Overview on β-delayed neutron emission measurements made with the BELEN detector at ISOL and In-Flight facilities and future perspective

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Introduction

• BELEN is one of the key detectors, that will be used to measure beta-delayed neutrons from the decay of exotic nuclei at the future international facility FAIR within the DESPEC Project of NuSTAR.

• The facility will start to be operational in 2017-2018.

• However, we have built already a prototype, which is fully operational (slightly lower efficiency than the final version).

• This detector has been already successfully used for several experiments both at ISOL and in-Flight facilities (a summary of these measurements is presented in this talk).

• Until FAIR becomes operational, we plan to continue with beta-delayed measurements at GSI-FRS, JYFL and RIKEN.
β-delayed neutron emission probability

$P_n$: Moeller et al PRC67(2003)055802

- Motivation
- Experiment
- Data analysis
- Preliminary results
- Perspective
Beta dELayEd Neutron detector - BELEN

- Motivation
- Experiment
- Data analysis
- Preliminary results
- Perspective

\[ P_n \]

\[ \beta\text{-delayed neutron emission probability} \]

\[ P_n: \text{Moeller et al PRC67(2003)055802} \]

\[ N>50 \text{ with BELEN at Jyvaskylä (Finland)} \]
Motivation (I): microscopic summation calculations of $\bar{V}_d$

- The delayed neutron fraction $\beta_{\text{eff}}$ is a key parameter in the control of reactor power.
- Microscopic summation calculations lack still the accuracy of the Keepin six-group formula.
- Reason: inaccuracies in fission yields $Y$ and delayed neutron emission probabilities $P_n$.

\[ \bar{V}_d = \sum_i Y_i \cdot P_n^i \]

Can be used to identify $P_n$ values that should be re-measured with improved accuracy.

Number of delayed neutrons per fission

\[ Y_i \cdot P_n^i \]

$Y_i$ : ENDF/B-VII.0

$P_n$ : Pfeiffer et al., PNE41(2002)39
Motivation (II): nuclear structure for Z>28, N>50

- Role of FF transitions

Moeller et al., PRC67(03)55802
Moeller et al., ADNDT66(97)131

Borzov, PRC71(05)65801
Motivation (Ill): r-process close to the 1st abundance peak

- Beta delayed neutron emission alters the final abundances by shifting the decay path toward lower masses and providing neutrons reactivating the r-process after freeze-out.
- Disentangling weak s-process, cold and hot r-process.
Choice of nuclei for the experiment with BELEN around N=50

<table>
<thead>
<tr>
<th>87Br</th>
<th>88Br</th>
<th>89Br</th>
<th>90Br</th>
<th>91Br</th>
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<td>82Ge</td>
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<td>86Ge</td>
</tr>
</tbody>
</table>

Contribution to $\nu_d$ for thermal fission of $^{235}U$:
- $^{91}\text{Br}$: $\sim3\%$
- $^{85,86}\text{As, 85Ge}$: $\sim7\%$

RAS: Rudstrom et al. ADNDT53 (93)
PKM: Pfeiffer et al. PNE41(02)39
BELEN-20 experiment at JYFL (Jyväskylä)

JYFL Cyclotron Laboratory @ Univ. Jyväskylä

**IGISOL separator + ion guide source:** refractory elements

\[ p(25\text{MeV}) + \text{Th} \rightarrow \text{FF} \]

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rate (s(^{-1}))</th>
<th>Isotope</th>
<th>Rate (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{88}\text{Br})</td>
<td>1450</td>
<td>(^{85}\text{Ge})</td>
<td>6</td>
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<tr>
<td>(^{94}\text{Rb})</td>
<td>1030</td>
<td>(^{85}\text{As})</td>
<td>175</td>
</tr>
<tr>
<td>(^{95}\text{Rb})</td>
<td>760</td>
<td>(^{86}\text{As})</td>
<td>30</td>
</tr>
<tr>
<td>(^{137}\text{I})</td>
<td>100</td>
<td>(^{91}\text{Br})</td>
<td>80</td>
</tr>
</tbody>
</table>

**JYFLTRAP** Penning trap: isotopic purification
BELEN-20 experiment at JYFL (Jyvaskylä)

20 Ø2.5cm×60cm 3He tubes @20atm

Efficiency up to 48%

R_{hole} = 5.5cm
8 tubes at 9.5cm
12 tubes at 14.5cm

n-background: 0.9 cps

Self triggered DACQ:
-Time-energy pairs for every neutron or β
-Clean noise separation
-Minimum dead time:<0.5%

GasificTL:
Efficiency up to 48%
**Experiment: analysis**

\[
P_n = \frac{\varepsilon_\beta N_n}{\varepsilon_n N_\beta}
\]

