I. INTRODUCTION

This paper is the last one in a series about studies relevant for the long-lived nuclide $^{182}$Hf. These measurements were possible because of the availability of the unique Hf sample material with a high $^{182}$Hf concentration and minimal interference from other activities (see Sec. II A).

First, the half-life of $^{182}$Hf was remeasured and a value of $t_{1/2} = (8.90 \pm 0.09) \times 10^6$ yr [1] has been determined, in agreement with a measurement shortly after its discovery [2] but with greatly improved precision. The high precision is necessary for the application of the so-called Hf-W geochronometer for the early Solar System [3–5]. The fractionation between Hf and W during core formation leads to an anomaly in the $^{182}$W isotopic concentration depending on how much $^{182}$Hf was present at that time. The short half-life of $^{182}$Hf relative to the age of the Solar System allows a high time resolution for these early processes. During the course of the half-life measurement the absolute intensities of the $\gamma$ rays following the $\beta^-$ decay to $^{182}$W were measured precisely [6].

Second, the neutron capture cross section of $^{182}$Hf was measured at stellar temperatures relevant for the astrophysical $s$-process for the first time at the Forschungszentrum Karlsruhe (FZK) 3.7-MV Van de Graaff accelerator using the activation technique [7]. This cross section is related to the question of the origin of the high abundance of $^{182}$Hf in the early Solar System, which leads to the application of the Hf-W system.

In particular, the relation to other short-lived nuclides and the fact that $^{182}$Hf can be produced in both the $r$- and $s$-process is challenging [8]. The $^{182}$Hf($n, \gamma$)$^{183}$Hf reaction is responsible for the destruction of $^{182}$Hf in the $s$-process. The result is, in turn, important for the minimum in the $r$-process abundance distribution around $A = 180$, which indicates a smaller $r$ component than assumed before. This has implications on the time interval between the last production of the short-lived nuclides and the formation of solid bodies.

Third, additional neutron irradiations at thermal energies were performed at the TRIGA Mark-II reactor of the Atomic Institute of the Austrian Universities (ATI) in Vienna, Austria, to support the measurements at astrophysically relevant energies. A small time dependence of the cross section was found and this motivated a remeasurement of the half-life of the reaction product $^{183}$Hf. The new half-life of $^{183}$Hf is $1.018 \pm 0.002$ h [9], which is 4.6% shorter and eight times more precise than the previous recommended value.

In this paper we present the measurement and determination of the thermal cross section and the resonance integral for the $^{182}$Hf($n, \gamma$)$^{183}$Hf reaction and the precise measurement of the absolute $\gamma$-ray intensities of the two main lines in the decay of $^{183}$Hf.

II. MEASUREMENTS

A. $^{182}$Hf samples

We used $^{182}$Hf material that was originally produced by irradiation of hafnium in an intense thermal neutron flux by Helmer and Reich more than 30 years ago [10–12]. Because of the long time since its production all the short-lived nuclides...
produced have already decayed and this now allows γ-ray spectroscopy with minimal interference from other activities. This material (called “Helmer-2”) was recently prepared for the half-life measurement of $^{182}$Hf at the Department of Earth Sciences, ETH–Zurich, Switzerland, and split into four samples (for details see Ref. [1]). A high $^{182}$Hf abundance of $(0.11237 \pm 0.00002\%)$ was measured by using isotope dilution and a multicollector inductively coupled plasma mass spectrometer (MC-ICPMS). From one sample (B3) containing $2.861 \times 10^{16}$ $^{182}$Hf atoms Hf-graphite samples Hf-1 and Hf-2 were prepared at ATI. The radiochemically controlled separation of Ta by ion exchange is described in Ref. [7] and was applied to reduce the γ background from the activity of $^{182}$Ta. The number of $^{182}$Hf atoms in samples Hf-1 and Hf-2 was determined by measuring the 270-keV γ-ray line intensity from the decay of $^{182}$Hf with various detectors [7]. Table I summarizes the important quantities of the $^{182}$Hf samples.

These samples were also used for the measurement of the stellar neutron capture cross section at $kT = 25$ keV [7] and the half-life measurement of $^{183}$Hf [9].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Diameter (mm)</th>
<th>Mass (mg)</th>
<th>$N_i$ ($10^{16}$ atoms) $^{180}$Hf</th>
<th>$^{182}$Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hf-1</td>
<td>8</td>
<td>39.2$^a$</td>
<td>772.8</td>
<td>1.851</td>
</tr>
<tr>
<td>Hf-2</td>
<td>8</td>
<td>26.5$^a$</td>
<td>414.1</td>
<td>0.992</td>
</tr>
</tbody>
</table>

$^a$Sample Helmer-2 plus graphite.

