo S_n = 8112 (8) keV
Predicted NLD: 10^5 levels/MeV at S_n

Facility: nuCARIBU at ANL

Detection system: TAS detector (SuN + tape station SuNTAN)

How long do I need to run? Time for some math!

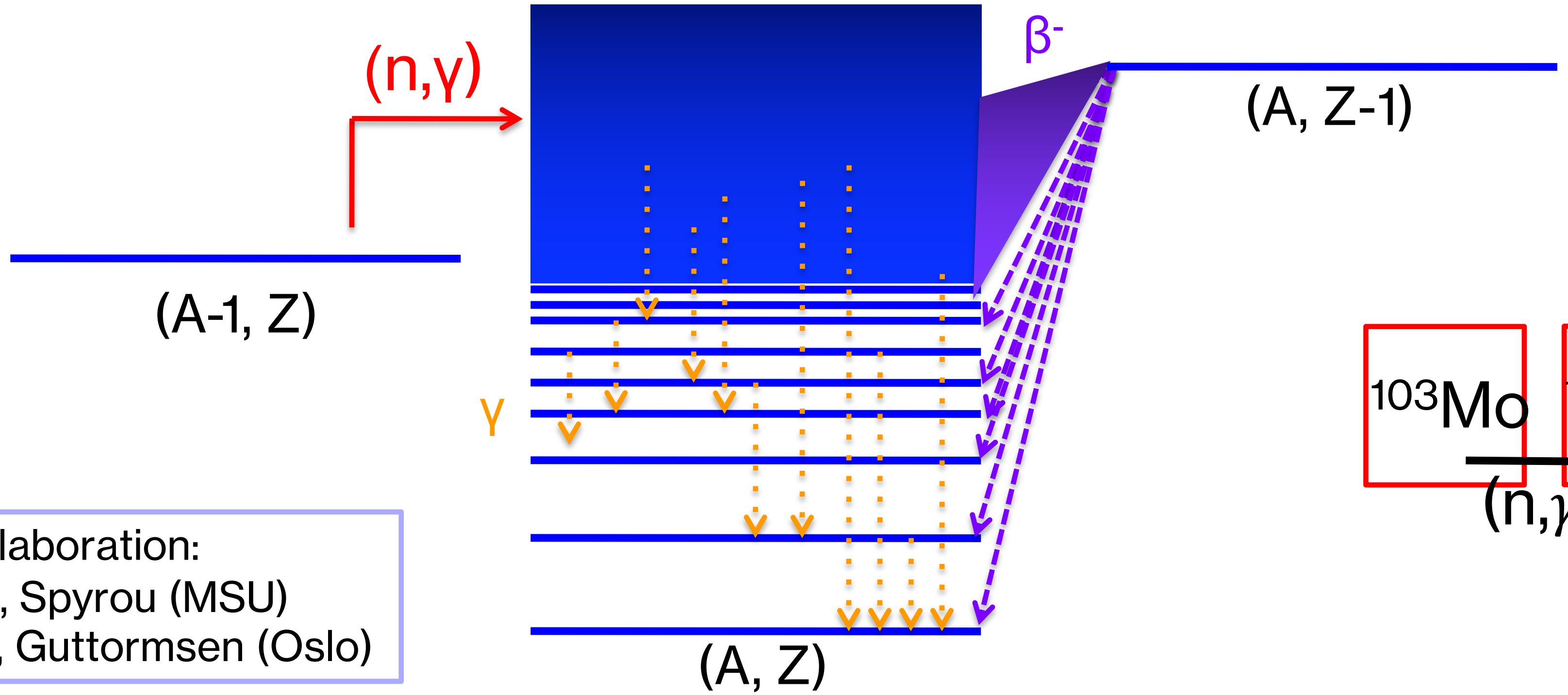
Beam rate: 78,000 pps
Assumptions:
transmission to the detector is 50%, decay feeding to continuum,
β detector efficiency 30%, SuN summing efficiency 30%, other losses*
Rate at SuN: ~250 pps ⇒ 24 hours to complete!

