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Studies of ^{123}Ag β -decay at ALTO

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Abstract The neutron rich ^{123}Ag nucleus was pop-
ulated via induced photofission of UC_x at the ALTO
ISOL facility. Its β -decay properties were studied by
means of detecting β -delayed γ and neutron activities.
The measured half-life $T_{1/2} = 0.350(20)$ s agreed with
the earlier data; the β -delayed neutron emission branch-
ing $P_{1n} = 1.01(24)\%$ was reestablished using γ and neu-
tron counting.

Keywords β -decay · β -delayed neutron emission ·
beams of radioactive nuclei

1 Introduction

The delayed neutron emission probability (P_n) and the
half-life are the two key ingredients of β -decay that de-
pend on the integrated quantities of the nuclear struc-
ture. The half-life provides information on an integrated
total strength function, whereas P_n value probes the
part of the strength function above the neutron separa-
tion energy (S_n). Therefore, measurements of these
values in experiments often provides the first insight
into the nuclear structure. Although the mechanism of
 β -decay of nuclei is in principle understood, develop-
ment of a satisfactory description coherent with new
data sets for neutron-rich species is highly required. A
significant experimental effort is currently underway to
reveal the role of neutron excess in the shell evolution
in these regions [1]. The current experimental study of
 β -delayed (multi) neutron emission in the regions of the
chart of nuclides, which are important from the astro-
physical point of view, is facing a new era: pure beams
of neutron-rich nuclei of hard-to-reach mass regions of

^{78}Ni and ^{132}Sn , have become available at radioactive
ion beam facilities [2].

Reliable knowledge of the nuclear physics proper-
ties for the extremely neutron-rich nuclei along the r -
process path are needed to interpret the observational
data in the framework of proposed astrophysical mod-
els [3–5]. As the neutron excess increases near the drip
line, we expect the properties of the giant resonances
and of the low-lying collective states to be dramatically
affected at extreme N/Z ratios [6]. The formation of
a neutron-skin may introduce a new type of collective
mode in neutron-rich nuclei corresponding to an out-of-
phase vibration of the skin against the neutron-proton
inert core [7]. The concentration of the electric dipole
($E1$) strength around the particle separation energy is
commonly called the pygmy dipole resonance (PDR).
The occurrence of non-negligible low-lying $E1$ -strength
can influence the radiative neutron capture cross sec-
tion by orders of magnitude and, consequently, also the
rate of the astrophysical r -process nucleosynthesis (see
details in ref. [8]). In case of the neutron-rich nuclei in
the vicinity of $A \approx 130$, the $E1$ strength could be sig-
nificantly more important than in nuclei close to the
valley of β -stability.

In this context, the β -decay properties of heavy Ag
and Cd isotopes are ideal candidates for such studies.
Particularly, in very neutron-rich Ag nuclei the total
energy released through beta-decay, Q_β , can go be-
yond 10 MeV (in case of ^{130}Ag , for example, $Q_\beta =$
15.42(30) MeV [9]) and subsequently even deeply bound
neutrons can decay into protons. When the Cd daugh-
ter nucleus is produced in a high-energy configuration
above the neutron separation energy (S_n), it usually
de-excites through the neutron emission. On the other
hand, the rearrangement of nuclear matter could pro-
ceed through collective modes of de-excitation in the

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daughter isotope, involving also the most superficial nucleons. Namely, microscopic calculations by refs. [10,11] showed that the Gamow-Teller (GT) transitions of deeply-bound neutrons can trigger coherent dipolar oscillations (like the PDR), which in turn engender a significant emission of $E1$ γ -radiation. It is worth mentioning that the inclusion of the coupling terms with more complex configurations than $1p - 1h$ ones substantially enriches the low-energy spectrum of nuclei in the $A \approx 130$ mass range, see, e.g., ref. [12].

The r-process abundance region around $A \approx 110$ prior to the $A = 130$ peak, is one of the regions of intense interest, where the astrophysical models estimate the abundances by an order of magnitude or more [13]. The newly measured P_n values in this region will directly affect the final r-process abundance pattern between the abundance „trough” the region ($A = 114 - 120$) and the onset ($A \approx 123$) of the $A = 130$ peak region.

