FIESTA 2024

LOS ALAMOS, NEW MEXICO

NOVEMBER 18TH 2024

Direct Fission Product Yield Measurements

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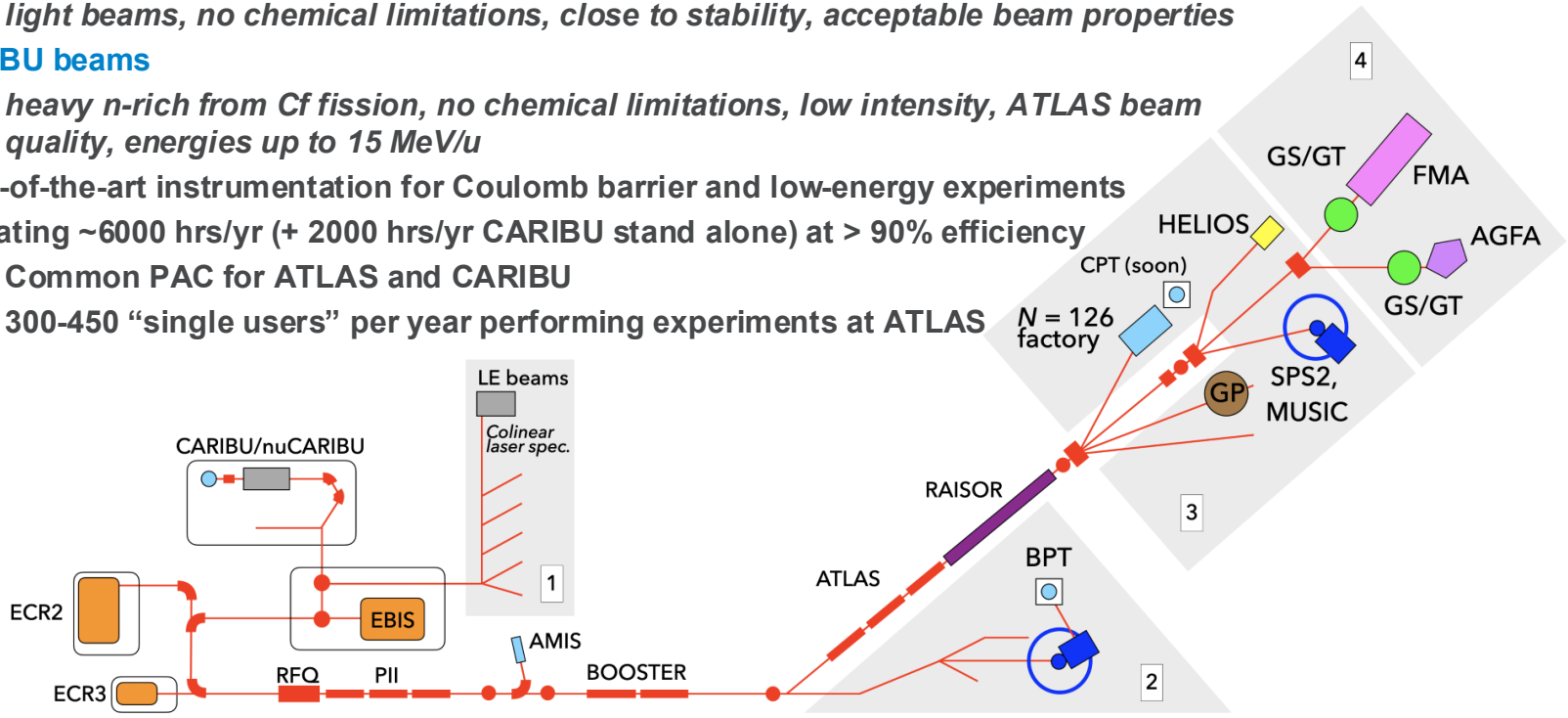
and University of Chicago

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

ATLAS/CARIBU FACILITY

- **DOE nuclear physics national user facility**
- Stable beams at **high intensity** and energy up to 10-20 MeV/u
- Light in-flight radioactive beams with **RAISOR**
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- **CARIBU beams**
  - *heavy n-rich from Cf fission, no chemical limitations, low intensity, ATLAS beam quality, energies up to 15 MeV/u*
- State-of-the-art instrumentation for Coulomb barrier and low-energy experiments
- Operating ~6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone) at > 90% efficiency
  - Common PAC for ATLAS and CARIBU
  - 300-450 "single users" per year performing experiments at ATLAS



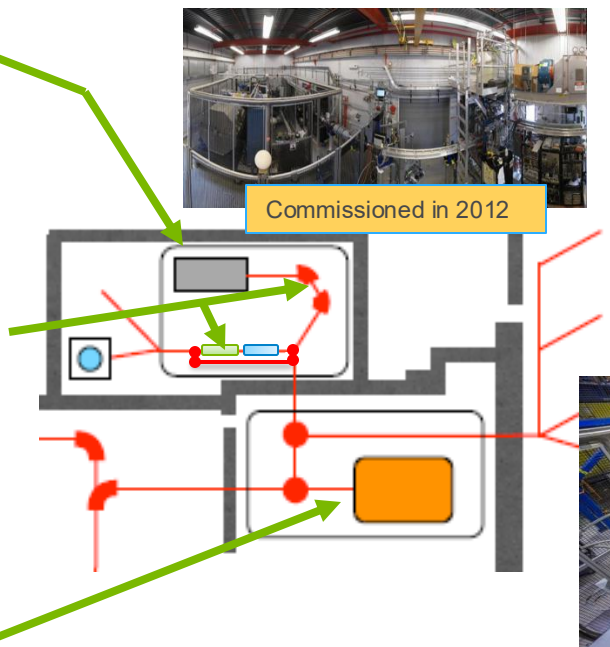
FISSION FRAGMENT YIELD INFORMATION

- Fission produces hundreds of neutron-rich fission fragments. These isotopes have different lifetimes and chemical properties
- The fission fragment distribution experimental information is mostly obtained on longer-lived isotopes through decay measurements. Yield for shorter-lived isotopes is mostly from modeling to reproduce the measurement on longer-lived isotopes.
- Quantitative knowledge of the decay properties of these isotopes is critical for most of these measurements.
- This data is at best unreliable … we have a number of projects (many at CARIBU) to improve this information on medium and shorter-lived isotopes to support the measurement techniques based on decay radiation detection, but this is not the topic of this talk.
- We have developed a new approach for these measurements that works by detecting isobarically selected ions to directly determine the yield. This technique is essentially independent from the chemical properties of the isotope and can be applied to isotopes with half-life down to ~ 25 ms.

