AFRL-AFOSR-VA-TR-2022-0010

New Superconductors near Broken Rotational Symmetry Instabilities

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10/24/2021
Final Technical Report

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
24-10-2021	Final	01 Jul 2017 - 30 Jun 2021

4. TITLE AND SUBTITLE
New Superconductors near Broken Rotational Symmetry Instabilities

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-17-1-0217

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Jiun-Haw Chu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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SEATTLE, WA
US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTA1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2022-0010

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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a striking transport-structural correspondence of the nematic state in the iron pnictide superconductors. It also uncovered an unusual coupling between the Eu and Fe moments in the Eu based iron pnictides. During the four-year report period, we have total 5 publications,

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			KENNETH GORETTA
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	4	426-7349

Standard Form 298 (Rev.8/98)
Prescribed by ANSI Std. Z39.18

AFOSR-YIP Final Report

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Principle Investigator: Jiun-Haw Chu (Department of Physics, University of Washington, Seattle, WA 98195)

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Narrative

High temperature superconductivity emerges in the vicinity of rotational symmetry-breaking instabilities in the iron-based and copper-based materials. It has been argued that the superconducting paring might be enhanced by the quantum critical fluctuations with a nematic character. In this four-year research program, we have made significant progress towards the understanding and the application of this idea. We discovered a new mechanism to control superconductivity by suppressing the nematic fluctuations with an anisotropic strain. We also developed a new experimental platform, the elasto x-ray diffraction, to study the electron-lattice coupling of the broken rotational symmetry phase. The elasto x-ray diffraction revealed a striking transport-structural correspondence of the nematic state in the iron pnictide superconductors. It also uncovered an unusual coupling between the Eu and Fe moments in the Eu based iron pnictides.

During the four-year report period, we have total 5 publications, including one Nature Materials, one Nature Physics and one Nature Communications. Below we present a summary of research highlights.

a. Drastic suppression of superconductivity near a nematic quantum critical point (Nature Physics 2020)

Most unconventional and high temperature superconductors share a similar phase diagram. As the system is tuned by chemical doping or pressure, superconductivity emerges as a nearby symmetry breaking phase is suppressed. The empirical observation of this common phase diagram has led to the belief that the fluctuations associated with the symmetry breaking phase are beneficial, if not responsible, for the superconducting pairing. A direct test to verify this hypothesis is to observe the decrease of superconducting T_c by applying the symmetry breaking conjugate field that suppresses the dynamic fluctuations of the competing order. Nevertheless, most of the competing phases in unconventional superconductors break translational symmetry, which requires a spatially modulated conjugate field that is difficult to realize experimentally. In this work, we show that anisotropic strain, the conjugate field of nematicity, drastically suppresses the superconducting T_c of an iron pnictide superconductor. We discovered a fivefold reduction of T_c for the optimally doped samples for less than one percent of strain, whereas for the underdoped samples the suppression of T_c extends to zero temperature with the recovery of a fully metallic ground state. In addition to providing direct evidence of the role played by the nematic fluctuations in the formation of the superconducting state, these results also demonstrate tunable mechanical control of a high temperature superconductor, an important step forward regarding the technological applications of superconductivity, as well as provide a new platform for studying a superconductor to metal