B. Activation with thermal neutrons

The activation of $^{182}$Hf with thermal neutrons ($kT = 25$ meV; 300 K) was performed at the TRIGA Mark-II reactor at ATI. To ensure a good thermal spectrum, the samples were placed besides the core in a neutron flux of about $4 \times 10^{11}$ cm$^{-2}$ s$^{-1}$. In total, three irradiations were performed, the first one with sequential irradiation of the samples, the second one with simultaneous irradiation of the samples, and the third one with simultaneous irradiation of both samples but with Hf-1 in a Cd capsule. The samples were sandwiched between zirconium foils, which served to measure the neutron exposure and to determine the epithermal fraction of the neutron spectrum. The reactor was operated at constant power, which assured constant neutron flux during the one-hour irradiations.

The induced activity of the samples was measured by using a 222 cm$^3$ coaxial high-purity germanium (HPGe) detector (Canberra GC4518) with 50% relative photo-peak efficiency and a resolution of 1.8 keV at 1.33-MeV γ-ray energy. The detector electronics consisted of a transistor reset preamplifier, a digital signal processor (Canberra 2060), and a loss-free counting module (Canberra 599) [13]. Data acquisition and analysis of the γ spectra were done with the Canberra software GENIE 2000. The samples were placed at the top of the detector at distances of 29 mm (geometry 1) and 89 mm (geometry 2). To minimize effects from coincidence summing and sample extension only data taken in geometry 2 were used for the final evaluation.

The efficiency of the detection setup was determined with two calibrated sources placed at the same position as the $^{182}$Hf samples. The sources (from a mixed radionuclide γ-ray reference standard solution QCY48 of Amersham, UK) contained ten radionuclides with γ-ray lines in the energy range from 59 to 1836 keV. Between 166 and 1836 keV an exponential decay function was fitted to the data points for interpolation. The 279-keV line from the decay of $^{203}$Hg was omitted in the fit, because it is potentially affected by evaporation losses (Fig. 1).

After the first irradiation, several γ-ray spectra were recorded for a few hours to follow the $^{182}$Hf activity (with a typical spectrum being shown in Fig. 2) and a few days later for determining the $^{183}$Ta activity ($t_{1/2} = 5.1 \pm 0.1$ d). In the first few measurements the total count rate exceeded $10^4$ cps owing to the high induced activity. Although no significant effects were observed in these spectra, only runs with a total count rate below $10^4$ cps were considered in the analysis. A separate count rate test was performed by measuring a source in fixed geometry while changing the total count rate with a strong $^{137}$Cs source from 500 to 10$^3$ cps. The activities above the Compton background showed deviations of less than ±1%, thus confirming that the data acquisition system works under all conditions of the present measurement.

After the second irradiation, 1800-s spectra of sample Hf-1 were recorded in geometry 2 in an automated way for two days. This series of runs was also used for the half-life measurement of $^{181}$Hf [9]. To reduce effects of true coincidence summing in the $783.8$ keV/73.2 keV cascade in the $^{180}$Hf decay, a 0.565-mm-thick Cd absorber foil was used. For an independent check, the activity of Hf-2 after the second irradiation was measured with a 15% HPGe detector at distances of 65 and 145 mm as well.
FIG. 2. $\gamma$-ray spectrum of sample Hf-1 measured 175 min after activation with thermal neutrons. Main peaks are labeled with corresponding $\gamma$-ray energies. The spectrum was accumulated for 1309 s.

The $\gamma$-ray measurements after the third irradiation were similar to those of the second series. The activity of sample Hf-1 (irradiated in the Cd capsule) was measured at the 50% HPGe without the Cd absorber foil; Hf-2 (without Cd capsule) was measured at the 15% HPGe at 65 mm.

### III. DATA ANALYSIS

In our analysis we follow Westcott’s convention (see, e.g., Ref. [14]) to deduce the thermal ($v = 2200$ m/s) neutron capture cross section, $\sigma_0$, and the resonance integral, $I_0$, from the irradiation with reactor neutrons.

