Design, commissioning and validation of a moderated neutron detector at UPC

M. B. Gómez Hornillos, V. Gorlychev, G. Cortés, R. Caballero, A. Poch, C. Pretel, F. Calviño

SEN, UNIVERSIDAD POLITÉCNICA DE CATALUÑA

J.L. Taín, J. Agramunt and Gamma Spectroscopy Group
IFIC- Valencia

D. Cano, T. Martínez, and Nuclear Innovation Group
CIEMAT-Madrid

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Motivations for the construction of the detector
Simulation work and construction of the detector
detector
Detector Test
Experiment at JYFL, Finland
Study of beta delayed neutron emission

✓ What is beta decay delayed neutron emission?
✓ Why is it important?
✓ FAIR / DESPEC Collaboration, Germany.
BETA DELAYED NEUTRON EMISSION

\[ \beta^- : \quad n \rightarrow p + e^- + \nu \]

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

If \( Q_{\beta} - B_n > 0 \) \( \Rightarrow \)

Neutron emission possible
Nuclear power safety:

Some fission products undergo Beta Delayed Neutron Emission which contributes significantly to the sustainability of the reaction and the decay heat.

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].

<table>
<thead>
<tr>
<th>Group</th>
<th>Time (s)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>54.5</td>
<td>3.8%</td>
</tr>
<tr>
<td>2</td>
<td>21.8</td>
<td>21.3%</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>18.8%</td>
</tr>
<tr>
<td>4</td>
<td>2.2</td>
<td>40.7%</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>12.8%</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
<td>2.6%</td>
</tr>
</tbody>
</table>

$^{235}$U delayed neutron groups 1.7%
Rapid neutron-capture process of stellar nucleosynthesis:

For the understanding of stellar abundances in $A=110$ the 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.

J. Pereira et al. PRC 79, 035806 (2009)
FAIR FACILITY (Germany)

Most intense exotic beams worldwide => expand the limits of nuclear physics research

International facility more than 20 countries involved

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SEN, UPC, Barcelona
DESPEC (DEcay SPECTroscopy)

Study of particle emission in nuclear decay

Modular experiment, different detectors can be used together to study different aspects of decay

AIDA: Active implantation target
Ge detectors
Neutron emission probability detectors
Neutron energy detectors
Total Absorption spectrometers for beta decay
✓ Characteristics of the detector.
✓ Monte Carlo simulations.
Mechanisms of detecting neutrons are based on indirect methods

\[ ^{3}\text{He} + \text{n} \rightarrow ^{3}\text{H} + ^{1}\text{H} + 765 \text{ keV} \]

\[ ^{10}\text{B} + \text{n} \rightarrow ^{7}\text{Li}^{*} + ^{4}\text{He} + 2310 \text{ keV} \]

\[ ^{10}\text{B} + \text{n} \rightarrow ^{7}\text{Li} + ^{4}\text{He} + 2790 \text{ keV} \]

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 µs. 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.
Comparison of neutron detection reactions for $^3$He and BF$_3$
<table>
<thead>
<tr>
<th>Source energy</th>
<th>10 μs</th>
<th>50 μs</th>
<th>100 μs</th>
<th>150 μs</th>
<th>200 μs</th>
<th>No time limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 eV</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>1 keV</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>1 MeV</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td>5 MeV</td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
<td><img src="image21.png" alt="Image" /></td>
<td><img src="image22.png" alt="Image" /></td>
<td><img src="image23.png" alt="Image" /></td>
<td><img src="image24.png" alt="Image" /></td>
</tr>
<tr>
<td>10 MeV</td>
<td><img src="image25.png" alt="Image" /></td>
<td><img src="image26.png" alt="Image" /></td>
<td><img src="image27.png" alt="Image" /></td>
<td><img src="image28.png" alt="Image" /></td>
<td><img src="image29.png" alt="Image" /></td>
<td><img src="image30.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**NEUTRON FLUX IN MODERATOR BLOCK**
### STUDY OF A RING OF $^{3}$HE COUNTERS

<table>
<thead>
<tr>
<th>Counter</th>
<th>Gas</th>
<th>Max. length (cm)</th>
<th>Effect length (cm)</th>
<th>Max. diam (cm)</th>
<th>Effect diam (cm)</th>
<th>Gas pressure (torr)</th>
<th>Cathode material</th>
</tr>
</thead>
<tbody>
<tr>
<td>LND inc 2527</td>
<td>$^{3}$He</td>
<td>38.68</td>
<td>30.48</td>
<td>2.54</td>
<td>2.43</td>
<td>15200</td>
<td>Stainless steel</td>
</tr>
</tbody>
</table>

