

# Activation cross sections of alpha-induced reactions on $^{nat}\text{In}$ for $^{117\text{m}}\text{Sn}$ production

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## ABSTRACT

The production of  $^{117\text{m}}\text{Sn}$  by charged-particle induced reactions is an interesting topic for medical application. Production cross sections of  $\alpha$ -induced reactions on  $^{nat}\text{In}$  for  $^{117\text{m}}\text{Sn}$  up to 50 MeV were measured using the stacked foil technique and activation method. The integral yield of  $^{117\text{m}}\text{Sn}$  was estimated using the measured cross sections. The results were compared with experimental data investigated earlier and theoretical calculation. Measured cross sections for  $^{113}\text{Sn}$  and  $^{116\text{m}},^{117},^{118\text{m}}\text{Sb}$  isotopes were also presented.

## 1. Introduction

The radioisotope (RI)  $^{117\text{m}}\text{Sn}$  ( $T_{1/2} = 13.76$  d) decays with emissions of conversion electrons (126.82, 129.369 and 151.56 keV) and  $\gamma$  rays (158.56 keV). It is available as a theranostic RI because the electrons and  $\gamma$  rays are appropriate for therapy and imaging, respectively [1,2]. The production reactions of  $^{117\text{m}}\text{Sn}$  for clinical applications have recently been investigated and discussed in [3,4]. Batch production of appropriate quantities for routine use in hospitals is still of much concern. We focused on one of the reactions, the  $^{115}\text{In}(\alpha, x)^{117\text{m}}\text{Sn}$  reaction. Three reports on the cross sections of the reaction [5,6,7] were found in the EXFOR library [8]. The data show large discrepancy from each other and more reliable and accurate data are required. Therefore, we performed a new experiment to measure the cross sections of the reaction. From the measured cross sections, the integral yield of  $^{117\text{m}}\text{Sn}$  was estimated. In addition, the cross sections for other Sn and Sb isotopes were also presented.

## 2. Method

The experiment was performed at the AVF cyclotron of the RIKEN RI Beam Factory by using the stacked foil technique, activation method and high resolution  $\gamma$ -ray spectrometry. Natural In foils (purity: 99.99%, Nilaco Corp., Japan) of which isotopic composition is listed in Table 1 were stacked with  $^{nat}\text{Ti}$  monitor foils (purity: 99.6%, Nilaco Corp., Japan) as a target. The thicknesses of the In and Ti foils were estimated from the measured area and weight of large foils

( $50 \times 50 \text{ mm}^2$ ) and found to be  $16.60 \text{ mg/cm}^2$  and  $2.44 \text{ mg/cm}^2$ , respectively. The stacked target consisted of 11 sets of the In-In-Ti-Ti foils ( $8 \times 8 \text{ mm}^2$ ) cut off from the large foils. The foils at the downstream side of the beam would be measured to compensate for losses of recoil products. However, the 2 adjoining In foils were partially molten during the irradiation (low melting point at  $156.6^\circ\text{C}$ ) and could not be separated when dismantling the target. Each pair of In foils was therefore considered as one foil of  $33.20 \text{ mg/cm}^2$ . The target was irradiated by a 51.6 MeV  $\alpha$  beam with an average intensity of 202.1 nA for 2 h. The intensity and beam energy were measured by a Faraday cup like target holder and the time-of-flight method using a plastic scintillator monitor [9]. The beam energy degradation in the stacked target was calculated using the SRIM code [10]. After adequate cooling time, the irradiated foils were subjected to  $\gamma$ -spectrometry with a HPGe detector. Decay data of reaction products were obtained from online databases, e.g. NuDat 2.7 [11], Lund/LBNL Nuclear Data Search [12], and Q-value Calculator (QCalc) [13] (Table 2).