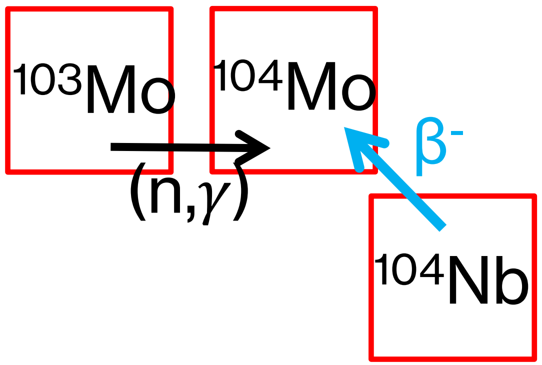
Looks feasible… now the PAC decides!

This was accepted to run at nuCARIBU this Fall ☺

Overview of the β-Oslo Method

for ^{104}Nb decay and ^{103}Mo(n,γ)^{104}Mo





β-Oslo collaboration:
- Liddick, Spyrou (MSU)
- Larsen, Guttormsen (Oslo)

- Populate the compound nucleus via β-decay
- Study nuclei far from stability
- Feasible with low beam intensities

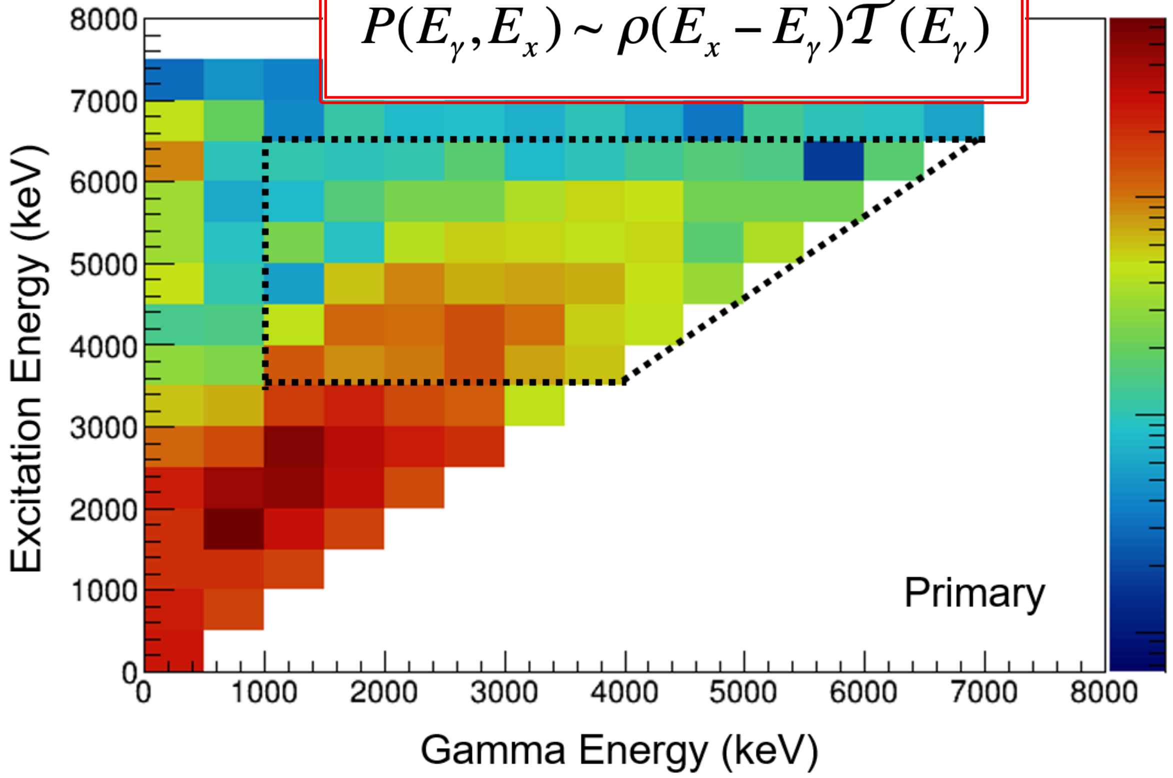
•Need:
✓ Radioactive Beam
✓ Segmented γ-ray calorimeter (TAS)

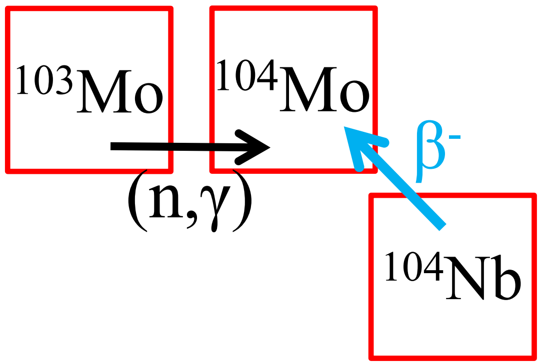
•Measure β-γ coincidences:
✓ Excitation Energy
✓ Gamma-Ray Energy

