β-Delayed Neutron Emission Studies of Trapped Ions at CARIBU

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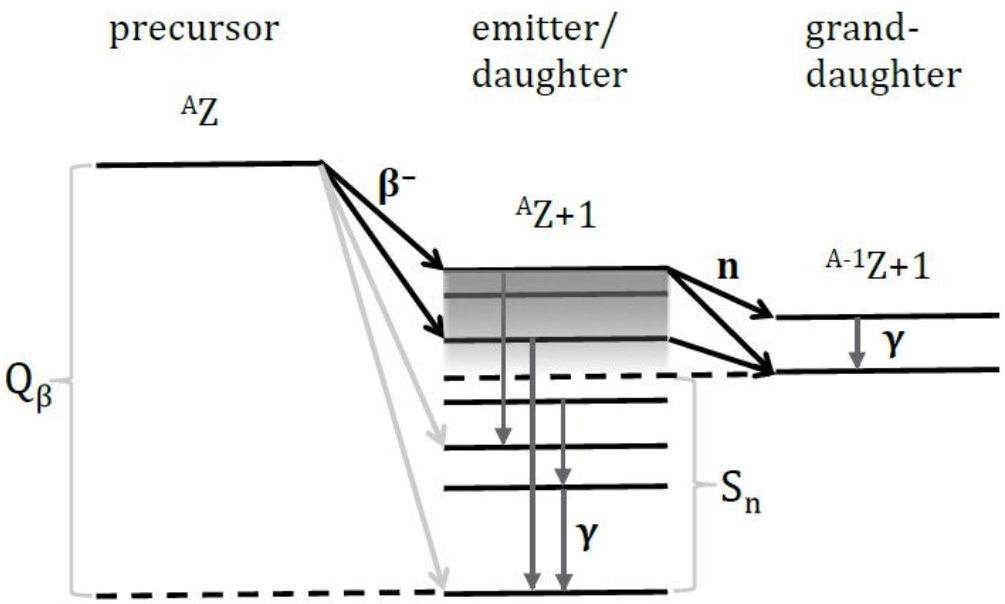
Louisiana State University
Workshop on Nuclear Astrophysics Opportunities at ATLAS
ANL, July 13th, 2019

β-delayed Neutron (βn) Emission



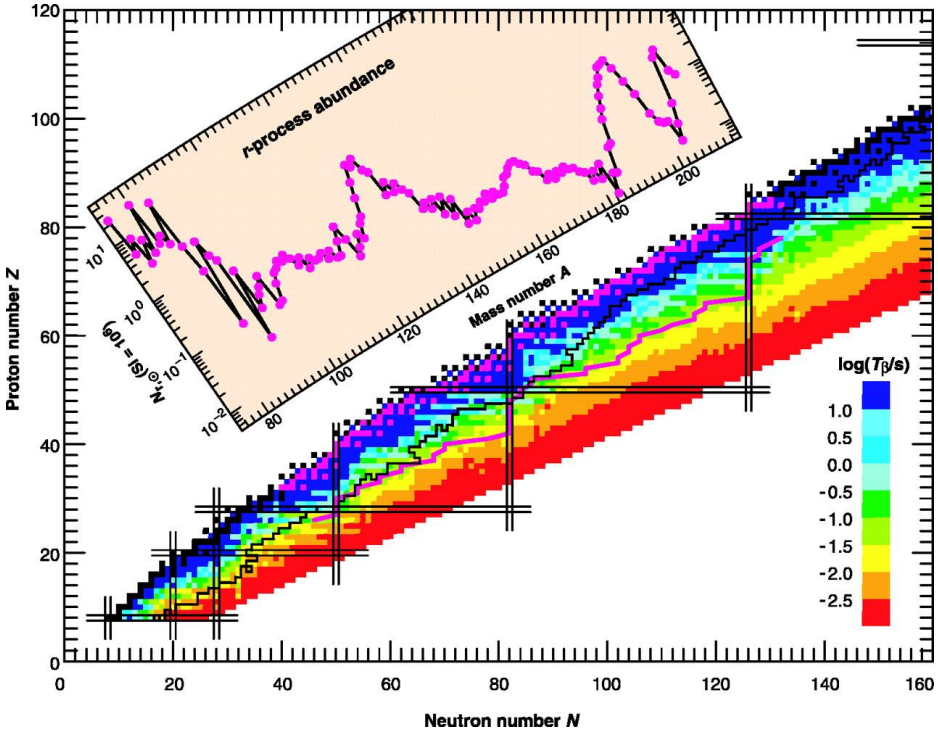
Nuclear Structure – Common decay mode for n-rich nuclei. Information on level densities and decay widths for states above S_n

Nuclear Astrophysics – Influential to *r*-process nucleosynthesis; impacts elemental abundances at late times

Nuclear Energy – Control & operation of reactor (kinetics), safety, and impacts current and future reactor designs

Stockpile Stewardship – properties of fission fragments of great interest; identification

r-process nucleosynthesis: nuclear data needs



Sneden et al., ARA&A 46, 241 (2007)

Rapid neutron-capture process responsible for about half of elements formed from Fe/Ni to U

Path defined by:

- astrophysical environment (i.e. CCSN, NS-NS merger)
- properties of nuclei populated

Nuclear Data necessary to improve models and help constrain astrophysical site(s) of the r-process:

- Nuclear masses
- ***(n,γ) rates***
- ***β-lifetimes***
- ***β-delayed neutron emission probabilities (P_{xn} , x=1,2,3...)***

Studies of βn emission can inform on three of the four above...

