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Temperature dependent characteristics of neutron signals from a current-biased Nb nanowire detector with ^{10}B converter

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Abstract. We are developing a new type of the neutron imager based on a superconducting neutron detector. We previously succeeded in constructing and demonstrating neutron detection capability of a superconducting current-biased kinetic inductance detector (CB-KID). In order to improve the spatial resolution and detection efficiency, the characteristics of a superconducting neutron detector have been studied systematically in the present work. As an extension of studying the characteristics of neutron detector, we investigated temperature dependence of neutron signal such as propagation velocity and the signal amplitude as a function of time of flight (ToF) with temperature. We consider that it is important to understand the temperature dependence of the signal to improve the spatial resolution and detection efficiency of a superconducting neutron detector.



1. Introduction

Neutron imaging has been recognized as a powerful technique in conducting non-destructive analysis in the wide areas such as science, medical field, and industrial technology to study the properties of materials, product components, and various systems without causing damage. Since the neutron beam can penetrate deeply into most materials except hydrogen, lithium and boron. Therefore, neutron imaging is in many instances suitable than X-ray or gamma-ray imaging because some matters are more visible with neutron beams whenever it is almost impossible to see with X-ray imaging techniques. Neutron imaging in non-destructive transmission imaging, tomography, dark-field image and visualization of magnetic-field distribution has been applied to various materials [1], intermetallic alloys [2], fuel cells [3], lithium ion batteries [4], cultural heritages [5], and others. The study of neutron imaging was started in the late nineteen thirties and the neutron radiographs of reasonable quality were first taken by Thewlis in UK in 1955 [6]. In recent decades, neutron-imaging technology has been developed rather rapidly to achieve high resolution, energy-dispersive imaging and high-speed readout system. The neutron imagers are known as a photographic-film detector [7], a scintillator-and-storage-phosphor detector [5], a gas neutron detector [8,9], a semiconductor (solid-state) detector [10].

Our work aims at obtaining a neutron imager with high-spatial resolution, high sensitivity, high temporal resolution, and high-speed measurement instrumentation by constructing a new delay-line current-biased kinetic inductance detector (CB-KID) system. The CB-KID system consists of an orthogonal X- and Y-meanderlines and an enriched ^{10}B neutron absorption layer superimposed on top of CB-KID [11–13]. Koyama and Ishida [14] proposed a theory of the signal propagation along a superconducting waveguide having an S-I-S structure within the framework of the London-Maxwell theory to explain operating mechanism of the CB-KID. They predicted the propagation velocity as a function of temperature, of which we would like to verify the validity of the theoretical prediction of the propagation velocity. We also intend to study the temperature-dependent characteristics of neutron signals, i.e., the signal height and the signal width as a function of detector temperature. We design the superconducting neutron detector with eight layers by a computer-aided-design software (Layout Editor) to fabricate the superconductive device at the Clean Room for Analog-Digital-Superconductivity (CRAVITY) of the National Institute of Advanced Industrial Science and Technology (AIST). We use a Gifford-McMahon (GM) cryocooler to cool down a neutron detector. The temperature of detector is controlled by a temperature controller (Cryocon Inc.) using a LabVIEW program.

2. Operation principle of neutron detector

A neutron detector is constructed by a pair of X- and Y-CB-KIDs [11–13], orthogonal to each other, which consist of superconducting-nanowire meanderlines (Fig.1(a)) and a ^{10}B layer working as a neutron particle converter (Fig.1(b)). A pulsed voltage signal is generated by a local transient change in n_s induced by the nuclear reaction between a ^{10}B nucleus and an incident neutron through a change in local kinetic inductance L_k in a superconducting wire. The kinetic inductance L_k is expressed by