The β -delayed neutron emission of ^{123}Ag has been reported previously from the OSIRIS mass-separator in refs. [14, 15]. The mass separated heavy fission products have been studied using a neutron counter comprised of 30 ^3He tubes. The weak neutron activities seen at the 122 and 123 masses were assigned to the silver isotopes. Consequently, due to 390(30) ms half-life measured for the 123 mass the neutron activity (still weak) was assigned to decay of ^{123}Ag . Later at the TRISTAN on-line isotope separator facility at Brookhaven National Laboratory, the half-lives and P_n values have been measured for $^{121-124}\text{Ag}$ [16]. In a single set of experiments, using mass-separated fission fragments, the neutron and β growth (decay) curves were measured simultaneously at masses 120-124 and at 127. The neutron decay curve resulted in a 300(10) ms half-life which was assigned to decay of ^{123}Ag . The P_n value of 0.55(9)% was determined as a ratio of the neutron to β saturation activities, corrected by the corresponding efficiencies. Neutrons were straight detected by 40 ^3He proportional tubes embedded in polyethylene. The more recent measurements of the β -delayed neutron emission branching for neutron-rich Ag isotopes, populated in a fragmentation reaction, have been done at the National Superconducting Cyclotron Laboratory at Michigan State University [17]. The yielded half-life of 272(24) ms was derived using time difference between the ion implantation and the correlated β -decay. The half-life was slightly shorter than reported previously [15, 16]. The P_n value was determined as 1.0(5)% based on the number of β -neutron coincidence events divided by the number of β decays following the implantation of ^{123}Ag heavy ions. Neutrons were detected by the NERO array consisting of 60 ^3He and BF_3 counters.

Regardless the numerous studies the ^{123}Cd level scheme populated in the decay of ^{123}Ag was only reported in the study performed at the Buenos Aires Tandem accelerator facility [18]. The ^{123}Ag nuclei was produced as a mass-separated fission product from the fast-neutron fission of natural U. Then γ -spectrometry measurements were performed using two Ge(HP) detectors. Spins and parities for the most important states were suggested upon $\log(ft)$ values obtained from measured γ -ray transition intensities.

In the work presented here the neutron-rich ^{123}Ag nucleus was revisited to study for the first time its β -decay by simultaneous detection of β -delayed neutron- and γ activities. The heavy Ag nuclei were populated using induced photofission of uranium at the ALTO ISOL facility [19, 20] and measured at the BEDO β -decay tape station [21] equipped with the TETRA neutron detector containing 80 proportional counters of ^3He [22]. Up to now at ALTO the studies were concentrated in the region of heavy Ga nuclei crossing the $N = 50$ neutron closed shell: competition of the neutron emission process with the emission of high energy γ -rays [10]; population in β -decay resonance low-energy structures [23]. In the present paper we report the first measurement of β -delayed neutron precursor in the ^{132}Sn region performed at ALTO.

2 Experimental details

Neutron-rich isotopes were produced via induced photofission at ISOL facility ALTO [19, 20]. A 50 MeV, $\sim 7 \mu\text{A}$ electron beam was applied to a UC_x production target heated up to 2000 °C to obtain low energetic beams (~ 30 keV) of radioactive isotopes. Photofission products were extracted from the target with a hot plasma universal ion source FEBIAD (Forced Electron Beam Induced Arc Discharge) [24] with 1+ charge state and delivered to the mass separator PARRNe. The resolution ($m/\delta m \approx 1500$) was high enough to provide isobaric selection of $A = 123$. The members of the isobaric chain such as Pd and Rh were refractory metals whose efficiency to release from the source was very low.

The modular detection system equipped with the BEDO tape station [21] was installed behind the mass separator PARRNe and was operated in the neutron detection configuration. It consisted of highly efficient neutron detector TETRA [22]; a $\sim 4\pi$ β scintillator and a High-Purity coaxial Germanium γ -ray detector (EUROGAM-1 type [25]). Mass-separated beams were collected onto an Al-coated Mylar movable tape at the geometrical centre of the array. TETRA is one of the long-neutron counters constructed at JINR Dubna originally for spontaneous fission studies [26] but modified to allow β

171 delayed neutron measurements. TETRA response to
 172 the β -delayed neutron is fully understood by means of
 173 MCNP simulations [27] and by the reference measure-
 174 ments of β -decay of heavy $^{96,97}\text{Rb}$ isotopes [28]. The
 175 neutron efficiency $\epsilon_n = 53(2)\%$ was measured with a
 176 ^{252}Cf source. The Ge(HP) detector was calibrated using
 177 standard sources of ^{60}Co and ^{152}Eu . The absolute
 178 efficiency measured for 1.3 MeV γ -rays was $\epsilon_\gamma \sim 0.6\%$.
 179 The efficiency of the β detector $\epsilon_\beta = 37(4)\%$ was de-
 180 termined using ratios of area under peaks for identified
 181 transitions in β -decay daughters in the direct γ and β
 182 gated γ -spectra using the coincidence method described
 183 in ref. [22, 28].

