Trial for the long neutron counter TETRA using $^{96,97}$Rb radioactive sources

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ABSTRACT: The TETRA long neutron counter is operated at ALTO ISOL facility behind the PARRNe mass separator. TETRA has been proven to be a unique instrument for measurements of $\beta$-decay properties of short-lived neutron-rich nuclei having applications for the nuclear structure and/or astrophysical r-process calculations. A proper calibration of TETRA can allow validation of the experimental procedure used for determination of $\beta$-delayed one-neutron emission probabilities ($P_{1n}$). It requires the use of a well-known $\beta$-neutron decaying radioactive source which can be only produced and measured on-line due to its short half-life. Thus, the present paper reports on measurements of $P_{1n}$ and $T_{1/2}$ of $^{96,97}$Rb nuclei using TETRA. The results obtained are in a good agreement with the values available in the literature. This proves that the developed techniques can be applied to unknown $P_{1n}$ and $T_{1/2}$ of neutron-rich species.

KEYWORDS: Data processing methods; Gaseous detectors

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1 β-delayed neutron emission

Nowadays the interest in the phenomenon of β-delayed (multi) neutron emission is arising but the mechanism which drives this process in neutron-rich nuclei is still not understood. However, β-delayed neutrons play a significant role for the astrophysical calculations and the nuclear reactor physics. Today many nuclei are being revisited for detailed examination of this phenomenon. Modern detection systems such as TETRA [1, 2] or BEDO [3] installed at ALTO ISOL facility [4] make it possible to measure β-decay properties of nuclei far away from the line of β-stability.

Many experiments performed at TETRA aimed at measurements of β-decay properties of the ground-state of neutron-rich medium-mass nuclei. The recent results obtained using TETRA/BEDO revealed the population of low-lying Gamow-Teller states in the β-decay of $^{83}$Ga [5] and high energy γ-ray emission [6] which can be interpreted as a competition between γ-ray and neutron emission beyond the neutron separation energy threshold. Measurements of half-life ($T_{1/2}$) and β-delayed (multi) neutron emission probability ($P_{xn}$) are very sensitive to the parameters of the experimental setup. The performance of a neutron-detector can be characterized using standard neutron calibration (spontaneous-fission) sources, for example $^{252}$Cf. However, the energy range of β-delayed neutrons is different from that of prompt fission neutrons emitted by $^{252}$Cf. The response of TETRA to $^{252}$Cf source emissions is well understood by extensive simulations validated by measurements [7]. But $^{252}$Cf source, obviously, does not allow the validation of the data-analysis protocol for a β-decay experiment. Therefore, in order to test the experimental setup and the analysis procedure we performed two experiments using short-lived radioactive sources created at the centre of TETRA: $^{96}$Rb and $^{97}$Rb in the first and second runs respectively. The $T_{1/2}$ and $P_{1n}$ values measured in the present experiment using previously adopted methods [1, 5] are in fair agreement with the values available in the literature.

2 Measurements of β-delayed neutron emission using the TETRA setup

To produce neutron-rich nuclei, the UC$_x$ target placed in a Ta oven heated up to >2000°C was exposed to the primary 50 MeV electron beam delivered by the ALTO linear accelerator [4]. The average beam current on the target was 10 μA. For this experiment, the oven was connected to a W tube used to selectively surface ionize the fission products. The beam was then accelerated to 30 keV. TETRA was operated behind the mass separator PARRNe whose resolution ($\delta m/m=1300$)
was high enough to provide isobaric selection between $A = 96$ and $A = 97$. The other members of the isobaric chain (Sr, Y) have higher ionization potential and thus their production rate can be neglected in the experiment.

