Decay Spectroscopy of $^{128-131}$Cd

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Introduction
Introduction
Introduction - Neutron-rich Cd

- **Nuclear Structure**
  - Evolution of shell structure towards $^{132}$Sn
  - Test of current models far from stability

- **$r$-process**
  - Abundance peak at $A \approx 130$
  - Half-lives of $^{128-130}\text{Cd}$ from this campaign published:
    R. Dunlop *et al.*, PRC 93, 062801(R) (2016)

$r$-process abundance = measured solar – calculated $s$-process
Effect on $r$-process abundance

- In different scenarios, this region is consistently expected to have high impact.
- Importance of accurate half-life measurement in high-sensitivity regions.
  - $\gamma$-ray spectroscopy as a tool for half-life measurement.
- Decay spectroscopy provides information on nuclear structure to be included in the calculation in the future, e.g., $\beta$-decaying isomers.

![Graph showing average sensitivity measures for $\beta$-decay sensitivity studies in three example astrophysical scenarios.](Mumpower et al. AIP Advances 4, 041009)
Detectors

$^{129}\text{Cd}$

$T_{1/2}(3/2^+) = 157(8)\text{ ms}$

$T_{1/2}(11/2^-) = 147(3)\text{ ms}$

Abundance: 13.7%

$^{129}\text{In}$

$\gamma$-rays

$\beta$-tagging

SCEPTAR
SCintillating Electron-Positron Tagging ARray

A.B. Garnsworthy et al., NIM A 918, 9 (2019).
IG-LIS: Ion Guide Laser Ion Source

- Element selective ionization
  - Suppress surface-ionized species (e.g. Cs, In)
- Laser on/ blocked spectra to identify transitions

H. Heggen. ISAC Operators Talk. Feb 6, 2014
\[129^\text{Cd} \text{ Decay Spectroscopy}\]

- \(~150\) pps for \(~13\)h
- Populates levels in \(^{129}\text{In}\)
- 30 new transitions & 5 new levels established
- Confirm & expand previous results
  [Taprogge \textit{et al.} PRC 91, 054324 (2015)]
 Decay: $^{129}$Cd (11/2$^-$ and 3/2$^+$) → $^{129}$In

- log $ft$ : measure of reduced transition strength

<table>
<thead>
<tr>
<th>Type</th>
<th>$\Delta J$</th>
<th>log $ft$ (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superallowed (Fermi + Gamow-Teller)</td>
<td>0</td>
<td>≈ 3</td>
</tr>
<tr>
<td>Allowed (Gamow-Teller)</td>
<td>0, 1 (not 0$^+$ → 0$^+$)</td>
<td>≈ 4 – 6</td>
</tr>
<tr>
<td>First Forbidden</td>
<td>0, 1, 2</td>
<td>≈ 6 – 9</td>
</tr>
<tr>
<td>Second Forbidden</td>
<td>2, 3</td>
<td>≈ 11 – 13</td>
</tr>
<tr>
<td>Third Forbidden</td>
<td>3, 4</td>
<td>≈ 18</td>
</tr>
</tbody>
</table>

- Expected dominant decay mode for $^{129}$Cd: Allowed GT $\nu$ $g_{7/2}$ → $\pi$ $g_{9/2}$

**Diagram:**
- **Proton $\pi$:**
  - $^{50}$Zn
  - $0g_{9/2}$
  - $1p_{3/2}$
  - $1p_{1/2}$
  - $0f_{5/2}$

- **Neutron $\nu$:**
  - $^{82}$Se
  - $0h_{11/2}$
  - $1d_{3/2}$
  - $2s_{1/2}$
  - $1d_{5/2}$
  - $0g_{7/2}$
Decay: $^{129}$Cd $\rightarrow$ $^{129}$In

States that may be populated by GT
(states with $\log ft < 5.5$)

