First Measurements with the BEta deLayEd Neutron Detector (BELEN-20) at JYFLTRAP

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Abstract. A prototype version of the BEta deLayEd Neutron detector, which is being developed for the FAIR/DESPEC experiment, has been used for the first time in an experiment at JYFL (Finland). This detector is based on $^3$He counters and its first run was primarily intended to commission the detector and verify the working principles for future experiments. A new triggerless DAQ has been developed for these measurements. This DAQ time-stamps the events and allows complete flexibility to construct correlations offline.

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 BELEN-20 detector. The measurements were performed for known delayed neutron emitters of interest for nuclear power generation: $^{88}$Br, $^{94,95}$Rb, $^{138}$I.

The characteristics of the BELEN-20 detector and the first experiment at JYFL are presented in this paper.

1. Introduction

Beta-delayed neutron emission takes place when a precursor nucleus beta-decays and the resulting daughter emits a neutron. This neutron emission is energetically allowed if the Q-value of the beta decay is larger than the neutron binding energy of the daughter.

The study of beta-delayed neutron emission is of interest in different fields, such as technological applications, nuclear astrophysics and nuclear structure.

The technological interest of this type of studies is related to nuclear power generation. In nuclear fission this beta-delayed neutron emission plays an essential role in order to safely control the sustainability of the fission reaction. Therefore, research into these nuclei is fundamental for the design of safer and more efficient nuclear reactors. The 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” [1].

In nuclear astrophysics, the delayed neutron emission modulates the element abundance curve of stellar nucleosynthesis. Improved experimental data from delayed neutron emission represents an important input to r-process model calculations.

Furthermore, in nuclear structure, beta-delayed neutron emission constitutes an important probe for the structure of neutron-rich nuclei far away from the valley of stability where other measurements are not possible yet.

However, the existing experimental data on delayed neutron emission is scarce and it is necessary to perform new high precision measurements.

2. Detector design

The design of the detector was performed through Monte Carlo simulations with the GEANT4 [2] and MCNPX [3] codes. The aim was to obtain a detection efficiency as high and as constant as possible in the energy range of interest for these neutrons from 1 keV to a few MeV. This constant efficiency is crucial since the information on the initial energy of the neutron will be lost during the moderation process. For neutron-emitters with unknown neutron energy spectrum the same efficiency will be used regardless of neutron energy. However, for cases where the neutron energy spectrum is measured, the Monte Carlo simulation provides a method to correct for this type of systematic uncertainty as it is shown in section 2.1.

The detector consists of a matrix of polyethylene with 20 $^3$He counters arranged in two concentric rings around the detector cavity [4]. The detection of the neutrons is achieved via the detection of the charged particles that are produced in the reaction:

$$^3\text{He} + n \rightarrow ^3\text{H} + p + 763.7 \text{ keV}.$$ 

The cross section of this reaction increases as the energy of the neutron decreases, therefore the use of the polyethylene where the neutrons are moderated via collisions with hydrogen atoms.

The setup is presented in Fig. 1 displaying the two concentric rings of $^3$He counters, so called crowns, (with 8 and 12 counters respectively) around the detector cavity. The beam of ions is implanted into a transport tape directly in the centre of the neutron detector and in front of a Si detector where the signal of the beta decay is measured. According to MCNPX simulations, the neutron detection efficiency is 30% in the neutron energy range from 1 keV to 1 MeV (Fig. 2).

![Figure 1](image_url)

**Figure 1.** Sectional side and front view of the setup used at JYFL with the BELEN-20 neutron detector, the Si and Ge detectors and the implantation tape system.

2.1. BELEN-20 detection efficiency for the neutron emission of $^{88}\text{Br}$, $^{94,95}\text{Rb}$ and $^{138}\text{I}$

The neutron energy spectra from the beta-delayed neutron emission of each of the nuclei of interest were obtained from ENDF/B VI [8] (Figs. 3 and 4) and introduced in the Monte Carlo
Figure 2. MCNPX simulated efficiency. Contributions of 1\textsuperscript{st} and 2\textsuperscript{nd} crown as well as the total detection efficiency as a function of neutron energy.

Figure 3. Neutron energy distribution for $^{88}\text{Br}$ from ENDF/B VI.

Figure 4. Neutron energy distribution for $^{138}\text{I}$ from ENDF/B VI.

3. Experiment at JYFL

The first experiment with this detector was performed in JYFL, Finland, in November 2009 to measure the beta-delayed neutron emission from $^{88}\text{Br}$, $^{94,95}\text{Rb}$ and $^{138}\text{I}$. The isotopes were produced at the Ion Guide Isotope Separator On-Line (IGISOL) facility [5] with a 30 MeV deuteron beam impinging on a natural Uranium target. Subsequently, the double Penning trap setup JYFLTRAP [6] was used to prepare a monoisotopic beam which was implanted on a movable tape placed inside the neutron detector. The radioactivity was accumulated during a period of 3 $T_{1/2}$, while the measurement period was extended up to 10 $T_{1/2}$ in order to obtain
Table 1. BELEN-20 neutron detection efficiency for $^{88}\text{Br}$, $^{94,95}\text{Rb}$ and $^{138}\text{I}$ according to GEANT4 and MCNPX Monte Carlo simulations.