## 3. Result

The excitation function of the  $^{nat}\text{Ti}(\alpha, x)^{51}\text{Cr}$  monitor reaction was used to assess beam parameters, e.g. intensity and energy. The excitation function could be derived from measurements of the  $\gamma$ -line at 320.08 keV (9.91%) from the decay of  $^{51}\text{Cr}$  ( $T_{1/2} = 27.7025$  d). The measurements of the Ti foils were performed after a cooling time of 34 h for background reduction. During the measurements, the dead time was kept below 3.5%. The statistical uncertainty at maximum was

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**Table 1**  
Isotopic composition of natural indium.

|                   |        |
|-------------------|--------|
| $^{113}\text{In}$ | 4.29%  |
| $^{115}\text{In}$ | 95.71% |

about 6% at the lowest cross section of 0.7 mb. The result was compared with the recommended values [14] as shown in Fig. 1. The result is in good agreement with the recommended values and suggests no adjustment required for the beam parameters.

The cross sections of  $^{117\text{m}}\text{Sn}$  and  $^{117,118\text{m}}\text{Sb}$  obtained for  $^{\text{nat}}\text{In}$  were normalized to for 100%  $^{115}\text{In}$  target because no or negligible contribution from reactions on  $^{113}\text{In}$  are expected. The numerical data were presented in Table 3 and shown in Figs. 2–6 in comparison with the experimental data studied earlier [5,6,7,15,16,17] and the TENDL-2017 data [18].

The total uncertainty was estimated to be < 25.4% including statistical errors (< 24.1%). It was estimated as the square root of the quadratic summation of the components; the beam intensity (5%), target thickness (1%), target purity (1%), detector efficiency (5%),  $\gamma$  intensity (< 6%) and peak area determination (3%).

### 3.1. $^{117\text{m}}\text{Sn}$ production

The measurement of the 156.02 keV  $\gamma$ -line (2.113%) from the  $^{117\text{m}}\text{Sn}$  decay ( $T_{1/2} = 13.76$  d) was performed after a cooling time of about 45 h. The cooling time was set to be long enough for the decay of the parent nuclei,  $^{117\text{g}}\text{In}$  ( $T_{1/2} = 43.2$  min.),  $^{117\text{m}}\text{In}$  ( $T_{1/2} = 116.2$  min.) and  $^{117}\text{Sb}$  ( $T_{1/2} = 2.80$  h). The  $\gamma$ -line at 158.56 keV (86.4%) was not used to avoid the contribution of the 159.377 keV  $\gamma$ -line (68.3%) from  $^{47}\text{Sc}$  ( $T_{1/2} = 3.3492$  d) produced in the Ti catcher foils, which were measured together. Cumulative cross sections of the  $^{115}\text{In}(\alpha, x)^{117\text{m}}\text{Sn}$  reaction taking into account the  $^{115}\text{In}$  abundance were shown in Fig. 2 together with the previous experimental data [5,6,7] and the TENDL-2017 data [18]. The present result is almost coincident with the data by Qaim and Döhler (1984) [6] among the three earlier experimental data. The data by Fukushima et al. (1963) [5] and TENDL-2017 show much smaller amplitude than ours and the others, while the data by Bhardwaj et al. (1992) [7] are larger than others.

### 3.2. $^{113}\text{Sn}$ production

The excitation function of the  $^{\text{nat}}\text{In}(\alpha, x)^{113}\text{Sn}$  reaction were derived from the measurement of the  $\gamma$ -line at 391.698 keV (64.97%). Both  $^{113}\text{In}$  and  $^{115}\text{In}$  can contribute to the cross sections according to the Q-values (Table 2). The measurement of the long-lived  $^{113}\text{Sn}$  ( $T_{1/2} = 115.09$  d) was performed after a cooling time of about 45 h. It is long enough to obtain cumulative  $^{113}\text{Sn}$  production from the decay of  $^{113}\text{Sb}$  ( $T_{1/2} = 6.67$  min.) and  $^{113\text{m}}\text{Sn}$  ( $T_{1/2} = 21.4$  min.) and also to reduce disturbing signals from the shorter-lived activation products. The result is shown in Fig. 3 together with the experimental data earlier [6]