<table>
<thead>
<tr>
<th>$E_x$[keV]</th>
<th>$J^\pi$</th>
<th>$I_B$ [-]</th>
<th>$I_B$ -(3/2$^+$)[-]</th>
<th>$I_B$ -(11/2$^-$)[-]</th>
<th>$\log ft^{\text{lit}}$</th>
<th>$\log ft$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3151</td>
<td>(13/2$^-$)</td>
<td>21.7(7)</td>
<td>36(11)</td>
<td>4.2(1)</td>
<td>4.43(13)</td>
<td></td>
</tr>
<tr>
<td>3184</td>
<td>(5/2$^+$)</td>
<td>9.2(4)</td>
<td>22(10)</td>
<td>4.5(1)</td>
<td>4.74(19)</td>
<td></td>
</tr>
<tr>
<td>3347</td>
<td>(5/2$^+$)</td>
<td>5.9(2)</td>
<td>14.5(64)</td>
<td>4.7(1)</td>
<td>4.88(18)</td>
<td></td>
</tr>
<tr>
<td>3701</td>
<td>3.6(2)</td>
<td>8.9(40)</td>
<td>5.3(2)</td>
<td>5.0(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3888</td>
<td>1.5(1)</td>
<td>3.8(17)</td>
<td>5.4(2)</td>
<td>5.3(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3913</td>
<td>1.6(1)</td>
<td>2.7(8)</td>
<td>5.4(2)</td>
<td>5.31(14)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3966</td>
<td>1.9(1)</td>
<td>3.2(10)</td>
<td>5.1(1)</td>
<td>5.22(14)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3971</td>
<td>1.5(1)</td>
<td>3.8(17)</td>
<td></td>
<td>5.29(20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4082</td>
<td>2.5(1)</td>
<td>6.3(28)</td>
<td></td>
<td>5.05(22)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4118</td>
<td>1.2(1)</td>
<td>3.0(13)</td>
<td>5.3(2)</td>
<td>5.34(21)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Distribution of log $ft$ values for neutron-rich Odd A In & Cd isotopes taken from ENSDF

Literature value from J. Taprogge et al., PRC 91, 054324 (2015)

Potential cut off for allowed GT
Decay: $^{129}\text{Cd} \rightarrow ^{129}\text{In}$

- Comparison with the theoretical prediction:
  Gamow-Teller strength $B(\text{GT})$

\[ B(\text{GT}) = K \left( \frac{g_v}{g_A} \right)^2 \frac{1}{f T_{1/2}} \]

\[ K = 6143.6(17), \quad g_A/g_v = -1.270(3) \]

- Calculation predicts GT feeding at the observed levels with $\log ft < 5.5$

- If the decay is allowed GT, spin & parity of the state can be narrowed down:
  $11/2^- \rightarrow 13/2^-, 11/2^-, 9/2^-$
  $3/2^+ \rightarrow 5/2^+, 3/2^+, 1/2^+$

Figure courtesy of H. Grawe
Comparison with Shell-Model

- Shell-Model calculation can be tested against experimental results
- Model space: $^{129}$In = $^{132}$Sn core + 1 proton hole + 2 neutron holes

Proton $\pi$

- $50$ (50)
- $10$:
  - $0g_{9/2}$
- $2$:
  - $1p_{1/2}$
- $6$:
  - $0f_{5/2}$
- $4$:
  - $1p_{3/2}$

Neutron $\nu$

- $82$ (82)
- $12$:
  - $0h_{11/2}$
- $4$:
  - $1d_{3/2}$
- $2$:
  - $2s_{1/2}$
- $6$:
  - $1d_{5/2}$
- $8$:
  - $0g_{7/2}$

Single-particle orbitals
Energy adjusted to the $^{132}$Sn region
Comparison with Shell-Model

- Shell-Model calculation can be tested against experimental results.
Comparison with Shell-Model

- “NA-14” interaction seems to reproduce experimental results well in this model space, compared to “jj45” interaction, although both are derived from the same nucleon-nucleon interaction CD-Bonn.
Comparison with Shell-Model

