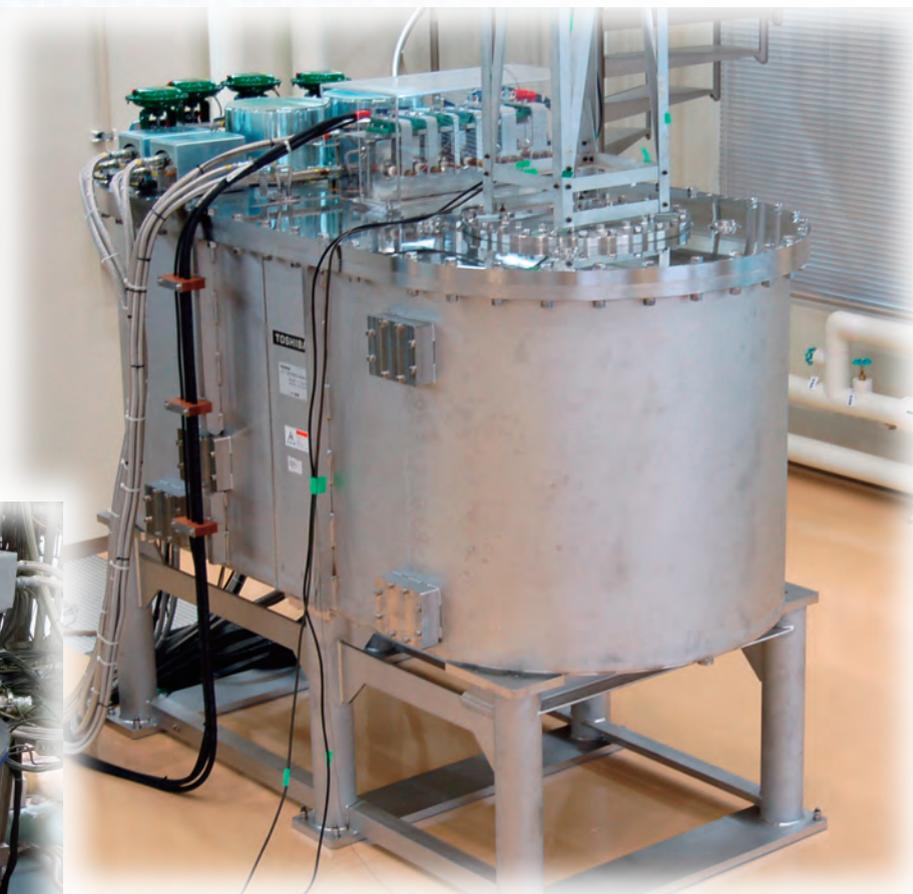


Selected Topics in 2021 Research Highlight at HFLSM



28T-CHM



25T-CSM



High Field Laboratory for Superconducting Materials,
Institute for Materials Research, Tohoku University

< FRONT COVER EXPOSITION >

**Cryogen-Free 28 T Hybrid Magnet and
25 T Cryogen-Free Superconducting Magnet**

The world's first 28 T cryogen-free hybrid magnet developed by the HFLSM. The inner double Bitter type water-cooled resistive magnet generates 19.0 T in a room temperature experimental bore of 32 mm with the electric power of 7.2 MW. The outer cryogen-free superconducting magnet generates 9.0 T in a 360 mm room temperature bore. The cryogen-free superconducting magnet generates 25.1 T in 52 mm room temperature bore by the combination of metallic and high- T_c superconductors.

◆◆◆ Preface ◆◆◆

This booklet reports the highlights of researches and the new improvements during FY2021 performed in HFLSM: High Field Laboratory for Superconducting Materials at Sendai. HFLSM has been developed numbers of new magnet technologies including cryogen-free hybrid magnet and cryogen-free superconducting magnets beyond 20 T. At HFLSM, the unique 25 T cryogen-free superconducting magnet (25T-CSM) has been operational for user program and has attracted many users. Such cryogen-free superconducting magnets surely offer long-term stable and high-quality steady fields. HFLSM offers varieties of magnets for researches in materials science, physics, applied superconductivity, chemistry and other pure and inter-disciplinary sciences performed in steady magnetic fields. The upgrade project of 25T-CSM is shifted to the 33T-CSM project since 2022 based on our original technologies. This project is one of the main objectives in the Japan High Magnetic Field Collaboratory started operation in April 2020.

