Measurement of neutron capture on $^{50}$Ti at thermonuclear energies

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(January 19, 2018)

At the Karlsruhe and Tübingen 3.75 MV Van de Graaff accelerators the thermonuclear $^{50}$Ti(n, $\gamma$)$^{51}$Ti(5.8 min) cross section was measured by the fast cyclic activation technique via the 320.852 and 928.65 keV $\gamma$-ray lines of the $^{51}$Ti-decay. Metallic Ti samples of natural isotopic composition and samples of TiO$_2$ enriched in $^{50}$Ti by 67.53% were irradiated between two gold foils which served as capture standards. The capture cross-section was measured at the neutron energies 25, 30, 52, and 145 keV, respectively. The direct capture cross section was determined to be $0.387\pm0.011$ mbarn at 30 keV. We found evidence for a bound state s-wave resonance with an estimated radiative width of 0.34 eV which destructively interferes with direct capture. The strength of a suggested s-wave resonance at 146.8 keV was determined. The present data served to calculate, in addition to the directly measured Maxwellian averaged capture cross sections at 25 and 52 keV, an improved stellar $^{50}$Ti(n, $\gamma$)$^{51}$Ti rate in the thermonuclear energy region from 1 to 250 keV. The new stellar rate leads at low temperatures to much higher values than the previously recommended rate, e.g., at $kT = 8$ keV the increase amounts to about 50%. The new reaction rate therefore reduces the abundance of $^{50}$Ti due to s-processing in AGB stars.

PACS numbers: 25.40.Lw, 24.50.+g

I. INTRODUCTION

For a long time it has been known that the solar-system abundances of elements heavier than iron have been produced by neutron-capture reactions [1]. However, neutron capture is also of relevance for abundances of isotopes lighter than iron especially for neutron-rich isotopes, even though the bulk of these elements has been synthesized by charged-particle induced reactions. The attempts to understand neutron-induced nucleosynthesis require as important ingredients the knowledge of neutron-capture rates. The influence of shell effects on neutron capture is one of the most interesting aspects of neutron capture, especially since neutron capture in the vicinity of magic numbers is often a bottleneck in neutron-induced nucleosynthesis. This is the case also in neutron capture on neutron-rich isotopes close to the magic proton and neutron numbers $Z = 20$ and $N = 28$, i.e., in the vicinity of the double-magic nucleus $^{48}$Ca. In particular, the reaction rate of neutron capture for Ti-isotopes is of relevance for isotopic abundance anomalies in silicon carbide (SiC) grains occurring in carbonaceous meteorites [2]. Contrary to most other solar system solids this type of grains has not been reprocessed an/or homogenized. Therefore, they can be can be potentially associated with their stellar origin. The main part of presolar SiC grains have isotopic compositions implying that they most likely condensed in the winds of a variety of asymptotic giant branch (AGB) stars [3].

The SiC grains show a large spread of $^{48}$Ti, the permille deviation from the solar ratio with $^{48}$Ti as reference isotope, which is evidence for s-processing [3]. The very small neutron capture cross section of the neutron magic nucleus $^{50}$Ti makes it behave as a bottleneck in the s-process path, building up a considerable abundance. The predictions of AGB models discussed in Refs. [3] show for the neutron-rich isotopes $^{49,50}$Ti that the deviations from their solar ratio are essentially in agreement with their measured values in SiC grains [1]. However, for $^{50}$Ti the calculated permille deviations from the solar ratio seem a little too high [3]. This was one of the motivations to remeasure and reinvestigate the neutron capture cross section on $^{50}$Ti in the thermonuclear energy range.

In Sect. II the measurements using the fast cyclic activation technique, the neutron production and the time-of-flight measurements are described. The analysis of the thermonuclear capture cross-sections and their interpretation in form of the non-resonant and resonant capture follows in Sect. III. Furthermore, the Maxwellian averaged capture cross section is derived. Finally, in the last section the experimental results and their theoretical interpretation are discussed and compared with previous data. Possible astrophysical consequences of the new neutron capture rate of $^{50}$Ti with respect to the abundance of this isotope are discussed.
The thermomuclear measurements have been carried out at the Karlsruhe and Tübingen 3.75 MV Van de Graaff accelerators. In the investigated reaction $^{50}$Ti(n,$\gamma$)$^{51}$Ti(5.8 min) the characteristic $\gamma$-ray lines of the $^{51}$Ti product nucleus with $E_{\gamma}$=320 and 928 keV served as an excellent signature for the capture events because of the high accuracy of 0.4% with which the intensity per decay of the 320 keV line is known (Table I). The capture cross sections were determined relative to the $^{197}$Au(n,$\gamma$)$^{198}$Au(2.695±17d) standard reaction $^{[53]}$, where the 411.8044 keV $\gamma$-ray line of the $^{198}$Au decay is known with high precision (Table I).

