Decay Spectroscopy at CARIBU using an Ion Trap

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S&T/P&LS/Physics/N-section

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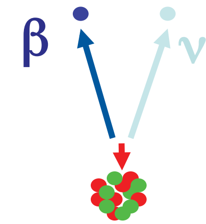
Traps enable precision β-decay spectroscopy

Traps have favorable properties:

- radioactive nuclei suspended in vacuum
- activity localized (<1mm^3) in a well-defined geometry
- nuclei nearly at rest

Neutrinos in β decay



Neutrino escapes detection!

Provide way to study difficult-to-measure particles through conservation of momentum

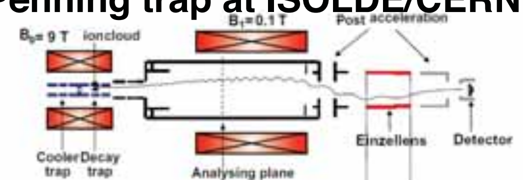
Measurement of nuclear recoil and β allow opportunity to reconstruct ν energy/momentum event-by-event

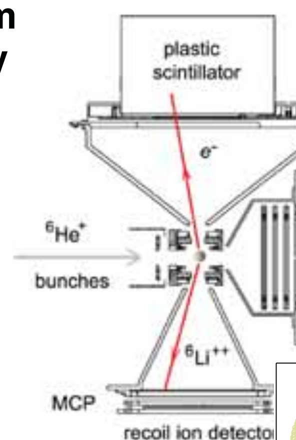
Experimenters around the world now use atom traps and ion traps to perform precise β-decay angular correlation studies to study fundamental symmetries of electroweak interaction (V-A interaction for example)

Recoiling daughter nucleus following β decay emerges from trap without scattering and is available for study
→ direct detection of daughter ion
→kinematic shifts

Energies/shifts often only ~0.1 keV!