NEUTRON-RICH BEAM SOURCE FOR ATLAS: CARIBU "FRONT END" LAYOUT

Main components of CARIBU

- **PRODUCTION**: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator and MR-TOF
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics

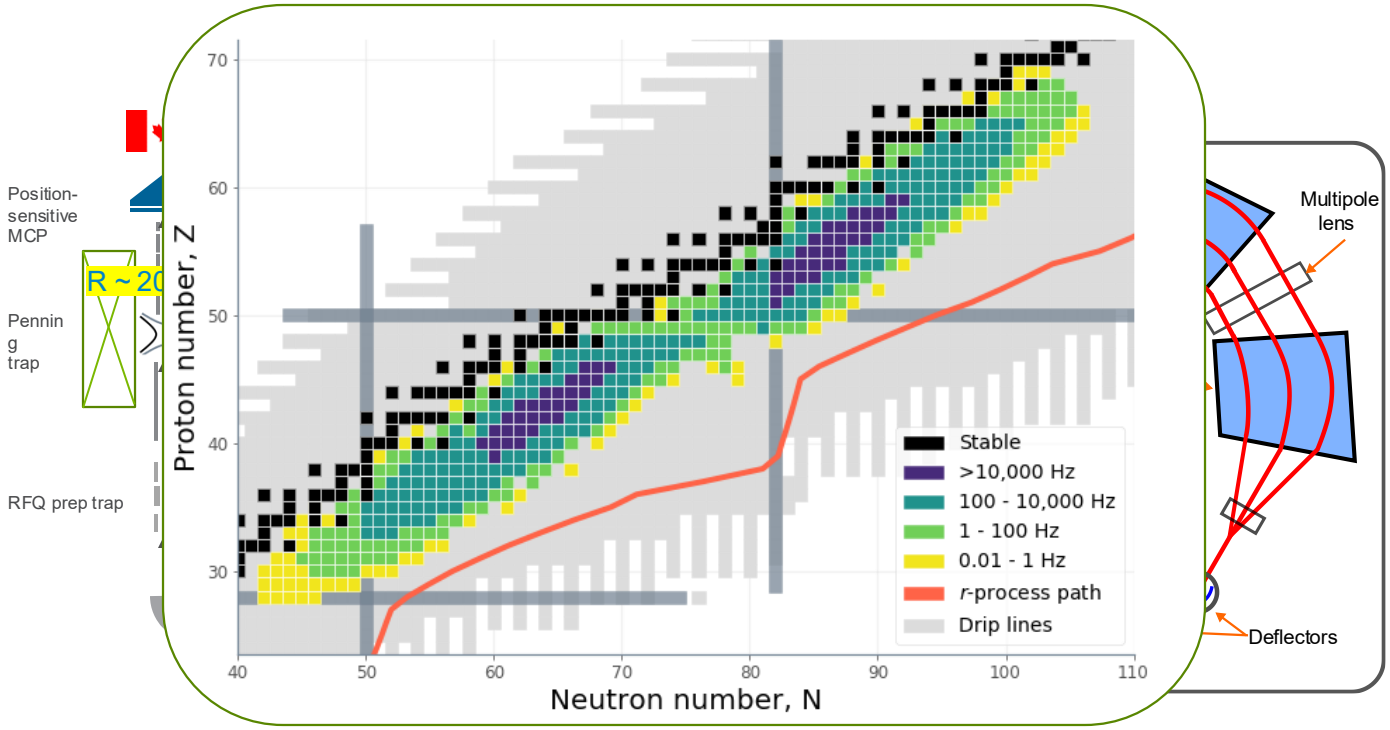


Commissioned in 2012

Commissioned in 2020

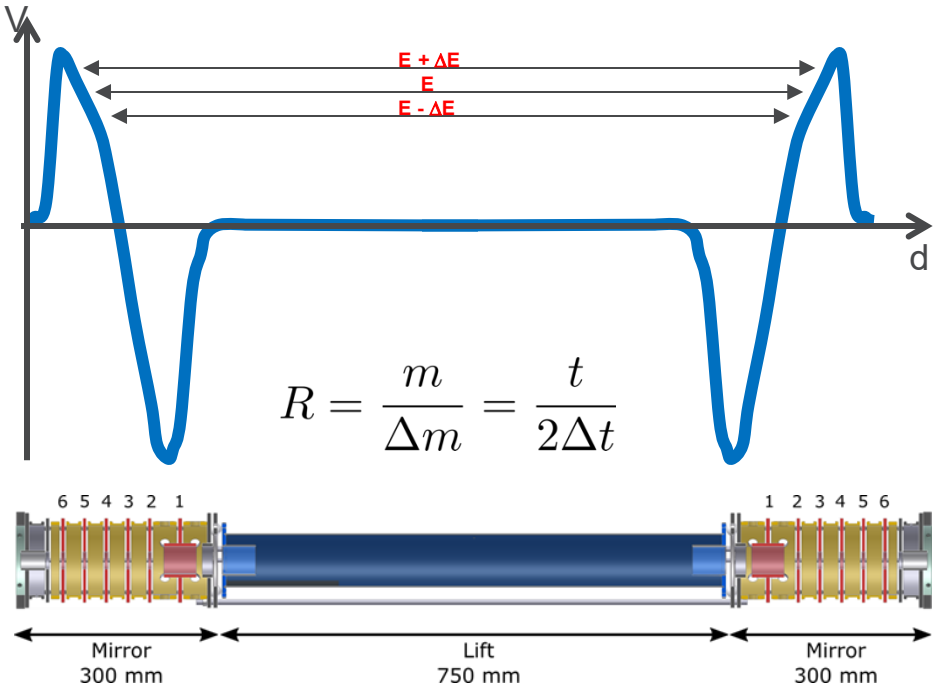
Commissioned in 2017

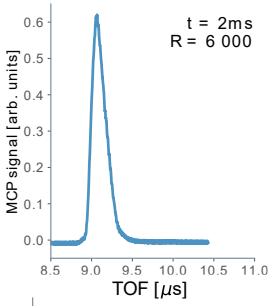
CARIBU
CALIFORNIUM RARE ISOTOPE BREEDER UPGRADE

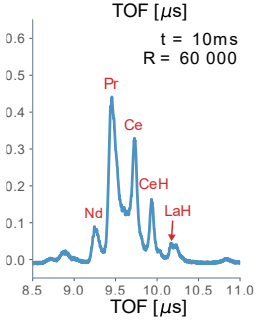


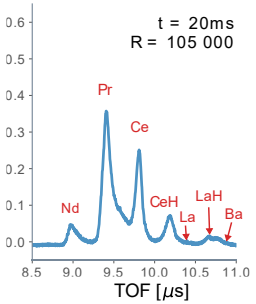
MR-TOF
MULTI-REFLECTION TIME-OF-FLIGHT MASS SEPARATOR

- System built to be isochronous with respect to energy …. i.e. $\Delta t / \Delta E = 0$
- Keep time dispersion from mass difference

