Spatially resolved remote measurement of temperature by neutron resonance absorption

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Abstract

Deep penetration of neutrons into most engineering materials enables non-destructive studies of their bulk properties. The existence of sharp resonances in neutron absorption spectra enables isotopically-resolved imaging of elements present in a sample, as demonstrated by previous studies. At the same time the Doppler broadening of resonance peaks provides a method of remote measurement of temperature distributions within the same sample. This technique can be implemented at a pulsed neutron source with a short initial pulse allowing for the measurement of the energy of each registered neutron by the time of flight technique. A neutron counting detector with relatively high timing and spatial resolution is used to demonstrate the possibility to obtain temperature distributions across a 100 μm Ta foil with ~millimeter spatial resolution.

Moreover, a neutron transmission measurement over a wide energy range can provide spatially resolved sample information such as temperature, elemental composition and microstructure properties simultaneously.

Keywords: Neutron resonance spectroscopy; Pulsed neutron sources; Remote sensing; Temperature sensing.

1. Introduction

Thermal and cold neutron diffraction and radiography methods are complementary to corresponding X-ray techniques and sometimes provide unique information about samples, especially in cases where the measurement of the bulk material is important. A large variety of neutron imaging techniques have been developed for non-destructive testing in various applications[1]-[12], most of them utilizing thermal and cold neutrons (~ 1 to ~ 100 meV). Several elements(e.g. H, B, Gd, Cd) have relatively high cross sections for neutron induced reactions,while a number of engineering materials have relatively low cross sections for neutron reactions and are opaque to X-rays. The wavelengths of neutrons available at neutron beamline facilities are moderated to be comparable to the lattice spacings of many crystalline materials (several angstroms), satisfying the diffraction conditions.Imaging techniques where the contrast is provided by neutron diffraction have been extensively developed to study the internal structures of crystalline samples[1],[3],[6],[13]-[15] in transmission. Energy resolved neutron imaging with thermal and cold neutrons can provide both absorption and diffraction contrast and has been demonstrated to reveal the spatial distributions of hydrogen-containing materials, residual stresses, texture and compositions of various samples [1],[13]-[19]. The energy dependence of neutron transmission is probed either by energy selection using a

42 monochromator, a velocity selector[6] or by the time of flight (TOF) technique, with the highest
43 energy resolution available at pulsed neutron sources[3]. Pulsed neutron sources with short initial
44 pulses (e.g., ISIS at Rutherford Appleton Laboratory, UK[20], J-PARC in Japan[21], LANSCE at
45 Los Alamos Laboratory[22], SNS at Oak Ridge National Laboratory, USA[23], GELINA in
46 Belgium[24] and others) provide the possibility to extend the spectral range of neutron
47 transmission spectroscopy into the epithermal regime (~ 1 eV to ~ 100 keV) and even into the
48 range of fast neutrons with MeV energies [24]. At these energies some materials have very sharp
49 absorption features, at characteristic energies specific to individual elements and their specific
50 isotopes [25], [26]. Element and/or isotope-specific imaging through neutron resonance
51 absorption can be performed simultaneously with all the before-mentioned imaging techniques,
52 providing the beamline optics at the spallation source and the detection systems allow the
53 measurement of neutron transmission over the broad energy range required. The higher degree of
54 penetration of epithermal neutrons compared to cold neutrons and their corresponding sensitivity
55 to specific elements and their isotopes is attractive for many applications where other non-
56 destructive methods are not capable of penetrating the samples or cannot differentiate between
57 various materials - such as imaging of high-Z materials mixed within other high-Z materials[27]-
58 [31]. In addition to elemental analysis, it has been demonstrated that the *temperature* of samples
59 can be measured remotely via the Doppler broadening of observed resonance profiles[25], [32]-
60 [39]. This method has been used, for example, to measure phonon spectral parameters [40] as
61 well as to determine the temperature in a shocked metal [36], [38], and has even been suggested
62 for remote tomographic reconstruction of temperature distributions[39]. The challenge of the
63 resonance imaging technique is to detect both position (~ 100 μ m) and time of arrival (~ 10 - 100
64 ns) of individual neutrons at the detection plane. On existing beamlines typical flight times for

epithermal neutrons are in the range of 10-1000 μ s. Multiple events need to be detected for each neutron pulse and accumulated over many neutron pulses in order to acquire adequate counting statistics. To date, some experiments have been conducted with high spectral resolution, but limited spatial information using single-pixel detectors, [32]-[38], [40], [41]. In some cases coarse spatial resolutions with comparatively small numbers of pixels were achieved, however the spectral resolution and counting statistics were low due to count rate limitations of those neutron detectors [39], [42]-[44].

