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

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

KEYWORDS: Neutron detectors, Gaseous detectors

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1 Introduction

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

Ground-state β -decay properties have been the aim of many experiments performed at TETRA. The recent results obtained using TETRA/BEDO are 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. Neutron-detector performance 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 from ^{252}Cf source 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 correspondingly. 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 Experiment Details

To produce neutron-rich nuclei the UC_x target placed in a Ta oven heated up to $>2000^\circ\text{C}$ 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 surface-ionize the fission products. The beam was then accelerated at 30 keV. TETRA was operated behind the mass separator PARNNe 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. This fact makes $^{96,97}\text{Rb}$ good references nuclei to verify experimental methods.

The β -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 a 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 β detection. A High Purity Ge detector was used for γ 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, β and γ activities from the source during $T_m = T_{bg} + T_{beam} + T_{dec}$. Then the tape was moved for 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} the duration of the beam collection and T_{dec} 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} , ϕ are the values obtained from the analysis of the β - 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} %	Φ pps	ϵ_{eff}^β %	ϵ_{eff}^n %
^{96}Rb	500	100	1900	191	200(1)	12.0(1.1)	$\sim 3.4 \cdot 10^4$	29(4)	58(4)
^{97}Rb	500	500	1500	500	169(1)	27.8(2.4)	$\sim 0.9 \cdot 10^4$	29(4)	56(4)

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

The effective efficiency of the β detector (ϵ_β) and the TETRA array (ϵ_n) was derived from coincidence γ -ray spectra recorded for $A=96$ and $A=97$ mass separator settings plotted in Fig. 2. The efficiencies were obtained from the observed ratios of an area of i^{th} peak in singles (S_γ^i), β gated ($S_{\gamma\beta}^i$), and β -neutron gated ($S_{\gamma\beta n}^i$) γ -ray spectra. The relative intensities of the observed transitions are summarized in Tables 2 and 3. The ϵ_β was derived as a weighted average of $S_{\gamma\beta}^i/S_\gamma^i$ ratios measured for the i -th transition. Due to lack of statistics in the β -n γ -gated spectrum ϵ_n was found using only the most strong transitions at 352 keV and 815 keV in ^{95}Sr and ^{96}Sr respectively as reported in Table 2 and 3. All the γ activities recorded could be identified and no isobaric contaminants were observed within our detection limits. Moreover, no evidence for contamination from surface ionized $^{96,97}\text{Sr}$ isotopes was found in the analysis of the activity curves. Indeed, such

