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## Test of long $^3\text{He}$ 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  $\beta$ -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  $\beta$ -delayed neutron emission ( $P_{1n}$ ) is only possible using a well-known  $\beta$ -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  $\beta$ -delayed (multi-neutron) neutron emission is arising. The mechanism which drives this process in neutron-rich nuclei is still not understood. Whereas,  $\beta$ -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  $\beta$ -decay properties of nuclei far away from the line of nuclei  $\beta$ -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  $\beta$ -decay of  $^{83}\text{Ga}$  [5] and high energy  $\gamma$ -ray emission [6] which can be interpreted as a competition between  $\gamma$ -ray and neutron emission beyond the neutron separation energy threshold. Thus, measurements of half-life ( $T_{1/2}$ ) and probability of  $\beta$ -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  $^{252}\text{Cf}$ . The limitation of this source is the different energy ranger of prompt fission neutrons emitted by the source and  $\beta$ -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,  $^{252}\text{Cf}$  source, obviously, does not allow verification of analysis procedure to proceed data from a  $\beta$ -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:  $^{96}\text{Rb}$  in the first and  $^{97}\text{Rb}$  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  $\text{UC}_x$  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.

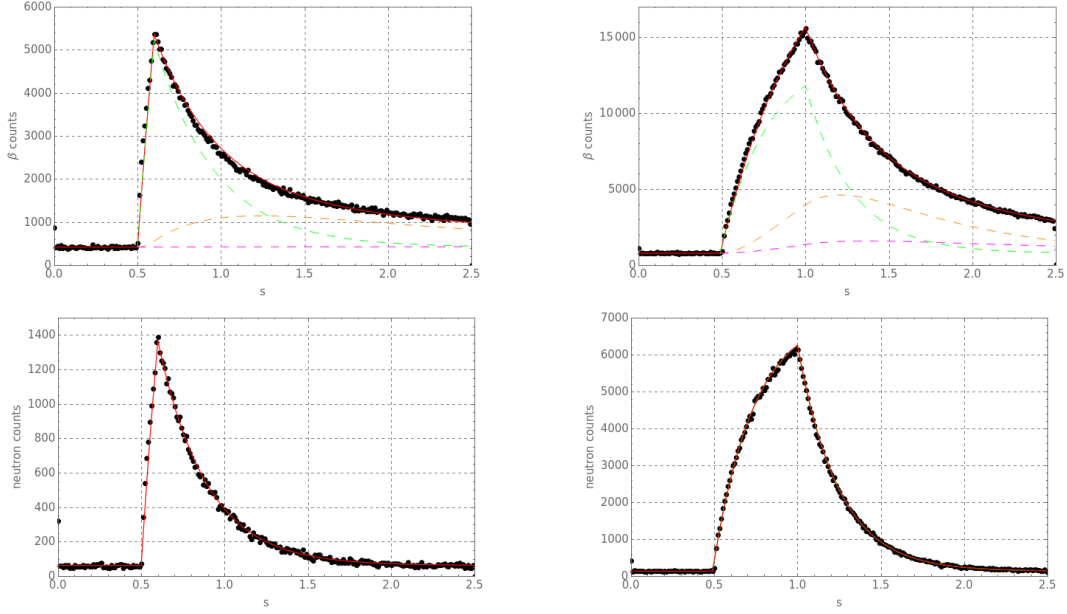
The  $\beta$ -decay station installed at the ALTO experimental hall was used in the neutron detection mode [3, 7]. The detailed description of the setup is provided in Ref. [7]: the surface-ionized mass-separated beams were collected on a Al-coated mylar tape at the centre of the long-neutron counter TETRA creating a radioactive source. The collection point was surrounded by a plastic scintillator for  $\beta$  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 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,  $\beta$  and  $\gamma$  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  $\beta$ - 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	$P_{1n}$ %	$\Phi$ pps	$\epsilon_{eff}^{\beta}$	$\epsilon_{eff}^n$
$^{96}\text{Rb}$	500	100	1900	191	200(1)	12.0(1.1)	$\sim 3.4 \cdot 10^4$	29(4)	58(4)
$^{97}\text{Rb}$	500	500	1500	500	169(1)	27.8(2.4)	$\sim 0.9 \cdot 10^4$	29(4)	56(4)