In this paper we present the results of our proof-of-principle experiments on imaging the temperature distribution by neutron transmission resonance spectroscopy with relatively high spatial and temporal resolution. The Doppler broadening of the width of the measured resonance profile of a 100 μ m Ta foil is used to reconstruct the temperature distribution across the foil, which was heated between 25 and 375°C. The recently developed Microchannel Plate (MCP)/Timepix neutron counting detector with <100 ns timing and <100 μ m spatial resolution [45]-[47] was used to measure neutron transmission spectra in each of the 262144 pixels simultaneously, without the need for time-gating or sample translation. With this detector installed at a pulsed neutron source, a wide range of energies can be covered in one experiment, enabling simultaneous measurements of resonance spectra in the epithermal range and variation of transmission in the thermal and cold range of energies - where neutron diffraction and absorption provide contrast due to variation of sample composition and microstructural properties.

2. Experimental setup

The experiments described in this paper were performed on the ROTAX beamline at the ISIS pulsed neutron source at the Rutherford Appleton Laboratory with a pulse repetition rate of 50 Hz. The fast MCP/Timepix neutron counting detector capable of simultaneous registration of multiple neutron events was installed at a distance of ~ 16.05 m from the target, Fig. 1. The spatial resolution of our experiment was determined by the size of the Timepix pixel ($55 \times 55 \mu\text{m}^2$) [48]. The active area was 28 mm in diameter; limited by the size of the previous generation of neutron sensitive microchannel plates fabricated by Nova Scientific. Currently larger MCPs can be fabricated and the active area is determined by the readout electronics, $28 \times 28 \text{ mm}^2$ with a 2×2 array of Timepix chips [47]. Each Timepix chip consists of independently operating 256×256 pixels, forming our detector readout with 512×512 pixels thus enabling detection of a large number of neutrons arriving at the detector within the first few hundred microseconds after the spallation. Individual neutrons impinging on the detector are converted into secondary electrons and amplified by neutron sensitive MCPs to $\sim 10^5$ electrons/incident neutron within < 1 ns and subsequently registered by the Timepix pixels. The arrival time and position of each registered neutron was transferred over a fiberoptic cable from the detector to the data acquisition computer. The detection events were sorted out in real time into the images with the corresponding time of flight. As a result of each data acquisition a set of 512×512 -pixel images (typically several thousands, depending on the time binning chosen) was acquired, with each image corresponding to a particular time of flight. From these images the transmission as a function of neutron time of flight can be extracted for each pixel or for a group of pixels if needed. The energy of the detected neutrons was calculated from their time of flight (T) from the equation:

$$E = m \frac{L^2}{2(T + \Delta T_0)^2} \quad (1)$$

where m is the mass of a neutron, L is the flight path and ΔT_0 is the time offset of the source trigger received by the data processing electronics. Both L and ΔT_0 were calibrated by fitting the measured transmission to the transmission calculated from a tabulated dataset (see Section 3.1).

For each registered neutron the time of its arrival at the detector was measured with a 160 ns or 240 ns resolution relative to the time of spallation, which was encoded by an external trigger synchronous with the neutron source operating at 50 Hz frequency. Every 5th trigger pulse did not contain neutrons as the proton pulse was sent to the target station 2 of the ISIS facility. No chopper was used to cut the bright gamma flash at the time of the spallation process. The gamma flash is another challenge for any detection system used for resonance spectroscopy as it must be radiation hard and not be blinded by the bright bursts of gamma photons and fast neutrons at time T_0 . The relatively high radiation hardness of the Timepix readout placed in the direct beam was very important for our measurements.

