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Test of long ^3He neutron counter TETRA using $^{96,97}\text{Rb}$ radioactive sources.

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

KEYWORDS: Neutron detectors, Gaseous detectors

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1 Introduction

Nowadays the interest to the phenomenon of β -delayed (multi-neutron) 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 in 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.

Beta-decay ground state properties have been the aim for many experiments performed at TETRA. The recent results obtained using TETRA/BEDO lead to observation of unusual population resonance structures in 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. Thus, measurements of half-life ($T_{1/2}$) and probability of β -delayed (multi) neutron emission (P_{xn}) are very sensitive to the parameters of the experimental setup. Performance of this detector can be characterized using standard neutron calibration (spontaneous-fission) sources, for an example ^{252}Cf . The limitation of this source is the different energy ranger of prompt fission neutrons emitted by the source and β -delayed neutrons. Nevertheless, response of TETRA to prompt neutrons from this kind of a source is well understood by extensive simulations validated by measurements [7]. However, ^{252}Cf source, obviously, does not allow verification of analysis procedure to proceed data from a β -decay experiment. Therefore, test the setup and the analysis approaches we performed two experiments using short-lived radioactive sources created at the centre of TETRA: ^{96}Rb in the first and ^{97}Rb runs correspondingly. The ground state properties of these nuclei are know. We report $T_{\frac{1}{2}}$ and P_{1n} measured in the present experiment using previously adopted methods [1, 5] to be in a fair agreement with the literature values.

2 Experiment Details

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 bt the ALTO linear accelerator [4]. The average beam current on the tareget was $10\ \mu\text{A}$. For this experiment, the oven was connected to a W tube used to surface ionized fission products. The beam was then accelated at 30 keV. TETRA was operated behind the mass separator

PARNNe whose resolution ($\delta m/m=1300$) was high enough to provide isobaric selection $A = 96, 97$. The other members of the isobaric chain, (Sr, Y) have higher (than Rb) 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 at the ALTO experimental hall was used in the neutron detection mode [3, 7]. The detailed description of the setup is provided in Ref. [7]: 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 irradiation (T_{beam}) when the beam was impinging on the tape; and the decay time (T_{decay}) when the beam was deviated allowed decay of the accumulated isotopes. Therefore, the data acquisition system was recording neutron, β and γ activity from the source during $T_m=T_{bg}+T_{beam}+T_{decay}$. Then the tape was moved for 2 m to transport the source outside the detection system. The time settings and number of repeated cycles for $A = 96, 97$ is 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_{coll} 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. Summary of the results obtained from the analysis of the cumulated β - and neutron-activity curves for the $A = 96, 97$ settings.

Beam	T_{bg} ms	T_{coll} ms	T_{dec} ms	N_{cycles}	$T_{\frac{1}{2}}$ 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} , see Table 1, are plotted in Fig. 1. All neutrons detected for a selected mass of rubidium were attributed either to the background or to β -n 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 -n gated ($S_{\gamma\beta n}^i$) γ -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 statistic 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 is reported in Table 1. 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

