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Title: Multi-channel probes to understand fission dynamics

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Multi-channel probes to understand fission dynamics

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P-27; Nuclear Astrophysics and Structure
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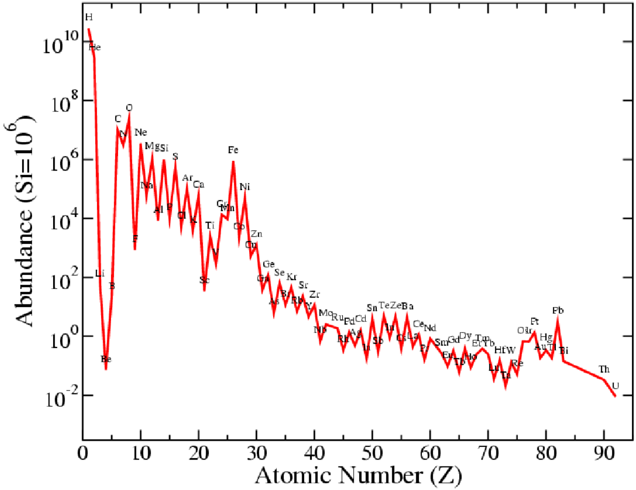
April 6, 2016

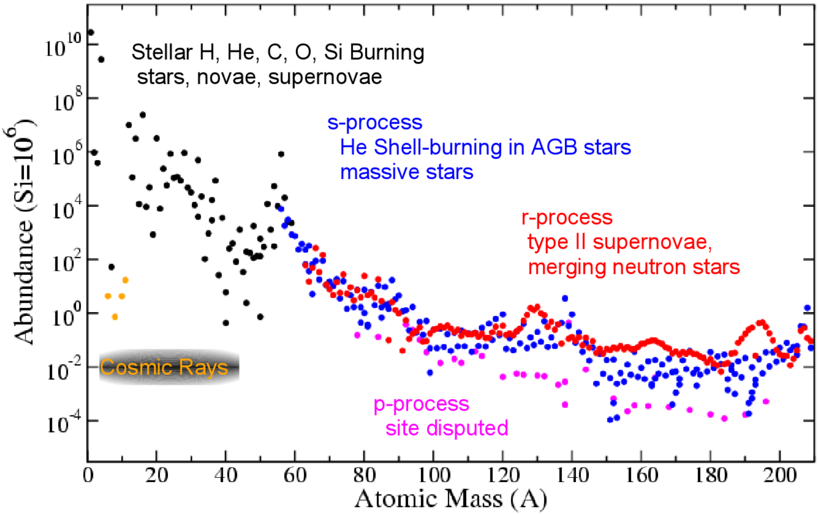
ANL Heavy-ion Discussion

A profoundly straightforward question: element genesis



- Explaining the origin of the elements is a major outstanding question in nuclear astrophysics
- Observed elemental abundance distribution shows strong nuclear physics effects

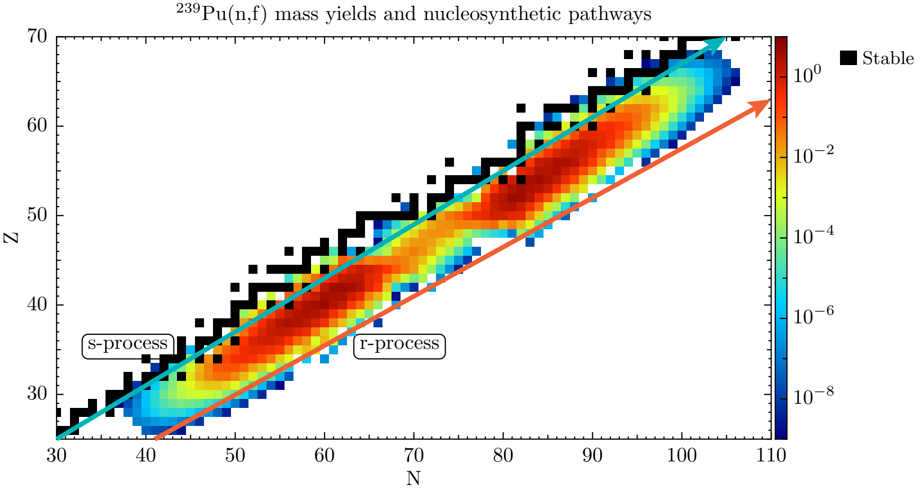
Isotopic abundances and astrophysical sites