The experimental transmission T_{exp} was derived from the ratio of a sample-in and sample-out TOF spectrum, denoted by C_{in} and C_{out} , respectively:

$$T_{exp} = \frac{C_{in}}{C_{out}} \quad (2)$$

The spectra C_{in} and C_{out} were acquired with equal TOF-bin width and normalized to the same neutron flux and image acquisition time. Since only the transmission dips around the 4.26 eV and 10.3 eV resonances of ^{181}Ta were used in the temperature analysis and the background level below 10 eV was found to be very low, the C_{in} and C_{out} spectra in Eq. 2 were not corrected for any background contribution. The independently operating pixels of our neutron counting detector enable dead-time free measurements and therefore no dead-time corrections were

applied to our experimental data. An initial calibration of our setup was performed with a 1 mm-thick silver foil as well as a 1.18 mm-thick Ta foil installed upstream in the neutron beam at several meters distance from the detector. For the remote measurements of the temperature distribution a thin Ta foil (100 μm) was mounted on a Cu heater and placed at a ~ 8 cm distance from the active area of the detector (Fig. 2). The transmission of a ~ 3 mm thick copper heater used in the experiment is nearly constant at $\sim 80\%$ up to the energy of ~ 230 eV and had little effect on the shape of the spectra of the Ta foil below 100 eV energies, the latter of which was used to reconstruct the temperature profiles through Doppler broadening of the resonance absorption. On one end the Ta foil was thermally coupled to the Cu heater, which provided a uniform temperature distribution across that area of the foil mounted on the heater, Fig. 2. The other end was connected to a passive aluminium radiator, acting as a heat sink at room temperature. The distance between the heat source and sink was ~ 4 cm. This geometry created a smooth temperature gradient across the foil, which was allowed to come to equilibrium, changing from the value set at the copper heater on one side to the ambient room temperature of $\sim 25^\circ\text{C}$ on the other side.

3. Results

3.1. Calibration of the experimental setup by the materials with tabulated data

Prior to the temperature measurements two samples of known thicknesses (1 mm Ag and 1.18 mm Ta) were used to calibrate the distance from the source L and the time offset of the source trigger ΔT_0 . First the cross sections for $^{\text{nat}}\text{Ag}$ and ^{181}Ta (99.988 abundance in $^{\text{nat}}\text{Ta}$) tabulated in Ref. [49] were used to calculate the theoretical transmission through these filters, then the parameters L and ΔT_0 were determined by minimizing the differences between the locations of the theoretical and

experimental transmission dips. The flight path of 16.05 m and time delay on the trigger of 1 μ s were determined from this calibration measurement. The background levels at the energies used in our temperature distribution study (3-12 eV) was confirmed to be very low in our setup, Fig. 3.

The measured TOF-spectra (C_{in}) taken with the Ag and Ta samples in the beam are shown in Fig. 3a. They reveal saturated resonances due to the presence of Ag and Ta as well as the impact of the energy dependence of the neutron beam and detection efficiency on the shape of the spectrum. Normalization of these spectra to the C_{out} spectrum eliminates the dependence on both the intensity of the incoming neutron beam and on the detection efficiency. This is illustrated in Figs. 3b, 3c and 3d where the experimental transmissions through a Ta (1.18 mm), Ag (1 mm), and Ta (100 μ m) sheet, respectively, are shown. The depths of resonance dips in the transmission can be used to quantify the amount of elements present in the illuminated part of a sample. A determination of the elemental (and isotopic) composition requires an accurate determination of the experimental transmission, including a correction for the time dependent and independent background contributions. Such quantitative analysis of the sample elemental composition was not performed in this work, since it was focused on the reconstruction of temperature distributions. In the present study changes in the width of the observed transmission dips for the 4.26 and 10.3 eV resonances due to Doppler broadening were used to determine temperature distributions. The resonance absorption for the 100 μ m Ta foil at these two energies is shown in Fig. 4.

3.2. *Temperature reconstruction technique: constant temperature across the Ta sample*

Before performing the transmission experiments, the temperature of the copper heater element was verified to be uniform across the field of view using a thermocouple and a thermal imaging camera. Measurements with a 100 μm thick Ta foil that was kept at constant temperature across the field of view were carried out to calibrate the width parameter that was derived from the observed resonance dip as a function of the sample temperature. The experimental transmission was determined for temperatures between 25 $^{\circ}\text{C}$ and 375 $^{\circ}\text{C}$. Fig. 4 shows a typical transmission as a function of neutron energy for a temperature of 25 $^{\circ}\text{C}$. The transmission in Fig. 4a illustrates that the background level around 4.3 eV in the TOF-spectra is in the order of a few percent. The width parameter extracted from fitting the transmission spectra was calibrated from these measurements at a constant temperature. Comparison of different variations of our reconstruction method (e.g. fitting multiple parameters at the same time, fixing some of them and repeating the fit with only a limited subset of parameters, etc.) was also performed with that data for which the temperature was known. It was determined that the best reconstruction of sample temperature was performed by fitting the experimental data with all parameters fixed, except for the width parameter of the measured resonance profile.