The $\beta$-decay station installed in the ALTO experimental hall was used in the neutron detection mode [1, 3]. The detailed description of the setup is provided in ref. [1]: the surface-ionized mass separated beams were collected on an Al-coated mylar tape at the centre of the long-neutron counter TETRA creating a radioactive source. The collection point was surrounded by a plastic scintillator for $\beta$ detection. A High Purity Ge detector was used for $\gamma$ detection. One cycle of data taking consisted of a short background measurement ($T_{bg}$) followed by an irradiation time ($T_{beam}$) when the beam was impinging on the tape, and a decay time ($T_{dec}$) when the beam was deviated. Therefore, the data acquisition system recorded neutron, $\beta$ and $\gamma$ activities from the source during $T_m = T_{bg} + T_{beam} + T_{dec}$. Then the tape was moved by two meters to transport the source outside the detection system. The time settings and the number of completed cycles for $A = 96, 97$ are listed in table 1.

Table 1. Tape-cycle parameters used for the $A = 96, 97$ settings: $T_{bg}$ is the background counting time before beam collection, $T_{beam}$ is the duration of the beam collection and $T_{dec}$ is the beam-off source decay counting time, in ms. $N_{cycles}$ is the total number of tape cycles for each mass setting. $T_{1/2}$, $P_{1n}$, $\Phi$ are the values obtained from the analysis of the $\beta$- and neutron-activity curves for the $A = 96, 97$ settings.

| Beam  | $T_{bg}$ ms | $T_{beam}$ ms | $T_{dec}$ ms | $N_{cycles}$ | $T_{1/2}$ ms | $P_{1n}$ % | $\Phi$ pps | $\epsilon_{\beta}$ eff % | $\epsilon_{\gamma}$ eff % |
|-------|-------------|---------------|--------------|--------------|-------------|-------------|------------|------------------|------------------|
| $^{96}$Rb | 500         | 100           | 1900         | 191          | 200(1)      | 12.0(1.1)   | $\sim 3.4 \times 10^4$ | 29(4)           | 58(4)           |
| $^{97}$Rb | 500         | 500           | 1500         | 500          | 169(1)      | 27.8(2.4)   | $\sim 0.9 \times 10^4$ | 29(4)           | 56(4)           |

The resulting $\beta$- and neutron activity curves for $A = 96, 97$ mass separator settings accumulated over $N_{cycles}$ are plotted in figure 1. All neutrons detected for a selected mass of rubidium were attributed either to the background or to $\beta$-neutron decay of rubidium isotopes. Even if $\beta$-delayed neutron emission is energetically allowed, there is no experimental evidence of $\beta$-delayed neutron emission of $^{96,97}$Sr so far. The simultaneous fit of the grow-in and decay patterns of accumulated neutron curves leads to half-lives of $^{96,97}$Rb as reported in table 1, where the uncertainty is the uncertainty from the fit.

The effective efficiency of the $\beta$ detector ($\epsilon_{\beta}$) and the TETRA array ($\epsilon_{\gamma}$) was derived from coincidence $\gamma$-ray spectra recorded for $A=96$ and $A=97$ mass separator settings plotted in figure 2. The efficiencies were obtained from the observed ratios of an area of $i^{th}$ peak in singles ($S_i^\gamma$), $\beta$ gated ($S_{\gamma\beta}^i$), and $\beta$-neutron gated ($S_{\gamma\beta \gamma}^i$) $\gamma$-ray spectra. The relative intensities of the observed transitions are summarized in tables 2 and 3. The $\epsilon_{\beta}$ was derived as a weighted average of $S_{\gamma\beta}^i/S_i^\gamma$ ratios measured for the $i^{th}$ transition. Due to lack of statistics in the $\beta$-$\gamma$-gated spectrum $\epsilon_{\gamma}$ was found using only the most strong transitions at 352 keV and 815 keV in $^{95}$Sr and $^{96}$Sr respectively as reported in tables 2 and 3. All the $\gamma$ activities recorded were identified and no isobaric contaminants were observed within our detection limits. Moreover, no evidence for contamination from surface ionized $^{96,97}$Sr isotopes was found in the analysis of the activity curves. Indeed, such a contamination is unlikely due to the higher ionization potential of Sr.
Figure 1. $\beta$ (top) and neutron (bottom) activity curves recorded for the $A = 96$ (left) and $A = 97$ (right) setting of the mass separator. The number of cycles is given in table 1. The different $\beta$-activity components are singled out with coloured curves. Left: $^{96}$Rb in green, $^{96}$Sr in orange, $^{96}$Y in purple; the $\beta$-delayed neutron activity curve originating from $^{96}$Rb (red) decays is shown by the red curve in the lower panel. Right: $^{97}$Rb in green, $^{97}$Sr in orange, $^{97}$Y in purple and $^{96}$Sr in blue; the $\beta$-delayed neutron activity curve originating from $^{97}$Rb is shown by the red curve in the lower panel.

