Measurement Of The Heaviest Beta-Delayed Neutron-Emitters With BELEN

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Adjunct Professor (University of Victoria)

September 12, 2016
1. The r-process and $\beta$-delayed neutron emitters
2. BELEN-30@ GSI Darmstadt
3. BELEN-48@ IGISOL Jyväskylä
4. Outlook: BRIKEN project @ RIKEN
- \( S_n < Q_\beta \)
- "Delayed": emission with \( \beta \)-decay half-life of the precursor \( ^AZ \) (\( t_{1/2} = \text{ms...90 s} \))
- \( n \) branching ratio (\( P_{1n} \)-value)
\( S_{2n} < Q_\beta \)
β-delayed neutron emitters (Z=0-30)

https://github.com/ciccons/TRIUMF-BDNE-Chart
β-delayed neutron emitters (Z=31-60)

Experimentally Known Beta-Delayed Neutron Emitters

https://github.com/ciccons/TRIUMF-BDNE-Chart
β-delayed neutron emitters (Z=61-92)

Experimentally Known Beta-Delayed Neutron Emitters

P_{1n}: $^{210}$Tl

https://github.com/ciccons/TRIUMF-BDNE-Chart
### Canadian Evaluation efforts

<table>
<thead>
<tr>
<th></th>
<th>Energetically possible</th>
<th>Measured</th>
<th>Fraction measured (%)</th>
<th>Mass region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1n$</td>
<td>606</td>
<td>227</td>
<td>37.5%</td>
<td>$^8\text{He-}^{150}\text{La (}^{210}\text{Tl)}$</td>
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<tr>
<td>$\beta_2n$</td>
<td>295</td>
<td>24</td>
<td>8.1%</td>
<td>$^{11}\text{Li-}^{100}\text{Rb}$</td>
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<td>$\beta_3n$</td>
<td>104</td>
<td>6</td>
<td>5.8%</td>
<td>$^{11}\text{Li, }^{14}\text{Be, }^{17,19}\text{B, }^{23}\text{Na, }^{31}\text{Na}$</td>
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<tr>
<td>$\beta_4n$</td>
<td>60</td>
<td>1</td>
<td>1.7%</td>
<td>$^{17}\text{B}$</td>
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</tbody>
</table>

**Table 1:** Number of energetically possible vs. measured $\beta n$-emitters. (“Energetically possible” means every case where $Q_{\beta n} > 0$ keV (using masses from the AME2012).)

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**Coordinated Research Project (2013-2017)**

- Evaluation of $Z=29-84$ underway (publication in 2017)
r-process path:
depends on astrophysical site

Motivation: explore the
Terra Incognita
Why are half-lives and $\beta n$ so important?

- **Masses**: define reaction path
- **Half-lives**: define shape
- **Shell structure far off stability**: defines position of abundance peaks
- **Neutrons from $\beta$-delayed neutron emission or ($\gamma$,n)**: smoothing of abundance curve

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需实验信息，需了解Terra Incognita中的同位素的信息！

- **TERRA INCOGNITA**
- *Identified*
- *Known half-life*
- *$r$-process waiting point*
High-pressure $^3$He long counters in polyethylene moderator:

$^3$He + n → $^3$H + p + 765 keV
BELEN-30 at
GSI Darmstadt/ Germany

R. Caballero-Folch$^{1,2}$, C. Domingo-Pardo$^{3,*}$, J. Agramunt$^3$, A. Algora$^{3,4}$, F. Ameil$^5$, A. Arcones$^5$, Y. Ayyad$^6$, J. Benlliure$^6$, I.N. Borzov$^{7,8}$, M. Bowry$^9$, F. Calviño$^1$, D. Cano-Ott$^{10}$, G. Cortés$^1$, T. Davinson$^{11}$, I. Dillmann$^{2,5,12}$, A. Estrade$^{5,13}$, A. Evdokimov$^{5,12}$, T. Faestermann$^{14}$, F. Farinon$^5$, D. Galaviz$^{15}$, A.R. García$^{10}$, H. Geissel$^{5,12}$, W. Gelletly$^9$, R. Gernhäuser$^{14}$, M.B. Gómez-Hornillos$^1$, C. Guerrero$^{16,17}$, M. Heil$^5$, C. Hinke$^{14}$, R. Knöbel$^5$, I. Kojouharov$^5$, J. Kurcewicz$^5$, N. Kurz$^5$, Yu. A. Litvinov$^5$, L. Maier$^{14}$, J. Marganiec$^{18}$, T. Marketin$^{19}$, M. Marta$^{5,12}$, T. Martínez$^{10}$, G. Martínez-Pinedo$^5$, F. Montes$^{20,21}$, I. Mukha$^5$, D.R. Napoli$^{22}$, C. Nociforo$^5$, C. Paradela$^6$, S. Pietri$^5$, Zs. Podolyák$^9$, A. Prochazka$^5$, S. Rice$^9$, A. Riego$^1$, B. Rubio$^3$, H. Schaffner$^5$, Ch. Scheidenberger$^{5,12}$, K. Smith$^{5,20,21,23,24}$, E. Sokol$^{25}$, K. Steiger$^{14}$, B. Sun$^5$, J.L. Tain$^3$, M. Takechi$^5$, D. Testov$^{25,26}$, H. Weick$^5$, E. Wilson$^9$, J.S. Winfield$^5$, R. Wood$^9$, P. Woods$^{11}$ and A. Yeremin$^{25}$
Implantation detector SIMBA

Neutron detector BELEN-30
($\varepsilon_{1n} \approx 40\%$)

≈ 1 m

Neutron-rich $^{238}$U fragments

Shielding (PE + borated rubber)
Results: New half-lives

9 first $t_{1/2}$ measurements

First Measurement of Several $\beta$-Delayed Neutron Emitting Isotopes Beyond $N = 126$

R. Caballero-Folch, C. Domingo-Pardo, J. Agramont, A. Algora, F. Ameil, A. Arcones, Y. Ayyad, J. Benlliure, I. N. Borzov, M. Bowry, F. Calviño, C. Cano-Ott, G. Cortés, T. Davinson, I. Dillmann, A. Estrade,
- Different agreement before and behind shell closure:
  - New RHB+RQRPA (Marketin et al., 2015) better for N<126 proton-neutron relativistic quasiparticle phase approx. based on the Hartree-Bogoliubov model

<table>
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<th>Element</th>
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- FRDM+QRPA (Moeller et al.,

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\[ t_{1/2} \text{ overestimated} \]
Heaviest $\beta n$-emitters measured so far!

Apart of a measurement of $^{210}$Tl in 1962, the heaviest $\beta n$- emitter measured was $^{150}$La.

8 first $P_{1n}$-value measurements

Heaviest $\beta$-delayed neutron emitter measured so far.

First Measurement of Several $\beta$-Delayed Neutron Emitting Isotopes Beyond $N = 126$


September 12, 2016

Iris Dillmann - INPC Adelaide
Belen-48 at IGISOL/Finland

UPC Barcelona: R. Caballero-Folch, F. Calvino, G. Cortès, A. Riego, P. Salvador-Castiñeira

IFIC Valencia: J. Agramunt, J.L. Tain, A. Algora, V. Guadilla, A. Montaner-Pizá, S. Orrigo, B. Rubio

TRIUMF Vancouver: I. Dillmann

GSI Darmstadt: M. Marta

CIEMAT Madrid: E. Mendoza

U of Surrey: B. Gelletly

U of Brighton: Ch. Nobs

U of Istanbul: E. Ganioglu

U of Helsinki: J. Äysto

GSI experiments:
\[ \varepsilon_{1n}(\text{BELEN-30}) = 40\% \]

IGISOL experiments:
Matrix 1: Hybrid
\[ \varepsilon_{1n}(\text{BELEN-48}) = 40\% \]

Matrix 2: High efficiency
\[ \varepsilon_{1n}(\text{BELEN-48}) = 60\% \]
\[ \varepsilon_{2n}(\text{BELEN-48}) = 36\% \]
• IAEA top priority list for remeasurement of $P_{1n}$ values for reactor physics:

The result of this study showed that the delayed neutron fraction was overestimated, and that top priority nuclides for new measurements are as follows:

1st priority: $^{86}$Ge, $^{85}$As, $^{91}$Br, $^{93}$Rb, $^{98m,98}$Y, $^{99}$Y, $^{135}$Sb, $^{139}$I

2nd priority: $^{88}$As, $^{96}$Rb, $^{105,106}$Nb, $^{137}$Sb, $^{136}$Te, $^{140}$I, $^{143,144}$Cs

I. Dillmann et al., IAEA(NDS)-0643 (2014)

• 2 weeks beamtime: measured 12 isotopes with high accuracy:

1 week: $^{95}$Rb, $^{98,98m}$Y, $^{99}$Y
$^{136,138}$Te, $^{135,137}$Sb, $^{137,138,139,140}$I

1 week $^{136}$Sb

I have measured $^{136}$Sb, the heaviest $\beta$2n emitter so far!
ALTO measurement not conclusive: \( P_{2n} \approx 1.4\% \) ?