Anders and Grevesse, 1989
Kappeler, Beer, and Wisshak, 1989

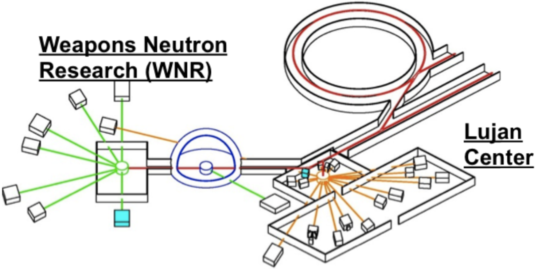
A. Couture

Overlapping interests



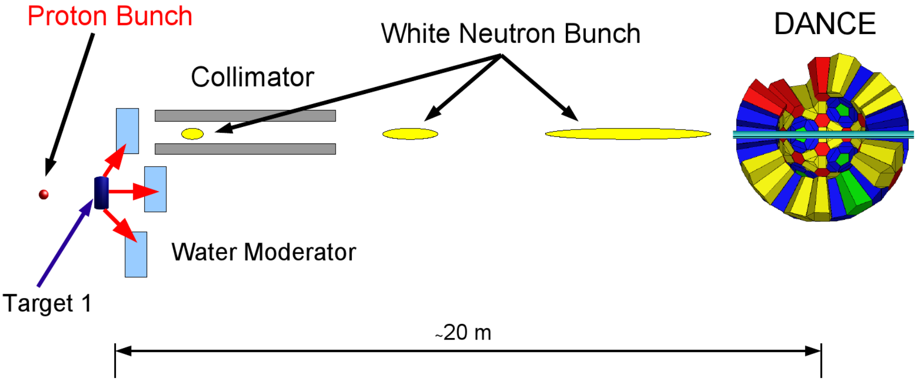
- Fission product yields and both neutron-driven nucleosynthetic processes require neutron capture rates in the same region of the nuclear chart
- ...so there is common ground between astrophysics and applications.

LANSCE physical overview



- 1/2 mile long LINAC drives 800 MeV proton beam
- Neutrons produced by spallation on Tungsten
- Beam delivered to multiple areas simultaneously:
  - WNR: nuclear physics
  - Lujan Center: materials science / nuclear physics
  - Proton Radiography: applications
  - Ultra Cold Neutrons: fundamental physics
  - Isotope Production Facility: medical / applications
- Nuclear physics program is 10 flight paths / 30k hours per year

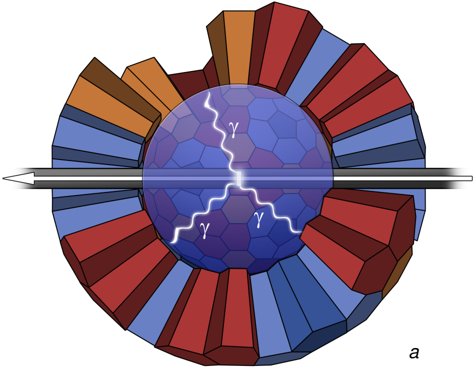
Time of flight measurements



E_p= 800 MeV ν_p=20 Hz 10 meV < E_n < 500 keV

A Detector for Advanced Neutron Capture Experiments

- 160 BaF_2 crystals w/ 4 crystal geometries
- 85% Efficiency - calorimeter
- Capable of high trigger rates: 250 kHz/ch or $>$1 MHz on array
- Radioactive / Rare targets (39 MBq / 5 μg)
- γ-ray energy / multiplicity information
- Capture identified by unique Q-value
- ^{6}LiH sphere reduces scattered neutron background



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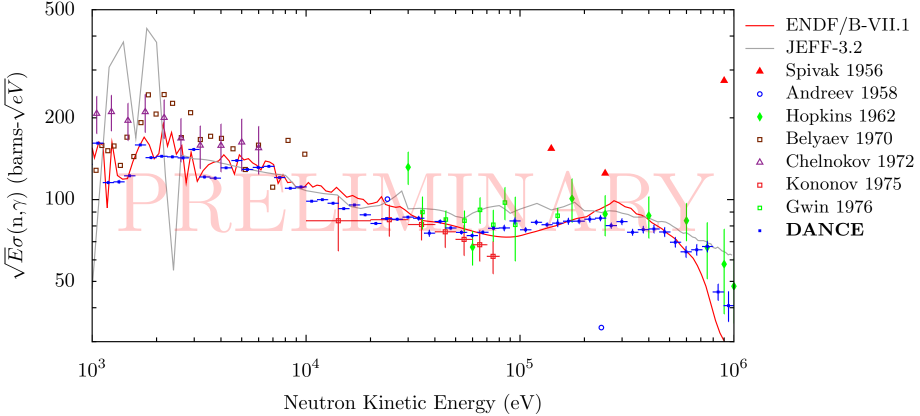
[a]M. Weigand, 2013