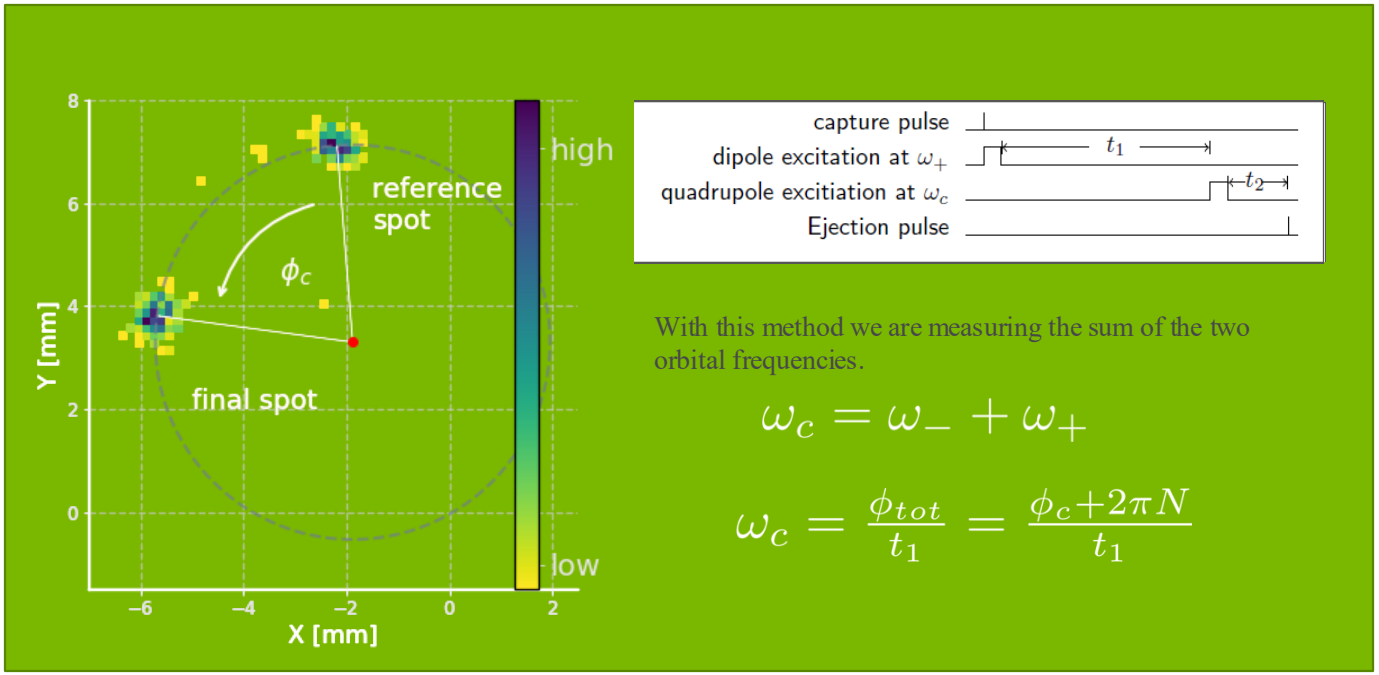








PHASE-IMAGING ION CYCLOTRON RESONANCE (PI-ICR) METHOD IN THE CPT PENNING TRAP SPECTROMETER

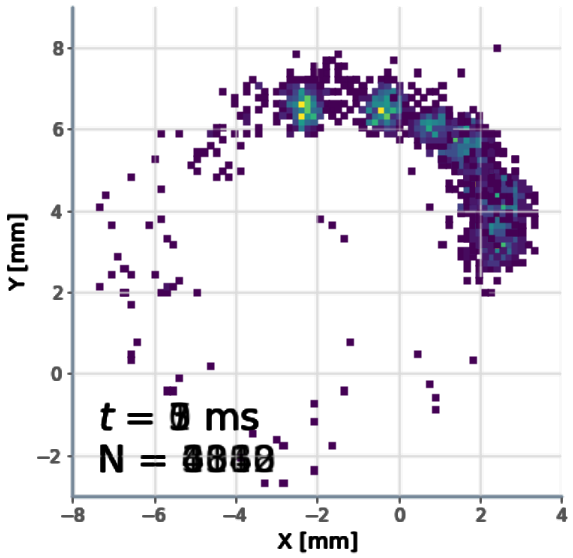


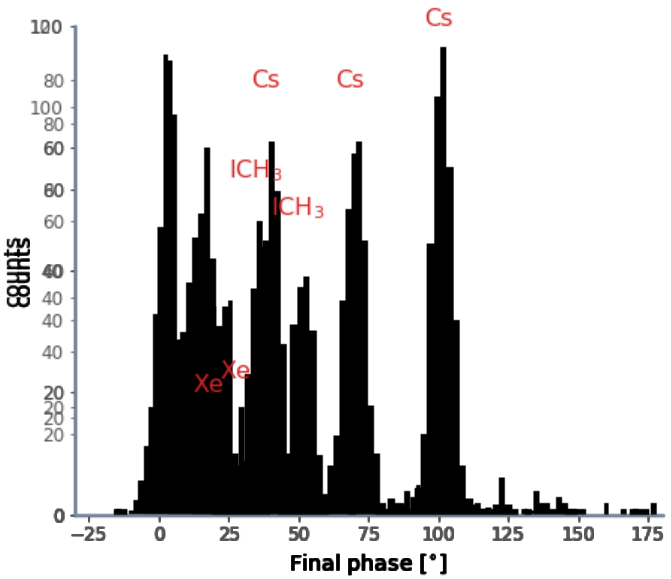
Originally developed off-line by S. Eliseev et al, PRL 110 (2013) 082501

We have demonstrated resolution of over 10,000,000 allowing to easily separate isomers

PI-ICR MASS SEPARATION

$$\nu_c = \frac{\phi_{tot}}{2\pi t} = \frac{\phi_c + 2\pi N}{2\pi t}$$

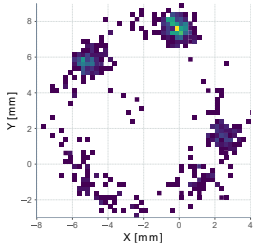


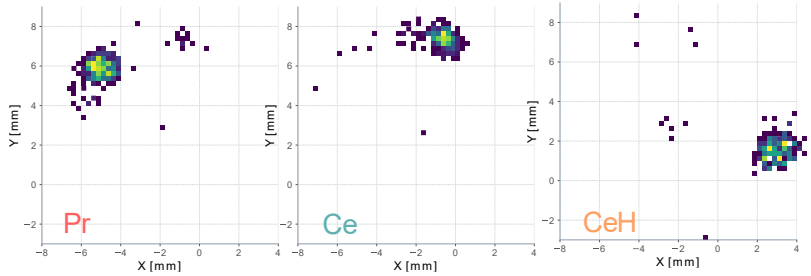


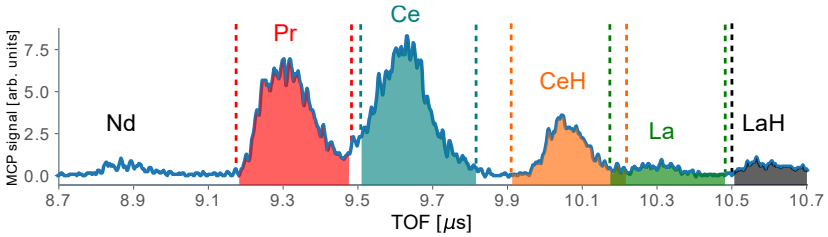
MR-TOF + PI-ICR

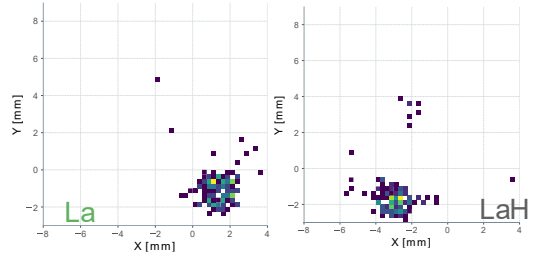
BEAM OF A/Q = 150/2+

- MR-TOF is a crucial device for the CPT
- What does R = 100,000 really mean?
- Moving 300ns BNG window around allows us to select a single isobar and suppress others