II. MEASUREMENTS

The activation technique $^{[1,2]}$, especially the fast cyclic activation has been described in previous publications $^{[1,2]}$. An activation cycle is characterized by an irradiation and activation counting period. For the short lived $^{198}$Ti product nucleus it is essential to repeat these cycles frequently to gain statistics. The time constants for each cycle are the irradiation time $t_b$, the counting time $t_c$, the waiting time $t_w$ (the time to switch from the irradiation to the counting phase) and the total time $T=t_b+t_w+t_c+t_w'$ ($t_w'$ the time to switch from the counting to the irradiation phase). In the actual $^{50}$Ti measurements the runs were carried out with $t_b=119.6$ s, $t_c=119.6$ s, the waiting time $t_w=0.40$ s and the total time $T=240$ s. The decay of the $^{51}$Ti product nuclei during irradiation and the fluctuations of the neutron beam intensity are taken into account by the factor $f_b$.

The accumulated number of counts from a total of $N$ cycles, $C = \sum_{i=1}^{n} C_i$, where $C_i$, the counts after the i-th cycle, are calculated for a chosen irradiation time, $t_b$ is $^{[3]}$.

$$C = \epsilon_i K_{\gamma} f_{\gamma} \lambda^{-1} [1 - \exp(-\lambda t_c)] \exp(-\lambda t_w) \sum_{i=1}^{n} \Phi_i$$

(2.1)

with

$$f_b = \frac{\sum_{i=1}^{n} \Phi_i \exp[-(n-i)\lambda T]}{\sum_{i=1}^{n} \Phi_i}$$

The following additional quantities have been defined: $\epsilon_i$: Ge-efficiency, $K_{\gamma}$: $\gamma$-ray absorption, $f_{\gamma}$: $\gamma$-ray intensity per decay, $N$: the thickness (atoms per barn) of target nuclei, $\sigma_{\gamma}$: the capture cross section, $\Phi$: the neutron flux in the i-th cycle. The quantity $f_b$ is calculated from the registered flux history of a $^6$Li glass monitor.

The activity of $^{198}$Au is additionally counted after the end of the cyclic activation consisting of $n$ cycles using

$$C_n = \epsilon_i K_{\gamma} f_{\gamma} \lambda^{-1} [1 - \exp(-\lambda T_{W})] \exp(-\lambda T_{W}) \sum_{i=1}^{n} \Phi_i$$

(2.2)

Here $T_M$ is the measuring time of the Ge-detector and $T_W$ the time elapsed between the end of cyclic activation and begin of the new data acquisition.

B. Neutron production, time-of-flight measurements

Neutrons were generated by the $^7$Li(p,n) and T(p,n) reactions. Measurements with neutron spectra of mean neutron energies of 25, 30, 52, and 145 keV were carried out by adjusting with the accelerator the appropriate proton energy. The energy spread of the neutron spectra produced is dependent on the energy loss of the protons in the target layer. For proton energies close to reaction threshold the target layers were chosen thick enough that the energy loss of the protons reached the reaction threshold within the layer. This makes the neutron spectrum independent of the target thickness. Using the $^7$Li(p,n) and T(p,n) reactions in this way we generated quasi-Maxwellian spectra with thermal energies $kT=25$ and 52 keV, respectively $^{[3]}$. The spectrum with a mean neutron energy of 30 keV was obtained via the $^7$Li(p,n) reaction with a proton energy of 1882 keV very close to the reaction threshold energy $E_{th}=1881$ keV. With this spectrum it was possible to perform a measurement in between the resonances, where the 16.99 keV p-wave resonance $^{[4]}$ is most critical. A typical TOF spectrum at 0° and the respective neutron distribution are shown in Fig. 1. With a proton energy much higher than the reaction threshold energy of the $^7$Li(p,n) reaction and a thin Li-target the neutron energy distribution is dependent on the thickness of the Li layer. The spectrum at 145 keV (Fig. 2) was generated using Li-targets of 2.5 $\mu$m.
The Li-targets were carefully prepared. Metallic Li was evaporated onto 1.5 mm thick copper backing. The thickness of the Li layer is determined during evaporation. For each new target also a new copper backing is used because of Li diffusion into the copper. Targets of good quality were always freshly made before use because long term storage under liquid nitrogen already leads to slight damage of the metallic Li through the onset of oxidation.