The resulting  $\beta$ - 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  $\beta$ -n decay of rubidium isotopes. Even if,  $\beta$ -delayed neutron emission is energetically allowed, there is no experimental evidence of  $\beta$ -delayed neutron emission of  $^{96,97}\text{Sr}$  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  $\beta$  detector ( $\epsilon_{\beta}$ ) and the TETRA array ( $\epsilon_n$ ) was derived from coincidence  $\gamma$ -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 ( $S_{\gamma}^i$ ),  $\beta$  gated ( $S_{\gamma\beta}^i$ ), and  $\beta$ -n gated ( $S_{\gamma\beta n}^i$ )  $\gamma$ -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  $S_{\gamma\beta}^i/S_{\gamma}^i$  ratios measured for the  $i$ -th transition. Due to lack of statistic in the  $\beta$ -n  $\gamma$ -gated spectrum  $\epsilon_n$  was found using only the most strong transitions at 352 keV and 815 keV in  $^{95}\text{Sr}$  and  $^{96}\text{Sr}$  respectively as is reported in Table 1. All the  $\gamma$  activities recorded could be identified and no isobaric contaminants were observed within our detection limits. Moreover, no evidence for contamination from surface ionized



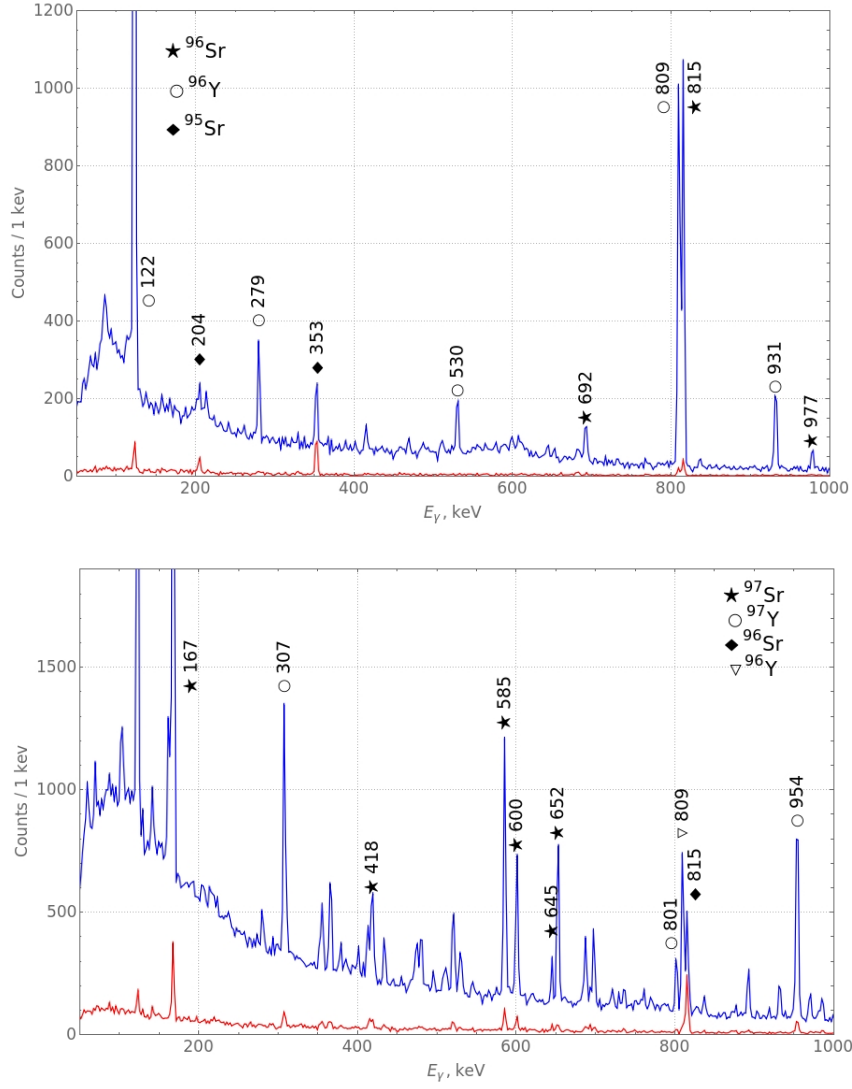
**Figure 1:** Left:  $\beta$  (top) and neutron (bottom) activity curves recorded for the  $A = 96$  setting of the mass separator. These curves were accumulated over 191 tape cycles; the different  $\beta$ -activity components are singled out with coloured curves for  $A = 96$ :  $^{96}\text{Rb}$  in green,  $^{96}\text{Sr}$  in orange,  $^{96}\text{Y}$  in purple and the background level is represented by the dotted line; one component of the  $\beta$ -delayed neutron activity curve originating from  $^{96}\text{Rb}$  (green) decays is singled out. Right: the same for the  $A = 97$  setting of the mass separator:  $\beta$ -activity components are singled out with coloured curves for  $A = 97$ :  $^{97}\text{Rb}$  in green,  $^{97}\text{Sr}$  in orange,  $^{97}\text{Y}$  in purple; the  $\beta$ -delayed neutron activity curve originating from  $^{97}\text{Rb}$  (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  $\phi$  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  $\phi$  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  $N_{\beta}^{exp}$  and  $N_n^{exp}$  are total numbers of  $\beta$  and neutrons detected;  $N_{\beta}^{bg}$  and  $N_n^{bg}$  are the total numbers of background events;  $\epsilon_{\beta}$  and  $\epsilon_n$  the measured, as explained above, the effective