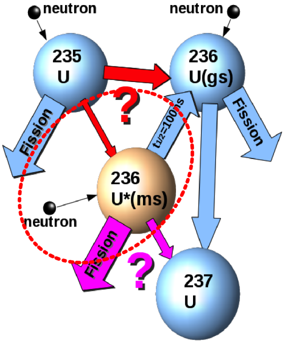
DANCE results on ^{239}Pu

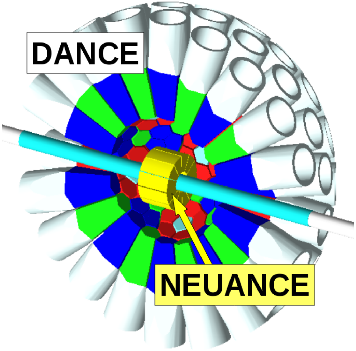


- Closer consistency with ENDF across the board
- Now have one self-consistent dataset across the whole region

January 2016: Capture Isomers and NEUANCE

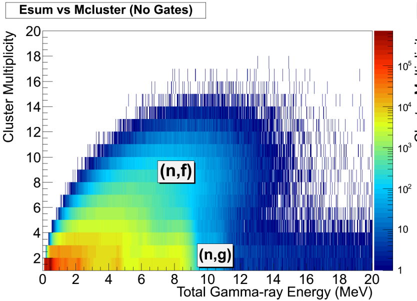
- Short-lived actinide isomers can influence secondary reaction rates in high fluence environments
- Studying these isomers requires high count-rates for capture and fission

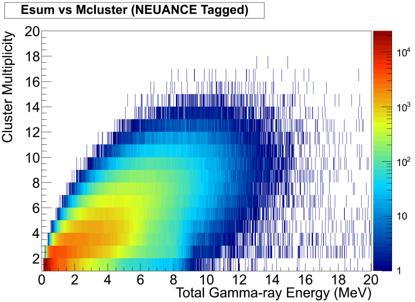




- Large sample masses are hard to do with charged particle detectors
- NEUANCE: 20 - 28 Stilbene detectors inside of DANCE
- Thresholds make NEUANCE only to fission neutrons
- May also improve traditional capture measurements via γ-ray tracking

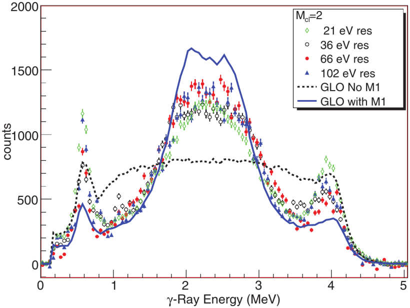
January 2016: First experiments with NEUANCE

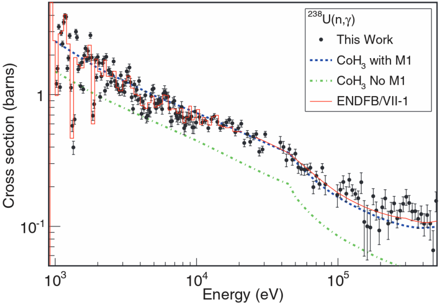


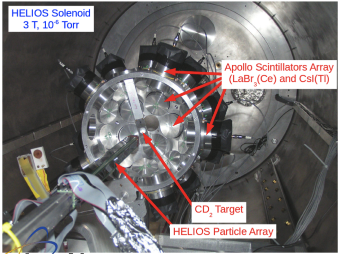


- PSD provides sensitivity to fission neutrons, blind to the beam
- Multiplicity / energy spectra show NEUANCE tagging the fission
- 2.5 - 3 TB/day with 2 week run, so detailed analysis will take a while...
- Putting together a dedicated analysis cluster