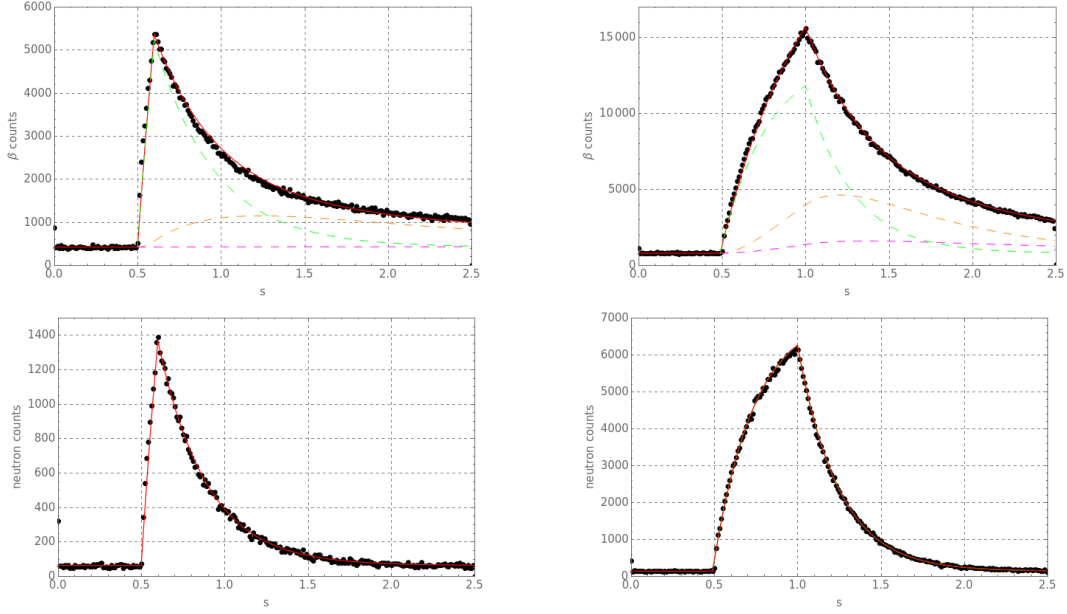


Figure 1: Left: β (top) and neutron (bottom) activity curves recorded for the $A = 96$ setting of the mass separator. These curves were accumulated over 191 tape cycles; the different β -activity components are singled out with coloured curves for $A = 96$: ^{96}Rb in green, ^{96}Sr in orange, ^{96}Y in purple and the background level is represented by the dotted line; one component of the β -delayed neutron activity curve originating from ^{96}Rb (green) 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 (green) decays is singled out.

$^{96,97}\text{Sr}$ isotopes was found in the analysis of the activity curves. Indeed, such a contamination is unlikely due to the higher ionization potential of Sr.

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.

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

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 numbers of background events; ϵ_{β} and ϵ_n the measured, as explained above, the effective

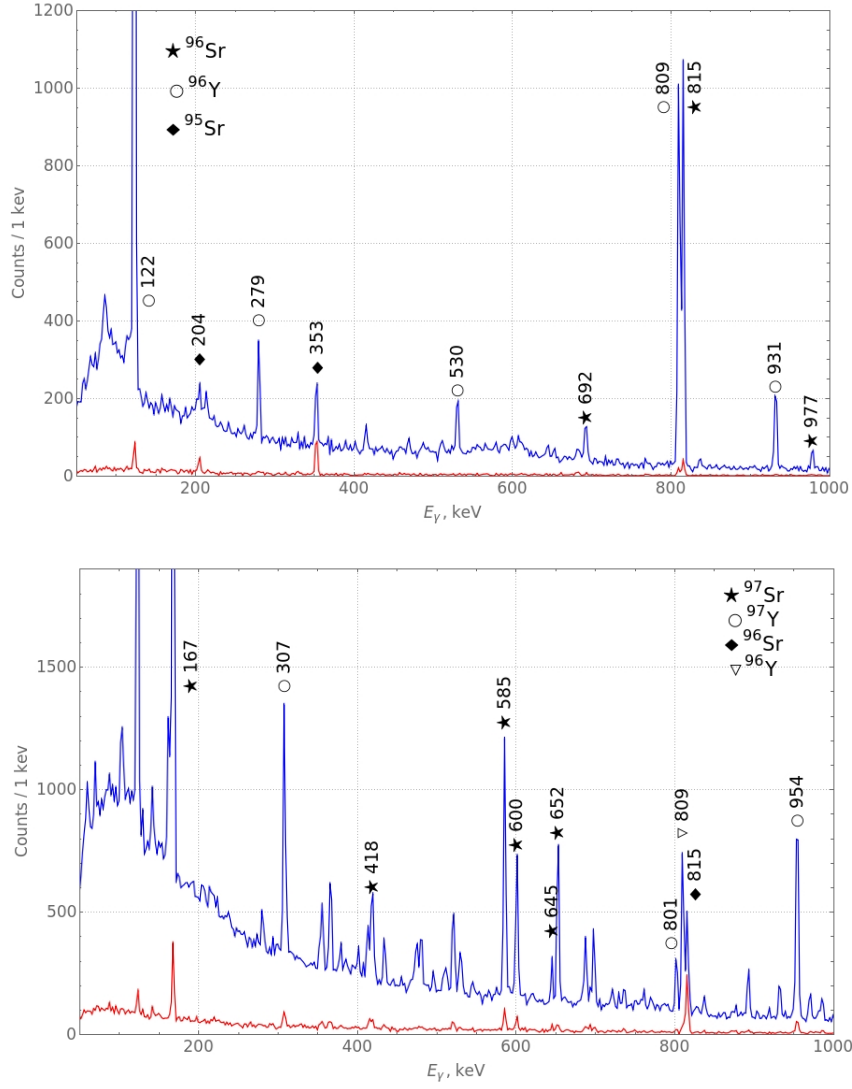


Figure 2: β gated (blue) and β -n gated (red) γ -spectra recorded for the $A = 96$ (top) and $A = 97$ (bottom) settings of the mass separator [spectra to be re-formatted].

