β and γ-ray spectroscopy of fission products of importance to reactor antineutrino flux modelling at CARIBU

Workshop on “The Status of Reactor Antineutrino Flux Modelling”
January 22, 2015

Nicholas Scielzo
Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory

LLNL-PRES-659421

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Collaborators

I am relying heavily on slides provided to me by Stephen Padgett and Libby McCutchan

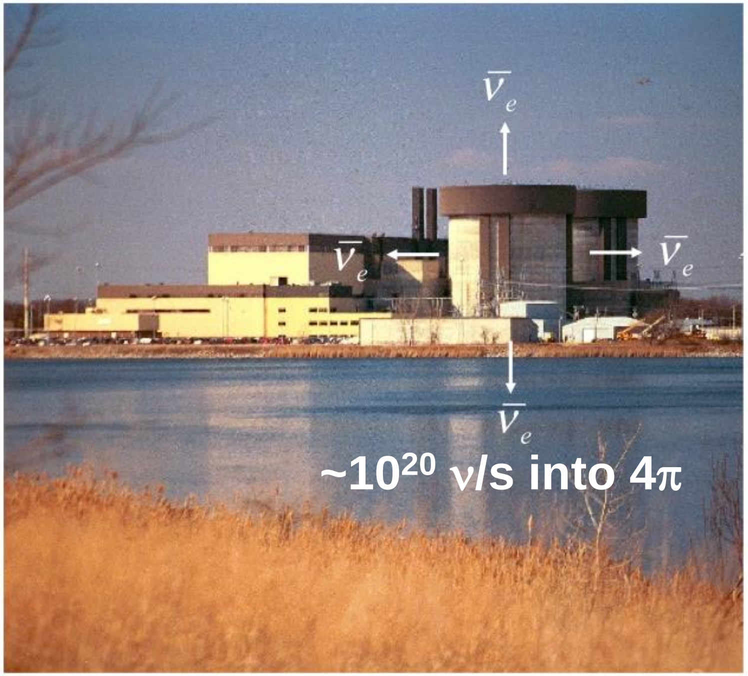
S. Padgett[1], E.A. McCutchan[2], N.D. Scielzo[1], A. Aprahamian[3], S. Caldwell[4,5], M.P. Carpenter[4], P. Chowdhury[6], J.A. Clark[4], P. Copp[6], A. Czeszumska[1,7], A. Pérez Galván[4], T.D. Johnson[2], C.J. Lister[6], S.T. Marley[3], E. Merchán[6], A.J. Mitchell[6], G. Morgan[8], E.B. Norman[1,7], A. Nystrom[3], R. Orford[9], N. Paul[3], G. Savard[4,5], R.E. Segel[10], K. Sharma[8], K. Siegl[3], A.A. Sonzogni[2], S. Strauss[3], B. Wang[7], S. Zhu[4]

[1]Lawrence Livermore National Laboratory, [2]Brookhaven National Laboratory, [3]University of Notre Dame, [4]Argonne National Laboratory, [5]University of Chicago, [6]University of Massachusetts at Lowell, [7]University of California at Berkeley, [8]University of Manitoba, [9]McGill University, [10]Northwestern University

Introduction and Motivation

Fundamental neutrino science

Nuclear reactors are the strongest sources of “man-made” antineutrinos.



~1000 different neutron-rich isotopes produced in reactors undergo beta decay, emit antineutrinos.

Measured antineutrino flux from short-baseline reactor experiments is in disagreement with expectation

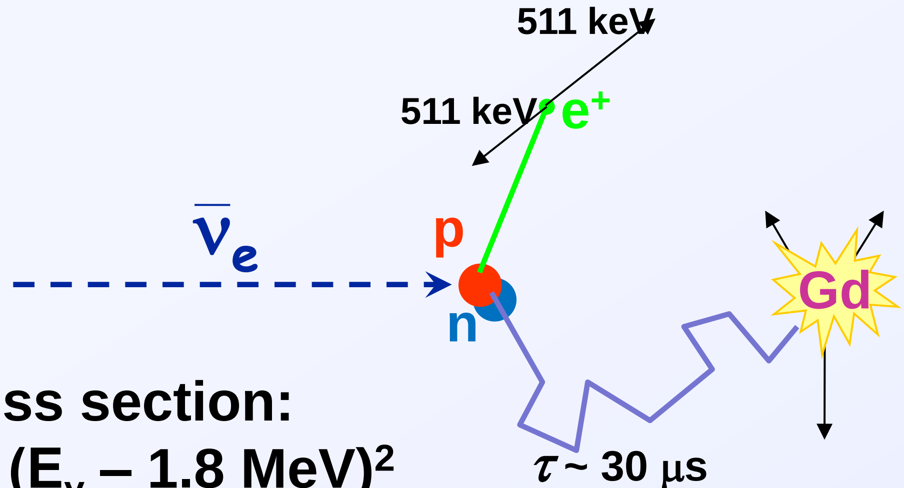
The reactor anomaly:

$$\frac{\text{Observed antineutrinos}}{\text{Predicted antineutrinos}} = 0.943 \pm 0.023$$

Possible explanations:

1. A fourth, sterile neutrino? A NEW, EXOTIC PARTICLE?
2. Predicted antineutrino number is incorrect.

Detecting Reactor Antineutrinos: Inverse Beta Decay

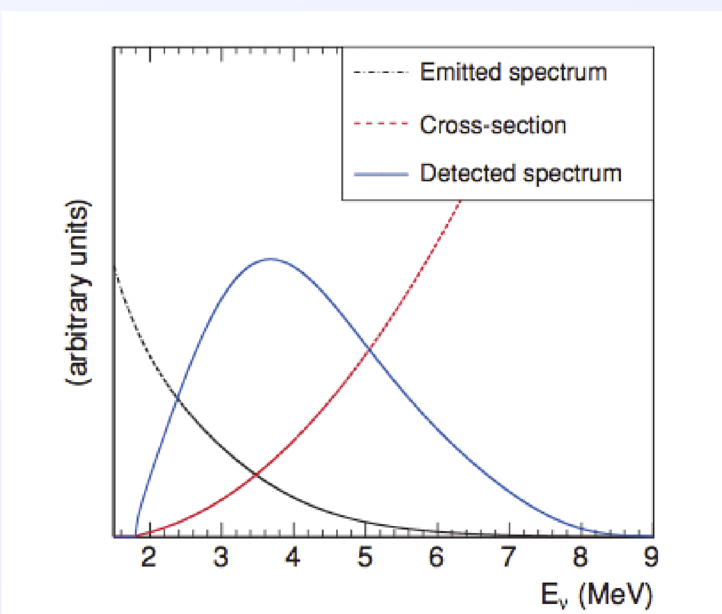


$$\bar{\nu}_e + p \rightarrow n + e^+$$

Cross section:
$\sigma \sim (E_\nu - 1.8\ \text{MeV})^2$

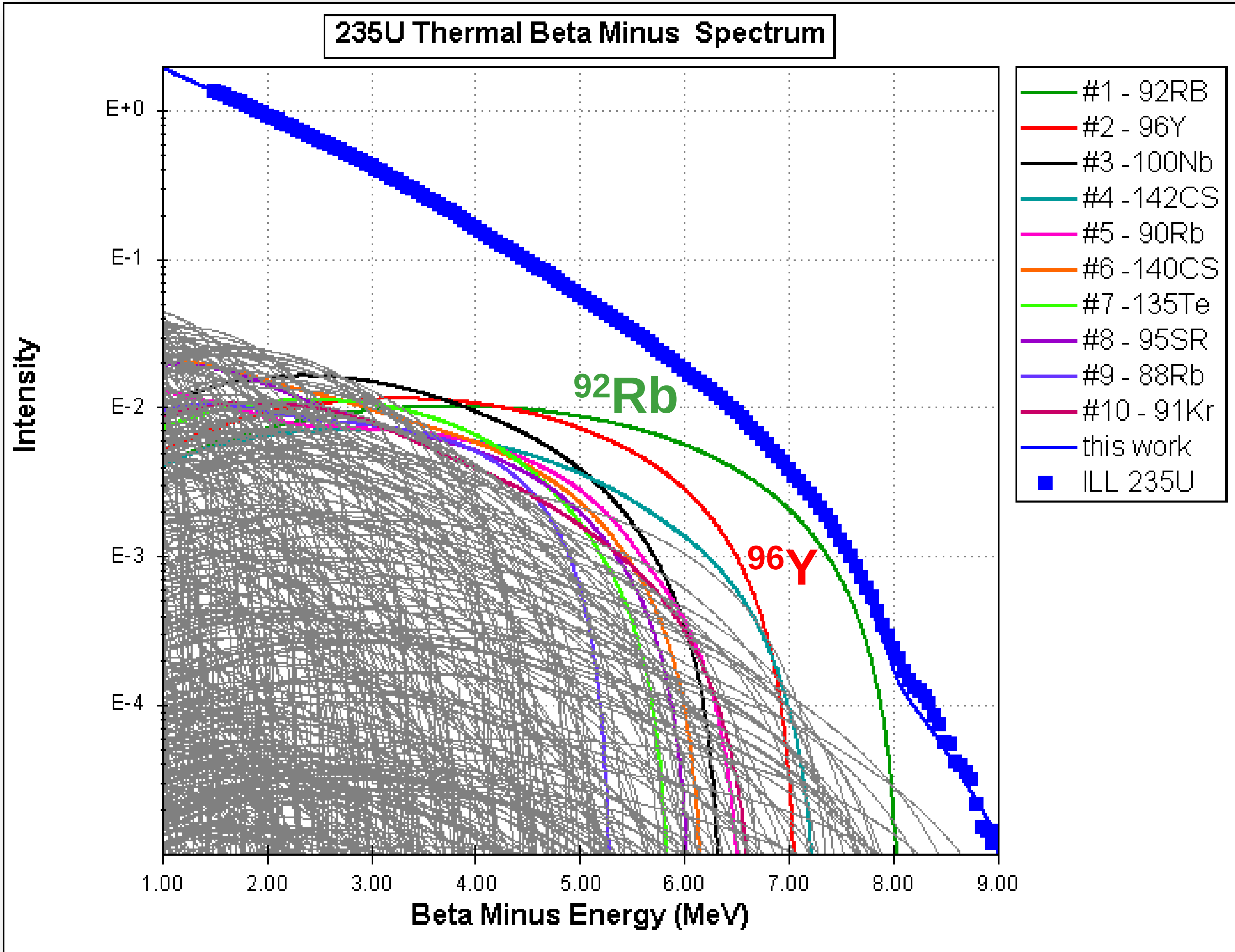
- **Inverse beta decay provides powerful means of separating neutrino signal from background.**
- **Positron and neutron energy depositions occur close in time and space.**

Need fission product isotopes with:
- **Large cumulative fission yields**
- **Large Q values**
- **Large BR to low-lying states**



Th. A. Mueller *et al.*, PRC **83**, 054615 (2011)

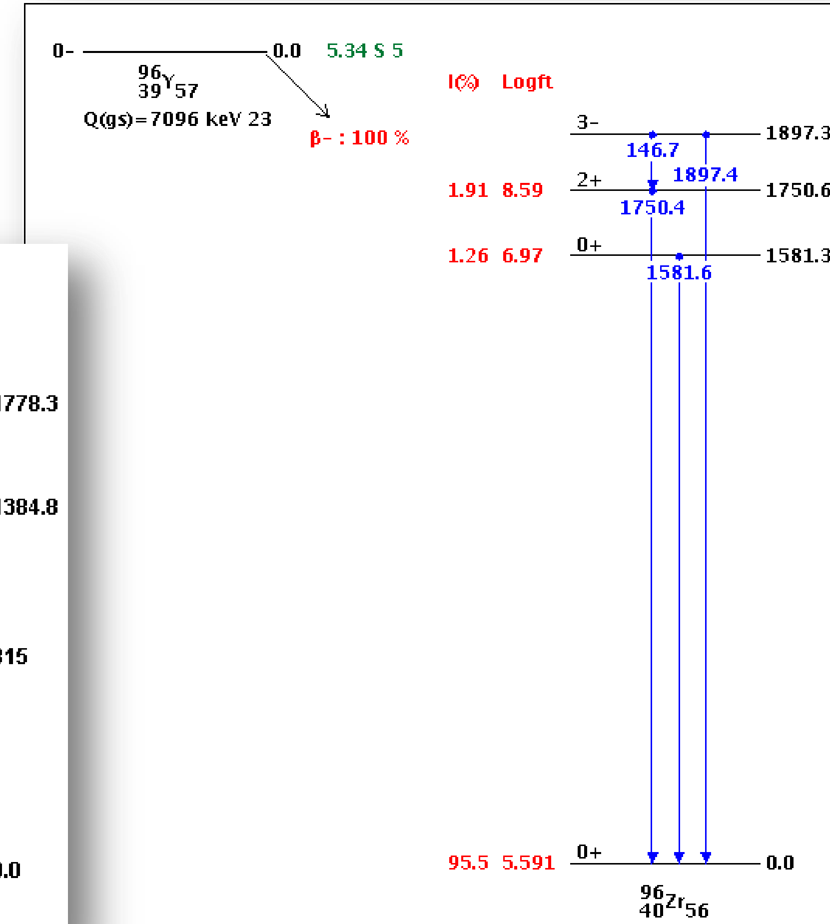
Isotopes such as ^{92}Rb, ^{96}Y, ^{142}Cs, etc. are the most important fission product nuclei…
… and in particular their decay to the GS

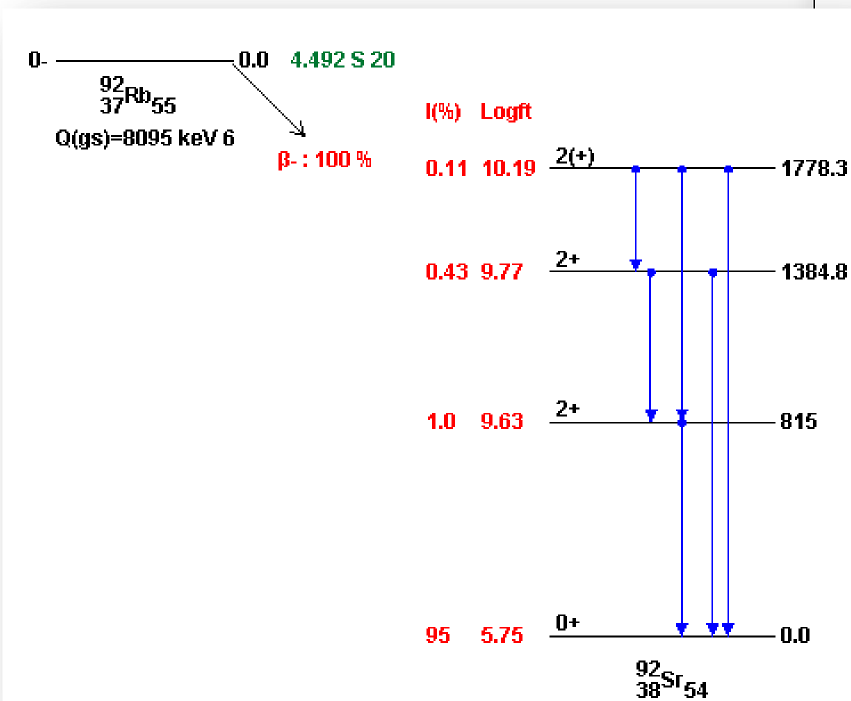


235U Thermal Beta Minus Spectrum
Intensity
E+0
E-1
E-2
E-3
E-4
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
Beta Minus Energy (MeV)
92Rb
96Y
#1 - 92RB
#2 - 96Y
#3 -100Nb
#4 -142CS
#5 - 90Rb
#6 -140CS
#7 -135Te
#8 - 95SR
#9 - 88Rb
#10 - 91Kr
this work
ILL 235U

What do the top 2 have in common?