The first Ta resonance peak (~ 4.26 eV) is fully saturated for the 100 μm Ta foil, i.e. the foil practically absorbs 100% of all incoming neutrons at this resonance energy. For a thicker Ta sample the analysis procedure below may require some modification (namely a different fitting function for the saturated resonance) to determine the temperature. To extract the width parameter of the resonance profile a nonlinear leastsquares fit to the experimental data was performed. The theoretical transmission around a resonance with index k was parameterized by the analytical function

$$T(E) = [T_k - B_k] * \exp(-F(E) * n) + B_k \quad (3)$$

197 where T_k and B_k are the transmission at the energies outside of the resonance with index k and
 198 background signal, respectively, n is the areal density of the sample or the total number of atoms
 199 per unit area, calculated from the equation $n = \frac{d\rho}{m_a}$, where d is the thickness of the sample, ρ and
 200 m_a are the density of the Ta-foil and mass of the Ta atom, respectively. The function $F(E)$ was
 201 given by

$$202 \quad F(E) = \left[\frac{F_k}{4} \Delta_k^2 + S_k * (E - E_k) \Delta_k \right] * \frac{1}{\left(\frac{|E - E_k|}{E_0} \right)^{\alpha_k} + \frac{\Delta_k^2}{4}} \quad (4)$$

203 where Δ_k, F_k, S_k and α_k are empirical parameters and $E_0 = 1 \text{ eV}$. It should be noted that, although Eq.
 204 4 is inspired by the Single Level Breit-Wigner (SLBW) formula [50], Eq. 3 combined with Eq. 4
 205 is a pure empirical description of the transmission dip around a resonance. The parameter E_k is
 206 the energy at which the experimental transmission has the lowest value, i.e. e^{-F_k} , S_k is a
 207 parameter representing a neutron scattering contribution and Δ_k is a width parameter to account
 208 for the overall impact of the total resonance width, the Doppler broadening and the resolution of
 209 the TOF-spectrometer. The parameter α_k is introduced to allow for a better fit of the analytical
 210 profile to the experimental data. The parameter Δ_k can be used in a calibration approach to
 211 determine the sample temperature.

212 The theoretical transmission can be derived rigorously based on a full metrological approach
 213 starting from a calculation of the total cross section using tabulated resonance parameters. Such
 214 an approach allows a direct adjustment of the effective sample temperature (e.g. [33],[36],
 215 [37],[40], [51]) and of the areal number density (e.g. [27]-[37], [40], [41], [52]) from a fit to the
 216 experimental data without any calibration requirements. It requires, however, a good knowledge
 217 of the response function of the TOF-spectrometer, a model to account for the Doppler broadening
 218 and an experimental transmission which does not suffer from bias effects due to background

219 contributions, dead time effects or detector instabilities. The empirical analysis utilized in the
220 present study was intended to demonstrate the possibility of temperature mapping with relatively
221 high spatial resolution in a realistic experimental setup. The challenge of fitting nearly a quarter
222 million spectra required for the spatially resolved temperature mapping is addressed in our study
223 by fitting a simplified empirical function (equations 3 and 4).

224 Initially we established that the width of the experimental transmission dip exhibited a
225 measurable dependence on the sample temperature by normalizing the experimental transmission
226 at elevated temperatures to the transmission obtained at 25 °C, similar to the analysis described in
227 references [32] and [37]. The effect of the increase in the width of the resonance dips with
228 increasing temperature is clearly visible in the transmission ratios shown in Figs. 5 and 6. Such
229 profiles can be used for a temperature reconstruction as shown in previous studies, e.g. [32] and
230 [37]. However, this method is not adequate for spatially resolved mapping, for which the
231 transmission through an area as small as a 55 μm pixel has to be analyzed. Therefore the method
232 in Refs. [32] and [37], which relies on the ratio of transmission profiles at a given energy, suffers
233 from limited counting statistics. A method based on fitting transmission profiles by an analytical
234 expression provides more precise temperatures and is better suited for a spatially resolved
235 temperature reconstruction.