$$L_k = m_s l / n_s q_s^2 S \quad (1)$$

where m_s is the effective mass of the Cooper pair, q_s is the electric charge of the Cooper pair, n_s is the Cooper pair density, l is the length of stripline, and S is the cross-sectional area of superconducting nanowire. A nuclear reaction mainly produces a 1.47-MeV ^4He particle and a 0.88-MeV ^7Li particle, of which one particle reaches the Nb nanowire to create a hot spot in a stripline of the detector, where a rapid reduction of n_s occurs locally at a tiny spot of stripline with a length Δl ($\ll l$) to yield a transient change in L_k . According to equation (2), a pair of pulsed-voltage signals are generated in the stripline biased by the DC current while the sign (polarity) of the signal is dependent on the current direction and the propagation direction. The pulsed-voltage signal (Fig. 1(c)) propagates as an electromagnetic wave pulse along the stripline (meanderline) toward one of the end electrodes with an opposite polarity and the electromagnetic wave is always confined in between the superconducting meanderline and superconducting ground plane as a Swihart wave [14,15]. After the output signals from CB-KID were amplified by ultra-low noise amplifiers, the position (x,y) of neutron nuclear event was evaluated with the aid of a time-to-digital converter (TDC) of the Kalliope-DC readout circuit. By combining two X and Y meanderlines, orthogonal to each other, we can detect a correct position of neutron beam arrival by using equation (3) (see below).

Phenomenological, the voltage V across the hot spot (Fig. 1(c)) is expressed as

$$V = I_b \left(\frac{dL_k}{dt} + \frac{dL_m}{dt} \right) + (L_k + L_m) \frac{dI_b}{dt} \simeq I_b \frac{dL_k}{dt} \quad (2)$$

where the magnetic inductance L_m is kept constant with time and $dI_b/dt \simeq 0$ as far as the detector remains in the superconducting state. As shown in Fig. 1 (b), the hot spots are created by a charged particle emitted from the neutron reaction in both the X meanderline and the Y meanderline. A pair of a positive signal and a negative signal start to propagate toward the opposite electrodes. The negative signal is inverted by using a differential amplifier. As shown in Fig. 1 (c), we can measure the differences in the timestamps Δt_x and Δt_y of pulsed signals arrived at anode electrode and cathode electrode of X, Y meanderline. Therefore, the position of a nuclear event (x, y) is calculated as

$$\begin{cases} x = \text{ceil} \left(\frac{\Delta t_x v_x}{2h_x} \right) p_x \\ y = \text{ceil} \left(\frac{\Delta t_y v_y}{2h_y} \right) p_y \end{cases} \quad (3)$$

where the origin of a coordinate is at the center of a detector, p_x, p_y are the repetition pitches for the X, Y meanderline; v_x, v_y are velocities of neutron pulsed in x, y meanderline; h_x, h_y are the lengths of a single-microstrip segment in X, Y meanderline. The ceil is a function to give an integer of the operand. In our neutron detector, we design $p_x = p_y = p$ and $h_x = h_y = h$ to obtain a square sensitive area of the detector. This also simplifies the imaging process in building neutron image.