First forbidden non-unique, g.s. to g.s. transition accounting for 95% of β intensity





Need precise characterization of β transitions to g.s.

→ γ-ray cascade for g.s. to g.s. intensity

→ β spectroscopy for spectral shape

Previous studies of ^{92}Rb decay

Detailed spectroscopy last studied more than 40 years ago !!!

PHYSICAL REVIEW C VOLUME 5, NUMBER 6 JUNE 1972

Gamma-Ray Studies of the Decays of ^{92}Kr, ^{92}Rb, and ^{92}Sr

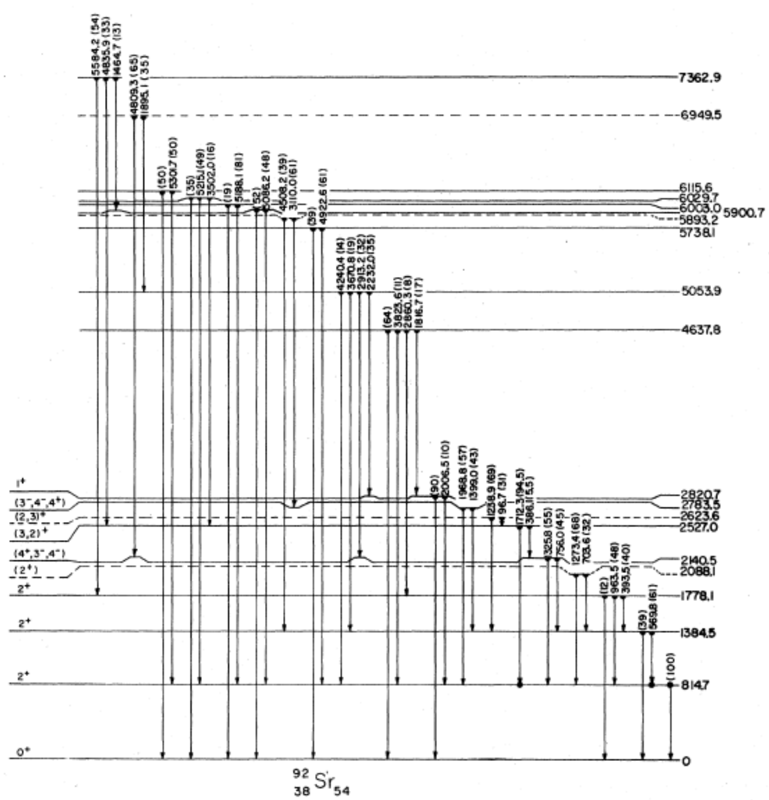
R. J. Olson, W. L. Talbert, Jr., and J. R. McConnell
Ames Laboratory, U. S. Atomic Energy Commission and Department of Physics, Iowa State University, Ames, Iowa 50010
(Received 17 February 1972)

Absolute intensity of $2^+ \rightarrow 0^+$ transition determined recently

PHYSICAL REVIEW C 74, 017308 (2006)

Absolute branching intensities in the decay of ^{92}Rb to ^{92}Sr

G. Lhersonneau, V. Rizzi, O. Alyakrinskiy, A. Lanchais, and L. B. Tecchio
INFN, Laboratori Nazionali di Legnaro, Viale dell'Università 2, I-35020 Legnaro (PD), Italy

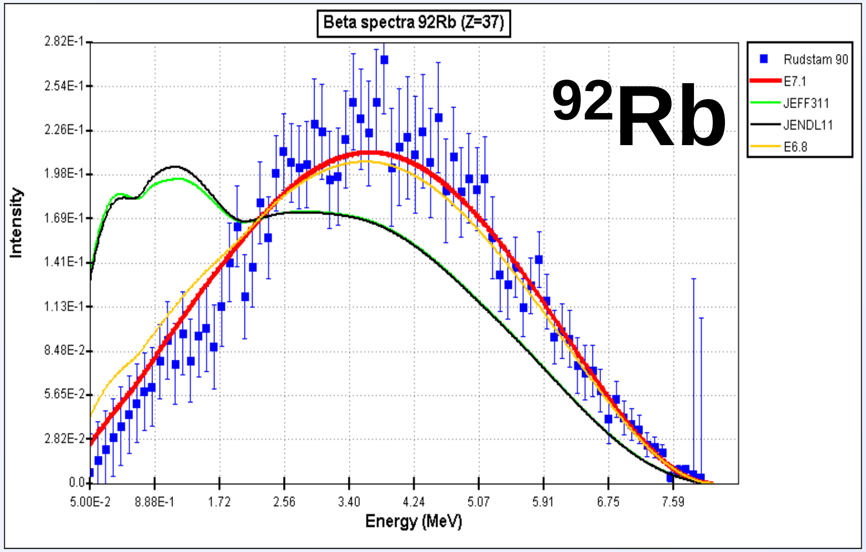


- β-decay feeding to g.s. determined by subtracting γ-ray intensity to g.s.
- Only a handful of g.s. transitions identified
- With parent $J^\pi=0^-$, expect population of J=1 states which then could decay to g.s.
- Can be thoroughly investigated with modern HPGe array
- Work published 5 years before Pandemonium introduced
  (J.C. Hardy *et al.*, Phys. Lett. B **71**, 307 (1977))

Existing direct measurement of β spectrum

Rudstam *et al*., Atomic Data and Nucl. Data Tables 45, 239 (1990)

- Only set of direct β spectral shape measurements for most relevant isotopes
- Minimal isobaric separation – isobar signatures disentangled by half-life
- Limited statistical uncertainty



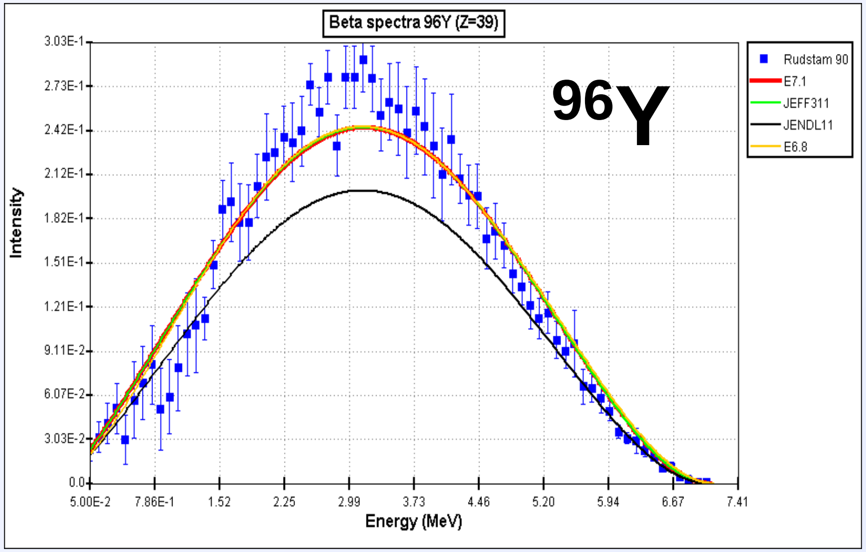
However, no solid determination of BR to g.s.

- β spectrum is evidence that gs transition is large
- Early evaluations estimated **(51±18)%** based on log(ft) prejudice
- Intensity of 815-keV transition (strongest discrete by ×5) most recently measured to be (3.2±0.4)%
- BR is **(95.2±0.7)%** when including all other observed transitions (down to 0.03%)
- Are transitions missed (Pandemonium)?
- Part of normalization relies on comparison to ^{92}Sr BR determined in 1957!

