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

D. Testov,[a,b,1] **D. Verney**[c] **Yu. Penionzhkevich**[a,d] **A. Boso**[e] **C. Delafosse**[f] **F. Didierjean**[g] **I. Deloncle**[h] **F. Ibrahim**[c] **F. Le Blanc**[c] **C. Gaulard**[h] **J. Guillot**[c] **S. Lukyanov**[a] **V. Maslov**[a] **I. Matea**[c] **B. Roussière**[c] **A. Severyukhin**[a] **Yu. Sobolev**[a] **E. Sokol**[a] **V. Smirnov**[a] **R. Thoër**[h] **D. Thisse**[c] **G. Tocabens**[c] **and ALTO people**

[a]*Joint Institute for Nuclear Research, Dubna, Moscow region, Russia*
[b]*Dipartimento di Fisica e Astronomia and INFN, Sezione di Padova, Padova, Italy*
[c]*Institut de Physique Nucléaire, IN2P3/CNRS and University Paris Sud, Orsay, France*
[d]*National Research Nuclear University, Kashirskoye Shosse 31, Moscow 115409, Russia*
[e]*National Physical Laboratory, Teddington, Middlesex, UK*
[f]*Department of Physics, University of Jyväskylä, Finland*
[g]*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
[h]*Centre de Sciences Nucléaires et de Sciences de la Matière, IN2P3/CNRS, Orsay, France*

E-mail: dmitry.testov@lnl.infn.it

Abstract: The TETRA long neutron counter is operated at ALTO ISOL facility behind the PARRNe 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}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

[1]Corresponding author.

Contents

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°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 (δm/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}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: $T_{\rm bg}$ is the background counting time before beam collection, $T_{\rm beam}$ the duration of the beam collection and $T_{\rm dec}$ the beam-off source decay counting time, in ms. $N_{\rm cycles}$ 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	$T_{\rm bg}$ ms	$T_{\rm beam}$ ms	$T_{\rm dec}$ ms	$N_{\rm cycles}$	$T_{1/2}$ ms	P_{1n} %	Φ pps	ϵ^{β}_{eff} %	ϵ^{n}_{eff} %
^{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 $N_{\rm cycles}$ 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}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^i_γ), β gated ($S^i_{\gamma\beta}$), and β-neutron gated ($S_{\gamma\beta}{}^i_n$) 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 $S^i_{\gamma\beta}/S^i_\gamma$ 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}Sr isotopes was found in the analysis of the activity curves. Indeed, such