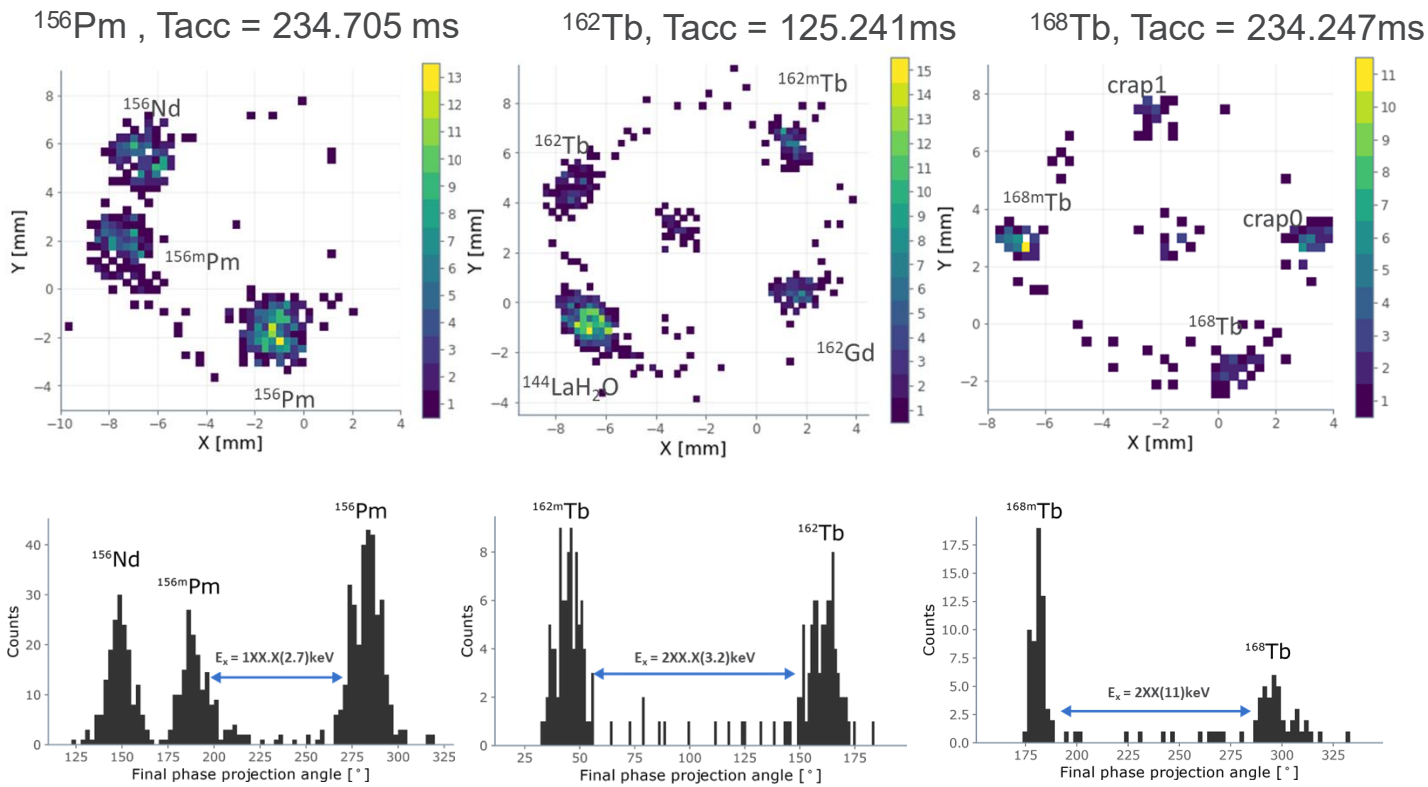






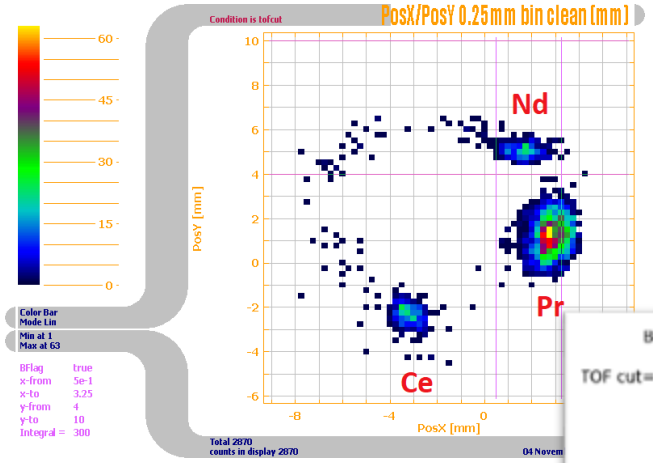


Ion counting Isomer measurements: fission yield, excitation energy, ….

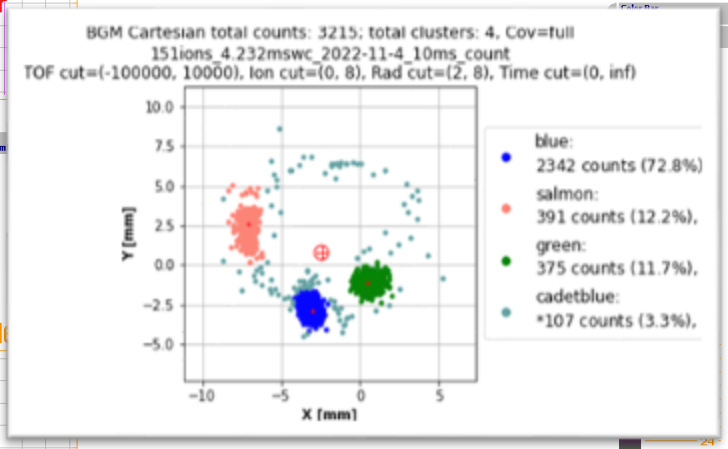


A number of results related to the influence of these isomers on nuclear structure and astrophysics (astromers) have already been published … a big compilation of ^{252}Cf fission isomeric yield is coming.

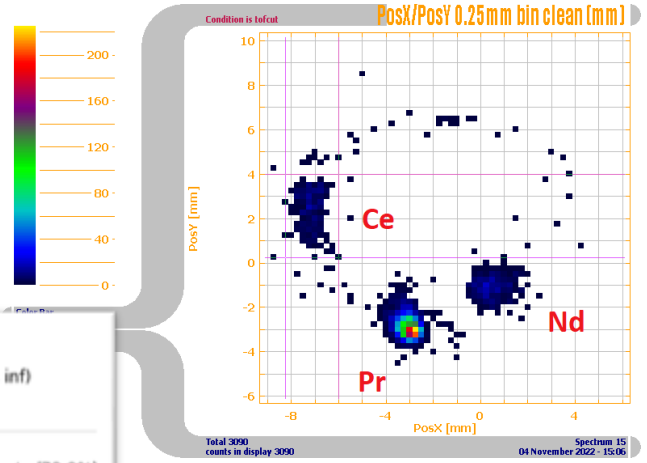
Ion counting for fission yield: use shorter excitation (~ 4 ms) and probe various angles