Existing direct measurement of β spectrum

Rudstam *et al*., Atomic Data and Nucl. Data Tables 45, 239 (1990)

- Only set of direct β spectral shape measurements for most relevant isotopes
- Minimal isobaric separation – isobar signatures disentangled by half-life
- Limited statistical uncertainty



However, separation of ^{96}Y from ^{96m}Y?

- Half-lives are similar (^{96}Y: 5.3 s, ^{96m}Y: 9.6 s)
- ^{96m}Y is ~25% of cumulative yield
- ^{96m}Y decay scheme is quite different (~50% of energy to γ rays)
- Same potential Pandemonium issue as in ^{92}Rb

Most important β transitions are first-forbidden

Calculations all assume basically an allowed spectral shape

Probably a good assumption as the important transitions have log(ft) values of ~6 and most FF transitions have a nearly allowed shape

But is this good enough? An average shift of dN/dE_e of +3%/MeV is enough explain the anomaly

(P. Huber, PRC **84**, 024617 (2011))

Never been precisely tested for short-lived fission products

The ξ approximation, or "quasi-allowed" approximation, requirements aren't satisfied well:

$$\xi = \frac{\alpha Z}{E_0 R} >> 1$$

For important transitions ξ~1

Interference between the various matrix elements that contribute to a FF β decay can cause distortions from allowed shape

Recently Anna Hayes *et al.* (PRL **112**, 202501 (2014)) called into question how FF well shape factors and leading-order weak magnetism corrections are known

The CARIBU Facility at Argonne National Laboratory

Transforming ^{252}Cf fission products into a mass-separated low-energy beam

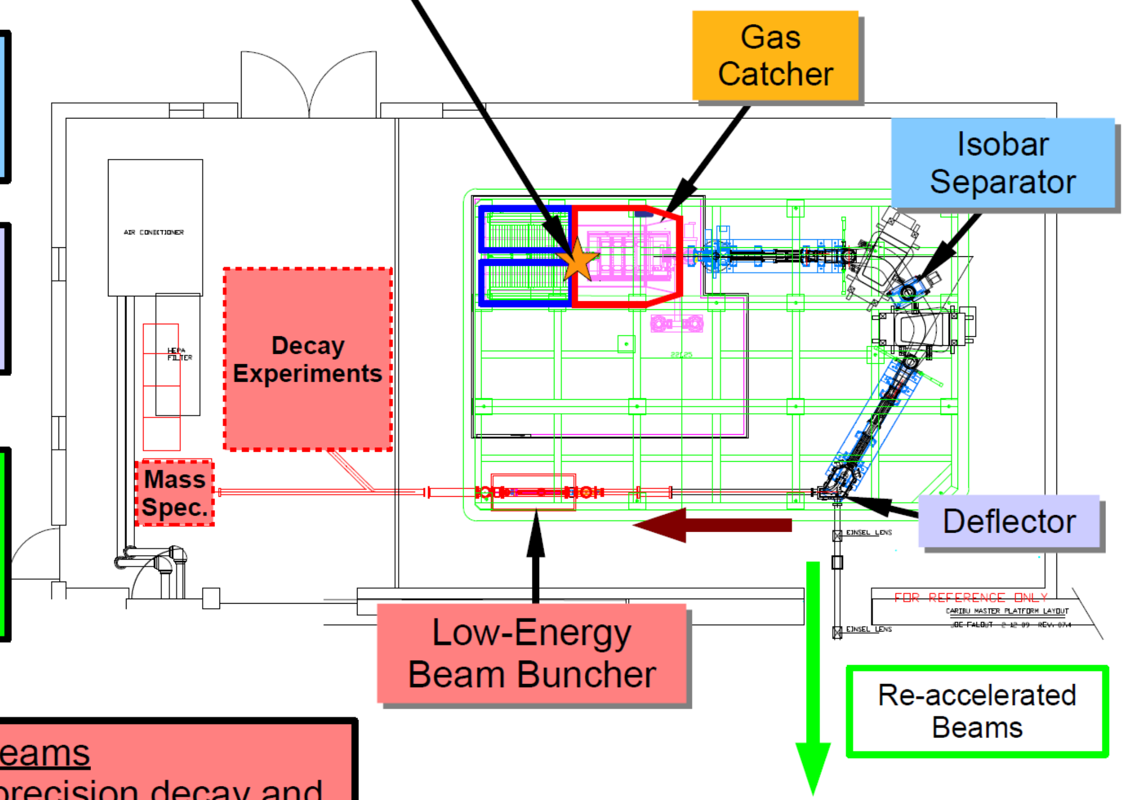
^{252}Cf fission fragments are slowed and focused in a helium-gas catcher

Beams of a desired mass are selected by a 120º magnetic isobar separator

The neutron-rich beams can be deflected to low-energy or re-accelerated beam lines

Re-accelerated beams
Charge bred and injected into ATLAS resulting in energies up to ~15 MeV/A

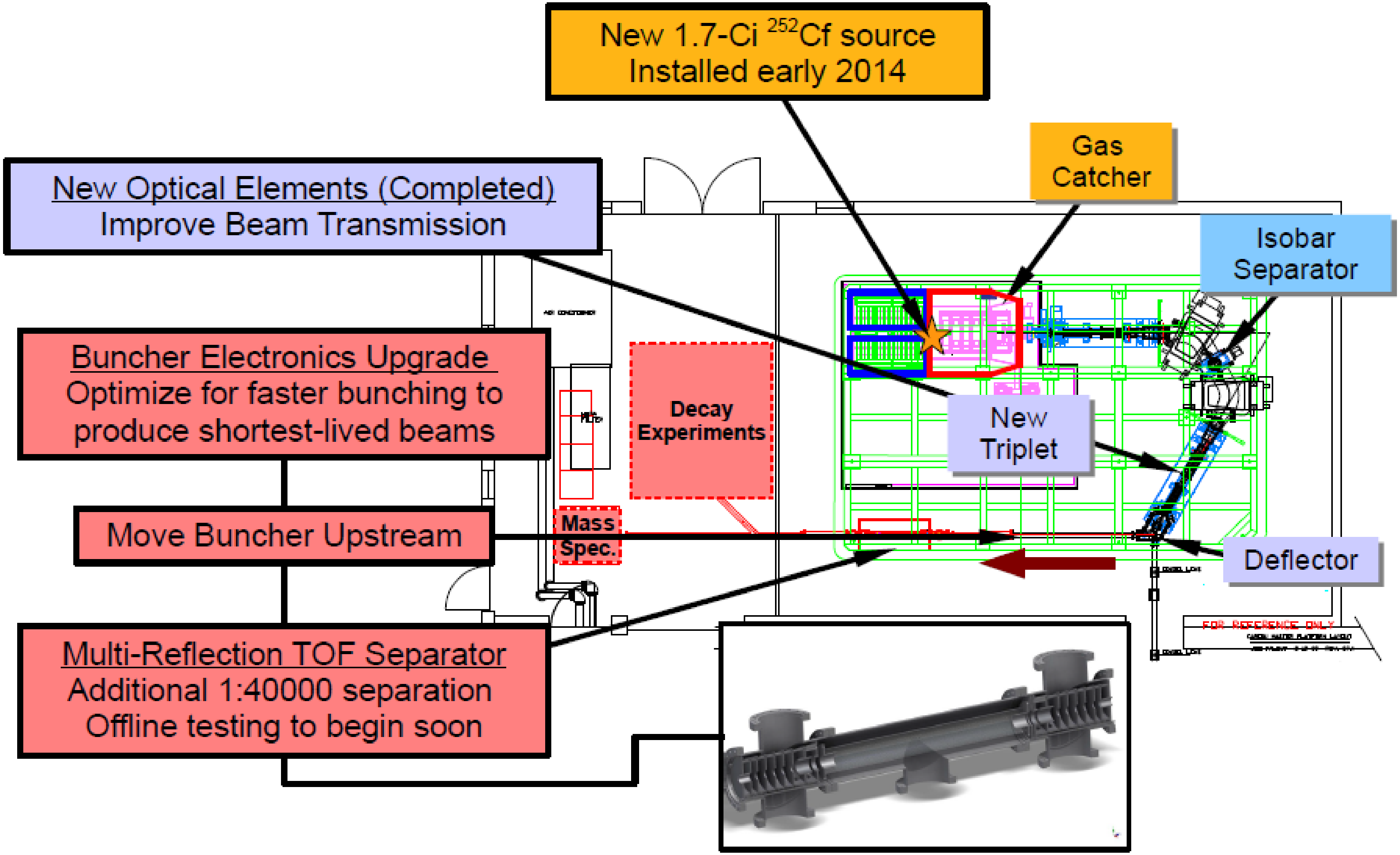
^{252}Cf Source ($t_{1/2}$=2.6 y)
~1.7 Ci~6.3x10^{10} dps
[96.9% α, 3.1% S.F.]