**Table 2**  
Reactions and decay data of reaction products.

| Nuclide                   | Half-life | Decay mode (%)                | $E_{\gamma}$ (keV)            | $I_{\gamma}$ (%)         | Contributing reactions                                                                                   | Q-value (MeV)    |
|---------------------------|-----------|-------------------------------|-------------------------------|--------------------------|----------------------------------------------------------------------------------------------------------|------------------|
| $^{117\text{m}}\text{Sn}$ | 13.76 d   | IT (100)                      | 156.02                        | 2.113(12)                | $^{115}\text{In}(\alpha, d)$                                                                             | −9.85            |
|                           |           |                               | 158.56                        | 86.4                     | $^{115}\text{In}(\alpha, 2p)^{117}\text{In}(\beta^-)$<br>$^{115}\text{In}(\alpha, 2n)^{117}\text{Sb}(e)$ | −12.75<br>−14.61 |
| $^{113}\text{Sn}$         | 115.09 d  | $\varepsilon$ (100)           | 391.698                       | 64.97(17)                | $^{115}\text{In}(\alpha, t3n)$                                                                           | −37.95           |
|                           |           |                               |                               |                          | $^{113}\text{In}(\alpha, tn)$                                                                            | −21.64           |
|                           |           |                               |                               |                          | $^{115}\text{In}(\alpha, n)$                                                                             | −7.19            |
| $^{118\text{m}}\text{Sb}$ | 5.00 h    | $\varepsilon + \beta^+$ (100) | 253.678<br>1050.69<br>1229.65 | 99(6)<br>97(5)<br>100(5) |                                                                                                          |                  |
| $^{117}\text{Sb}$         | 2.80 h    | $\varepsilon + \beta^+$ (100) | 158.562                       | 85.9                     | $^{115}\text{In}(\alpha, 2n)$                                                                            | −14.61           |
| $^{116\text{m}}\text{Sb}$ | 60.3 m    | $\varepsilon + \beta^+$ (100) | 542.867                       | 48.1(4)                  | $^{115}\text{In}(\alpha, 3n)$                                                                            | −24.50           |
|                           |           |                               | 972.564                       | 74.2(7)                  | $^{113}\text{In}(\alpha, n)$                                                                             | −8.19            |

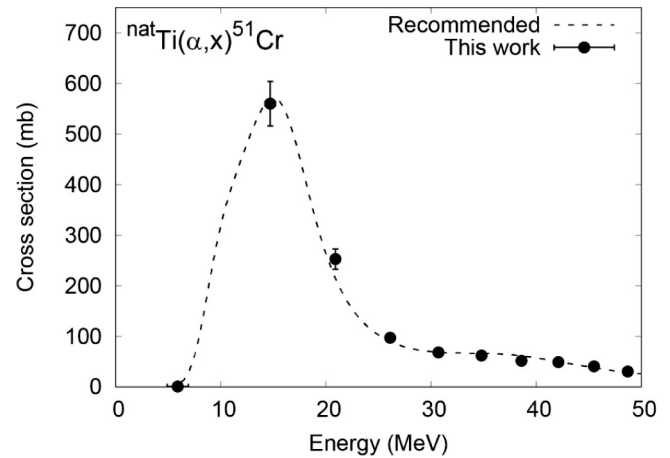


Fig. 1. Excitation function of the monitor reaction  $^{\text{nat}}\text{Ti}(\alpha, x)^{51}\text{Cr}$ .

and the TENDL-2017 data [18]. Our result is in good agreement with the data by Qaim and Döhler (1984) [6] as was the case of  $^{117\text{m}}\text{Sn}$ . The TENDL-2017 data overestimate the experimental data in the energy region as shown in the figure.