184 The measurement cycle was divided into three stages.
 185 The data was collected for $T_{meas} = T_{beam} + T_{decay}$:
 186 after the accumulation of a source during T_{beam} , the
 187 beam was deviated to allow counting the decay of the
 188 source for T_{decay} . At the third stage the data acquisi-
 189 tion system was stopped and the tape was rewound for
 190 2 m to transport the source, accumulated on the tape,
 191 outside the detection system. Adjusting the T_{beam} and
 192 T_{decay} parameters, see Table 1, it was possible to fa-
 193 vour detection of decay radioactivity from ^{123}Ag . Since the
 194 half-life of ^{123}Ag is in a hundred ms range, in the of-
 195 fline analysing procedure for every cycle, only the data
 196 collected within $\tau_{meas} = \tau_{data} + \tau_{bg}$, defined as in Fig. 1
 197 was sorted. The γ -ray spectra incremented within τ_{data}
 198 and τ_{bg} were denoted as S_{data} and S_{bg} correspondingly.

199 Figure 2 (top), displays the β gated γ -spectrum
 200 (S_{data}^β) which reveals transitions characterising β -decay
 201 of the $A = 123$ isobaric multiplet (Ag, Cd, In). Whereas
 202 the background spectra S_{bg}^β , Fig. 2 (middle), shows tran-
 203 sitions only in the longer lived In and Sn. The subtrac-
 204 tion of both spectra resulted in S_{sub}^β spectrum plotted in
 205 Fig. 2 (bottom). In this spectrum transitions in ^{123}Cd
 206 were favoured to be on the positive part of the scale
 207 whereas the γ -ray transitions in the longer-lived daugh-
 208 ters are „reversed” to the negative part. This method
 209 allowed us to clearly observe five transitions previously
 210 attributed to ^{123}Cd [18]. The relative intensities mea-
 211 sured in both S_{data}^β and S_{sub}^β are in agreement with the
 212 ones quoted in ref. [18], see Table 2. The high pro-
 213 duction rates of Cd and In isotopes together with a
 214 small P_{1n} value for ^{123}Ag as well as large neutron coin-
 215 cidence window (100 μs due to the neutron moderation)
 216 resulted in a fact that the neutron tag did not lead to
 217 further purification of the recorded γ -ray spectra.

218 3 P_{1n} extraction procedure

219 The P_{1n} value of a neutron precursor (A, Z) is the ra-
 220 tio of the number of decays to the β -delayed neutron
 221 daughter ($N_{\beta dn}$) to the total number of β -decays of the

Table 1 Tape-cycle parameters in ms used for the $A = 123$ settings: T_{beam} and T_{decay} are the duration of the beam collection and the beam-off source decay running acquisition time correspondingly; τ_{data} , τ_{bg} and τ_{decay} are as defined in Fig. 1 and N_{cycles} is the total number of tape cycles.

T_{beam}	T_{decay}	τ_{data}	τ_{decay}	τ_{bg}	N_{cycles}
1000	4000	1500	500	1500	63

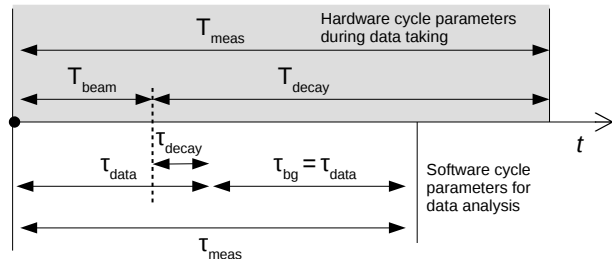


Fig. 1 Time-cycling parameters for the data taking and analysis

Table 2 Transitions observed in $^{123}\text{Ag} \xrightarrow{\beta^-} ^{123}\text{Cd}$ decay. Relative intensities ($I_{\gamma\beta}^{rel}$) measured in the $\gamma(\beta)$ full (S_{data}^β) and subtracted (S_{sub}^β) spectra; relative (I_{ref}^{rel}) and absolute (I_{abs}^β) intensities taken from ref. [18].

