

High-precision α -induced cross sections and half-life measurements for terbium radioisotopes produced using natural europium

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This paper reports on high-precision measurements of terbium half-lives and cross-section data using α beams on natural europium targets. Energy uncertainties have been minimized through accurate measurement of the α -beam energy and high-precision cross sections obtained by a combination of foil thickness characterization, two independent measurement and acquisition systems, and careful monitoring of the irradiated foils over at least four weeks. This has resulted in the most precise cross-section data to-date for natural europium targets with α beams in the 25–40 MeV range. TALYS-2.0 calculations have been performed, and comparisons made with other available cross-section data, with good agreement attained. Half-lives with increased precision for $^{152}\text{Tb}(\text{g.s.})$, $^{152}\text{Tb}^{m1}(\text{g.s.})$, $^{153}\text{Tb}(\text{g.s.})$, $^{154}\text{Tb}^{m1}$, $^{154}\text{Tb}^{m2}$, and $^{155}\text{Tb}(\text{g.s.})$ are reported.

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I. INTRODUCTION

The $A \approx 150$ terbium isotopes ($Z = 65$) have been the focus of renewed interest over the last eight years [1–4] due to the potential for several radioisotopes to benefit the medical field; specifically, the possibility of using theragnostic pairs of radioisotopes [5]. Theragnostic (also known as theranostic) refers to the use of a single radioisotope with both diagnostic and therapeutic emissions, or a radioisotope pair, in which one radioisotope is used for imaging and the other for therapy. This ensures identical chemistry and comparable *in vivo* distribution, supporting improved patient-dose estimation. The two terbium diagnostic radioisotopes, ^{152}Tb (PET—positron emission tomography) and ^{155}Tb (SPECT—single-photon emission computed tomography) could be combined with the two promising treatment radioisotopes ^{149}Tb (α therapy and PET imaging) and ^{161}Tb (β^- therapy). These radioisotopes are shown in Fig. 1 along with decay properties.

The majority of recent studies have focused on the production of terbium from proton bombardment of gadolinium targets. However, the large number of observationally stable Gd isotopes (152, 154, 155, 156, 157, 158, and 160) means enriched targets are necessary to limit the number of terbium radioisotopes produced (note only ^{159}Tb is stable). Prior to this work, only one study had measured production cross sections for α -particle bombardment of europium targets, of which only ^{151}Eu and ^{153}Eu are stable with relative

abundances of 0.4781(6) and 0.5219(6), respectively [6]. The previous study by Gyürky and coworkers [7] was motivated by the astrophysical gamma process and as such investigated ^{151}Eu using α -particle beams in the 12–17 MeV range.

The present work [8] reports new results for the production cross sections and half-lives for terbium radioisotopes $A = 151$ –156 in the energy range 10–40 MeV using natural abundance europium targets. These include separate data for the ^{154}Tb and ^{152}Tb isomers. Comparisons are also made with the TALYS [9] reaction model code. Since our investigations were completed in 2021 [8] two further studies have been published. One by Moiseeva *et al.* [10] has reported $^{151}\text{Eu}(\alpha, xn)$ cross sections in the 19–60 MeV region, focusing on ^{149} – ^{153}Tb . A second by Kormazeva *et al.* [11] in 2025 reports a study using ^{153}Eu 99.8(1)% targets. Finally, unpublished thesis data from 2024 by Colucci [12] has also used α beams on natural europium targets. All of these recent works are referred to in the discussion section. Note, the Colucci, Kormazeva, and part of the Moiseeva data are not yet available in the EXFOR database [13].

II. EXPERIMENTAL METHOD

The terbium radioisotopes were produced using $^{nat}\text{Eu}(\alpha, xn)$ reactions with stacked foil targets. The α beam was provided by the Birmingham Scanditronix MC40 Cyclotron [14,15]. To minimize uncertainties, prior to the Eu foil irradiations, the beam energy was measured using elastic scattering from self-supporting gold targets of thicknesses 200 and 300 $\mu\text{m}/\text{cm}^2$. The scattered α particles were detected in a double-sided silicon strip detector (DSSD) centered at 24.5° to the beam axis in the horizontal plane. The DSSD was calibrated using a triple α source (^{239}Pu , ^{241}Am , and ^{244}Cm) and the beam energy was found to be 39.06(0.21) MeV across three independent measurements and taking into account energy loss in the Au scattering foils using SRIM [16].

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TABLE I. Europium foil energy spans, with foil No. 1 closest to the beam entrance. Maximum and minimum beam energies on entrance and exit have been obtained by using the foil thicknesses with one standard deviation subtracted or added respectively. Central energy corresponds to that in the middle of each foil. SRIM [16] was used for all energy-loss calculations. The uncertainty on the central energy values is half of the maximum energy change across the foil combined in quadrature with the 0.21 MeV beam-energy uncertainty.

Eu foil No.	Max. entrance energy	Central energy (MeV)	Min. exit energy	Energy uncert.
1	39.04	38.34	37.62	$-0.42 + 0.41$
2	37.64	36.86	36.06	$-0.45 + 0.44$
3	36.19	35.35	34.46	$-0.49 + 0.47$
4	34.71	33.77	32.81	$-0.52 + 0.51$
5	33.18	32.16	31.08	$-0.58 + 0.55$
6	31.59	30.47	29.30	$-0.62 + 0.60$
7	29.97	28.72	27.45	$-0.67 + 0.66$
8	28.25	26.90	25.48	$-0.74 + 0.71$
9	26.46	25.00	23.40	$-0.83 + 0.76$

As europium is the most reactive lanthanide, target handling was performed quickly, although an argon atmosphere was found to be unnecessary. Once irradiated, each Eu foil was sealed within two plastic bags for measurement. The foils were completely oxidized to black powder within 24 hours after removal from the irradiation position. To avoid adjacent Eu foils (99.95% purity) fusing together during irradiation, each was wrapped in aluminum foil—covering both front and back—meaning only nine Al-Eu-Al ‘envelopes’ needed to be handled and stacked into the target holder. This precaution of sealing the Eu in Al was important in case of inadvertent oxidation during irradiation. The energy span of each Eu foil is shown in Table I.

Again, to minimize uncertainties in the final cross section data, the Eu and Al foil thicknesses were measured using the triple α source and the DSSD setup in vacuum, but at 0° . The weighted average thickness obtained for europium was $21.3 \pm 0.5 \mu\text{m}$, corresponding to $11.2 \pm 0.3 \text{ mg/cm}^2$ (using $\rho(\text{Eu}) = 5.94 \text{ g/cm}^3$) [16]. The Al foil thickness measurements yielded $6.6 \pm 0.4 \mu\text{m}$.

Upstream tantalum collimators with a minimum diameter of 2.90(2) mm limited the beam-spot size impinging on the foils. The α -beam ($^4\text{He}^{2+}$) current was measured after the stacked foils at the end of the beam line using a Brookhaven model 1000c charge integrator set to a full-scale of 60 nC. The charge accumulation was recorded approximately every minute during the irradiation. An average current of 22 nA was sustained over 26.55 min. ($=1533 \text{ s}$).

