Studies of β-delayed neutron emission using trapped ions

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Collaboration performing β-delayed neutron spectroscopy with ion traps

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G. Savard, S. Caldwell, J.A. Clark, A.F. Levand, A. Perez Galvan, M. Burkey

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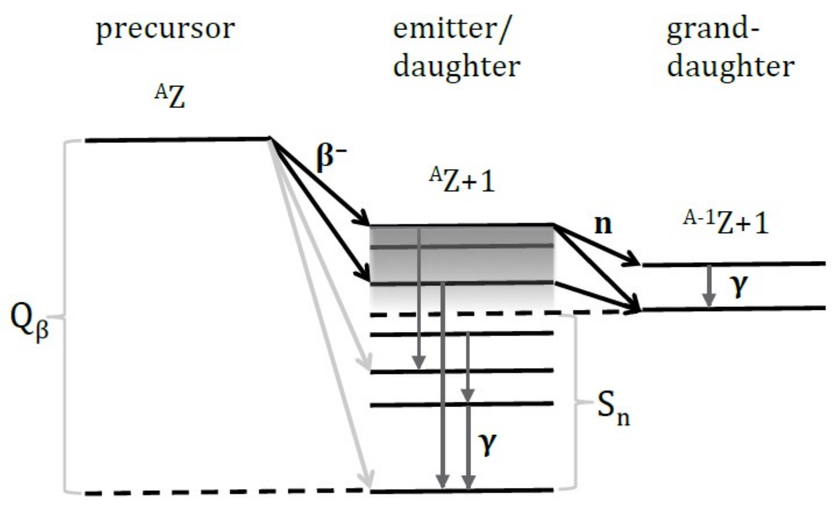
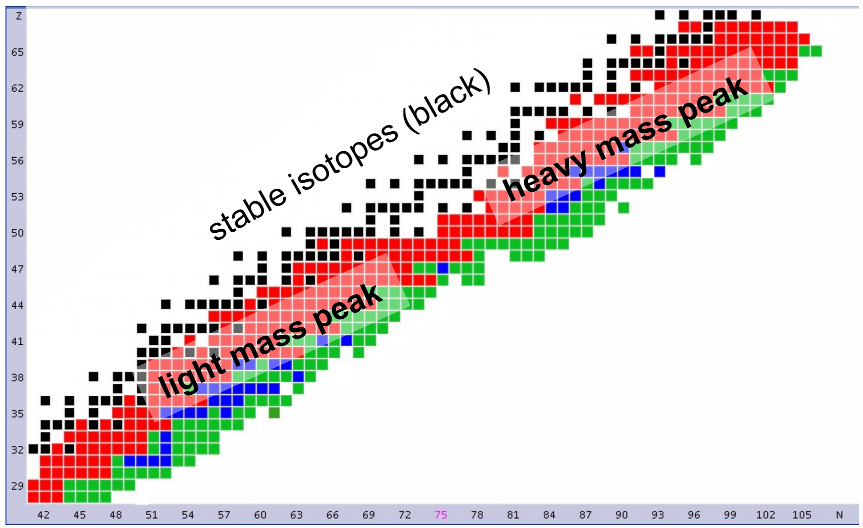
S. Marley

F. Buchinger, R. Orford

K.S. Sharma, G. Morgan

Beta-delayed neutrons play a fundamental role in many basic and applied sciences





Isotopes produced in ^{252}Cf fission

β-delayed neutron emission energetically allowed

Nuclides where P_n measurement precision < 10%

Need better data for:

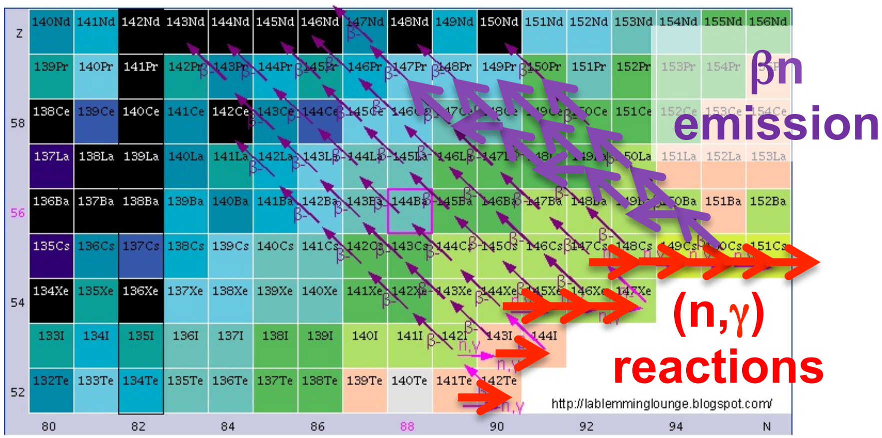
Astrophysics: neutron-rich nuclei produced in *r* process decay back to stability