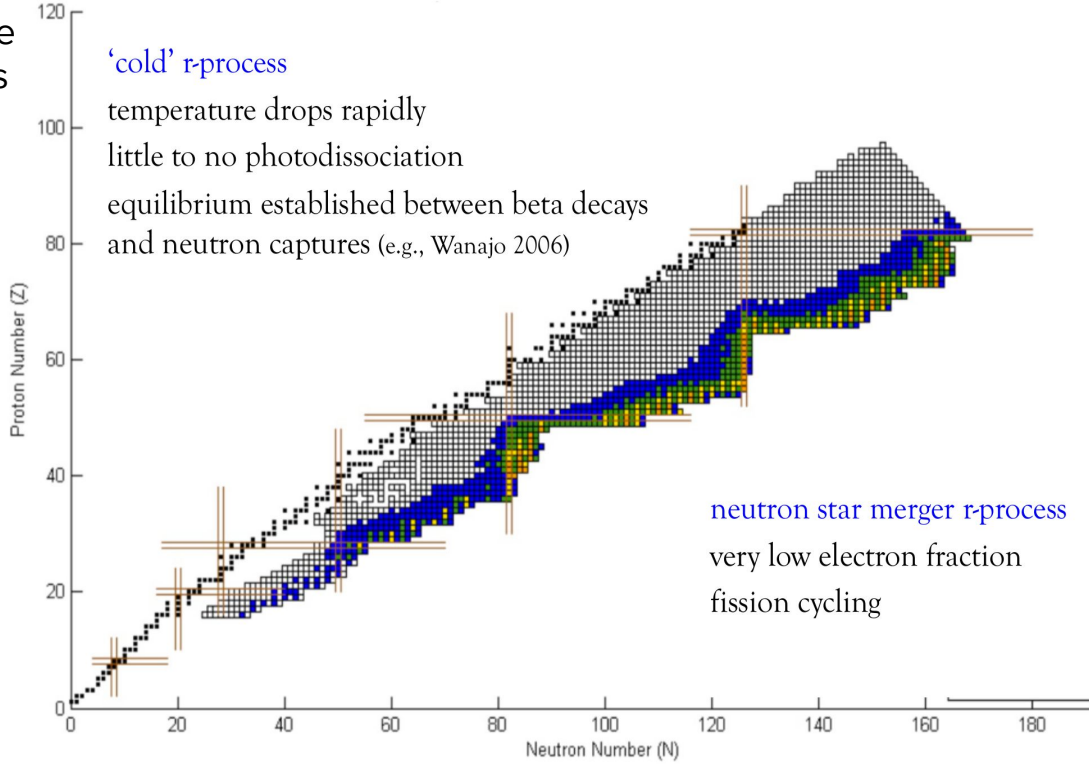
βn emission in r-process nucleosynthesis

βn emission plays a role in the late stages of the r-process during neutron freezeout and impacts decay back to stability

Increasingly dominant decay mode for neutron-rich nuclei

If r-process is colder:
- spends little time in (n,γ)-(γ,n) equilibrium
- path pushed out toward the drip line where several neutrons can be emitted per β decay

Extreme processes:
- yield heavy isotopes that undergo fission and contribute n-rich fragments (β,βn,βγ)



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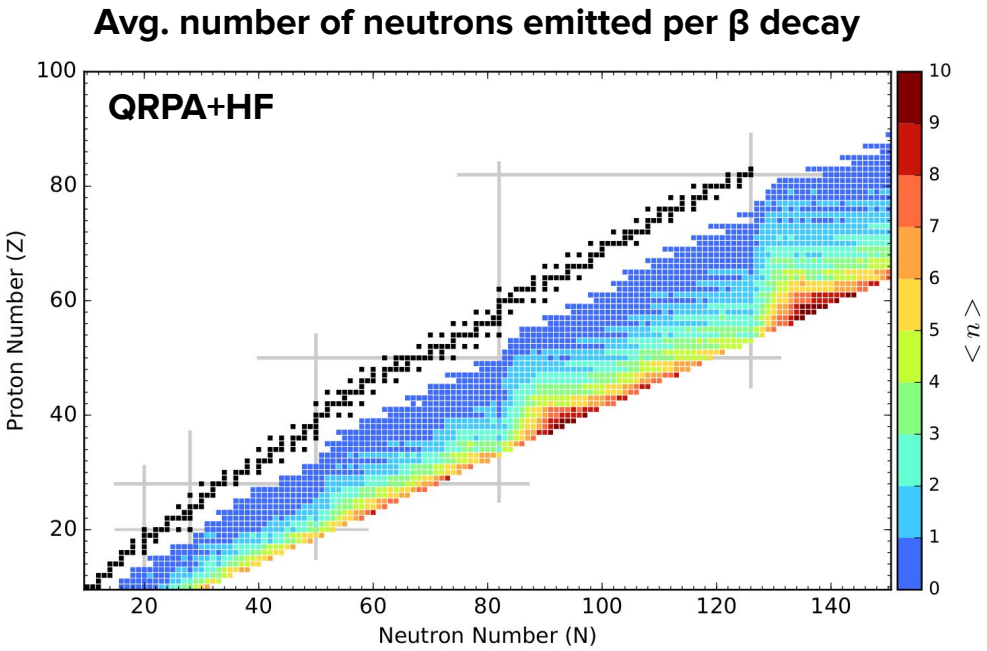


Mumpower et al., PRC 94, 064317 (2016)

Neutron Spectroscopy Methods

Many approaches… all with benefits and limitations

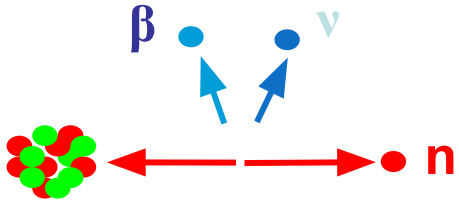
	^{3}He *(not thermal)*	Proton Recoil	Neutron TOF	^{3}He/^{6}Li/^{10}B *(thermal)*	Decay γ rays	Recoil Ion TOF Spectroscopy
E_n	✓ ~2-5% …but complicated	✓ ~5% …but complicated	✓ >5% …but complicated	X	X	✓
P_n	✓	✓	✓	✓	✓	✓
Efficiency	X ~0.1%	X ~0.001%	✓ ~50% …with loss of resolution	✓ ~50%	varies	✓
Backgrounds	X	X	X	✓	✓ …but need structure info	✓ can be dealt with detector geometry

Recoil-Ion TOF Spectroscopy provides *some* of the best of all techniques

Recoil-Ion Time-of-Flight Spectroscopy

Confine ions in a RFQ trap (~1 mm^3)