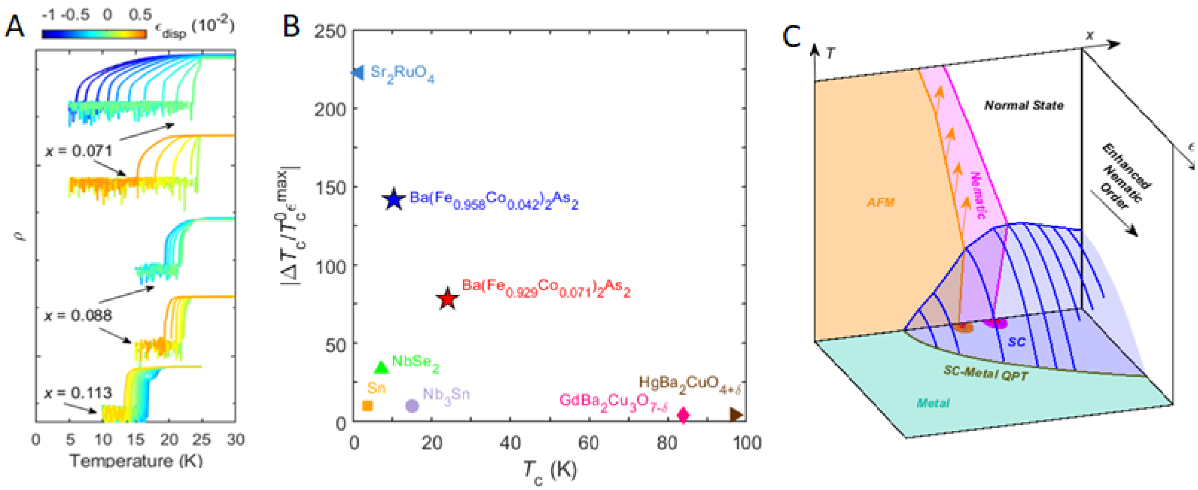

Fig. 1 Suppression of superconductivity by anisotropic strain (A) Resistivity as a function of temperature under uniaxial stress for optimally and overdoped compositions. Resistivity is on a log scale and sets of curves that overlap are offset for clarity **(B)** Sensitivity of T_c to strain for a variety of superconductors. (C) Schematic doping-strain-temperature (x-ϵ-T) phase diagram.

quantum phase transition in a three-dimensional system.

b. The transport structural correspondence across the nematic transition probed by elasto x-ray diffraction (Nature Materials 2021)

Electronic nematicity in iron pnictide materials is coupled to both the lattice and the conducting electrons, which allows both structural and transport observables to probe nematic fluctuations and the order parameter. A key question is in what regime one can establish a one-to-one correspondence between transport and structural variables. This question is especially important for 2D systems such as graphene where thermodynamic measurements are difficult. It also has important implications to the nearby superconducting phase, since the transport measurements probe the conducting electrons that form copper pars. In this work, we combine simultaneous transport and x-ray diffraction measurements with in-situ tunable strain (elasto-XRD) to measure the temperature dependence of the shear modulus and elastoresistivity above the nematic transition and the spontaneous orthorhombicity and resistivity anisotropy below the nematic transition, all within a single sample of $Ba(Fe_{0.96}Co_{0.04})_2As_2$. With our unprecedented multi-modal measurement, we show the four quantities perfectly follows a mean-field temperature dependence. Furthermore, the ratio of transport to structural quantities is a constant across the phase transition, suggesting that the resistivity anisotropy behaves just like a thermodynamic variable even for large values of the nematic order parameter. While the shear modulus and elastoresistivity and the spontaneous orthorhombicity and resistivity anisotropy can be well described by the Landau free energy framework, two unexpected findings stand out. First, using the shear modulus and elastoresistivity data from the previous studies, we discovered a strong doping dependence of the ratio between transport and structural quantities, increasing by more than fivefold towards optimal doping. Second, when driving the system deep into the non-linear regime with large uniaxial stress, we found that the resistivity anisotropy shows a non-saturating behavior that is drastically different from the dampened response of the lattice, which may reveal the intertwined nature of nematicity.