Nuclear Structure: understand properties of neutron-rich nuclei

Nuclear Energy: reactor design, performance, and safety studies

Understanding the nucleosynthesis of elements from Fe to U

Heavy elements built up through *r*-process neutron-capture reactions



Neutron captures occuring rapidly in a high neutron-density environment build up very neutron-rich isotopes

At end of process, exotic nuclei produced decay back to stability

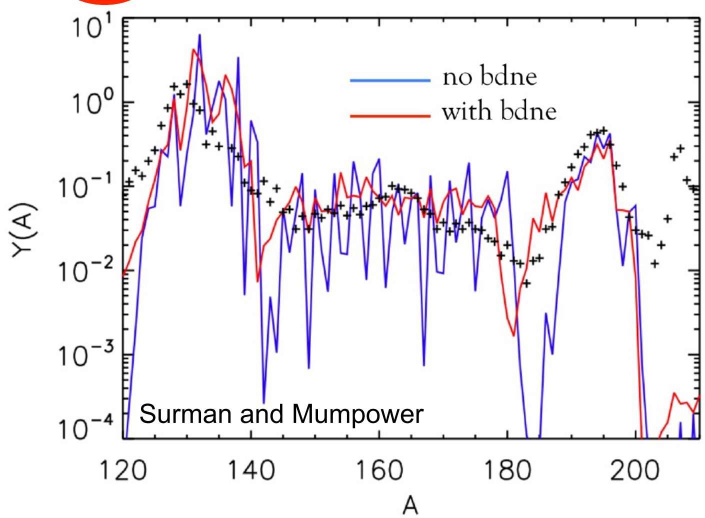
r-process open questions:

- Astrophysical site?

  Core-collapse supernova, neutron-star mergers, γ-ray bursts...

- Properties of exotic nuclei involved?

  need binding energies, β-decay properties ($t_{1/2}$, P_n), cross sections, …



We have a new way to determine this nuclear property

Beta-decay Paul Trap (BPT) developed for precision β-decay studies

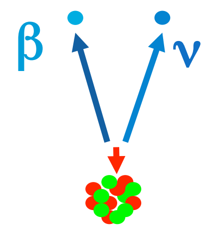
BPT uses E fields to confine ions within ~1-mm^3 volume at low energy (<1 eV) until decay

- **Nuclear recoil available for study**
  → reconstruct particles from energy/ momentum
- **Open electrode geometry**
  → allows radiation detectors to surround sample
- **Make efficient use of rare nuclei**
  → high statistics needed for precision measurements
- **Element independent**
  → many isotopes available for study and calibrations

New opportunities for precise studies of:

(1) Neutrinos

β + recoil
→ neutrino

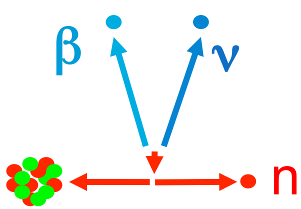


G. Li *et al*., Phys. Rev. Lett. **110**, 092502 (2013)

M.G. Sternberg *et al*., Phys. Rev. Lett. **115**, 182501 (2015)

(2) Neutrons

recoil
→ neutron



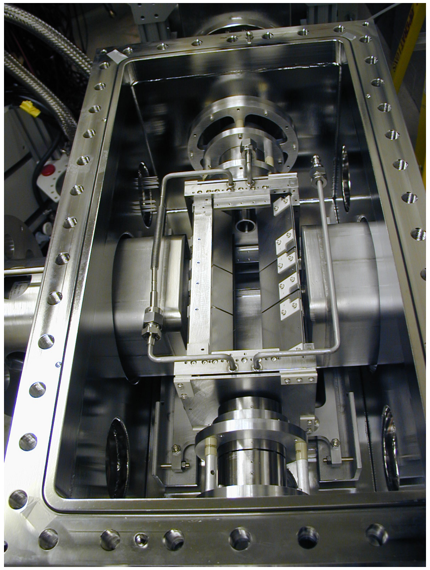
Neutron emission

R.M. Yee *et al*., Phys. Rev. Lett. **110**, 092501 (2013)

Beta-decay Paul Trap (BPT)

BPT uses E fields to confine ions within ~1-mm^3 volume at low energy (<1 eV) until decay