- “NA-14” interaction seems to reproduces experimental results well in this model space, compared to “jj45” interaction
- Some experimental information still missing: e.g. ground state $J^\pi$ in $^{129}$Cd

Ch. Lorenz et al. PRC 99, 044310 (2019)
Neutron-rich Cd isotopes summary

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Data collection</th>
<th>Results summary</th>
<th>Interesting findings</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{128}$Cd</td>
<td>~1000 pps for 6.5 hours</td>
<td>32 new transitions &amp; 11 new states</td>
<td>Longer 248 keV isomer half-life than previous report</td>
<td>Paper in preparation</td>
</tr>
<tr>
<td>$^{129}$Cd</td>
<td>~150 pps for 13 hours</td>
<td>30 new transitions &amp; 5 new states</td>
<td>New candidate levels fed by allowed-GT</td>
<td>Paper in preparation</td>
</tr>
<tr>
<td>$^{130}$Cd</td>
<td>15-30 pps for 38 hours</td>
<td>Previous transitions &amp; levels confirmed</td>
<td>$\gamma$-ray intensities inconsistent with previous results</td>
<td>Analysis underway</td>
</tr>
<tr>
<td>$^{131}$Cd</td>
<td>0.7 pps for 32 hours</td>
<td>21 of 23 previous transitions confirmed</td>
<td>$\gamma$-ray transition placements inconsistent with previous results</td>
<td>Analysis underway</td>
</tr>
</tbody>
</table>

$^{129}$Cd, Y. Saito UBC MSc Thesis (2018)
Summary

• Detailed spectroscopy of neutron-rich Cd isotopes
  ➡ Number of new transitions & levels, even for previously well studied isotopes
  ➡ GRIFFIN was able to capture low-intensity hitherto unobserved γ-rays

• Re-confirmed β-decay half-lives contributes to the reliability of r-process abundance calculation
Acknowledgement

- **TRIUMF**

- **Department of Physics, University of Guelph**

- **Instituto de Estructura de la Materia**
  A. Jungclaus

- **Department of Chemistry, Simon Fraser University**
  C. Andreoiu, F. Garcia, J. L. Pore

- **Department of Physics, Colorado School of Mines**
  S. Ilyushkin

- **Universidad Nacional Autónoma de México, Instituto de Ciencias Nucleares**
  E. Padilla-Rodal

- **Centre de Sciences Nucléaires et Sciences de la Matière**
  C. M. Petrache

- **Department of Physics, Florida State University**
  S. L. Tabor

Thank you!
Data collection with ~ 1000 pps for 6.5h
32 new transitions and 11 new states
248 keV isomer: $T_{1/2} = 56(5)$ µs
(previous: 23(2) µs)
Decay Spectroscopy of Neutron-Rich $^{128}$Cd Near the $N = 82$ Shell Closure

N. Bernier,1–4 R. Krüchmen,1,2 J. Dillmann,1,3 J.D. Holt,1 C. Andrieu,1 G.C. Ball,1 H. Bildman,5 V. Billiet,1 P. Béclard,3 M. Boven,3 C. Burbridge,2 R. Calahorra-Felch,1 J.R. Dunlop,6 J.R. Dunlop,6 L.J. Evitts,1 F. Garcia,6 A.B. Garnsworthy,1 P.E. Garrett,6 G. Hackman,1 S. Hallam,1 J. Henderson,1 S. Iyibilkin,1 A. Jungclaus,3 D. Kisil,2 J. Lassen,1,5 R. Li,1 E. MacComachie,1 A.D. MacLean,3 E. McGee,1 J. Messers,5 M. Monkadham,1 B. Oliinich,1 E. Padilla-Rodríguez,10 J. Park,2 V.P. Paetsch,1 C.M. Petzschke,1 J.L. Poire,3 A.J. Radich,3 P. Runosuelaín,3 J. Sandbol,1 J.K. Smith,3 D. Southall,1 C.E. Svensson,3 S.L. Tabor,3 A. Teigellöder,1,5 M. Tieu,1 J. Turková,1 and T. Zdarský2