| Isotope | GEANT4(%) | MCNPX(%) |
|---------|-----------|-----------|
| $^{88}\text{Br}$ | 31.7 ± 1.8 | 30.1 ± 1.7 |
| $^{94}\text{Rb}$ | 32.3 ± 1.8 | 29.9 ± 1.7 |
| $^{95}\text{Rb}$ | 32.2 ± 1.8 | 29.8 ± 1.7 |
| $^{138}\text{I}$ | 31.5 ± 1.8 | 30.0 ± 1.7 |

the growth and decay curves. The setup also included a Si detector (27 mm diameter and 910 µm thick) to detect $\beta$-particles and a Ge detector for $\gamma$-ray detection as shown in Fig. 5.

Figure 5. Experimental setup in the JYFLTRAP line. Neutron and Ge detectors.

The data acquisition worked in a triggerless mode [7], the signals from all detectors above a threshold were time-stamped and energy-time pairs were stored with minimum dead time. This system allowed full flexibility for the definition of the time correlation between the beta and the neutron detection. This time is of the order of hundreds of µs due to the time required for neutron moderation in polyethylene. In this way large time windows and several correlation modes can be defined in order to achieve an optimal determination of the true coincidences.

4. Preliminary analysis

In the preliminary analysis the Bateman equation [9] was fitted to the growth and decay curves for the $\beta$-particles (Fig. 6) and the neutrons (Fig. 7) in order to separate the contributions of each nucleus in the decay chain and that of the background. These growth and decay curves were obtained by plotting with respect to the time of the cycle, the counts corresponding to the betas from the Si spectrum (above channel 20000) shown in Fig. 8 and similarly with the neutron counts (above channel 50000) from Fig. 9.

The fit to the Bateman equation disentangles the contribution from each nucleus of the decay chain and from the background and singles out the counts for the nucleus of interest, $N_{\beta}$.

A further plot was constructed with the coincidences between the neutrons and betas in a 1ms time window forward and backward from the detection of a neutron (Fig. 10). True beta-neutron coincidences ($N_{\beta n}$) are the counts on the left half of the spectrum on top of the flat background of random coincidences which is defined by the counts on the right half of the spectrum. The neutron emission rate ($P_n$) is obtained with the following formula using the number of beta
counts due to the decay of the mother nucleus ($N_{\beta}$), the number of beta-neutron coincidences ($N_{\beta n}$) and the detector efficiency ($\epsilon_n$)

$$P_n = \frac{1}{\epsilon_n} \frac{N_{\beta n}}{N_{\beta}}.$$ 

This way of determining $P_n$ is independent of systematic uncertainties in the absolute value of the beta detection efficiency ($\epsilon_{\beta}$). The latter is sensitive to the exact positioning of the sample with respect to the beta detector and the exact value of the electronic threshold. The $P_n$ values of $^{88}$Br and $^{95}$Rb were used as references to calculate the efficiency of BELEN-20 since there is good agreement in the values obtained from different experimental sources as it is reflected in the agreement between the recommended values of the most recent compilations, [10] and [11]. The values obtained, once applied the dead time correction, are shown in Table 2. From these two values the average efficiency for BELEN-20 is $(27.1 \pm 0.8)\%$.

Using the above average efficiency, the $P_n$ obtained for $^{94}$Rb and $^{138}$I are presented in Table 3 along with the values reported in [10] and [11]. Our value for $^{94}$Rb is close to the value from [10] and definitively will allow to reduce the large uncertainty quoted in [11]. In the case of $^{138}$I the result is just in between the values from [10] and [11] and will allow also to reduce the uncertainty of the recommended value.

The results of this experiment prove the suitability of the BELEN-20 detector and the
Table 2. BELEN-20 detection efficiency obtained using $^{88}$Br and $^{95}$Rb [10] as calibration.

| Isotope | $P_n$ (%) [10] | $N_\beta$ | $N_{\beta n}$ | $\epsilon_n$ (%) |
|---------|----------------|-----------|----------------|-----------------|
| $^{88}$Br | 6.58 ± 0.18 | 867701 | 14350 | 27.6 ± 0.7 |
| $^{95}$Rb | 8.73 ± 0.20 | 588116 | 13301 | 26.6 ± 0.8 |

triggerless DACQ to perform these measurements at JYFL. Further measurements for other fission fragments will be performed in the future in this facility.

Table 3. $P_n$ values for $^{94}$Rb and $^{138}$I for this work, compared to other authors [10] [11].

| Isotope | $N_\beta$ | $N_{\beta n}$ | $P_n$ (%) | Author |
|---------|-----------|----------------|-----------|--------|
| $^{94}$Rb | 3005635 | 83768 | 10.28 ± 0.31 | This work |
|          |          |         | 10.01 ± 0.23 | Rudstam [10] |
|          |          |         | 9.1 ± 1.1    | Pfeiffer [11] |
| $^{138}$I | 343890 | 4955 | 5.32 ± 0.2 | This work |
|          |          |         | 5.46 ± 0.18 | Rudstam [10] |
|          |          |         | 5.17 ± 0.36 | Pfeiffer [11] |

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