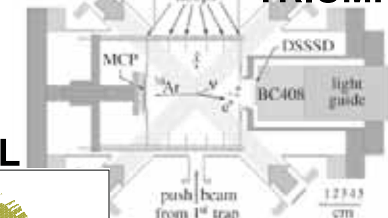
Penning trap at ISOLDE/CERN



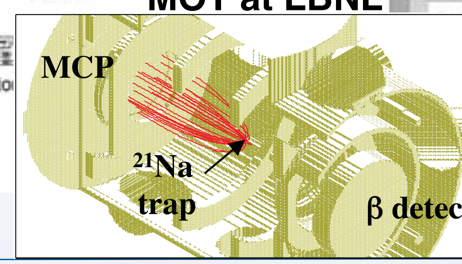


Paul trap at GANIL

MOT at TRIUMF

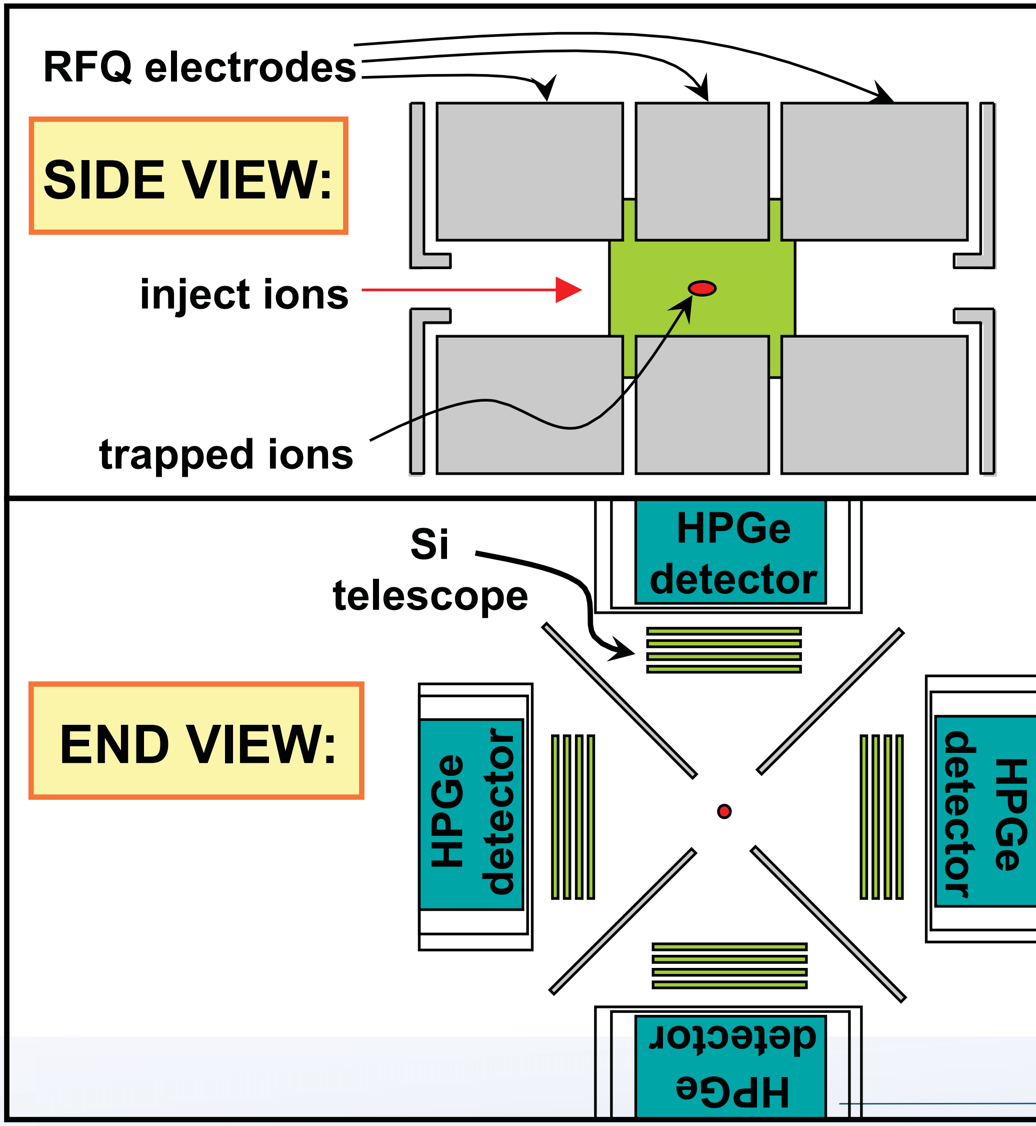


MOT at LBNL



and others…

Beta-decay Paul Trap (BPT): an ion trap for decay studies at ANL



Ions confined using RF and DC electric fields in 1-mm³ volume

- element independent
- ~90% capture efficiency
- $\leq 10^{-5}$ torr He buffer gas cooling
- ion energy <0.1 eV
- storage times > 30 sec
- LN_2 cooling of apparatus

Open-geometry trap structure accommodates 4 sets of radiation detectors

- large solid-angle coverage
- RF shielding for semiconductor detectors
- silicon, scintillators, HPGe, MCP detectors have been used

Beta-decay Paul Trap (BPT): an ion trap for decay studies at ANL

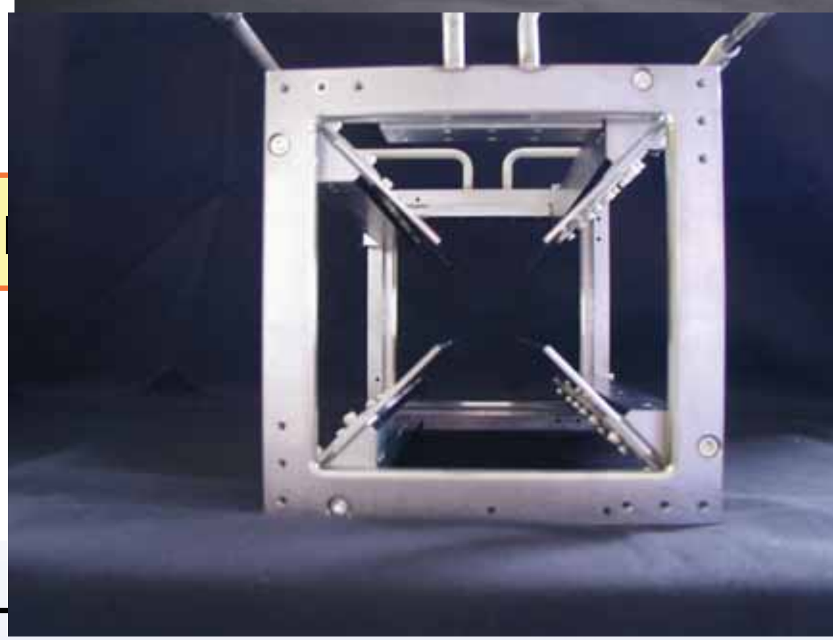
RFQ electr

SIDE VIE

inject

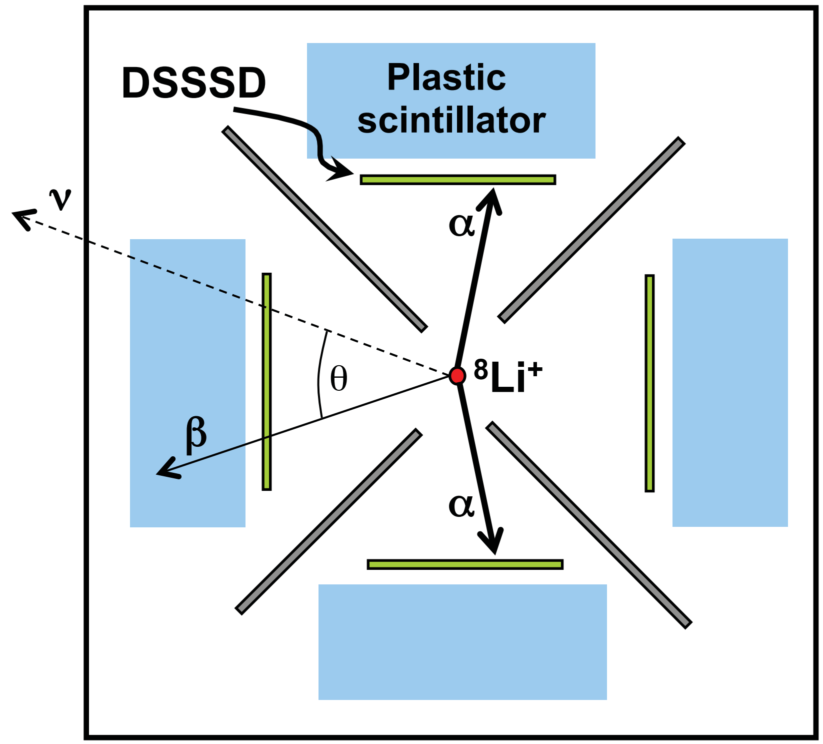
trapped

END VI



1st experiment: ^{8}Li β-decay angular correlation

Surround trapped-ion sample with position-sensitive detector system to precisely reconstruct momentum vectors of all emitted particles (including neutrino!)