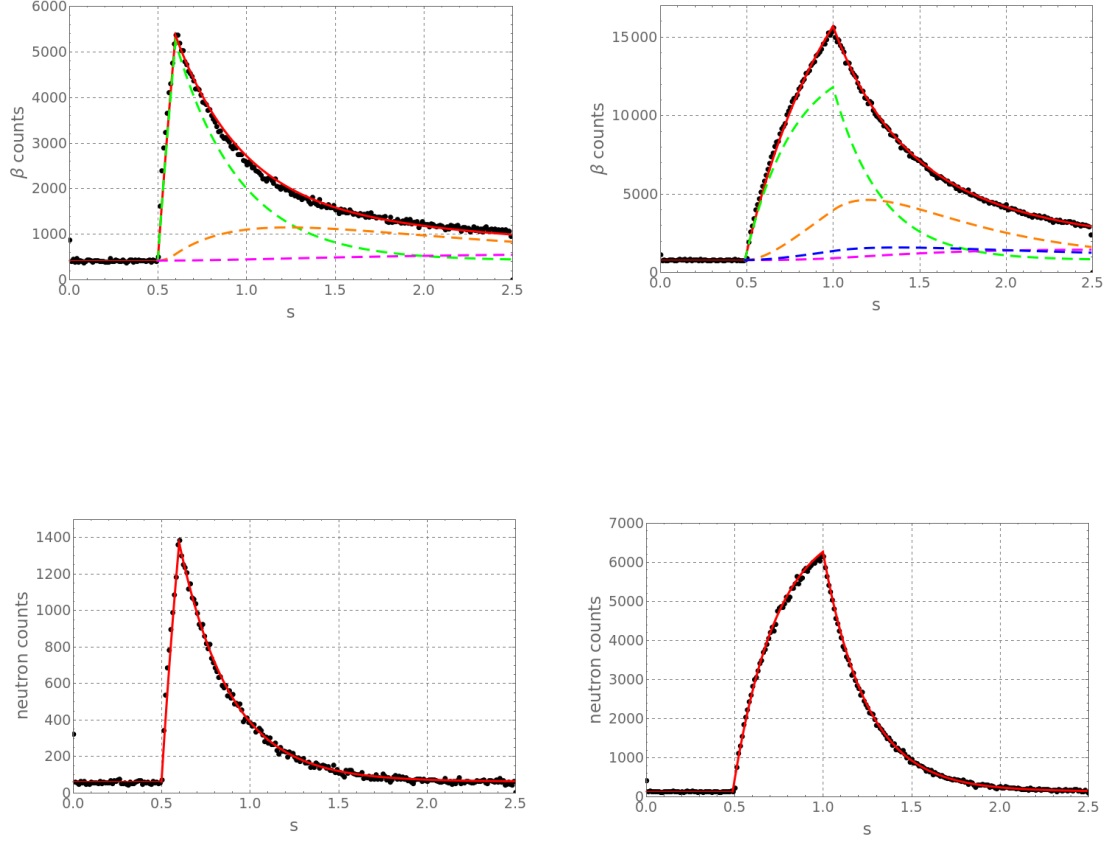


Figure 1: Left: β (top) and neutron (bottom) activity curves recorded for the $A = 96$ setting of the mass separator. The number of cycles is given in Table 1; the different β -activity components are singled out with coloured curves for $A = 96$: ^{96}Rb in green, ^{96}Sr in orange, ^{96}Y in purple; one component of the β -delayed neutron activity curve originating from ^{96}Rb (red) decays is singled out. Right: the same for the $A = 97$ setting of the mass separator: β -activity components are singled out with coloured curves for $A = 97$: ^{97}Rb in green, ^{97}Sr in orange, ^{97}Y in purple; the β -delayed neutron activity curve originating from ^{97}Rb (red) decays is singled out.

a contamination is unlikely due to the higher ionization potential of Sr.

To extract P_{1n} values and the production rates ϕ we used the method reported previously [7]. The method is based on the system of Bateman equations describing decay of a given radioactive source. In this method the P_{1n} and ϕ values are determined as roots of a corresponding system of Bateman equations 2.1.

