

Activation cross sections of alpha-induced reactions on natural ytterbium up to 50 MeV

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ARTICLE INFO

Keywords:

^{nat}Yb target

Alpha particle induced reaction

Stack-foil activation

Off-line γ -ray spectrometry

Excitation function

¹⁷⁷Lu-medical isotope

ABSTRACT

Activation cross sections of α -particle induced reactions on ^{nat}Yb were measured. The stacked foil technique, the activation method and the γ -ray spectrometry were used. The stacked target consisted of ^{nat}Yb and ^{nat}Ti foils was irradiated with a 51.0-MeV α beam at the RIKEN AVF cyclotron. The γ rays emitted from the irradiated foils were measured using a high-resolution HPGe detector. Production cross sections of ^{170,171,172,173,175}Hf, ^{171,172,173,177}Lu and ¹⁶⁹Yb were determined. The results were compared with previous experimental studies and theoretical calculations. For most of the reactions a consistent agreement was found.

1. Introduction

Many radioisotopes can be used for medical investigations and/or treatments. One candidate of such medical radioisotopes is ¹⁷⁷Lu ($T_{1/2} = 6.647$ d) [1]. It decays with emissions of a β^- particle ($E_{\text{mean}} = 134.2$ keV) and γ rays (e.g., $E_\gamma = 112.95$ keV and 208.37 keV with $I_\gamma = 6.17\%$ and 10.36%, respectively). ¹⁷⁷Lu is useful for theranostic application (therapy + diagnosis) because the energy of the β^- particles and γ rays are suitable for therapeutic and diagnostic investigations, respectively.

For practical use of ¹⁷⁷Lu, every production reaction and all possible side reactions of the by-products should be investigated. Beside neutron production routes there are several charged-particles induced reactions to produce ¹⁷⁷Lu. We focused on charged-particle reactions on ^{nat}Yb which has seven stable isotopes (¹⁶⁸Yb: 0.13%, ¹⁷⁰Yb: 3.04%, ¹⁷¹Yb: 14.28%, ¹⁷²Yb: 21.83%, ¹⁷³Yb: 16.13%, ¹⁷⁴Yb: 31.83%, and ¹⁷⁶Yb: 12.76%). The radionuclide ¹⁷⁷Lu can be produced in the (p, γ) and (d,n) reactions on ¹⁷⁶Yb and the α -particle induced reactions on ¹⁷⁴Yb and ¹⁷⁶Yb. In this paper, the ^{nat}Yb(α ,x)¹⁷⁷Lu reaction cross-section among other possible reactions on ^{nat}Yb was investigated.

Only one previous study of the ^{nat}Yb(α ,x)¹⁷⁷Lu reaction [2] could be found in the EXFOR database [3]. The previous study shows production cross sections of ¹⁷⁷Lu up to 37.7 MeV. Therefore, it is worth

performing an additional experiment to extend the data up to 50 MeV and to increase reliability of the available cross section data. In addition, production cross sections of the by-products, ^{170,171,172,173,175}Hf, ^{171,172,173}Lu and ¹⁶⁹Yb, were also determined.

2. Experimental

The experiment was performed by using the AVF cyclotron at the RI Beam Factory, RIKEN, Japan. The stacked foil technique, the activation method and the high-resolution γ -ray spectrometry were used. The stacked target consisted of pure metallic foils of ^{nat}Yb (99% purity, Goodfellow Co., Ltd., UK) and ^{nat}Ti (99.6% purity, Nilaco Corp., Japan). The ^{nat}Ti foils were inserted into the stack for monitoring the beam parameters and target thicknesses via the ^{nat}Ti(α ,x)⁵¹Cr reaction by determining the excitation function of the reaction and comparing to the recommended values provided in one of the database maintained by the IAEA [4]. The size and weight of the ^{nat}Yb foils (3 pieces, 25 $\times$ 25 mm²) and ^{nat}Ti foil (1 piece, 50 $\times$ 100 mm²) were measured and the thickness of each foil was determined, which were found to be 16.60, 16.32, 17.11 mg/cm² for the ^{nat}Yb foils and 2.40 mg/cm² for the ^{nat}Ti foil, respectively. The foils were cut up for 8 $\times$ 8 mm² pieces to fit into the target holder. The irradiation of the target was done in vacuum. The α -particle beam energy was measured as 51.0 MeV by the TOF

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Table 1

Decay data and contributing reactions of the investigated reaction products [7–11].