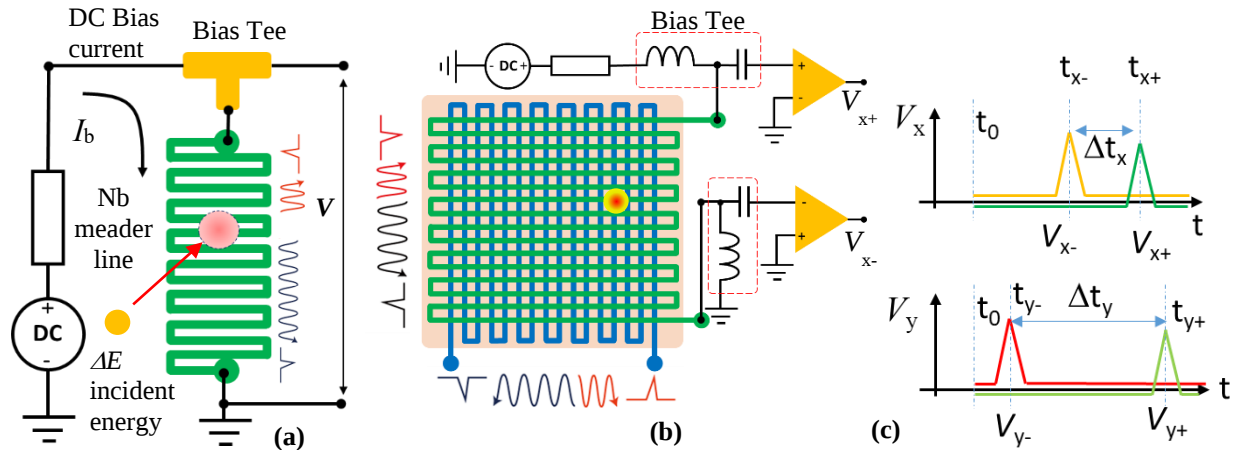


Fig 1 (a). A structure of single CB-KID with DC bias current; (b). The operating principle of delay-line CB-KID with two orthogonal meanderlines; (c) The schematic wave forms of the pulsed signals amplified by a non-inverted amplifier and an inverted amplifier to produce output signals with positive polarity. The event time t_0 should be the same in both the X and Y meanderlines.

3. Neutron detector and experimental details

3.1. Neutron detector

Fig. 2 (a) shows the schematic view of our delay-line CB-KID system while Fig. 2 (b) is a cross sectional image of the X-Y CB-KID system. Our superconducting neutron detector is designed by a computer-aided design (CAD) software (Layout Editor) so as to meet the requirement of AIST standard process. Fig. 2 (c) is a schematic drawing of a corner of our neutron detector CB-KID. The neutron detector consists of two superconducting nano-wires (X and Y) in a form of meanderlines. The neutron absorption layer consists of an assembly of very fine enriched ^{10}B particles, which were painted uniformly on top of the meanderlines in a form of ethanol solution of ^{10}B fine particles. Using this method, the thickness of the ^{10}B layer was thick enough more than $10\mu\text{m}$ compared to the ranges of ^4He and ^7Li particles. In fabrication, the turning points of X and Y meanderlines are rounded to ensure smooth propagations of the electromagnetic waves along the whole meanderline. In addition, the meanderline width is kept constant even at a turning point. This is to reduce the refraction of the pulsed signals by minimizing a

change in the matching impedance along the whole meanderline. Both the X and Y superconducting Nb meanderlines consist of 10000 microstripline segments of $0.9\text{-}\mu\text{m}$ width, and $0.6\text{-}\mu\text{m}$ spacing of segment-length 15 mm with a sensitive area as $15\times 15\text{ mm}^2$. The repetition period (pitch) is $1.5\text{ }\mu\text{m}$ while the total length of the meanderline extends to a scale of 151 m . Our detector consists of seven layers deposited on a thermally oxidized Si substrate as shown schematically in cross section [16] of Fig. 2 (b). We expect that the neutron detector would have the specification of high resolution of $15\times 15\mu\text{m}^2$ and megapixel imaging.

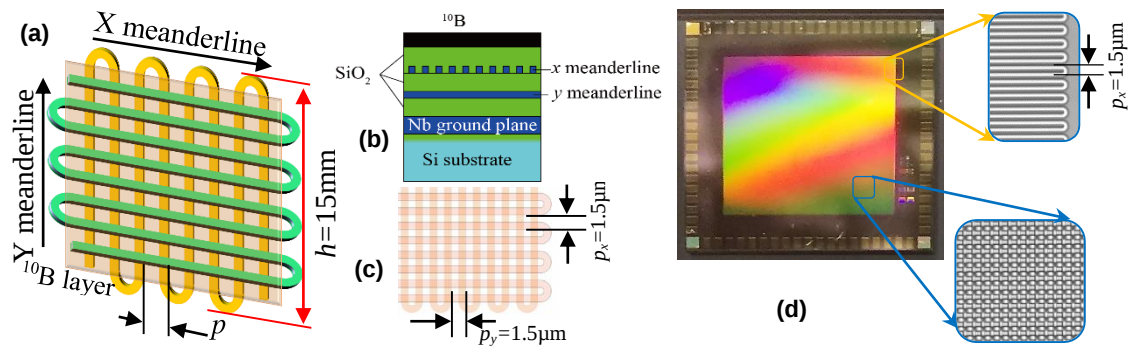


Fig. 2. (a) Schematic image of the CB-KID system. An X CB-KID meander is orthogonal to a Y CB-KID meander. The ^{10}B conversion layer is superimposed on the CB-KID system. (b) Schematic cross sectional image of the $X Y$ CB-KID system (c) Layout editor design image has the repetition pitch of x and y by $1.5\mu\text{m}$. (d) Photograph of a neutron detector fabricated by us and photographs taken by a laser microscope.