N.D. Scielzo *et al.*, NIM A **681**, 94 (2012)

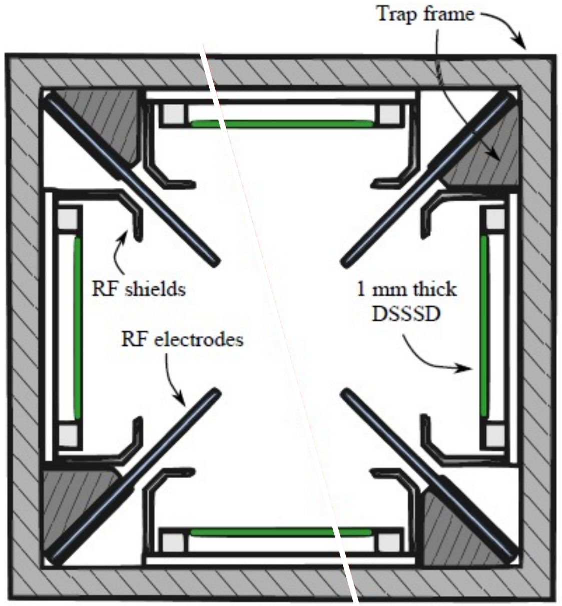


Ions confined radially using RF electric fields and axially using DC electric fields

Ions cooled using He buffer gas (~10^{-5} torr)

Confine up to ~10^6 ions at once

Large solid angle for radiation detectors



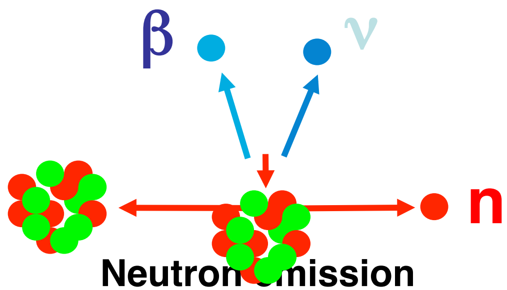
~30% solid angle for detector arrays (show here with double-sided strip detectors)

MCP, HPGe, and plastic scintillator detectors are used for βn studies

New approach to β-delayed neutron spectroscopy

Collect ions in the trap

Detect β and recoil ion – determine nuclear recoil from TOF



β (1 MeV): ~0.01 keV recoil

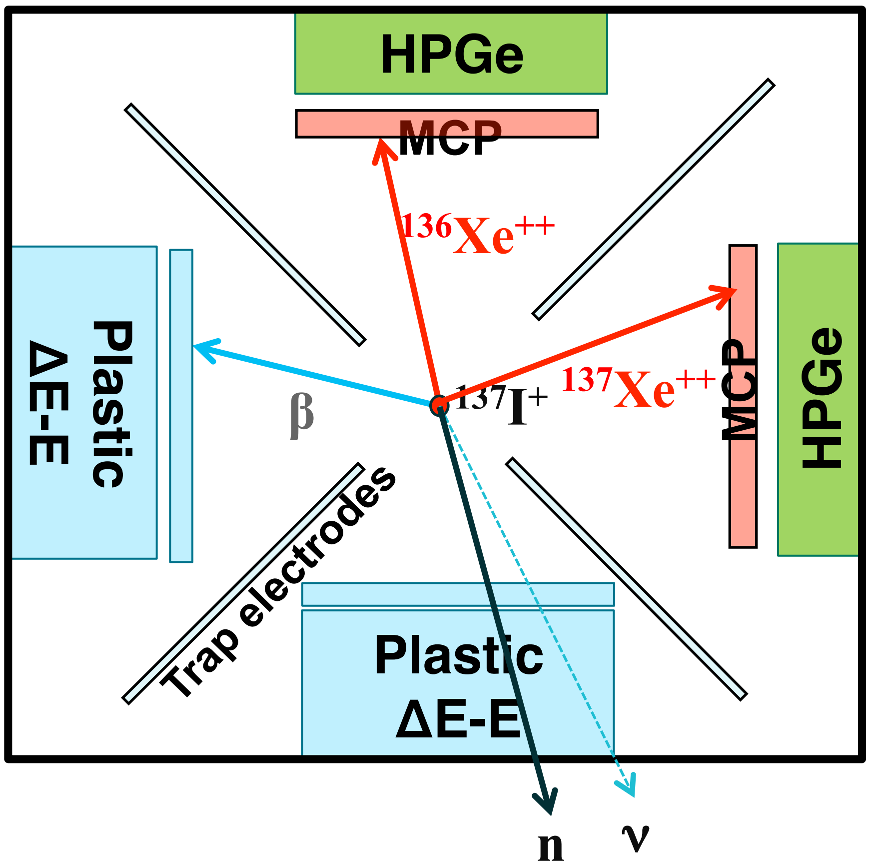
n (1 MeV): ~10 keV recoil

Identify neutron emission from larger nuclear recoil. Ion TOF transformed in to neutron energy.