The proton energy and the thickness of the Li target were checked by a a time-of-flight measurement before an activation run was started. In the flight time measurements typically a pulse width of 10 ns and a repetition rate of 1 MHz was used. The neutrons were counted by a $^6$Li glass detector (2.54 cm dia × 1 mm) at a flight path of 91 cm.

To determine the neutron distribution at the sample position time-of-flight spectra normalized to the proton beam current were recorded at zero degree and at different angles in steps of 5 degrees. These spectra are needed for calculating the angle integrated spectrum at the sample position by Monte Carlo methods, where the extended Li-target of 6 mm diameter and the mean free path of the neutrons through the sample are taken into account. The neutron spectra shown in the figures have been determined in this way.

During the activation runs beam currents up to 100 $\mu$A could be applied without damage of the Li-layer because of an effective water cooling system. For the kT=52 keV measurement with the tritium target a beam current of 12 $\mu$A was used, and no significant deterioration of the tritium target was observed during the experiment. In the activations four spectra were continuously recorded, an 8K spectrum of the relative neutron flux vs time from the neutron monitor, an 8K spectrum of the proton beam current vs time, an 8K $\gamma$-ray spectrum from the Ge-detector and an 1K pulse height spectrum of the $^6$Li glass monitor. For safety every two hours a backup was stored from these spectra automatically. From the ratio neutron flux and proton beam the actual quality of the target was controlled and from the $^6$Li glass pulse height spectrum the threshold for $\gamma$-ray background suppression was checked.

### III. ANALYSIS

#### A. Thermoneutial capture cross-sections

Eqs. (2.1) and (2.2), respectively, contain the quantities $\sigma_i$ and the total neutron flux $\sum_i^{n} \Phi_i$. The unknown capture cross-section of $^{50}$Ti is measured relative to the well-known standard cross section of $^{197}$Au. As the metallic natural Ti and $^{50}$TiO$_2$ samples, respectively, to be investigated are characterized by a finite thickness it is necessary to sandwich the sample by two comparatively thin gold foils for the determination of the effective neutron flux at sample position. The activities of these gold foils were counted also individually after termination of the cyclic activation. The effective count rate of gold was obtained from these individual rates as well as from the accumulated gold count rate during the cyclic activation run. Therefore, the effective neutron flux at sample position was determined in two ways by the gold activation according to the Eqs. (2.1) and (2.2). Using Eq. (2.1) has the advantage that saturation effects in the gold activity for irradiations over several days are avoided.

The efficiency determination of the 60% HPGe-detector has been performed with calibrated radioactive sources and the detector simulation program GEANT [14] as already reported elsewhere [13]. The $\gamma$-ray absorption in the samples was calculated using tables published by Storm and Israel [16] and Veigele [17]. The half-lives and the $\gamma$-ray intensities per decay of $^{51}$Ti and $^{198}$Au given in Table II were taken from [18].

Table III gives a survey of the sample weights and the measured $^{50}$Ti capture cross-sections. The metallic Ti and the $^{50}$TiO$_2$ samples of 6 mm diameter were sandwiched by thin gold foils of the same dimensions. At 25 keV neutron energy measurements were carried out with titanium oxide sample masses between 40 and 100 mg. The samples of the $^{50}$TiO$_2$ powder were heated to 1000°C for 3 hours to get stable self-supporting tablets. No measurable weight loss was observed. Only thin samples were used to minimize corrections for neutron scattering or self-absorption effects, e.g. from oxygen, the Ti isotopes and from the gold foils back into the sample. Estimations show that these effects are below 2%. Three runs were carried out with metallic Ti foils of natural isotopic composition (Table II). The largest multiple scattering effects would have been expected from oxygen. However the runs with the metallic Ti samples and the runs with the $^{50}$TiO$_2$ samples show no measurable differences. In Fig. 3 the accumulated $\gamma$-ray intensity from one of the $^{50}$Ti activations is shown. The relevant $\gamma$-lines are well isolated on a low level of background counts.