236 First we fitted the analytical function, i.e. Eq. 3 combined with Eq. 4, to the transmission
237 resulting from the measurements with the sample at 25 °C and adjusted the parameters Δ_k , S_k , F_k ,
238 α_k , T_k and B_k for the profiles around the 4.26 eV and 10.3 eV resonances. The values of these
239 parameters were 0.018 ± 0.003 , 200 ± 50 barn/eV, $(1.11 \pm 0.01) \cdot 10^5$ barn, 2.70 ± 0.05 , 1.000 ± 0.002 ,
240 0.053 ± 0.002 for the 4.26 eV resonance, and 0.090 ± 0.025 , 10 ± 5 barn/eV, 3800 ± 100 barn,
241 2.70 ± 0.05 , 0.990 ± 0.005 , 0.050 ± 0.005 for the 10.3 eV resonance, respectively. The parameter

242 T_k differs from 1 for the 10 eV resonance and B_k varies from 0 for both the 4.26 eV and 10.3 eV
 243 resonances. This is due to the fact that over a wider range of energies the experimental
 244 transmission derived in this work is affected by background contributions that are not removed
 245 from the C_{in} and C_{out} spectra and a pure empirical expression is used to fit the data. Around a
 246 single resonance T_k and B_k are nearly constant and were fitted as energy independent
 247 parameters. For the reconstruction of a temperature distribution across the sample, the
 248 transmission spectra measured at different sample temperatures were fitted with only the width
 249 parameter Δ_k as an adjustable parameter. To correlate the width parameter to the sample
 250 temperature a set of measurements with a constant temperature across a Ta foil was performed
 251 and the parameter Δ_k was obtained by fitting. In this process the transmissions resulting from the
 252 spectra within $3.3 \times 3.3 \text{ mm}^2$ around each pixel were summed up to increase the counting
 253 statistics and the width parameter Δ_k was derived from a fit to the resulting transmission. For each
 254 image nearly 200000 transmissions were fitted. The distribution of the width parameters Δ_k
 255 resulting from the fit to the 4.26 eV and 10.3 eV profiles are represented by a color code (online
 256 version only) or by the gray value in Figs. 7 and 8, respectively. The parameter Δ_k changes
 257 linearly with the sample temperature as shown in Fig. 9. This linear relationship was used for a
 258 reconstruction of unknown temperature profiles within the same 100 μm thick Ta foil.

259 The distribution of fitted width parameter values shown in Fig. 10 indicates that the
 260 precision of temperature reconstruction in this spatially-resolved analysis is not better than
 261 $\sim 20^\circ\text{C}$ rms. A more comprehensive fitting of the broader energy spectrum (rather than using one
 262 resonance as implemented here) with an analytical function derived from first principles should
 263 provide better accuracy ($\pm 10^\circ\text{C}$ [35],[37]; even $\pm 1^\circ\text{C}$ as it was demonstrated previously [32]),
 264 and also enable reconstruction of temperatures with a better spatial resolution or allow

shorter measurement times. However, the present temperature analysis method is a good compromise between the accuracy of temperature reconstruction and the calculation time required for the analysis of ~200000 spectra in one measured data set.

3.3. *Mapping the temperature gradient across the Ta foil*

The same Ta foil was used to demonstrate the possibility to reconstruct the temperature distribution with sub-mm spatial resolution. One side of the foil in that experiment was clamped to the copper heater maintained at 375°C whilst the other side of the foil was cooled to ~ 25°C (room temperature) by two Al radiators, thus providing a ~350°C temperature gradient across the field of view as shown in Fig. 2b. The same function (equations 3 and 4) was used for the analysis of the temperature distribution. All parameters in that function were fixed to the values used for the constant temperature calibration except for the width of the resonance profile, which was fitted to the spectra acquired across the detector active area. In principle the spatial resolution of our reconstruction can be as high as the pixel area ($55 \times 55 \mu\text{m}^2$) providing the spectrum measured in each pixel has sufficient statistics. In the analysis of the gradient temperature data shown in Fig. 11 we still combined spectra within a $2.2 \times 2.2 \text{ mm}^2$ area around each pixel and thus the reconstructed temperature distribution has a 2.2 mm-wide smoothing. For each pixel the width of the resonance profile parameter Δ was found by fitting the function of eq. (3) to the measured spectra accumulated over the $2.2 \times 2.2 \text{ mm}^2$ area around that pixel. Then the calibration curves of Fig. 9 were used to calculate the temperature of the sample within that area. The process was repeated for each pixel of the measured data. Selected regions with 1 mm width across the temperature maps (Fig. 12) demonstrate the possibility to spatially map an arbitrary temperature distribution across the sample if an initial calibration of the width of resonance profiles is performed. It should be noted that the use of a saturated ('black') resonance