The relation among reaction rate $R$, neutron flux, and capture cross section is defined by

$$R/\sigma_0 = g\phi_1 G_{\text{th}} + \phi_2 G_{\text{epi}}.$$  \hspace{1cm} (1)

Here, $\phi_1$ and $\phi_2$ denote the neutron flux in the thermal and epithermal energy regions, respectively, $G_{\text{th}}$ and $G_{\text{epi}}$ are the self-shielding factors for thermal and epithermal neutrons, respectively, and $g$ is the deviation of the cross section from the $1/v$ law. In our analysis we set $g = 1$. The $s_0$ parameter is defined by

$$s_0 = \frac{2}{\sqrt{\pi}} \frac{I_0'}{\sigma_0},$$  \hspace{1cm} (2)

where

$$I_0' = I_0 - 0.4844\sigma_0$$  \hspace{1cm} (3)

is the reduced resonance integral, that is, the resonance integral after subtracting the $1/v$ component for a Cd cutoff energy of 0.5 eV (1 mm Cd thickness).

The self-shielding factors $G_{\text{th}}$ and $G_{\text{epi}}$ are calculated according to the description in Beckurts and Wirtz [15] and Martinho et al. [16], respectively. Owing to the thin Zr samples and the dilution of the Hf samples in the graphite matrix these factors are close to 1 (Table II).

The reaction rate $R$ was calculated by using

$$R = \frac{N}{f_b t_a N_s},$$  \hspace{1cm} (4)

with $N_s$ the respective number of (stable or long-lived) nuclides in the sample and

$$f_b = \frac{1 - e^{-\lambda t_a}}{\lambda t_a}$$  \hspace{1cm} (5)

for the correction of the decay of the activated nuclei (with the decay constant $\lambda$) during the irradiation time $t_a$, under the assumption of a constant neutron flux.

The total number $N$ at the end of the irradiation was deduced from the number of events, $C_\gamma$, in a particular $\gamma$-ray line.
registered in the $\gamma$ detector during the measuring time $t_{\text{me}}$ [19]:

$$N = \frac{C_\gamma}{\epsilon_\gamma} \frac{I_\gamma}{k_\gamma} \left(1 - e^{-\lambda_{\text{abs}} t_{\text{me}}}\right) e^{-\lambda_{\text{abs}} t_{\text{me}}}.$$  \hfill (6)

The factors $\epsilon_\gamma$ and $I_\gamma$ account for the $\gamma$-ray efficiency and the absolute $\gamma$-ray intensity per decay of the respective transition, and $t_{\text{me}}$ denotes the waiting time between the irradiation and the activity measurement. Corrections for the preceding activations was applied but was only relevant for the calculation of the $^{183}$Hf activity. The decay parameters used in the present analysis are given in Table III. The absorption of $\gamma$ rays in the sample as well as in possible additional absorber materials is corrected by the factor $k_\gamma$, which is determined by the respective absorption coefficients $\mu$ (taken from Ref. [20]) and the sample thickness $l$ (in $\mu$g/cm$^2$). For the far counting geometry used after the activations, this correction was obtained in good approximation by

$$k_\gamma = \frac{(1 - e^{-\mu_{\text{abs}} l_{\text{sam}}})}{\mu_{\text{sam}} l_{\text{sam}}} e^{-\mu_{\text{abs}} t_{\text{me}}}.$$  \hfill (7)

although this expression is exactly valid only for radiation parallel to the axis of the disk-shaped samples. For measurements without the absorber only the first term of $k_\gamma$ is used. The absorption coefficient for the $^{182}$Hf samples is the sum of the two components:

$$\mu_{\text{Hf+C}} = \mu_{\text{Hf}} f_{\text{Hf}} + \mu_{\text{C}} f_{\text{C}},$$  \hfill (8)

where $f_i$ are the corresponding mass fractions.

### IV. Results and Discussion

#### A. Determination of thermal and epithermal neutron flux

The values for the thermal neutron flux $\phi_1$ and the flux in the epithermal energy region, $\phi_2$, for the irradiation with and without the Cd capsule was determined by solving Eq. (1) with well-known nuclear data of the Zr standards [18]. The measured reaction rates are summarized in Table IV. Figure 3 shows the experimental relation of $R/\sigma_0$ and $s_0$. The flux $\phi_2$ is deduced from the intercept at $s_0 = 0$ of the linear regression, and $\phi_1$ is found from the slope. Values for $\phi_1 = 3.593 \times 10^{11}$ n cm$^{-2}$ s$^{-1}$ and $\phi_2 = 4.716 \times 10^{10}$ n cm$^{-2}$ s$^{-1}$ were found for the irradiation without the Cd capsule and $\phi_1 = 4.680 \times 10^9$ n cm$^{-2}$ s$^{-1}$ and $\phi_2 = 4.954 \times 10^9$ n cm$^{-2}$ s$^{-1}$ for the irradiation with the Cd capsule. The time-integrated neutron flux $\Phi_{\text{tot}}$ (without the Cd capsule) was around $1.3 \times 10^{15}$ n cm$^{-2}$ in all three irradiations.