To extract $P_{1n}$ values and the production rates $\phi$ we used the method reported previously [1]. The method is based on the system of Bateman equations describing decay of a given radioactive source. In this method the $P_{1n}$ and $\phi$ values are determined as roots of a corresponding system of Bateman equations (2.1).

$$
\begin{align*}
\left\{ \begin{array}{l}
(N_\beta^{\text{exp}} - N_\beta^{\text{bg}}) \frac{1}{\epsilon_\beta} = \int_{T_{\text{bg}}}^{T_m} \left[ A(A,Z)(t) + A(A,Z+1)(t) + A(A,Z+2)(t) + A(A-1,Z+1)(t) + A(A-1,Z+2)(t) \right] dt, \\
(N_n^{\text{exp}} - N_n^{\text{bg}}) \frac{1}{\epsilon_n} = P_{1n} \cdot \int_{T_{\text{bg}}}^{T_m} A(A,Z)(t) dt,
\end{array} \right.
\end{align*}
$$

(2.1)

where $N_\beta^{\text{exp}}$ and $N_n^{\text{exp}}$ are the total numbers of $\beta$ and neutrons detected; $N_\beta^{\text{bg}}$ and $N_n^{\text{bg}}$ are the total numbers of background events; $\epsilon_\beta$ and $\epsilon_n$ are the measured effective efficiencies of the $\beta$ detector and the TETRA array; $A(A,Z+1)(t), \ldots, A(A-1,Z+2)(t)$ are the activities of daughter, grand-daughter nuclei characterized by their decay constants $\lambda(A,Z+1), \ldots, \lambda(A-1,Z+2)$ respectively. The activity of the mother nuclei $A(A,Z)(t)$ at a $t$-moment, populated by the beam, depends on both the decay constant $\lambda(A,Z)$ and the intensity of the beam, $\phi$:

$$
A(A,Z)(t) = \begin{cases} 
\phi \left( 1 - e^{-(t - T_{\text{bg}}) \cdot \lambda(A,Z)} \right), & T_{\text{bg}} \leq t \leq T_{\text{bg}} + T_{\text{beam}} \\
 e^{-(t - T_{\text{bg}} - T_{\text{beam}}) \cdot \lambda(A,Z)} (1 - e^{-(T_{\text{bg}} + T_{\text{beam}}) \cdot \lambda(A,Z)}), & T_{\text{bg}} + T_{\text{beam}} \leq t \leq T_m 
\end{cases}
$$

(2.2)
The system of the equations (2.1) was solved for the $A=96$ and $A=97$ collected datasets. Whereas $\lambda_{(A,Z)}$ was fixed to the value obtained from the fit of neutron activities, the $\lambda_{(A,Z+1)}, \ldots, \lambda_{(A-1,Z+2)}$ were fixed to their tabulated values. The obtained $P_{1n}$ and $\phi$ for $^{96}$Rb and $^{97}$Rb are reported in table 1. A constant average production yield was assumed. The errors on $P_{1n}$ and $\phi$ were mostly dominated by associated statistical errors but also by uncertainties on $\beta$ and neutron efficiencies and uncertainties on half-lives of Sr and Y daughters as given in the literature. Once $P_{1n}$ and $\phi$ were derived the contributions due to the decay of the parent nucleus and its daughters to the $\beta$-activity curve accumulated after $N_{\text{cycles}}$ were determined. The results for $A=95$ and $A=96$ mass separator settings are shown.