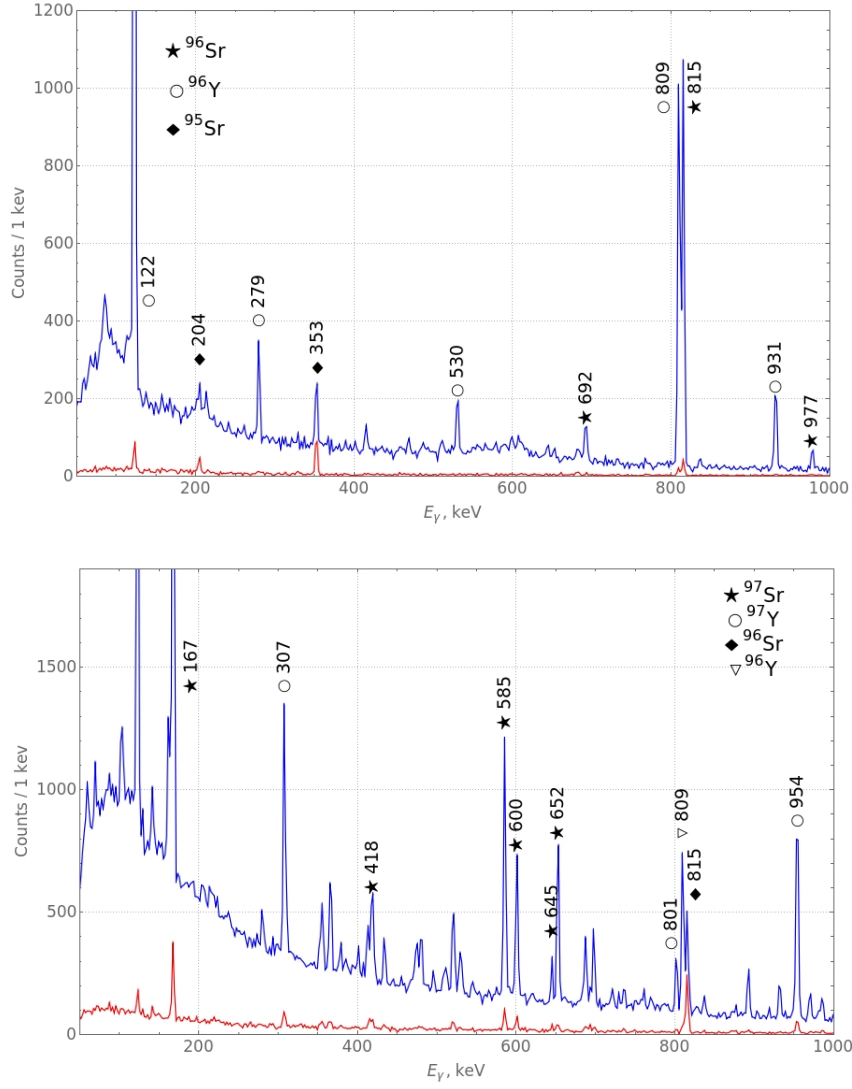


Figure 2: β gated (blue) and β -n gated (red) γ -spectra recorded for the $A = 96$ (top) and $A = 97$ (bottom) settings of the mass separator.

$$\left\{ \begin{array}{l} (N_{\beta}^{exp} - N_{\beta}^{bg}) \frac{1}{\bar{\epsilon}_{\beta}} = \int_{T_{bg}}^{T_m} \left(A_{(A,Z)}(t) + A_{(A,Z+1)}(t) + A_{(A,Z+2)}(t) + \right. \\ \left. + A_{(A-1,Z+1)}(t) + A_{(A-1,Z+2)}(t) \right) dt, \\ (N_n^{exp} - N_n^{bg}) \frac{1}{\bar{\epsilon}_n} = P_{1n} \cdot \int_{T_{bg}}^{T_m} A_{(A,Z)}(t) dt, \end{array} \right. \quad (2.1)$$

where N_{β}^{exp} and N_n^{exp} are total numbers of β and neutrons detected; N_{β}^{bg} and N_n^{bg} are the total

Table 2: Photopeaks attributed to the β and β -n decays of ^{96}Rb identified in the spectrum recorded for the $A = 96$ setting of the mass-separator. γ -intensities are given relative to the transition at 815.5 keV or 122.5 keV observed in ^{96}Sr or ^{96}Y respectively.

E_γ [keV]	Spectrum	I_γ^{rel} [%]	$S_\gamma^i/S_{\gamma\beta}^i$ [%]	assignment
122.5(3)	γ	100(2)	29(1)	$^{96}\text{Sr}(\beta)$
	$\gamma\beta$	100(3)		
204.5(3)	γ	28(4)	-	$^{96}\text{Rb}(\beta n)$
	γn	25(4)		
279.5(3)	γ	13.0(5)	27(2)	$^{96}\text{Sr}(\beta)$
	$\gamma\beta$	12.0(9)		
353.2(3)	γ	100(8)	29(3)	$^{96}\text{Rb}(\beta n)$
	$\gamma\beta$	100(14)		
	$\gamma\beta n$	100(15)		
	γn	100(8)		
530.1(4)	γ	11.3(6)	30(3)	$^{96}\text{Sr}(\beta)$
	$\gamma\beta$	11.0(9)		
692.2(4)	γ	9.0(1.5)	36(6)	$^{96}\text{Rb}(\beta)$
	$\gamma\beta$	10.5(1.5)		
809.6(4)	γ	110(3)	28(1)	$^{96}\text{Sr}(\beta)$
	$\gamma\beta$	108(3)		
815.2(4)	γ	100(3)	31(1)	$^{96}\text{Rb}(\beta)$
	$\gamma\beta$	100(4)		
931.9(4)	γ	23(1)	32(3)	$^{96}\text{Sr}(\beta)$
	$\gamma\beta$	25(2)		
977.9(4)	γ	23(1)	30(5)	$^{96}\text{Rb}(\beta)$
	$\gamma\beta$	25(2)		
1037.5(4)	γ	7.5(5)	27(4)	$^{96}\text{Rb}(\beta)$
	$\gamma\beta$	6.6(8)		
1180.5(5)	γ	4.0(4)	31(7)	$^{96}\text{Rb}(\beta)$
	$\gamma\beta$	4.1(6)		