### 3.3. $^{118\text{m}}\text{Sb}$ production

The cross sections of  $^{118\text{m}}\text{Sb}$  were derived from the measurement of the 253.5 keV  $\gamma$ -line (99%) from the  $^{118\text{m}}\text{Sb}$  decay ( $T_{1/2} = 5.00$  h). The measurement was performed after a cooling time of about 6 h. The cross sections of the  $^{115}\text{In}(\alpha, n)^{118\text{m}}\text{Sb}$  reaction could be derived by considering the isotopic ratio of  $^{115}\text{In}$  due to no contribution from  $^{113}\text{In}$ . The result is shown in Fig. 4 in comparison with the experimental data studied earlier [7,15] and the TENDL-2017 data [18]. The peak position is consistent with the experimental data [15] and the TENDL-2017 data. However, the peak amplitude of our result is lower than the two experimental data and higher than the TENDL-2017 data. One of the reasons for our lower amplitude than the other experimental data may be the thicker In foils used in this study.

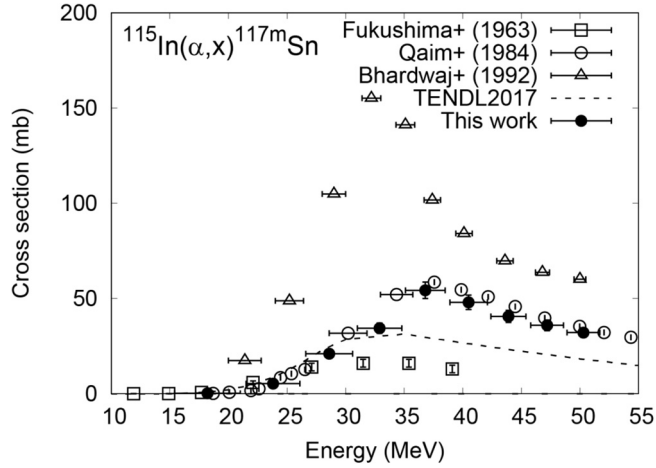
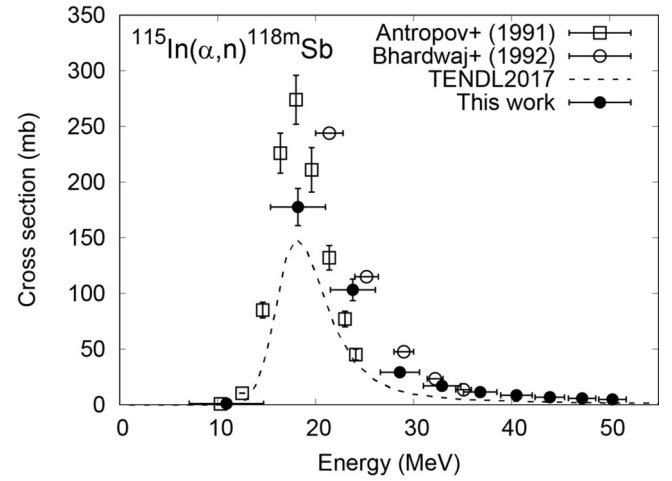
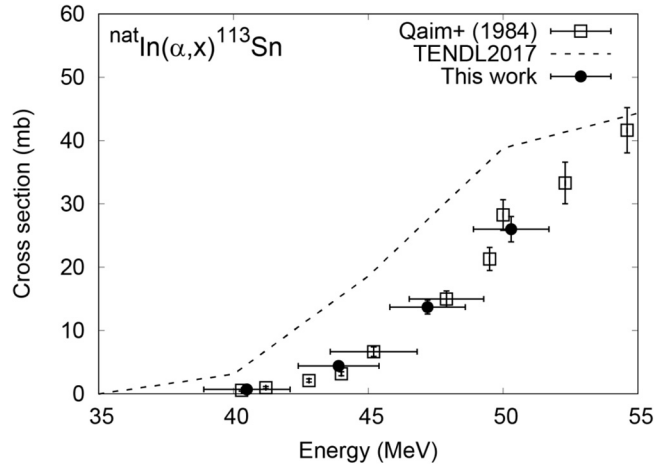
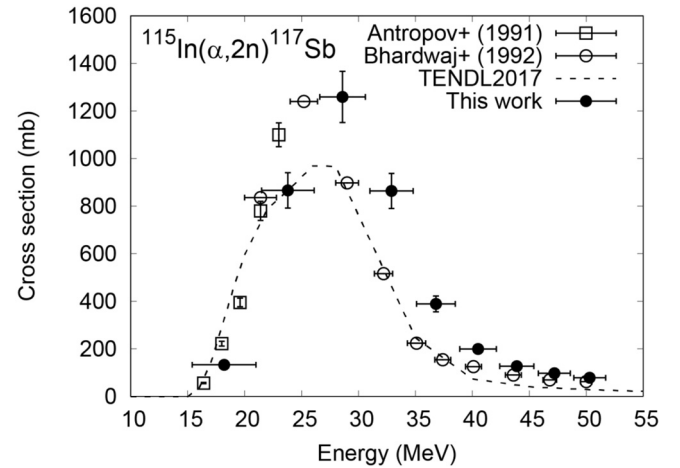
### 3.4. $^{117}\text{Sb}$ production