Nuclide	Half-life	Decay mode (%)	E_γ (keV)	I_γ (%) ^a	Contributing reactions	Q-value (MeV)
¹⁷⁵ Hf	70 d	ϵ (100)	343.40	84 ± 3	¹⁷¹ Yb(α, γ) ¹⁷² Yb(α, n) ¹⁷³ Yb($\alpha, 2n$) ¹⁷⁴ Yb($\alpha, 3n$) ¹⁷⁶ Yb($\alpha, 5n$)	–2.4 –10.4 –16.8 –24.3 –36.9
¹⁷³ Hf	23.6 h	$\epsilon + \beta^+$ (100)	123.68 296.97	83 ± 4 33.9 ± 1.4	¹⁷⁰ Yb(α, n) ¹⁷¹ Yb($\alpha, 2n$) ¹⁷² Yb($\alpha, 3n$) ¹⁷³ Yb($\alpha, 4n$) ¹⁷⁴ Yb($\alpha, 5n$)	–11.0 –17.6 –25.6 –32.0 –39.5
¹⁷² Hf	1.87 y	ϵ (100)	125.81	11.3 ± 0.9	¹⁶⁸ Yb(α, γ) ¹⁷⁰ Yb($\alpha, 2n$) ¹⁷¹ Yb($\alpha, 3n$) ¹⁷² Yb($\alpha, 4n$) ¹⁷³ Yb($\alpha, 5n$) ¹⁷⁴ Yb($\alpha, 6n$)	–2.8 –18.1 –24.7 –32.7 –39.1 –46.5
¹⁷¹ Hf	12.1 h	$\epsilon + \beta^+$ (100)	662.1	14.6 ± 1.7	¹⁶⁸ Yb(α, n) ¹⁷⁰ Yb($\alpha, 3n$) ¹⁷¹ Yb($\alpha, 4n$) ¹⁷² Yb($\alpha, 5n$) ¹⁷³ Yb($\alpha, 6n$)	–11.8 –27.1 –33.7 –41.8 –48.1
¹⁷⁰ Hf	16.01 h	ϵ (100)	164.71	26 ± 7	¹⁶⁸ Yb($\alpha, 2n$) ¹⁷⁰ Yb($\alpha, 4n$) ¹⁷¹ Yb($\alpha, 5n$) ¹⁷² Yb($\alpha, 6n$)	–19.0 –34.4 –41.0 –49.0
¹⁷⁷ Lu	6.647 d	β^- (100)	208.37	10.36 ± 0.07	¹⁷⁴ Yb(α, p) ¹⁷⁶ Yb(α, t) ¹⁷⁶ Yb($\alpha, ^3\text{He}$) ¹⁷⁷ Yb(β^- decay)	–9.4 –13.6 –15.0
¹⁷³ Lu	1.37 y	ϵ (100)	272.11	21.2 ± 0.8	¹⁷⁰ Yb(α, p) ¹⁷¹ Yb(α, d) ¹⁷² Yb(α, t) ¹⁷³ Yb(α, tn) ¹⁷⁴ Yb($\alpha, t2n$) ¹⁷³ Hf(ϵ decay)	–8.7 –13.1 –14.9 –21.3 –28.7
¹⁷² Lu	6.70 d	$\epsilon + \beta^+$ (100)	1093.63	63 ± 3	¹⁷⁰ Yb(α, d) ¹⁷¹ Yb(α, t) ¹⁷² Yb(α, tn) ¹⁷³ Yb($\alpha, t2n$) ¹⁷² Hf(ϵ decay)	–14.7 –15.1 –23.1 –29.5
¹⁷¹ Lu	8.24 d	$\epsilon + \beta^+$ (100)	739.79	47.9 ± 1.3	¹⁶⁸ Yb(α, p) ¹⁷⁰ Yb(α, t) ¹⁷¹ Yb(α, tn) ¹⁷² Yb($\alpha, t2n$) ¹⁷³ Yb($\alpha, t3n$) ¹⁷⁴ Yb($\alpha, t4n$) ¹⁷¹ Hf(ϵ decay)	–8.6 –15.5 –22.1 –30.1 –36.5 –43.9
¹⁶⁹ Yb	32.018 d	ϵ (100)	197.96	35.93 ± 0.12	¹⁶⁸ Yb($\alpha, ^3\text{He}$) ¹⁷⁰ Yb($\alpha, \alpha n$) ¹⁷¹ Yb($\alpha, \alpha 2n$) ¹⁷² Yb($\alpha, \alpha 3n$) ¹⁷³ Yb($\alpha, \alpha 4n$) ¹⁷⁴ Yb($\alpha, \alpha 5n$) ¹⁷⁶ Yb($\alpha, \alpha 7n$) ¹⁶⁹ Hf(ϵ decay) ¹⁶⁹ Lu(ϵ decay) ¹⁶⁹ Lu(ϵ decay)	–13.7 –8.5 –15.1 –23.1 –29.5 –36.9 –49.6
⁵¹ Cr	27.7025 d	ϵ (100)	320.08	9.91 ± 0.01		

method [5]. The beam was collimated down to a 3 mm diameter. The irradiation lasted for 2 h. The average beam intensity measured with a Faraday-cup was 413.9 nA. Energy degradation of the bombarding particles in the target was calculated by the SRIM code [6]. No electron suppression voltage was applied for the Faraday-cup since its geometry assured that the solid angle in which the secondary electrons could escape was small.

The irradiated foils were separated each other from the stack after the end of bombardment. The γ -ray spectra of each irradiated foil were measured without chemical separation. To follow the decay of the

reaction products with half-lives between 12.1 h and 1.87 y spectra were measured five times. The cooling times of the measurements are 10 h, 33 h, 3.1 d, 14.1 d and 143 d, respectively. A high-resolution HPGe detector (ORTEC GEM-25185-P) was used for the γ -ray spectrometry. The detector efficiency was calibrated by using a standard γ -ray point source consisted of a mixture of multiple radioisotopes ^{57,60}Co, ⁸⁸Y, ¹⁰⁹Cd, ¹¹³Sn ¹³⁷Cs, ¹³⁹Ce and ²⁴¹Am. The γ lines detected by the detector were analyzed by the software Gamma Studio (SEIKO EG&G). Reaction and decay data for γ -ray spectrometry were taken from NuDat 2.7 [7], Lund/LBNL Nuclear Data Search [8], LiveChart [9] and QCalc

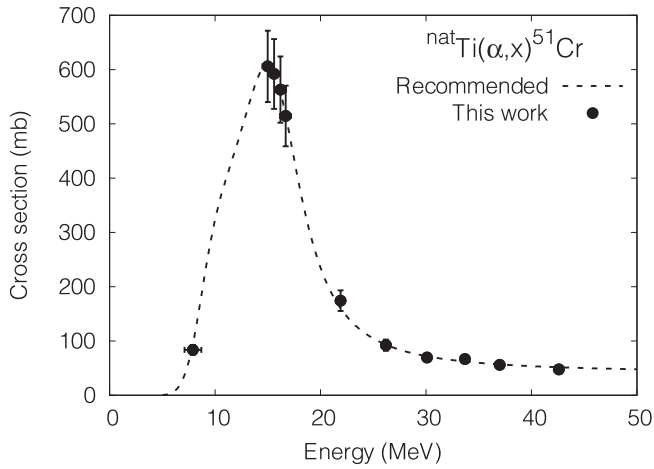


Fig. 1. Cross section data measured for the $^{nat}\text{Ti}(\alpha, x)^{51}\text{Cr}$ monitor reaction in comparison with the IAEA recommended values [4].

