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Two-dimensional Thermometry by Using Neutron Resonance Absorption Spectrometer DOG

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Abstract

We applied the neutron resonance absorption spectroscopy to thermometry of a bulk object. The measurement was done by using the neutron resonance absorption spectrometer, DOG, installed at KENS, High Energy Accelerator Research Organization Neutron Source, which enables us to investigate effective temperature of a particular element by analyzing line width of resonance absorption spectrum. The effective temperature becomes consistent with the sample temperature above room temperature. For the analysis we applied the computed tomography method to reconstruct the temperature distribution on the object cross section. The results and the calculated distribution by the heat conducting equation are well agreed on the temperature difference inside the object.

1. Introduction

Neutron resonance absorption spectroscopy (N-RAS) is a method which measures the dynamics of atoms by analyzing the Doppler broadening of their resonance spectra. The method enables us to investigate motions of a particular element, because the resonance energies are peculiar to the element[1]. Some of the resonance absorption cross sections are very large values, then the method has very high sensitivity. ⁷³Ta has 13000 barns at 4.28 eV, for example. From the character, N-RAS can be applied to the microchemical analysis or dynamical analysis of the small amount components.

The measurement is done by recording the prompt gamma ray from the absorption phenomenon. From the resonance absorption

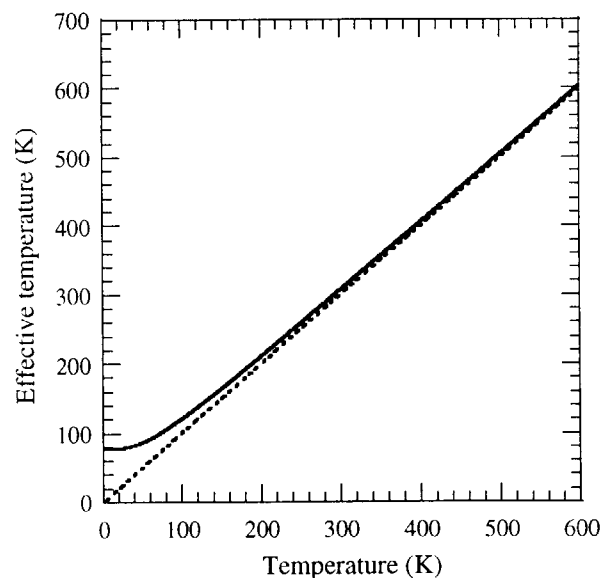


Fig. 1. Effective temperature of Ta (solid line). The line is calculated by using the Debye model with $\theta_D = 240$ K. The dashed line is a guide to eyes.

spectrum, we can obtain a parameter which called effective temperature, T_{eff} . T_{eff} has a trend to coincide with the real temperature of the sample above sufficiently high temperature as shown in figure 1. By using this feature, we have tried to measure the temperature of a sample object, and deduced the temperature distribution over the cross section in the object by the computational method.

2. Experimental

The measurements were carried on the neutron resonance absorption spectrometer DOG installed in KENS at High Energy Accelerator Research Organization (KEK) in Japan. Figure 2 shows the schematic layout of DOG. DOG is set up at the thermal source port and its flight path length to the sample is 9.53 m. The sample absorbs neutrons with a resonance energy E_R and then emit the prompt gamma ray by (n, γ) reaction. Plastic scintillators installed both sides of the sample detect the gamma rays and the events are recorded by time analyzers. The time analyzer has a time channel width of 31.25 ns and a number of channels of 16000. The absorbed neutron energy is determined by the time-of-flight method. The energy resolution of the DOG was governed by incident neutron pulse width and neutron flight time and $\Delta E/E = 0.38\%$ in the energy range of more than 1 eV.

Figure 3 shows the apparatus of the measured sample. The sample object had a cylindrical shape of 20 mm diameter containing Ta atoms for the neutron resonance absorption. Inside the object there was the temperature gradient from the center of the cylinder to the rim, the temperature at the center was 380 K and the rim was 313 K. We obtained the resonance spectrum by irradiating neutrons against the object through a slit of 2 mm width. The slit was moved as 2 mm step for 10 times.

3. Analysis

Generally, the neutron resonance absorption cross section is usually expressed as Bethe and Placzek formula taking account of the Doppler effect[2]. It is applicable only to the ideal gas but invalid to solids. For this reason, Lamb has deduced a formula for the neutron resonance absorption cross section by using a weak binding approximation that treats a crystal as a Debye continuum[3]. The cross section is given by the equation,

$$\sigma(E) = \frac{\sigma_0 \xi}{2\sqrt{\pi}} \int dy \exp\left[-(\xi/2)^2(x-y)^2\right] / (1+y^2), \quad (1)$$

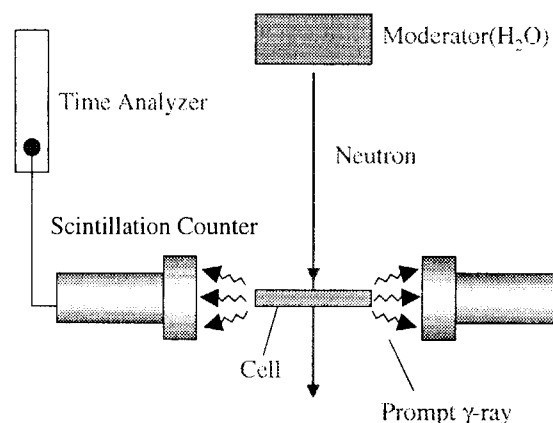


Fig. 2. Schematic layout of DOG spectrometer.