The measurements in 6–8 h after the end of bombardment were used to derive the cross sections of  $^{117}\text{Sb}$  ( $T_{1/2} = 2.80$  h). The  $\gamma$ -line at 158.562 keV (86%) from the decay of  $^{117}\text{Sb}$  was contributed from the decay of  $^{117\text{g}}\text{In}$  ( $T_{1/2} = 43.2$  min.),  $^{117\text{m}}\text{In}$  ( $T_{1/2} = 116.2$  min.) and  $^{117\text{m}}\text{Sn}$  ( $T_{1/2} = 13.76$  d). Each contribution to the  $\gamma$ -line was estimated independently from other  $\gamma$ -lines. The contributions of  $^{117\text{g}}\text{In}$  and  $^{117\text{m}}\text{In}$  were estimated using the more intense  $\gamma$ -lines at 552.9 keV (100%) from  $^{117\text{g}}\text{In}$  and 315.302 keV (19%) from  $^{117\text{m}}\text{In}$ . There were no peaks at the energies and therefore the  $^{117\text{g},117\text{m}}\text{In}$  contributions to the  $\gamma$ -line at 158.562 keV were found to be negligibly small. The contribution

**Table 3**

Measured cross sections for Sn and Sb isotope production.

| Energy (MeV)   | $^{115}\text{In}(\alpha, x)^{117\text{m}}\text{Sn}$ (mb) | $^{\text{nat}}\text{In}(\alpha, x)^{113}\text{Sn}$ (mb) | $^{115}\text{In}(\alpha, n)^{118\text{m}}\text{Sb}$ (mb) | $^{115}\text{In}(\alpha, 2n)^{117}\text{Sb}$ (mb) | $^{\text{nat}}\text{In}(\alpha, x)^{116\text{m}}\text{Sb}$ (mb) |
|----------------|----------------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------|-----------------------------------------------------------------|
| $50.3 \pm 1.4$ | $32.1 \pm 2.5$                                           | $26.0 \pm 2.0$                                          | $5.2 \pm 0.5$                                            | $76.5 \pm 6.6$                                    | $393 \pm 31$                                                    |
| $47.2 \pm 1.4$ | $35.9 \pm 2.8$                                           | $13.7 \pm 1.1$                                          | $5.8 \pm 0.6$                                            | $95.4 \pm 8.2$                                    | $614 \pm 49$                                                    |
| $43.9 \pm 1.5$ | $40.6 \pm 3.2$                                           | $4.4 \pm 0.4$                                           | $7.1 \pm 0.7$                                            | $125 \pm 11$                                      | $827 \pm 65$                                                    |
| $40.5 \pm 1.6$ | $48.0 \pm 3.8$                                           | $0.65 \pm 0.08$                                         | $8.7 \pm 0.9$                                            | $196 \pm 17$                                      | $949 \pm 75$                                                    |
| $36.8 \pm 1.7$ | $54.3 \pm 4.3$                                           |                                                         | $11.8 \pm 1.2$                                           | $386 \pm 33$                                      | $782 \pm 62$                                                    |
| $32.9 \pm 1.9$ | $34.4 \pm 2.7$                                           |                                                         | $17.1 \pm 1.7$                                           | $861 \pm 74$                                      | $386 \pm 31$                                                    |
| $28.6 \pm 2.0$ | $21.0 \pm 1.7$                                           |                                                         | $29.9 \pm 3.0$                                           | $1258 \pm 108$                                    | $33.7 \pm 5.0$                                                  |
| $23.8 \pm 2.3$ | $5.3 \pm 0.4$                                            |                                                         | $106 \pm 11$                                             | $866 \pm 74$                                      |                                                                 |
| $18.2 \pm 2.8$ | $0.20 \pm 0.05$                                          |                                                         | $182 \pm 18$                                             | $133 \pm 11$                                      |                                                                 |