[10], which are given in Table 1. For the ^{171}Hf radionuclide, only relative γ intensities were provided in the Lund/LBNL data library [8]. Thus, the factor to obtain absolute intensities was taken from Baglin [11]. The derivation of the γ intensity of ^{171}Hf was the same way as in Király et al. [2].

Cross sections σ were deduced from measured net peak area T_γ by using the equation,

$$\sigma = \frac{T_\gamma \lambda}{\varepsilon_d \varepsilon_\gamma \varepsilon_t N_t N_b (1 - e^{-\lambda t_b}) e^{-\lambda t_c} (1 - e^{-\lambda t_m})} \quad (1)$$

with parameters; surface density of target atoms N_t , number of bombarding particles per unit time N_b , detector efficiency ε_d , γ -ray abundance ε_γ , measurement dead time ε_t , decay constant λ , bombarding time t_b , cooling time t_c , and acquisition time t_m . The cross sections were assigned to the mid energy of each target foil.

Cross sections of the $^{nat}\text{Ti}(\alpha, x)^{51}\text{Cr}$ monitor reaction were derived from measurements of the 320.08 keV γ line from the decay of ^{51}Cr ($T_{1/2} = 27.7025$ d). The dead time throughout the series of the measurements after a cooling time of 38.3 h was kept below 0.6%. The derived cross sections were compared with the IAEA recommended values [4], and the beam intensity was corrected to 379.2 nA, which was 8.4% lower than the measured value. The foil thicknesses were also adjusted only within their uncertainties ($< 1\%$) to reach proper agreement for the energy scale. Our cross section data for the monitor reaction determined in this experiment are shown in Fig. 1 in comparison with the IAEA recommended values [4]. A complete agreement between our result and the recommended values was obtained.

3. Result and discussion

Activation cross sections of the α -particle induced reactions on ^{nat}Yb were determined for the production of $^{170,171,172,173,175}\text{Hf}$, $^{171,172,173,177}\text{Lu}$ and ^{169}Yb isotopes. Data are presented in Table 2 and are shown in Figs. 2–11. The results are compared with the previous studies [2,12,13] and the results of theoretical calculation taken from the TENDL-2017 data [14].

The total uncertainty of the cross sections was 11.4–36.0% including contribution of statistical and systematical uncertainties. It was calculated from the square root of the quadratic summation of the following components; statistical uncertainty ($< 22.7\%$), target thickness (1%), target purity (1%), beam intensity (9%), detector efficiency (5%), γ -ray intensity ($< 26.9\%$), and peak fitting (3%). Uncertainty on the time parameters (irradiation, cooling and measuring time) were not included because of the relatively long half-life of the investigated isotopes, whose contribution is negligibly small.

Table 2
Measured $^{nat}\text{Yb}(\alpha, x)$ reaction cross sections.

Energy (MeV)	$^{nat}\text{Yb}(\alpha, x)^{175}\text{Hf}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{173}\text{Hf}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{172}\text{Hf}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{171}\text{Hf}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{170}\text{Hf}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{177}\text{Lu}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{172}\text{Lu}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{171}\text{Lu}^{(cum)}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{171}\text{Lu}^{(ind)}$ (mb)	$^{nat}\text{Yb}(\alpha, x)^{169}\text{Yb}$ (mb)
49.4 ± 0.7	224.8 ± 25.6	538.2 ± 62.4	391.3 ± 52.9	188.8 ± 29.7	67.5 ± 19.6	23.9 ± 2.7	520.8 ± 59.9	293.7 ± 32.8	110.0 ± 19.0	10.5 ± 1.5
48.3 ± 0.7	190.8 ± 21.8	471.3 ± 54.6	345.4 ± 46.7	180.1 ± 28.3	52.7 ± 15.3	19.0 ± 2.2	449.5 ± 51.7	258.3 ± 28.8	107.9 ± 18.6	8.9 ± 1.4
47.1 ± 0.7	171.1 ± 19.5	430.3 ± 49.9	323.3 ± 43.7	156.1 ± 24.6	39.9 ± 11.6	15.7 ± 1.8	410.9 ± 47.3	225.9 ± 25.2	79.5 ± 13.8	6.5 ± 1.1
46.0 ± 0.7	163.0 ± 18.6	419.4 ± 48.6	307.9 ± 41.6	146.0 ± 23.0	33.2 ± 9.7	13.8 ± 1.6	395.1 ± 45.4	208.5 ± 23.3	78.5 ± 13.8	7.8 ± 1.1
44.8 ± 0.7	174.4 ± 19.9	450.6 ± 52.2	307.2 ± 41.5	143.5 ± 22.5	32.5 ± 9.6	12.6 ± 1.5	425.4 ± 48.9	203.3 ± 22.7	71.5 ± 13.9	6.5 ± 1.0
43.6 ± 0.7	180.4 ± 20.6	434.9 ± 50.4	282.6 ± 38.2	117.6 ± 18.4	21.1 ± 6.2	10.2 ± 1.1	412.5 ± 47.4	166.6 ± 18.6	62.2 ± 10.8	5.7 ± 1.0
40.6 ± 0.7	310.3 ± 35.4	490.4 ± 56.8	250.1 ± 34.3	70.7 ± 11.1	2.3 ± 0.8	8.7 ± 1.0	456.7 ± 52.7	103.4 ± 11.5	35.5 ± 6.1	4.8 ± 0.5
39.4 ± 0.7	376.9 ± 43.0	477.8 ± 55.3	227.4 ± 30.9	51.3 ± 8.1	1.5 ± 0.5	7.4 ± 0.8	435.8 ± 50.1	75.2 ± 8.4	26.0 ± 4.5	3.9 ± 0.4
38.1 ± 0.8	433.8 ± 49.4	439.2 ± 50.9	199.7 ± 27.2	37.4 ± 5.9	6.4 ± 0.7	6.4 ± 0.7	405.5 ± 46.6	55.3 ± 6.2	19.4 ± 3.4	3.0 ± 0.4
34.9 ± 0.8	490.0 ± 55.8	367.9 ± 42.6	168.4 ± 23.0	23.6 ± 3.7	4.4 ± 0.5	4.4 ± 0.5	335.5 ± 38.6	32.7 ± 3.6	9.9 ± 1.8	1.0 ± 0.1
31.4 ± 0.9	436.1 ± 49.7	306.1 ± 35.5	111.1 ± 15.2	6.9 ± 1.1	3.8 ± 0.5	3.8 ± 0.5	271.7 ± 31.2	9.1 ± 1.0	2.5 ± 0.6	
27.6 ± 0.9	225.7 ± 25.7	187.2 ± 21.7	32.9 ± 4.6		2.2 ± 0.3	0.52 ± 0.10	163.3 ± 18.7	0.35 ± 0.04		
23.4 ± 1.1	129.9 ± 14.8	112.0 ± 13.0	13.7 ± 1.9		0.52 ± 0.10		97.0 ± 11.1	0.55 ± 0.06		
18.6 ± 1.3	33.5 ± 3.8	9.2 ± 1.1					7.9 ± 0.9	0.20 ± 0.02		