$$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}^{*} + \beta^{-} + \nu$$
$$\hookrightarrow \alpha + \alpha$$

$Q \approx 13$ MeV
$t_{1/2} = 0.808$ sec

^{8}Be recoil (up to 12 keV) determined from α break-up

- energy difference up to ±400 keV
- angle deviation from 180^{0} by up to 7^{0}

momentum/energy of αs (+ β direction) measured from double-sided silicon-strip detectors (DSSSD) → decay fully determined

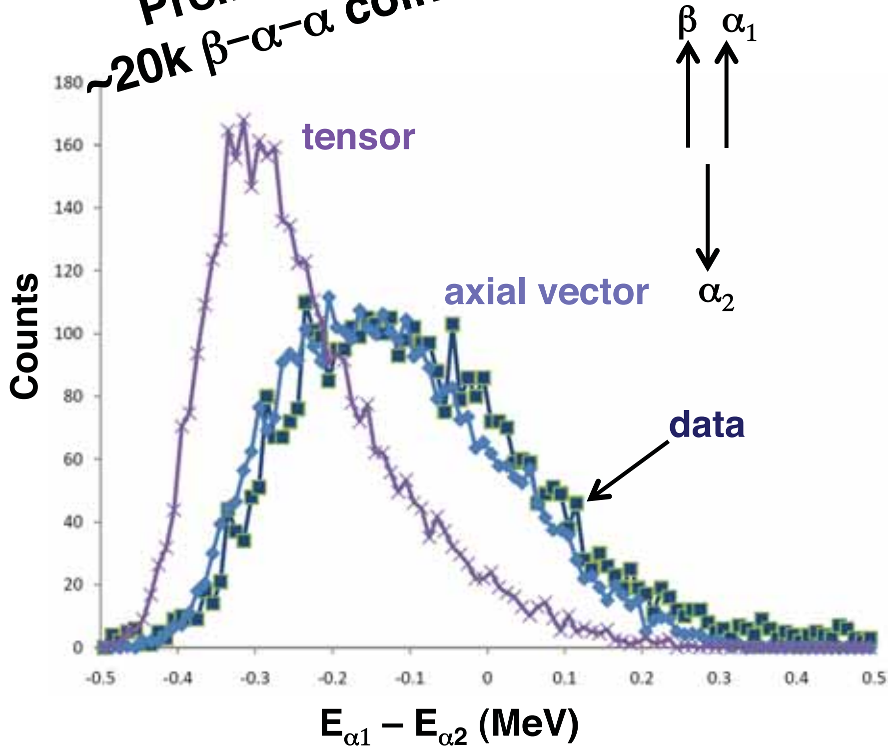
Add plastic scintillator for β energy measurement → decay overconstrained

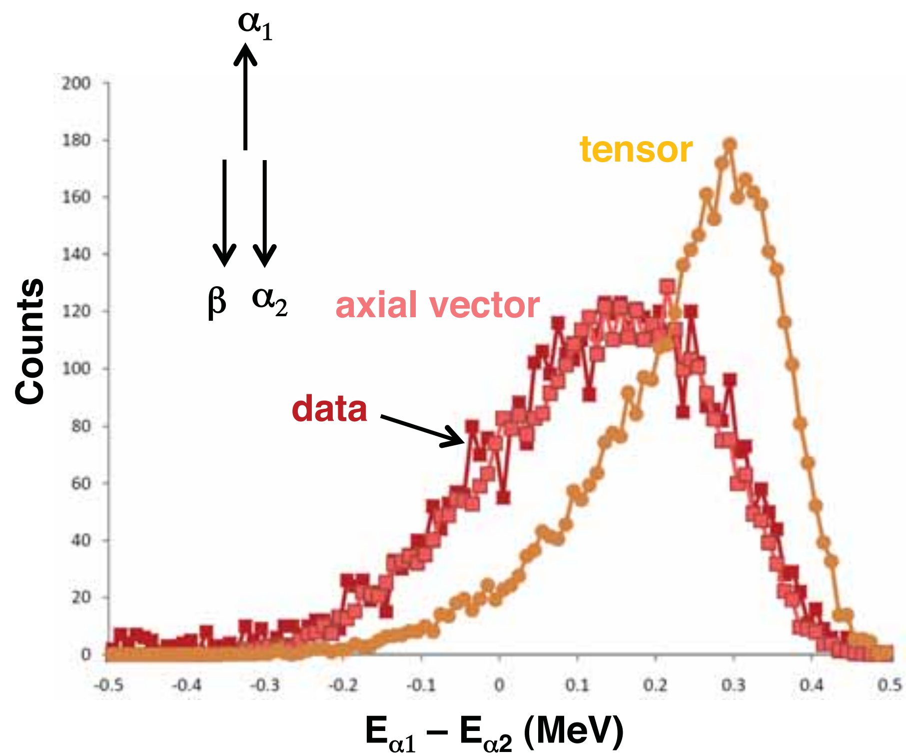
^{8}Li β decay results

DSSDs used to observe the kinematic shifts – E_α resolution of 50 keV and angular resolution of <2^0 → reveal nuclear recoil and ν energy/momentum