3.2. Experimental details

The superconducting neutron detector is cooled down to 4 K by using a Gifford–McMahon (GM) refrigerator to conduct a long-time measurement at a stable cryogenic temperature. A Cernox thermometer and a heater are installed in the neighbourhood of the neutron detector. The temperature of the CB-KID sensor is controlled by a temperature controller (Cryocon Model 42) using a LabVIEW program. Two DC adjustable voltage sources are used to feed a DC bias current to X and Y meanderlines. The DC currents of the X and Y detectors are adjusted to obtain proper amplitudes of pulsed voltages of neutron events, which are suitable to be measured by a high-speed digital oscilloscope and a time-to-digital converter (TDC) of the Kalliope-DC readout circuit [17]. The voltage signal from neutron event on the meanderline is amplified by a low-noise amplifier (NF SA-430F5) to feed the TDC module of the Kalliope-DC readout circuit or a 2.5-GHz sampling digital oscilloscope (Teledyne LeCroy HDO4104-MS). A signal pulse from the CB-KID was transmitted through SMA and MMCX connectors and semi-rigid cables to reduce noises in the cryostat.

4. Experimental results

4.1. Temperature dependence of propagation velocity

In the preceding studies, we have investigated the temperature-dependent characteristics of propagation velocity of a superconducting neutron detector both theoretically and experimentally [14,18]. Since the propagation of pulsed voltage along a meanderline would be important to confirm the operating principle of a neutron detector. We conducted the signal transmission measurement as was reported earlier [18], and we extended our investigation to the pulsed voltage amplitude as a function of temperature, where we controlled the temperature of Nb-wire meanderlines from 3.8 K to 8.3 K but did not feed a DC bias current to a superconducting Nb meanderline. We inputted a test pulse to one electrode of the meanderline and detected a transmitted signal after reaching the opposite electrode. The test pulse signal was created by using a digital function generator and a passive RC differentiation circuit with the repetition frequency of 100 kHz . The signal width of the output pulse from the differentiation circuit was determined by a rise time, and was much sharper than the original square wave of 100 ns width. The sharp pulsed signals were applied to X and Y meanderlines with the length ($l_x = l_y$) as 151 m , and the

same signal was fed to two short superconducting lines ($l_s \approx 0$) fabricated on the same CB-KID chip to compensate a possible delay caused by inside semi-rigid wiring in the cryostat. Four outputs of superconducting lines were connected to four channels of a high-speed oscilloscope. Since the relation of $l_x, l_y \gg l_s \approx 0$ is satisfied, the outputs of two short superconducting lines can be used to compensate the delay time of the cryostat wiring in evaluating a delay time in transmitting along meanderlines (see a start pulsed signal of the inset of Fig. 3 at $t = 0$). A difference between the output signal from a short superconducting line and the output signal from the meanderline, we calculated the propagation velocity of the pulsed signal along the superconducting nano-striplines. Figure 3 shows our experimental results (circle point curve) on the propagation velocity of a pulsed signal along a nanowire-stripline as a function of temperature. The propagation velocity of a pulsed signal decreases rapidly toward zero when the temperature increases very close to T_c . However, the propagation velocity is rather stable at lower temperatures. We understand that the propagation velocity depends on the structure of stripline, i.e., the thickness of insulating layer, the thickness of the nanowire, and the critical temperature T_c . The solid line of Fig. 3 is a least-squares fitting line of experimental results by the theoretical equation (4) derived by Koyama and Ishida [14] as

$$v = \frac{c}{\sqrt{\epsilon}} \sqrt{\frac{d}{d + \lambda_L(1 + \coth(s/\lambda_L))}} \quad (4)$$