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

efficiencies of  $\beta$  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,  $\phi$ :

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

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

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

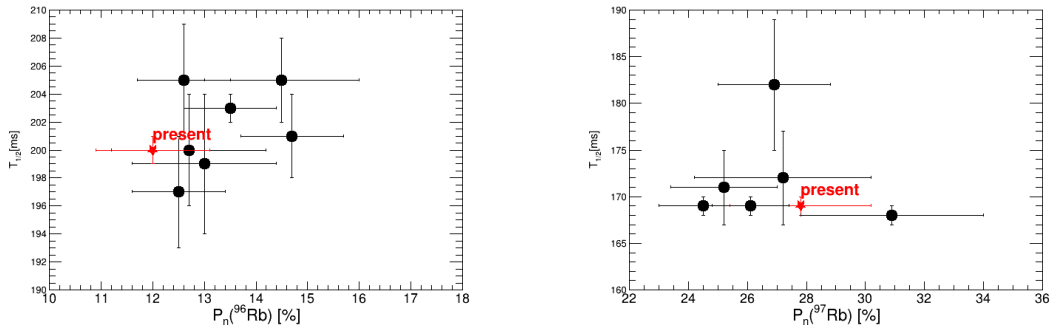
$\lambda_{(A,Z)}$  was fixed to the value obtained from the fit of neutron activities, the  $\lambda_{(A,Z+1)}, \dots, \lambda_{(A-1,Z+2)}$  were fixed to their table values. The obtained  $P_{1n}$  and  $\phi$  for  $^{96}\text{Rb}$  and  $^{97}\text{Rb}$  are reported in Table 1. A constant average production yield was assumed. The errors on  $P_{1n}$  and  $\phi$  are mostly dominated by associated statistical errors but also by uncertainty on  $\beta$  and neutron efficiencies and uncertainties on half-lives of Sr and Y daughters known from the literature. Once  $P_{1n}$  and  $\phi$  were determined contributions to the  $\beta$ -activity curve accumulated after  $N_{\text{cycles}}$  from  $\beta$ -decay of the parent nucleus and its daughters in two experiments ( $^{96}\text{Rb}$  or  $^{97}\text{Rb}$ ) 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  $^{96}\text{Rb}$  (left panel) and  $^{97}\text{Rb}$  (right panel) from the experiments cited in the literature where these two properties of  $\beta$ -decay were measured simul-

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

$E_\gamma$ [keV]	Spectrum	$I_\gamma^{rel}$ [%]	$S_\gamma^i/S_{\gamma\beta}^i$ [%]	assignment
167.0(4)	$\gamma$	100(2)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	100(4)	27(1)	
418.2(2)	$\gamma$	23(1)		$^{97}\text{Rb}(\beta n)$
	$\gamma\beta$	27(2)	33(2)	
585.1.5(2)	$\gamma$	13.0(5)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	12.0(9)	28(1)	
600.1(2)	$\gamma$	37(1)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	43(3)	32(2)	
644.8(2)	$\gamma$	11.9(6)		$^{97}\text{Rb}(\beta)$
	$\gamma\beta$	12.5(5)	28(3)	
815.4(2)	$\gamma$	100(2)		$^{97}\text{Rb}(\beta n)$
	$\gamma\beta$	100(6)	27(1)	
	$\gamma\beta n$	100(11)		
953.9(2)	$\gamma$	103(4)		$^{97}\text{Sr}(\beta)$
	$\gamma\beta$	103(7)	28(1)	
1905.2(2)	$\gamma$	100(4)		$^{97}\text{Sr}(\beta)$
	$\gamma\beta$	100(8)	29(1)	
2212.3(2)	$\gamma$	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  $^{96}\text{Rb}$  and  $^{97}\text{Rb}$  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  $\beta$ -decay of neutron-rich nuclei. The configuration of  $\beta$ -decay station configured to the neutron detection mode allows possibility of simultaneous detection of  $\beta$ ,  $\gamma$  and neutron radioactivity followed  $\beta$ -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  $^{238}\text{U}$ . 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 experimental procedures. The half-lives and the probabilities of  $\beta$ -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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