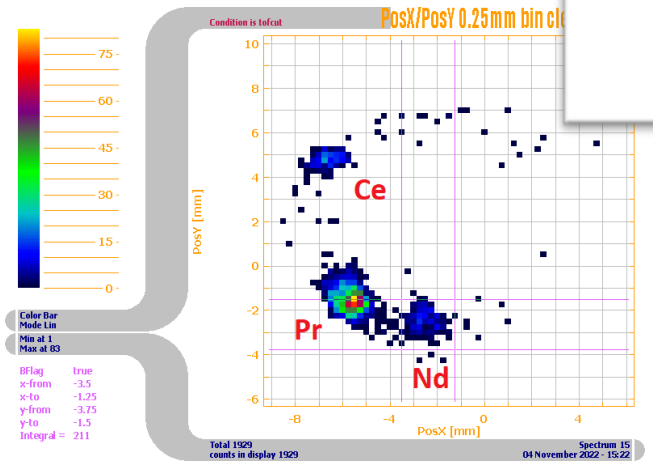
T_{acc} =4.212 ms



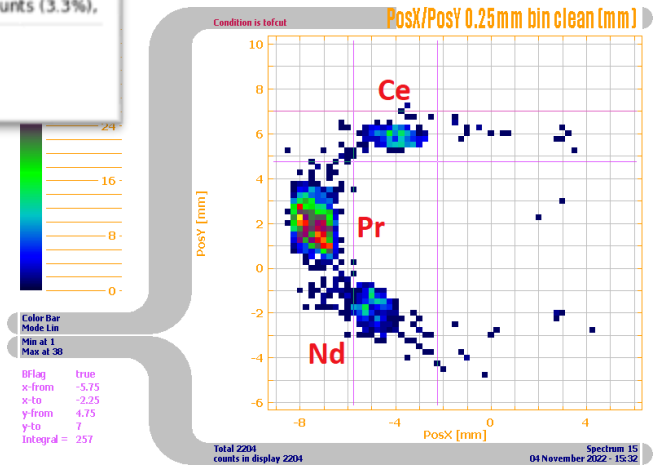
clustering algorithm



T_{acc} =4.232 ms

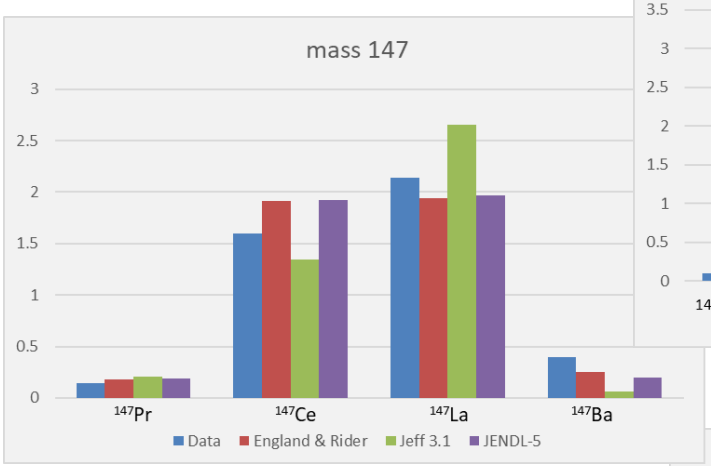


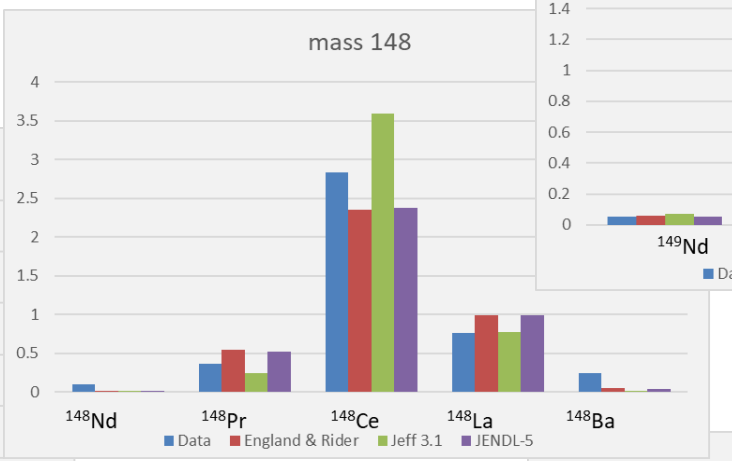
T_{acc} =4.242 ms

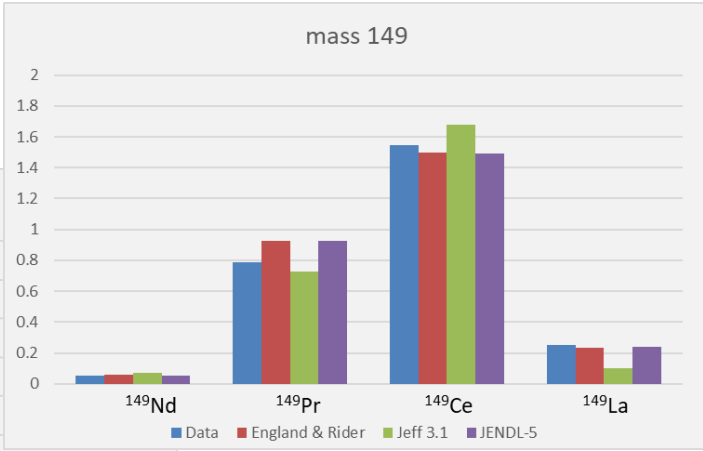


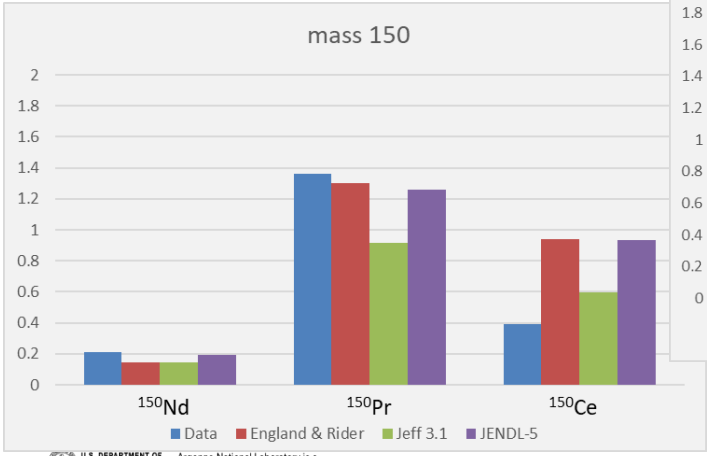
T_{acc} =4.252 ms

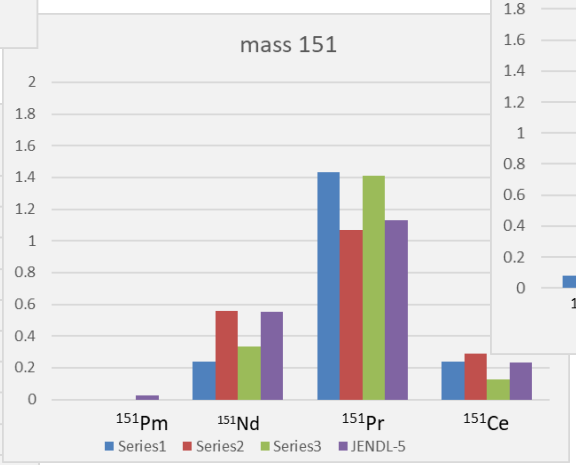
NO CLEAR WINNER BETWEEN VARIOUS FISSION YIELD TABULATIONS

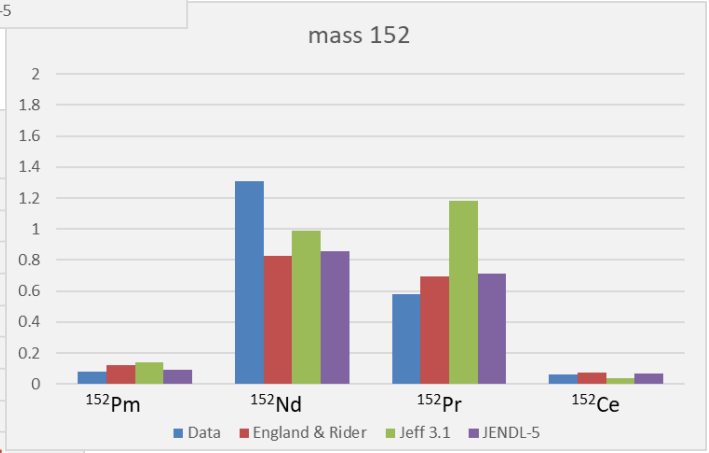




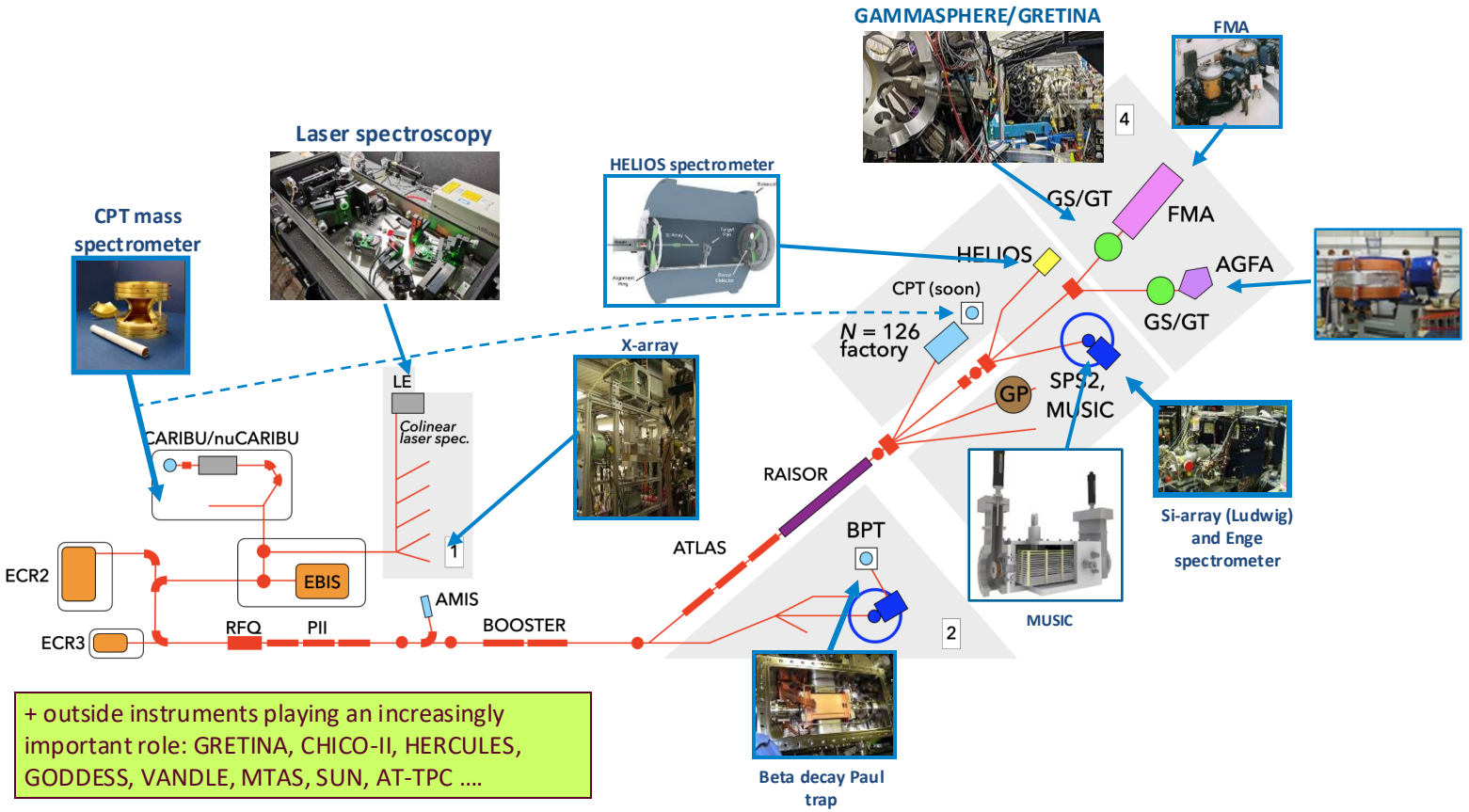








DISTRIBUTION OF EXPERIMENTAL EQUIPMENT

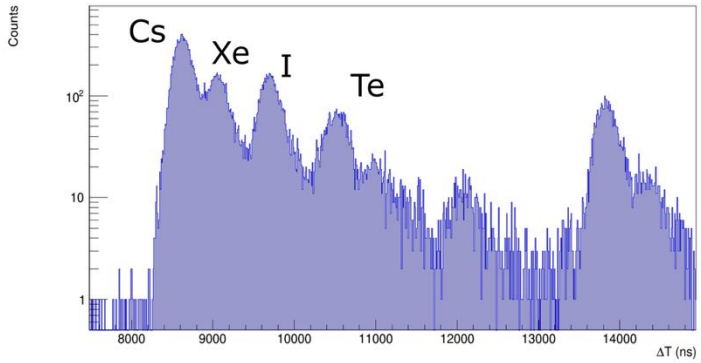