III. ANALYSIS

The rate of production of an isotope via a reaction with cross section σ is

$$R = \sigma N_{tgt} I^b. \quad (1)$$

Here, I^b is the beam current in particles per second and $N_{tgt} = \frac{\rho N_{Avo}}{A} x$ —the areal number density of the target (the

α therapy/PET	PET	SPECT	β^- therapy
^{149}Tb	^{152}Tb	^{155}Tb	^{161}Tb
4.12 h $\varepsilon=83.3\%$ $\alpha=16.7\%$ $\alpha 4.0 \text{ MeV}$	17.48 h $\varepsilon=100\%$ $\gamma 271, 344, 511, 586 \text{ MeV}$	5.32 d $\varepsilon=100\%$ $\gamma 87, 105 \text{ keV}$	6.96 d $\beta=100\%$ $\beta 0.5, 0.6 \text{ MeV}$

FIG. 1. Terbium theragnostic radioisotopes with half-life, decay properties and potential medical uses.

number of nuclei per unit area)—where N_{Avo} is Avogadro’s number, A is the mass number of the target nuclei, x is the target thickness, and ρ is the mass density.

The activity of a radioisotope at the end of an irradiation of time, t_{irrad} , with a constant beam current, is $A_t(t_{\text{irrad}})$ such that,

$$A_t(t_{\text{irrad}}) = \sigma N_{tgt} I^b (1 - e^{-\lambda t_{\text{irrad}}}), \quad (2)$$

which takes into account radioactive decay (with decay constant, λ) during production. To account for fluctuations in the beam current, Eq. (2) can be modified to

$$A_t(t_{\text{irrad}}) = \sigma N_{tgt} \sum_{k=1}^n I_k^b (1 - e^{-\lambda \Delta t_k}) e^{-\lambda (t_{\text{irrad}} - t_k^{\text{end}})}. \quad (3)$$

Here I_k^b is the beam intensity for the k th time interval, Δt_k and t_k^{end} are the duration and end times of the k th irradiation time interval (with the irradiation starting at time $t = 0$) such that the total irradiation time, $t_{\text{irrad}} = \sum_{k=1}^n \Delta t_k = t_n^{\text{end}}$. Therefore, using the beam exposure data and observed activity enabled the extraction of the cross section for a particular radioisotope via rearrangement of Eq. (3).

The activities of the irradiated foils have been measured using two high-purity germanium (HPGe) detectors for which the geometries are detailed in Fig. 2. Calibration sources ^{152}Eu and ^{60}Co were recorded twice per day to monitor gain stability

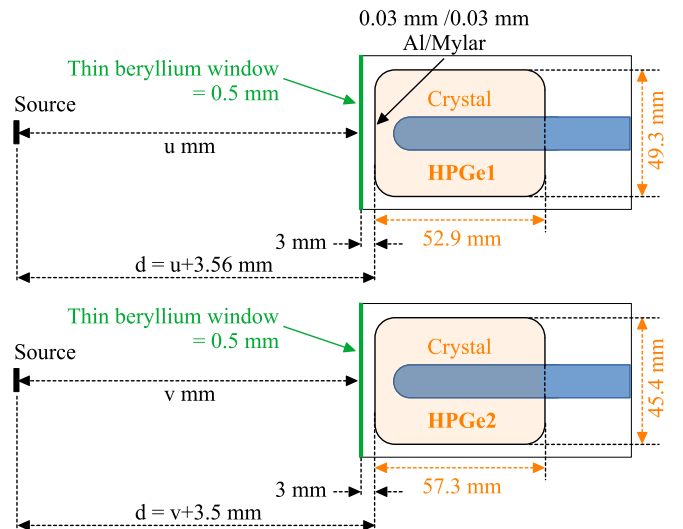


FIG. 2. Schematic diagram of the two HPGe detectors used for the foil Eu activity measurements. Here, u and v represent the sample distances from the front detector faces for HPGe1 and 2, respectively.

of the detectors and electronics. For efficiency characterization, additional sources of ^{44}Ti and ^{133}Ba were used. The RadWare γ -ray analysis package [17] was used for energy, efficiency, and peak fitting. Once the europium foils were fully oxidized they formed a powder. The powder (sealed in polythene) from each foil was formed into an approximate disk on the HPGe source holder, the radius of which was measured to be $r = 0.29 \pm 0.02$ cm (in contrast with the point-like calibration sources). This finite size was used to obtain the fractional solid angle f subtended by each detector during the measurements by numerically solving Ruby's [18] equation for an axially aligned source-detector geometry,

$$f = \frac{R}{r} \int_0^\infty \frac{e^{-kd} J_1(rk) J_1(Rk)}{k} dk, \quad (4)$$

for the known detector radius R and detector-source distance d . Note, J_1 is a spherical Bessel function of the first kind, $J_1(x) = (\sin x)/x^2 - (\cos x)/x$. While the impact of this finite-size approach on the efficiency correction was negligible, it enabled the increased geometric uncertainty to be quantified and included in the measurement errors. Detector dead times during the measurements were kept in the range 0.1%–6.1% by using source-detector distances in the range 4.8–15.4 cm. The dead-time correction error for the ORTEC Easy-MCAs [7,19,20] used is $<0.3\%$. No systematic differences in results between the two independent detectors and acquisition systems were observed.

Finally, a correction was made to the activity obtained due to radioactive decay during a measurement—particularly important when the spectrum measurement time is of the same order as the half-life. For this correction, the measured counts C under a peak depend on the instantaneous activity A such that $A = dC/dt$, where $A = A_C e^{-\lambda t}$. Here, A_C is the desired activity at the start of the measurement. Therefore, an expression for obtaining A_C from C can be found by integrating

$$\frac{dC}{dt} = A_C e^{-\lambda t} \quad (5)$$

over the measurement duration t_{meas} such that

$$A_C = \frac{\lambda C}{1 - e^{-\lambda t_{\text{meas}}}}. \quad (6)$$

When measuring activities, care was taken in selecting appropriate gamma rays to separate the isomeric and ground-state populations. Note, possible population of Gd parent nuclei and subsequent β^- decay into the Tb radioisotopes measured is not a complicating factor because the Gd nuclides are either stable or have >100 -day half-lives.

Table II summarizes the radioisotope and isomer properties along with reaction information from α beams on natural europium targets.

IV. RESULTS

A series of measurements straight after the irradiation was made to characterize short half-lives. However, for $^{151}\text{Tb}^{m1}$, with $t_{1/2} = 25$ s, this was not possible, with the shortest half-life measured being the $^{152}\text{Tb}^{m1}$ 4.2(1) min. state [22]. Based on TALYS predictions (see Sec. V) for the likelihood of

populating this short-lived metastable state, Eu foils numbers 1–4 were selected for initial monitoring via recording 1 min. spectra. The spectra recorded for each foil are summarized in Table III.

For each measurement, the half-life obtained from each γ decay and foil pair was compared, and a weighted average half-life was obtained. Example half-life data for each radioisotope—and, where relevant, each metastable state—are shown in Figs. 3, 5, and 6, along with representative fits. The resulting weighted average half-lives are summarized in Table IV. Cross sections were obtained by using the activity (y intercept) at $t = 0$ —corresponding to the end of the irradiation—from the half-life analysis and Eq. (3).

A. Tb-151 half-life

As discussed above the ^{151}Tb 25 s $m1$ isomeric state was too short to measure directly in this work. Therefore, only the 17.6 h ^{151}Tb ground-state (g.s.) decays were measured. However, the 252 and 287 keV γ peaks were only discernible in the first two foils, and the statistics, particularly in foil No. 2, were low. As a result, the half-life fits [see Fig. 3(a)] were constrained to vary within the published half-life uncertainty in order to reliably extract production cross sections from the activity corresponding to the end of the irradiation.

B. Tb-152 half-lives

For $^{152}\text{Tb}^{m1}$ the 4 min. half-life was long enough to measure directly in foils numbers 1–4 and twenty consecutive 1 min. spectra were collected for foil No. 1 within the first eight half-lives, see Fig. 3(b) for the 283 keV γ decay. A weighted average from measuring seven transitions gave 4.22 ± 0.02 min., in excellent agreement with the literature value of 4.2 ± 0.1 min. [22], but with a reduced uncertainty.