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(Dated: April 27, 2010)

The neutron-rich indium isotopes ($Z = 49$) near the well-known magic numbers at $Z = 50$ and $N = 82$ are prime candidates to study the evolving shell structure observed in exotic nuclei. Additionally, the nuclear properties of nuclei around the doubly-magic $^{128}$Sn have direct implications for astrophysical models, leading to the second r-process abundance peak at $A = 130$ and the corresponding waiting-point nuclei around $N = 82$. The $\beta$-decay of $^{128}$Cd into $^{128}$Sn was investigated using the GRIFFIN spectrometer at TRIUMF. 32 new transitions and 11 new states have been observed in addition to the four previously observed excited states. These new results are compared with recent shell model calculations as well as new calculations using two-body matrix elements derived using the in-medium similarity renormalization group (IM-SRG) approach. These data highlight the unique capabilities of GRIFFIN for decay spectroscopy on the most exotic, short-lived isotopes, and the necessity to re-investigate even less exotic decay schemes for missing information.

**130Cd Decay Spectroscopy**

- Beam intensity of 15-30 pps for ~38 hours
- Confirm previously reported transitions, but discrepancies in relative γ-ray intensities observed.
- Further analysis underway

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**Figure 1:**
- -ray decay addback spectra in prompt coincidence of 130Cd observed by the GRIFFIN experiment. Peaks marked with "#" are transitions from the subsequent decay of 130In into 130Sn. The "&" label indicates the expected positron annihilation peak at 511 keV.

**Figure 2 and 3:**
- Coincident gates placed at 451 keV and 950 keV are shown in Fig. 2 and 3. Figure 2 confirms the high energy feeding transitions introduced by Jungclaus et al. of the 20 new rays proposed by Jungclaus, GRIFFIN observed 15 peaks at the same energies. Checking the energy coincidences, this work is able to confirm the rays at 229.5(2), 499(1), and 1103.08(5) keV. But, due to background in the high energy regions of the coincidence matrix, coincidences could not be confirmed for the higher energy peaks.

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A. Murphy, TRIUMF Co-op report (2018)

A. Jungclaus *et al.*, PRC 94, 024303 (2016)
**$^{131}$Cd Decay Spectroscopy**

- Beam intensity of $\sim$0.7 pps for 32 hours
- 21 of 23 transitions reported by EURICA confirmed
  

- Many of the transitions not placed due to lack of coincidence information
- 5 transitions in $^{130}$In observed (βn-decay)
- Several discrepancies between the previous publication

$\Rightarrow$ Further investigation

States populated by βn-decay of $^{131}$Cd

Effect on $r$-process abundance

- $^{130}\text{Cd} (N = 82$ shell closure) half-life

$162 (7) \text{ ms}$

$126 (4) \text{ ms}$
R. Dunlop et al., PRC 93, 062801(R) (2016).

$127 (2) \text{ ms}$

Calculated $r$-abundance using PRISM

Abundance [arb. unit]

$A$

$T_{1/2} = 162\text{ms}$

$T_{1/2} = 126\text{ms}$

$2 \times 10^{-4}$
Effect on $r$-process abundance

- $^{130}\text{Cd} (N = 82 \text{ shell closure})$ half-life
  
  162 (7) ms  

  126 (4) ms  
  *Data from this campaign
  R. Dunlop et al., PRC 93, 062801(R) (2016)

  127 (2) ms  

- Effect of $^{130}\text{Cd}$ half-life on $r$-process abundance in NS merger scenario: < 0.01\% of the largest abundance

  Contribution from single half-life is marginal

Calculated $r$-abundance using PRISM

- $T_{1/2} = 162$ ms
- $T_{1/2} = 126$ ms

Abundance [arb. unit] vs. $A$

$2 \times 10^{-4}$