where c is the speed of light in a vacuum, ϵ is the dielectric constant, d is the thickness of insulating layer, s is the thickness of the nanowire, respectively, T_c is the critical temperature and T is the temperature of superconducting nanowire, respectively. The London penetration depth can be approximated by the two fluid model as

$$\lambda_L(T) = \lambda_L(0)/\sqrt{1 - (T/T_c)^4} \quad (5)$$

In the inset of Fig. 3, we found that the amplitude of pulsed voltage also depends on the temperature of the striplines. Firstly, we notice that the amplitude of a pulsed signal after transmitting the

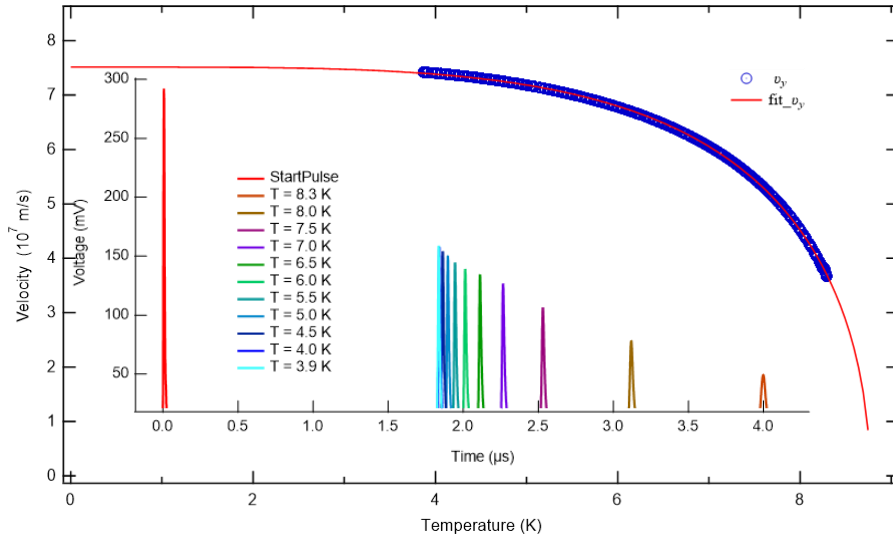


Fig. 3. Temperature dependence of propagation velocity and the transmitted signal of a pulsed voltage along the meanderline. The experimental results (open circles) on the propagation velocity of a pulse along the nano-stripline is shown as a function of temperature. The solid line is the fitting line with equation (4), where the parameters are $c = 2.99792458 \times 10^8$ m/s, $d = 300$ nm, $s = 40$ nm are fixed while others are the fitting parameters as $T_c = 8.6736 \pm 0.000341$ K, $\lambda(0) = 2.3121 \times 10^{-7} \pm 3.39 \times 10^{-10}$ m, $\epsilon = 2.0397 \pm 0.00473$. We find a good agreement between experimental observations and theoretical predictions. The inset shows a start-pulse as a function of time and the transmitted pulses from the meander.

meanderline is reduced compared with the “start pulse” at $t=0$ of the inset of Fig. 3. The transmitted pulsed voltage gives a smaller amplitude as the temperature increases toward the critical temperature of Nb nano-wire. Note that we did not apply the DC bias current to meanderline in conducting the velocity

measurements, and the pulsed voltage was fed from outside of CB-KID as an external signal. This is because the small DC bias current does not change the propagation velocity appreciably compared to the bias-free case. Therefore, the meanderline works as a superconducting transmission line. The temperature variation of the propagation velocity is primarily due to the reduction of the Cooper pairs in the superconducting nano-wire. As seen in the inset of Fig. 3, the amplitude of the transmitted signal decreases as the temperature increases toward to the critical temperature T_c . We consider that this is caused by energy dissipation due to excess quasi particles at higher temperatures.