The ^{152}Tb ground state was measured using four γ transitions, visible in foil numbers 1–7. Data collection commenced after nine half-lives of the $m1$ isomer. The weighted average half-life [see example Fig. 3(c)] comprised 28 measurements and yielded 17.07 ± 0.07 h; in agreement at three standard deviations with the published value of 17.5 ± 0.1 h [22].

C. Tb-153 half-life

Two γ -ray energies of 110 and 212 keV were monitored over 20 days for the ^{153}Tb ground state. There are no known metastable states longer than 1 s in this nucleus. Figure 3(d) shows a representative half-life curve measured here, and a weighted half-life from all nine foils yields 2.291 ± 0.006 d, within three standard deviations of the published value of 2.34 ± 0.01 d [23], but with increased precision.

D. Tb-154 half-lives

The most complicated decay paths present in this study occur in ^{154}Tb due to the presence of two isomers, one of which ($m2$) has a half-life comparable to the ground state. All three states were populated in the current work. However, while the excitation energies of the isomers have not been uniquely established, the energy ordering and decay branches

TABLE II. Decay properties of the observed terbium radioisotopes, including the prominent γ rays for determining activities and half-lives. In the decay mode column, ε denotes the sum of EC (electron capture) and β^+ decay. Gamma-ray energies and intensities in brackets were analyzed but not used for the final results in the current work. Some contributing reactions are given and struck through to demonstrate explicitly that they are energetically forbidden. See text for details.

Isotope or isomer	Lit. half-life	E_x (keV)	I^π	Decay mode (%)	E_γ (keV)	I_γ (%)	Contributing reaction(s)	Q value ^a (MeV)	Ref.
¹⁵¹ Tb	17.609(14) h	0.0	$\frac{1}{2}^{(+)}$	ε : 99.9905(15) α : 0.0095(15)	251.86(1) 287.36(1)	26.3(11) 28.3(12)	¹⁵¹ Eu(α , 4n) ~~¹⁵³Eu(α, 6n)~~	−32.890 −47.747 ($< -E_{\text{beam}}$)	[21]
¹⁵¹ Tb ^{m1}	25(3) s	99.5	$(\frac{11}{2}^-)$	IT : 93.4(20) ε : 6.6(20)	27.1(1) 379.70(6) 522.40(10) 830.50(10)	 6.3(20) 1.5(5) 3.3(10)	¹⁵¹ Eu(α , 4n) ~~¹⁵³Eu(α, 6n)~~	−32.990 −47.847 ($< -E_{\text{beam}}$)	[21]
¹⁵² Tb	17.5(1) h	0.0	2 [−]	ε : 100	271.09(7) 586.27(7) 764.89(7) 778.9045(24)	9.53(21) 9.21(21) 2.74(7) 5.54(13)	¹⁵¹ Eu(α , 3n) ~~¹⁵³Eu(α, 5n)~~	−25.725 −40.582 ($< -E_{\text{beam}}$)	[22]
¹⁵² Tb ^{m1}	4.2(1) min.	501	8 ⁺	IT : 78.9(6) ε : 21.1(6)	159.59(10) 235.4(1) 277.2(1) 283.29(1) 385.9(1) 471.9(1) (526.8(2)) (647.4(2)) 1166.9(2)	16.6(8) 4.2(3) 8.5(4) 59.8(5) 3.27(20) 11.8(7) (1.64(13)) (4.3(3)) 3.7(3)	¹⁵¹ Eu(α , 3n) ~~¹⁵³Eu(α, 5n)~~	−26.232 −41.089 ($< -E_{\text{beam}}$)	[22]
¹⁵³ Tb	2.34(1) d	0.0	$\frac{5}{2}^+$	ε : 100	(82.86(2)) 109.758(15) 212.00(2)	(5.4(7)) 6.2(4) 28.5(19)	¹⁵¹ Eu(α , 2n) ¹⁵³ Eu(α , 4n)	−17.057 −31.914	[23]
¹⁵⁴ Tb	21.5(4) h	0.0	(0)	ε : 100	(704.90(11)) 2064.11(10) 2187.10(16)	(4.8(3)) 7.1(4) 9.9(8)	¹⁵¹ Eu(α , n) ¹⁵³ Eu(α , 3n)	−10.143 −24.000	[24]
¹⁵⁴ Tb ^{m1}	9.973(44) h ^b	$x \leq 25$	3 [−]	ε : 78.2(7) IT : 21.8(7)	540.18(6) (1208.06(14)) (1229.42(20)) (1288.39(14)) (1490.37(22))	19.5(31) (0.51(9)) (0.59(14)) (1.39(25)) (1.04(18))	¹⁵¹ Eu(α , n) ¹⁵³ Eu(α , 3n)	−10.143 − x −24.000 − x	[24]
¹⁵⁴ Tb ^{m2}	22.7(5) h	$y > x^c$	7 [−]	ε : 98.2(6) IT : 1.8(6)	225.94(3) 426.78(7) (1061.39(9))	26.8(28) 17.3(12) (4.1(7))	¹⁵¹ Eu(α , n) ¹⁵³ Eu(α , 3n)	−10.143 − y −24.000 − y	[24]
¹⁵⁵ Tb	5.32(6) d	0.0	$\frac{3}{2}^+$	ε : 100	105.318(3) 148.64(1) 160.51(10) 161.29(1) 163.28(1)	25.1(13) 2.65(14) 0.78(4) 2.76(15) 4.44(23)	¹⁵³ Eu(α , 2n)	−15.835	[25]
¹⁵⁶ Tb	5.35(10) d	0.0	3 [−]	ε : 100	534.29(6) (1065.11(64)) (1154.07(15)) (1222.44(9)) (1421.67(9))	67(6) (10.8(10)) (10.4(10)) (31(3)) (12.2(12))	¹⁵³ Eu(α , n)	−8.923	[26]
¹⁵⁶ Tb ^{m1}	24.4(10) h	49.630+x	(7 [−])	IT : 100	49.63(10)	(100)	¹⁵³ Eu(α , n)	−8.973	[26]
¹⁵⁶ Tb ^{m2}	5.3(2) h	88.4	(0 ⁺)	IT : <100 ε : >0	88.4	(100)	¹⁵³ Eu(α , n)	−9.011	[26]

^a Q values are calculated using the AME2020 mass evaluation [27].

^bThis value is from the 2025 compilation [24] representing a weighted average of half-life measurements. The previous, 2009 compilation [28] quoted an unweighted half-life of 9.4(4) h as the most precise values at the time were the highest, and there was concern over contamination from the higher-lying 22.7 h, $I^\pi = 7^-, m2$ isomer.

^cIn Ref. [29] y is estimated from systematics as 200(150) keV.