Low Energy Beams
Beams bunched for use in precision decay and mass spectrometry experiments

Upgrades to the CARIBU facility

Beam intensities of ~10^4-10^5 pps currently delivered to low-energy experiments



Decay Studies at CARIBU at ANL

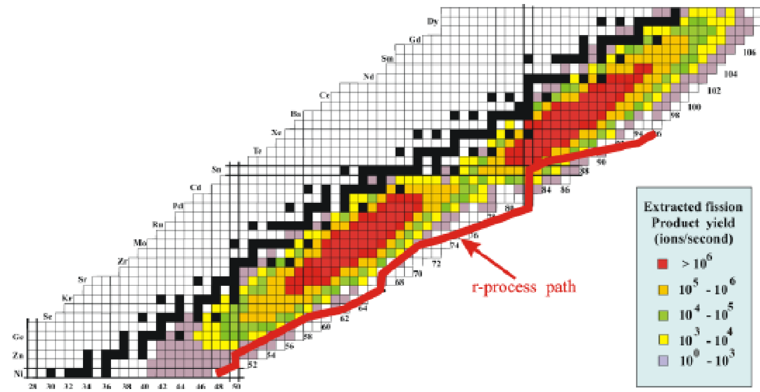
Nuclear Instruments and Methods in Physics Research A 763 (2014) 232–239

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

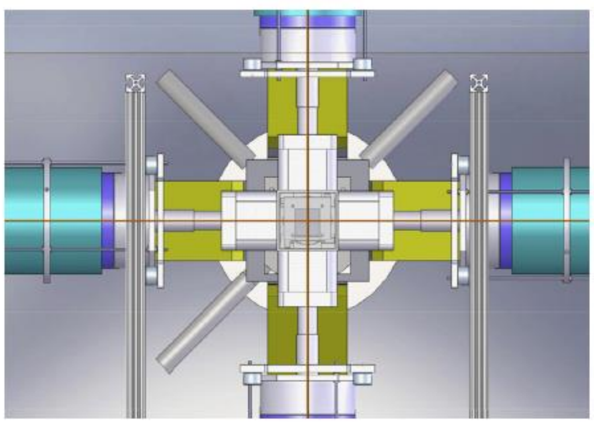
ELSEVIER



The X-Array and SATURN: A new decay-spectroscopy station for CARIBU

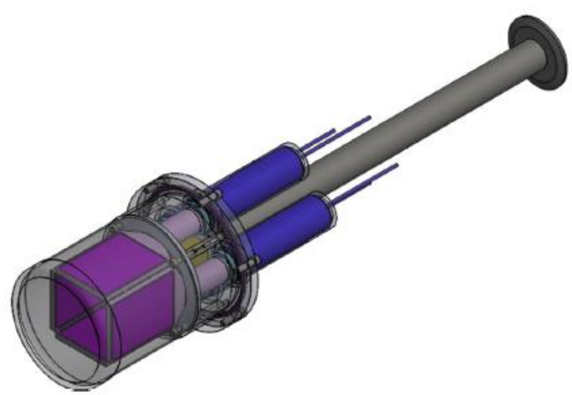
A.J. Mitchell[a,*], P.F. Bertone[b,1], B. DiGiovine[b], C.J. Lister[a], M.P. Carpenter[b], P. Chowdhury[a], J.A. Clark[b], N. D'Olympia[a], A.Y. Deo[a,2], F.G. Kondev[b,c], E.A. McCutchan[b,3], J. Rohrer[b], G. Savard[b,d], D. Seweryniak[b], S. Zhu[b]

X- Array



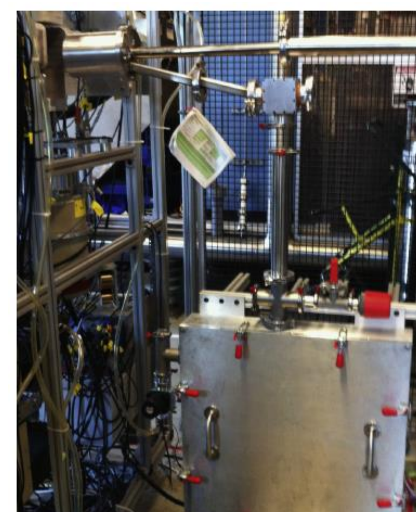
4 Standard Clovers (6 cm x 6 cm crystals)
1 “Super” Clover (7 cm x 7 cm crystals)