Preliminary results
~20k β–α–α coincidences

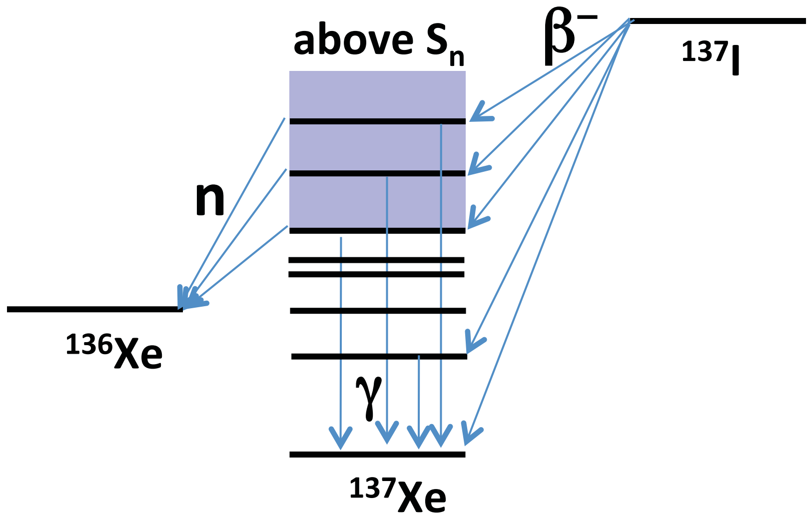
Gamow-Teller decay → only axial vector or tensor contribute



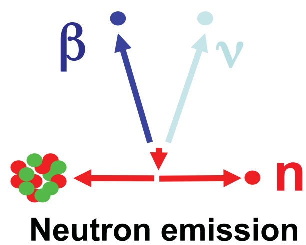


Apply these precision approaches to β-delayed neutron spectroscopy

β-delayed neutron emission



Identify neutron emission from large nuclear recoil



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

Accessible radioactive-decay half-lives are ~50 ms (transport and cooling times) to >100 sec (limited by trap storage time) → nice overlap with β-decay half-lives of delayed-neutron emitters

Delayed Neutrons play a fundamental role in many basic and applied sciences

Need better (or any) data for:

Astrophysics: how were the elements made?

r process: P_n of exotic nuclei define decay path back to stability
→ needed to compare the isotopic abundances observed today to nucleosynthesis mechanisms

Nuclear Energy: how can we best generate nuclear energy?

P_n and energy spectrum → reactor design and safety studies

- fast breeder reactors
- modeling different fuel-cycle concepts, actinide mixes, and irradiation histories
- modeling unexpected conditions

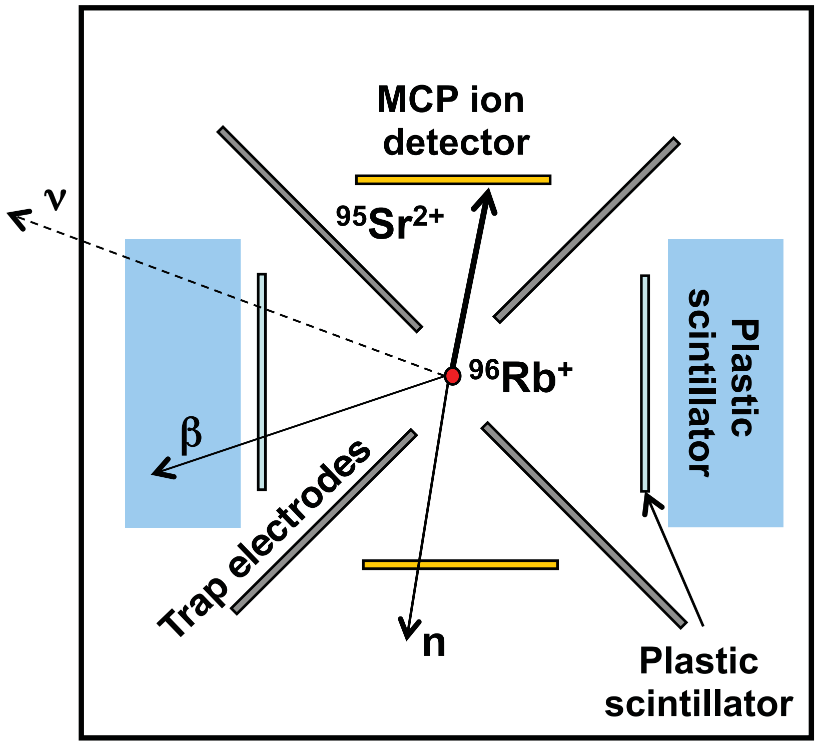
Stockpile Stewardship: how do fission fragments behave in different environments?

→ delayed-neutron emission provides access to the nuclear states populated in (n,γ) reactions
→ Level densities and decay modes (n vs. γ emission) measurable – needed to improve statistical model calculations

Nuclear Structure: how do the properties of nuclei evolve as they become more neutron rich? How do we improve our nuclear models for all of these applications?