+ outside instruments playing an increasingly important role: GRETINA, CHICO-II, HERCULES, GODDESS, VANDLE, MTAS, SUN, AT-TPC ….

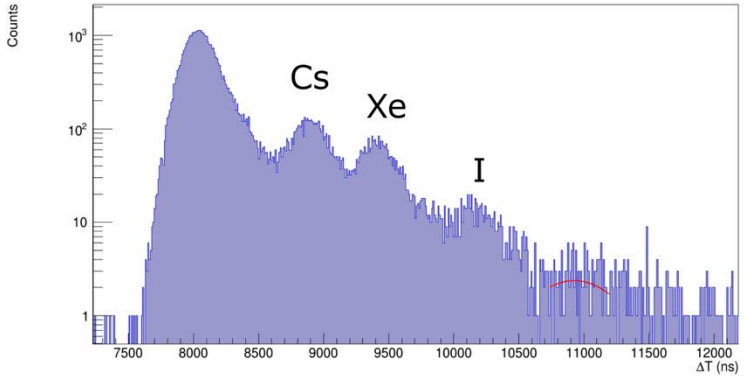
STAND ALONE MRTOF

- With CPT moving to an other experimental area (N=126 factory), can continue this work with the MRTOF system

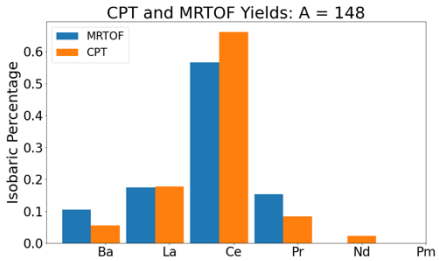
Mass 137

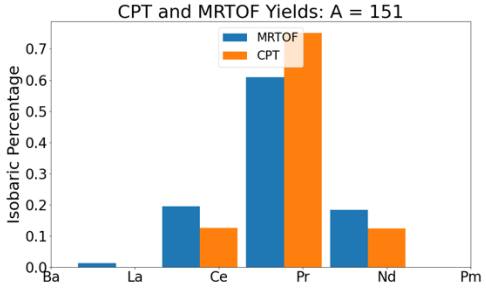


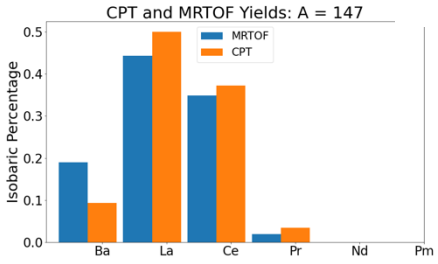
Mass 139

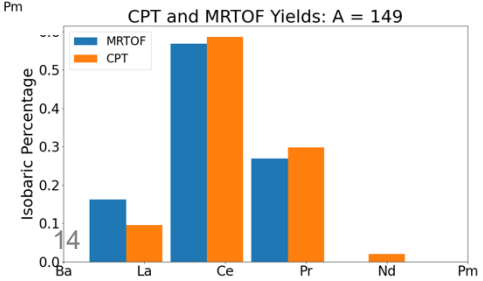


- Resolution is not as high so have to be more careful of contaminants … but the methods are in reasonable agreement