Since 2019, IMR has recognized as the new international user program named Global Institute for Materials Science Tohoku (GIMRT). It will enhance the diverse and strong collaboration in a global framework. Under difficulties in Covid-19 pandemic, HFLSM is in operational with strict anti-infection majors by the strong supports and collaborations of users. We accept users from abroad in 2021 for onsite experiments under the GIMRT. In addition, limitations and requirements for new entry of foreign nationals into Japan are now almost removed since 2022 October. We hope that the booklet helps you to see the overview of our activities and stimulate future research collaborations with domestic and oversea users in HFLSM and in the High Magnetic Field Co-laboratory of Japan.

1 November 2022

Satoshi Awaji

Director of HFLSM

Selected Topics in 2021 – Research Highlight at HFLSM

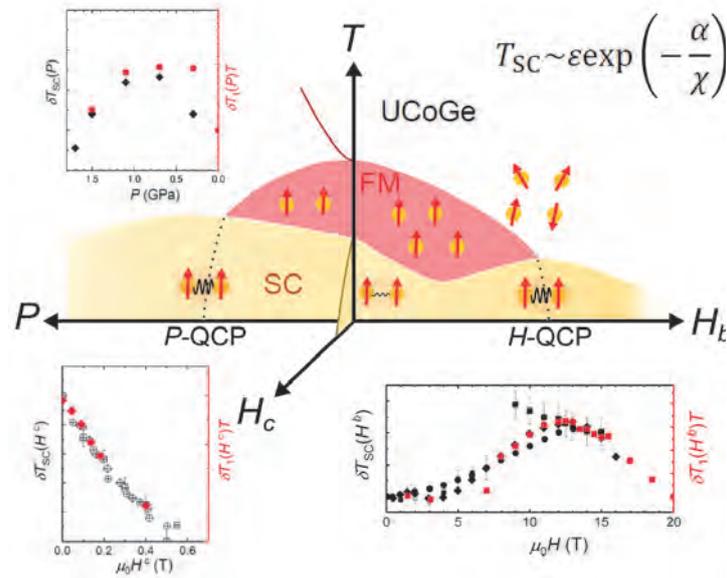
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Pairing Interaction in Superconducting UCoGe Tunable by Magnetic Field

超伝導引力が磁場・圧力で制御される超伝導



The mechanism of unconventional superconductivity, has been studied as a central issue in condensed-matter physics. Spin fluctuations, instead of phonons, are considered to be responsible for the formation of Cooper pairs, and many efforts have been made to confirm this mechanism experimentally. Here, we show a semiquantitative comparison between the superconducting-transition temperature (T_{SC}) and spin fluctuations derived from the NMR experiment on the ferromagnetic (FM) superconductor UCoGe in which the FM fluctuations and superconductivity are tunable by external fields. The enhancement and abrupt suppression of T_{SC} by applied fields, as well as the pressure variation of T_{SC} around the FM criticality are well understood by the change in the FM fluctuations on the basis of the single-band spin-triplet theoretical formalism proposed by V. P. Mineev.

K. Ishida¹, S. Matsuzaki, S. Kitagawa¹, M. Hirata², T. Sasaki², D. Aoki^{2,3}

¹ Dept. of Physics, Kyoto Univ., ² IMR, Tohoku Univ., ³ Univ. Grenoble Alpes, CEA, France

Reference: K. Ishida *et al.*, “Pairing interaction in superconducting UCoGe tunable by magnetic field”, *Phys. Rev. B.* **104**, 144505 (2021).

