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Test of long ³He neutron counter TETRA using ^{96,97}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 an 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_{1/2} properties of ^{96,97}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_{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 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 ⁸³Ga [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, ²⁵²Cf 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: ⁹⁶Rb in the first and ⁹⁷Rb 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 $>2000^{\circ}$ 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 μ 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 (δ 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}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}	$T_{\rm coll}$	T _{dec}	N _{cycles}	$T_{\frac{1}{2}}$	P_{1n}	Φ	ϵ_{eff}^{β}	ϵ_{eff}^n
	ms	ms	ms		ms	%	pps		
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 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 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 ($S_{\gamma\beta}^{i}$) 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: ⁹⁶Rb in green, ⁹⁶Sr in orange, ⁹⁶Y in purple and the background level is represented by the dotted line; one component of the β -delayed neutron activity curve originating from ⁹⁶Rb (green) decays is singled out. Right: the same for the A = 97: ⁹⁷Rb in green, ⁹⁷Sr in orange, ⁹⁷Y in purple; the β -delayed neutron activity curve originating from ⁹⁷Sr in orange, ⁹⁷Y in purple; the β -delayed neutron activity curve originating from ⁹⁷Rb (green) decays is singled out.

 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.

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.

$$\begin{cases} (N_{\beta}^{exp} - N_{\beta}^{bg}) \frac{1}{\bar{\epsilon}_{\beta}} = \int_{T_{bg}}^{T_{m}} \left(A_{(A,Z)}(t) + A_{(A,Z+1)}(t) + A_{(A,Z+2)}(t) + A_{(A,Z+2)}(t) \right) \\ + A_{(A-1,Z+1)}(t) + A_{(A-1,Z+2)}(t) \right) dt, \\ (N_{n}^{exp} - N_{n}^{bg}) \frac{1}{\bar{\epsilon}_{n}} = P_{1n} \cdot \int_{T_{bg}}^{T_{meas}} A_{(A,Z)}(t) dt, \end{cases}$$

$$(2.1)$$

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

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

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

E_{γ} [keV]	Spectrum	I^{rel}_γ [%]	$\mathbf{S}^i_{\gamma}/\mathbf{S}^i_{\gammaeta}$ [%]	assignment	
100 5(0)	γ	100(2)	20(1)	96 Sr(β)	
122.3(2)	γeta	100(3)	29(1)		
204 5(2)	γ	28(4)		96 Rb(β n)	
204.3(2)	γn	25(4)	-		
270 5(2)	γ	13.0(5)	27(2)	96 Sr(β)	
219.3(2)	γeta	12.0(9)	27(2)		
	γ	100(8)			
252 2(5)	γeta	100(14)		$96\mathbf{Ph}(\beta \mathbf{n})$	
555.2(5)	γeta n	100(15)	20(3)	κυ(ρπ)	
	γn	100(8)	29(3)		
530 1(2)	γ	11.3(6)	30(3)	96 c +(B)	
550.1(2)	γeta	11.0(9)	30(3)	$\mathbf{SI}(p)$	
6022(2)	γ	9.0(1.5)	36(6)	96 Db (<i>B</i>)	
092.2(2)	γeta	10.5(1.5)	30(0)	$\mathbf{KU}(p)$	
800 6(2)	γ	110(3)	28(1)	$96\mathbf{Sr}(\beta)$	
809.0(2)	γeta	108(3)	20(1)	31(p)	
815.2(2)	γ	100(3)	31(1)	96 Dh (B)	
013.2(2)	γeta	100(4)	31(1)	κυ(ρ)	
0.210(2)	γ	23(1)	32(3)	$96\mathbf{Sr}(\beta)$	
931.9(2)	γeta	25(2)	32(3)	$\mathbf{SI}(p)$	
077 0(2)	γ	23(1)	30(5)	96 Rb(β)	
911.9(2)	γeta	25(2)	30(3)		
1027 5(2)	γ	7.5(5)	27(4)	96 Dh (B)	
1037.3(2)	γeta	6.6(8)	27(4)	$\mathbf{KU}(p)$	
1180 5(2)	γ	4.0(4)	31(7)	96 Rb(eta)	
1100.3(2)	$\gamma\beta$	4.1(6)	31(7)		

Table 2: Photopeaks attributed to the β and β -n decays of ⁹⁶Rb 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 ⁹⁶Sr or ⁹⁶Y respectively.

 $\lambda_{(A,Z)}$ was fixed to the value obtained from the fit of neutron activities, the $\lambda_{(A,Z+1)}$, ..., $\lambda_{(A-1,Z+2)}$ were fixed to their table values. The obtained P_{1n} and ϕ for ⁹⁶Rb and ⁹⁷Rb 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 (⁹⁶Rb or ⁹⁷Rb) were derevied 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 ⁹⁶Rb (left panel) and ⁹⁷Rb (right panel) from the experiments cited in the literature where these two properties of β -decay were measured simul-

E_{γ} [keV]	Spectrum	I^{rel}_γ [%]	${ m S}^i_\gamma/{ m S}^i_{\gammaeta}$ [%]	assignment	
167.0(4)	γ	100(2)	27(1)	$^{97}{ m Rb}(eta)$	
107.0(4)	γeta	100(4)	27(1)		
418 2(2)	γ	23(1)	22(2)	97 Rb(β n)	
416.2(2)	γeta	27(2)	33(2)		
595 1 5(2)	γ	13.0(5)	28(1)	97 D L(2)	
383.1.3(2)	γeta	12.0(9)	28(1)	$\mathbf{KD}(p)$	
600 1(2)	γ	37(1)	22(2)	97 Db (<i>B</i>)	
000.1(2)	γeta	43(3)	32(2)	$\mathcal{KD}(p)$	
644 8(2)	γ	11.9(6)	28(2)	97 Db (β)	
044.8(2)	γeta	12.5(5)	28(3)	$\mathbf{KU}(p)$	
	γ	100(2)	27(1)	97 Ph (β p)	
815.4(2)	γeta	100(6)	27(1)	^{sh} KO(<i>p</i> II)	
	γeta n	100(11)			
052 0(2)	γ	103(4)	28(1)	$97\mathbf{Sr}(\beta)$	
955.9(2)	γeta	103(7)	20(1)	$\mathbf{SI}(p)$	
1005 2(2)	γ	100(4)	20(1)	97 Sr(β)	
1903.2(2)	γeta	100(8)	29(1)		
2212(2(2))	γ	39(2)	28(2)	97 Sr(β)	
2212.3(2)	$\gamma\beta$	38(4)	20(3)		

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.

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 ⁹⁶Rb and ⁹⁷Rb 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}Rb produced from the photo-fission of ²³⁸U. 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 and the probabilities of β -delayed neutron emission for ^{96,97}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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