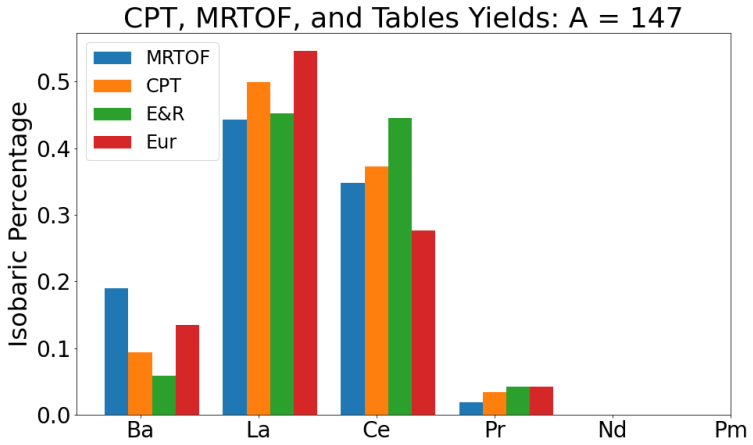


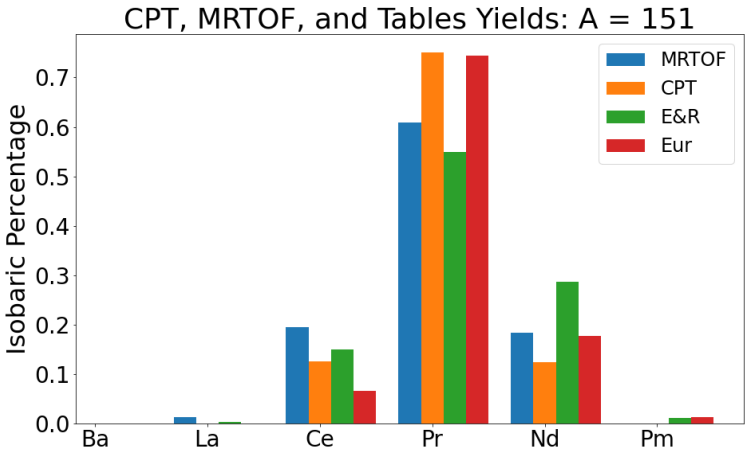


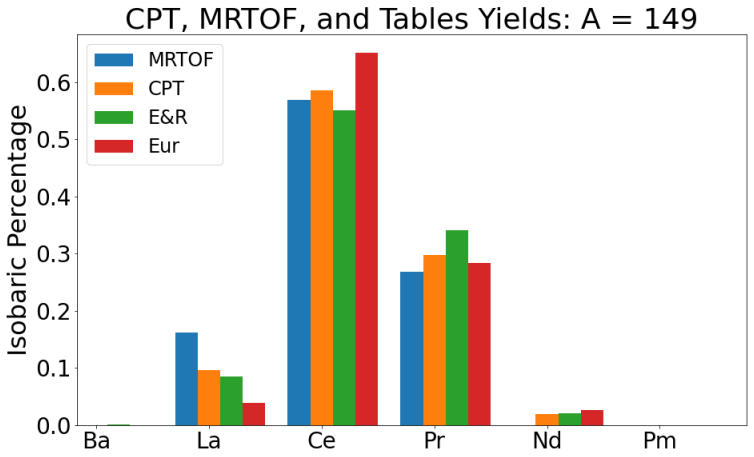


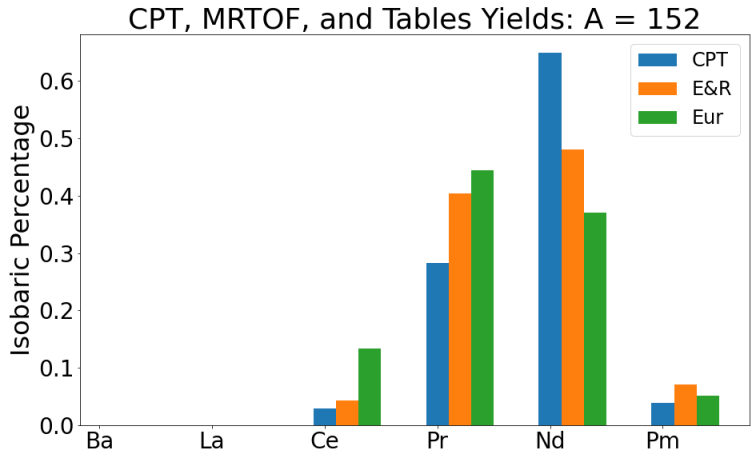
Completing analysis for spontaneous fission yield of ^{252}Cf

- Lots of data … still working on the normalization, but looks like old E&R table is as good as new tables



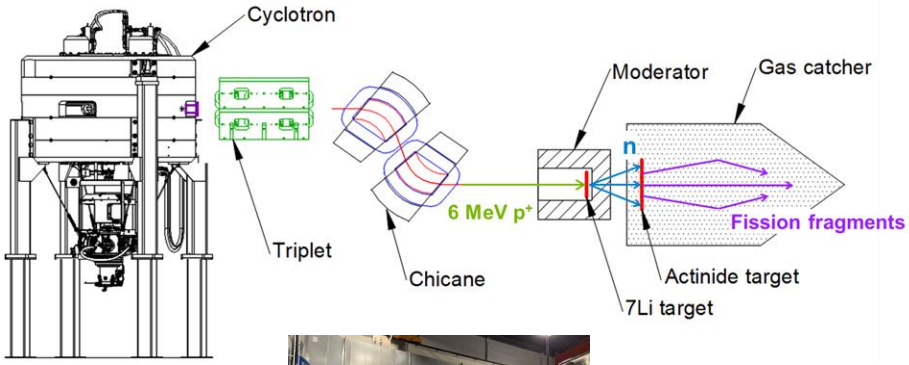


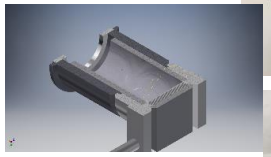


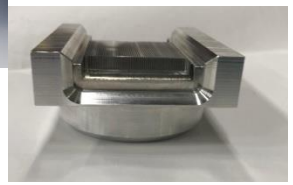


nuCARIBU (fission-fragment beams)

- Move from spontaneous fission of ^{252}Cf to neutron-induced fission of actinides (starting with ^{235}U)
  - Higher yield
  - Easier to maintain and operate
- Serving all areas of ATLAS
  - seven low-energy beam lines in area 1
  - ~6 MeV/u beams in area 2
  - up to 12 MeV/u beams in areas 3 & 4
- Major programs in Coulomb excitation (GS and GRETINA and in the future Clarion), and with the AT-TPC and HELIOS, direct reaction studies and resonant elastic scattering
- Cyclotron commissioning completed, triplet and chicane installed, ^{7}Li neutron generator tested online at ATLAS, working on SAD/ASE approval with goal of extracted radioactive beam by end of year

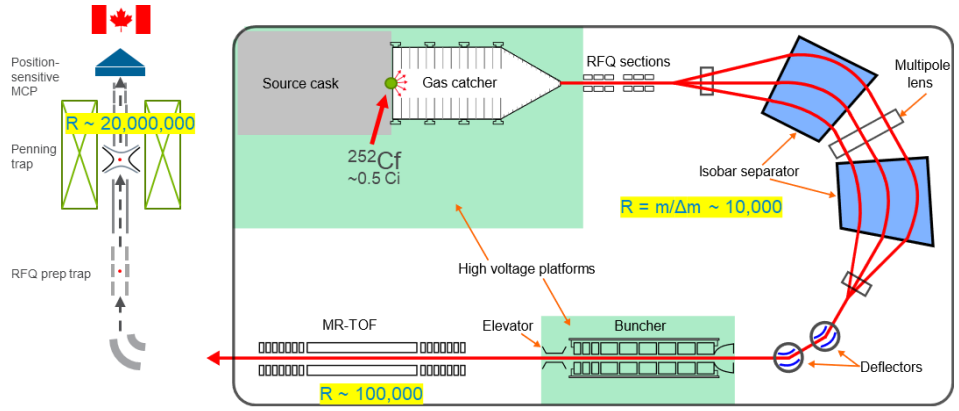


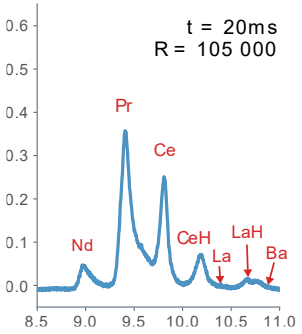




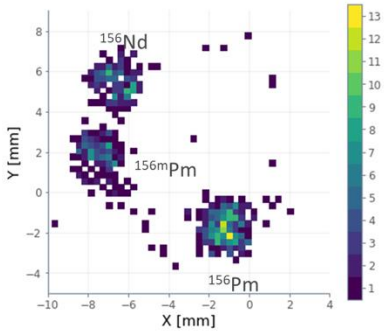
INDEPENDENT FISSION YIELD MEASUREMENTS STATUS

- The technique we have developed relies on the universality of the CARIBU extraction system and high-resolution mass separation followed by ion counting. The technique is fast and insensitive to lack of, or incorrect, decay information.