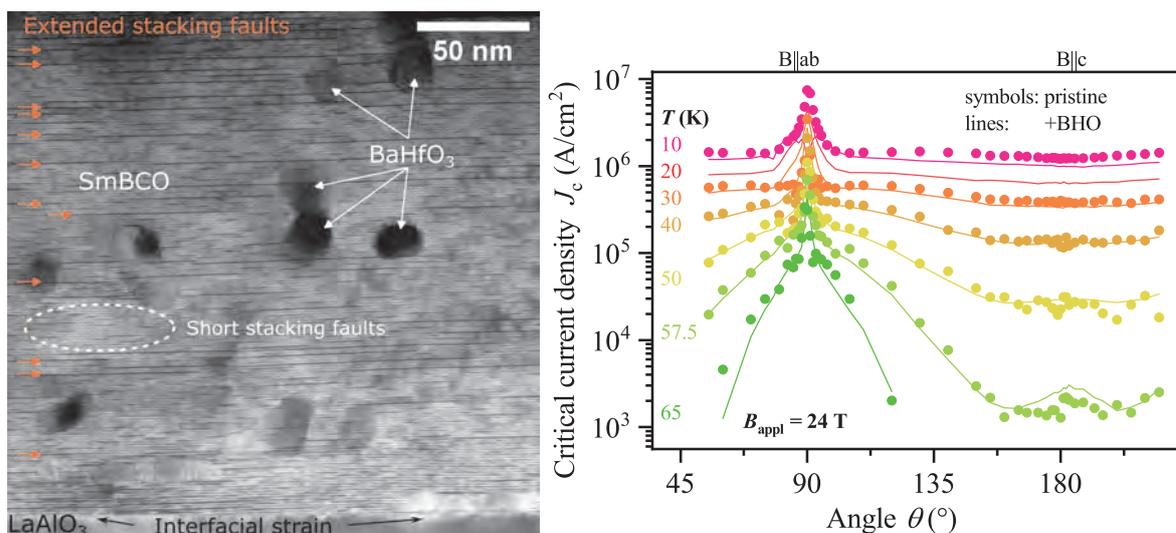
ウラン化合物強磁性超伝導体 UCoGe では、磁場や圧力で変化する強磁性ゆらぎで超伝導が実現していることが実験結果を用いた半定量的な議論から示された。同様な結論は、比熱や熱伝導の実験からも示されている [B. Wu *et al.*, *Nat. Comm.* **8**, 14480 (2017)]。強磁性ゆらぎで引き起こされる超伝導はスピン三重項超伝導と考えることが出来、強磁性超伝導体ではスピン三重項超伝導が実現していると考えられる。

石田憲二¹, 松崎聡¹, 北川俊作¹, 平田啓倫², 佐々木孝彦², 青木大^{2,3}

¹京大理, ²東北大金研, ³グルノーブル大

Detailed Study on BHO-doped SmBCO Thin Films Grown by TFA-MOD

TFA-MOD 法で作製した BHO 添加 SmBCO 薄膜の微細構造と超伝導特性



We have grown $\text{SmBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (SmBCO) thin films with a 12 mol% nano-sized BaHfO_3 (BHO) by TFA-MOD for the first time and investigated their microstructural and transport properties in detail. By optimizing the growth condition, epitaxial thin films with a T_c of 94 K were realized. As shown in figure, large densities of stacking faults were observed in the film. These defects were also observed in the pristine film. Therefore, further improvement of critical current properties by BHO-doping was limited to low magnetic fields, and few improvements of $J_c(\theta)$ at a high field of 24 T were observed irrespective of BHO addition. In future, we will try to optimize the microstructure in which BHO nanoparticles work more effectively as strong pinning centers.

J. Hänisch¹, K. Iida^{2,3}, P. Cayado⁴, M. Erbe¹, L. Grünewald⁵, T. Hatano², T. Okada⁶, D. Gerhsen⁵, S. Awaji⁶, B. Holzapfel¹

¹ ITEP KIT, ² Nagoya Univ., ³ Nihon Univ., ⁴ Univ. Geneva, ⁵ KIT-LEM, ⁶ IMR, Tohoku Univ.

Reference: J. Hänisch *et al.*, “Microstructure, pinning properties, and aging of CSD-grown $\text{SmBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films with and without BaHfO_3 nanoparticles”, *Supercond. Sci. Technol.* **35** (2022) 084009.