A. Spyrou *et al.* PRL **113**, 232502 (2014)

Neutron-capture constraints for $^{103}Mo(n,\gamma)^{104}Mo$

$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

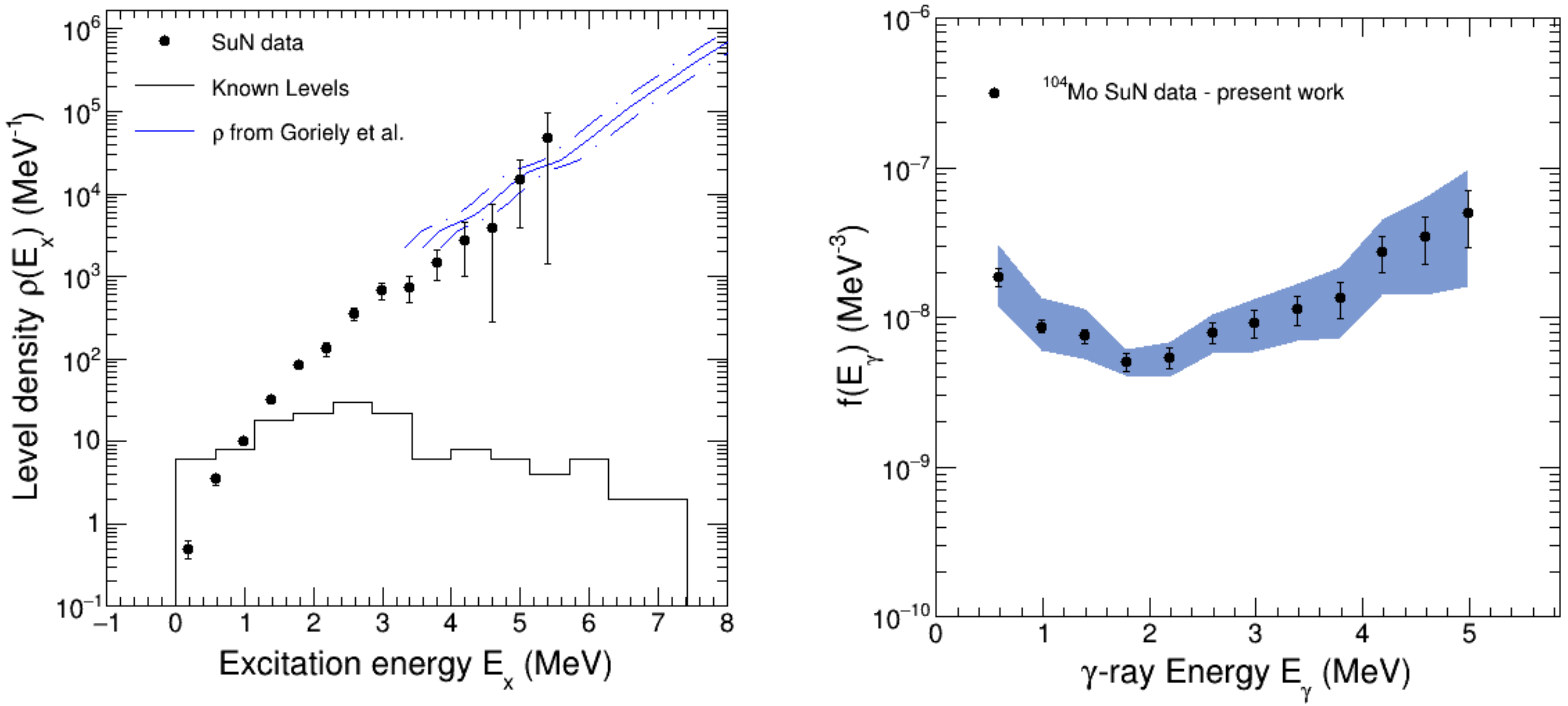




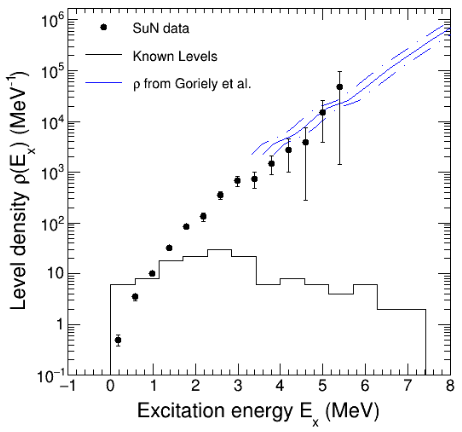
Three normalization points:

- Low-lying levels (from NNDC)
- Level density at neutron-separation energy (from previous data or from theory)
- Average radiative width or giant dipole resonance (GDR) data

Neutron-capture constraints for $^{103}Mo(n,\gamma)^{104}Mo$



Neutron-capture constraints for $^{103}Mo(n,\gamma)^{104}Mo$



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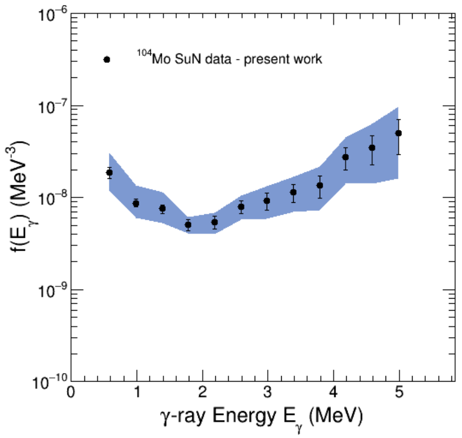

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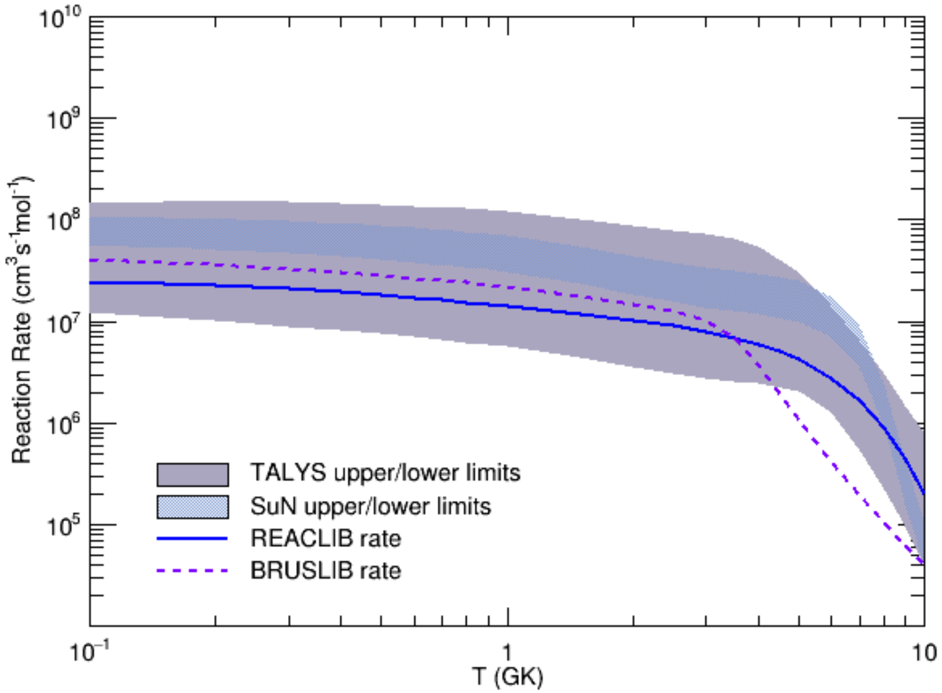

JINA-CEE

NUGRID

Design Your Own Experiment ☺

- What is your motivation?
- How would you measure it?
  - What detectors? What DAQ?
- Where would you measure it?
- Is it feasible within a 3-5 days of beam time?

Some ideas:

^{16}O(α,n)

^{7}Be(p,n)

^{40}Ca(n,α)

^{104}Rh(n,γ)

^{82}Se(d,pγ)

^{180}Hf(n,γ)

^{41}Mg

Thank you! Questions?

E-mail me anytime!

richarda1@ohio.edu