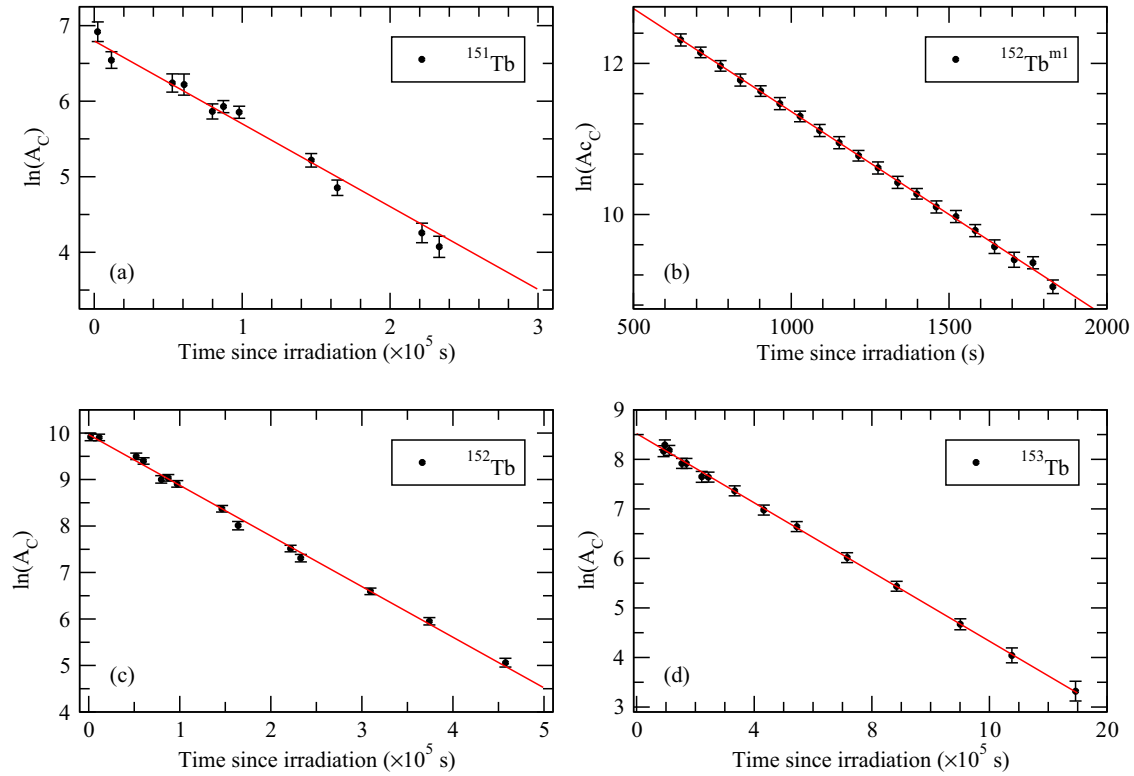


FIG. 3. Example terbium half-life data (points) and weighted linear fits (solid lines) for time since irradiation (x) versus log of activity (y). (a) ^{151}Tb ground state from the 287 keV γ transition monitored in foil No. 1. (b) $^{152}\text{Tb}^{m1}$ isomeric state from the 283 keV γ transition monitored in foil No. 1. (c) ^{152}Tb ground state from the 271 keV γ transition monitored in foil No. 1. (d) ^{153}Tb ground state from the 212 keV γ transition monitored in foil No. 7.

(though not the decays themselves) are known (see Fig. 4 and Table II).

The highest excitation energy is for $^{154}\text{Tb}^{m2}$ which was detectable in foil numbers 1–7 and was monitored via the 226 (26.8(28)%), 427 (17.3(12)%) and 1061 keV (4.1(7)%) γ transitions [see Fig. 5(a)]. There was some variation in the weighted half-lives obtained for each transition: 24.0 ± 0.2 h (226 keV), 22.9 ± 0.2 h (427 keV), and 11.4 ± 0.3 h (1061 keV). Although the 9.97 h $^{154}\text{Tb}^{m1}$ state also decays by a 1061 keV transition, the lower intensity of 0.14(3)% was initially

considered negligible, being a factor of 29 times lower than that for the $m2$ level. However, the population of the $m1$ state was ten times greater than the $m2$ isomer in this study, which, coupled with the shorter $m1$ half-life (and thus higher activity), led to the observed significant contamination of the 1061 keV transition. It was therefore omitted from the half-life and cross section determinations for the $m2$ level.

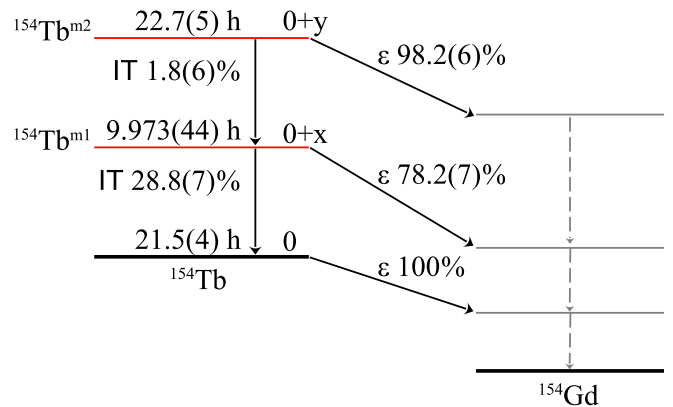


FIG. 4. Simplified decay scheme (not to scale) for the ^{154}Tb isomers and ground state. Note, as for several states in the terbium radioisotopes, the excitation energies of the isomeric states are not established. Literature half-lives and decay branches are given [24,28].

TABLE III. Summary of the Eu foil HPGe measurements made.

Eu foil No.	Days since irradiation	Spectrum duration	No. of spectra per foil
1	0	1 min.	20
2, 3, 4	0	1 min.	6
1–9	0	15 min.	1
	0	30 min.	1
	1	30 min.	3
	2	1 h	2
	3	1 h	2
	4	2 h	1
	5–7	5 h	1
	8–14	7 h	2
	14–29	7 h	9–11

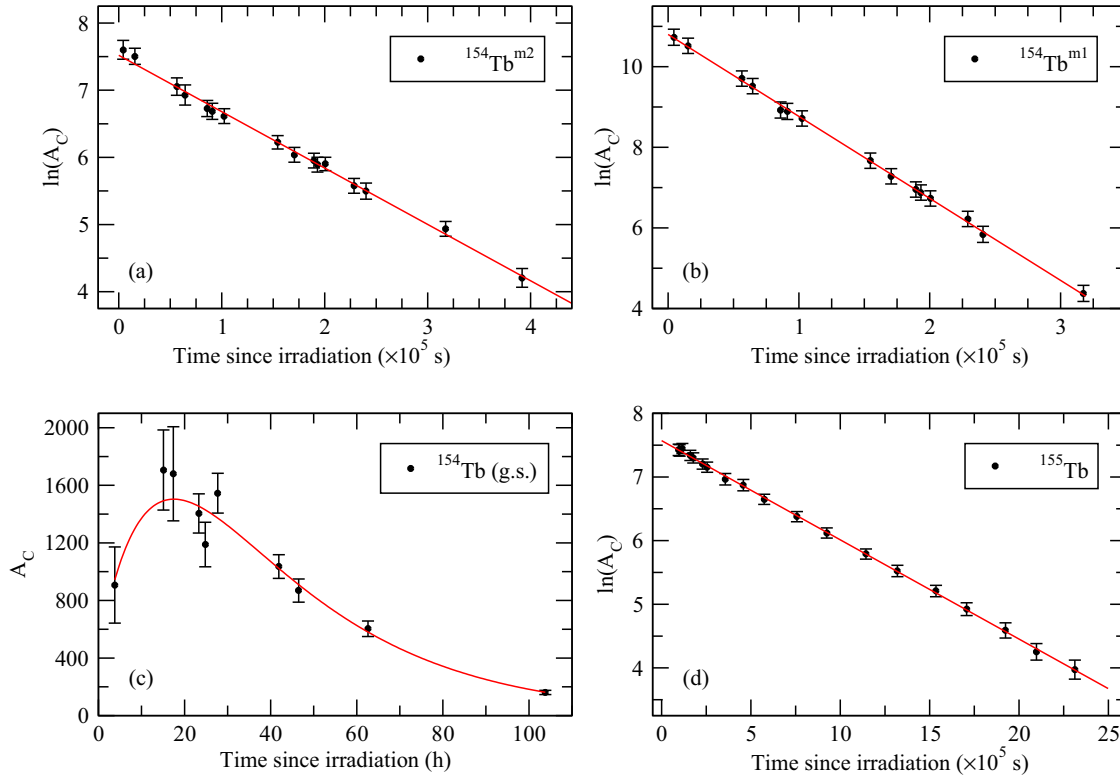


FIG. 5. Example terbium half-life data (points) and weighted fits (solid lines) for time since irradiation (x) versus (log of) activity (y). (a) $^{154}\text{Tb}^{m2}$ isomeric state from the 427 keV γ transition monitored in foil No. 3. (b) $^{154}\text{Tb}^{m1}$ isomeric state from the 540 keV γ transition monitored in foil No. 3. (c) ^{154}Tb ground state from the 2064 keV γ transition monitored in foil No. 2. Note the horizontal axis units and the linear vertical scale (see text for details). (d) ^{155}Tb ground state from the 105 keV γ transition monitored in foil No. 9.