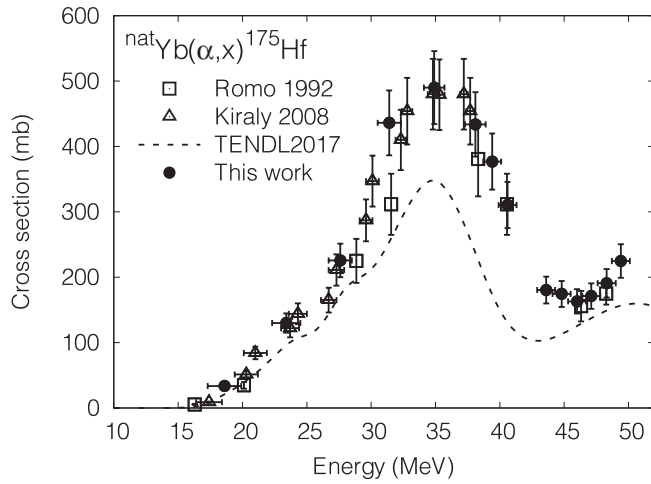


Fig. 2. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{175}\text{Hf}$ reaction with the previous data [2,12] and the TENDL-2017 data [14].

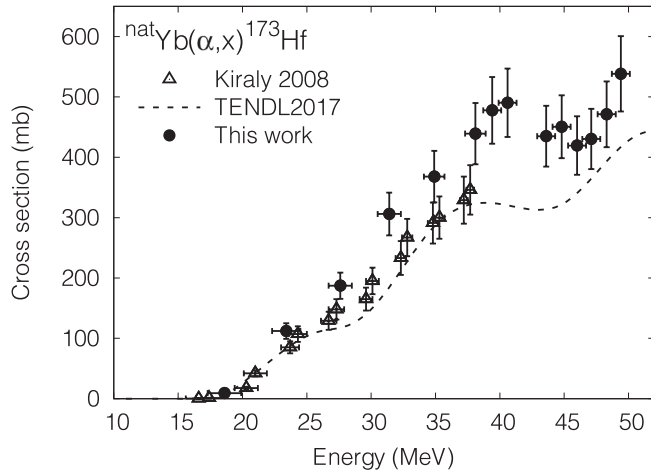


Fig. 3. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{173}\text{Hf}$ reaction with the previous data [2] and the TENDL-2017 data [14].

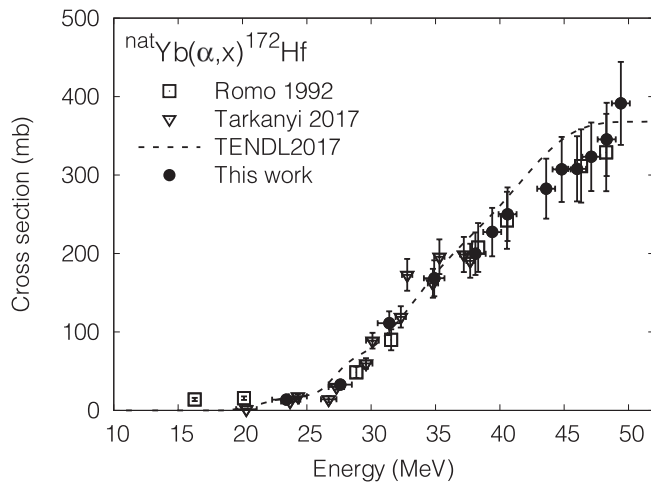


Fig. 4. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{172}\text{Hf}$ reaction with the previous data [12,13] and the TENDL-2017 data [14].