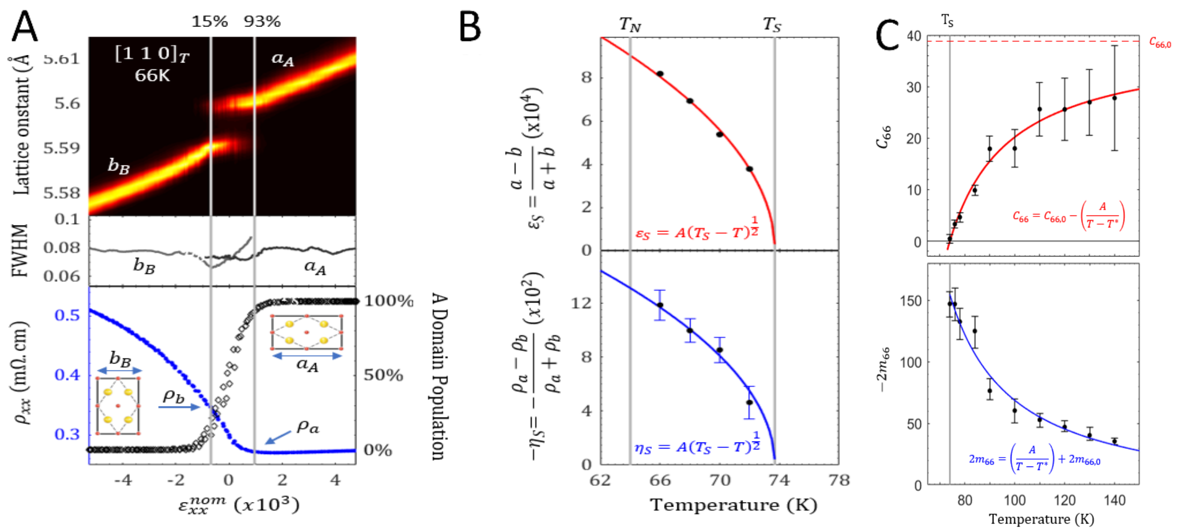

Fig. 2 Elasto X-ray diffraction measurement (A) Simultaneous x-ray diffraction (upper) and resistivity (lower, blue curve) measurement as a function of strain. These measurements allow us to extract spontaneous lattice distortion (B, upper), resistivity anisotropy (B, lower), shear modulus (C, upper) and elastoresistivity (C, lower) all in one sample.

c. **Strongly anisotropic antiferromagnetic coupling in $EuFe_2As_2$ revealed by stress detwinning (Phys. Rev. B 2021)**

Of all parent compounds of iron-based high-temperature superconductors, $EuFe_2As_2$ exhibits by far the largest magneto-structural coupling due to the sizable biquadratic interaction between Eu and Fe moments. While the coupling between Eu antiferromagnetic order and Fe structural/antiferromagnetic domains enables rapid field detwinning, this prevents simple magnetometry measurements from extracting the critical fields of the Eu metamagnetic transition. In this work, we measure these critical fields by combining x-ray magnetic circular dichroism spectroscopy with in-situ tunable uniaxial stress and applied magnetic field. The combination of two tuning knobs allows us to separate the stress-detwinning of structural domains from the field-induced reorientation of Eu moments. Intriguingly, we find a spin-flip transition which can only result from a strongly anisotropic interaction between Eu planes. We argue that this anisotropic exchange is a consequence of the strong anisotropy in the magnetically ordered Fe layer, which presents a new form of higher-order coupling between Eu and Fe magnetism.