SATURN

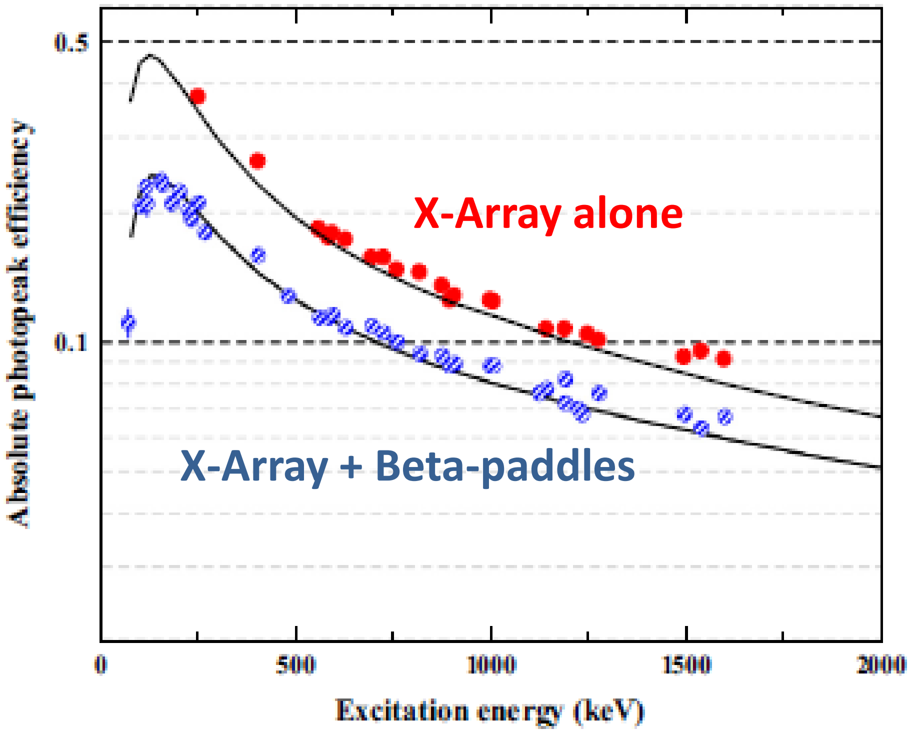


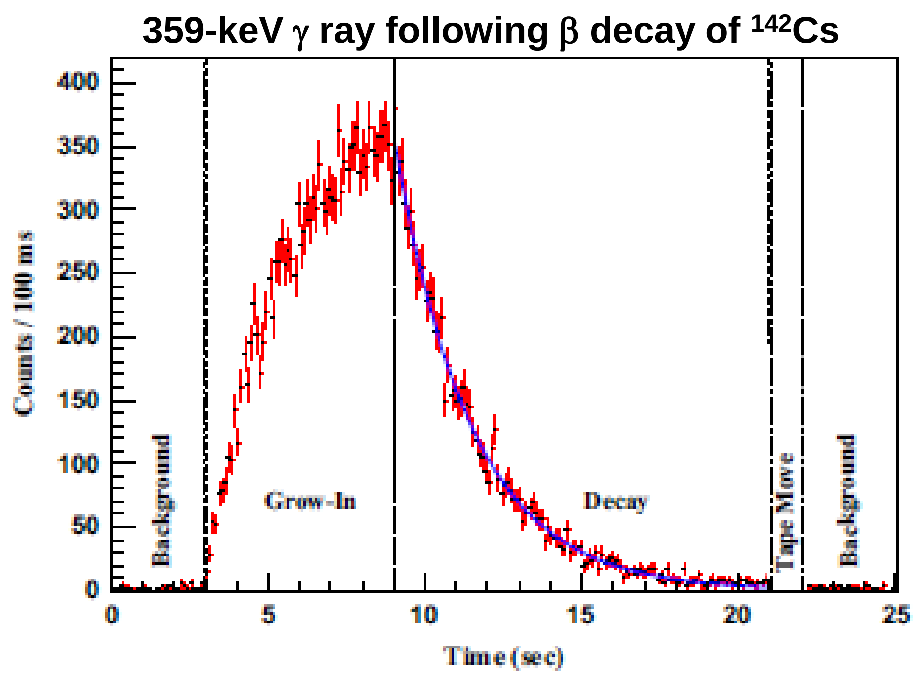
Plastic Beta Paddles or
(Cylindrical Beta detector)

Tape System



X-Array Performance





- ~2% efficiency for 5-7 MeV transitions
- In 2 days, collect ~20,000 counts in weakest previously observed transitions
- Achieve sensitivity to discrete transitions with intensities as low as ~0.005%

- Half-life analysis to confirm placement

A.J. Mitchell *et al.*, NIM A **763**, 232 (2014)

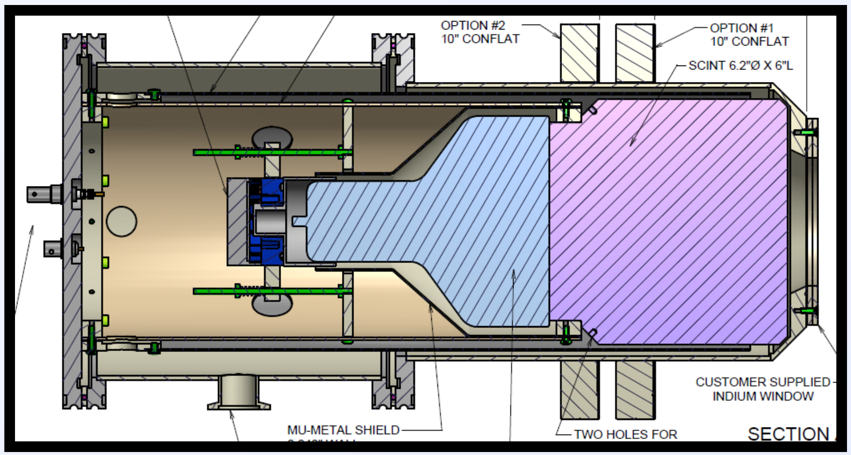
Beta-decay Spectroscopy at CARIBU

Experimental setup (under development):

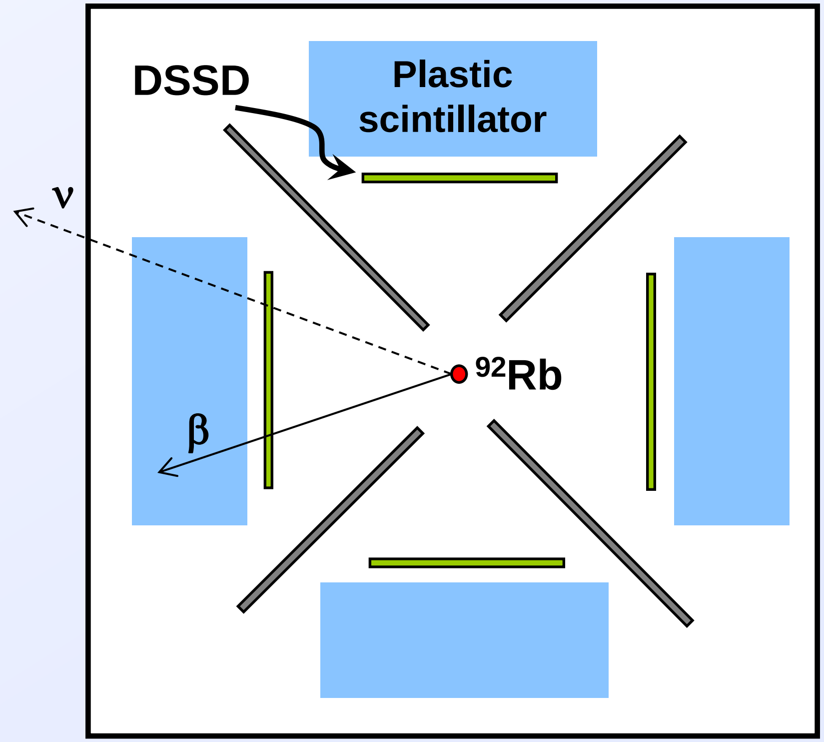
^{252}Cf source (CARIBU) provides high-intensity, isobarically-pure beams

Activity collected and transported using tape station

Energy measurement performed with ΔE-E β detector



Activity implanted on tape surrounded by silicon and plastic scintillators



Detectors based on β-detectors from delayed neutron effort and will be used for ^{8}Li/^{8}B experiment

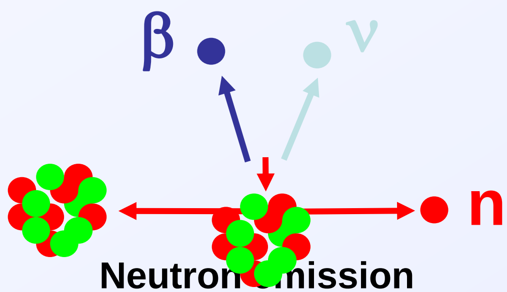
Plastic scintillator minimizes β backscatter and bremsstrahlung effects