3.1. $^{nat}\text{Yb}(\alpha,x)^{175}\text{Hf}$ reaction

Experimental cross sections of the $^{nat}\text{Yb}(\alpha,x)^{175}\text{Hf}$ process were derived from measurements of the γ line at 343.40 keV ($I_\gamma = 84\%$). The

measurements were performed after a cooling time of 143 days to reduce unnecessary background. The result shown in Fig. 2 is compared with the previous studies [2,12] and the TENDL-2017 data [14]. The previous data are consistent with our result, however the TENDL-2017 data underestimate all experimental data.

3.2. $^{nat}\text{Yb}(\alpha,x)^{173}\text{Hf}$ reaction

Measurements of the γ line at 296.97 keV ($I_\gamma = 33.9\%$) from the decay of ^{173}Hf ($T_{1/2} = 23.6$ h) were performed after a cooling time of 10 h. The more intense γ line at 123.68 keV ($I_\gamma = 83\%$) was not selected because of possible interferences with the γ lines at 124.4 and 124.6 keV from ^{171}Hf ($T_{1/2} = 12.1$ h). The obtained cross sections are shown in Fig. 3 in comparison with the data of the previous study [2] and the TENDL-2017 data [14]. The previous data are slightly smaller than our data. The TENDL-2017 data underestimate our data though they agree with the previous data.

3.3. $^{nat}\text{Yb}(\alpha,x)^{172}\text{Hf}$ reaction

The radionuclide ^{172}Hf ($T_{1/2} = 1.87$ y) decays with emission of the γ rays with 125.81 keV ($I_\gamma = 11.3\%$), which was used to determine the excitation function of the $^{nat}\text{Yb}(\alpha,x)^{172}\text{Hf}$ reaction. The series of the measurements after a cooling time of 143 days was used. The results are shown in Fig. 4 and compared with the previous studies [12,13] and the TENDL-2017 data [14]. Both previous data and the TENDL-2017 data are in good agreement with our data.

3.4. $^{nat}\text{Yb}(\alpha,x)^{171}\text{Hf}$ reaction

Only relative γ -ray intensity is available for ^{171}Hf ($T_{1/2} = 16.01$ h) in the Lund/LBNL Nuclear Data library [8]. To obtain the absolute cross sections, the normalization factor reported by Baglin [11] was adopted for the relative intensity in the same as the previous study [2]. The specific γ line at 662.2 keV ($I_\gamma = 14.6\%$) were measured after a cooling time of 33 h. The cross sections of the $^{nat}\text{Yb}(\alpha,x)^{171}\text{Hf}$ reaction are shown in Fig. 5. The results are compared with the previous study [2] and the TENDL-2017 data [14]. The previous data and our data are in good agreement with each other, while the TENDL-2017 data are higher than the experimental data above 30 MeV.

3.5. $^{nat}\text{Yb}(\alpha,x)^{170}\text{Hf}$ reaction

We adopted the γ line at 164.71 keV ($I_\gamma = 26\%$) to derive the cross sections of the $^{nat}\text{Yb}(\alpha,x)^{170}\text{Hf}$ reaction. The radionuclide ^{170}Hf has a half-life $T_{1/2} = 16.01$ h. The measurements after a cooling time of about 33 h were used for the cross section determination. The cross sections are shown in Fig. 6 in comparison with the previous study [2] and the TENDL-2017 data [14]. The previous dataset is available up to 37.7 MeV while ours is between 39.4 MeV and 49.4 MeV. Since the previous cross sections at 37.7 MeV and ours at 39.4 MeV are 1.24 ± 0.38 mb and 1.5 ± 0.5 mb, respectively, the two excitation functions can be connected smoothly. The TENDL-2017 data show the similar shape as the experimental data, however with higher amplitude above 37 MeV.

3.6. $^{nat}\text{Yb}(\alpha,x)^{177\text{g}}\text{Lu}$ reaction

To determine the cumulative production cross sections of $^{177\text{g}}\text{Lu}$ ($T_{1/2} = 6.647$ d), the measurements of the γ line at 208.37 keV ($I_\gamma = 10.36\%$) were performed after a cooling time of 3.1 days to decay out its parent nuclide ^{177}Yb ($T_{1/2} = 1.911$ h). The negligible contribution of $^{177\text{m}}\text{Lu}$ ($T_{1/2} = 160.44$ d, β^- : 78.60%, IT: 21.40%) could be confirmed using the measurements of a cooling time of 143 days. The cumulative cross sections of the $^{nat}\text{Yb}(\alpha,x)^{177\text{g}}\text{Lu}$ reaction are compared with the previous study [2] and the TENDL-2017 data [14] in Fig. 7.

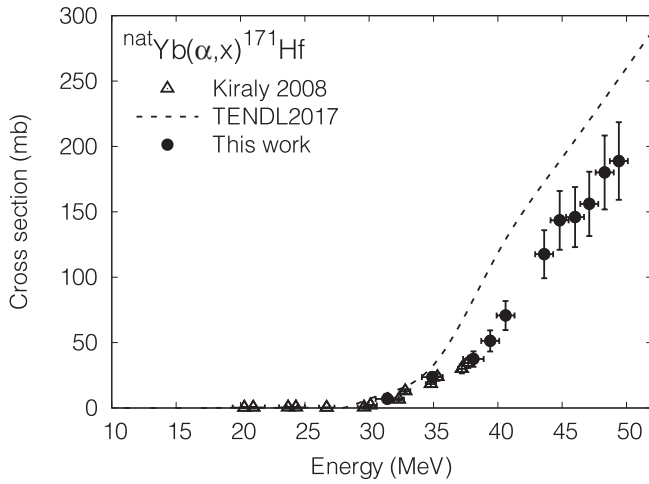


Fig. 5. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{171}\text{Hf}$ reaction with the previous data [2] and the TENDL-2017 data [14].