The following systematic uncertainties were combined by quadratic error propagation: Au standard cross section: 1.5-3%, Ge-detector efficiency: 2%, $\gamma$-ray intensity per decay: 0.5% for the $^{51}$Ti and 0.1% for the $^{198}$Au decay, divergence of neutron beam: 2-7%, factor $f_i$: 1.5%, sample weight: <0.5%.
B. Direct capture

Our measurement in between the region of resonances, at 20 to 40 keV is interpreted as direct capture (DC). The size of this cross section shows that it is not a negligible effect. Because of the selectivity of our activation method only capture in $^{50}$Ti can contribute to this value. The contributions from the tails of $^{50}$Ti resonances are estimated to be not more than 0.005 mbarn and are neglected. This estimate is in agreement with the value which can be derived from the respective value for thermal capture given in Ref. [13]. Theoretical estimations suggest that we have to treat our measured direct capture value as pure s-wave capture with a 1/$v$ energy dependence. A p-wave contribution would be, as a rough calculation shows, at 30 keV ≤ 17.5 μbarn. If we assume that the thermal capture is also essentially direct capture we can make a comparison. The 1/$v$ extrapolation of our measured direct capture cross section to thermal energy gives 0.421 ± 0.012 barn which is, however, significantly larger than the measured value of 0.179 ± 0.003 barn [13]. But if the bound s-wave resonance at -16.8 keV specified in the compilation of Mughabghab et al. [13] exists destructive interference of resonance capture could occur. As the first positive resonance lies at 56.5 keV and the s-wave level spacing is estimated to be $D_0 = 125 ± 70$ keV [3], this bound state resonance seems to be not unlikely. A capture cross section of this resonance at 25.3 meV of 0.051 barn which corresponds to a radiative width of this resonance of 0.34 eV can reduce the direct capture to the observed thermal value.

A theoretical DC calculation was performed using a realistic neutron-nucleus folding potential [19,20] and spectroscopic factors of $^{51}$Ti from the (d,p) experiment of Ref. [21]. The result of the DC calculation overestimates our experimental value at 30 keV by a factor of 2; the calculated cross section depends on the choice of the potential parameters and the uncertainties of the spectroscopic factors. The resulting uncertainty of the calculated value is also roughly a factor of 2.

A further indication of the strong influence of the subthreshold state on the thermal capture cross section comes from the comparison of the experimental [22] and theoretical branching ratio. In the DC calculations the strongest transition is the ground state (3/2$^-$) transition with a branching of about 60% (independent on the choice of the potential parameters). However, experimentally the transition to the first excited 1/2$^-$ state at 1167 keV is dominating with 35%, and the ground state branching is almost negligible (4.2%). It should be noted that this experimental branching ratio is very surprising because in the neighboring nucleus $^{48}$Ca the experimental and the theoretical branching ratios agree well and show a dominating transition to the first 3/2$^-$ state. The disappearance of the ground state transition in $^{50}$Ti can be explained by destructive interference with the proposed 1/2$^+$ subthreshold state at -16.8 keV. Furthermore, a strong branching ratio of this subthreshold state can be predicted from the interference effect which mainly influences the ground state transition at thermal energies.

C. Resonance capture at 145 keV

The $^{50}$Ti capture cross section has been previously measured by Allen et al. [23] using the time-of-flight technique. These data have been essentially adopted in the compilation of Mughabghab et al. [13] except for the $g \Gamma_n \Gamma_\gamma / \Gamma$ value of the 97.6 keV p-wave resonance which was changed from 0.77 to 0.16 eV. In an additional publication Allen et al. [24] corrected the $\Gamma_\gamma$ value of the 56.5 keV s-wave resonance from 1.1 ± 0.2 eV to 0.2 ± 0.2 eV and estimated also the $\Gamma_\gamma$ widths for the s-wave resonances at 146.8 and 184.9 keV to be < 0.1 and 0.9 ± 0.3 eV, respectively. These revisions were necessary as the Oak Ridge capture detection setup had turned out to be very sensitive to scattered neutrons resulting in a high prompt (time dependent) capture $\gamma$-ray background which requires large corrections to the capture areas of the s-wave resonances with a large ratio of neutron scattering and capture width [22]. The areas of the s-wave resonances at 56.5 and 184.9 keV had to be corrected for prompt background contributions of 87 and 73 % [24], respectively. For the energy interval 100 to 150 keV Allen et al. [23,24] report an average capture cross section of 0.54 ± 0.08 mbarn which could contain contributions of the 146.8 keV s-wave resonance. However, Allen’s average cross section is, it seems to be, only derived from the two identified resonances in this energy region. The resonance strengths of the 101.4, 120.6, and 185.6 keV resonances and the 146.8 keV s-wave resonance to be investigated. The average capture cross section of a narrow resonance compared to the neutron spectrum used can be described in the following way