4.2. Temperature dependence of pulsed voltage amplitude

To study the temperature-dependent characteristics of the superconducting neutron detector, we performed the experiment with the neutron beam. The experiment was conducted at the beam line 10 (BL10) of Materials and Life Science Division (MLF) of the J-PARC Center, Japan Atomic Energy Agency (JAEA). Pulsed neutron beam appears at 25-Hz repetition rate, and the start pulse of each pulsed neutron beam is available as the MLF trigger. The BL10 is intended to provide a suitable neutron environment for testing various novel detectors devices, and the ideas for novel experimental techniques. The experimental system is described in Fig. 1 (b). To obtain systematic characteristics of neutron signal, we collected data from the neutron signal by using the time-to-digital convertor (TDC) of the Kalliope-DC readout circuit and the high speed digital oscilloscope, where the temperature was controlled from 4.0 K to 7.5 K, the meanderline was biased by a DC current $I_b = 50\mu\text{A}$ and the number of MLF triggers was 2500 to accumulate data for the measurements at each temperature. Figure 4 shows the histogram of the peak voltage with the changing of detector temperature, which was taken by the high-speed 2.5 GHz oscilloscope with the time duration from 8 ms to 13 ms in the time-of-flight (ToF) after each MLF trigger pulse. We found that the peak voltage of neutron signal changes as a function of temperature. In the value of peak signal smaller than 5 mV, the amplitude of neutron signal almost does not change appreciably. We assume that this is the contribution of the noises in signal which is not so strongly affected by a change in temperature while the amplitude of neutron signal ($V_p > 5$ mV) increases clearly when the temperature of neutron detector approaches to the critical temperature of Nb. In order to explain the experimental results, Koyama and Ishida [19] studied the Ginzburg-Landau theory for the operation principle of superconducting delay-line inductance detectors which would be explained the changing of amplitude of neutron signal with temperature.

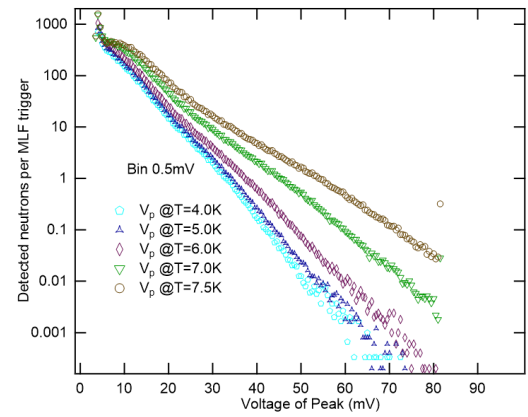


Fig. 4. The histogram of the peak voltage with changing temperature. The neutron intensity is evaluated for a given bin of 0.5 mV.

$$\hat{V}^{(\pm)}(Z^{\pm}) = K L W v^2 \int_0^{\infty} dr \left(1 - e^{-\frac{r}{v\tau_{qp}}} \right) \left(\frac{v\tau}{r} \right)^{\frac{3}{2}} \left(\frac{r - z^{(\pm)}}{x_h} \right) \times \exp \left[-\frac{r}{v\tau_z} - \frac{1}{2} \left(\frac{r}{v\tau_z} \right) \left(\frac{r - z^{(\pm)}}{x_h} \right)^2 \right] \cdot I \equiv \tilde{L}^{(\pm)}(Z^{\pm}) I \quad (6)$$

where $\hat{V}^{(\pm)}(Z^{\pm})$ are the voltage signals propagating in the $+x$ - and $-x$ -directions, with $z(\pm) = x \mp vt$, respectively; $K = (\lambda_L/c) \coth(s/\lambda_L)$; $W = q_0 \eta \xi^2 x_h / C_s$; L is inductance of meanderlines; v is the propagation velocity. The explicit expression for the voltage pulse is derived equation (6) which these expressions include the velocity v , K and W (see [19] for further details of notations).

As mentioned by Koyama and Ishida [14], the propagation velocity v is a function of temperature and K , W are also the functions of the London penetration depth. That is, these coefficients also cause the temperature dependence of the voltage pulse. We conclude that the amplitude of pulsed voltage is strongly affected by the temperature of superconducting meanderline. Detailed comparisons will be done in our future work.