Problem: isobaric contaminations

\[ 2n/1n = 3 \times 10^{-4} \]

Probably the observed two neutron activity belong to \( ^{136}\text{Sb} \), then

\[ P_{\beta-2n}^{^{136}\text{Sb}} \approx (1.4 \pm 0.2)\% \]

Predictions: \( P_{\beta-2n}^{^{136}\text{Sb}} = (10.6 - 0.28) \%^{*} \)

\( D.\text{Testov, ESP-RUS conference (2011)} \)
$^{136}\text{Sb} \beta 1n$ correlation
(6 days of beamtime)

$^{136}\text{Sb} \beta$-1n correlation

$\beta$ – neutron correlation

7907 net events

Roger Caballero et al.,
presented at Zakopane (2016) and
Nuclear Data Conf. (Bruges 2016)

P$_{1n}$ results for $\beta 1n$ correlation of measured isotopes

This work

Previous exp.

FRDM+QRPA

Higher P$_{1n}$ than previously measured
After 6 days of beamtime, $\beta^2\text{n}$-events confirmed!

Preliminary result:
$$P_{2n} > 0.138\%$$

Heaviest $\beta^2\text{n}$-emitter so far!

Roger Caballero et al., presented at Zakopane (2016) and Nuclear Data Conf. (Bruges 2016)
The BRIKEN project (>2016)

“Beta-delayed neutron measurements at RIKEN for nuclear structure, astrophysics, and applications”
• >148 $^3$He counters from Germany, Japan, Russia, Spain, USA
• 2 clovers (ORNL)
• Implantation detector AIDA (Edinburg, Daresbury)

$\varepsilon(1n) = 69\%$
$\varepsilon(2n) \approx 50\%$

More info at https://www.wiki.ed.ac.uk/display/BRIKEN/
Setup: July 2016
Commissioning: Nov. 2016
$^{76}$Co-$^{92}$Se (ca. 30 isotopes)

$^{93}$Se-$^{121}$Tc: 90 new $P_{1n}$, 20 new $P_{2n}$, 23 new half-lives

$^{121}$Rh-$^{152}$Ba (ca. 33 isotopes)

More to follow soon!

<table>
<thead>
<tr>
<th>Title</th>
<th>Spokepersons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of $\beta$-delayed neutron emission probabilities relevant to the $A = 130$ r-process abundance peak</td>
<td>A.V. Estradé, G.Lorusso, F.Montes</td>
</tr>
<tr>
<td>Measurements of new $\beta$-delayed neutron emission properties around doubly-magic $^{78}$Ni</td>
<td>K.P. Rykaczewski, J.L. Tain, R.K. Grzywacz, I. Dillmann</td>
</tr>
<tr>
<td>Decay properties of r-process nuclei in deformed region around $A = 100 \sim 125$</td>
<td>S. Nishimura, A. Algora</td>
</tr>
</tbody>
</table>
• Recent boost of $\beta n$-program
  - Present focus on isotopes around $N=50-82$
  - Access to $N=126$: up to now only at GSI (-\rightarrow FAIR, FRIB) $\Rightarrow$ soon also at RIKEN

• Huge program for measurements of neutron-rich key-isotopes planned in next few years
• Extrapolation to r-process regions require reliable theoretical models
Thank you!
Merci!
r-process abundances

\[ N_r = N_\odot - N_s - N_p \]

measured

negligible

well-known

Connection between nuclear structure far off stability and observed abundances

\[ N=50 \]

A≈100
Peak

N=82

Rare Earth Peak

N=126
List of isotopes implanted into SIMBA

Nuclei implants

Number of implants per nuclei

PT  AU  HG  TL  PB  BI

200-205 Pt  203-209 Au  206-213 Hg  209-216 TI  212-219 Pb  215-222 Bi

September 12, 2016
Iris Dillmann - INPC Adelaide