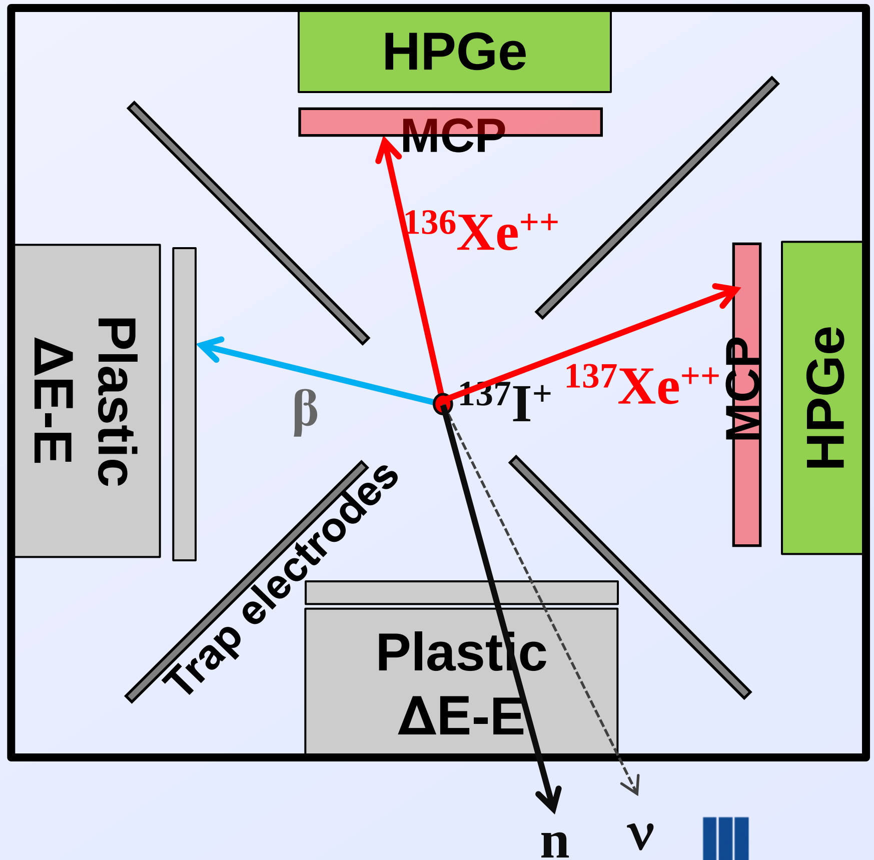
Experience performing precision β-decay spectroscopy at CARIBU

Collect ions in the trap

Detect β and recoil ion – determine nuclear recoil from TOF

$$^{137}\mathrm{I} \rightarrow {}^{137}\mathrm{Xe}^* + \beta^- + \nu$$
$$\hookrightarrow {}^{136}\mathrm{Xe} + n$$





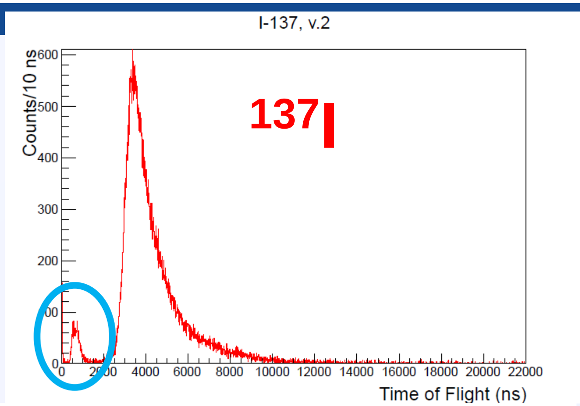
β (1 MeV): ~0.01 keV recoil

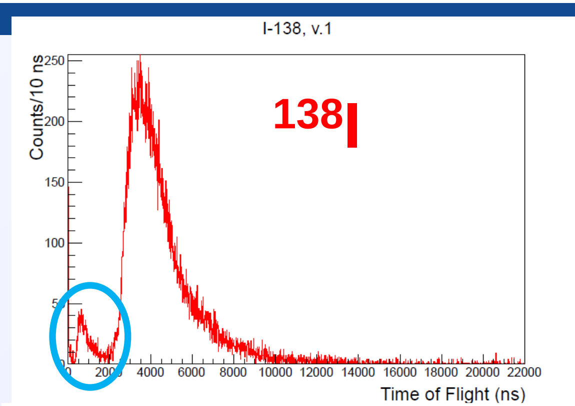
n (1 MeV): ~10 keV recoil

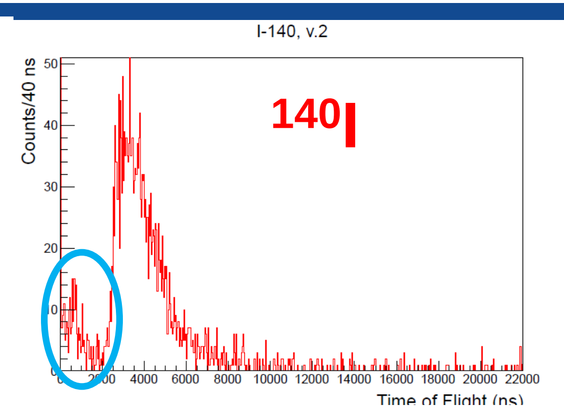
Identify neutron emission from larger nuclear recoil.
Avoid neutron detection challenges…

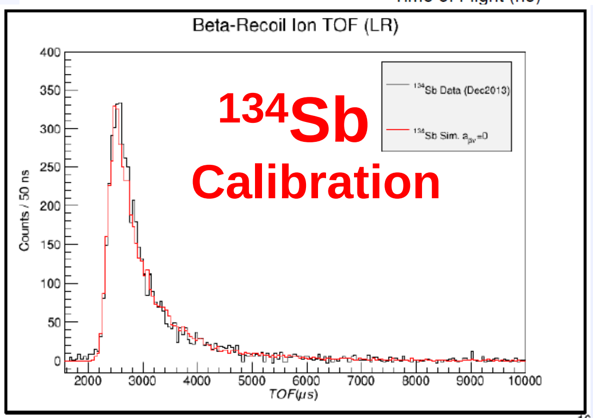
Analysis of β-delayed neutron data from recoil-ion TOF is underway…

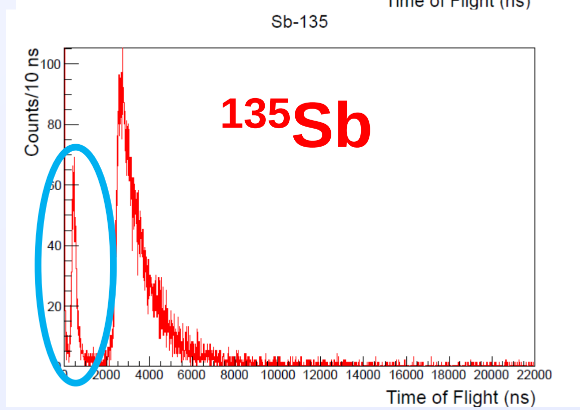
Aga Czeszumska – PhD thesis, UC Berkeley
Shane Caldwell – PhD thesis, UChicago

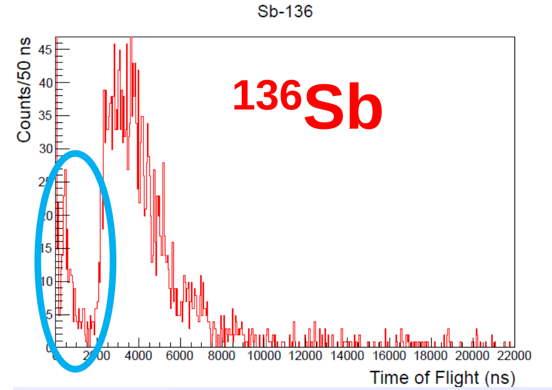


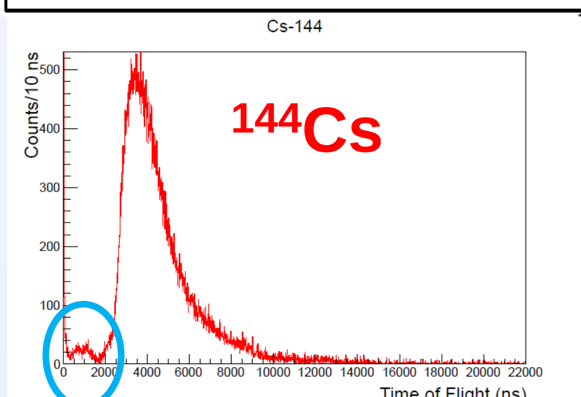


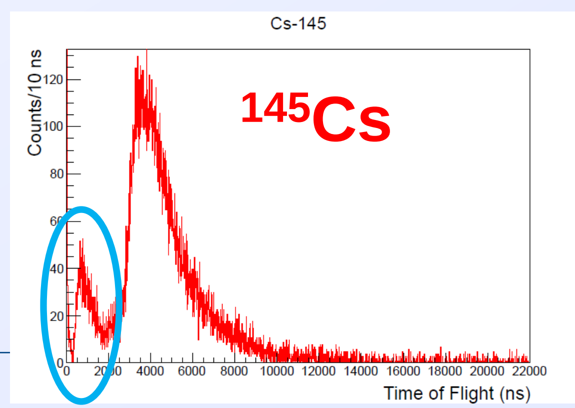












^{134}Sb β decay:

Q = 8.5 MeV
$0^- \rightarrow 0^+$ transition
GS BR ~ 98%

Beta-decay Spectroscopy

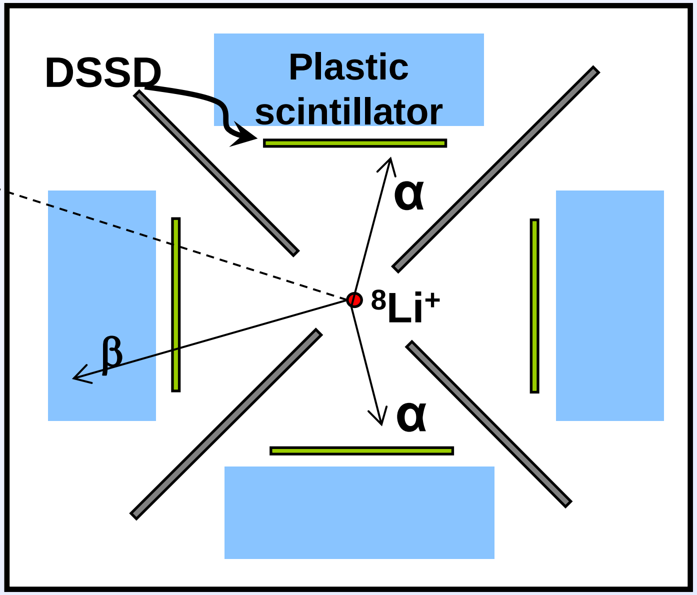
Detector system will be used in $^{8}Li/^{8}B$ β-decay angular correlation measurements using trapped ions

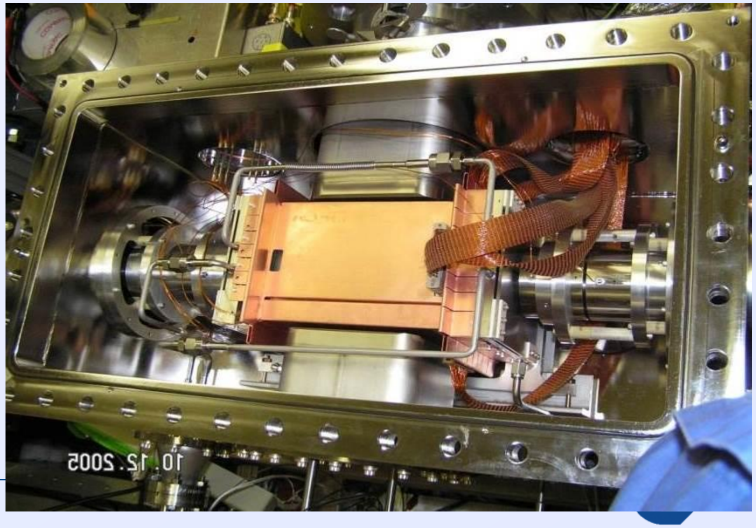
Here the allowed decays are studied to very high precision (β-ν correlation at the <1% level)

$^{8}Li/^{8}B$ have large Q values (16-18 MeV) and ~3×10^5 β-α-α coincidences have been observed with improvements in production and transport efficiency expected to result in $10\times$ increase in statistics

Ion trap experiment allows decay to be over-constrained by detecting β-α-α coincidences

→ β energy can be determined from DSSDs alone event by event
→ reconstructed energy compared to energy deposited in plastic scintillator
→ detector response (energy, position dependence) can be thoroughly investigated

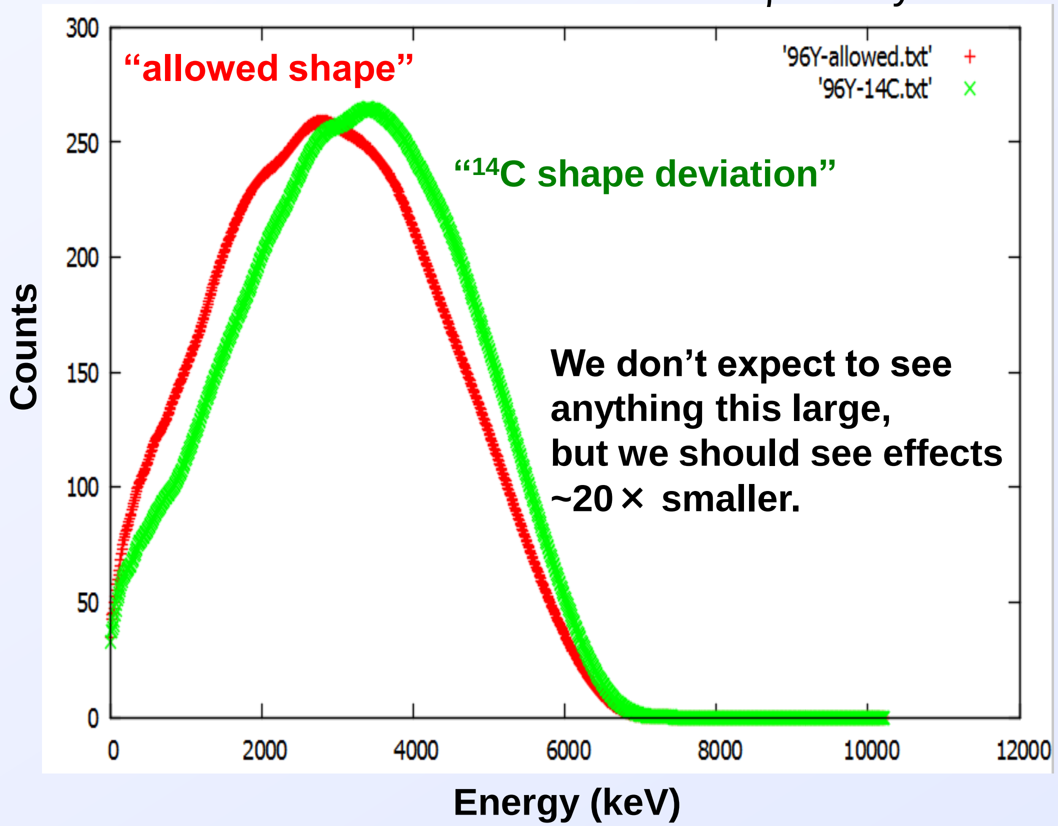




Shape Factor Deviations

10^7-10^8 β counts can be collected in 1 day at CARIBU
β-γ coincidences with HPGe detectors

GEANT4 **simulations** of ^{96}Y β decay



Summary

- Measurements of reactor antineutrino flux fall short of expectation
  - A tantalizing hint of new physics?
  - Or something more mundane, like limitations in nuclear data?
- Identification of "new physics" would be put on firmer footing with better data on "traditional physics" such as β-decay spectra
- Detailed γ-ray and β-decay spectroscopy on key fission products can be performed with high-intensity, pure beams
- Experiments at CARIBU will utilize X-Array+Saturn and build off of existing β-delayed neutron and $^{8}Li/^{8}B$ measurement campaigns to better characterize the β decays of the key isotopes
- Perhaps first-forbidden β decays aren't as well behaved as we would like…