#### B. Absolute $\gamma$-ray intensities in $^{183}$Hf decay

The decay of $^{183}$Hf was first studied in detail in 1969 [26], but the absolute intensities of the two main $\gamma$ rays in the decay of $^{183}$Hf decay at 459.1 keV and 783.8 keV, which determine directly the accuracy of the $(n, \gamma)$ measurements, remained fairly uncertain. The values ($I_{\gamma,\text{old}}$) given in Ref. [27] (27.3 $\pm$ 3.0)% and (65.7 $\pm$ 7.0)%, respectively) still have uncertainties larger than 10%.

These values can be significantly improved by comparison of the number of produced $^{183}$Hf atoms at the end of the

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$t_{1/2}$</th>
<th>$E_\gamma$ (keV)</th>
<th>$I_{\gamma}$ (%)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{95}$Zr</td>
<td>64.032 $\pm$ 0.006 d</td>
<td>724.2</td>
<td>44.17 $\pm$ 0.13</td>
<td>[21]</td>
</tr>
<tr>
<td>$^{97}$Zr</td>
<td>16.755 $\pm$ 0.013 h</td>
<td>743.4</td>
<td>93.06 $\pm$ 0.16</td>
<td>[22]</td>
</tr>
<tr>
<td>$^{181}$Hf</td>
<td>42.39 $\pm$ 0.06 d</td>
<td>133.0</td>
<td>43.31 $\pm$ 0.50</td>
<td>[23]</td>
</tr>
<tr>
<td>$^{182}$Hf</td>
<td>(8.90 $\pm$ 0.09) $\times 10^6$ yr</td>
<td>156.1</td>
<td>7.0 $\pm$ 0.2</td>
<td>[1,24]</td>
</tr>
<tr>
<td>$^{183}$Hf</td>
<td>1.018 $\pm$ 0.002 h</td>
<td>73.2</td>
<td>38.4 $\pm$ 4.0</td>
<td>[9,25]</td>
</tr>
<tr>
<td>$^{183}$Ta</td>
<td>5.1 $\pm$ 0.1 d</td>
<td>244.3</td>
<td>8.50 $\pm$ 0.24</td>
<td>[25]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>246.1</td>
<td>26.8 $\pm$ 1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>354.0</td>
<td>11.23 $\pm$ 0.29</td>
<td></td>
</tr>
</tbody>
</table>

This work; see Sec. IV B.
TABLE IV. Measured reaction rates averaged over several $\gamma$-ray measurements.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$E_\gamma$ (keV)</th>
<th>$R \times 10^{-13}$ s$^{-1}$</th>
<th>$R' \times 10^{-13}$ s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{95}$Zr</td>
<td>724.2</td>
<td>0.1912 ± 0.0004</td>
<td>0.01396 ± 0.0002</td>
</tr>
<tr>
<td>$^{97}$Zr</td>
<td>756.7</td>
<td>0.1897 ± 0.0004</td>
<td>0.01444 ± 0.0001</td>
</tr>
<tr>
<td>$^{181}$Hf</td>
<td>743.4</td>
<td>0.3741 ± 0.0013</td>
<td>0.2862 ± 0.0010</td>
</tr>
<tr>
<td>$^{183}$Hf</td>
<td>482.2</td>
<td>46.45 ± 0.04</td>
<td>1.831 ± 0.007</td>
</tr>
<tr>
<td>$^{183}$Ta</td>
<td>459.1</td>
<td>787.2 ± 4.8</td>
<td>301.0 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>783.8</td>
<td>770.8 ± 1.6</td>
<td>296.5 ± 0.2</td>
</tr>
</tbody>
</table>

irradiation derived from the $^{183}$Hf activity [Eq. (6); $N_{\gamma}^{183}$Hf] and from the $^{183}$Ta activities ($N_{\gamma}^{183}$Hf, $N_{\gamma}^{183}$Ta), the daughter of $^{183}$Hf. One finds

$$I_\gamma = \frac{N_{\gamma}^{183}{\text{Hf}}}{N_{\gamma}^{183}{\text{Ta}}} N_{\gamma}^{183}{\text{Hf}},$$

