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Reliability estimation of neutron resonance thermometry using tantalum and tungsten

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Abstract

The reliability of neutron resonance thermometry was discussed based on measurements of neutrons transmitted through tantalum (0.1 mm thick) and tungsten (1 mm thick) indicators at 26, 96, 189, and 285 degrees Celsius using the energy-resolved neutron imaging system, RADEN, at the Japan Proton Accelerator Complex (J-PARC). The intensity of transmitted neutrons at the sides of resonance dips were found to decrease with increasing temperature. Sensitivity coefficients to convert this decrease to temperature were derived, and two-dimensional distributions of the decreasing rates, being proportional to the temperature distribution, were obtained. The reliability of estimated temperature was calculated as a function of temporal and spatial resolution assuming that the dominant factor of the reliability was the uncertainty in the neutron counts. The authors set a target of neutron resonance thermometry for practical applications, and found a required efficiency of the neutron detector for resonance thermometry.

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Keywords: Energy-resolved neutron imaging ; Time-of-flight ; Temperature measurement ; Neutron resonance ; Statistical uncertainty ; RADEN ; J-PARC

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1. Introduction

Energy-resolved neutron imaging has attracted attention as an advanced technique to obtain various physical properties using the transmitted neutron energy spectra in conjunction with a conventional neutron radiograph. The energy-resolved neutron imaging system, RADEN (Shinohara et al. (2016)), was installed at an intense short-pulsed neutron source at the Japan Proton Accelerator Complex (J-PARC), and has been in operation since 2015. Neutron resonance thermometry, which derives material temperature by analyzing a neutron resonance peak (or dip in the transmitted

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neutron energy spectrum), is one application of these energy-resolved neutron imaging techniques. At the atomic level, the temperature of a material is described as a vibration of a nucleus. The vibration velocity increases with the temperature resulting in an increasing shift of the relative velocity to that of an incoming neutron. This effect, called Doppler broadening, is observed as a broadening of the neutron resonance peak.

Kamiyama et al. (2005) measured a tomographic distribution of tantalum temperature in aluminum oxide by measuring neutron energy dependent prompt γ-rays. Position dependent γ-ray data were obtained via slit-scanning at different rotation angles of the sample, and were used for computed tomography. The temperature was derived from fitting a theoretical function to the measured neutron energy dependence. Tremsin et al. (2015) also demonstrated that spatial distribution of temperature is obtainable by using a two-dimensional neutron detector. In their experiments, energy-dependent neutron transmission spectra of a 100-μm thick tantalum sheet were measured by the imaging detector without need of a slit-scanning method. The rapid depression of neutron transmission at the tantalum resonance energy was fitted by an empirical function, and the values of the fitted parameters were converted to temperature at each position based on a calibration curve obtained by measurements at known temperatures.

Neutron resonance thermometry is a powerful application; however, it has not been utilized as a common technique due to the limited number of neutron facilities having the high neutron energy resolution required for the resonance analysis. Neutron imaging beam lines at intense short-pulse neutron sources are expected to provide the opportunity to carry out neutron resonance thermometry taking full advantage of the high resolution of neutron energy obtainable by the time-of-flight technique. In this study, the authors discuss such principle parameters as reliability and temporal, spatial and temperature resolutions based on experimental results. The determination of these parameters is indispensable to promote neutron resonance thermometry for potential users.

2. Experiment

2.1. Experimental setup

The measurements were carried out using RADEN at J-PARC operating at 200 kW of proton beam power. Two-dimensional distributions of neutrons transmitted through a tantalum (0.1mm in thickness) or a tungsten (1 mm in thickness) sheet (Fig. 1 (left)) were measured by the gas-electron multiplier (GEM) neutron detector developed by Uno et al. (2012). Tantalum and tungsten were selected as temperature indicators due to the fact that they possess sharp resonances at lower energies. The lowest resonance energies are 4.28 eV for tantalum and 4.15 eV for tungsten. Unnecessary thermal and cold neutrons were eliminated by a cadmium filter, and the T_0 and disk choppers were not used. The distances from the neutron source to the detector and from the sample to the detector were about 24 m and 0.77 m, respectively. The neutron shutter and the rotary collimators were set to provide the highest neutron intensity (L/D was 240). The neutron beam was collimated to about 55×55 mm^2 just upstream of the sample by boron-containing polyethylene blocks. Figure 1 (center) shows the two dimensional distribution of transmitted neutrons between 4.14 and 4.29 eV covering both resonances of tantalum and tungsten.

The tantalum and tungsten sheets were set inside a vacuum quartz tube (inner diameter: ca. 36 mm) of a furnace (Fig. 1 (right)) having an Inconel heater surrounded by a gold-coated reflector. The temperature of the samples

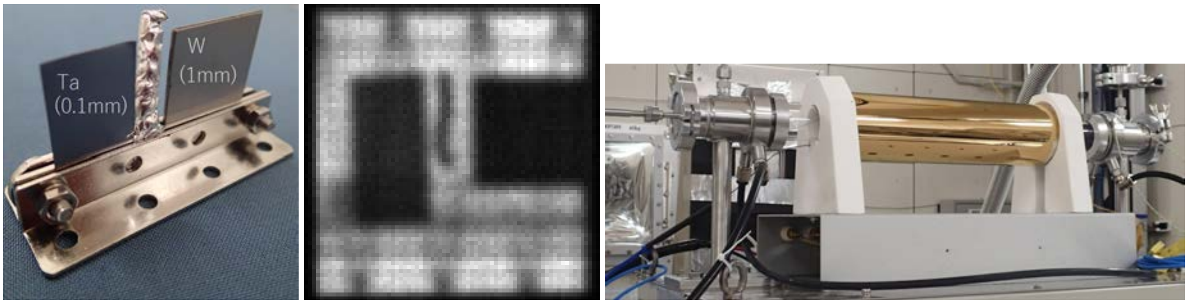

Fig. 1. Tantalum and tungsten sheets (left), transmission image of neutrons between 4.14 and 4.29 eV (center) and photograph of furnace (right). Tungsten carbide balls (3 mm in diameter), located between the tantalum and tungsten sheets, are not used in this study.