$$\bar{\sigma}_{\text{res}} = \frac{\int \sigma_{\text{eff}} \Phi(E) dE}{\int \Phi(E) dE} = A_\gamma \frac{\Phi(E_{\text{res}})}{\int \Phi(E) dE} = A_\gamma \Phi_{\text{norm}}(E_{\text{res}})$$

(3.1)
where $\sigma_{BW}$ is the Breit-Wigner formula for the resonance capture, $\Phi(E)$ the experimental neutron spectrum and $\Lambda_{s} = (2\pi^{2}/k^{2})g\Gamma_{\gamma}/\Gamma$ the resonance area with $k$ the wave number, $g=(2J+1)/[2(2I+1)]$ the statistical spin factor with $J$ the compound and $I$ the nuclear spin, and $\Gamma_{\gamma}$, $\Gamma_{n}$ and $\Gamma$ the radiation, neutron and total widths, respectively. After subtraction of the direct capture and the resonance capture from the 101.4, 120.6, and 185.6 keV resonances, where the resonance capture contribution of the 120.6 keV resonance of 0.15±0.07 mb is comparable in magnitude with the direct capture part, we obtain for the average resonance capture of the 146.8 keV s-wave resonance 0.22±0.13 mb which corresponds with a radiation width $g\Gamma_{\gamma}/\Gamma = 0.37±0.24$ eV. The dominant uncertainties in this analysis come from the neutron spectrum determinations $\Phi_{\text{norm}}(E_{\text{res}} = 120.6 \text{ keV}) = (7±3) \times 10^{-3}$ keV$^{-1}$, $\Phi_{\text{norm}}(E_{\text{res}} = 146.8 \text{ keV}) = (21±5) \times 10^{-3}$ keV$^{-1}$, and $\Phi_{\text{norm}}(E_{\text{res}} = 185.6 \text{ keV}) = (4±5) \times 10^{-3}$ keV$^{-1}$. The uncertainties of the capture areas for the 101.4, 120.6 keV and 185.6 keV resonances have been taken from Allen et al. [23,24].

D. Maxwellian averaged capture cross sections and reaction rate factors

The Maxwellian averaged capture cross section (4.0±0.5 mbarn at kT=30 keV) recommended until now in literature [20,21] has been calculated using the resonance parameters given in the tables of Mughabghab et al. [13] which are based on the reported resonance strengths in Ref. [23]. Direct capture was neglected and the revised radiation widths of the s-wave resonances [24] were not considered. In order to compare our measured Maxwellian averaged capture (MAC) cross sections at kT=25 keV and 52 keV, respectively with the corresponding values calculated from the resonance parameters we have to take into account the above mentioned changes. In Table III we calculated first the MAC cross sections at kT=25 keV and 52 keV using the resonance parameters from Ref. [13] (CALC1), then we took into account the revised s-wave resonance widths reported in Ref. [24] (CALC2), we included in CALC3 the direct capture contribution and in CALC4 our determined radiation width of the 146.8 keV resonance. The direct capture contribution (CALC3) was calculated using our measured cross section value at 30 keV and the known 1/v energy dependence, where the MAC cross section $\langle \sigma \nu \rangle_{vT}(kT=E_{n}) = \sigma_{DC}(E_{n})$ is the experimental neutron spectrum and $A_{s}$ the experimental neutron spectrum and A the average neutron spectrum. The biggest changes are caused by considerably smaller radiation widths for the s-wave resonances, especially for the 56.5 keV resonance (CALC2) and the inclusion of the direct s-wave capture contribution (CALC3). Finally, CALC4 is distinctly in better agreement with our experimental MAC cross sections than CALC1. In Fig. 4 the results of CALC1 and CALC4 vs kT are plotted together with our measurements at kT=25 and 52 keV and the 30 keV MAC cross section reported in Refs. [13,23]. Below 17 keV where there are no $^{50}$Ti resonances the direct capture starts to provide the dominant contribution. This part of the capture cross section is well determined by our direct capture measurement at 30 keV and the known temperature dependence. Theoretical determinations are also shown. The curves WHFZ and SMOKER refer to these Hauser-Feshbach calculations given in [28,29]. In the SMOKER calculation [28] a pure 1/v temperature dependence was assumed, and the temperature dependence of the WHFZ calculation [29] is practically also 1/v. As there are no $^{50}$Ti resonances below neutron energies of 17 keV these calculations overestimate the MAC cross section in the temperature range below kT=20 keV.