- Disentangle contributions fitting with solution of Bateman equations
- All parameters fixed except production

**Problem:**
- Fit was not good for $^{88,91}\text{Br}$, $^{137}\text{I}$
- Their daughters are noble gases: escape from implantation tape

**Solution:**
- Add a loss term to Bateman equations
Experiment: calibration

- Accurate
- Weak dependence of efficiency on neutron energy distribution (verified also by MC simulations)

\[ \frac{\varepsilon_\beta}{\varepsilon_n} = P_n \frac{N_\beta}{N_n} \]

Preliminary new result for $^{137}\text{I}$:

\[ P_n = 7.75(12)% \]

Rudstam et al., ADNDT 53 (93) 1

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$P_n$</th>
<th>$\varepsilon_\beta$</th>
<th>$\varepsilon_n$</th>
<th>Source</th>
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<td>$^{137}\text{I}$</td>
<td>24</td>
<td>3.0(5)</td>
<td>3.0(5)</td>
<td>$n - \beta$</td>
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<td></td>
<td>4.7(10)</td>
<td>4.7(10)</td>
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<td>24.13(12)</td>
<td>7.46(30)</td>
<td>7.46(30)</td>
<td>This work</td>
</tr>
</tbody>
</table>

# $P_n$ values taken from Abriola et al. IAEA-INDC(NDS)-0599
Preliminary results:

$^91\text{Br}$

$P_n = 29.5(5)\%$

$^86\text{As}$

$P_n = 35.5(6)\%$
Preliminary results:

$^{85}\text{As}$

Preliminary uncertainties include only statistical- and efficiency-calibration uncertainties.
Results:

- Low statistics, daughter strong delayed neutron emitter
- Graph of log-likelihood of simultaneous beta and neutron fit for a fixed $P_n$ with production as parameter: value and uncertainty

$P_n = 17.2(18)\%$
Results: comparison with previous data

<table>
<thead>
<tr>
<th>Pn (%)</th>
<th>RAS</th>
<th>PKM</th>
<th>this work</th>
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<td>85As</td>
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<tr>
<td>85Ge</td>
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<td>17.2(18)</td>
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RAS: Rudstam et al., ADNDT 53 (1993) 1

<table>
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<td>59.3(25)</td>
<td></td>
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</tbody>
</table>

This work
Results: comparison with theoretical estimates

FRDM-QRPA: Moeller et al., PRC67(03)55802
DF3-cQRPA: Borzov, PRC71(05)65801, NPA777(06)445

...and empirical formulas

Kratz-Hermann formula:

\[ P_n = a \left( \frac{Q_\beta - S_n}{Q_\beta - C} \right)^b \]

McCutchan et al PRC86(12):

\[ \frac{P_n}{T_{1/2}} = d \left( Q_\beta - S_n \right)^b \]
Conclusion & Perspective of BELEN@JYFL:

• New accurate $P_n$ measurements have been performed for $(^{137}I), ^{91}Br, ^{86,85}As, ^{68}Ge$ which had relatively large uncertainties are important contributors to the delayed neutron fraction in reactors, to the first abundance peak of the r-process and sensitive to the nuclear structure for $Z>28, N>50$

• New experiments at JYFL in 2013 on one (J.L. Tain et al) and two-neutron emitters (I. Dillmann et al.)

• IAEA-CRP has been launched on beta-delayed neutron emission

http://www-nds.iaea.org/beta-delayed-neutron/
Beta dELayEd Neutron detector - BELEN

• Motivation
• Experiment
• Data analysis
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β-delayed neutron emission probability

$P_n$: Moeller et al. PRC67(2003)055802

N=82 with BELEN at GSI-FRS (Germany)
BELEN@S323 Experiment: GSI FRS (F. Montes et al.)

Identified nuclei:

- $^{129-131}$In
- $^{127-131}$Cd
- $^{124-129}$Ag
- $^{121-128}$Pd

Analysis is in progress, part of the PhD Thesis of K. Smith (NSCL-MSU).
Beta dELayEd Neutron detector - BELEN

- Motivation
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Preliminary results:
- Nuclei in the Cosmos XII, Cairns, Australia, 2012
- Nuclear Data for Science and Technology, NY, USA, 2013
State of the art SNe simulations (e.g. A. Arcones, et al.) do NOT yield the termo-conditions (entropy) for the reproduction of the third r-process peak → SNe are not the r-process environment?
Decay measurements around the third r-process peak

- Explosive nucleosynthesis and the r-process around the third abundance peak

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State of the art SNe simulations (e.g. A. Arcones, et al.) do NOT yield the thermodynamic conditions (entropy) for the reproduction of the third r-process peak → SNe are not the r-process environment?
Large intensity ($2 \times 10^9$ ions/pulse) & high-energy (1 GeV/u) for $^{238}$U beams

The detection system is based on a stack of SSSD- and DSSD-detectors for measuring ion implants and beta-decays (SIMBA). Implants-region was surrounded by the 4m neutron detector BELEN.
Isomer tagging was used for Z identification and two centred settings on $^{211}\text{Hg}$ and $^{215}\text{Tl}$ were measured during 4.5 days. The implantation area was optimized for Hg and Tl region where good resolution has been obtained.