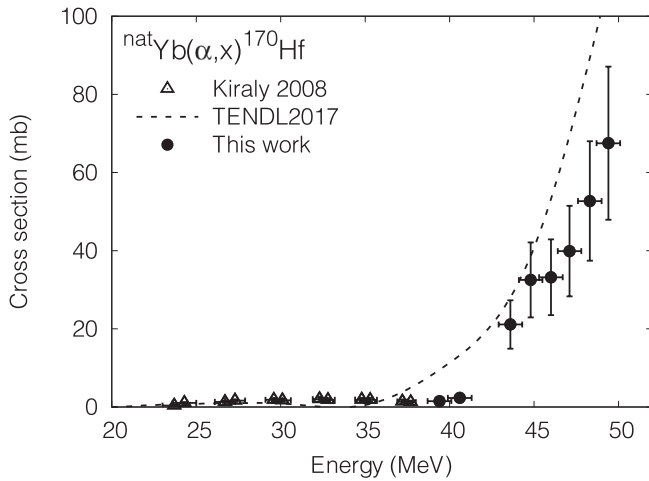


Fig. 6. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{170}\text{Hf}$ reaction with the previous data [2] and the TENDL-2017 data [14].

The previous data are in good agreement with the present data. The TENDL-2017 data are much smaller than the experimental data.

3.7. $^{nat}\text{Yb}(\alpha,x)^{173}\text{Lu}$ reaction

For the cumulative cross sections of the $^{nat}\text{Yb}(\alpha,x)^{173}\text{Lu}$ reaction, we used the series of the measurements after a cooling time of 143 days to decay out its parent nuclide ^{173}Hf ($T_{1/2} = 23.6$ h). The radionuclide ^{173}Lu has a half-life of $T_{1/2} = 1.37$ y and decays with emission of the γ rays with 272.11 keV ($I_\gamma = 21.2\%$). The cross sections were compared with the previous studies [12,13] and the TENDL-2017 data [14] in Fig. 8. The previous data show higher amplitude than ours. On the contrary, the TENDL-2017 data are smaller than our experimental data.

3.8. $^{nat}\text{Yb}(\alpha,x)^{172}\text{Lu}$ reaction

The radionuclide ^{172}Lu has a metastable state ^{172m}Lu ($T_{1/2} = 3.7$ min, IT: 100%). The metastable state decayed to the ground state ^{172g}Lu ($T_{1/2} = 6.7$ d) during a cooling time of 3.1 days. The γ line at 1093.63 keV ($I_\gamma = 63\%$) was measured to derive the cross sections of the $^{nat}\text{Yb}(\alpha,x)^{172}\text{Lu}$ reaction. The contribution of ^{172}Hf ($T_{1/2} = 1.87$ y) was corrected using the cross sections derived in Section 3.3. The excitation function is shown in Fig. 9 in comparison with the previous

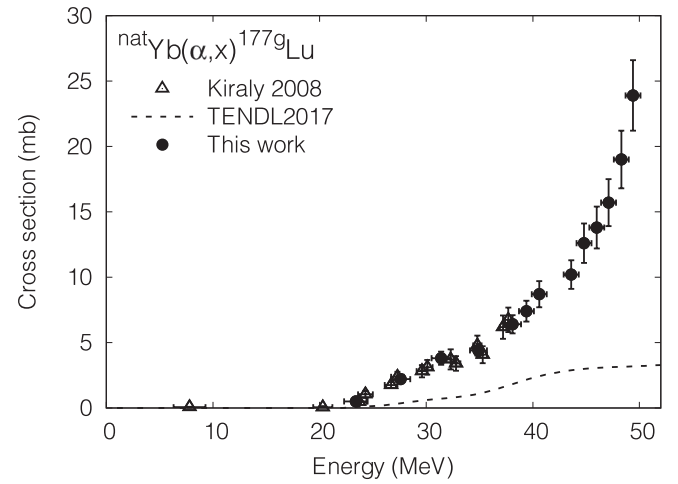


Fig. 7. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{177g}\text{Lu}$ reaction with the previous data [2] and the TENDL-2017 data [14].

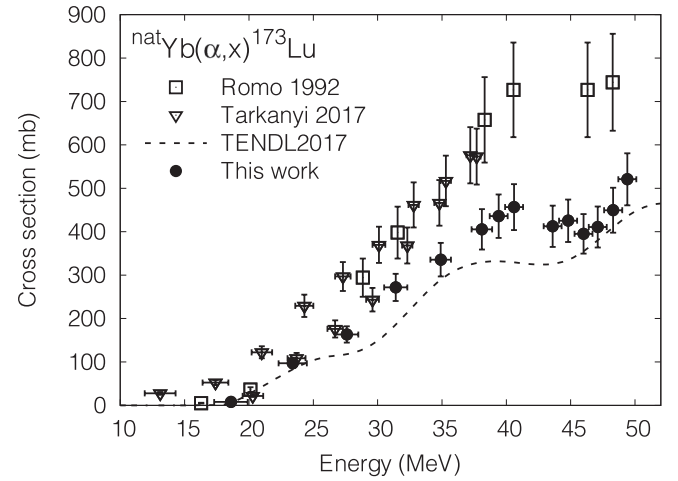


Fig. 8. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{173}\text{Lu}$ reaction with the previous data [12,13] and the TENDL-2017 data [14].

studies [2,12] and the TENDL-2017 data [14]. The previous data show higher amplitude than the present data. The TENDL-2017 data are smaller than both the previous and our experimental data.