The final MAC cross sections and reaction rate factors (CALC4) are listed vs temperature kT in Table IV.

E. Conclusions

In our experiment we found the direct s-wave capture component characterising this magic shell isotope. Our measured direct capture cross section at 30 keV is one of the few examples, where the measurement of the direct part in the presence of strong resonance capture was successful. The measured thermal cross section is most likely the product of destructive interference with a bound s-wave resonance the existence of which was already suggested [13]. The present investigations yields confirmative arguments. The estimated resonance strength of 0.34 eV is in accord with the radiation widths of the positive s-wave resonances determined by Allen et al. [24] and in this work. The inclusion of a direct capture component into the calculation of the stellar reaction rate of $^{50}$Ti is of importance. It compensates the decrease of the MAC cross section at kT=25 keV due to the necessary reduction of the s-wave radiation width especially of the 56.5 keV resonance so that the calculation from the resonance parameters remains in agreement with our direct MAC cross section measurement. This may be considered also as an evidence for the consistence of the present data. It is also important to note that the stellar $^{50}$Ti reaction rate is not constant because the capture cross section has a non 1/v dependence in the thermonuclear temperature range important for the investigation of the isotopic titanium anomalies which are supposed to be of s-process origin. For a further improvement of the $^{50}$Ti MAC cross section a new time-of-flight measurement is recommended in order to determine more accurately especially the s-wave radiation widths.
The direct capture contribution becomes a significant part of the MAC cross section at low thermonuclear energies, i.e. at kT = 8 keV, where the $^{13}$C($\alpha$,n) neutron source is ignited and s-processing takes place in low-mass AGB stars [5]. Compared to the old data (CALC1) the direct capture increases the MAC cross section at kT= 8 keV by about 50% (see Fig. 4). This also reduces the calculated abundance of $^{50}$Ti in AGB models [5]. As was stated in Ref. [3] such a reduction could give better agreement with the measured values of the solar ratio with $^{50}$Ti as reference isotope in SiC grains [2].

ACKNOWLEDGEMENTS

The interest and support of Prof. G. J. Wagner of the Universität Tübingen is gratefully acknowledged. We would like to thank the technicians of the Van de Graaff accelerators M. Brandt and G. Rupp, respectively, and the Karlsruhe Van de Graaff staff members E.P. Knaetsch, D. Roller, and W. Seith for their help and support of the experiment especially in the preparation of the metallic Li-targets. We thank the Fonds zur Förderung der wissenschaftlichen Forschung in Österreich (project S7307-AST), the Deutsche Forschungsgemeinschaft (DFG) (project Mo739/1-1), and Volkswagen-Stiftung (Az: I/72286) for their support.

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TABLE I. Sample characteristics and decay properties of the product nuclei $^{51}\text{Ti}$ and $^{198}\text{Au}$

| Isotope | Chemical form | Isotopic composition (%) | Reaction | $T_{1/2}$ (min) | $E_\gamma$ (keV) | Intensity per decay (%) |
|---------|---------------|--------------------------|----------|-----------------|-----------------|------------------------|
| $^{50}\text{Ti}$ | TiO$_2$ metallic | 2.87(46), 2.54(47), 23.97(48), 3.09(49), 67.53(50) | $^{50}\text{Ti}(n,\gamma)^{51}\text{Ti}$ | 5.76 | 320.0852 | 93.1$\pm$0.4$^a$ |
| $^{197}\text{Au}$ | metallic natural | 100 | $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ | 2.69 | 411.8047 | 95.50$\pm$0.096 |