The weighted average $^{154}\text{Tb}^{m2}$ half-life obtained in the current work from combining 14 determinations is 23.58 ± 0.15 h, within two standard deviations of the 22.7 ± 0.5 h published half-life [24], but with reduced uncertainty.

For the $^{154}\text{Tb}^{m1}$ metastable state, the 540 keV transition was monitored for foil numbers 1–9. The work by Lau and Hogan [30] in 1973 suggests that there is feeding of the $m1$ isomer by a 1.8(6)% internal decay branch of the longer-lived

$m2$ isomer. This was based on a long-lived component in the 540 keV half-life data at long times (>80 h or 288 000 s) following 45 MeV proton irradiation of natural gadolinium targets. Such a deviation from linearity has not been observed in the current work [see Fig. 5(b)]. This might be due to the lower population of the $m2$ state in $\alpha + \text{Eu}$ reactions. It might also be due to contamination in the earlier work due to

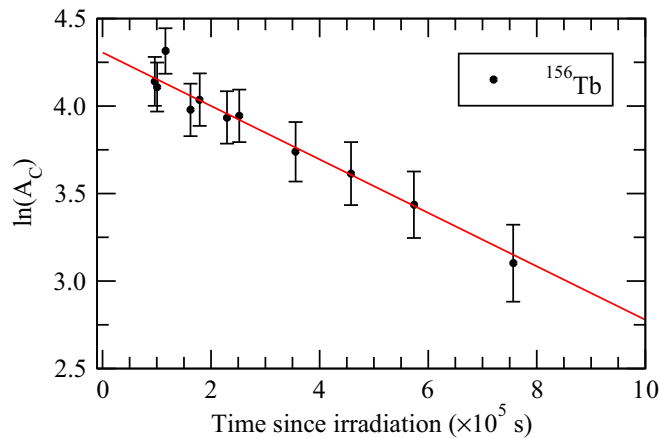


FIG. 6. Terbium-156 half-life data (points) and fit (solid line) using the 534 keV γ transition monitored in foil No. 9. See text for details.

TABLE IV. A summary of weighted average half-lives measured in the current work compared with literature values. The final column gives the number of half-life measurements contributing to the weighted average.

Isotope or isomer	Half-life			No. of meas. weighted
	Lit.	NDS Ref.	This work	
^{151}Tb	17.609(14) h	[21]		
^{152}Tb	17.5(1) h	[22]	17.07(7) h	28
$^{152}\text{Tb}^{m1}$	4.2(1) min.	[22]	4.22(2) min.	7
^{153}Tb	2.34(1) d	[23]	2.291(6) d	18
^{154}Tb	21.5(4) h	[24]		
$^{154}\text{Tb}^{m1}$	9.973(44) h ^a	[24]	9.43(4) h	9
$^{154}\text{Tb}^{m2}$	22.7(5) h	[24]	23.58(15) h	14
^{155}Tb	5.32(6) d	[25]	5.25(1) d	36
^{156}Tb	5.35(10) d	[26]		

^aSee text for details.

the higher bombarding energies and greater number of target isotopes (six isotopes of Gd are naturally occurring). It is noteworthy that a low-energy tail seems to be present in Ref. [30], which could be from the $^{151}\text{Tb}(\text{g.s.})$ (537.3 keV (0.419%), 17.6 h), the $^{156}\text{Tb}(\text{g.s.})$ (538 keV, 5.35 d) transitions, or some as yet unidentified contaminant transition. Further work to unambiguously establish internal isomeric deexcitations in ^{154}Tb is needed. The weighted average half-life for $^{154}\text{Tb}^{m1}$ obtained in the present work is 9.43 ± 0.04 h. This is over six standard deviations away from the published half-life of 9.973 ± 0.044 h [24]. This compiled value has been obtained from a weighted average of (in chronological order): 9.9(1) h [31], 9.0(5) h [30], 9.0(10) h [32], 9.8(3) h [33], and 9.994(39) [34]. (Aside, while these values do indeed give 9.973 h as the weighted mean, the weighted mean error is 0.036 h, rather than 0.044 h quoted in Ref. [24].) Although the previous compilation [28] recommended an unweighted average of 9.4(4) h due to possible contamination from the longer-lived $m2$ state, it is worth noting that, in Ref. [34] (the most precise half-life measurement), the reaction $\alpha + ^{151}\text{Eu}$ at energies of 13.5–17 MeV is the same mechanism as employed here, albeit at lower beam energies.

Finally, concerning the ^{154}Tb ground state, only limited data using the 2064 and 2187 keV transitions were used for half-life measurements from foil numbers 1–7. A typical grow-in curve is shown in Fig. 5(c) due to the shorter $m1$ isomer feeding the longer-lived ground-state with a published half-life of 21.5 ± 0.4 h [24]. To fit these curves, the series decay formula was used

$$A_i(t) \approx (BR)A_{Tm1} \frac{\lambda_g}{\lambda_g - \lambda_{m1}} (e^{-\lambda_{m1}t} - e^{-\lambda_g t}) + A_{Tg} e^{-\lambda_g t}. \quad (7)$$

Here $A(t)$ is the measured activity as a function of time t since irradiation, and λ_g and λ_{m1} are the decay constants for the ground and first isomeric states, respectively. The $m1$ to ground-state internal branching ratio BR was fixed at 0.218 and the $m1$ half-life was fixed at 9.43 h. The initial activities immediately after irradiation of the ground state and $m1$ isomer are A_{Tg} and A_{Tm1} , respectively. Thus, accurate extraction of A_{Tg} was needed for the ground-state cross section. To simplify the complex feeding and constrain the fits, the $m2 \rightarrow m1$ branch was ignored due to the low $m2$ population in this work, supported by the high linearity of, e.g., Fig. 5(b). The 2064 keV data resulted in a weighted ground-state half-life of 22.0 ± 0.6 h, and the 2187 keV data a value of 22.7 ± 0.5 h. These are both within two standard deviations of the published value, but have larger uncertainties due to the low number of data points to the left of the maximum in the grow-in curves, leading to significant variations in the fits.

E. Tb-155 half-life

The ^{155}Tb isotope has no known long-lived isomeric states. The ground state was observed in foil numbers 1–9 and the half-life measured using deexcitations of 105, 149, 161, and 163 keV, yielding a weighted average of 5.25 ± 0.01 d. This is within the errors of the published value of 5.32 ± 0.06 d [25], but with increased precision. See Fig. 5(d).