3.9. $^{nat}\text{Yb}(\alpha,x)^{171}\text{Lu}$ reaction

The metastable state of ^{171m}Lu ($T_{1/2} = 79$ s, IT: 100%) contributed to the formation of ground state ^{171g}Lu ($T_{1/2} = 8.24$ d) during the beam irradiation and shortly after the end of bombardment. The measurements of the γ line at 739.79 keV ($I_\gamma = 47.9\%$) after a cooling time of 3.1 days were used to derive cross sections of the $^{nat}\text{Yb}(\alpha,x)^{171}\text{Lu}$ reaction. The contribution of its parent ^{171}Hf can be corrected using the cross sections derived in Section 3.4. In Fig. 10, both the cumulative and independent cross section data sets, which include (cum) and exclude (ind) the contribution of ^{171}Hf , are shown. The cumulative data in the previous studies [2,12] show good agreement with ours and the TENDL-2017 data [14].

3.10. $^{nat}\text{Yb}(\alpha,x)^{169}\text{Yb}$ reaction

The radionuclide ^{169}Yb has a metastable state ^{169m}Yb with a short half-life of $T_{1/2} = 46$ s (IT: 100%), which decayed to ^{169g}Yb ($T_{1/2} = 32.018$ d) during the irradiation and a cooling time of 14.1 days. Cross sections of the $^{nat}\text{Yb}(\alpha,x)^{169}\text{Yb}$ reaction were derived using the γ

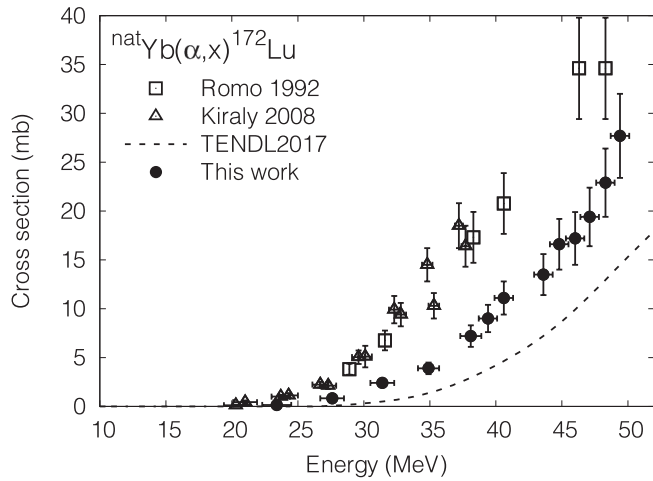


Fig. 9. Cross sections of the $^{nat}\text{Yb}(\alpha, x)^{172}\text{Lu}$ reaction with the previous data [2,12] and the TENDL-2017 data [14].

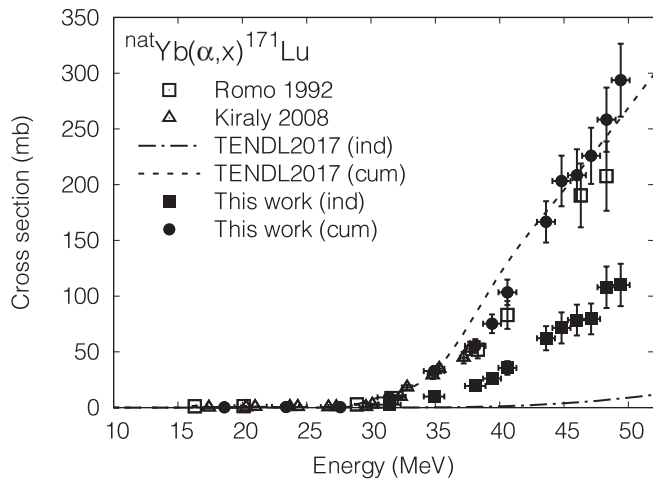


Fig. 10. Cross sections of the $^{nat}\text{Yb}(\alpha, x)^{171}\text{Lu}$ reaction with the previous data [2,12] and the TENDL-2017 data [14].

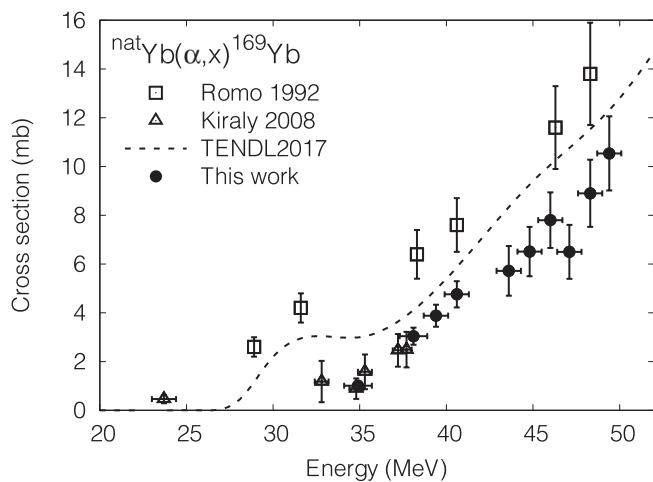


Fig. 11. Cross sections of the $^{nat}\text{Yb}(\alpha, x)^{169}\text{Yb}$ reaction with the previous data [2,12] and the TENDL-2017 data [14].

line at 197.96 keV ($I_\gamma = 35.93\%$). The present results are compared with the previous studies [2,12] and the TENDL-2017 data [14] in Fig. 11. One set of data of the previous work [2] shows good agreement with the present data. The TENDL-2017 data overestimate ours.

4. Summary

We measured activation cross sections of the α -particle induced reactions on ^{nat}Yb using the stacked target activation technique and high resolution γ -ray spectrometry. Five series of the activity measurements were performed for radionuclides with largely different half-lives. The production cross sections of $^{170,171,172,173,175}\text{Hf}$, $^{171,172,173,177}\text{Lu}$ and ^{169}Yb were determined. The measured data were compared with the previous experimental data and the theoretical data of TENDL-2017 data library. For most of the reactions, good agreement was found with the previous studies.