$^a$ Reference [18]

TABLE II. Sample weights and experimental $^{50}\text{Ti}$ capture cross-sections at thermonuclear energies

| Mean neutron energy (keV) | Mass of Au back side (mg) | Mass of sample (mg) | Chemical form | Mass of Au front side (mg) | Isotopic composition of Ti sample | $\sigma_\gamma$ (mbarn) | Uncertainty (%) |
|--------------------------|---------------------------|---------------------|---------------|----------------------------|----------------------------------|----------------------|----------------|
| kT=25                    | 16.253                    | 95.447              | TiO$_2$       | 16.253                     | enriched                         | 4.117                | 0.50            | 3.98           |
|                          | 16.640                    | 49.185              | TiO$_2$       | 16.580                     | enriched                         | 3.134                | 0.32            | 6.43           |
|                          | 16.070                    | 40.900              | Ti            | 16.110                     | natural                          | 3.550                | 0.50            | 2.84           |
|                          | 16.033                    | 40.892              | Ti            | 16.063                     | natural                          | 3.643                | 0.72            | 2.84           |
|                          | 15.857                    | 49.185              | TiO$_2$       | 15.843                     | enriched                         | 3.468                | 0.72            | 5.13           |
|                          | 16.600                    | 95.447              | TiO$_2$       | 16.593                     | enriched                         | 3.267                | 0.50            | 4.10           |
|                          | 16.433                    | 40.830              | Ti            | 16.413                     | natural                          | 3.795                | 0.98            | 3.18           |

Average 3.612$\pm$0.005 |

| kT=52                    | 16.386                    | 95.447              | TiO$_2$       | 16.590                     | enriched                         | 2.536                | 0.72            | 4.41           |
|                          | 16.587                    | 49.185              | TiO$_2$       | 16.567                     | enriched                         | 2.857                | 1.21            | 4.19           |

Average 2.736$\pm$0.113 |

| 30 ± 5                   | 16.420                    | 95.447              | TiO$_2$       | 16.405                     | enriched                         | 0.390                | 1.04            | 2.80           |
|                          | 16.067                    | 49.185              | TiO$_2$       | 16.053                     | enriched                         | 0.383                | 3.03            | 4.65           |
|                          | 16.010                    | 49.185              | TiO$_2$       | 16.017                     | enriched                         | 0.421                | 1.03            | 4.13           |
|                          | 16.507                    | 95.447              | TiO$_2$       | 16.500                     | enriched                         | 0.181                | 11.91           | 12.86          |
|                          | 16.386                    | 95.447              | TiO$_2$       | 16.323                     | enriched                         | 0.450                | 5.62            | 6.21           |

Average 0.387$\pm$0.011 |

| 145 ± 16                 | 16.173                    | 49.185              | TiO$_2$       | 16.200                     | enriched                         | 0.605                | 2.94            | 7.57           |
|                          | 16.320                    | 95.447              | TiO$_2$       | 16.327                     | enriched                         | 0.679                | 0.71            | 4.70           |
|                          | 16.127                    | 49.185              | TiO$_2$       | 16.110                     | enriched                         | 0.586                | 1.53            | 6.60           |

Average 0.650$\pm$0.029 |
TABLE III. Comparison of the measured Maxwellian averaged capture (MAC) cross sections with calculations from the resonance parameters.

| kT (keV) | CALC1<sup>a</sup> | CALC2<sup>b</sup> | CALC3<sup>c</sup> | CALC4<sup>d</sup> | Present measurement |
|----------|-----------------|-----------------|-----------------|-----------------|---------------------|
| 8        | 1.54±0.19       | 1.47±0.18       | 2.23±0.19       | 2.23±0.19       | 3.612±0.095         |
| 25       | 3.82±0.48       | 3.02±0.38       | 3.45±0.38       | 3.45±0.38       | 3.612±0.095         |
| 30       | 4.00±0.50<sup>e</sup> | 3.18±0.40       | 3.57±0.40       | 3.58±0.40       | 3.612±0.095         |
| 52       | 3.51±0.44       | 2.84±0.36       | 3.14±0.36       | 3.17±0.36       | 2.736±0.113         |