(9)

The $^{183}$Ta activity depends on how much $^{183}$Hf was produced as well as on irradiation history, ingrowth, and decay time. $N_{\gamma}^{183}{\text{Hf}}$ from the $^{183}$Ta activity was calculated by solving the differential equations for ingrowth and decay with a MATHEMATICA simulation (Fig. 4):

$$N_{\gamma}^{183}{\text{Hf}}(t) = \phi(t) N_{\gamma}^{182}{\text{Hf}}(t) - \lambda_{\gamma}^{183}{\text{Hf}} N_{\gamma}^{183}{\text{Hf}}(t),$$

$$N_{\gamma}^{183}{\text{Ta}}(t) = \lambda_{\gamma}^{183}{\text{Hf}} N_{\gamma}^{183}{\text{Hf}}(t) - \lambda_{\gamma}^{183}{\text{Ta}} N_{\gamma}^{183}{\text{Ta}}(t),$$

(10)

with the integrated $^{183}$Ta counts per $\gamma$ ray as input from the measurement, and the neutron flux $\phi(t) = \Phi(t)/t_a$ for $t \leq t_a$ and $\phi(t) = 0$ for $t > t_a$. Contributions from $^{182}$Ta($n, \gamma$)$^{183}$Ta reactions can be ignored despite the large cross section (8700 b), because of the low $^{182}$Ta concentration. Losses from $^{183}$Ta($n, \gamma$)$^{184}$Ta are negligible, because most of the $^{183}$Ta comes from ingrowth after the irradiation (Fig. 4).

From the two main $\gamma$-ray lines of $^{183}$Ta, only the 354.0-keV line was used in the evaluation since the 246.1-keV line has an interference with the 244.3-keV line. Effects from coincidence summing are small owing to the far geometry and low efficiencies. In geometry 2 losses of the peak area of the 354.0-keV line from summing with lines at 99.1 keV and 52.6/46.5 keV are estimated to be less than 0.1%; additions from the 107.9/246.1 keV cascade are less than 0.3%. Values for $N_{\gamma}^{183}{\text{Hf}}$ have been calculated for each of the $\gamma$-ray spectra and compared to the value derived from the $^{183}$Hf activities as shown in Fig. 5. Only data from late runs were considered in the calculation of the absolute $\gamma$-ray intensities when practically all $^{183}$Hf and the interference at 355.4 keV from $^{116}$In($n, \gamma$) had decayed.

The final values, which include the relevant uncorrelated uncertainties in the evaluation of the $N_{\gamma}^{183}{\text{Hf}}$ and of the $^{183}$Ta $\gamma$-ray line, are $I_{459} = (29.8 \pm 0.9)\%$ and $I_{784} = 65.5 \pm 1.9)\%$, respectively. The absolute intensities of the other $\gamma$-ray lines in the decay of $^{183}$Hf were checked as well. Within uncertainties,
the results agree with the recommended values of Ref. [27] in most cases.

C. Calculation of thermal neutron capture cross section and resonance integral

From the neutron flux in the thermal and epithermal energy regions determined by the Zr standards and the measured reaction rates (Table IV) for irradiations without and with Cd capsule [marked with a prime (′)], the parameter $s_0$ can be calculated as

$$s_0 = -\frac{\phi_1 - \phi_2[R/R]}{\phi_2[R/R]} \frac{G_{th}}{G_{epi}}.$$  (11)

Inserting $s_0$ in Eq. (1) gives the thermal neutron capture cross section $\sigma_0$. The resonance integral $I_0$ is then calculated by using Eq. (3).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$E_\gamma$ (keV)</th>
<th>$s_0$</th>
<th>$\sigma_0$ (b)</th>
<th>$I_0$ (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{181}$Hf</td>
<td>482.2</td>
<td>2.18 ± 0.20</td>
<td>12.51 ± 0.93</td>
<td>30.2 ± 2.8</td>
</tr>
<tr>
<td>$^{183}$Hf</td>
<td>459.1</td>
<td>49.0 ± 6.5</td>
<td>134.3 ± 11.7</td>
<td>5890 ± 840</td>
</tr>
<tr>
<td></td>
<td>783.8</td>
<td>49.5 ± 6.6</td>
<td>131.0 ± 11.4</td>
<td>5810 ± 820</td>
</tr>
<tr>
<td>average values</td>
<td></td>
<td>49.2 ± 5.2</td>
<td>132.6 ± 9.9</td>
<td>5850 ± 660</td>
</tr>
</tbody>
</table>