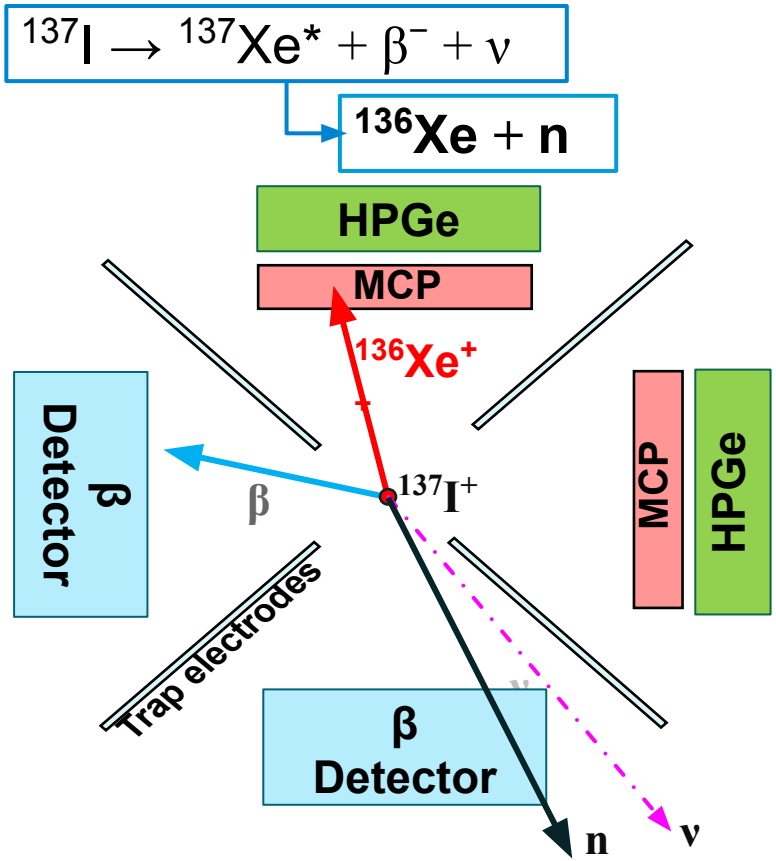
Detect β and recoil ion:
determine nuclear recoil from TOF



Neutron emission

β (1 MeV): ~0.01 keV recoil
n (1 MeV): ~10 keV recoil

– Identify neutron emission from faster TOF nuclear recoil!
– Determine E_n from (fast) recoil ion TOF spectrum
– β-delayed neutron emission probability (P_n) can be determined multiple ways



Measure P_n three different ways...

$$P_n = \frac{N_{\beta n}}{N_{\beta}}$$

"Fast" recoil ions

β Singles:

Beta singles from precursor decay

Less sensitive to details of decay...

***but* prone to backgrounds**

β-γ Events:

Delayed γ-rays from precursor decay

Insensitive to other decays from trap center

γ branching ratios must be known

β-slow recoil

Slower recoil ions

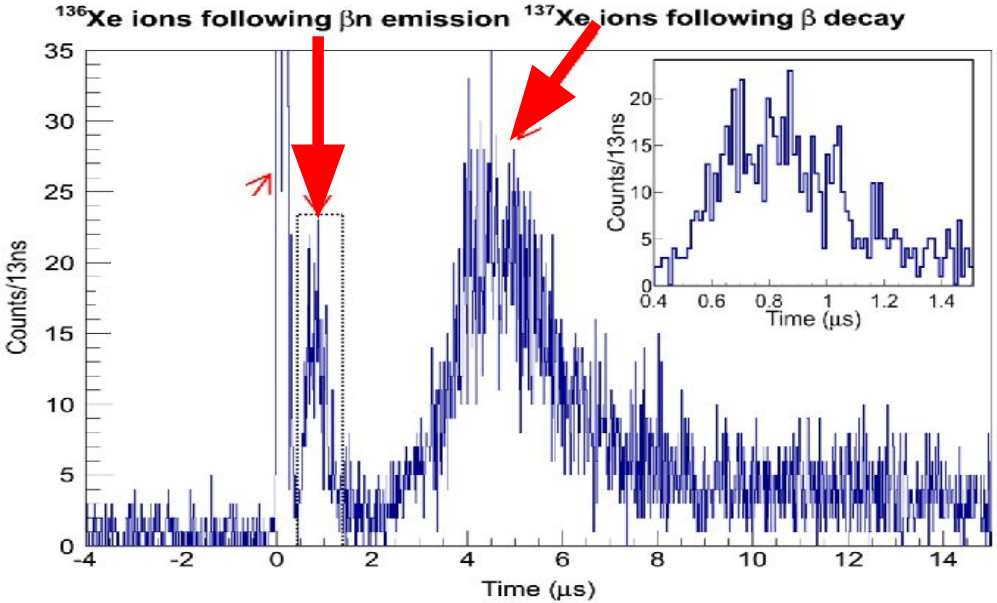
Less sensitive to MCP efficiency...

***but* depends on details of β-decay and RF-electric fields**

First βn measurement using trapped ions

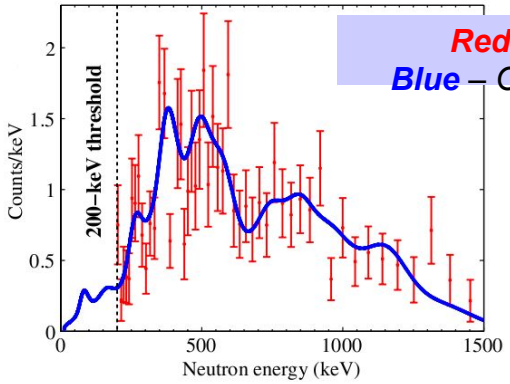
Results of experiment measuring decay of ^{137}I (~30 ion/s) in the BPT