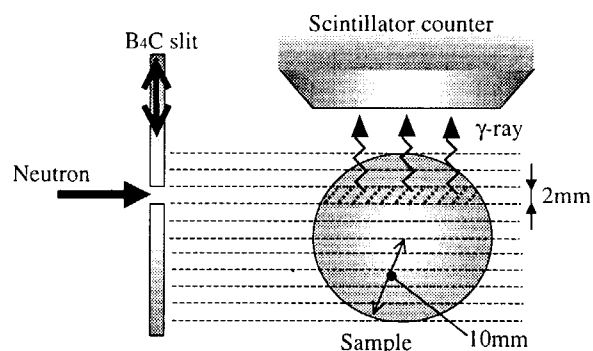


Fig. 3. Measured sample layout (top view).

$$x = 2(E - E_0 - R)/\Gamma_i, \quad \xi = \Gamma_i/\Delta,$$

$$R = (m/M)E_0, \quad \Delta = 2\sqrt{Rk_B T_{\text{eff}}},$$

where m and M are a neutron mass and a mass of absorbing atom, respectively. σ_0 is a peak value of cross section of a neutron absorption, k_B is the Boltzmann constant and R is recoil energy of the absorbing atom. The intrinsic line width Γ_i is defined as the full width at the half-maximum of the resonance level E_0 , and Δ is a Doppler width. T_{eff} , so-called effective temperature, is corresponding to the average energy for vibrational degree of freedom of the lattice (including zero-point energy). T_{eff} is defined as

$$k_B T_{\text{eff}} = \frac{1}{2} \int_0^\infty E f(E) \coth\left(\frac{E}{2k_B T}\right) dE, \quad (2)$$

where $f(E)$ is phonon density of states for the solid and T is temperature. If the absorption cross section of the crystal is represented by eq. (1), the probability of the neutron absorption in the matter is given by

$$P_a(E) = 1 - \exp[-N_d \sigma(E)], \quad (3)$$

where N_d is the number density of resonant absorbing atoms per unit area perpendicular to the neutron beam. The time-of-flight spectrum for the neutron resonance absorption $I_a(t)$ considering a shape of the neutron pulse $I_0(t)$ is given by

$$I_a(t) = \int dE dt_0 P_a(E) I_0(E; t_0) \delta(t - t_0 - l/v_R), \quad (4)$$

where l is the neutron flight path length from the neutron source to the sample. v_R is the neutron velocity for the resonance energy E_R [4]. By analyzing $I_a(t)$ we can obtain information about T_{eff} and finally also $f(E)$. Figure 4 shows time-of-flight spectrum of resonance peaks of Ta. These peaks are corresponding to the resonance energy of 4.28 eV of Ta at temperatures of 13 K and 300 K. The curves show the least square fittings for each neutron absorption spectrum. It is found that the resonance peak is broader and lower with increasing temperature because of the Doppler effect. We deduced the effective temperatures from these resonance peaks. The fitting curves are also superimposed in figure 4. We can see that the curves agree with the measured spectra very well.

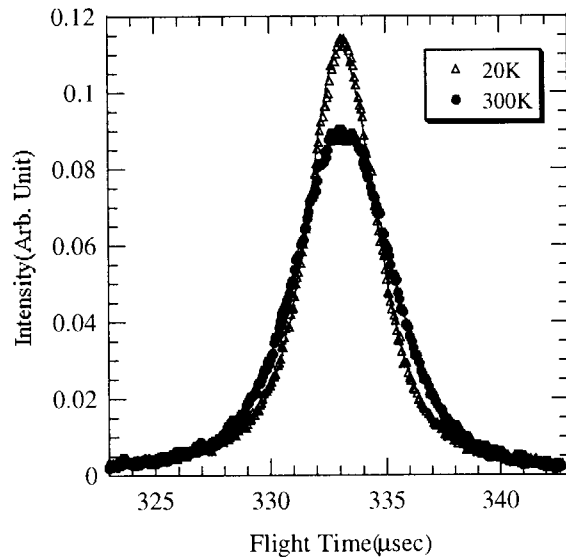


Fig. 4. Time-of-flight spectra of the resonance peak of Ta. These spectra (open triangles: 20 K, closed circles: 300 K) are corresponding to the resonance energy of 4.28 eV. Lines are the results of fitting by eq. (4).