New directions: DANCE + Apollo





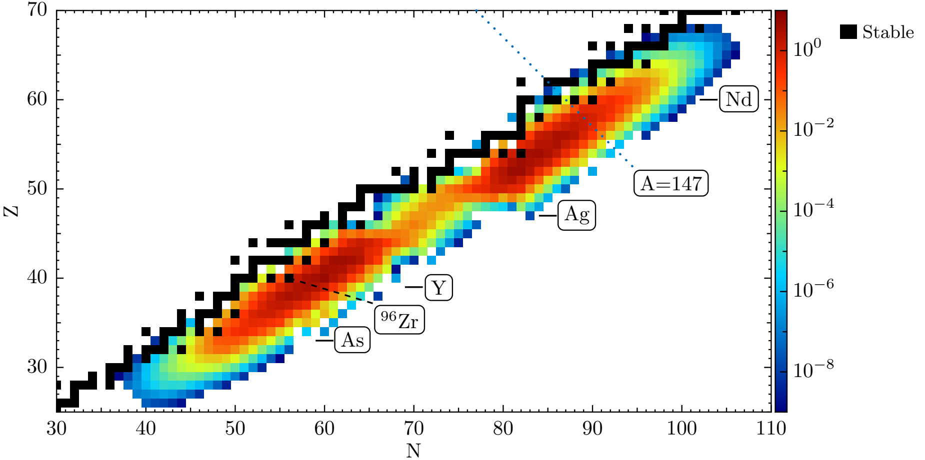


- DANCE can constrain γ-ray strength functions through capture cascades
- Improves physics inputs to capture cross section calculations
- In ^{238}U case this has been demonstrated
- Apollo: extension to unstable nuclei with (d,p) at Helios

A. Couture

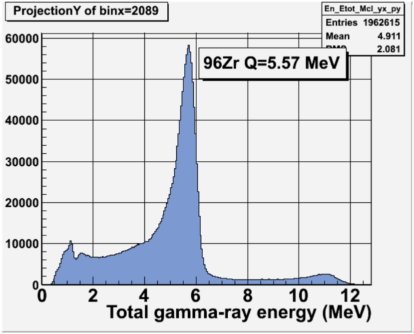
J. Ullmann *et al*, PRC 89, 034603

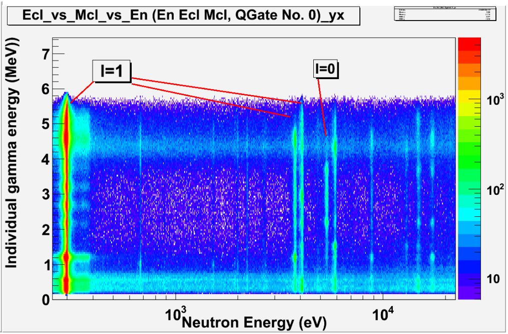
Capture on fission fragments: ^{96}Zr (J. Winkelbauer)



- Reaction networks for nuclear fuel are important for applications
- Must benchmark Apollo with DANCE prior to use for short-lived species
- ^{96}Zr lies near the light mass peak of the ^{239}Pu fission fragment distribution

^{96}Zr at DANCE (J. Winkelbauer)





- DANCE measurement completed 12/2015
- On-line analysis of DANCE data shows significant resonance-to-resonance variation in the capture cascades (right)
- Running Apollo now(!)

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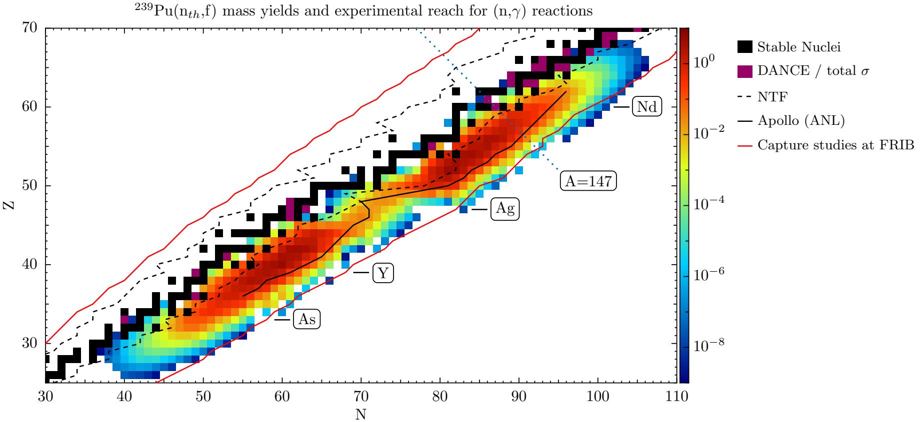
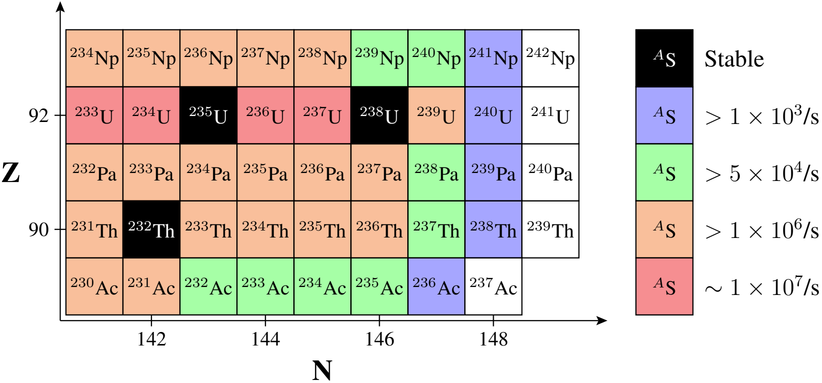
Where do we go from here? Fission fragments