Branching ratio determined from the number these fastest ions compared to total β decays from β, γ rays, and ions

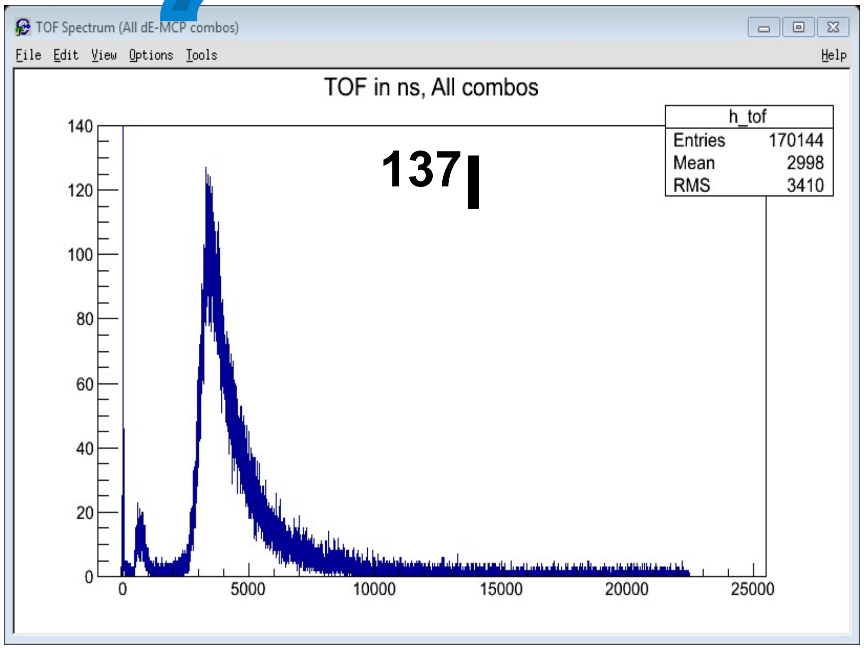
$^{137}I \rightarrow {}^{137}Xe^{*} + \beta^{-} + \nu$

