First measurements with a beta delayed neutron detector at the JYFL Penning trap

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SUMMARY

✓ Motivation: Beta Delayed Neutron Emission
✓ Detector Layout
✓ Simulations
✓ Experiment at JYFL
Beta decay of neutron rich nuclei

- For many neutron-rich nuclei $S_n$ lies below $Q_\beta$
- If the decay proceeds to states above $S_n$, neutron emission dominates over $\gamma$-ray de-excitation

\[ \beta^- : \ n \rightarrow p + e^- + \bar{\nu} \]

\[ {}_{\text{Z}}^{\text{A}}X \rightarrow {}_{\text{Z+1}}^{\text{A}}Y + e^- + \bar{\nu} \]

- Far enough from the stability, β-delayed neutron emission becomes the dominant decay process

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\[ \nu \nu \beta \sim \nu \nu \beta \rightarrow {}_{\text{Z}}^{\text{A}}X \rightarrow {}_{\text{Z+1}}^{\text{A}}Y + e^- + \bar{\nu} \]
Nuclear power safety:
Some fission products undergo Beta Delayed Neutron Emission which is essential to control the reaction.

Nuclear Energy Agency (NEA) highlights the importance of experimental measurements and data evaluation of delayed neutron emission in its working group 6 “Delayed neutron data” [WPEC-SG6].

Rapid neutron-capture process of stellar nucleosynthesis:
Stellar abundances: delayed neutron emission probability ($P_n$) of r-process isobaric nuclei define the decay path towards stability during freeze-out, and provide a source of late time neutrons.

Nuclear Structure:
Additionally the measured half-lives ($T_{1/2}$) and $\beta$-delayed neutron-emission probabilities ($P_n$) can be used as first probes of the structure of the $\beta$-decay daughter nuclei in this mass region.
Mechanisms of detecting neutrons are based on indirect methods. The reaction $^3\text{He} + n \rightarrow ^3\text{H} + ^1\text{H} + 765 \text{ keV}$ can be observed.

The idea is to detect the beta decay and the neutron detection and correlate both. Moderation time in the polyethylene is very long ~ hundreds of $\mu$s. It needs to be taken into account in the simulation since it requires a long correlation time/trigger window between the beta decay and the neutron detection.
Detector consists of two crowns of (8+12) $^3$He detectors embedded in a polyethylene matrix with total dimensions 90x90x80 cm$^3$ and a r=5 cm beam hole.

<table>
<thead>
<tr>
<th>Counter</th>
<th>Gas</th>
<th>Maximum length (mm)</th>
<th>Effective length (mm)</th>
<th>Maximum diameter (mm)</th>
<th>Effective diameter (mm)</th>
<th>Gas pressure (torr)</th>
<th>Cathode material</th>
</tr>
</thead>
<tbody>
<tr>
<td>2527 LND inc</td>
<td>$^3$He</td>
<td>686.84</td>
<td>604.8</td>
<td>25.4</td>
<td>24.38</td>
<td>15200</td>
<td>Stainless Steel</td>
</tr>
</tbody>
</table>
Energy deposition and time correlation in GEANT4

Neutron detection reaction: \(^{3}\text{He} + n \rightarrow ^{3}\text{H} + p + 764\) keV

Energy deposited in the \(^{3}\text{He}\) gas in the first and second crown.

Particles other than proton and tritons have a very small contribution compared to the neutron detection events.
Correlation time from the emission of the neutron (β decay of precursor) and neutron detection in the $^3$He gas. This time is of the order of 100s µs and it is due to the moderation process in the polyethylene.

A different slope can be appreciated for the two crowns.
SIMULATION VALIDATION AT UPC WITH $^{252}$CF

$^{252}$Cf source
700n/s

$^3$He counters + Mesytec electronics

Nal detector for prompt fission $\gamma$. CIEMAT

IFIC. Triggerless DAQ to allow us to change the beta-neutron correlation time offline

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**Simulation Validation with $^{252}$Cf Source in UPC Lab**

**Wall Effect**
- 190 keV
- 575 keV
- 765 keV

<table>
<thead>
<tr>
<th></th>
<th>Exp %</th>
<th>MCNPX %</th>
<th>GEANT4 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner crown</td>
<td>21.3 ± 3.2</td>
<td>21.3 ± 1.5</td>
<td>25.0 ± 1.6</td>
</tr>
<tr>
<td>Outer crown</td>
<td>4.9 ± 0.7</td>
<td>6.0 ± 0.8</td>
<td>5.4 ± 0.7</td>
</tr>
<tr>
<td>Tot</td>
<td>26.1 ± 3.9</td>
<td>27.3 ± 1.7</td>
<td>30.4 ± 1.7</td>
</tr>
</tbody>
</table>

Experimental uncertainty due to source activity uncertainty (15%)
First experiment with BELEN-20 at JYFL: IGISOL+JYFLTRAP

Measurement of $^{88}\text{Br}$, $^{94,95}\text{Rb}$, $^{138}\text{I}$, $^{138}\text{Te}$

JYFLTRAP = Isotopically pure beams!