This identification information should allow us to estimate fragmentation cross-sections for $^{238}\text{U}$ at 1 GeV/u.

The results will be compared versus the CSs reported in *PRC82 (2010), H.Alvarez-Pol, et al.*, which represent the only experimental information available so far.

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The Beta dELayEd Neutron (BELEN) detector, based in $^3\text{He}$ counters embedded in a polyethylene matrix, located around Silicon IMplantation Beta Absorber (SIMBA).
Experiment with BELEN @ RIB of GSI, N>126

Identified and Implanted Nuclei

31161 total implants

Region of Interest

208-211\text{Hg}

211-215\text{Tl}

214-218\text{Pb}

Implants on the high segmented layers of SIMBA detector DSSD area.
Analysis method to determine half-lives: $^{212}\text{TI}$

As first approach, we apply the method developed at USC for long half-lives in complex background environments (NIM-A-589 (2008), T.Kurtukian).

Basically, the method consists of comparing implant-beta time-correlation spectra (actually the ratios forward/backward) for several values of the unknown quantities: beta efficiencies and half-lives, for certain (known) rates of implantation and beta-decay events.

Ref. Value from G.Benzoni et al. PLB 715 (2012) $t_{1/2} = 96\, (^{+42}_{-38})\,$s

**RED:** experimental ratios forward-backward

**BLUE:** simulated ratios for different half-lives and silicon efficiencies

Experiment with BELEN @ RIB of GSI, N>126
Experiment with BELEN  @ RIB of GSI, N>126

Analysis method to determine half lives: $^{211}\text{Tl}$

Ref. Value from G.Benzoni et al. PLB 715 (2012)

$$t_{1/2} = 88 \pm (46^{+29}_{-29}) \text{ s}$$

RED: experimental ratios
BLUE: simulated ratios
Experiment with BELEN @ RIB of GSI, N>126

Analysis method to determine half lives: $^{211}\text{Tl}$

Ref. Value from G.Benzoni et al. PLB 715 (2012)  
$t_{1/2} = 88^{(+46)}_{(-29)}\text{ s}$

$t_{1/2} = 50^{(+70)}_{(-40)}\text{ s}$

Experiment with BELEN @ RIB of GSI, N>126
Experiment with BELEN @ RIB of GSI, N>126

Implied in ROI with enough statistics:
- $^{208-211}$Hg, $^{211-215}$Tl, $^{214-218}$Pb
- Other implants of $^{212-213}$Hg, $^{216}$Tl, $^{219}$Pb, and $^{202-204}$Pt, $^{203-208}$Au, $^{217-221}$Bi

Analysis is in progress, part of the PhD Thesis of R. Caballero-Folch. (UPC-BCN)
Future Plans, BRIKEN Campaign: BELEN @ RIKEN

- Until FAIR becomes operational (2017-2018), we plan to keep measuring with BELEN at GSI-FRS, at JYFL, and at RIKEN.
- A 1st Workshop on Opportunities with BELEN at RIKEN (BRIKEN) was made in Valencia (Spain), on 17-18/XII/2012.
- The plan is to combine BELEN with the Advanced Implantation Detector Array (AIDA) developed by Edinburgh – Liverpool – STFC DL & RAL.

- 12x 8cm x 8cm DSSSDs
- 24x AIDA FEE cards
- 3072 channels

- Already many interesting physics cases discussed at the 1st BRIKEN workshop:
  - Combined measurement of masses, half-lives and neutron branchings (Univ. of Edinburgh, UK)
  - Measurement of multiple neutron emitters around N=50 and N=82 (GSI, Germany)
  - Neutron emission by fission fragments for improved v_d calculations for reactor technologies and safety (CIEMAT, Spain).
  - Nuclear astrophysics: understanding the origin of the REP (A=135) (IFIC, Spain)
  - Nuclear astrophysics: 1st for the 2nd r-process abundance peak (NSCL-MSU, USA).

- Many more proposals are coming for the BRIKEN campaign... and more new ideas are welcome!