$\rightarrow {}^{136}Xe + n$

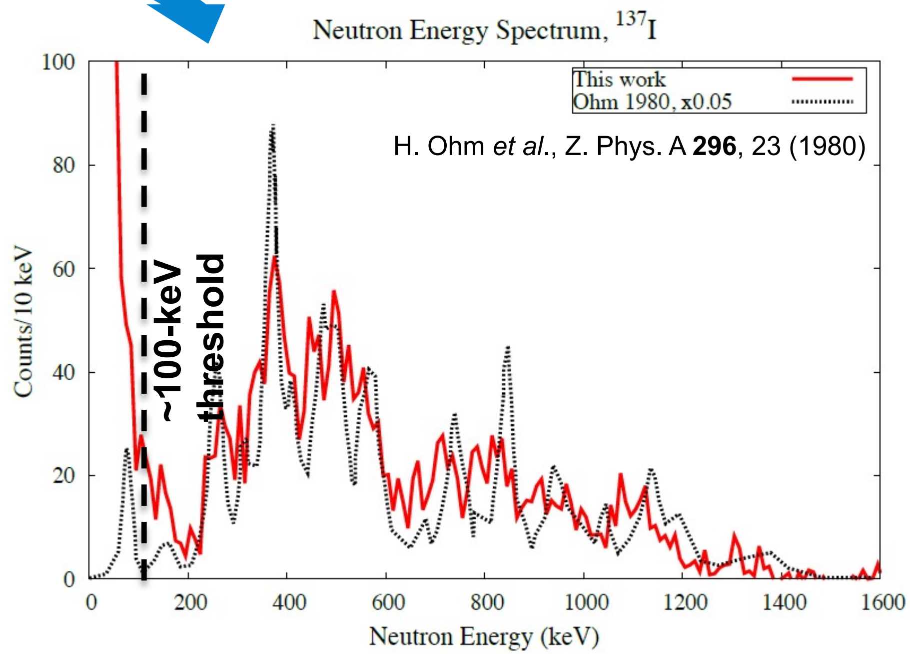


^{137}I: recoil ions → neutrons

$$E_n = \frac{M_r E_r}{m_n} = \frac{\frac{1}{2} M_r^2 (d/t_{TOF})^2}{m_n}$$



S. Caldwell, Ph.D. Thesis, U Chicago (2015)
A. Czeszumska, Ph.D. Thesis, UC Berkeley (2016)



~600 ions/s beam

Ω_β ~ 12%, Ω_r ~ 12%

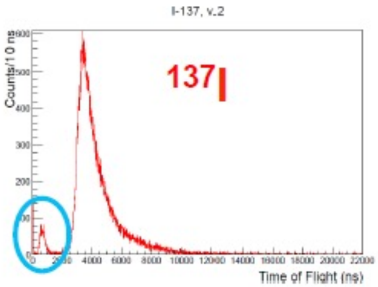
100 βn/hr

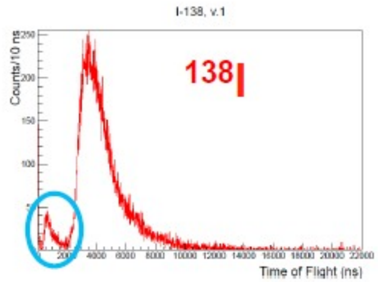
smaller E field distortions

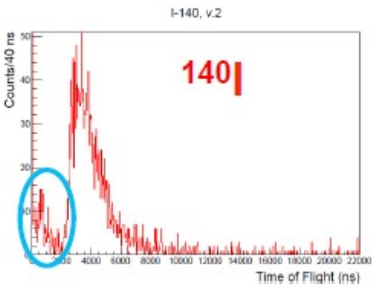
E_n determined from recoil-ion TOF and trajectory with small corrections for:

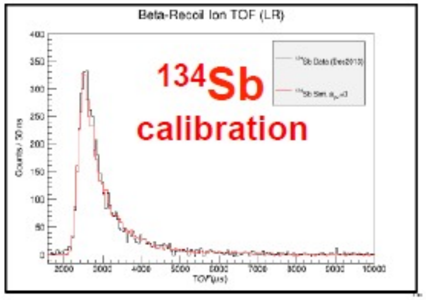
- E-field TOF distortions
- β detector efficiency
- MCP efficiency
- Neutrons triggering β detector
- Lepton contribution to recoil

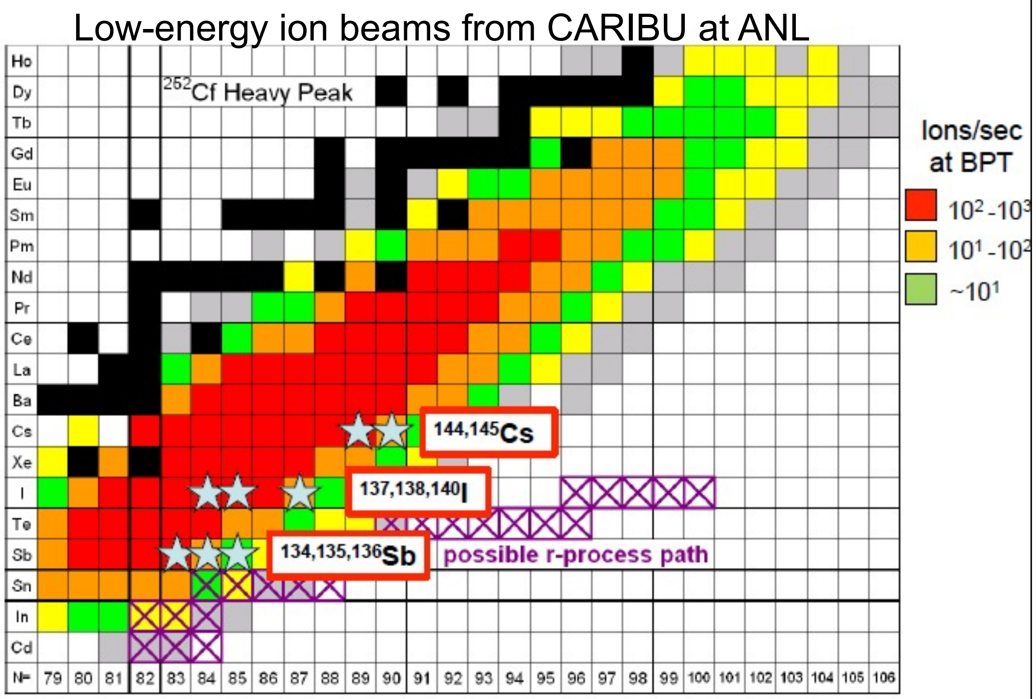
Data collected at CARIBU for several isotopes