Simulation of 1MeV neutrons
Optimization of counters distribution
2nd ring of counters

Optimization of counters distribution
2nd ring of counters

Efficiency vs counter number

- Ring A=16 counters. All the rest are in ring B.
- Ring A=12 counters. All the rest are in ring B.
- Ring A=8 counters. All the rest are in ring B.
- All counters are in ring A
Ring A=12 counters, Ring B=16 counters

Efficiency vs source energy for 30, 40 and 50 cm $^3$He counters long.

- L=60 cm
- L=50 cm
- L=40 cm
- L=30 cm

$t=200\mu$s
STUDY OF GAS PRESSURE VS EFFICIENCY

Ring A=12 counters, Ring B=16 counters

efficiency vs source energy for different gas pressure

- 15200 torr
- 11400 torr
- 7800 torr
- 3800 torr

$t=200\mu s, L=30\text{cm}$
Simulation of time elapsed from neutron emission to neutron detection.

Times are of the order of hundreds of µs due to thermalisation time. Very important for experiment design.
As the correlation time between the beta detector and the He3 detector increases, more neutrons are detected, but also more background and random coincidences.
It is necessary to shield the detector from background neutrons originating both from cosmic background and from the accelerator.
20 cm polyethylene shielding seems ok

- 2.5% detection of 2 MeV neutrons
- No need to add Cadmium according to simulations

Unknown neutron background
A prototype with 20 counters has been designed to be used in an experiment at JYFL-Finland with the Penning trap to ensure high purity beam.

Ring A: 8 counters @ \( R_A = 11 \) cm
Ring B: 12 counters @ \( R_A = 20 \) cm

Beam hole radius: 5 cm
Dimensions: 50 x 50 x 80 cm\(^3\) + shielding (90 x 90 x 80 cm\(^3\))
Comparison of efficiencies with GEANT4 and MCNPX simulations.

About 10% difference between both codes due to difference in the moderation process.

Very flat efficiency achieved up to 2 MeV.
Outer layer of polyethylene added to shield detector from background neutrons.

The addition of Cadmium between the two layers of polyethylene did not reduce the background detection.

Simulation to study detection of background neutrons emitted from a sphere surrounding the detector.
In the experiment we will only receive a pulse from the detectors.

We need to be able to discriminate if this pulse is a “good signal” (i.e. neutron from our nucleus) or a “bad signal” (i.e. background or other particle).

A simulation of the experiment can help us understand what type of particles will be produced in the experiment and whether they will interact with our detectors and give us false signals.

Simulations help us foresee experimental problems and avoid them.
The neutron cross section of the reaction increases as neutron is thermalised.

\[ ^3\text{He} + \text{n} \rightarrow ^3\text{H} + \text{p} + 765 \text{ keV} \]

Layout of triton production in the detector ensemble. Tritons are only produced in the \(^3\text{He}\) gas.
Simulation of deposited energy in each crown of $^3$He counters

$^{252}$Cf neutron source, 100 000 neutrons

Wall effect

- Full energy peak: 765 keV
- Wall effect: 575 keV
- e$^-$

p: 575 keV

3$^3$He counter

t: 190 keV
Simulation of time elapsed from neutron emission to neutron detection.

Times are of the order of 100s us due to thermalisation time. Very important for experiment design.
Neutron detection distribution along the length of the $^3$He counter.
Other particles produced in the ensemble

Simulation has shown that these particles do not deposit their energy in the $^3$He gas therefore they don’t interfere with the experiment.
✓ Simulation validation.
✓ Design of a prototype detector for JYFL
✓ Prototype construction and Test.
EXPERIMENTAL TEST OF MCNPX RESULTS

- Test of $^3$He proportional counters with $^{252}$Cf source in UPC, Barcelona
- Simple setup, easy to reproduce in simulations.
$^3\text{He} \rightarrow ^3\text{H} + p + 760 \text{ keV}$

<table>
<thead>
<tr>
<th></th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental data</td>
<td>$2.3 \pm 0.3$</td>
</tr>
<tr>
<td>MCNPX data</td>
<td>$2.4 \pm 0.5$</td>
</tr>
</tbody>
</table>