- DANCE / total σ directly probe high impact radionuclides close to stability
- CARIBU potentially provides most of the relevant neutron-rich nuclei
- FRIB completes neutron rich, gives access to proton rich side for (n,Xn) reaction products

Where do we go from here? Actinides

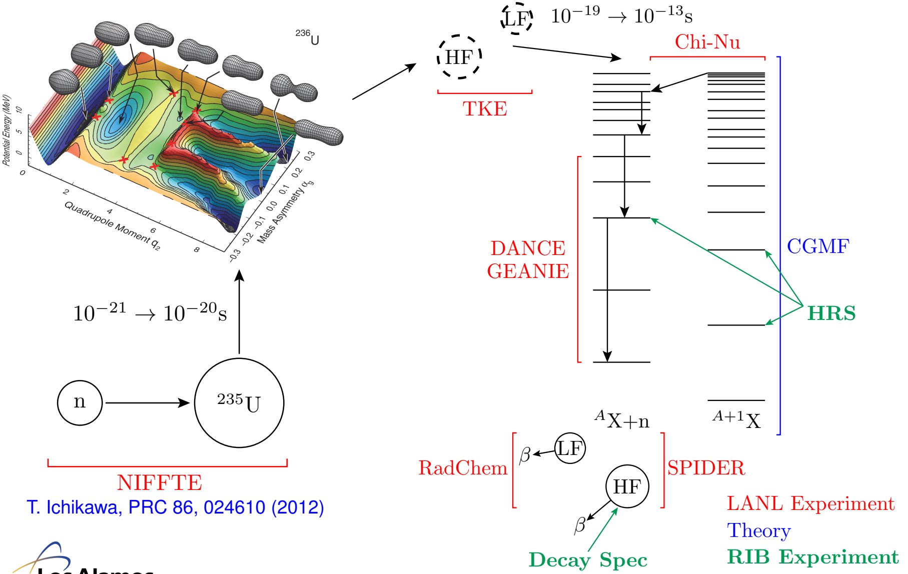


- Reactions on unstable nuclei near the major actinides are interesting for applications
- Working with such high Z, A nuclei presents additional challenges

Great, but isn't this a supposed to be a *fission* talk?

...and now for the rest of the story

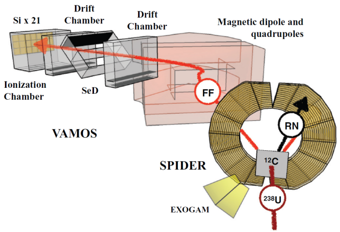
Background: LANL's fission program

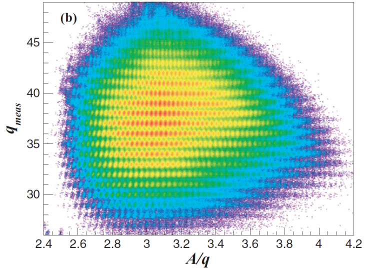


T. Ichikawa, PRC 86, 024610 (2012)

What happens when you can't use LANSCE?

...you move to inverse kinematics...

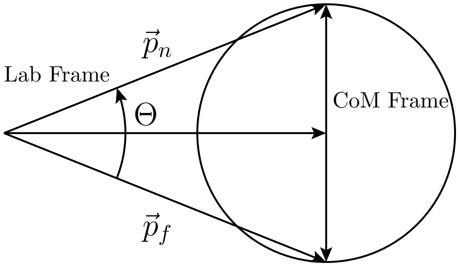




M. Caamano *et al*, PRC 88, 024605 (2013)

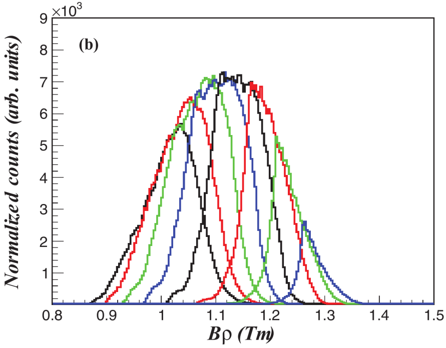
- VAMOS + EXOGAM: example of fragment + γ-ray studies in inverse kinematics (studied ^{238}U at 6 MeV/A)
- Measured independent yields w/ $\Delta A/A \leq 0.8$, $\Delta Q/Q \approx 0.7$ (FWHM) for several hundred isotopes along with coincident γ-rays w/ HPGe Clovers