Recoil-Ion Time-of-flight spectrum



R. M. Yee et al., PRL 110, 092501 (2013)

Neutron spectrum from ^{137}I βn decay



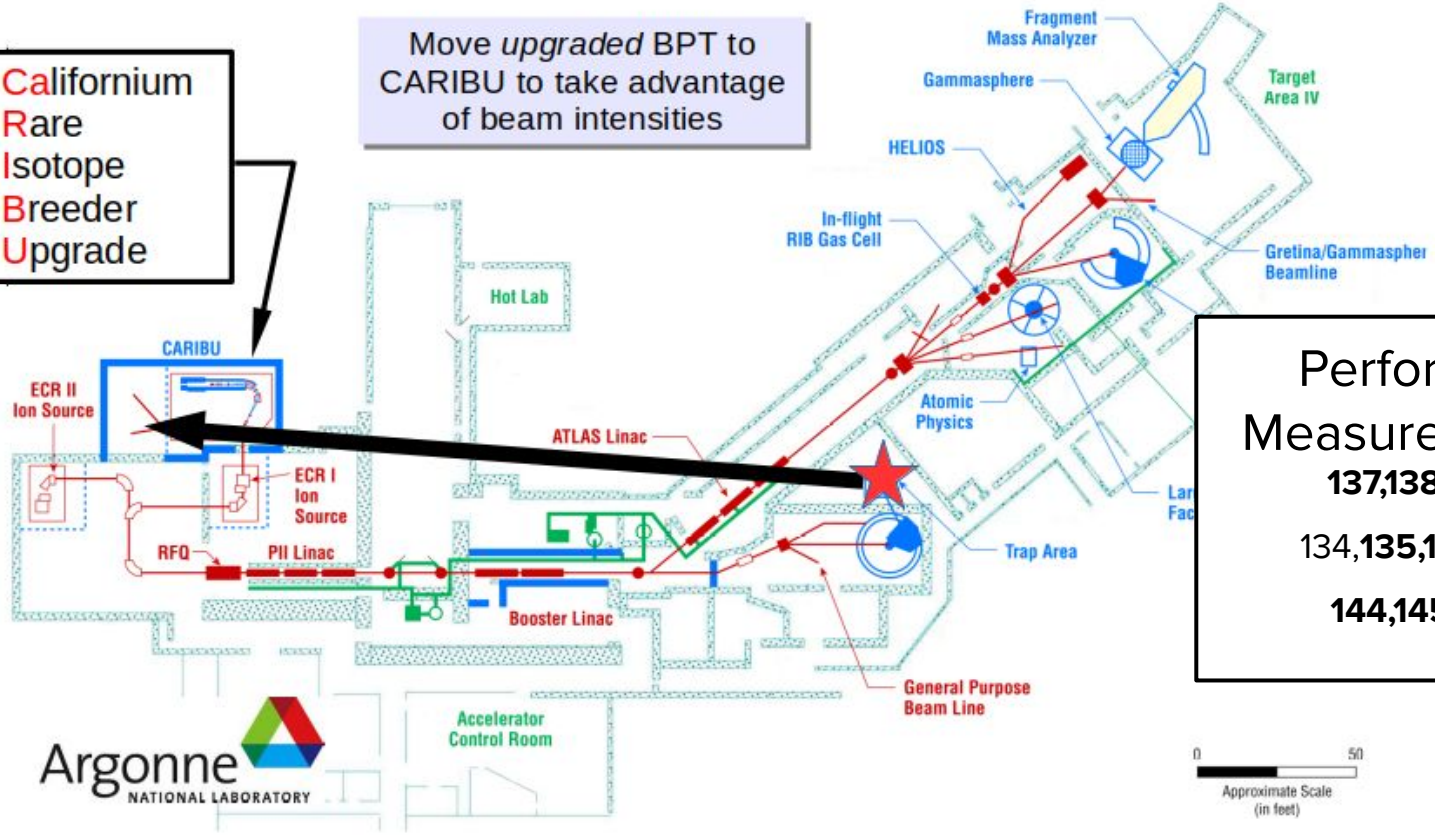
Red *– BPT Data*
Blue *– Ohm et al. (1980)*

Measured P_n =6.8±0.9 %
IAEA P_n =7.3±0.4 %

Moved BPT to CARIBU for βn Measurements

Californium
Rare
Isotope
Breeder
Upgrade

Move *upgraded* BPT to CARIBU to take advantage of beam intensities



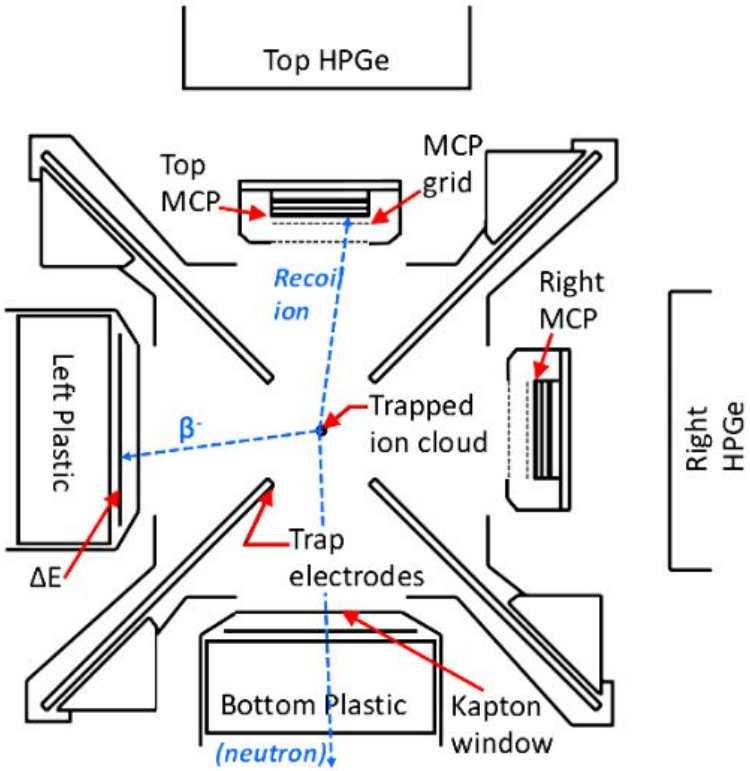
Performed Measurements:

^{137,138,140}I

^{134,135,136}Sb

^{144,145}Cs

BPT at CARIBU: Experimental Setup



(2) ΔE-E Plastic Beta Spectrometers:

- ΔE detector: 1 mm thick, 10.6 cm diameter (EJ-204)
- E detector: 10.2 cm thick, 13.3 cm diameter (EJ-204)
- ΔE scintillator has low intrinsic efficiency for γ & n
- Isolated in separate vacuum separated by Al-Kapton window
- Electron detection threshold of ~70keV