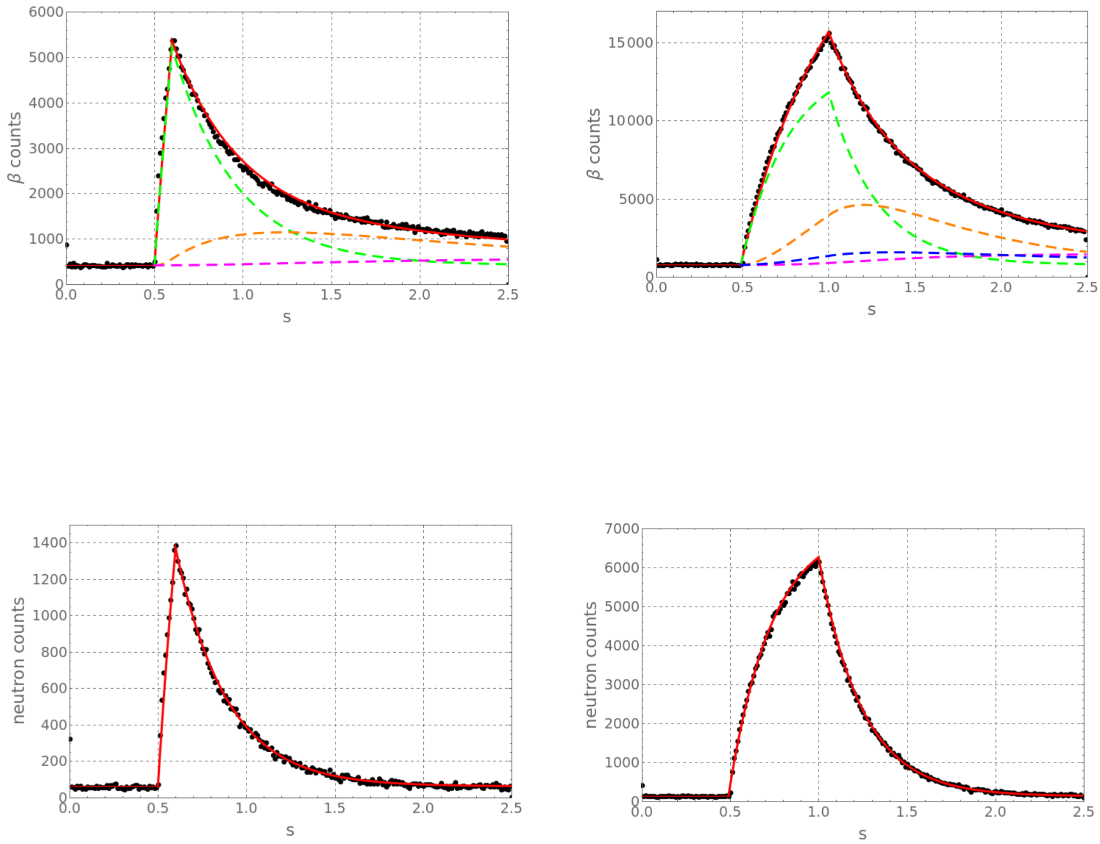

Figure 1: Left: β (top) and neutron (bottom) activity curves recorded for the $A = 96$ setting of the mass separator. The number of cycles is given in Table 1; the different β-activity components are singled out with coloured curves for $A = 96$: ^{96}Rb in green, ^{96}Sr in orange, ^{96}Y in purple;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

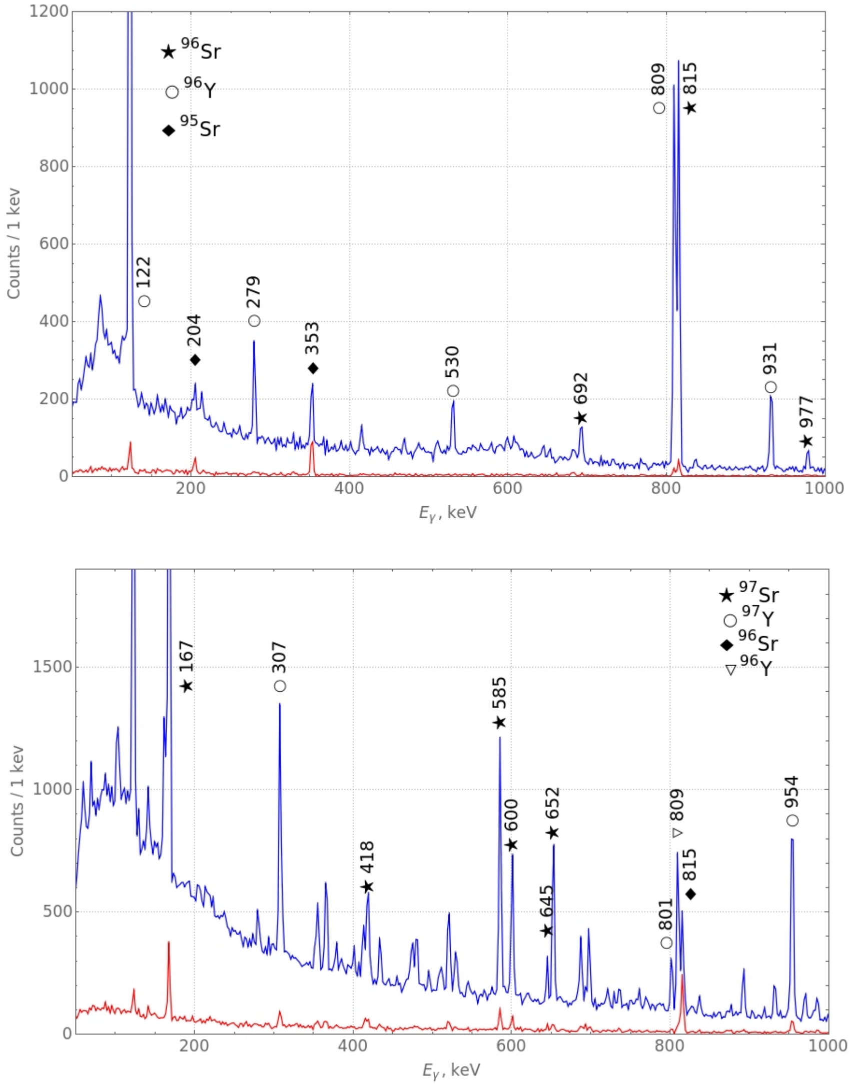

Figure 2: β gated (blue) and β-n gated (red) γ-spectra recorded for the $A = 96$ (top) and $A = 97$ (bottom) settings of the mass separator.