E_γ	$I_{\gamma\beta}^{rel}, \%$		I_{ref}^{rel}	I_{abs}^β
	$S_{sub}^{\gamma\beta}$	$S_{data}^{\gamma\beta}$		
keV	%		%	
116.7(5)	25(3)	27(3)	21(4)	7.6(1)
123.9(5)	15(2)	<i>n.o.</i>	16(2)	5.8(4)
264.3(5)	100(8)	100(9)	100(3)	36(3)
410.1(5)	40(5)	54(7)	40(12)	13.2(5)
591.8(5)	28(4)	30(6)	29(15)	8.2(3)

precursor (N_{total}). The experimental methods to derive P_{1n} differ in a way how $N_{\beta dn}$ and N_{total} are inferred. In the present measurements $N_{\beta dn}$ was assumed to be equal to the number of neutrons detected by TETRA corrected by the background events and the neutron efficiency ϵ_n . The integrated neutron activity curve accumulated over 63 cycles for the $A = 123$ mass separator settings is presented in Fig. 3. The neutron background was of the magnitude of ≈ 20 n/s thanks to the boron polyethylene shield of TETRA and to the additional separator shielding (see ref. [22]). Due to a negative $Q_{\beta n}$ window for other members of the $A = 123$ isobaric multiplet the recorded neutron activity was solely at-

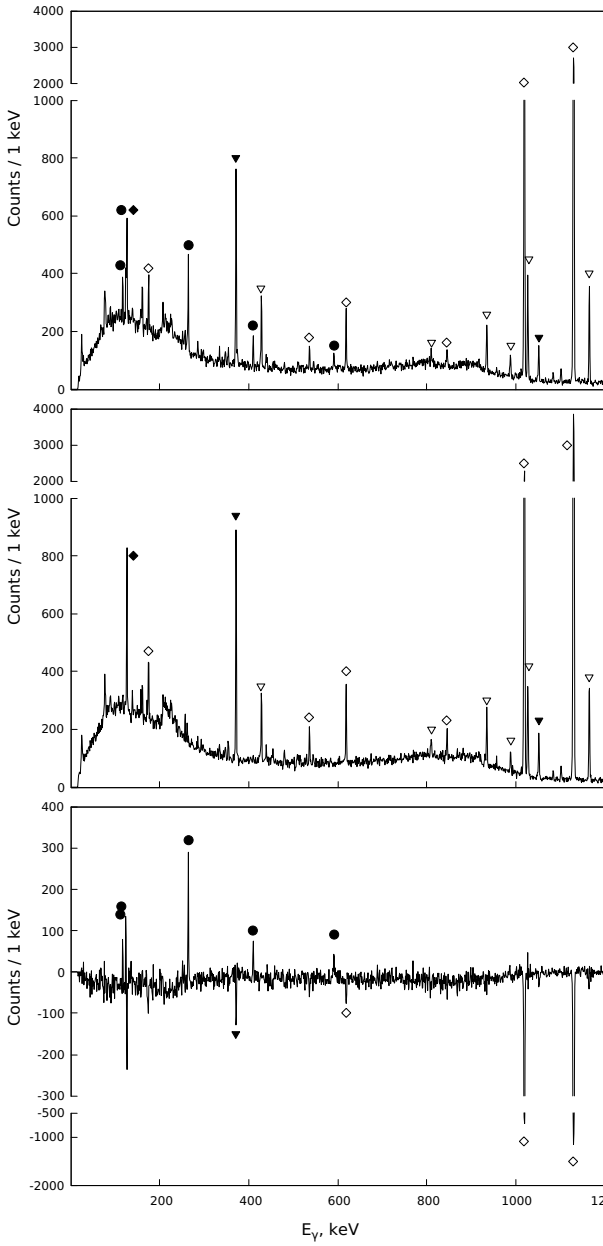


Fig. 2 β gated γ -spectra integrated over 63 cycles recorded for the mass $A = 123$ settings. S_{data}^{β} (top), S_{bg}^{β} (middle), S_{sub}^{β} (bottom) see text for details. Transitions are indicated in the daughter nuclei: $^{123}\text{Ag} \rightarrow ^{123}\text{Cd}$ (●); $^{123}\text{Cd} \rightarrow ^{123}\text{In}$ (▼); $^{123}\text{Cd}^m \rightarrow ^{123}\text{In}$ (▽); $^{123}\text{In} \rightarrow ^{123}\text{Sn}$ (◇); $^{123}\text{In}^m \rightarrow ^{123}\text{Sn}$ (◆)

tributed to the $\text{Ag}^{123} \xrightarrow{\beta-n} \text{Cd}^{122}$ decay or background activity. The half-life found fitting the neutron activity curve resulted in 0.350(20) s.