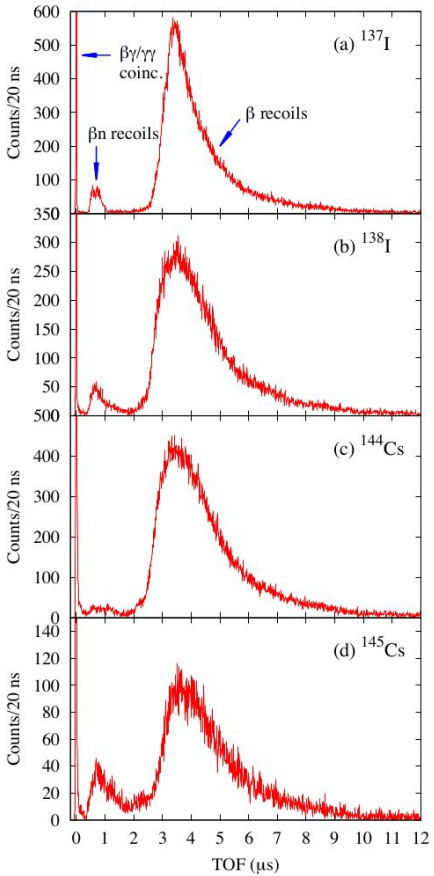
(2) Microchannel plate (MCP) detectors :

- 50.3 x 50.3 mm^2 Chevron MCPs w/ resistive anodes
- Packaged in grounded housing w/ 89% transmission grid
- sub-mm position resolution
- 1-ns timing resolution

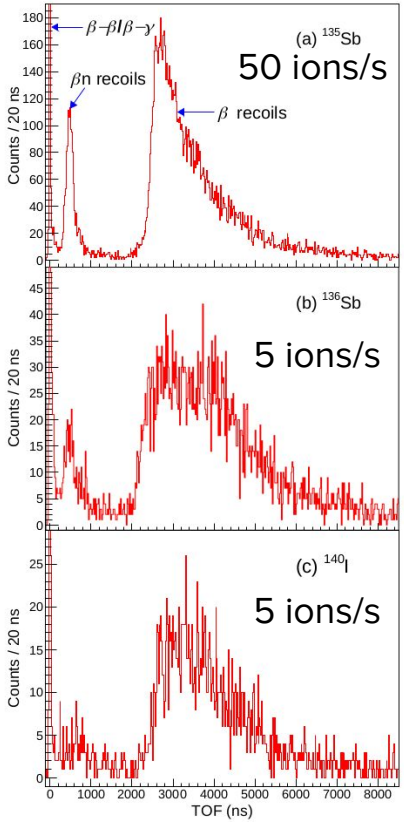
(2) HPGe detectors:

- coaxial single-crystal (p-type)
- Relative-efficiency: 140% (Top) and 80% (Right)
- Calibration/Efficiencies measured with calibrated sources up to 3.3 MeV (^{56}Co source)

Recoil-ion Time of Flight Spectra



A. Czeszumska et al, submitted to PRC



B. S. Alan. et al, submitted to PRC

Measured seven βn precursors: ^{137,138,140}I, ^{135,136}Sb, and ^{144,145}Cs

CARIBU beams optimized with CPT and then delivered to BPT (pre-MRToF era)

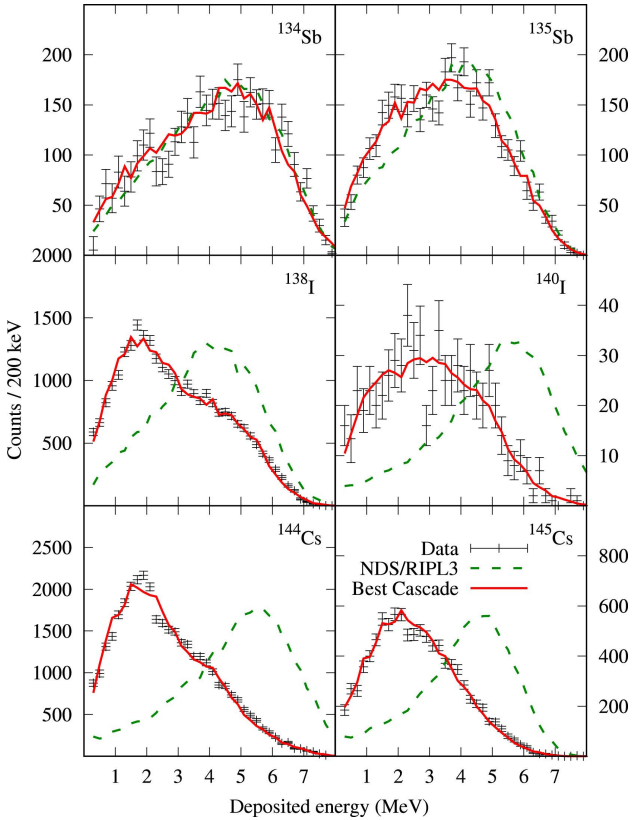
^{134}Sb (P_n=0) was studied to help determine response of trap/detector system to well-understood β-decay:

- NDS: 97.6% 0^- to 0^+ FF transition to the ground state of ^{134}Te ($a_{b\nu}$ ~ 1)
- Determine intrinsic efficiency of MCP detectors for slow recoil ions (29-33%)

^{134}Sb (BPT):
K. Siegl et al., Phys. Rev. C 97, 035504 (2018)

^{134,134m}Sb in X-Array at CARIBU:
K. Siegl et al., Phys. Rev. C 98, 054307

BPT at CARIBU: Beta Energy Spectra



J. Munson et al., NIMA 898, 60-66 (2018).

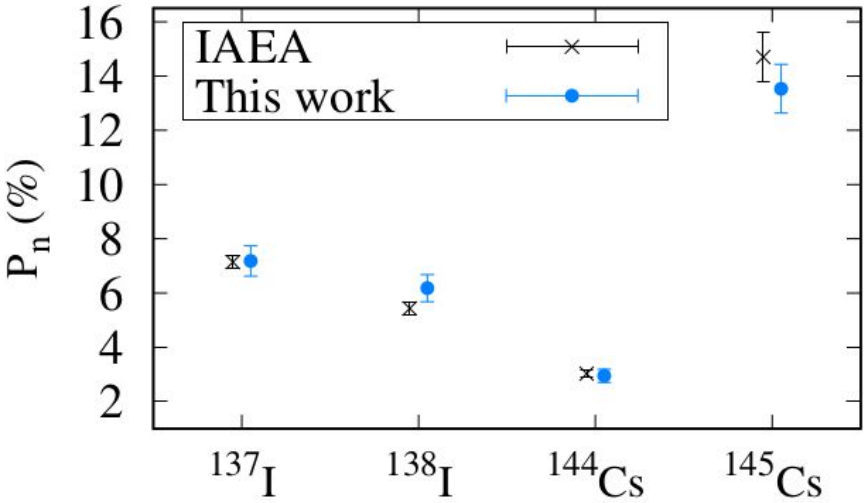
β-recoil coincidence detection is very selective and useful to obtain quality beta-decay data