Figure 3 shows $T_{1/2}$ plotted versus $P_{1n}$ values for $^{96}$Rb (left) and $^{97}$Rb (right). The cited references correspond to reported experiments in which these two quantities were measured simultaneously. The $T_{1/2}$ and $P_{1n}$ values presently obtained are in a remarkable agreement with the existing systematics.
Table 2. Photopeaks attributed to the $\beta$ and $\beta$-n decays of $^{96}\text{Rb}$ identified in the spectrum recorded for the $A = 96$ setting of the mass-separator. $\gamma$-intensities ($I_{\gamma}^{\text{rel}}$) are given relatively to the transition at 815.5 keV or 122.5 keV observed in $^{96}\text{Sr}$ or $^{96}\text{Y}$ respectively.

| $E_{\gamma}$ [keV] | Spectrum | $I_{\gamma}^{\text{rel}}$ [%] | $S_{\gamma}/S_{\gamma\beta}$ [%] | assignment |
|-------------------|----------|------------------|-------------------------------|------------|
| 122.5(3)          | $\gamma$ | 100(2)           | 29(1)                        | $^{96}\text{Sr}(\beta)$ |
|                   | $\gamma\beta$ | 100(3)       |                               |            |
| 204.5(3)          | $\gamma$ | 28(4)            | –                             | $^{96}\text{Rb}(\beta\text{n})$ |
|                   | $\gamma\text{n}$ | 25(4)       |                               |            |
| 279.5(3)          | $\gamma$ | 13.0(5)          | 27(2)                        | $^{96}\text{Sr}(\beta)$ |
|                   | $\gamma\beta$ | 12.0(9)      |                               |            |
| 353.2(3)          | $\gamma$ | 100(8)           |                               | $^{96}\text{Rb}(\beta\text{n})$ |
|                   | $\gamma\beta$ | 100(14)     |                               |            |
|                   | $\gamma\beta\text{n}$ | 100(15) | 29(3)                        |            |
|                   | $\gamma\text{n}$ | 100(8)      |                               |            |
| 530.1(4)          | $\gamma$ | 11.3(6)          | 30(3)                        | $^{96}\text{Sr}(\beta)$ |
|                   | $\gamma\beta$ | 11.0(9)      |                               |            |
| 692.2(4)          | $\gamma$ | 9.0(1.5)         | 36(6)                        | $^{96}\text{Rb}(\beta)$ |
|                   | $\gamma\beta$ | 10.5(1.5)   |                               |            |
| 809.6(4)          | $\gamma$ | 110(3)           | 28(1)                        | $^{96}\text{Sr}(\beta)$ |
|                   | $\gamma\beta$ | 108(3)      |                               |            |
| 815.2(4)          | $\gamma$ | 100(3)           | 31(1)                        | $^{96}\text{Rb}(\beta)$ |
|                   | $\gamma\beta$ | 100(4)      |                               |            |
| 931.9(4)          | $\gamma$ | 23(1)            | 32(3)                        | $^{96}\text{Sr}(\beta)$ |
|                   | $\gamma\beta$ | 25(2)       |                               |            |
| 977.9(4)          | $\gamma$ | 23(1)            | 30(5)                        | $^{96}\text{Rb}(\beta)$ |
|                   | $\gamma\beta$ | 25(2)       |                               |            |
| 1037.5(4)         | $\gamma$ | 7.5(5)           | 27(4)                        | $^{96}\text{Rb}(\beta)$ |
|                   | $\gamma\beta$ | 6.6(8)       |                               |            |
| 1180.5(5)         | $\gamma$ | 4.0(4)           | 31(7)                        | $^{96}\text{Rb}(\beta)$ |
|                   | $\gamma\beta$ | 4.1(6)      |                               |            |
Table 3. Photopeaks attributed to the $\beta$ and $\beta$-n decays of $^{97}$Rb identified in the spectrum recorded for the $A = 97$ setting of the mass-separator. $\gamma$-intensities ($I_{\gamma}^{rel}$) are given relatively to the transition at 167.0 keV or 1905.2 keV observed in $^{97}$Sr or $^{97}$Y respectively.