288 at 4.26 eV gives good results in the case of a uniform sample thickness. For an arbitrarily shaped
289 and/or in-homogeneous sample with varying thickness and/or areal density of the nuclide across
290 the image, the transmission in the region of strong resonances is affected by both the temperature
291 and the sample characteristics. Therefore, use of black resonances should be avoided for the
292 reconstruction of temperature by a simplified approach, like that presented here, unless the
293 sample thickness/concentration does not vary across the pixels of the image. The effects of
294 sample thickness and sample temperature at a given point still should be distinguishable for the
295 non-saturated resonances, providing proper data processing methods are implemented.

296 **4. Conclusions**

297 The results of our experiments demonstrate that remote mapping of a temperature distribution
298 with a ~millimeter-scale spatial resolution is feasible. Although the sample in our study was
299 relatively simple in structure (i.e. a Ta foil clamped between two copper plates) this technique
300 can be used for studies of more complicated multi-element assemblies and for thick samples
301 where traditional methods cannot be implemented. The high penetration capability of epithermal
302 neutrons make this technique attractive for experiments and inspections where thermometry and
303 temperature mapping with conventional temperature probes, such as thermocouples, is not
304 possible or impractical. Another very attractive feature of remote temperature mapping through
305 resonance absorption is the possibility to perform these measurements simultaneously with
306 spatially resolved Bragg edge diffraction and transmission. Indeed, pulsed neutron sources
307 provide a considerable flux of neutrons with energies varying in a wide range from $\sim 10^{-3}$ eV to
308 $\sim 10^5$ eV. However, there are many materials that are not suitable for resonance analysis, i.e.
309 samples containing light elements or nuclides with a specific proton or neutron number which
310 have only high energy resonances. The limit of neutron resonance analysis applications at high

energies is due to the neutron transport in the spallation source and moderator, the width of the initial neutron pulse, typically from 100 to 600 ns, and the presence of a considerable background contribution at high energies. This limits application of this method of temperature measurement at current spallation sources to those elements/isotopes which have relatively low resonance energies. Practically, only materials with relatively low resonance energies < 100 eV can be used for accurate temperature mapping at spallation neutron sources, as at higher energies the Doppler broadening becomes small compared to instrument resolution, dominated by pulse broadening effects in the moderator. Other challenges of this technique are due to a limited sensitivity of present high resolution detection systems (relatively low quantum detection efficiency at energies above 100 eV), elevated background levels, and limited neutron fluxes. An analysis based on an analytical model that starts from the calculation of the total cross section from resonance parameters and includes a model for Doppler broadening and the response function of the TOF-spectrometer as in e.g. Refs. [36], [37], will substantially improve the precision and accuracy of the derived sample temperatures, or will allow for shorter acquisition times. Moreover, neutron counting detectors with higher detection efficiency in the epithermal range, now being developed, should prove to be very useful for such measurements.

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474

475 **Fig. 1.** Schematic diagram of the experimental setup. Pulsed neutron source with the pulse width
 476 of $<0.5 \mu\text{s}$ creates neutrons with a wide range of energies. At a distance of about 16.0 m from the
 477 source the 100 μm Ta foil is attached to a Cu heater block and installed in front of a position
 478 sensitive detector, recording X,Y,T for each registered neutron. The time of arrival is measured
 479 relative to the spallation pulse trigger. A stack of transmission images, each image corresponding
 480 to a given time of flight, hence neutron energy, are collected in one acquisition. A transmission
 481 spectrum can be obtained for each pixel from the resulting stack of images.