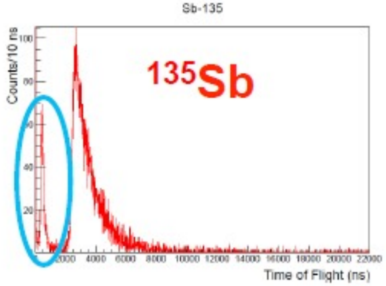


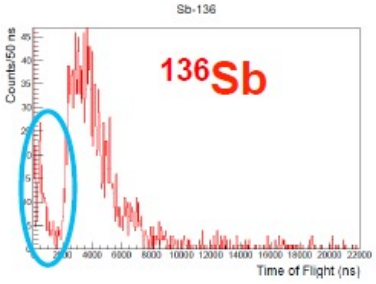


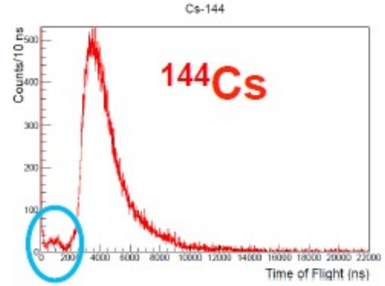


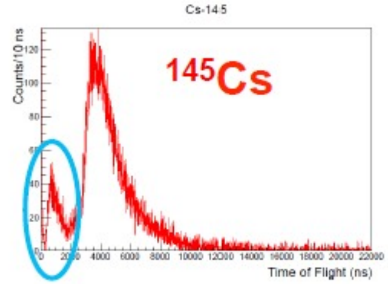




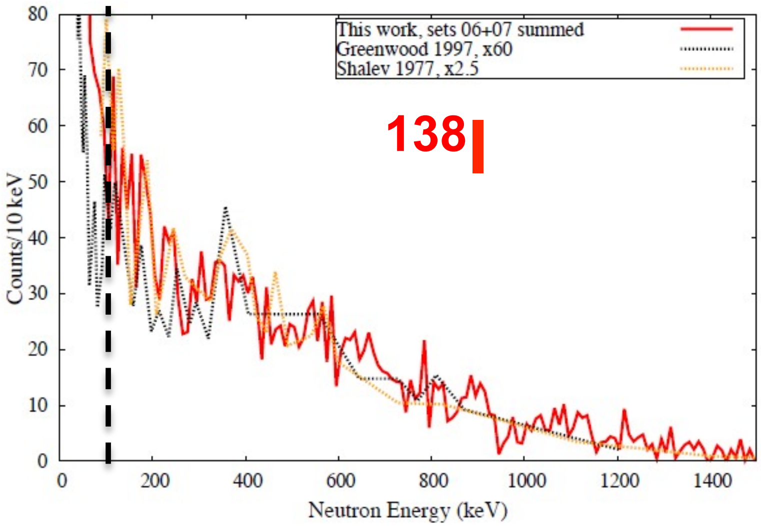


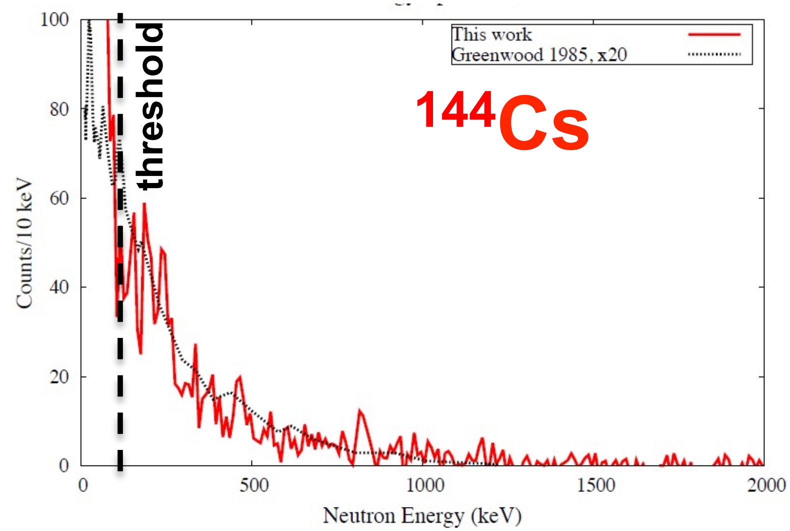


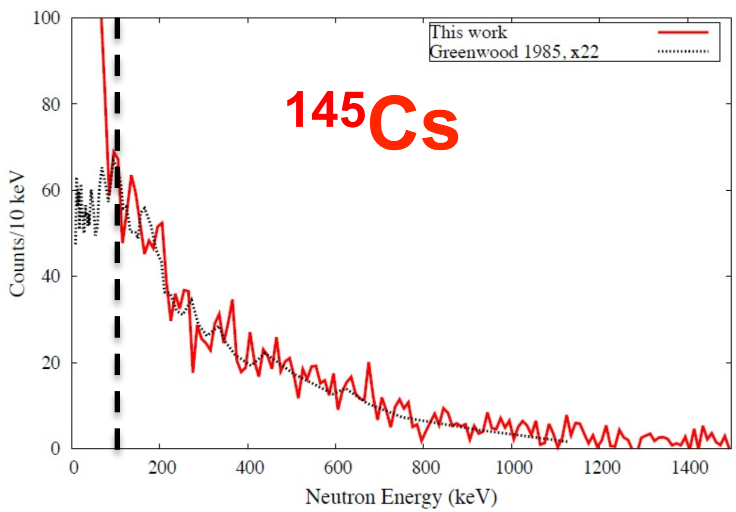




A few other E_n spectra…







Neutron energy spectra agree well with direct neutron spectra (where available)

R.C. Greenwood and K.D. Watts, Nucl. Sci. Eng. **126**, 324 (1997).

S. Shalev and G. Rudstam, Nucl. Phys. A **275**, 76 (1977).