Apply these precision approaches to delayed-neutron spectroscopy

Surround ion trap with plastic scintillator and MCP detectors – the energy/momentum of the emitted neutron can be precisely reconstructed from the time-of-flight of recoiling daughter ion



Many anticipated advantages to recoil-ion detection

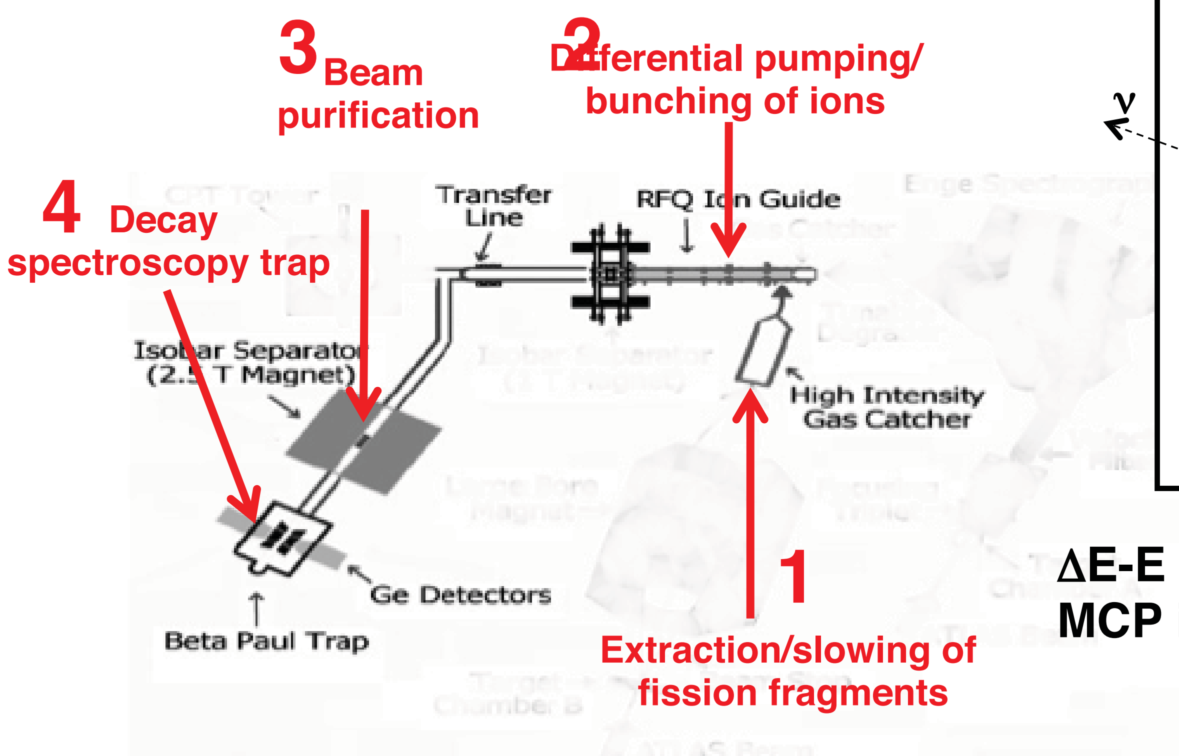
- excellent energy resolution
- reduced systematic effects
- negligible backgrounds
- high efficiency
- chemistry-independent technique

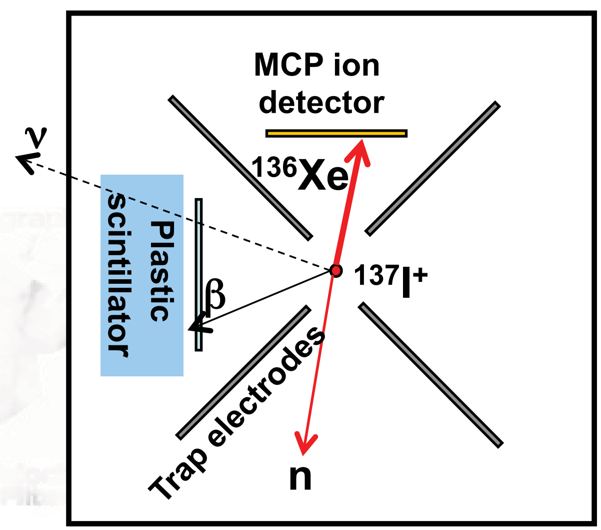
Demonstrate technique offline by studying well-characterized ^{137}I decay

demonstrate technique with smaller fission-fragment set-up (1 mCi ^{252}Cf source in Area II) and simpler detectors