The total number of ^{123}Ag decays (N_{total}) was derived using the observed γ -ray transitions, listed in Table 2, and known, from ref. [18], absolute intensities of β -decay to the ^{123}Cd excited states. Thus for a i -th

γ -ray transition in ^{123}Cd characterized by the I_{β}^i transition probability, the p_{1n}^i can be found as:

$$p_{1n}^i = \frac{N_{\beta dn}}{N_{total}} = \frac{N_n}{\epsilon_n} \cdot \frac{\epsilon_{\gamma i} \cdot \epsilon_{\beta} \cdot I_i^{\beta}}{A_{\gamma}^i} \cdot (1 - T_{dead}^{\gamma}), \quad (1)$$

where A_{γ}^i is the number of counts under the corresponding peak in the S_{data}^{β} (S_{sub}^{β}) spectra, ϵ_n , ϵ_{β} and $\epsilon_{\gamma i}$ are efficiencies of neutron, β and γ (for i -th transition) detection respectively and T_{dead}^{γ} is the dead time of the γ electronic channel. The dead time was estimated by monitoring the occupation fraction of the channel. The average dead time over τ_{meas} was $T_{dead}^{\gamma} = 34(6)\%$. The adopted P_{1n} value then was calculated as the weighted average of p_{1n}^i extracted for different transitions.

This procedure was applied twice to derive the P_{1n} value using S_{data}^{β} and S_{sub}^{β} spectra. In case of S_{data}^{β} the $N_{\beta dn}$ was measured as the number of neutrons detected within τ_{data} and corrected for the neutron background. In case of S_{sub}^{β} the $N_{\beta dn}$ was defined as the difference between the number of neutrons detected within τ_{data} and τ_{bg} . The 1.01(24) % and 1.03(36) % values for P_{1n} , obtained using S_{data}^{β} and S_{sub}^{β} spectra respectively, are consistent within the error bars. The adopted values $P_{1n} = 1.01(24) \%$ (as the most precise) and $T_{1/2} = 0.350(20)$ ms are in good agreement with the results of different experiments cited in Table 4.

After determining P_{1n} and $T_{1/2}$ the ^{123}Ag production yield (Φ) was estimated to be $\approx 7700 \text{ s}^{-1}$ from the equation:

$$\int_0^{T_{beam}} A^{beam}(t) dt + \int_{T_{beam}}^{\tau_{decay}} A^{decay}(t) dt = N_{total} \quad (2)$$

where $A^{beam}(t)$ and $A^{decay}(t)$ are the activity of ^{123}Ag during the collection and decay measurements respectively defined using the Bateman rules:

$$\int_0^{T_{beam}} \Phi \cdot (1 - e^{-t \cdot \lambda}) dt + \int_{T_{beam}}^{\tau_{decay}} \Phi \cdot e^{-(t-T_{beam}) \cdot \lambda} (1 - e^{-T_{beam} \cdot \lambda}) dt = N_{total}, \quad (3)$$

where λ is the decay constant of ^{123}Ag .

The production yields of ^{123}Cd , $^{123}\text{Cd}^m$ and ^{123}In , delivered with the beam in the present experiment and reported in Table 3, were estimated by using sets of Bateman equations similar to Eq. 2 and 3, known half-lives and the absolute intensities of β -decay to excited states in daughter nuclei cited in the literature [32].

Table 3 Measured production yields (Φ) for $A = 123$ mass²⁹⁴ isotopes implanted into the tape; P_{1n} and $T_{1/2}$ for ^{123}Ag ²⁹⁵ as measured in this work, for others as recommended by the evaluator [32].²⁹⁶

	$T_{1/2}$ s	P_{1n} , % %	Φ s^{-1}
^{123}Ag	0.350(50)	1.01(24)	$7.7(40) \cdot 10^3$
^{123}Cd	2.10(2)	—	$\sim 4.7 \cdot 10^4$
$^{123}\text{Cd}^m$	1.82(3)	—	$\sim 1.4 \cdot 10^5$
^{123}In	6.17(5)	—	$\sim 1.4 \cdot 10^6$