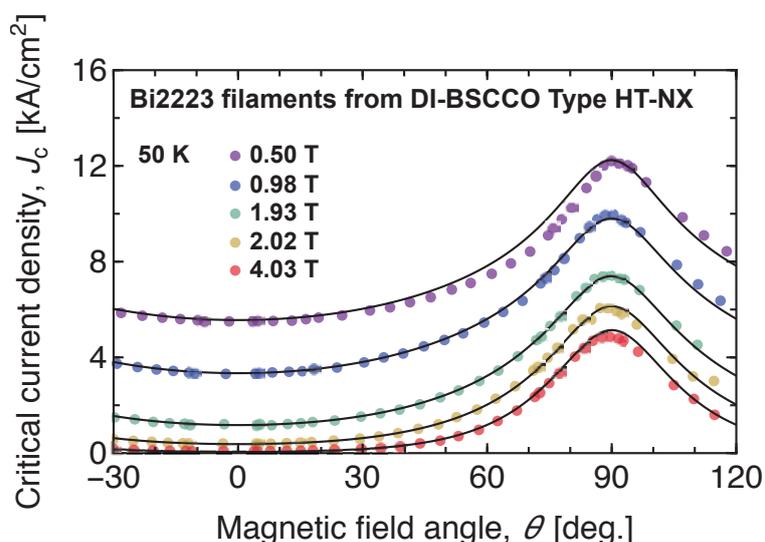
ナノサイズの BaHfO_3 (BHO) が 12 モル% 添加された $\text{SmBa}_2\text{Cu}_3\text{O}_{7-\delta}$ 薄膜を、これまで報告例がなかった TFA-MOD 法により作製した。成長条件を最適化することで T_c が 94 K のエピタキシャル薄膜が得られた。左図に示すように薄膜中には、多くの積層欠陥が観察された。これら欠陥は、BHO 無添加の薄膜でも見られた。そのため、BHO 添加による臨界電流特性の向上は低磁場領域に限定され、24 T の高磁場下では、BHO 添加・無添加による $J_c(\theta)$ は広い温度範囲にわたりおおむね一致した (右図)。今後は、BHO ナノ粒子が磁束ピンとしてより効果的に働くような微細構造の実現を目指す。

Jens Hänisch¹, 飯田 和昌^{2,3}, Pablo Cayado⁴, Manuela Erbe¹, Lukas Grünewald⁵, 畑野 敬史², 岡田 達典⁶, Dagmar Gerhsen⁵, 淡路 智⁶, Bernhard Holzapfel¹

¹ ITEP KIT, ² 名大, ³ 日大, ⁴ Univ. Geneva, ⁵ KIT-LEM, ⁶ 東北大金研

High-field Critical Current Characteristics of (Bi, Pb)₂Sr₂Ca₂Cu₃O_y Filaments

(Bi, Pb)₂Sr₂Ca₂Cu₃O_y フィラメントの強磁場通電特性



We abstracted (Bi, Pb)₂Sr₂Ca₂Cu₃O_y (BSCCO) filaments from a commercial BSCCO tape (DI-BSCCO Type HT-NX) and investigated those critical current characteristics as a function of temperature, and strength and orientation of magnetic field $I_c(T, B, \theta)$. Based on scaling behaviors of $I_c(T, B, 0\text{deg.})B$ vs. B and $\langle B|\cos\theta\rangle$, where $\langle X\rangle$ is a Gaussian average of X over misalignment angle of BSCCO polycrystals, we successfully constructed a model that reproduces $I_c(T, B, \theta)$ (solid curves in the figure). We clarified that 1) the orientation of BSCCO grains distributes with misalignment angle of $\sim 10\text{deg.}$, 2) the pinning curve $I_c(T, B, 0\text{deg.})B$ vs. B exhibits the T -scaling behavior, and 3) $I_c(T, B, \theta)$ of BSCCO filaments are dominated by $B||c$ components of the vortex pinning.

T. Okada¹, D. Kobayashi¹, and S. Awaji¹

¹ IMR, Tohoku Univ.

Reference: D. Kobayashi, T. Okada, and S. Awaji, “High-Field Critical Current Properties of (Bi, Pb)₂Sr₂Ca₂Cu₃O_y Filaments”, IEEE Trans. Appl. Supercond., **32** (2022) 6400105.