efficiencies of β detector and the TETRA array; $A_{(A,Z+1)}$, ..., $A_{(A-1,Z+2)}$ 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 :

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

The system of the Equations 2.1 was solved for $A=96$ and $A=97$ collected datasets. Whereas

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

$\lambda_{(A,Z)}$ 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 are 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 were determined contributions to the β -activity curve accumulated after N_{cycles} from β -decay of the parent nucleus and its daughters in two experiments (^{96}Rb or ^{97}Rb) were derived and are shown by different colour code in Fig. 1.

In Fig. 3, it is plotted P_{1n} values versus $T_{\frac{1}{2}}$ for ^{96}Rb (left panel) and ^{97}Rb (right panel) from the experiments cited in the literature where these two properties of β -decay were measured simul-

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(4)	γ	100(2)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	100(4)	27(1)	
418.2(2)	γ	23(1)		$^{97}\text{Rb}(\beta n)$
	$\gamma\beta$	27(2)	33(2)	
585.1.5(2)	γ	13.0(5)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	12.0(9)	28(1)	
600.1(2)	γ	37(1)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	43(3)	32(2)	
644.8(2)	γ	11.9(6)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	12.5(5)	28(3)	
815.4(2)	γ	100(2)		$^{97}\text{Rb}(\beta n)$
	$\gamma\beta$	100(6)	27(1)	
	$\gamma\beta n$	100(11)		
953.9(2)	γ	103(4)		$^{97}\text{Sr}(\beta)$
	$\gamma\beta$	103(7)	28(1)	
1905.2(2)	γ	100(4)		$^{97}\text{Sr}(\beta)$
	$\gamma\beta$	100(8)	29(1)	
2212.3(2)	γ	39(2)		$^{97}\text{Sr}(\beta)$
	$\gamma\beta$	38(4)	28(3)	

taneously. As seen, our P_{1n} and $T_{\frac{1}{2}}$ are in a remarkable agreement with the existing systematics.

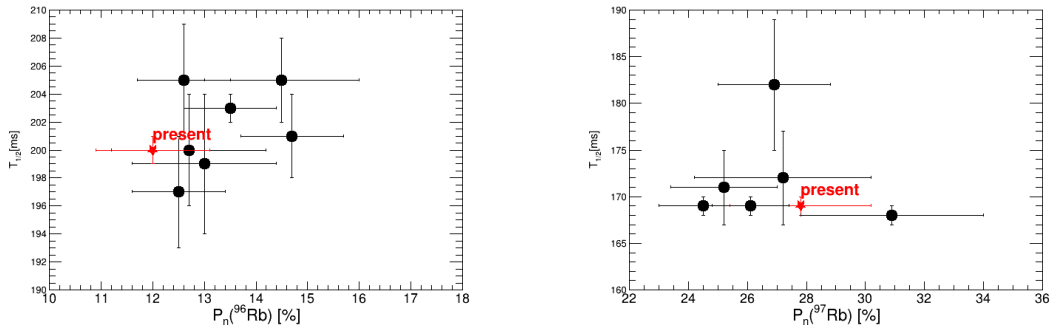


Figure 3: Comparison of P_{1n} (x-axis) versus $T_{\frac{1}{2}}$ for ^{96}Rb and ^{97}Rb known from the literature [8–14] to the values measured in the present work.

3 Conclusions

TETRA long neutron counter is a unique device which is currently used at ALTO ISOL facility to measure gross-properties of β -decay of neutron-rich nuclei. The configuration of β -decay station configured to the neutron detection mode allows possibility of simultaneous detection of β , γ and neutron radioactivity followed β -decay of the 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 experimental procedures. 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. This experimental procedure was necessary to validate the method exploited to extract un-known values of P_{1n} of different nuclei with large N/Z ratio (to be) produced at ALTO ISOL facility.

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