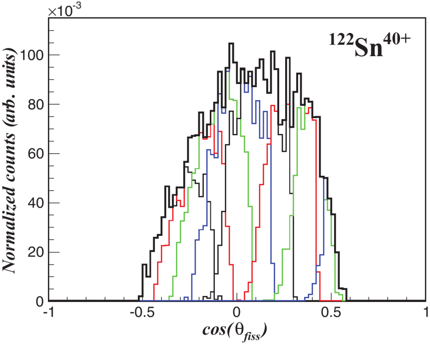
What inverse kinematics can buy you (besides radioactive ion beams)



- Physics happens in the CoM frame, measurements happen in the lab
- Detecting the relevant particles becomes a kinematics game involving Lorentz transformations
- Opportunity: isotropic CoM processes become focused, allowing finite detectors to gain effective angular acceptance

Acceptance issues at low beam energy

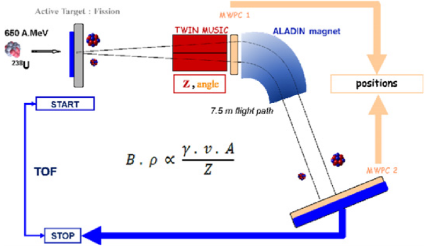




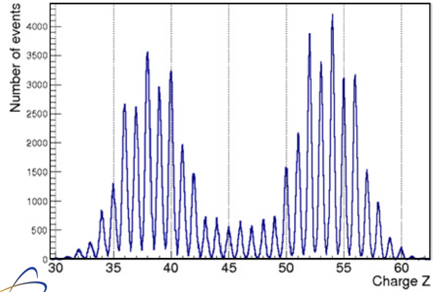
Colors show rigidity (left) and angle (right) settings to cover the fission fragments with VAMOS - fragments still emitted in a 25° cone at 6 MeV/A

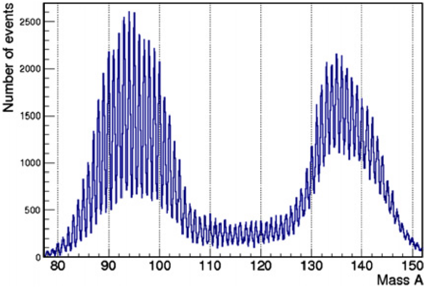
- Only get one fission fragment at a time

The other extreme: relativistic fissioning systems

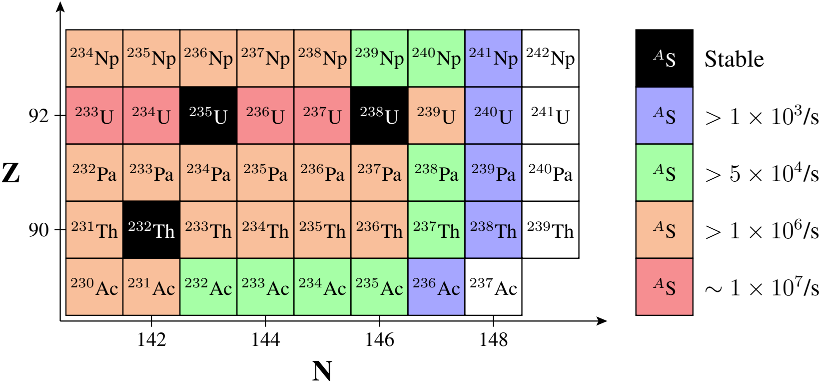


- SOFIA at GSI looks at fission fragment yields at 650 MeV/A(!)
- Z, A resolution (FWHM) of ∼0.4, ∼0.7 respectively
- Kinematic focusing puts all fission fragments in acceptances at once



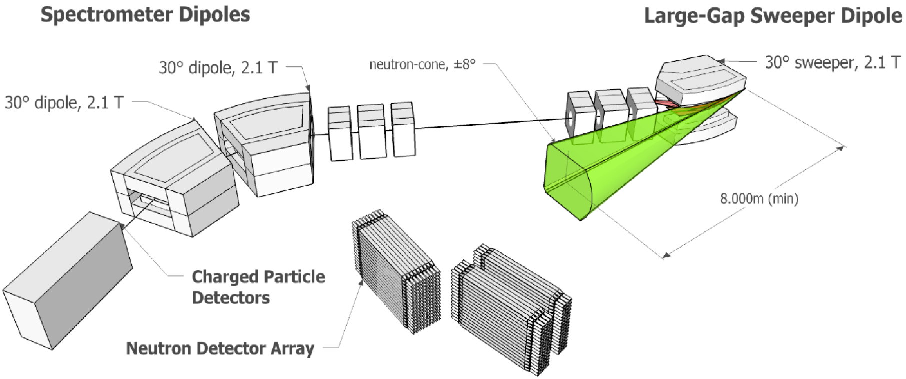


FRIB Rates (Slow Beams)



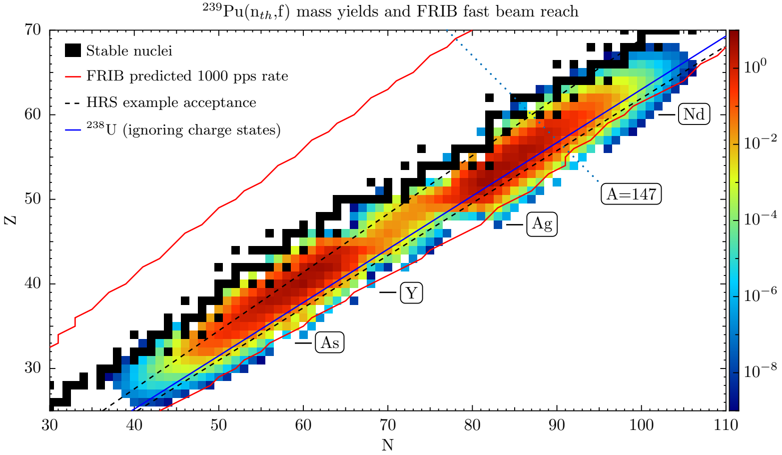
- Low limit for (n,f) studies: 10^6/s, need to see what the ISLA design can really do
- If you could use fast beams, gain $\sim$ 100x beam intensity...

A High Rigidity Spectrometer for fast FRIB beams



- Concept for charged particle spectrometer capable of bending the 200 MeV/A FRIB beams

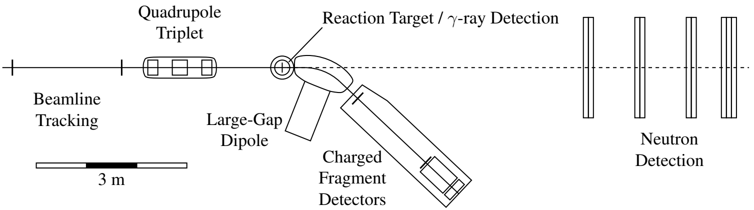
A naive look at fission fragment acceptances

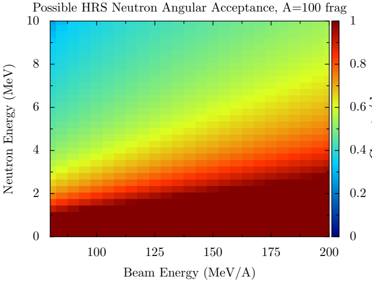


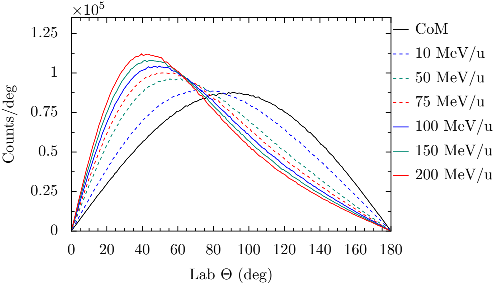
- The FRIB fast beam program can reach nearly all the fission products as secondary beams...
- ...but wait, HRS acceptances are pretty big. Look at fission directly?

Los Alamos NATIONAL LABORATORY EST. 1943

A rough experiment sketch

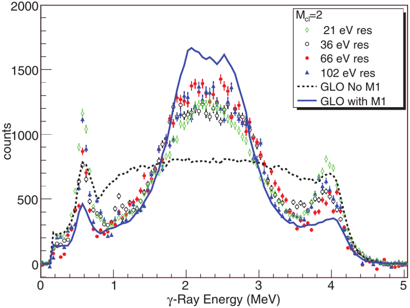


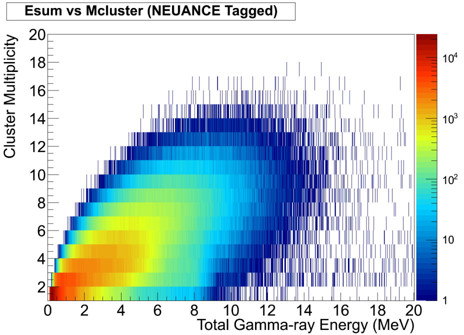




- Multi-hit FP tracking and PID + auxiliary detectors could enable measurement of all fission outputs and their correlations simultaneously

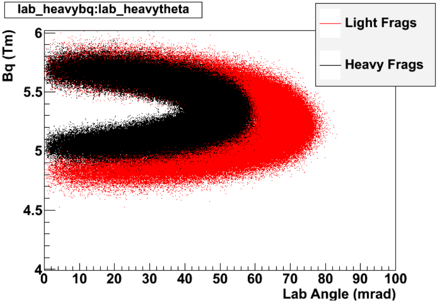
What we’re looking for / fission simulations



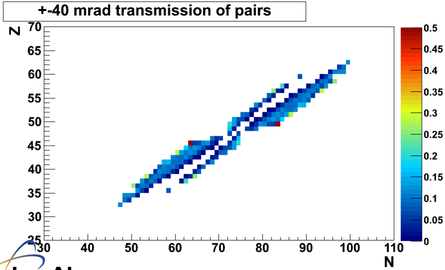


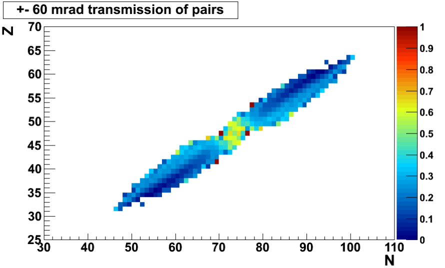
- Looking for statistical nuclear properties (e.g. capture cascades on left)
- Looking for many γ-rays at once (measured ^{235}U multiplicity / energy from DANCE on right) + neutrons + FF
- To estimate acceptance requirements, T-2 used their latest MCHF to generate 1 million ^{239}Pu(n_{th},f) reactions
- Took their fragment mass / kinetic energy splits in CoM, randomized angles, boost to 190 MeV/A

Capturing the fission fragments

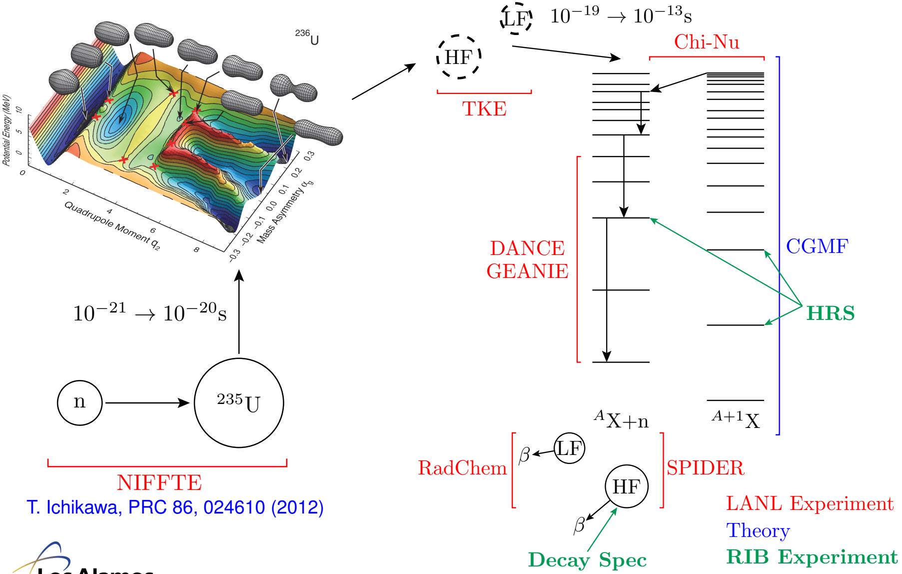


- Assume low beam emittance (otherwise intractable)
- Significant energy/angle correlations in the lab
- Assume transmission of fragments based on $\pm 5\%$ $\Delta p/p$ and $\Theta_{lab} < 40, 60$ mrad





Reminder: what we stand to gain



Conclusions

- Neutron induced reactions are important for nuclear astrophysics and applied fields in nuclear energy and security
- LANSCE has a program to address many of these questions directly with neutron beams on (near-)stable nuclei
  - Increasing demand for *correlated* data to test details of fission models poses additional challenges
- Possibilities exist to extend existing experimental efforts to radioactive beam facilities
  - Kinematic focusing from using inverse kinematics has potential to circumvent some challenges associated with measuring correlations between fission output channels

Acknowledgements

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G. Rusev (C-NR)
J. Ullmann (P-27)

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