F. Tb-156 half-life

The nuclide ^{156}Tb is similar in structure to ^{154}Tb in that it has two low-lying long-lived excited states, but the ordering of the states is different, with the 5.35(10) d ground-state having $I^\pi = 3^-$, with both the (7^-) $m1$ 24.4(10) h and (0^+) $m2$ 5.3(2) h isomers decaying almost exclusively internally to the ground-state with no observed $m2 \rightarrow m1$ feeding. Although ^{156}Tb decays were detected in foil numbers 1–9 the population was low compared with other isotopes, and the internal direct isomeric γ rays were not measurable due to their highly converted nature. Thus, only a total measurement of ^{156}Tb following its ground-state decay was possible using the 534 keV transition. The low statistics did not allow an improved half-life determination, and the fit shown in Fig. 6 was constrained to lie within the uncertainties of the published value, to facilitate the extraction of accurate cross sections.

G. Cross sections

Following the half-life analysis, cross sections have been extracted for the corresponding states or groups of states in the terbium isotopes from $A = 151$ to 156. The intercepts extracted from each half-life measurement, corresponding to the activities at the end of the irradiation, have been used with Eq. (3) to extract the cross sections σ^1 using newly measured half-lives where available (see Table IV). Cross sections are summarized in Table V and plotted in Figs. 7–9.

Since the current work was completed in 2021, several publications and other data have appeared for some of the isotopes, and these are included for comparison here, where available. The three sources are the 2021 work by Moiseeva *et al.* [10] who used enriched ^{151}Eu 97.5(1)% targets, the unpublished 2024 thesis work by Colucci [12] based on natural Eu targets, and the 2025 publication by Kormazeva *et al.* [11] who used ^{153}Eu 99.8(1)% targets. The enriched target data have been scaled to the natural abundance equivalent cross sections for comparison. Note, the 0.1% enrichment uncertainties and the 0.06% uncertainties in the natural abundances mean these errors are negligible compared with the cross-section uncertainties. Note that, in Ref. [10], no energy uncertainties are given in their tabulated data, but their text states that the “calculated total energy uncertainty was 1–1.7 MeV, depending on the position of the target in the stack” of foils. Here, a conservative value of 1.4 MeV has been adopted when plotting these data due to the points of interest being low in energy compared with the maximum measured energy of 60 MeV. These are discussed in Sec. V and included in Figs. 7–9. The low-energy data from Gyürky *et al.* [7] have been plotted (for values > 1 mb) for completeness. Although there is no overlap with the current data, they serve as a useful benchmark to elucidate the low-energy behavior, particularly for the TALYS calculations (see below).

¹Note, the cross sections here have been scaled up by a factor of 1.133 ± 0.032 compared with those appearing in Ref. [8], following remeasurement of the ^{152}Eu source activity used to obtain the HPGe efficiency curve—against high-accuracy ^{137}Cs and ^{60}Co sources.

TABLE V. Cross sections measured in the current work.

Isotope or isomer	Beam energy (MeV)								
	38.34 ^{+0.41} _{-0.42}	36.86 ^{+0.44} _{-0.45}	35.35 ^{+0.47} _{-0.49}	33.77 ^{+0.51} _{-0.52}	32.16 ^{+0.55} _{-0.58}	30.47 ^{+0.60} _{-0.62}	28.72 ^{+0.66} _{-0.67}	26.90 ^{+0.71} _{-0.74}	25.00 ^{+0.76} _{-0.83}
	Cross section (mb)								
¹⁵¹ Tb(tot.)	20.4(1.3)	5.7(1.1)							
¹⁵² Tb(tot.)	463(17)	450(16)	402(15)	324(12)	228(9)	114(5)	28.2(14)		
¹⁵² Tb ^{m1}	388(14)	372(15)	320(14)	240(16)					
¹⁵³ Tb(g.s.)	160(6)	141(5)	170(6)	244(9)	358(13)	448(16)	522(19)	499(18)	434(15)
¹⁵⁴ Tb(g.s.)	19 ⁺²⁷ ₋₁₉	23 ⁺²² ₋₂₀	28 ⁺²⁶ ₋₂₄	48 ⁺³⁷ ₋₃₅	43 ⁺¹⁰ ₋₁₀	10 ⁺⁹ ₋₉	10 ⁺⁷ ₋₇		
¹⁵⁴ Tb ^{m1}	596(27)	612(29)	588(27)	530(26)	431(23)	267(13)	124(8)	29.5(3.5)	24.9(2.4)
¹⁵⁴ Tb ^{m2}	65.7 ^{+4.9} _{-6.0}	63.4 ^{+4.9} _{-5.9}	60.0 ^{+7.0} _{-7.0}	49.9 ^{+8.1} _{-6.9}	39.7 ^{+4.7} _{-4.7}	26.1 ^{+3.5} _{-4.6}	10.2 ^{+1.2} _{-1.2}		
¹⁵⁵ Tb	60(2)	78(3)	103(4)	136(5)	213(8)	304(10)	423(14)	483(16)	420(14)
¹⁵⁶ Tb	4.0(6)	4.5(6)	5.0(4)	5.6(5)	6.1(4)	7.1(4)	7.6(6)	8.7(6)	12.0(7)

H. TALYS calculations

To further compare trends in the cross-section data, TALYS [9] calculations have been performed. The TALYS-2.0 code was used and run both unmodified (labeled TALYSUN) and

modified (labeled as TALYS). The modifications made only concerned the Tb.lev file, which contains details of the terbium excited states. In particular, the ¹⁵⁴Tb^{m1} level was absent in the unmodified version, and this was inserted at an excitation energy of 25 keV. Additionally, the *m2*