$^3\text{He}$ counter with s/n 300645, LND Inc.
252Cf neutron source.
Acquisition time 20000 sec. (Live time)
Cable length: between pre-amplifier and counter 5 cm
Data: 24.02.2000 (rev)

Channels from 0 to 150 = 30140 Cts

Full energy peak
760 keV

Wall effect
190 keV
Polyethylene: 10 cm thick vertical slices assembled => 90 x 90 x 80 cm³ ~650 Kg detector

Support structure requirements:
- Hold and transport 650 Kg
- Allow access to the beam hole
- Movable in Z for fine placement
- Table + tray movable on “z” on rails
- Polyethylene block hold together and can be lifted as a single unit.
The prototype and its support table are ready.

It has been tested with a $^{252}\text{Cf}$ source in the UPC lab.
PROTOTYPE TEST AT UPC

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

$^{3}$He counters + Mesytec electronics

$^{252}$Cf source

700 n/s

NaI detector. CIEMAT
SIMULATION VALIDATION WITH $^{252}$Cf SOURCE IN UPC LAB

<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%)
Comparison experimental vs Geant4 detection time.

Experimental detection time in inner and outer ring
✓ Aims of the experiment
✓ Experimental Set up
Decay properties of $\beta$ delayed neutron emitters $^{87}$Br, $^{88}$Br, $^{94}$Rb, $^{95}$Rb, $^{137}$I

Three complementary setups to study three aspects: 15 days beam time

- Neutron emission probability (4$\pi$ neutron detector, UPC)
- Neutron energy (ToF detector, CIEMAT)
- Beta decay energy (Total Absorption Spectrometer, IFIC)

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CIEMAT:

• Time of Flight (ToF) will measure the energy of emitted neutrons.

ToF consists of a set of 30 cylindrical modules filled with the BC501A liquid scintillator. Each cell has 20cm diameter and 5cm thickness and an intrinsic efficiency ranging from 50% at 1 MeV to 22% at 10 MeV.

The energy spectra of the delayed neutrons will be determined from the time difference between β-trigger and a signal in the neutron detector.
IFIC (Valencia):
Total Absorption Spectrometer (TAS) will measure beta decay probability distribution;
TAS consists of 12 BaF2 crystals covering a solid angle of almost $4\pi$.

The detection efficiency for gamma-ray cascades is essentially 100%.

In this setup the light output of each crystal is read independently with photomultiplier tubes so that additional information of the multiplicity of the gamma-ray.
Very pure beam of ions from a Penning trap

A proton beam impinges on an Uranium target and the products of fission are transported out of the target in a He gas flow. This beam is purified through IGISOL and a clean beam of the ions of interest is provided.
IGISOL layout

1- Ion guide
2- k130 cyclotron beamline
3- beam dump
4- acceleration chamber
5- dipole magnet
6- switchyard
7- RFQ cooler
8- tandem penning trap
9- miniquadrupole deflector
10- electrostatic deflector and beamline to upper floor
The ion beam purified in the Penning trap was implanted on a tape in the center of the neutron detector for $3T_{1/2}$ and left decay there for $7T_{1/2}$, then the tape was moved to take the contamination away and a new implant/decay cycle started.
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.
Experiment at JYFL

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A Ge detector was placed next to the tape to detect the gammas emitted after the beta decay of the implanted ions.
Preliminary analysis

Signal from the Si, Ge and $^3$He detectors were recorded with a time stamp in order to be able to correlate the events from these three detectors.

Signal from the Si (beta decay)

Signal from He3 counters (neutrons)
The implantation was done in cycles. Ions were implanted for $3 \text{T}_{1/2}$ and let decay for $7 \text{T}_{1/2}$ before moving the tape.

The implantation and decay cycles will be fitted with the Bateman equation to isolate the background and the components from the rest of the decay chain.
SUMMARY:

✓ A 4pi neutron detector has been designed to study beta delayed neutron emission.
✓ The detector has been fully built at UPC.
✓ A laboratory test has been carried out with a $^{252}\text{Cf}$ source to validate the simulations. Agreement is good within experimental uncertainty.
✓ The first experiment with this detector has been performed in JYFL Finland to study the neutron emission from fission products.
✓ Data from this experiment is under analysis.
Thanks for your attention