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

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



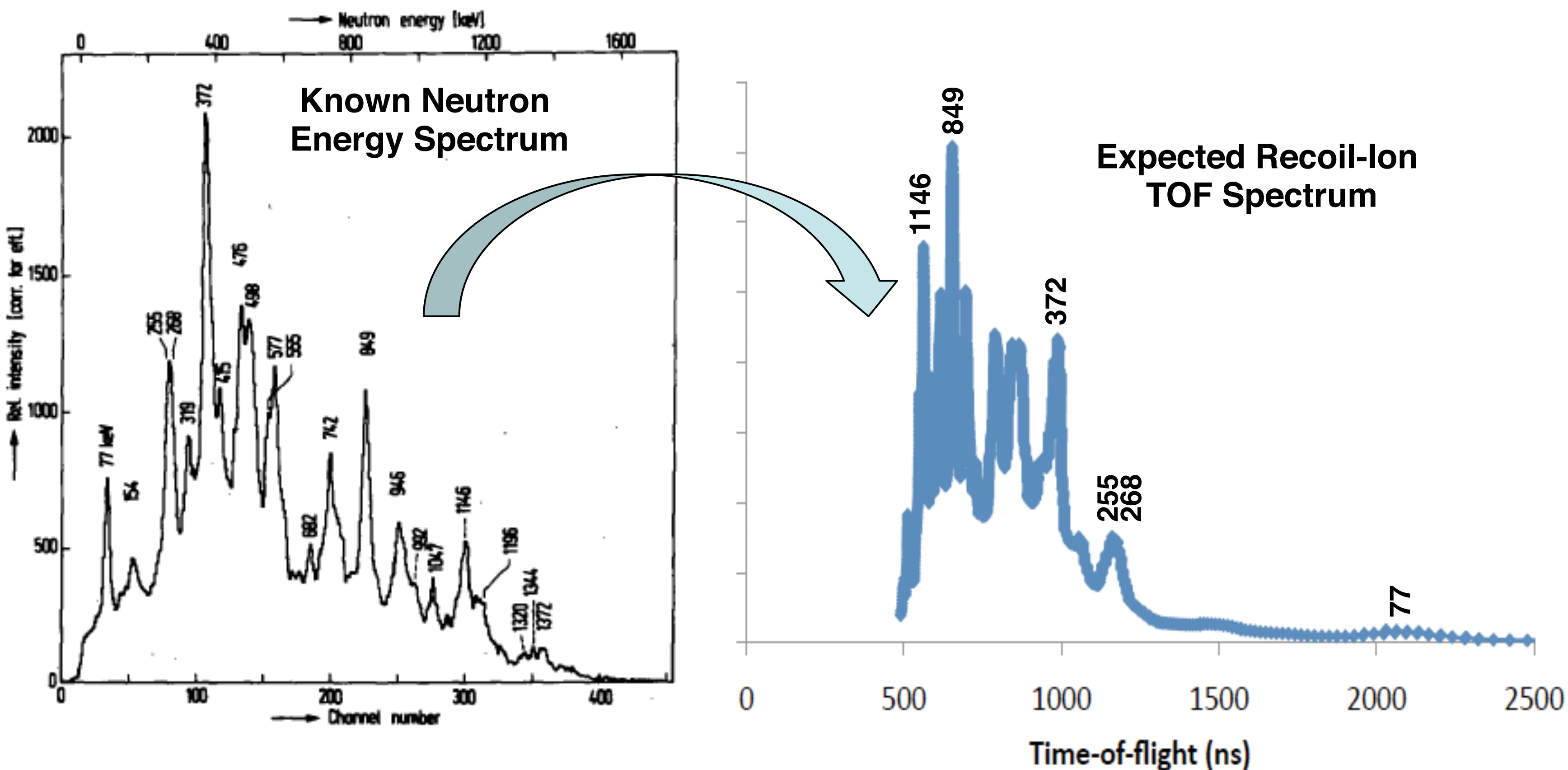


ΔE-E plastic scintillator: Ω_{β} = 3%

MCP ion detector: Ω_{ion}= 3%

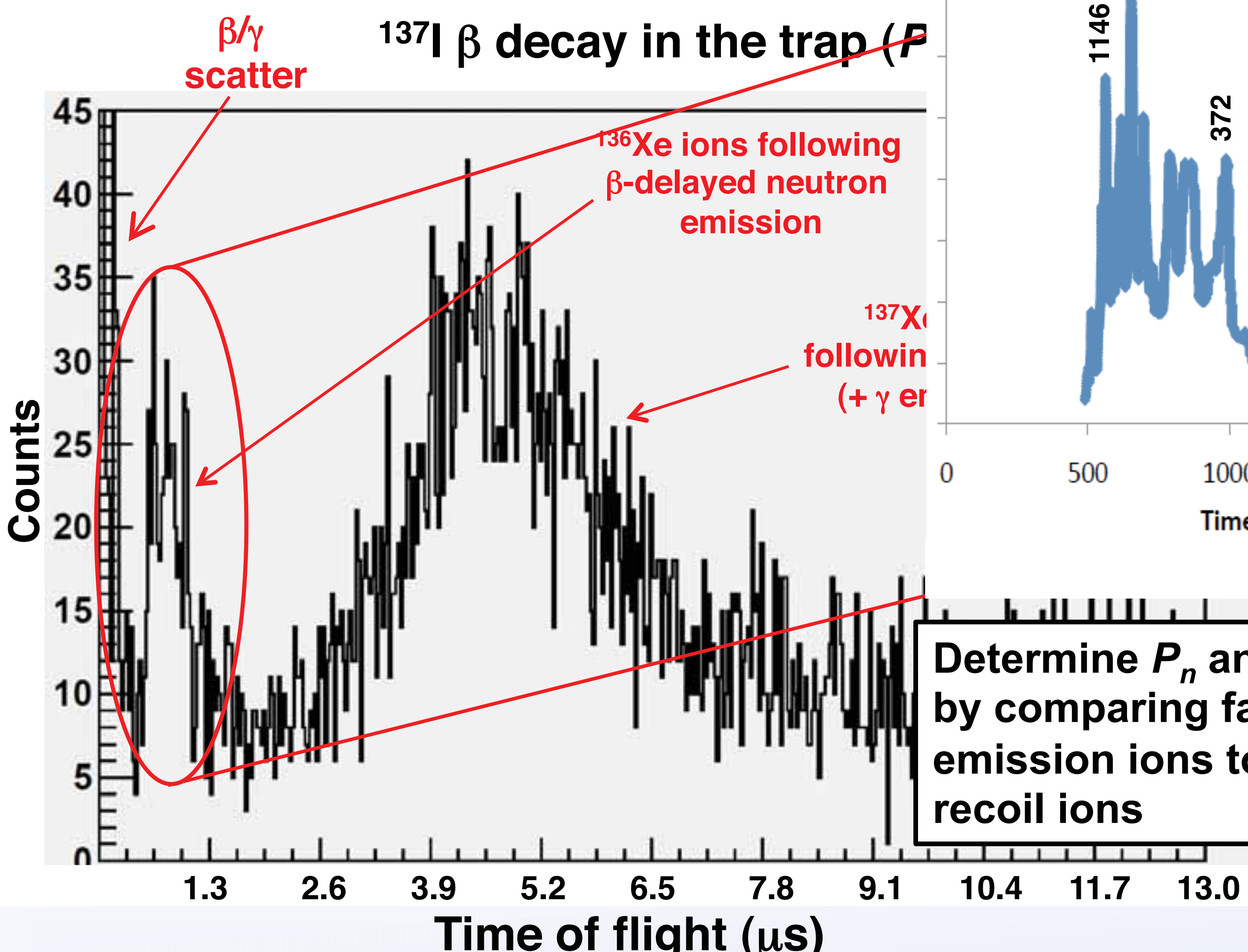
^{137}I delayed-neutron decay

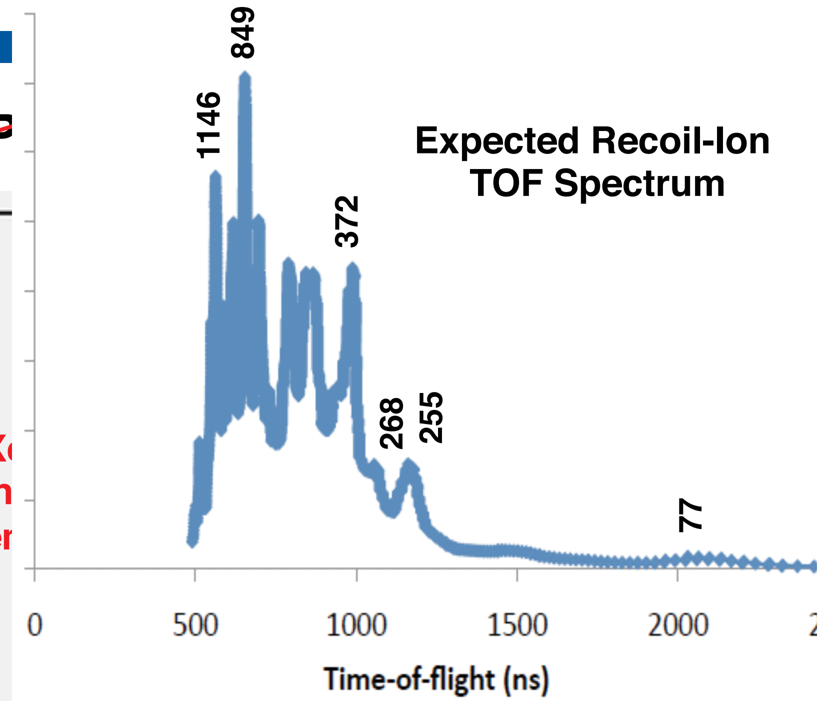
Energy spectrum → time-of-flight spectrum



K.-L. Kratz et al., Nucl. Phys. A317, 335 (1979)