Energy spectra can be measured using thick plastic scintillator detectors

Accumulated "slow ion" beta decay data were analyzed and compared to NDS levels/RIPL-3 decay data

Disagreement in the cases of ^{138,140}I and ^{144,145}Cs indicate a shift in decay strength to lower beta energies (higher E_x in daughter)

BPT at CARIBU: P_n Results



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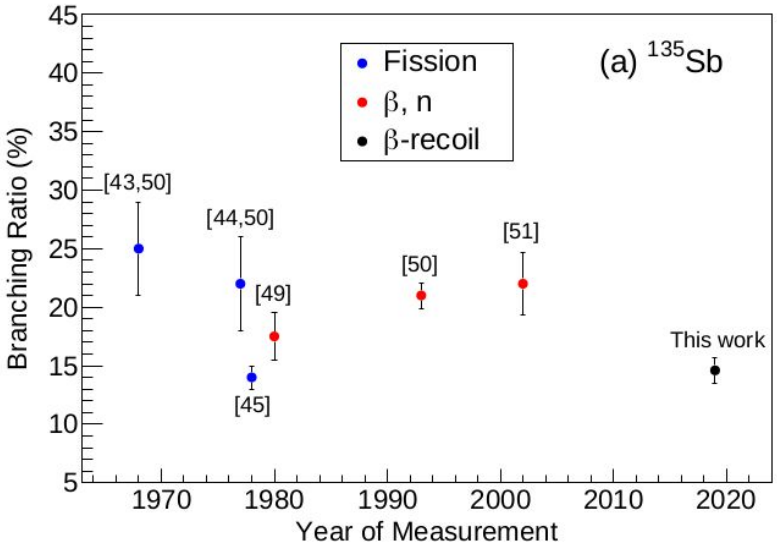
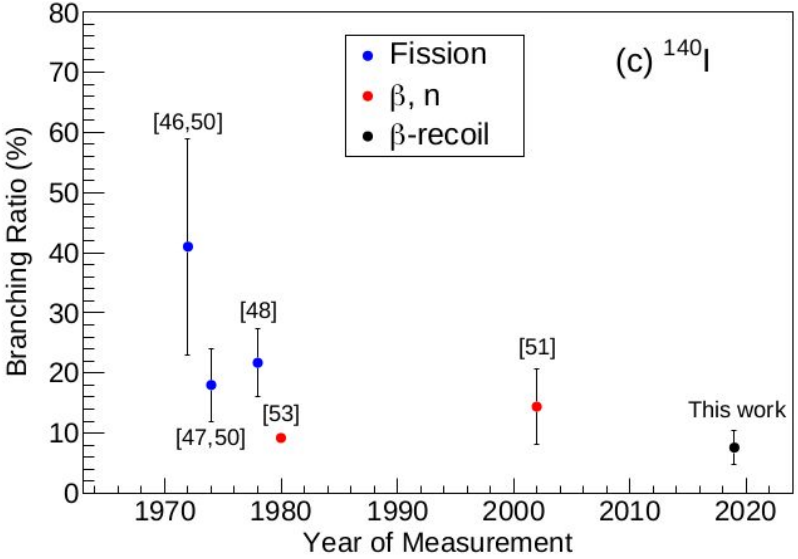
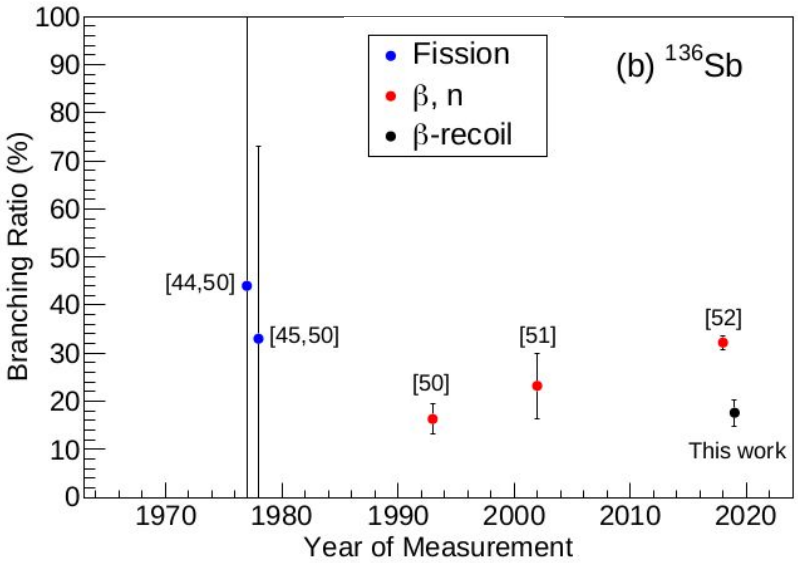