4. Results and Discussions

The fitting results of T_{eff} are shown in figure 5. We have done the correction for the sample thickness[5]. The measured T_{eff} shows a step-like change against the slit position for the sample object. This feature becomes from the cause that the measured spectra are the averaged ones over the neutron-irradiated area. Then we apply the computed tomograph (CT) method to calculate the temperature distribution in the object cross section from the results. The 2-dimensional temperature distribution can be written by the 2-parameters function $g(p, q)=f(x, y)$, where (p, q) means the position in the object cross section on the spectrometer coordination and (x, y) means the position on the object coordination. In the present apparatus, measured spectrum at the each slit position is the integrated one along the neutron beam.

$$a_{\phi}(p) = \int_{-\infty}^{\infty} g(p, q) dq. \quad (5)$$

Here, ϕ means the rotational angle between the object coordination and the spectrometer coordination. Eq. (5) corresponds to the layout that the neutron beam comes along the q -axis. Considering the equation of the 2-dimensional Fourier transformation,

$$\Lambda(\xi, \eta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(p, q) \exp[-2\pi i(\xi p + \eta q)] dp dq, \quad (6)$$

the Fourier transformation of $a_{\phi}(p)$ can be written as

$$\begin{aligned} A_{\phi}(\xi) &= \int_{-\infty}^{\infty} a_{\phi}(p) \exp(-2\pi i \xi p) dp \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(p, q) \exp(-2\pi i \xi p) dp dq \\ &= \Lambda(\xi, 0). \end{aligned} \quad (7)$$

We can fill up the data of Λ on the ξ - η space by the operation of ϕ rotation. Finally we get the 2-dimensional temperature distribution by inverse Fourier transformation,

$$g(p, q) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Lambda(\xi, \eta) \exp[2\pi i(p\xi + q\eta)] d\xi d\eta. \quad (8)$$

As the temperature gradient has a cylindrical symmetry in our present sample object, we interpolate the step-like data into 2-dimensional function, Λ , and calculate the 2-dimensional

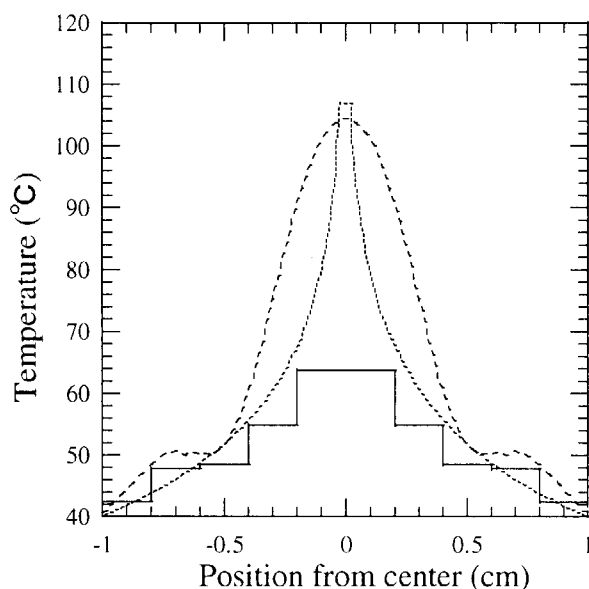


Fig. 5. Temperature distributions in the sample object. The solid line indicates the fitting results of T_{eff} . The Fourier transformation of T_{eff} is shown by the broken line, which corresponds to the temperature distribution along the diameter. The dotted line is the calculated distribution by using the heat conducting equation along the diameter.

temperature distribution, g , according to eq. (8). The reconstructed distribution is also shown in figure 5. The reconstructed result becomes higher temperature than the measured one over every position, because the measured temperature is averaged in the area formed by the slit width (2 mm) and the object thickness.

During the measurement the temperature was held at 380 K at the center of the object and 313 K at the rim, respectively. We can calculate the temperature gradient in the object cross section analytically by using the heat conducting equation,

$$t(x) = t_1 - \frac{t_1 - t_2}{\ln(d_2/d_1)} \ln \frac{d(x)}{d_1}. \quad (9)$$

t and d mean temperature and distance from the cylinder center. Subscript 1 and 2 correspond the positions inside the cylinder. The calculated gradient is shown in figure 5, too. The temperature distribution by the CT method and the one after eq. (9) become well agreement on the temperature difference between the center and the rim, but there still remains large discrepancy in the peak width around the object center. The experimental result is affected by the slit size and the sample thickness. We are checking the effect by simulation calculations now, and planning to carry on the improved experiment.

5. Conclusion

We applied the neutron resonance absorption spectroscopy to thermometry of a bulk object. By using the Fourier transformation computational tomography method, we can obtain the 2-dimensional temperature distribution tomogram in the object cross section. The result shows well agreement in the temperature difference inside the object with the heat conducting calculation. Now we are doing some simulations to realize the effect of the apparatus of the slit, object, etc. We consider that this method becomes important in the neutron application, because this will be able to apply to the nondestructive analysis of the temperature and element distributions at the same time in future.

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