Data collected with $^{137}I^+$ beam of 30 ions/sec





Determine P_n an additional way: by comparing fast, neutron-emission ions to slower β−γ recoil ions

From Demonstration to CARIBU

Proof-of-principle…

…at CARIBU

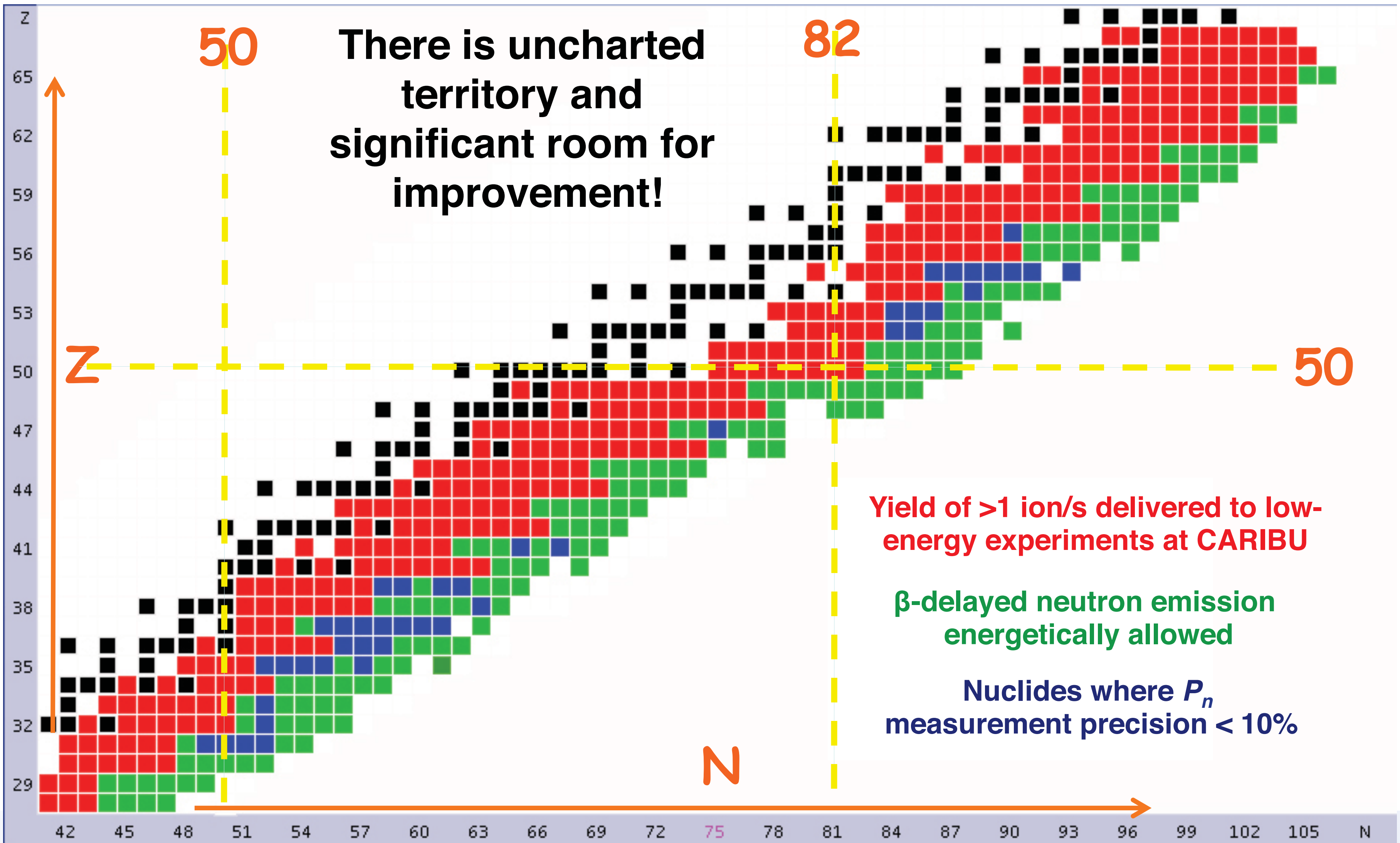
Detector array Ω_β, Ω_{ion} each 3% → Increase both Ω_β, Ω_{ion} to 10-20% with optimized detector array
→ coinc. efficiency: ×10-40