B. S. Alan. et al, submitted to PRC

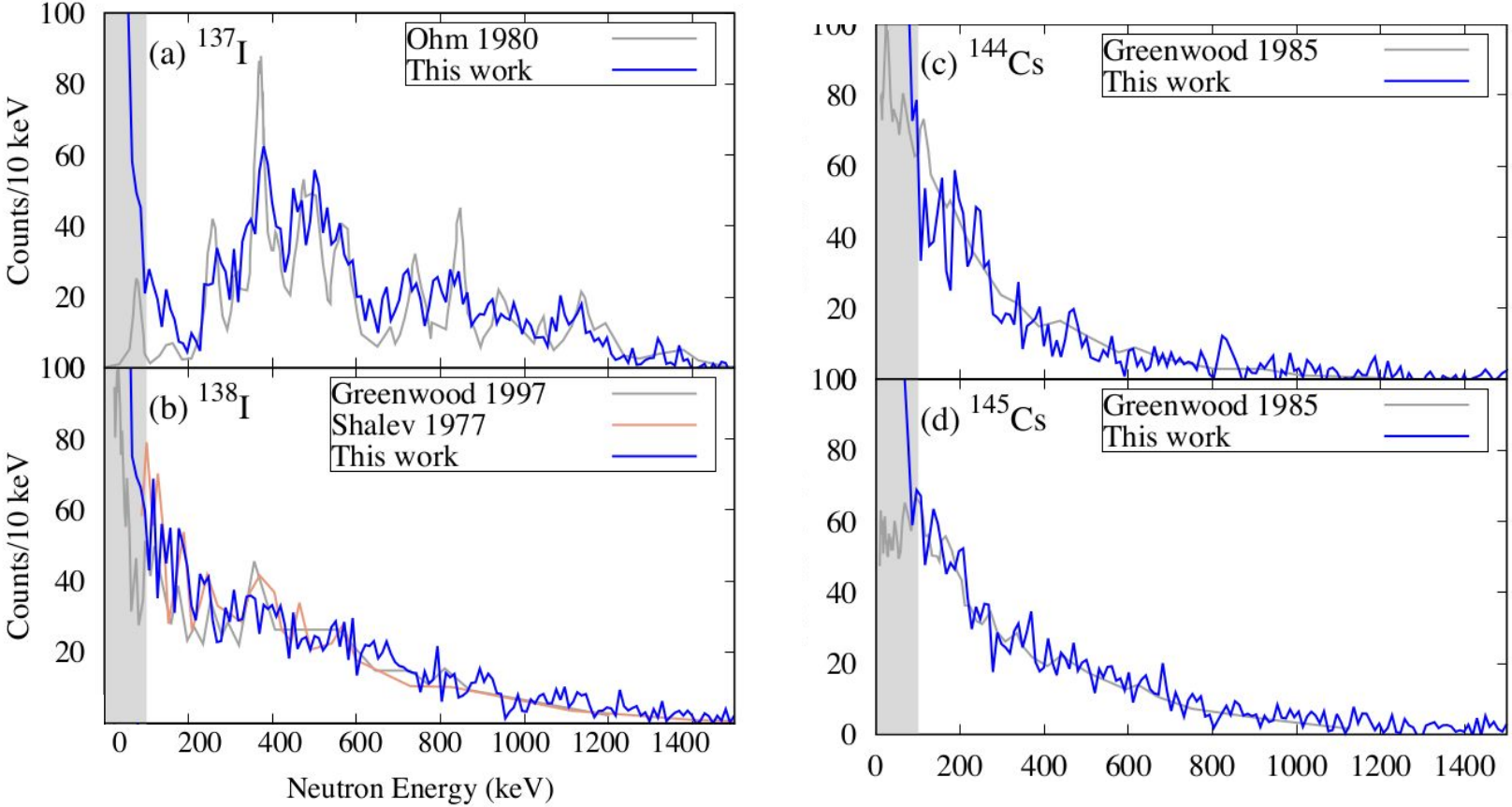
BPT at CARIBU: P_n Results (continued)





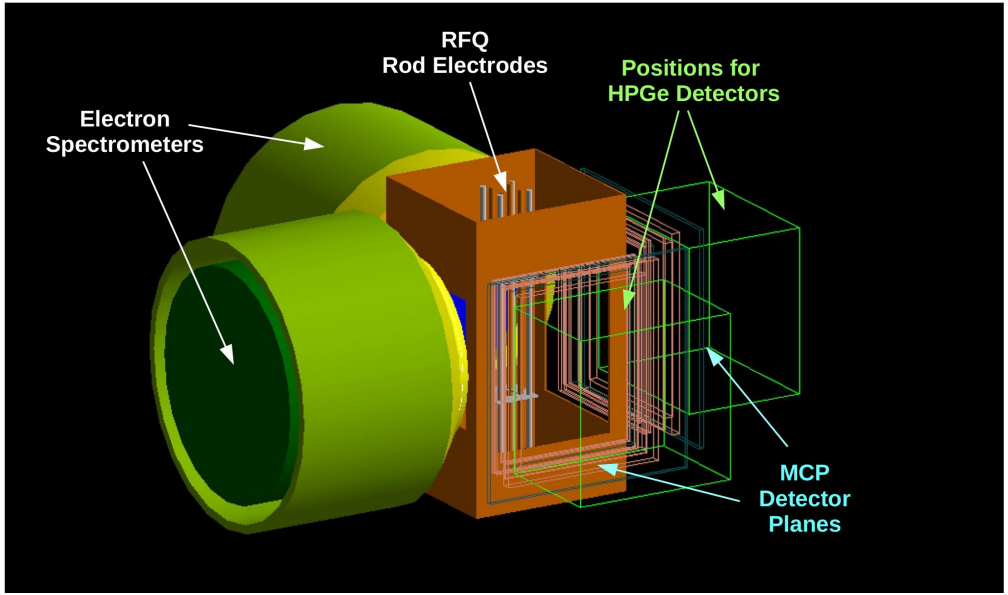
B. S. Alan. et al, submitted to PRC

BPT at CARIBU: E_n results



A. Czeszumska et al, submitted to PRC

Next Step: The BEtA Recoil-ion Trap (BEARtrap)



First dedicated instrument for recoil ion spectroscopy of βn precursors

Based on BPT design (fewer surprises)

- Compact trap geometry using rod electrodes
- Loading ion trap that will lead to smaller ion cloud size
- Larger area MCP detectors (80 x 100 mm^2)
- Segmented plastic ΔE detectors: allow identification of beta-*neutron* coincidence events ("background")
- Design to accomodate HPGe clovers behind MCP detectors

Design, GEANT simulations, detector characterization performed by LSU personnel:
Gemma Wilson (Postdoc resident at ANL/PHY)
Alex Laminack (GS)
Graeme Morgan (GS)

β-recoil ion coincidence efficiency: ~4%
Neutron energy threshold: ~50 keV
Make measurements with beams down to 0.1 ions/s