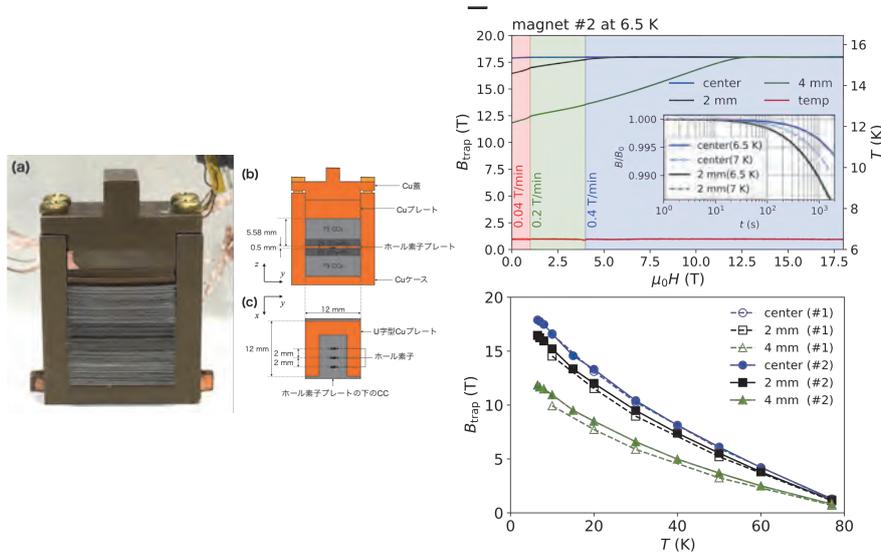
市販の(Bi, Pb)₂Sr₂Ca₂Cu₃O_y (BSCCO)線材から BSCCO フィラメントを抽出し、臨界電流の温度・磁場・磁場角度依存性 $I_c(T, B, \theta)$ を評価した。観測したピンニング曲線の温度および $\langle B|\cos\theta\rangle$ に対するスケール挙動から、 $I_c(T, B, \theta)$ を記述するモデルの構築に成功した。本研究により、(i)BSCCOフィラメントの配向は 10deg.程度分散している、(ii)ピンニング曲線は温度スケール則を示す、(iii)BSCCOフィラメントの $I_c(T, B, \theta)$ は磁束ピン止め力の $B||c$ 成分に支配されることが明らかになった。

岡田 達典¹, 小林 大地¹, 淡路 智¹

¹ 東北大金研

Trapping a Magnetic Field of 17.89 T in Stacked Coated Conductors

積層コーテッド・コンダクターによる 17.89 T の捕捉



We have succeeded in trapping a record-high magnetic field of 17.89 T in the center of a stacked magnet with dimensions of $\sim 12 \times 13 \times 11.7 \text{ mm}^3$. The stacked magnet consists of 200 sheets of $\text{EuBa}_2\text{Cu}_3\text{O}_7$ coated conductors (CC) with HfBaO_3 artificial pinning centers, each with $\sim 12 \times 13 \times 0.055 \text{ mm}^3$. Three small Hall probes are placed at the center of the stack for the evaluation of trapped field. Successful trapping of high magnetic field is achieved at 6.5 K within 75 min., which is contrasted to similar trapping in a much larger stacked magnet with a volume of $35,000 \text{ mm}^3$ at $\sim 8 \text{ K}$ in $\sim 19 \text{ h}$ and in a mechanically reinforced $\text{GdBaCu}_3\text{O}_7$ bulk at 26 K in $\sim 20 \text{ h}$. Flux jumps are suppressed by evaporating Pb with large heat capacity at $\sim 10 \text{ K}$ onto central pieces of CCs.

M. Suyama¹, S. Pyon¹, T. Tamegai¹, Y. Iijima², S. Awaji³

¹ Dept. of Appl. Phys., The Univ. of Tokyo, ² Fujikura Ltd., ³ IMR, Tohoku Univ.

Reference: M. Suyama *et al.*, “Trapping a magnetic field of 17.89 T in stacked coated conductors by suppression of flux jumps”, *Supercond. