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科研費 KAKENHI

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令和　６ 年　９ 月 １０ 日現在

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研究代表者
ＶＵ　ＴＨＥＤＡＮＧ（VU, THE DANG）

大阪公立大学・大学院工学研究科　・特任助教

研究者番号：６０８２６１２１

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研究成果の概要（和文）：超伝導検出器CB-KID動作原理を系統的に調べた。(1) 動作温度をT = 5K +/- 73uK で安定化し、遅延時間法による位置決め精度を向上させた。(2)測定試料をCB-KID検出器に密着して極低温に設置する必要があったが、クライオスタット再設計により試料をCB-KID素子に近い室温に設置することで様々な試料の測定が可能となった。 (3) CB-KID測定系を使って極低温試料で10μm、室温試料で24μmの分解能を実証した。(4)中性子のエネルギー1meV～500keVのエネルギーに対してスペクトロスコピィを可能とした。(4)興味ある測定試料の中性子透過像をとることに成功した。

研究成果の学術的意義や社会的意義
Our CB-KID method can be used for many scientific/industrial purposes such as (1) hydrogen embrittlement of steel, (2) imaging plant-soil systems, (3) water dynamics in cells, (4) magnetic domains in magnetism, (5) water removal efficiency from fuel cells, (5) ionic pulsation in Li batteries.

研究成果の概要（英文）：This project achieved the following things. (1) Stabilization of temperature was achieved as T = 5K +/- 73uK. Spatial resolution becomes better due to propagation velocity stability. (2) We built a new cryostat to mount a sample at room temperature. (3) We achieved the best resolution of 10um for a cryogenic-temperature sample and 24um for a room-temperature sample. (4) We can conduct the energy-resolving spectroscopy from 1meV to 500keV. (5) We conducted neutron transmission imaging using various interesting samples.　References: [1] T. Ishida, T.D. Vu, at al., J. Low Temp. Phys. 214, 152 (2024). [2] T.D. Vu, et al., Invited talks at 4th ICEBA2023 (Dec 8th 2023, HCM, Vietnam). [3] T.D. Vu et al., J. Phys. Conf. Ser. 2545, 012019 (2023). [4] H. Shishido, T.D. Vu, et al., J. Appl. Cryst. 56, 1108-1113 (2023).

研究分野：Physics and electronics

キーワード：Neutron detector　CB-KID　Neutron pulse　Neutron image

１．研究開始当初の背景

Neutron beams are sensitive not only to certain light elements, such as hydrogen, lithium, boron, carbon and oxygen, but also to exceptionally heavy elements with high neutron absorption cross-sections, such as gadolinium, samarium, europium and cadmium. The characteristics of experiments conducted using neutron beams are thus remarkably different from those using X-ray, electron or proton beams. Neutron imaging has been used as a non-destructive technique for investigating materials via transmission spectra, pore structures, and neutron tomography. High-ended neutron detectors are indispensable in enhancing system performances of the instrumental system.

The CB-KID system was proposed as a superconducting neutron detector. Its operating principle is somewhat similar to a superconducting single photon detector (SSPD), but in contrast to SSPD, CB-KID works even under a small bias current. A transient change in the density of electrons in the superconducting wire n_s occurs at a hot spot created by a passing charged particle. The CB-KID was proposed for neutron imaging. When used for neutron imaging, a ^{10}B conversion layer is needed to convert neutrons to charged particles, which in turn create hot spots in the meanderlines. London-Maxwell superconducting theory of CB-KID predicts that a negative pulse propagates in the downstream direction from the hot spot, while a positive pulse propagates upstream. A superconductor-insulator-superconductor planar structure in CB-KID provides an efficient waveguide to transmit electromagnetic pulse signals. This allows us a larger sensitive area of CB-KID as a neutron detector.

A spatial resolution for neutron imaging of 20 μm was reported using a scintillator camera detector using a CMOS sensor (D. S. Hussey *et al*., Nucl. Instruments Methods Phys. Res. A, **866**, 9 (2017)). A ^{10}B-doped multichannel plate was used for imaging with pulsed neutron sources with a resolution of 55 μm (A. S. Tremsin *et al*., Nucl. Instrum. Meth. Phys. Res. A **787**, 20 (2015)). Our group developed the current-biased kinetic inductance detector (CB-KID) and demonstrated resolution of 22 μm (H. Shishido *et al*. Phys. Rev. Appl. **10**, 044044 (2018)).

２．研究の目的

This project aims at understanding the operating principle of a 4-CH delay-line current-biased kinetic inductance detector (CB-KID) system. It is undoubtedly important to improve the detection efficiency of the CB-KID. We revealed that the number of neutron-detecting events remarkably increased when the operating temperature of the CB-KID detector increased toward the superconducting critical temperature. However, the detailed mechanism and underlining physics have not been elucidated yet. We plan to investigate systematic behavior of the CB-KID as a function of operating temperature by building a precise temperature-control system. We believe that my findings from this research will contribute to understand the operating principle of CB-KID for pioneering the way of ripple effect of CB-KID to various applications.

３．研究の方法

In **Fig. 1**, we show the instrumental system used for CB-KID neutron transmission studies. We played an important role in building this system, and we believe this system is useful and very crucial in conducting the present proposal. The first important equipment to develop a superconducting neutron imaging was a cryostat. The superconducting neutron detector is cooled down to 4K by a GM refrigerator which is working for long-time measurements under the stabilized temperature. In **Fig. 1**, a GM cryocooler was ready to mount a superconducting neutron detector CB-KID in conducting neutron imaging experiments.

We developed two independent measurement systems to check neutron-detector properties and to conduct the experiments under pulsed neutron beams. In order to acquire signals from neutron detector as timestamps of the signals, we use the Kalliope-DC circuit in combination with the delay-line CB-KID. A 12-bit oscilloscope (Teledyne LeCroy HDO4104-MS) with 2.5 GHz sampling is also used to assist a parameter tuning of the Kalliope readout circuit. The Kalliope-DC circuit acquires only the timestamps of the signals, and then is much more efficient to collect data without losing the pulsed neutrons at MLF (at 25 Hz) compared to the digital oscilloscope. We have enough knowledge to code a LabVIEW programing, which includes the recording of full waveforms of neutron pulse signals from CB-KID.

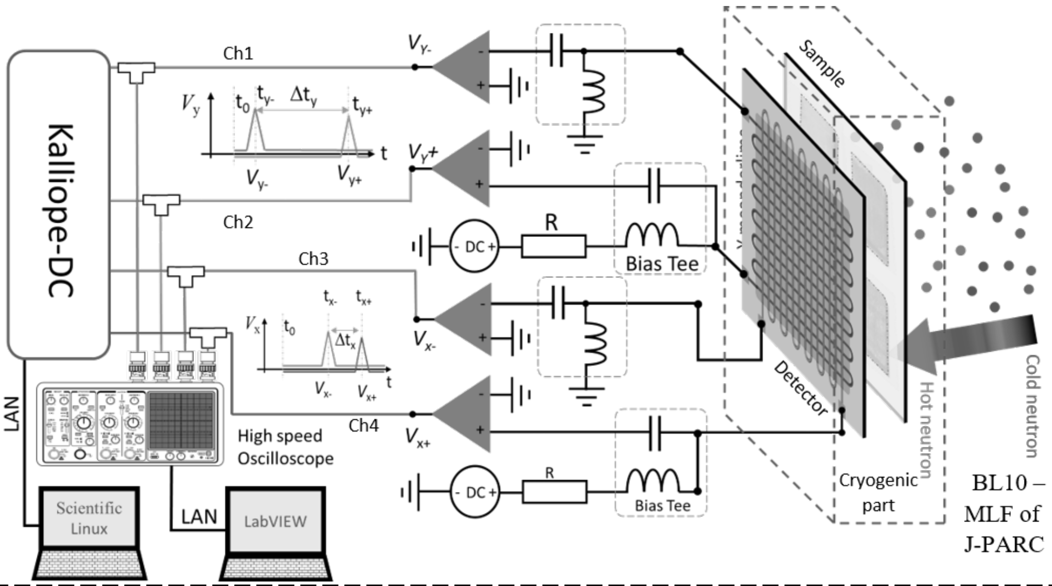

Fig. 1. Neutron imaging system with CB-KD for pulsed neutron beams at BL10 of the MLF of J-PARC. CB-KID. The X and Y-meanderlines are orthogonal to each other. Neutron signals from both ends of the two meanderlines are measured by the Kalliope-DC readout circuit and a digital oscilloscope. A temperature controller can improve the precision of the temperature stability.

We plan to improve the temperature stability for optimizing the detection efficiency at an optimized temperature and for pursuing the world-best spatial resolution of the neutron detector using a delay-line current biased kinetic inductance detector. The temperature controller (CRYOCON Model 54, AC resistance bridge) will be purchased by this budge to improve the temperature stability.

４．研究成果

We proposed a current-biased kinetic inductance detector (CB-KID) as a novel superconducting detector to construct a neutron transmission imager. We evaluated all results obtained in this project in view of publication missions and exploring new ideas for future studies. (1) To optimize neutron detectors, the stabilization of temperature very precisely as $T = 5\mathrm{K} \pm 73\mu\mathrm{K}$ was important to obtain high-resolution images under pulsed neutron. In preceding studies, we found the spatial resolution was dependent on the detector position at the central areas or at the detector edges. The delay-line technique is influenced by the propagation-velocity fluctuations in evaluating positions of the images. The temperature stability of neutron detector reduced such efforts appreciably. (2) We built a new cryostat to mount the test sample at room temperature [1]. This made it possible to apply our method to various different samples. (3) The characteristics of a superconducting neutron detector have been systematically studied to improve a spatial resolution down to $10\mu\mathrm{m}$ in transmission imaging. We achieved the best resolution of $10\mu\mathrm{m}$ using a cryogenic-temperature sample and $24\mu\mathrm{m}$ for a room-temperature sample. We can conduct the energy-resolving spectroscopy in the wide energy range from 1meV to 500keV [2]. We conducted neutron transmission imaging using various interesting samples. We conducted neutron transmission imaging for various samples such as $SmSn_3$ crystal, FeS_2 crystal, Ammonite Fe_2O_3, and Wood metal alloy [3], and $YbSn_3$ crystal [4].

REFERENCE

[1] T. Ishida, T.D. Vu, et al., J. Low Temp. Phys. 214, 152 (2024).

[2] T.D. Vu, et al., Invited talks at 4th ICEBA2023 (Dec 8th 2023, HCM, Vietnam).

[3] T.D. Vu et al., J. Phys. Conf. Ser. 2545, 012019 (2023).

[4] H. Shishido, T.D. Vu, et al., J. Appl. Cryst. 56, 1108-1113 (2023).

５．主な発表論文等

〔雑誌論文〕　計7件（うち査読付論文　7件／うち国際共著　7件／うちオープンアクセス　4件）

１．著者名 Dang Vu The、Shishido Hiroaki、Aizawa Kazuya、Oku Takayuki、Oikawa Kenichi、Harada Masahide、Kojima Kenji M.、Miyajima Shigeyuki、Soyama Kazuhiko、Koyama Tomio、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Machida Masahiko、Kawamata Shuichi、Ishida Takekazu	４．巻 2545
２．論文標題 Superconducting neutron transmission imaging for investigating a sequential change in phase separations of low-melting Wood's metal	５．発行年 2023年
３．雑誌名 Journal of Physics: Conference Series	６．最初と最後の頁 012019～012019
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1742-6596/2545/1/012019	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Shishido Hiroaki、Dang Vu The、Aizawa Kazuya、Kojima Kenji M.、Koyama Tomio、Oikawa Kenichi、Harada Masahide、Oku Takayuki、Soyama Kazuhiko、Miyajima Shigeyuki、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Kawamata Shuichi、Ishida Takekazu	４．巻 2545
２．論文標題 Crystalline Orientation of CaF2 window determined by Neutron Transmission Imaging using a Delay Line Current-Biased Kinetic-Inductance Detector	５．発行年 2023年
３．雑誌名 Journal of Physics: Conference Series	６．最初と最後の頁 012020～012020
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１．著者名 Shishido Hiroaki、Nishimura Kazuma、Vu The Dang、Aizawa Kazuya、Kojima Kenji M.、Koyama Tomio、Oikawa Kenichi、Harada Masahide、Oku Takayuki、Soyama Kazuhiko、Miyajima Shigeyuki、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Kawamata Shuichi、Ishida Takekazu	４．巻 31
２．論文標題 High Spatial Resolution Neutron Transmission Imaging Using a Superconducting Two-Dimensional Detector	５．発行年 2021年
３．雑誌名 IEEE Transactions on Applied Superconductivity	６．最初と最後の頁 1～5
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TASC.2021.3111396	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Vu The Dang、Shishido Hiroaki、Aizawa Kazuya、Oku Takayuki、Oikawa Kenichi、Harada Masahide、Kojima Kenji M.、Miyajima Shigeyuki、Soyama Kazuhiko、Koyama Tomio、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Malins Alex、Machida Masahiko、Ishida Takekazu	４．巻 2323
２．論文標題 Narrow-area Bragg-edge transmission of iron samples using superconducting neutron sensor	５．発行年 2022年
３．雑誌名 Journal of Physics: Conference Series	６．最初と最後の頁 012028～012028
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1742-6596/2323/1/012028	査読の有無 有
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１．著者名 Shishido Hiroaki、Vu The Dang、Aizawa Kazuya、Kojima Kenji M.、Koyama Tomio、Oikawa Kenichi、Harada Masahide、Oku Takayuki、Soyama Kazuhiko、Miyajima Shigeyuki、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Kawamata Shuichi、Ishida Takekazu	４．巻 2323
２．論文標題 Neutron Imaging toward Epithermal Regime using a Delay Line Current-Biased Kinetic-Inductance Detector	５．発行年 2022年
３．雑誌名 Journal of Physics: Conference Series	６．最初と最後の頁 012029～012029
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1742-6596/2323/1/012029	査読の有無 有
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２．論文標題 Orientation mapping of YbSn3 single crystals based on Bragg-dip analysis using a delay-line superconducting sensor	５．発行年 2023年
３．雑誌名 Journal of Applied Crystallography	６．最初と最後の頁 1108～1113
掲載論文のDOI（デジタルオブジェクト識別子） 10.1107/S1600576723005204	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Ishida Takekazu、Vu The Dang、Shishido Hiroaki、Aizawa Kazuya、Oku Takayuki、Oikawa Kenichi、Harada Masahide、Kojima Kenji M.、Miyajima Shigeyuki、Koyama Tomio、Soyama Kazuhiko、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Machida Masahiko、Kawamata Shuichi	４．巻 214
２．論文標題 Neutron Transmission CB-KID Imager Using Samples Placed at Room Temperature	５．発行年 2024年
３．雑誌名 Journal of Low Temperature Physics	６．最初と最後の頁 152～157
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10909-023-03030-9	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計7件（うち招待講演　2件／うち国際学会　7件）

１．発表者名 The Dang Vu, Hiroaki Shishido, Kazuya Aizawa, Takayuki Oku, Kenichi Oikawa, Masahide Harada, Kenji M. Kojima, Shigeyuki Miyajima, Kazuhiko Soyama, Tomio Koyama, Mutsuo Hidaka, Soh Y. Suzuki, Manobu M. Tanaka, Masahiko Machida, Shuichi Kawamata and Takekazu Ishida
２．発表標題 Experimental Studies on Spatial Resolution of a Delay-Line Current-Biased Kinetic-Inductance Detector
３．学会等名 the 3rd International Workshop on Engineering Physics, IC-MEMS-Sensors and Their Applications, HCM city, Viet Nam, November 25&26, 2022（招待講演）（国際学会）
４．発表年 2022年

１．発表者名 The Dang Vu, Hiroaki Shishido, Kazuya Aizawa, Takayuki Oku, Kenichi Oikawa, Masahide Harada, Kenji M. Kojima, Shigeyuki Miyajima, Kazuhiko Soyama, Tomio Koyama, Mutsuo Hidaka, Soh Y. Suzuki, Manobu M. Tanaka, Masahiko Machida, Shuichi Kawamata and Takekazu Ishida
２．発表標題 Superconducting neutron transmission imaging for investigating a sequential change in phase separations of low melting Wood’s metal
３．学会等名 The 35th International Symposium on Superconductivity (ISS2022)（国際学会）
４．発表年 2022年

１．発表者名 Hiroaki Shishido, The Dang Vu , Kazuya Aizawa , Kenji M. Kojima , Tomio Koyama , Kenichi Oikawa, Masahide Harada , Takayuki Oku, Kazuhiko Soyama, Shigeyuki Miyajima , Mutsuo Hidaka , Soh Y. Suzuki, Manobu M. Tanaka , Shuichi Kawamata and Takekazu Ishida
２．発表標題 Crystalline Orientation of CaF2 window determined by Neutron Transmission Imaging using a Delay Line Current-Biased Kinetic-Inductance Detector
３．学会等名 The 35th International Symposium on Superconductivity (ISS2022)（国際学会）
４．発表年 2022年

１．発表者名 Vu The Dang、Shishido Hiroaki、Aizawa Kazuya、Oku Takayuki、Oikawa Kenichi、Harada Masahide、Kojima Kenji M.、Miyajima Shigeyuki、Soyama Kazuhiko、Koyama Tomio、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Malins Alex、Machida Masahiko、Ishida Takekazu
２．発表標題 Narrow-area Bragg-edge transmission of iron samples using superconducting neutron sensor
３．学会等名 The 34th International Symposium on Superconductivity (ISS2021)（国際学会）
４．発表年 2021年

1．発表者名 Shishido Hiroaki、Vu The Dang、Aizawa Kazuya、Kojima Kenji M.、Koyama Tomio、Oikawa Kenichi、Harada Masahide、Oku Takayuki、Soyama Kazuhiko、Miyajima Shigeyuki、Hidaka Mutsuo、Suzuki Soh Y.、Tanaka Manobu M.、Kawamata Shuichi、Ishida Takekazu
2．発表標題 Neutron Imaging toward Epithermal Regime using a Delay Line Current-Biased Kinetic-Inductance Detector
3．学会等名 The 34th International Symposium on Superconductivity (ISS2021)（国際学会）
4．発表年 2021年

1．発表者名 The Dang Vu, Hiroaki Shishido, Kazuya Aizawa, Takayuki Oku, Kenichi Oikawa, Masahide Harada, Kenji M. Kojima, Shigeyuki Miyajima, Kazuhiko Soyama, Tomio Koyama, Mutsuo Hidaka, Soh Y. Suzuki, Manobu M. Tanaka, Masahiko Machida, Shuichi Kawamata, Takekazu Ishida.
2．発表標題 Application of energy-resolving neutron imaging to major-component analyses of materials using four-channel superconducting detector
3．学会等名 The 4th International Conference on Engineering Physics, MEMS-Biosensors and Applications (4th ICEBA2023), Dec 8, 2023（招待講演）（国際学会）
4．発表年 2023年

1．発表者名 The Dang Vu, Hiroaki Shishido, Kazuya Aizawa, Takayuki Oku, Kenichi Oikawa, Masahide Harada, Kenji M. Kojima, Shigeyuki Miyajima, Kazuhiko Soyama, Tomio Koyama, Mutsuo Hidaka, Soh Y. Suzuki, Manobu M. Tanaka, Masahiko Machida, Shuichi Kawamata, Takekazu Ishida
2．発表標題 Neutron transmission imaging system with a superconducting kinetic inductance detector
3．学会等名 The 36th International Symposium on Superconductivity (ISS2023), Nov 29, 2023（国際学会）
4．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関