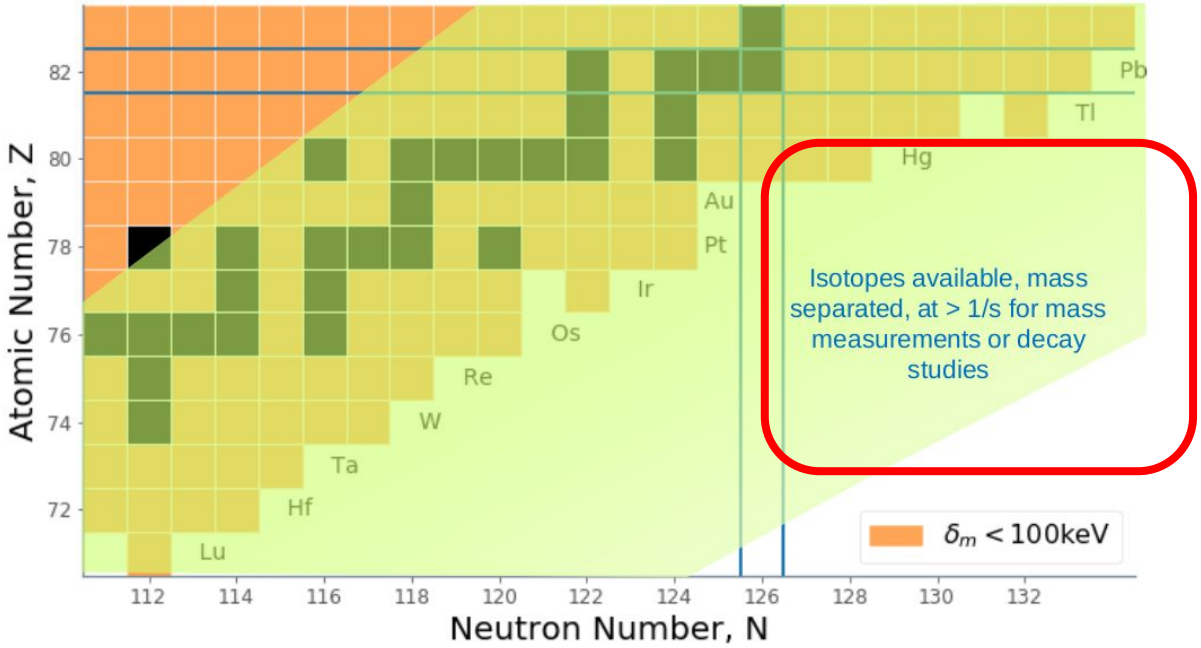
BEARtrap Status

Construction is underway!

- Microchannel plate detectors have been purchased (Photonis) and in the process of being packaged by Quantar
- Plastic Beta Spectrometer modules system design work completed (LSU); Quote pending from vendor (Eljen)
- HPGe Clover detectors from ANL decay group
- Vacuum chamber obtained (ANL)
- Design of new loading trap and main RFQ trap nearing completion (Fall 2019)
- Preparations for beam line design in new low-energy hall of ATLAS (2020)
- Commissioning beam time using ^{92}Rb and ^{137}I awarded in March 2019 ATLAS PAC (G. Morgan, LSU)
- Initial Science program: $^{134\text{-}136}$Sn (12 days) and $^{98m,99–103}$Y (6 days)

Opportunities at N=126 Factory

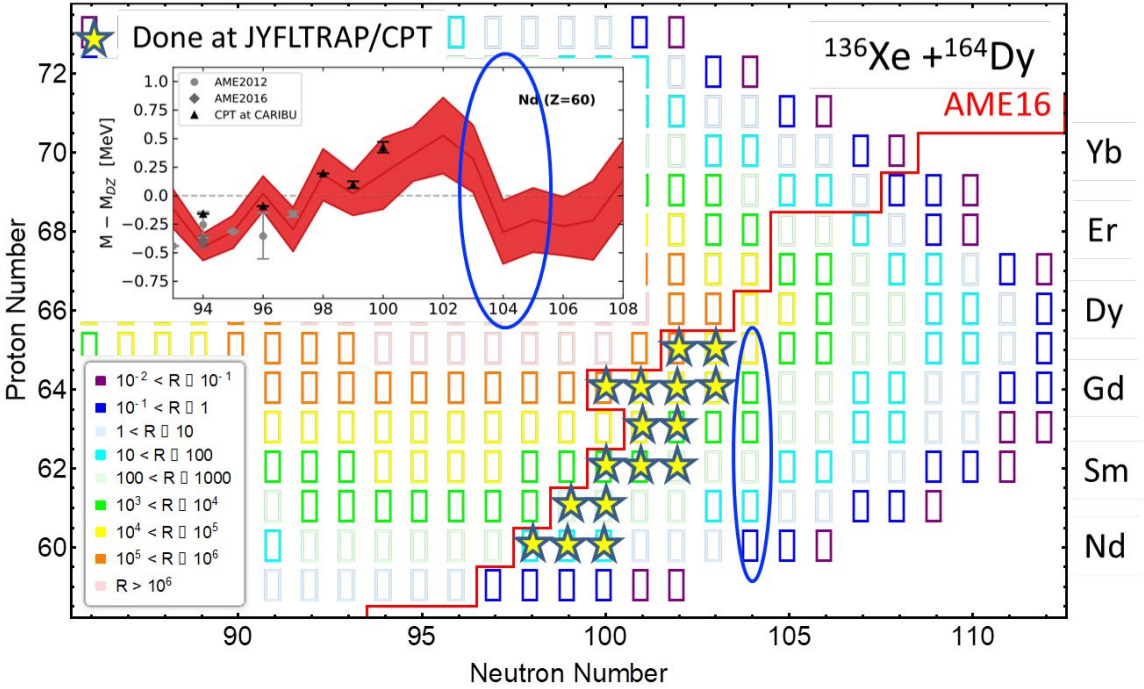
EXPECTED REACH OF N = 126 FACTORY



Slide courtesty of G. Savard (ANL)

Opportunities at The REP Factory?

N=126: RARE EARTH PEAK



R. Orford et al., PRL 120, 262702 (2018)

GRAZING calculations courtesy M. Brodeur

Slide courtesty of G. Savard (ANL)

Summary/Final Thoughts

βn properties are important to many applied fields including r-process nucleosynthesis

Successes with βn studies Beta-decay Paul Trap for at CARIBU has established recoil-ion time-of-flight spectroscopy as a new measurement technique

Many opportunities to measure βn precursors at CARIBU and N=126 factory

BEARtrap will be the first dedicated device for βn studies at ANL

These measurements are not simple and complementary measurements using different techniques (βγ, Total Absorption Spectroscopy, etc.) are needed

We need experimental and theoretical collaborators to get the most physics out of our measurements. More interaction/discussion is needed!

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