**Fig. 2.** Excitation function of the  $^{115}\text{In}(\alpha, x)^{117\text{m}}\text{Sn}$  reaction with experimental data measured earlier [5–7] and the TENDL-2017 data.**Fig. 4.** Excitation function of the  $^{115}\text{In}(\alpha, n)^{118\text{m}}\text{Sb}$  reaction with the experimental data earlier [7,15] and the TENDL-2017 data.**Fig. 3.** Excitation function of the  $^{\text{nat}}\text{In}(\alpha, x)^{113}\text{Sn}$  reaction with the experimental data measured earlier [6] and the TENDL-2017 data.**Fig. 5.** Excitation function of the  $^{115}\text{In}(\alpha, 2n)^{117}\text{Sb}$  reaction with the experimental data measured earlier [7,15] and the TENDL-2017 data.

from  $^{117\text{m}}\text{Sn}$  was estimated from the cumulative cross sections of  $^{117\text{m}}\text{Sn}$  derived in Section 3.1 and found to be small ( $< 2.2\%$ ). The net counts of the  $\gamma$ -line at 158.562 keV from  $^{117}\text{Sb}$  were obtained by subtracting the contribution of  $^{117\text{m}}\text{Sn}$ . The derived cross sections of the  $^{\text{nat}}\text{In}(\alpha, x)^{117}\text{Sb}$  reaction were normalized for the monoisotopic  $^{115}\text{In}$  because the  $^{113}\text{In}(\alpha, \gamma)^{117}\text{Sb}$  reaction less contributes the production of  $^{117}\text{Sb}$ .

The result is compared with the experimental data [7,15] found in the EXFOR library and the TENDL-2017 data [18] (Fig. 5). The peak of our result shows a small shift to the higher energy region than the data earlier [7], though its amplitude is nearly consistent. The TENDL-2017 data underestimate the experimental data above 25 MeV.

### 3.5. $^{116\text{m}}\text{Sb}$ production

The production cross sections of  $^{116\text{m}}\text{Sb}$  ( $T_{1/2} = 60.3$  min) were derived from the  $\gamma$ -line at 972.564 keV (74.2%) using the same measurement series with the  $^{117,118\text{m}}\text{Sb}$  production. The result is shown in Fig. 6 together with the experimental data of the  $^{113}\text{In}(\alpha, n)^{116\text{m}}\text{Sb}$  reaction [16,17]. The earlier experimental data were up to 25 MeV below the threshold energy of the  $^{115}\text{In}(\alpha, x)^{116\text{m}}\text{Sb}$  reaction and contributed only from  $^{113}\text{In}$ . The cross sections of the  $^{113}\text{In}(\alpha, n)^{116\text{m}}\text{Sb}$  reaction were normalized to the natural indium by considering the isotopic ratio of  $^{113}\text{In}$ . The cross sections above 25 MeV were measured for the first

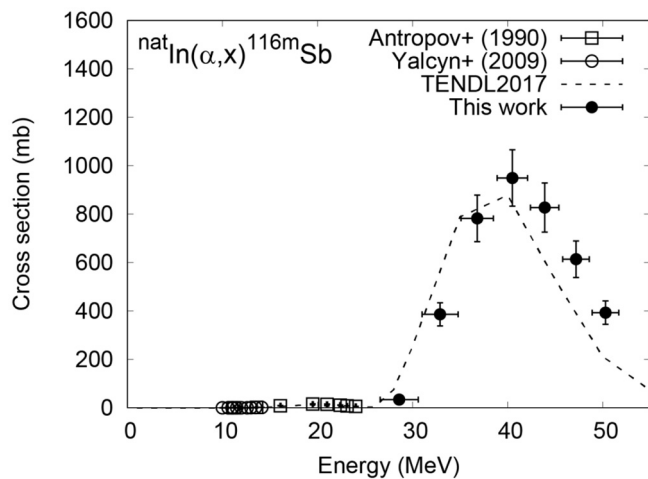


Fig. 6. Excitation function of the  $^{nat}\text{In}(\alpha, x)^{116m}\text{Sb}$  reaction with the experimental data measured earlier [16,17] and the TENDL-2017 data.

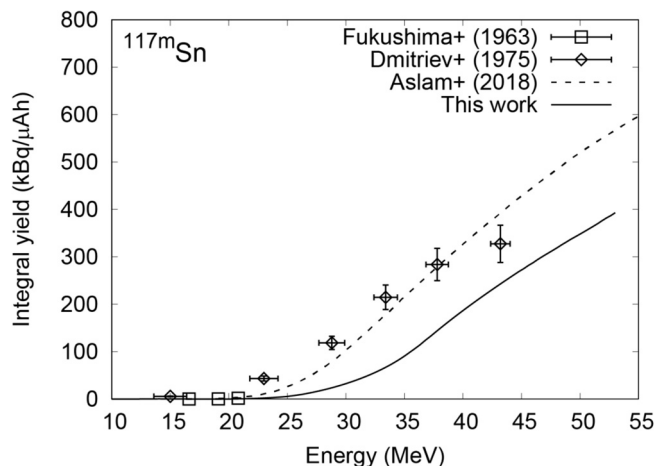


Fig. 7. Integral yield of  $^{117m}\text{Sn}$  with the experimental data measured earlier [5,19] and the calculated data [4].

time in this work. Our and earlier data were separated in energy, however smoothly connected as the TENDL-2017 data. The TENDL-2017 data reproduce well our data especially below 40 MeV.

### 3.6. Thick target yield of $^{117m}\text{Sn}$

The integral yield of  $^{117m}\text{Sn}$  was estimated using stopping powers calculated by the SRIM code [10] and the excitation function of the  $^{115}\text{In}(\alpha, x)^{117m}\text{Sn}$  reaction interpolated by the spline fit. The derived integral yield was compared with the experimental [5,19] and calculated data [4] (Fig. 7). The calculated data [4] were based on cross sections derived from EMPIRE and TALYS codes, which were larger than experimental data by Qaim and Döhler (1984) [6]. Our result is smaller than the other data at the whole energy region because the cross sections were consistent with the data by Qaim and Döhler (1984) [6] and lower than the calculated data [4].

## 4. Conclusion

Charged-particle reactions to produce a medical radioisotope  $^{117m}\text{Sn}$

are worthy investigated. One of the reactions to produce  $^{117m}\text{Sn}$  is the  $\alpha$ -induced reactions on  $^{115}\text{In}$ . We performed an experiment to measure the cross sections of the reaction up to 50 MeV at the AVF cyclotron of the RIKEN RI Beam Factory. The present result is almost consistent with the data by Qaim and Döhler (1984) [6] among the three experimental data earlier. From the measured cross sections, the integral yield of  $^{117m}\text{Sn}$  was estimated. The derived yield is smaller than the other data at the whole energy region.

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