$$\begin{cases} (N_\beta^{exp} - N_\beta^{bg})\frac{1}{\bar{\epsilon}_\beta} = \displaystyle\int_{T_{bg}}^{T_m} \Big(A_{(A,Z)}(t) + A_{(A,Z+1)}(t) + A_{(A,Z+2)}(t) + \\ + A_{(A-1,Z+1)}(t) + A_{(A-1,Z+2)}(t) \Big) dt, \\ \\ (N_n^{exp} - N_n^{bg})\frac{1}{\bar{\epsilon}_n} = P_{1n} \cdot \displaystyle\int_{T_{bg}}^{T_m} A_{(A,Z)}(t) dt, \end{cases} \tag{2.1}$$

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} [%]	$S^i_\gamma/S^i_{\gamma\beta}$ [%]	assignment
122.5(3)	γ	100(2)	29(1)	^{96}Sr(β)
	$\gamma\beta$	100(3)		
204.5(3)	γ	28(4)	-	^{96}Rb(βn)
	γn	25(4)		
279.5(3)	γ	13.0(5)	27(2)	^{96}Sr(β)
	$\gamma\beta$	12.0(9)		
353.2(3)	γ	100(8)		^{96}Rb(βn)
	$\gamma\beta$	100(14)		
	$\gamma\beta$n	100(15)	29(3)	
	γn	100(8)		
530.1(4)	γ	11.3(6)	30(3)	^{96}Sr(β)
	$\gamma\beta$	11.0(9)		
692.2(4)	γ	9.0(1.5)	36(6)	^{96}Rb(β)
	$\gamma\beta$	10.5(1.5)		
809.6(4)	γ	110(3)	28(1)	^{96}Sr(β)
	$\gamma\beta$	108(3)		
815.2(4)	γ	100(3)	31(1)	^{96}Rb(β)
	$\gamma\beta$	100(4)		
931.9(4)	γ	23(1)	32(3)	^{96}Sr(β)
	$\gamma\beta$	25(2)		
977.9(4)	γ	23(1)	30(5)	^{96}Rb(β)
	$\gamma\beta$	25(2)		
1037.5(4)	γ	7.5(5)	27(4)	^{96}Rb(β)
	$\gamma\beta$	6.6(8)		
1180.5(5)	γ	4.0(4)	31(7)	^{96}Rb(β)
	$\gamma\beta$	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 $\gamma\beta$	100(2) 100(4)	27(1)	^{97}Rb(β)
418.2(3)	γ $\gamma\beta$	23(1) 27(2)	33(2)	^{97}Rb(βn)
585.1.5(4)	γ $\gamma\beta$	13.0(5) 12.0(9)	28(1)	^{97}Rb(β)
600.1(4)	γ $\gamma\beta$	37(1) 43(3)	32(2)	^{97}Rb(β)
644.8(4)	γ $\gamma\beta$	11.9(6) 12.5(5)	28(3)	^{97}Rb(β)
815.4(4)	γ $\gamma\beta$ $\gamma\beta$n	100(2) 100(6) 100(11)	27(1)	^{97}Rb(βn)
953.9(4)	γ $\gamma\beta$	103(4) 103(7)	28(1)	^{97}Sr(β)
1905.2(5)	γ $\gamma\beta$	100(4) 100(8)	29(1)	^{97}Sr(β)
2212.3(5)	γ $\gamma\beta$	39(2) 38(4)	28(3)	^{97}Sr(β)

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

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 $\lambda_{(A,Z+1)}$, ..., $\lambda_{(A-1,Z+2)}$ 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.

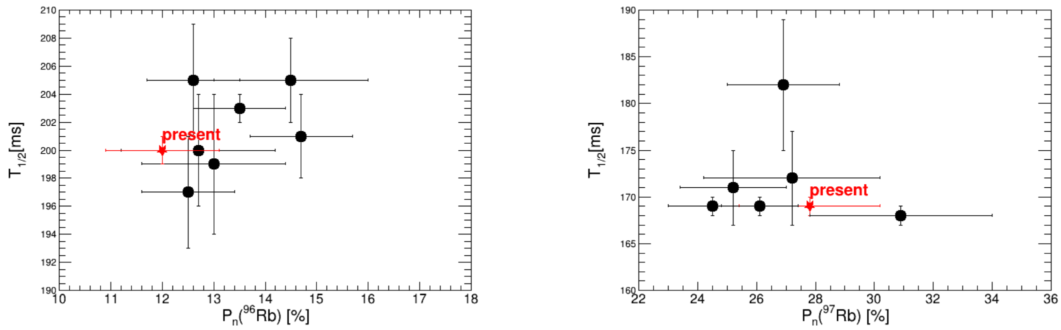

Figure 3: $T_{1/2}$ versus P_{1n} for ^{96}Rb and ^{97}Rb known from Refs. [8–14] as well as the valuesvalues measured in the present work.

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}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}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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