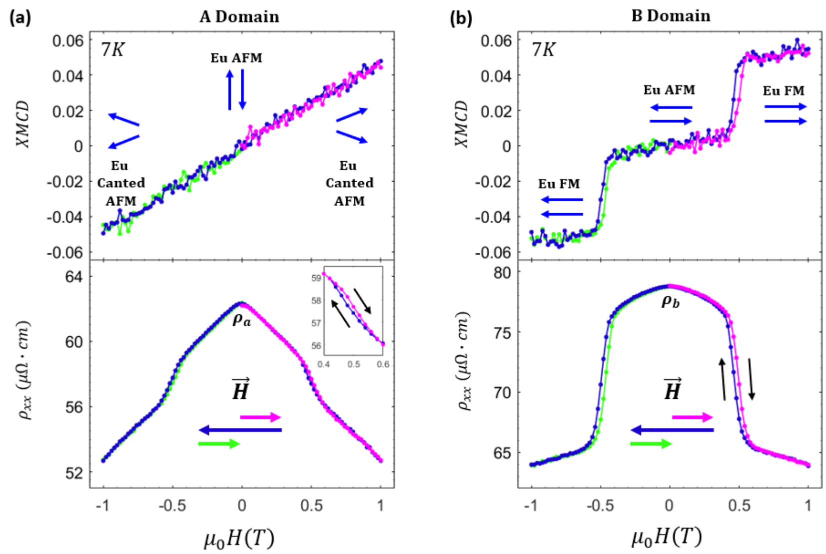

Fig. 3 Metamagnetic transition of detwinned crystals of $EuFe_2As_2$. (a) and (b) correspond to magnetic field perpendicular (A domain) and parallel (B domain) to the magnetic easy axes, respectively. Upper panels show the XMCD signal and lower panels show the resistivity.

Papers published and submitted

1. Junyi Yang, Lin Hao, Peyton Nanney, Kyle Noordhoek, Derek Meyers, Lukas Horak, Joshua Sanchez, Jiun-Haw Chu, Christie Nelson, Mark PM Dean, Jian Liu, "Epitaxial stabilization of $Sr_3Ir_2O_7$ thin films" ***Applied Physics Letters*** 114 (18), 182401 (2019)
2. Lin Hao, Zhentao Wang, Junyi Yang, D. Meyers, Joshua Sanchez, Gilberto Fabbris, Yongseong Choi, Jong-Woo Kim, Daniel Haskel, Philip J. Ryan, Kipton Barros, Jiun-Haw Chu, M. P. M. Dean, Cristian D. Batista, Jian Liu, "Anomalous Magnetoresistance due to Longitudinal Spin Fluctuations in a Jeff = 1/2 Mott Semiconductor", ***Nature Communications*** 10, 5301 (2019)
3. Paul Malinowski, Qianni Jiang, Joshua Sanchez, Zhaoyu Liu, Joshua Mutch, Preston Went, Jian Liu, Philip Ryan, Jong-Woo Kim, Jiun-Haw Chu, "Suppression of superconductivity by anisotropic strain near a nematic quantum critical point", ***Nature Physics*** 16 (12), 1189-1193, (2020)
4. Joshua J Sanchez, Paul Malinowski, Joshua Mutch, Jian Liu, J-W. Kim, Philip J Ryan, Jiun-Haw Chu, "The transport-structural correspondence across the nematic phase transition probed by elasto-x-ray diffraction", ***Nature Materials*** (2021). https://doi.org/10.1038/s41563-021-01082-
5. Joshua J Sanchez, Gilberto Fabbris, Yongseong Choi, Yue Shi, Paul Malinowski, Shashi Pandey, Jian Liu, II Mazin, Jong-Woo Kim, Philip Ryan, Jiun-Haw Chu, "Strongly anisotropic antiferromagnetic coupling in EuFe2As2 revealed by stress detwinning", **Phys. Rev. B** 104, 104413, (2021)
6. Qianni Jiang, Yue Shi, Morten H. Christensen, Joshua Sanchez, Bevin Huang, Zhong Lin, Zhaoyu Liu, Paul Malinowski, Xiaodong Xu, Rafael M. Fernandes, Jiun-Haw Chu, "Nematic Fluctuations in an Orbital Selective Superconductor Fe1+yTe1−xSex", arXiv:2006.15887 **(submitted)**

Invited talks and seminars

Jiun-Haw Chu

1. “Nematic quantum criticality in iron-based superconductors” International Conference on Quantum Liquid Crystals 2021 (QLC 2021) (online), May 2021
2. “Nematic Fluctuations in an Orbital Selective Superconductor $Fe_{1+y}Te_{1-x}Se_x$”, APS March Meeting, Mar 2021
3. “Nematic quantum criticality in iron-based superconductors”, LASSP Seminar, Cornell University, Oct 2020
4. Nematic quantum criticality in iron-based superconductors”, Condensed Matter Seminar, University of Florida, Oct 2020
5. “Nematic quantum criticality in iron-based superconductors”, Physics Colloquium, University of Washington, Sep 2020
6. “Nematic quantum criticality in iron-based superconductors”, Condensed Matter Seminar, Rice University, Sep 2020
7. “Nematic quantum criticality in iron-based superconductors” Online Summer Seminars for Correlated Electrons and Frustrated Magnets, Sep 2020
8. “Nematic quantum criticality in iron-based superconductors” Workshop on Multi-Modal X-Ray Techniques for Emergent Quantum Materials, Aug 2020