1. $^{180}$Hf ($\gamma$, $\gamma$)$^{181}$Hf

The 482.2-keV $\gamma$-ray line of $^{181}$Hf was evaluated and the cross section for $^{180}$Hf($\gamma$, $\gamma$)$^{181}$Hf was extracted in the same way as for the $^{182}$Hf($\gamma$, $\gamma$)$^{183}$Hf reaction. This reaction has been measured several times in the past (see Ref. [28] and references therein) and thus allows an independent check of our method. Our results $\sigma_0 = 12.5 ± 0.9$ b and $I_0 = 30.2 ± 2.8$ b are in agreement with previous measurements ($\sigma_0 = 13.04 ± 0.07$ b and $I_0 = 33.0 ± 1.0$ b [17]), although our values tend to be systematically lower by a few percent. The reason for that is unclear. But it should be noted that the determination of the neutron flux depends critically on the cross-section data of the Zr monitors; measurements of these data show some scatter [29].

2. $^{182}$Hf ($\gamma$, $\gamma$)$^{183}$Hf

The two main $\gamma$-ray lines at 459.1 and 783.8 keV in the decay of $^{183}$Hf were used in the calculation of the reaction rate for $^{182}$Hf($\gamma$, $\gamma$)$^{183}$Hf. Systematic effects from coincidence summing could be reduced by restricting the analysis to the measurements in far geometry 2 and with the Cd absorber previously described. For $^{183}$Hf, coincidence summing of the 783.8-keV line was estimated to be less than 0.1% compared to 1.5% in close geometry 1 and without the Cd absorber. The results for each $\gamma$-ray line are listed in Table V. The final results for the thermal neutron capture cross section $\sigma_0 = 133 ± 10$ b and the resonance integral $I_0 = 5850 ± 660$ b are the weighted average of both $\gamma$-ray lines and include the systematic uncertainty.

D. Uncertainties

Experimental uncertainties are listed in Table VI. The counting statistics are in all cases around 1%. The uncertainty values for $\gamma$-ray absorption and $\gamma$ efficiency are estimated to be 2% and contribute only to a small extent to the total error. The main uncertainty is coming from the determination of the thermal and epithermal neutron flux, which mainly depends on the systematic uncertainties in the reference cross sections of the Zr isotopes. Once these values are known more precisely, the $^{183}$Hf cross section values can be improved.

V. SUMMARY

The neutron capture cross sections of $^{182}$Hf at thermal and epithermal energies have been measured for the first time. The thermal cross section ($kT = 25$ meV) and the resonance integral were determined by irradiations with and without Cd capsule and evaluated by using Westcott’s convention. Our value for the thermal cross section is $\sigma_0 = 133 ± 10$ b, significantly larger than the value of 14.11 b listed in the JEFF-3.0/A data library (http://www.nea.fr/html/dbdata/JEFF/). The JEFF-3.0/A value is a calculated value based on the Hauser-Feshbach approach. As pointed out in Ref. [7] extrapolations toward the neutron-rich nuclei are problematic and can lead to large uncertainties in the theoretical predictions. The
resonance integral has been determined to be $I_0 = 5850 \pm 660$ b. The absolute intensities for the 459- and 784-keV $\gamma$-ray lines [$I_{459} = (29.8 \pm 0.9)\%$ and $I_{784} = (65.5 \pm 1.9)\%$] were determined by comparing the number of produced $^{183}$Hf atoms derived from the activities of $^{183}$Hf and $^{183}$Ta, respectively. The improved uncertainties allowed a more precise determination of the thermal and epithermal cross sections presented here and have already been used for obtaining the astrophysically relevant cross section at $kT = 25$ keV measured at the FZK [7].

In addition, the high cross section found in our measurement might be relevant for assessing the inventory of $^{182}$Hf in nuclear waste.

**ACKNOWLEDGMENTS**

We thank the reactor operation team of the TRIGA Mark-II reactor at ATI for assistance during the neutron irradiations.