In order to investigate the usefulness of the neutron detector as a function of time of flight (ToF) with changing temperature, we took the time-of-flight spectrum for each changing temperature by using the TDC module of the Kalliope-DC circuit. Note that ToF required for a 14-m flight path can be converted to neutron energy or wavelength. Fig. 5 (a) shows the signal intensity as a function of ToF with changing temperature. There is a clear difference in the event intensity as a function of time of flight (ToF) with changing temperature. The increase of signal intensity is strong when the temperature approaches to a

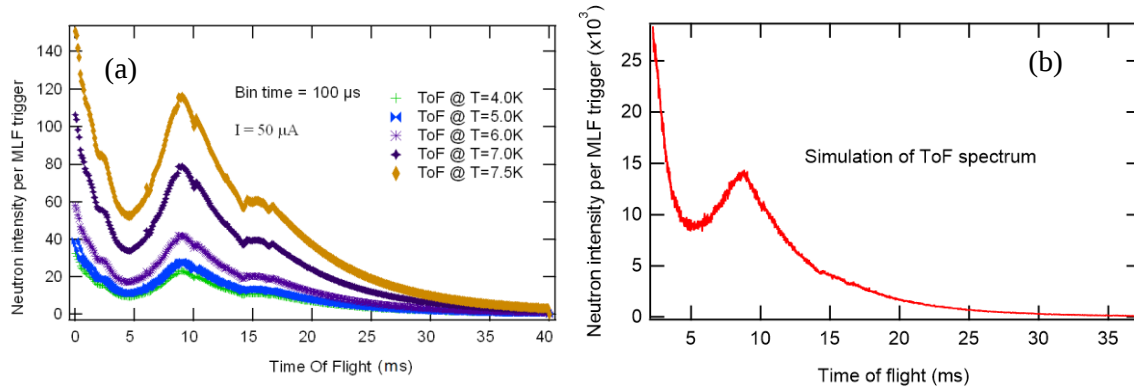


Fig 5. (a). Signal intensity as a function of ToF (time of flight) with changing temperature. (b) The simulated neutron flux as a function of ToF.

critical temperature. In order to improve the efficiency of our neutron detector, we compared the experimental ToF spectra at $T = 4.0$ K, 5.0 K, 6.0 K, 7.0 K, and 7.5 K with the predicted ToF spectrum obtained by simulations. Fig. 5 (b) shows the prediction of neutron intensity as a function of time of flight [20], of which the Monte Carlo particle and heavy ion transport code PHITS was used to deal with particle transport phenomena in a wide energy range. Detailed comparison with the prediction will be published elsewhere. The detection efficiency would be influenced by the $1/v$ law of the neutron absorption crosssection between ^{10}B and a neutron, where v is the velocity of incident neutron. In addition, the constituent materials near the CB-KID sensor also influence the shape of the neutron spectrum of Fig. 5 (a) from 5 ms to 20 ms. The important implication of Fig. 5 (a) is that we have to optimize the temperature of operating the superconducting neutron detector to enhance the detection efficiency of neutrons. Of course, the nuclear reaction rate does not depend on the detector temperature. Therefore, further theoretical studies on how the detector signal is created by the local heat dissipation on the superconducting meanderline. Our results suggest that the detector temperature is a key to enhance the detection efficiency of the CB-KID.

5. Summary

We systematically studied the temperature dependent characteristics of the neutron signal by using our superconducting neutron detector CB-KID. The temperature dependence of propagation velocity is in good agreement with the theoretical velocity derived by Koyama and Ishida. We observed the neutron signal of the CB-KID by using the beam line BL10 of Materials and Life Science Experimental Facility (MLF) of J-PARC. The features such as the peak voltage and the neutron intensity as a function of ToF revealed a strong temperature-dependent feature of the nanowire meanderline. The present results imply that the Ginzburg-Landau theory works well in explaining the operation principle of superconducting delay-line kinetic inductance detectors. Further understandings of the temperature-dependent features of superconducting neutron detector will be very important in order to improve the sensitivity and the resolution of our superconducting neutron detector.

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