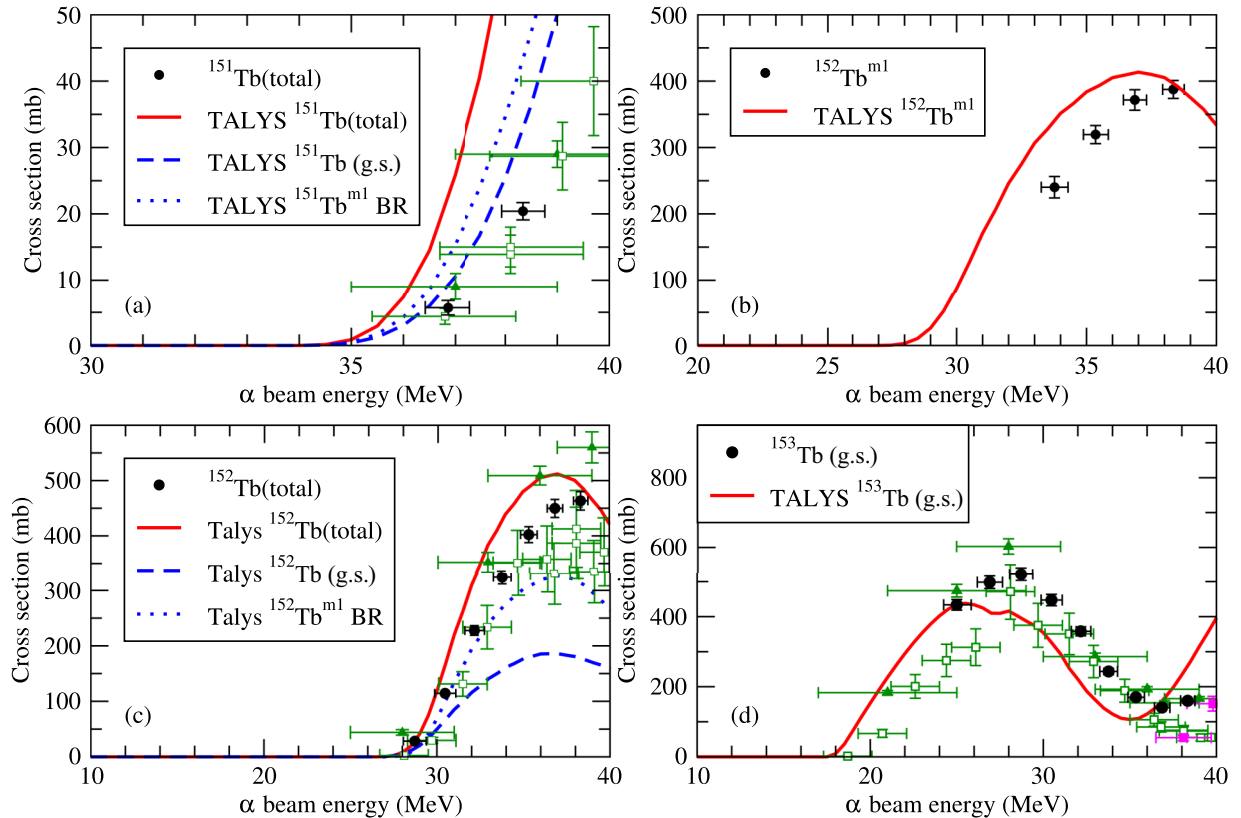


FIG. 7. Measured cross sections in this work (black data points) and output from TALYS calculations [9] (lines) as a function of α beam energy. Open green squares are data from Ref. [10], filled green triangles are from Ref. [12] and filled magenta squares are data from Ref. [11]. (a) ¹⁵¹Tb: total cross section for the *m1* isomer and ground state that could not be separated due to the short (25 s) *m1* half-life. The separate TALYS contributions for these two states are plotted, as well as the total calculated cross section. Note, the TALYS *m1* cross section has been multiplied by 0.943—the internal decay branching ratio (BR)—and the result is what is summed with the ground state to give the TALYS total line. (b) ¹⁵²Tb^{m1} (4.1 min.) isomeric state cross section. (c) ¹⁵²Tb total cross section comprising the ground state and isomeric contributions for which the calculated contributions are plotted. The isomeric contribution (dotted line) and its contribution to the total have been multiplied by 0.789, which is the *IT* branching ratio (BR) to the ground state. (d) ¹⁵³Tb ground-state cross section.

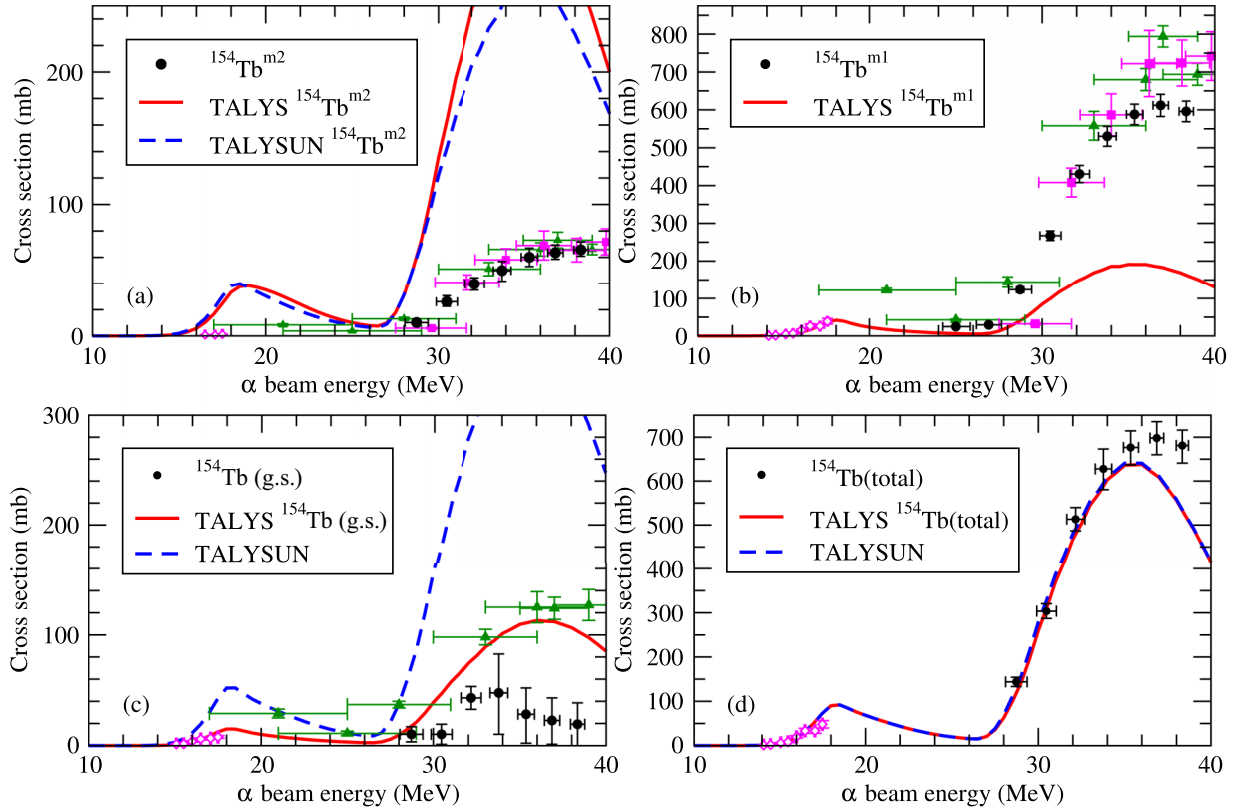


FIG. 8. Measured cross sections (points) and output from TALYS calculations [9] (lines) as a function of α beam energy. Open green squares are data from Ref. [10], filled green triangles are from Ref. [12], filled magenta squares are data from Ref. [11] and open magenta diamonds (below 20 MeV) are data from Ref. [7]. For explanation of the TALYS and TALYSUN labels, see text. (a) $^{154}\text{Tb}^{m2}$: cross section for the 22.7 h isomer. (b) $^{154}\text{Tb}^{m1}$: cross section for the 9.4 h isomeric state. (c) ^{154}Tb cross section for the 21.5 h ground state. (d) ^{154}Tb : sum of cross sections for all long-lived states.

excitation energy was adjusted from 400 to 200 keV based on information in Ref. [24]. These changes have little impact beyond ^{154}Tb but enable the calculation of the $m1$ cross section. These calculated cross sections are also shown in Figs. 7–9. When required, branching ratios have been used to

multiply isomeric contributions to the calculations (indicated by “BR” in the plot legends), i.e., when internal feeding is less than 100% and where the experimental data could not be corrected for this branching due to populating from multiple states.

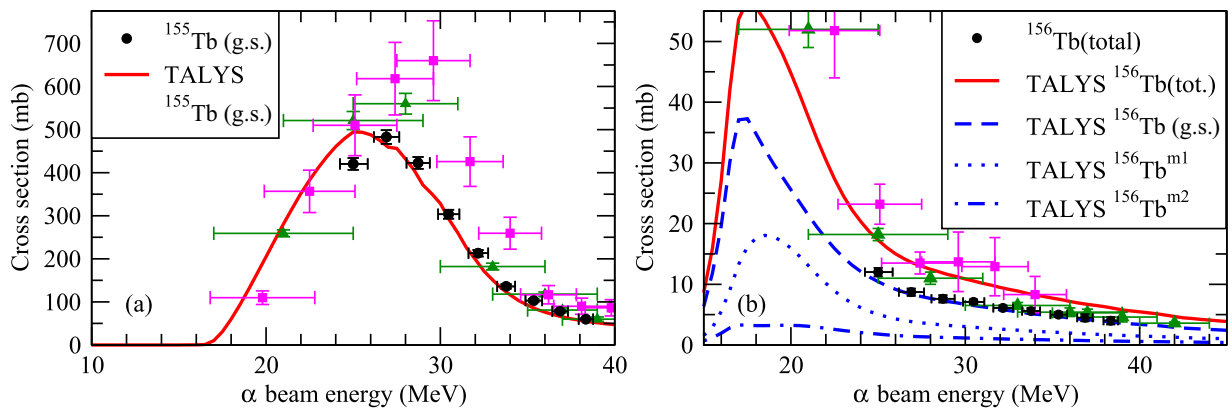


FIG. 9. Measured cross sections (points) and output from TALYS calculations [9] (lines) as a function of α beam energy. Open green squares are data from Ref. [10], filled green triangles are from Ref. [12] and filled magenta squares are data from Ref. [11]. See text for details. (a) ^{155}Tb : cross section for the 5.3 day ground state. (b) ^{156}Tb : total cross section for all long-lived states. The separate TALYS contributions to the total cross section are also shown. Note, for the Kormazeva data [11] in panel (b), there is an additional data point at 19.8(30) MeV with a ^{156}Tb cross section of 74.8(12.6) mb that is off the top of the plot in order to better display the majority of the data.