High-quality data can be obtained with ion beams of ~1 ion/sec
→ can reach very exotic nuclei: r-process, nuclear structure, etc.

Ion beam 30 ions/sec (for ^{137}I, near mass peak) → CARIBU 1-Ci source: 4×10^6 ions/sec (for ^{137}I at low-energy beamline)

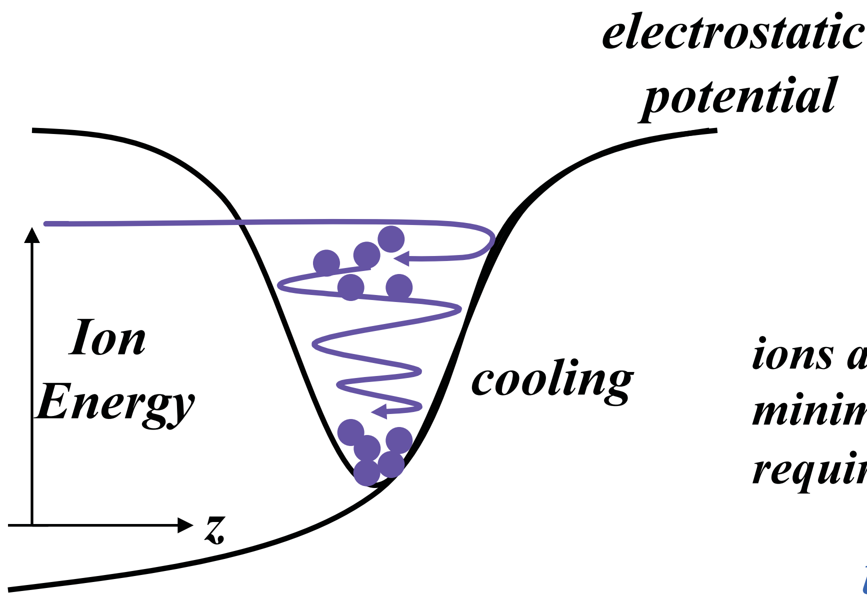
High statistics for precision measurements and systematic checks: nuclear energy, stockpile stewardship, etc.

Existing data is limited (and often inconsistent)



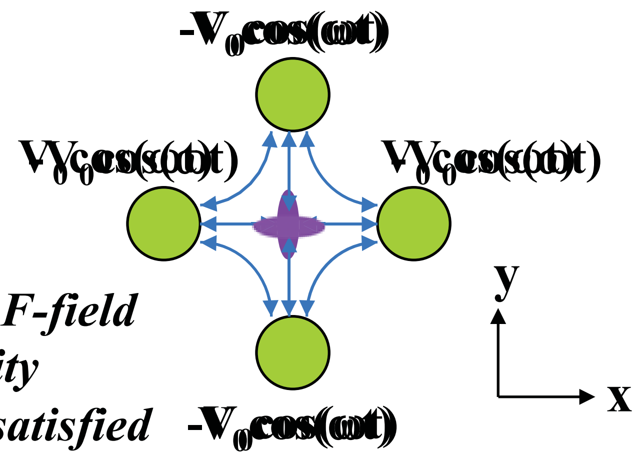
How Ions are Trapped in a Paul (RFQ) Trap

Confinement in Axial Direction



ions cooled using helium buffer gas

Confinement in Radial Direction



ions attracted to RF-field minimum if stability requirements are satisfied

inhomogeneous RF electric field

Stability requirements:

$$q = \frac{2eV}{mr_0^2\omega^2} \sim 0.5$$