Isobar resolution with MR-TOF



Isomer resolution with Penning trap

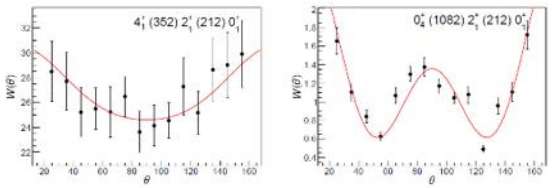
- We are finishing the analysis of the isomer ratio yield and independent fission product yield for spontaneous fission of ^{252}Cf.
- We have tested using only the MRTOF for next measurements and demonstrated that the two approaches agree.
- Preparing to shift to nuCARIBU where we can use the same technique to look at FPY for thermal neutron induced fission on ^{235}U and ^{239}Pu. This will allow **direct** measurements on n-induced fission fragments with sub-second lifetime … those are critical for a number of applications and have only been determined indirectly so far.

BETA DECAY FACTORY IN AREA 1

Gammasphere Decay Station

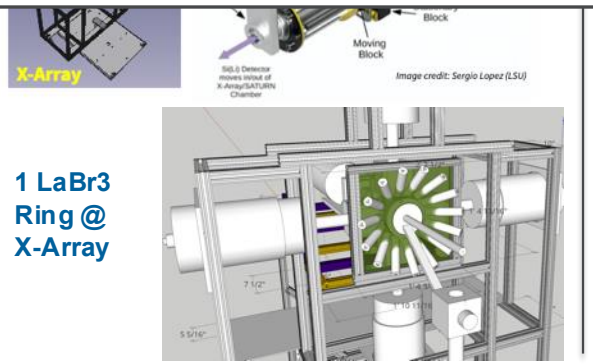
- β–γ coincidences for proper feeding intensities
- γ–γ, γ–γ–γ for level structure determination and spin assignments from angular correlations
- Red
  crys
  Arra
- Calc
  exci
  bas
- Gar
  prov
  contact @ 4, 8 and 20 MeV full range

γ ray angular correlations following ^{100}Y beta decay with Gammasphere



Saturn/X-Array Upgrades

- $LaBr_3$ to measure lifetimes – 2 rings, 15 1”x1” crystals each ring.
- Conversion electron measurements utilizing Laces



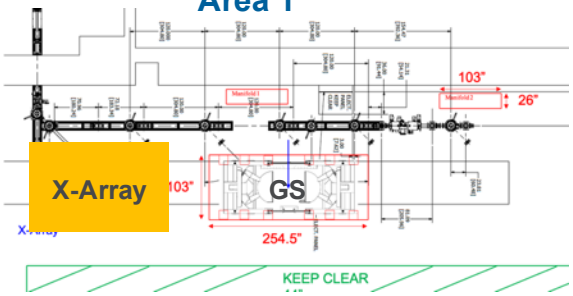
1 LaBr3 Ring @ X-Array

Beta Decay Factory

- Gammasphere upgrade project allows for relocation of device to Area 1.
- Using nuCARIBU, we estimate 2 orders of magnitude increase in implanted ions.

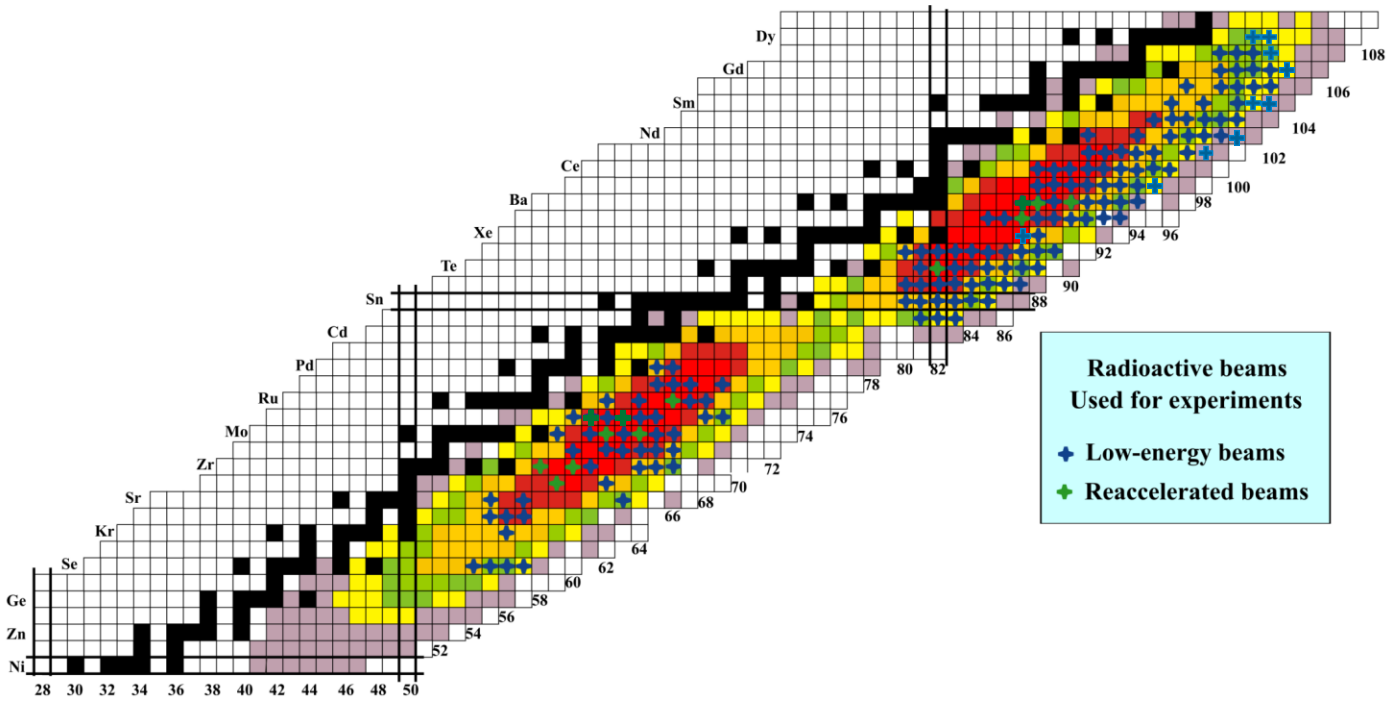
Decay Workshop to be held at Argonne **in early 2025** to gauge interest in moving Gammasphere to Area 1 for use in decay studies using isotopes extracted from *nu*CARIBU – details to follow.

30-50 parent decays



SUPPLEMENTARY MATERIAL

CARIBU BEAMS DELIVERED TO EXPERIMENTS SO FAR



All of these beams now available in the new low-background low-energy area (Area 1)

LAYOUT OF ATLAS FACILITY