V. DISCUSSION

In general, the current data demonstrate the lowest energy uncertainties in the sub-40 MeV region and, in many cases, the lowest cross-section uncertainties. Overall, there is good agreement between the current data and other studies.

For ^{151}Tb [Fig. 7(a)], only two cross sections have been measured in the current work, but these are of higher precision than other available data from Colucci [12] and Moiseeva *et al.* [10]. The cross section is rising rapidly at 37 MeV and the TALYS calculations predict this trend, but the cross-section calculations are too low in energy by approximately 2 MeV.

For $^{152}\text{Tb}^{m1}$ [Fig. 7(b)] no other data were available, and, again, although TALYS reproduced the trend, the calculation is again shifted to lower energies by ≈ 2 MeV compared with the current data. For the total cross section, including both the ground state and $m1$ isomer [Fig. 7(c)], the data by Moiseeva *et al.* [10] exhibit a lower peak value than both the current work and the data of Colucci [12], with our data lying between the two and having higher precision both in energy and magnitude. TALYS calculations predict the trend well, but overpredict the magnitude of the cross section compared with all but the Moiseeva data.

The cross sections measured for the ^{153}Tb ground-state production [Fig. 7(d)] demonstrate good agreement between all other datasets above 27 MeV. However, the Moiseeva data drop sharply in magnitude compared with the current work and that of Colucci below 27 MeV. Two data points from Kormazeva *et al.* [11] are available above 38 MeV. The TALYS-calculated cross sections again appear to be ≈ 2 MeV too low in energy. Interestingly, the current work and that of Kormazeva and Colucci measure an increase in cross-section around 37 MeV, as predicted by TALYS, but the Moiseeva data demonstrate a continued fall in cross section; as expected given the absence of ^{153}Eu in their target.

For the $^{154}\text{Tb}^{m2}$ cross sections [Fig. 8(a)] all the available data are in very close agreement, with relatively low uncertainties for all available data in the cross-section magnitude, but our current data additionally have much lower energy uncertainties. Here, the TALYS calculations dramatically overpredict the population, and the modified calculations are higher—presumably due to the reduction in the $m2$ level energy—being about five times higher than the experimental cross sections. The data of Gyürky *et al.* [7] (scaled to a natural abundance target) support the current work because their cross sections (≈ 1 mb) are also significantly below the TALYS predictions below 18 MeV. The cross-section peak in the data is about 2 MeV above that of the TALYS maximum.

The $m2$ calculations are in sharp contrast to the underprediction for the $^{154}\text{Tb}^{m1}$ state [Fig. 8(b)]. As this metastable state was added to TALYS, there is no unmodified calculation for comparison. The current data are the most comprehensive available, but there is good agreement with all three available datasets up to 34 MeV. At higher energies, the Kormazeva and Colucci data lie systematically higher, albeit within two standard deviations of our data due to their higher uncertainties. The TALYS calculations are a factor of ≈ 3 too low in the

30–40 MeV region, but match the low-energy data of Ref. [7] well.

The ^{154}Tb ground-state data in the current work are those with the largest uncertainties [Fig. 8(c)] due to the limited data at short times for fitting the grow-in curves. This is a consequence of the low ground-state population and short irradiation time. The only other available data are those from Colucci [12], which lie higher by two-to-three standard deviations. The TALYS predictions for the modified case are much reduced and close to the Colucci points in the 35 MeV region, as well as demonstrating good energy agreement for the maximum magnitude. Similar good agreement is also seen below 18 MeV to the data of Gyürky *et al.* [7]. This might suggest that our current cross sections are too low for this ground state, and the large uncertainties reinforce the low precision of our data for the $^{154}\text{Tb}(\text{g.s.})$. The large reduction in cross-section prediction compared with the unmodified TALYS calculations is due to the insertion of the $m1$ state, which removes strength from the ground-state population. Finally, Fig. 8(d) demonstrates that, while the individual cross-section calculations for states in ^{154}Tb show large discrepancies with the data, the sum over all three levels is quite well reproduced by TALYS (also for the total cross sections of Gyürky *et al.* [7] at low energies). The peak cross section in the 35 MeV region is again about 2 MeV too low compared with our data—as expected given that the same energy shifts are observed in the predictions for the individual contributing states.

The ^{155}Tb ground-state data [Fig. 9(a)] in the current work are broadly in agreement with other available data, although with reduced uncertainties. However, the Kormazeva data are systematically higher in magnitude between 24 and 34 MeV, and the shape of those data around the peak is asymmetric. However, given the large uncertainties in both energy and cross section for Ref. [11] they lie within about two standard deviations of our data. The Colucci data points available are close to those from our work. Note, the scaled low-energy cross sections measured by Gyürky *et al.* [7] for ^{155}Tb are all below 1 mb and so have been omitted from Fig. 9(a). The TALYS calculations reproduce the falloff in cross section beyond 28 MeV well, but seem to predict a broader peak than our data indicate, but are nevertheless within two standard deviations of all data points.

Finally, our data for the total production cross sections of ^{156}Tb data [Fig. 9(b)] are the most precise available to date. There is good agreement with Colucci and Kormazeva, but our points lie systematically lower, below 31 MeV. The TALYS cross-section calculations are in good agreement with the magnitude of other data, but lie systematically above our data. Indeed, the current data lie on the TALYS ground-state line calculations rather than on the line representing total production including the two isomeric levels. The low-energy points of Colucci and Kormazeva suggest that there may again be an ≈ 2 MeV shift to lower energies in the calculations compared with the data.

Overall, a wealth of new, high-precision production cross-section data for the $\alpha + \text{europium}$ reactions have been measured, for both ground and isomeric states. The small energy uncertainties enable definitive energy offsets in the

TALYS calculated cross sections to be identified and thus offer constraints enabling future improvements in the cross-section predictions. These offsets are supported by the accurate, but limited, complementary low-energy data available from Gyürky *et al.* [7].

VI. SUMMARY

The $^{nat}\text{Eu}(\alpha, xn)$ reaction has been used to populate the terbium isotopes from $A = 151$ to 156 at the Birmingham Cyclotron Facility. The stacked foil technique was used, resulting in α energies spanning 25 to 39 MeV. Considerable effort was made to reduce uncertainties in the measured cross sections. Five half-lives have been measured with higher precision than the literature values, and for the cross sections, the majority of the data represent the most precise data to date in this energy

region. Comparisons between available data and TALYS-2.0 have been made, with good agreement observed. These newly obtained data enable more robust planning for α -induced production of terbium isotopes for medical research.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [35], embargo periods may apply.

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