November 2009

<table>
<thead>
<tr>
<th>Delayed Neutron Precursor</th>
<th>Half life</th>
<th>$Q_\beta$</th>
<th>$\beta$-n branching</th>
<th>Daughter Nucleus</th>
<th>Half life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{88}_{35}\text{Br}$</td>
<td>16.3 s</td>
<td>8.96</td>
<td>6.58</td>
<td>$^{88}_{36}\text{Kr}$</td>
<td>2.84 h</td>
</tr>
<tr>
<td>$^{94}_{37}\text{Rb}$</td>
<td>2.70 s</td>
<td>10.31</td>
<td>10.4</td>
<td>$^{94}_{38}\text{Sr}$</td>
<td>75.3 s</td>
</tr>
<tr>
<td>$^{95}_{37}\text{Rb}$</td>
<td>377.5 ms</td>
<td>9.29</td>
<td>8.73</td>
<td>$^{95}_{38}\text{Sr}$</td>
<td>23.9 s</td>
</tr>
<tr>
<td>$^{138}_{53}\text{I}$</td>
<td>6.23</td>
<td>7.82</td>
<td>5.56</td>
<td>$^{138}_{54}\text{Xe}$</td>
<td>14.1 m</td>
</tr>
</tbody>
</table>

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Decay properties of $\beta$ delayed neutron emitters $^{88}\text{Br}$, $^{94}\text{Rb}$, $^{95}\text{Rb}, ^{138}\text{I}$

Simulation of the expected neutron detection efficiency for each neutron energy distribution. ENDF/B VII (and Greenwood [NSE 91, 305 (1985)] for $^{95}\text{Rb}$)
The expected efficiency of the detector was calculated using the energy distributions from ENDF/B VI as neutron source in the simulations. This simulation results will be compared to the experimental one, once the data analysis is finished.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>GEANT4(%)</th>
<th>MCNPX(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Unc</td>
</tr>
<tr>
<td>$^{88}$Br</td>
<td>31.7</td>
<td>1.8</td>
</tr>
<tr>
<td>$^{94}$Rb</td>
<td>32.3</td>
<td>1.8</td>
</tr>
<tr>
<td>$^{95}$Rb</td>
<td>32.2</td>
<td>1.8</td>
</tr>
<tr>
<td>$^{138}$I</td>
<td>31.5</td>
<td>1.8</td>
</tr>
</tbody>
</table>
An isotopically pure beam was obtained using the JYFLTRAP Penning trap setup at the IGISOL facility and it was implanted on a movable tape placed in the centre of the neutron detector.
Beta delayed neutron emissor precursors were implanted on a tape in the centre of the neutron detector. A Si detector was placed next to the implantation point in the tape in order to detect the beta decay and be able to correlate this signal with the one from the neutron counters.
IFIC Triggerless DACQ for neutron detector

- Experiments will be run with triggerless DACQ. Full flexibility to modify correlation time neutron emission-detection => clean data.

- New triggerless DACQ developed by IFIC Struck VME SIS3302 10MHz

- ADC signal above filter threshold (time mark) => energy filter (amplitude signal)

- Independent Time-Energy pairs for each channel.

- Data transfer to PC via the Struck SIS1100/3100 PCI/VME interface.

- The gasificTL DACQ software performs the system control, online analysis (event correlation), data visualization.
Online spectra

Counts

Neutron signal

Si signal

Beta signal

Noise

Full energy peak

Edge effect

Energy (ch)

Energy (ch)
Online spectra

Si_He3_tot

Counts

β-neutron coincidences

Random coincidences

B-n correlation time (10us)
Decay fits to Bateman equations. Ions were implanted on a tape for $3T_{1/2}$ and left decay for $7T_{1/2}$ before moving it away from the Si detector.

\[
\varepsilon_n = \frac{1}{P_n} \frac{N_{\beta n}}{N_\beta}
\]
The $P_n$ values of $^{88}\text{Br}$ and $^{95}\text{Rb}$ were used as references to calculate the efficiency of BELEN-20 since there is good agreement in their values. The average efficiency for BELEN-20 is $(27.1\pm0.8)$ %.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\varepsilon_n$</th>
<th>unc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{88}\text{Br}$</td>
<td>0.276</td>
<td>0.007</td>
</tr>
<tr>
<td>$^{95}\text{Rb}$</td>
<td>0.266</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Using the above average efficiency, the $P_n$ for $^{94}\text{Rb}$ and $^{138}\text{I}$ were calculated and they are in good agreement with values from other authors.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$P_n$ (%)</th>
<th>unc</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{94}\text{Rb}$</td>
<td>10.28</td>
<td>0.31</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>10.01</td>
<td>0.23</td>
<td>Rudstam</td>
</tr>
<tr>
<td></td>
<td>9.1</td>
<td>0.11</td>
<td>Pfeiffer</td>
</tr>
<tr>
<td>$^{138}\text{I}$</td>
<td>5.32</td>
<td>0.20</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>5.46</td>
<td>0.18</td>
<td>Rudstam</td>
</tr>
<tr>
<td></td>
<td>5.17</td>
<td>0.36</td>
<td>Pfeiffer</td>
</tr>
</tbody>
</table>
Beta Delayed Neutron detector has been designed through Monte Carlo simulations with MCNPX and GEANT4.

GEANT4 has been used to study the spectrum of the energy deposited in the $^3$He gas and the time correlation between neutron emission and detection.

This detector will be used with a Triggerless DACQ designed by IFIC group. Flexibility to modify correlation time.

First experiment at JYFL to measure beta delayed neutron emission.

Expected detector efficiencies according to neutron energy distributions have been calculated with MCNPX and GEANT4.

The results of the preliminary analysis are in good agreement with previous measurements from other authors.