Joshua Sanchez

9. “The transport-structural correspondence across the nematic phase transition probed by elasto-x-ray diffraction”, APS March Meeting, Mar 2022
10. “Tuning electronic and magnetic orders with strain and magnetic field” Workshop on Multi-Modal X-Ray Techniques for Emergent Quantum Materials, Aug 2020

Paul Malinowski

11. “Suppression of superconductivity by anisotropic strain near a nematic quantum critical point”, APS March Meeting, Virtual, March 2021
12. “Suppression of superconductivity by anisotropic strain near a nematic quantum critical point”, RCQM Symposium on Fe-based Superconductivity, Virtual (Rice University), Jan. 2021

Award and patents

Jiun-Haw Chu

Presidential Early Career Award for Scientists and Engineers, 2019

Packard Fellowship for Science and Engineer, 2018

Sloan Research Fellow, 2018

Paul Malinowski

Dehmelt Prize, UW Department of Physics 2019

Joshua Sanchez

Dehmelt Prize, UW Department of Physics 2018

Students and postdocs supported

Joshua Sanchez (PhD student, Graduated Aug 2021, Now NSF MPS-Ascend Postdoctoral Fellow at MIT)

Paul Malinowski (PhD student)

Qianni Jiang (PhD student)

Yue Shi (PhD student)

Major collaborations

Collaboration on the elasto X-ray and iridates

Phillip Ryan, Jong Woo Kim (Advanced Photon Source, Argonne National Laboratory)

Jian Liu (University of Tennessee, Knoxville)

Collaboration on the nematicity in iron chalcogenides

Rafael Fernades (University of Minesota)

Xiaodong Xu (University of Washington)

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Research Accomplishment

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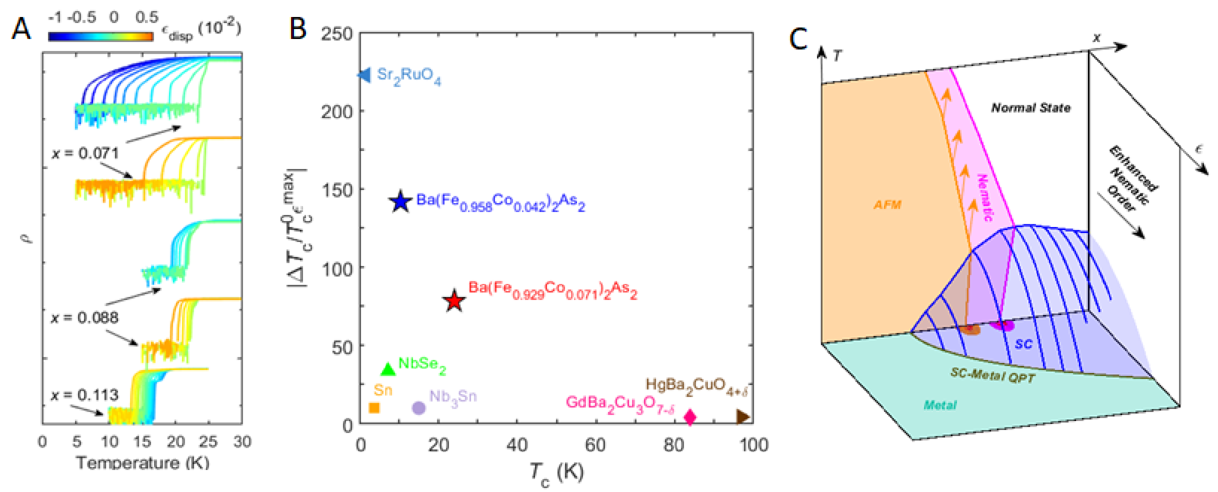