<sup>a</sup> resonances taken from Reference [13]
<sup>b</sup> same as in CALC1, but revised parameters of the s-wave resonances at 56.5, 146.8, and 184.9 keV from Reference [24]
<sup>c</sup> same as in CALC2, but a direct s-wave capture contribution measured in this work was included
<sup>d</sup> same as in CALC3, but with the resonance strength of the 146.8 keV resonance determined in this work
<sup>e</sup> this value is reported in Refs. [13,23] and was adopted in the compilations Refs. [26,27]

TABLE IV. The Maxwellian averaged capture (MAC) and stellar reaction rate from CALC4 between 1 and 250 keV.

| kT (keV) | <σv>/v<sub>T</sub> (mbarn) | Stellar rate factor (10<sup>4</sup> cm<sup>3</sup> mol<sup>−1</sup> s<sup>−1</sup>) |
|----------|-----------------|-----------------|
| 1        | 2.13±0.06       | 5.66            |
| 2        | 1.55±0.04       | 5.84            |
| 3        | 1.54±0.05       | 7.09            |
| 4        | 1.76±0.09       | 9.34            |
| 5        | 1.97±0.13       | 11.71           |
| 6        | 2.11±0.16       | 13.74           |
| 7        | 2.18±0.17       | 15.38           |
| 8        | 2.23±0.19       | 16.75           |
| 10       | 2.30±0.20       | 19.31           |
| 12       | 2.41±0.23       | 22.24           |
| 15       | 2.68±0.27       | 27.60           |
| 18       | 2.97±0.31       | 33.53           |
| 20       | 3.15±0.33       | 37.42           |
| 22       | 3.29±0.35       | 41.08           |
| 25       | 3.45±0.38       | 45.92           |
| 27       | 3.52±0.39       | 48.69           |
| 30       | 3.58±0.40       | 52.14           |
| 35       | 3.58±0.40       | 56.27           |
| 40       | 3.49±0.39       | 58.78           |
| 45       | 3.37±0.38       | 60.15           |
| 50       | 3.23±0.37       | 60.72           |
| 52       | 3.17±0.36       | 60.79           |
| 55       | 3.08±0.35       | 60.75           |
| 60       | 2.93±0.33       | 60.40           |
| 65       | 2.79±0.32       | 59.81           |
| 70       | 2.65±0.30       | 59.05           |
| 79       | 2.41±0.27       | 57.23           |
| 80       | 2.19±0.25       | 55.21           |
| 100      | 2.00±0.22       | 53.15           |
| 110      | 1.83±0.20       | 51.10           |
| 120      | 1.68±0.19       | 49.10           |
| 150      | 1.34±0.15       | 43.57           |
| 180      | 1.09±0.12       | 38.81           |
| 200      | 0.958±0.103     | 36.03           |
| 250      | 0.719±0.077     | 30.25           |
FIG. 1. Left: Time-of-flight (TOF) neutron spectrum from the $^7$Li(p,n) reaction 1 keV above reaction threshold. The position of the $^{50}$Ti p-wave resonance at 16.99 keV is shown together with a shaded area which is the uncertainty of the TOF measurement. Right: Angle integrated neutron spectrum from the $^7$Li(p,n) reaction 1 keV above reaction threshold.

FIG. 2. Neutron spectrum with a mean energy of 145.1 keV. The distribution has been generated from time-of-flight spectra measured at different angles. The integration has been performed by Monte Carlo methods.

FIG. 3. Accumulated intensities of the $^{51}$Ti and $^{198}$Au $\gamma$-ray decay lines from the activation with a 95.447 mg TiO$_2$ sample sandwiched by two Au foils using a neutron spectrum with a mean energy of $kT=25$ keV.

FIG. 4. Comparison of our measured MAC cross sections (full black circles) with the calculations CALC1 (dashed line) and CALC4 (solid line) from the resonance parameters. The 30 keV MAC cross section as reported in literature is shown as well. For the calculation CALC4 also the uncertainty is given. The influence of the direct capture contribution is clearly seen below 10 keV. Additionally theoretical determinations are given. The labels WHFZ $^{28}$ (dash-dot-dotted curve) and SMOKER $^{29}$ (dash-dotted curve) refer to these Hauser-Feshbach calculations.