| $E_{\gamma}$ [keV] | Spectrum | $I_{\gamma}^{rel}$ [%] | $S_{\gamma}^{I}/S_{\gamma\beta}^{I}$ [%] | assignment  |
|------------------|----------|------------------------|-------------------------------------|-------------|
| 167.0(3)         | $\gamma$ | 100(2)                 | 27(1)                               | $^{97}$Rb($\beta$) |
|                  | $\gamma\beta$ | 100(4)               |                                     |             |
| 418.2(3)         | $\gamma$ | 23(1)                  | 33(2)                               | $^{97}$Rb($\beta$) |
|                  | $\gamma\beta$ | 27(2)               |                                     |             |
| 585.1.5(4)       | $\gamma$ | 13.0(5)                | 28(1)                               | $^{97}$Rb($\beta$) |
|                  | $\gamma\beta$ | 12.0(9)             |                                     |             |
| 600.1(4)         | $\gamma$ | 37(1)                  | 32(2)                               | $^{97}$Rb($\beta$) |
|                  | $\gamma\beta$ | 43(3)               |                                     |             |
| 644.8(4)         | $\gamma$ | 11.9(6)                | 28(3)                               | $^{97}$Rb($\beta$) |
|                  | $\gamma\beta$ | 12.5(5)             |                                     |             |
| 815.4(4)         | $\gamma$ | 100(2)                 | 27(1)                               | $^{97}$Rb($\beta$) |
|                  | $\gamma\beta$ | 100(6)             |                                     |             |
|                  | $\gamma\beta$ | 100(11)            |                                     |             |
| 953.9(4)         | $\gamma$ | 103(4)                 | 28(1)                               | $^{97}$Sr($\beta$) |
|                  | $\gamma\beta$ | 103(7)             |                                     |             |
| 1905.2(5)        | $\gamma$ | 100(4)                 | 29(1)                               | $^{97}$Sr($\beta$) |
|                  | $\gamma\beta$ | 100(8)             |                                     |             |
| 2212.3(5)        | $\gamma$ | 39(2)                  | 28(3)                               | $^{97}$Sr($\beta$) |
|                  | $\gamma\beta$ | 38(4)               |                                     |             |

Figure 3. $T_{1/2}$ versus $P_{1n}$ for $^{96}$Rb and $^{97}$Rb known from refs. [8–14] as well as the values obtained in the present work.
3 Conclusions

The TETRA long neutron counter is a unique device which is currently used at the ALTO ISOL facility to measure global $\beta$-decay properties of neutron-rich nuclei. The $\beta$-decay station operated in neutron detection mode allows the simultaneous detection of $\beta$, $\gamma$ and neutron emissions from a radioactive sources formed by the accumulation of the beam at the centre of the detection system. The performance of the setup was characterized using pure radioactive sources of $^{96,97}$Rb produced from the photo-fission of $^{238}$U. The sources were carefully chosen because their $\beta$-decay properties are known and thus represent well-known reference cases to test neutron detectors and validate the data analysis procedure. The half-lives and the probabilities of $\beta$-delayed neutron emission for $^{96,97}$Rb measured in the experiment are in good agreement with the previously reported values. We plan to apply the described procedure to derive unknown values of $P_{1n}$ of different nuclei with large $N/Z$ ratio will be produced at ALTO ISOL facility.

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