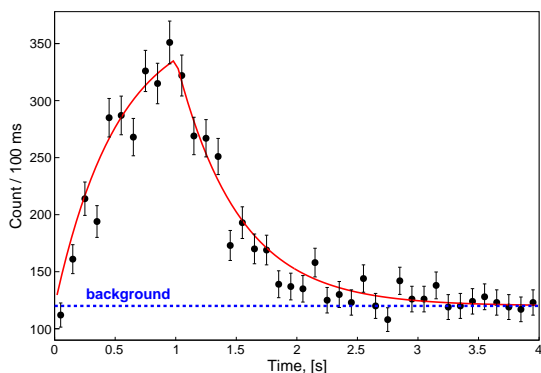


Fig. 3 Neutron activity curve from photo-fission fragments recorded for $A = 123$ mass separator settings. The curve denoted by black points was accumulated within 93 cycles, see Table. 1; the red curve is the result of the obtained fit with $T_{1/2} = 0.350$ (20) ms.³²²

4 Conclusions

The paper reports on the first measurement of a delayed neutron precursor in the neighbourhood of ^{132}Sn produced at ALTO facility. β -decay of the neutron-rich ^{123}Ag was investigated using a $A = 123$ mass-separated beam delivered to the neutron detector TETRA set up at the BEDO tape station. The detector arrangement allowed simultaneously recording of β -, neutron- and γ -radiation accompanying the decay of ^{123}Ag for the first time. In addition to the ^{123}Ag ground state, the isomeric and ground states in ^{123}Cd and ^{123}In were also populated by induced uranium photofission. The identification of the isotopes was reliably performed based on the recorded β gated γ -spectra. Due to the fact that neutron emission was not energetically possible in the members of the $A = 123$ isobaric multiplet, other than ^{123}Ag , the observed neutron activity was attributed to the β -n decay of ^{123}Ag . The half-life measured from the detected neutron activity agreed with values reported

from previous experiments. It is worth noting that, in general, $T_{1/2}$ for ^{123}Ag obtained by using neutron activity tends to be slightly longer in comparison to β and ion counting techniques. The P_{1n} value was found as the ratio of detected neutrons (background subtracted, efficiency corrected) to the total number of ^{123}Ag β -decays determined from the γ -rays observed. The adopted P_{1n} agreed within the error bars with results of another experiments where P_{1n} was derived directly by β - and neutron-countings. This agreement provided the indirect proof of the accuracy of the β -decay intensities to excited states in ^{123}Cd daughter. The results prove the ability of TETRA to be an effective tool using mass-separated beams extracted using the plasma ion source. In the particular case of this experiment, as the yield of Pd was negligibly small, and due to the fact that Ag was the only neutron precursor on the isobaric chain, the parameters of β -decay could be still properly measured. Similar techniques will be adopted to study decay of heavier Ag and Cd isotopes to be reported in a forthcoming publication.

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Table 4 $T_{1/2}$ and P_{1n} of ^{123}Ag neutron precursors. The type of β -delayed activity for half-life (γ , β , neutron or $i\text{-}\beta$ — ion- β correlated decay curve) is shown by the superscript; ^{123}Ag production method is indicated as *mass. sep.* or *laser* for ISOL mass separated and selectively laser ionized fission fragments correspondingly; or *frag.* — reaction of fragmentation.

$T_{1/2}$ ms	P_n %	Measured activities	Neutron detector	Production method	Facility
350(20) ⁿ	1.01(24)	γ , β , n	TETRA	<i>mass. sep.</i>	ALTO, <i>present</i>
272(24) ^{β}	1.0(5)	β , n, ion	NERO	<i>frag.</i>	MSU, [17]
293(7) ⁿ	-	β , n	not reported	<i>laser</i>	ISOLDE, [29]
300(10) ⁿ	0.55(9)	β , n	40 x ^3He	<i>mass. sep.</i>	TRISTAN, [16]
350(40) ^{γ}	-	γ	-	<i>mass. sep.</i>	TANDAR [18]
300(20) ^{γ}	-	γ , β	-	<i>mass. sep.</i>	TRISTAN, [30]
390(30) ⁿ	-	β , n	30 x ^3He	<i>mass. sep.</i>	OSIRIS [14,15]
0.296(7)	0.56(9)			<i>recommended by evaluator</i> [31]	

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