R.C. Greenwood and A.J. Caffrey, Nucl. Sci. Eng. **91**, 305 (1985)

Branching ratio can be measured different ways to provide cross-checks

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

Fastest recoil ions

Method 1:

Beta singles from precursor decay

Less sensitive to details of decay…

but prone to backgrounds

Method 2:

Delayed γ rays from precursor decay

Insensitive to other decays from trap…

but γ-ray branching ratio must be known

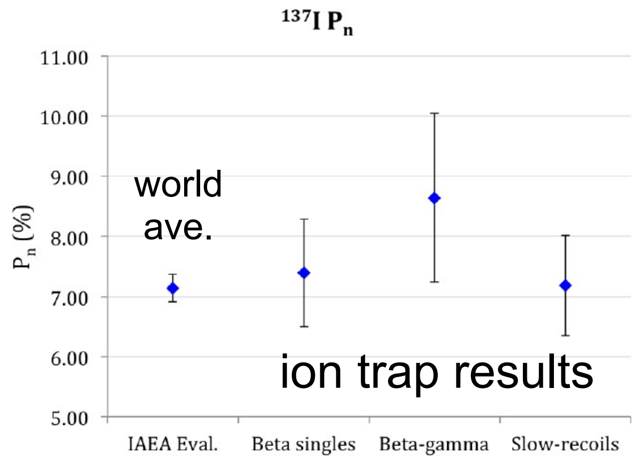
Method 3:

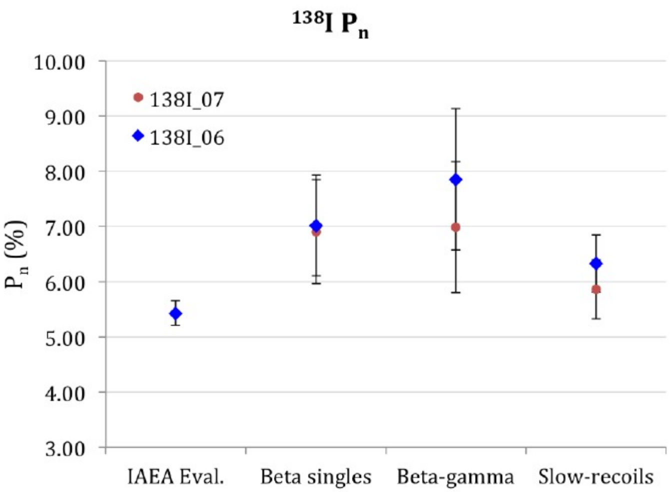
Slower recoil ions

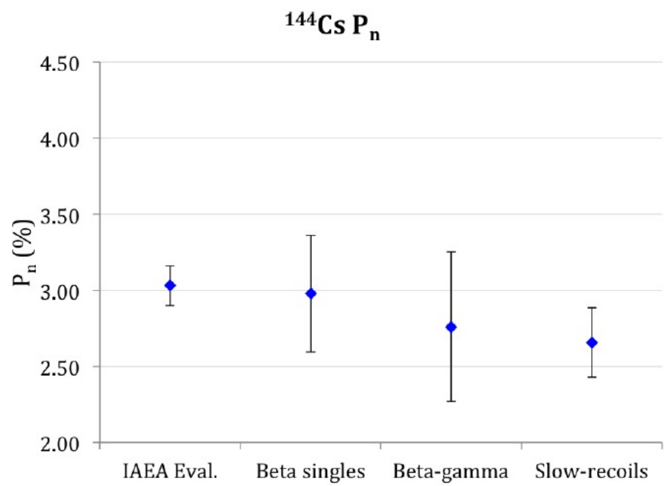
Less sensitive to MCP efficiency…

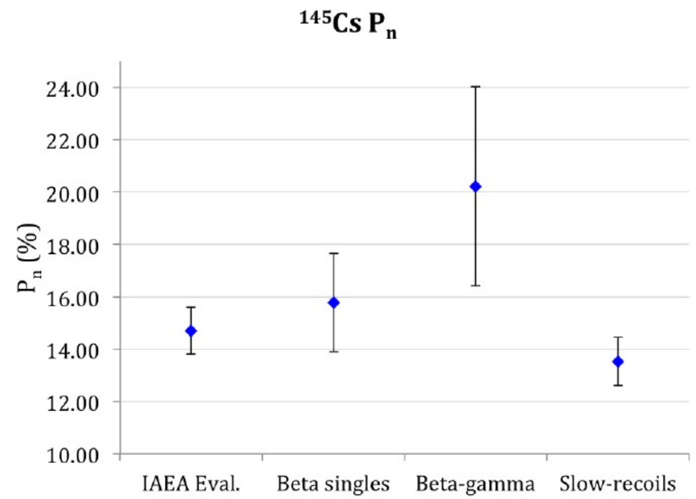
but depends on details of β decay and electric fields

Neutron emission branching ratios consistent with direct measurements





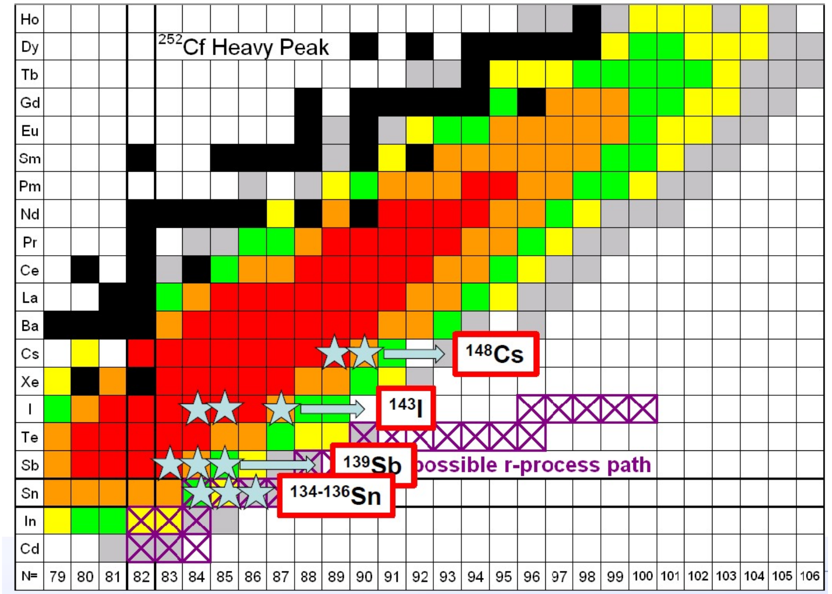




D. Abriola, B. Singh, and I. Dillman, IAEA, 2011

Future β-delayed neutron studies: A dedicated ion trap at CARIBU

	Stats. vs. 2013
We can further increase size of detector array	×4
CARIBU intensities are higher today	×25
TOTAL	×100



Will extend reach to more exotic nuclei and allow detailed studies at the mass peaks

Measurements can be made with beams as low as ~0.1 ion/s for r process

Summary

- Access to the nuclear recoil following the β decay of trapped ions enables a new way to study β-delayed neutron emission
  - r-process nucleosynthesis
  - structure of neutron-rich isotopes
  - nuclear-energy applications

- Analysis of high-quality data collected using CARIBU beams is nearly complete

- With higher beam intensities and an optimized apparatus, we can further push the precision of measurements and reach neutron-rich isotopes approaching the *r*-process path in the (near) future…