Decay Spectroscopy at CARIBU using an Ion Trap
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S&T/P&LS/Physics/N-section
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Option:UCRL#
Traps enable precision $\beta$-decay spectroscopy

Traps have favorable properties:
- radioactive nuclei suspended in vacuum
- activity localized (<1mm$^3$) in a well-defined geometry
- nuclei nearly at rest

Provide way to study difficult-to-measure particles through conservation of momentum
Measurement of nuclear recoil and $\beta$ allow opportunity to reconstruct $\nu$ energy/momentum event-by-event

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

Recoiling daughter nucleus following $\beta$ 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!
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
- ≤10⁻⁵ torr He buffer gas cooling
- ion energy <0.1 eV
- storage times > 30 sec
- LN₂ 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
1st experiment: $^8\text{Li}$ $\beta$-decay angular correlation

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

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

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

$^8\text{Be}$ recoil (up to 12 keV) determined from $\alpha$ break-up
- energy difference up to $\pm 400$ keV
- angle deviation from $180^0$ by up to $7^0$

momentum/energy of $\alpha$s (+ $\beta$ direction) measured from double-sided silicon-strip detectors (DSSSD) $\rightarrow$ decay fully determined

Add plastic scintillator for $\beta$ energy measurement $\rightarrow$ decay overconstrained
\(^8\text{Li} \beta \) decay results

DSSDs used to observe the kinematic shifts – \( E_\alpha \) resolution of 50 keV and angular resolution of \(<2^0\) reveal nuclear recoil and \( \nu \) energy/momentum.

Preliminary results ~20k \( \beta-\alpha-\alpha \) coincidences

Gamow-Teller decay \( \rightarrow \) only axial vector or tensor contribute

\[
\begin{align*}
\beta & \quad \alpha_1 \\
\alpha_2 & \quad \beta \\
\end{align*}
\]

\[
\begin{align*}
\text{Counts} & \quad \text{Counts} \\
E_{\alpha_1} - E_{\alpha_2} (\text{MeV}) & \quad E_{\alpha_1} - E_{\alpha_2} (\text{MeV}) \\
\text{axial vector} & \quad \text{axial vector} \\
tensor & \quad tensor \\
data & \quad data
\end{align*}
\]
Apply these precision approaches to $\beta$-delayed neutron spectroscopy

$\beta$-delayed neutron emission

Identify neutron emission from large nuclear recoil

Accessible radioactive-decay half-lives are ~50 ms (transport and cooling times) to >100 sec (limited by trap storage time) $\rightarrow$ nice overlap with $\beta$-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?

- \( P_n \) 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 \( \rightarrow \) 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 \((n,\gamma)\) reactions
- Level densities and decay modes \((n \text{ vs. } \gamma \text{ emission})\) 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$^+$ + $\beta^-$ + $\nu$

$^{136}$Xe + n

$\Delta E$-$E$ plastic scintillator: $\Omega_\beta = 3%$

MCP ion detector: $\Omega_{ion} = 3%$
137I delayed-neutron decay

Energy spectrum → time-of-flight spectrum

Known Neutron Energy Spectrum

Expected Recoil-Ion TOF Spectrum

K.-L. Kratz et al., Nucl. Phys. A317, 335 (1979)
Data collected with $^{137}$I$^+$ beam of 30 ions/sec

$^{137}$I $\beta$ decay in the trap ($P_n$)

$^{137}$I $\beta$ decay in the trap (\(P\))

$^{136}$Xe ions following $\beta$-delayed neutron emission

$^{137}$Xe ions following $\beta$-delayed neutron emission (+ $\gamma$ emission)

Expected Recoil-Ion TOF Spectrum

Determine $P_n$, an additional way: by comparing fast, neutron-emission ions to slower $\beta-\gamma$ recoil ions

Counts

Time of flight (\(\mu\)s)
From Demonstration to CARIBU

Proof-of-principle...

Detector array $\Omega_\beta$, $\Omega_{\text{ion}}$ each 3%

...at CARIBU

Increase both $\Omega_\beta$, $\Omega_{\text{ion}}$ to 10-20% with optimized detector array
→ coinc. efficiency: $\times 10^{-40}$

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: $4 \times 10^6$ 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)

There is uncharted territory and significant room for improvement!

Yield of >1 ion/s delivered to low-energy experiments at CARIBU

β-delayed neutron emission energetically allowed

Nuclides where $P_n$ measurement precision < 10%
How Ions are Trapped in a Paul (RFQ) Trap

Confinement in Axial Direction

Ion Energy

cooling

ions cooled using helium buffer gas

electrostatic potential

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

Confinement in Radial Direction

inhomogeneous RF electric field

Stability requirements:

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