numbers of background events; ϵ_β and ϵ_n the measured, as explained above, effective efficiencies of β detector and the TETRA array; $A_{(A,Z+1)}(t)$, ..., $A_{(A-1,Z+2)}(t)$ are the activities of daughter, grand-daughter nuclei characterized by their decay constants $\lambda_{(A,Z+1)}$, ..., $\lambda_{(A-1,Z+2)}$ respectively. Meantime the activity of the mother nuclei $A_{(A,Z)}(t)$ at a t -moment populated with the beam depends on both the decay constant $\lambda_{(A,Z)}$ and the intensity of the beam, ϕ :

Table 3: Photopeaks attributed to the β and β -n decays of ^{97}Rb identified in the spectrum recorded for the $A = 97$ setting of the mass-separator. γ -intensities are given relatively to the transition at 167.0 keV or 1905.2 keV observed in ^{97}Sr or ^{97}Y respectively.

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

$$A_{(A,Z)}(t) = \begin{cases} \phi \left(1 - e^{-(t-T_{bg}) \cdot \lambda_{(A,Z)}} \right), & T_{bg} \leq t \leq T_{bg} + T_{beam} \\ e^{-(t-T_{bg}-T_{beam}) \cdot \lambda_{(A,Z)}} (1 - e^{-T_{beam} \cdot \lambda_{(A,Z)}}) \cdot \phi, & T_{bg} + T_{beam} \leq t \leq T_m \end{cases} \quad (2.2)$$

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

In Fig. 3 the $T_{1/2}$ values are plotted versus P_{1n} for ^{96}Rb (left panel) and ^{97}Rb (right panel): all the results obtained measuring simultaneously the two properties and available in the literature have

been used. As seen, our P_{1n} and $T_{1/2}$ are in a remarkable agreement with the existing systematics.

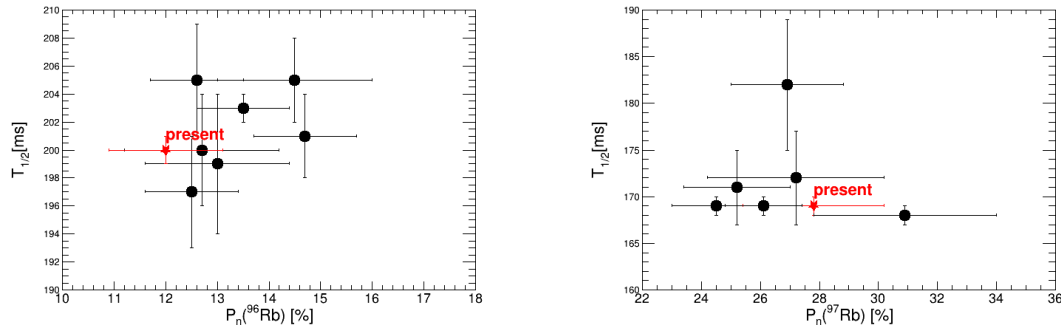


Figure 3: $T_{1/2}$ versus P_{1n} for ^{96}Rb and ^{97}Rb known from Refs. [8–14] as well as the values measured in the present work.

3 Conclusions

The TETRA long neutron counter is a unique device which is currently used at the ALTO ISOL facility to measure gross-properties of β -decay of neutron-rich nuclei. The β -decay station set in the neutron detection mode allows the simultaneous detection of β , γ and neutron radioactivity emitted by a radioactive source accumulated with the beam at the centre of the detection system. The performance of the setup was characterized using radioactive sources of $^{96,97}\text{Rb}$ produced from the photo-fission of ^{238}U . The sources were carefully chosen because their β -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 β -delayed neutron emission for $^{96,97}\text{Rb}$ measured in the experiment are in good agreement with the previously reported values. Therefore, the procedure used will be applied to extract unknown values of P_{1n} of different nuclei with large N/Z ratio (to be) produced at ALTO ISOL facility.

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