Acknowledgements

This work was carried out at the RI Beam Factory operated by RIKEN Nishina Center and CNS, University of Tokyo, Japan. Preliminary results were presented at the 18th Radiochemical Conference (RadChem 2018) held in Mariánské Lázně, Czech Republic, on 13–18 May 2018. This work was supported by Hokkaido University Nitobe School Advanced Program Research Grant 2017 from the Hokkaido University's Frontier Foundation and JSPS KAKENHI Grant Number 17K07004.

Declaration of Competing Interest

None.

References

- [1] K. Rahbar, H. Ahmadzadehfar, C. Kratochwil, U. Haberkorn, M. Schäfers, M. Essler, R.P. Baum, H.R. Kulkarni, M. Schmidt, A. Drzeza, P. Bartenstein, A. Pfestroff, M. Luster, U. Lützen, M. Marx, V. Prasad, W. Brenner, A. Heinzel, F.M. Mottaghy, J. Ruf, P.T. Meyer, M. Heuschkel, M. Eveslage, M. Bögemann, W.P. Fendler, B.J. Krause, German multicenter study investigating 177 Lu-PSMA-617 radioligand therapy in advanced prostate cancer patients, *J. Nucl. Med.* 58 (2017) 85–90, <https://doi.org/10.2967/jnumed.116.183194>.
- [2] B. Király, F. Tárkányi, S. Takács, A. Hermanne, S.F. Kovalev, A.V. Ignatyuk, Excitation functions of alpha-particle induced nuclear reactions on natural ytterbium, *Nucl. Instrum. Meth. Phys. Res. Sect. B Beam Interact. Mater. Atoms* 266 (2008) 3919–3926, <https://doi.org/10.1016/j.nimb.2008.07.002>.
- [3] N. Otuka, E. Dupont, V. Semkova, B. Pritychenko, A.I. Blokhin, M. Aikawa, S. Babykina, M. Bossant, G. Chen, S. Dunaeva, R.A. Forrest, T. Fukahori, N. Furutachi, S. Ganesan, Z. Ge, O.O. Gritzay, M. Herman, S. Hlavač, K. Kato, B. Lalremruata, Y.O. Lee, A. Makinaga, K. Matsumoto, M. Mikhaylyukova, G. Pikulina, V.G. Pronyaev, A. Saxena, O. Schwerer, S.P. Simakov, N. Soppera, R. Suzuki, S. Takács, X. Tao, S. Taova, F. Tárkányi, V.V. Varlamov, J. Wang, S.C. Yang, V. Zerkov, Y. Zhuang, Towards a More complete and accurate experimental nuclear reaction data library (EXFOR): International collaboration between nuclear reaction data centres (NRDC), *Nucl. Data Sheets* 120 (2014) 272–276, <https://doi.org/10.1016/j.nds.2014.07.065>.
- [4] A. Hermanne, A.V. Ignatyuk, R. Capote, B.V. Carlson, J.W. Engle, M.A. Kellett, T. Kibédi, G. Kim, F.G. Kondev, M. Hussain, O. Lebeda, A. Luca, Y. Nagai, H. Naik, A.L. Nichols, F.M. Nortier, S.V. Suryanarayana, S. Takács, F.T. Tárkányi, M. Verpilli, Reference cross sections for charged-particle monitor reactions, *Nucl. Data Sheets* 148 (2018) 338–382, <https://doi.org/10.1016/j.nds.2018.02.009>.
- [5] T. Watanabe, M. Fujimaki, N. Fukunishi, H. Imao, O. Kamigaito, M. Kase, M. Komiya, N. Sakamoto, K. Suda, M. Wakasugi, K. Yamada, Beam energy and longitudinal beam profile measurement system at the RIBF, in: *Proc. 5th Int. Part. Accel. Conf. (IPAC 2014)*, 2014, pp. 3566–3568.
- [6] J.F. Ziegler, J.P. Biersack, M.D. Ziegler, SRIM: the Stopping and Range of Ions in Matter, (2008). <http://www.srim.org>.
- [7] National Nuclear Data Center, Nuclear structure and decay data on-line library, Nudat 2.7, (2017). <http://www.nndc.bnl.gov/nudat2/>.
- [8] S.Y.F. Chu, L.P. Ekström, R.B. Firestone, The Lund/LBNL Nuclear Data Search, (n.d.). <http://nucleardata.nuclear.lu.se/toi/>.
- [9] International Atomic Energy Agency, LiveChart of Nuclides, (2009). <https://www->

- nds.iaea.org/livechart/.
- [10] B. Pritychenko, A. Sonzogni, Q-value Calculator (QCalc), (2003). <http://www.nndc.bnl.gov/qcalc/>.
- [11] C.M. Baglin, Nuclear Data Sheets for A = 171, Nucl. Data Sheets 96 (2002) 399–610, <https://doi.org/10.1006/ndsh.2002.0014>.
- [12] A.S.M.A. Romo, A.A. Sonzogni, D.A. Rodriguez Sierra, S.J. Nassiff, Nuclear reactions induced by alpha particles on natural ytterbium, Radiochim. Acta. 57 (1992) 57–61, <https://doi.org/10.1524/ract.1992.57.23.57>.
- [13] F. Tárkányi, F. Ditrói, S. Takács, A. Hermanne, B. Király, Activation cross-section data for alpha-particle induced nuclear reactions on natural ytterbium for some longer lived radioisotopes, J. Radioanal. Nucl. Chem. 311 (2017) 1825–1829, <https://doi.org/10.1007/s10967-016-5139-0>.
- [14] A.J. Koning, D. Rochman, J. Sublet, N. Dzysiuik, M. Fleming, S. van der Marck, TENDL: complete nuclear data library for innovative nuclear science and technology, Nucl. Data Sheets 155 (2019) 1–55, <https://doi.org/10.1016/j.nds.2019.01.002>.