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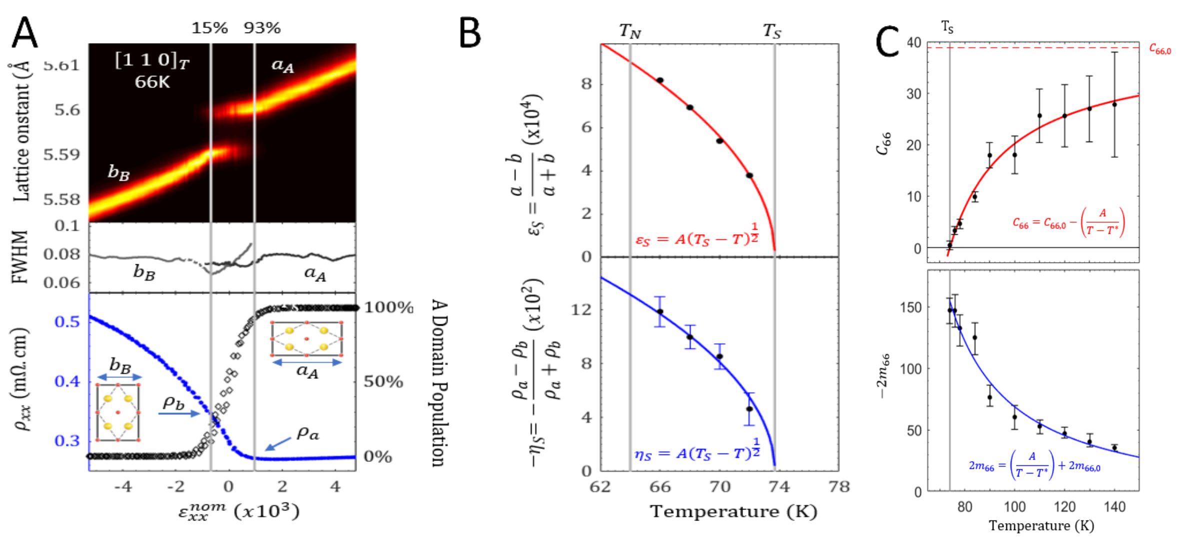

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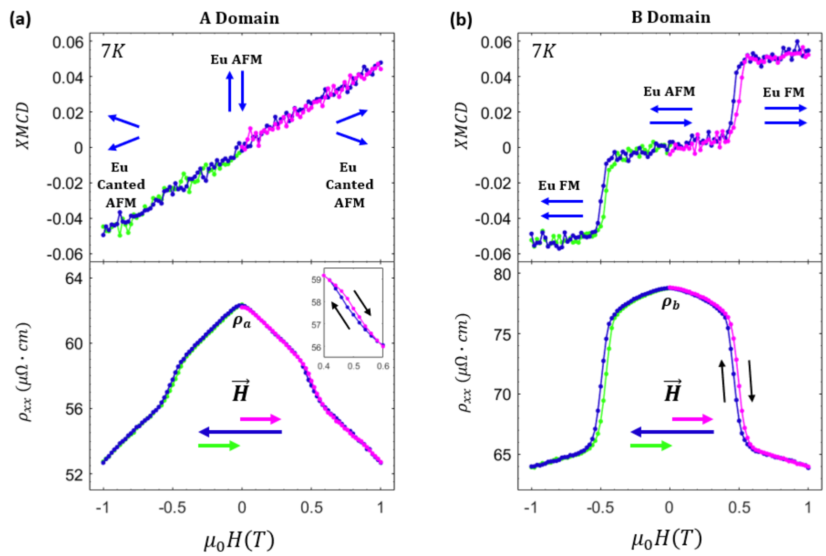

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Product During the Report Period

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