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484 **Fig. 2.**(a) Photograph of the copper heater with two heater elements and a thermocouple onto
 485 which a 100 μm thick Ta foil was attached. One side of the foil was clamped to the heater and
 486 the other side was clamped between two Al radiators. The temperature of the heater and foil
 487 clamped to the heater remained constant across its entire area. The temperature across the free-
 488 standing Ta foil changed from the temperature of the heater on one side to ambient temperatures
 489 on the other side, enabling measurement of one temperature (in the area of the heater) and
 490 measurement of the temperature gradient in the free standing area. (b) Thermal image of the
 491 setup shown in figure (a). The calibration bar is tuned for the emissivity of the copper heater,
 492 therefore the temperature of the free-standing Ta foil heated from one side is not displayed
 493 correctly.

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Fig. 3.(a) The measured raw transmission spectrum (not normalized for the variation of beam intensity) of combined 1 mm thick Ag and 1.18 mm thick Ta sheets. Multiple resonances of Ta and Ag, some of them down to the baseline of the background baseline, are present. (b), (c), (d) Measured transmission curves of 1.18 mm Ta, 1 mm Ag and 100 μ m Ta, respectively.

Fig. 4. Resonance absorption for a 100 μm Ta foil at 4.26 and 10.3 eV. The markers are the measured values and the solid lines are fits to the measured data according to equation (3).

Fig. 5. Ratio of 100 μm Ta transmission around the 4.26 eV resonance measured at various temperatures (kept constant across the sample) to the spectrum measured at 25 $^{\circ}\text{C}$. The resonance broadening is clearly visible. The depths of two peaks or the integrated areas of the double-peaks can be used as parameters identifying the temperature of the sample. The neutron spectra from all pixels within a relatively large area of $\sim 1.5 \times 1.5 \text{ cm}^2$ are combined in order to increase the number of detected neutron counts per spectral bin.

Fig. 6. Same as Fig. 5, except calculated for the 10.3 eV resonance.

Fig. 7. Maps of the fitted width parameter Δ of the 4.26 eV resonance. Spectra in a $3 \times 3 \text{ mm}^2$ area around each $55 \text{ }\mu\text{m}$ pixel were combined in order to improve counting statistics. The $100 \text{ }\mu\text{m}$ Ta foil was kept at constant temperature during the measurement. Integration time was ~ 20 min for each temperature.

Fig. 8. Same as Fig. 7, except fitted for the 10.3 eV resonance.

Fig. 9. Temperature calibration, with the sample temperature plotted as a function of measured width parameter Δ for two resonances at 4.26 and 10.3 eV within a $2 \times 2 \text{ cm}^2$ area (Figs. 7 and 8). The error bars represent one standard deviation of the measured width parameter Δ , which was calculated from ~ 200000 profile fits for areas centered on each pixel. The markers represent the measured mean values of parameter Δ at a given temperature. The equations shown as inserts are used to reconstruct the sample temperature for a measured width of the resonance profile.

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538 **Fig. 10.**Distributions of measured temperatures for the 100 μm Ta foil kept at constant
539 temperature during each measurement. The temperature can be reconstructed with $\sim 23^\circ\text{C}$ rms
540 and 51°C rms precision for 4.26 and 10.3 eV, respectively, as determined by the fits to ~ 200000
541 resonance profiles around each pixel in the images shown in Figs. 7 and 8 and with the
542 temperature calibration of Fig. 9.

543

Fig. 11. Measured temperature distribution across a 100 μm Ta foil heated to $\sim 375^\circ\text{C}$ on the right side (beyond the field of view) and cooled to room temperature on the left side. The data set was accumulated over several hours. The temperature maps are calculated from the fitted widths of the resonance profiles according to the calibration curve shown in Fig. 9. The spectra from a $2.2 \times 2.2 \text{ mm}^2$ area around each pixel were combined before fitting in order to increase counting statistics. The dashed areas indicate a 1-mm wide region across the temperature maps corresponding to line profiles shown in Fig. 12.

553

554 **Fig. 12.** Temperature profiles for regions (1 mm-wide) across the temperature maps of 100 μm Ta
 555 foil shown in Fig. 11. The dotted lines indicate $\pm$ one standard deviation of measured values,
 556 which were obtained from the fits of Fig. 10.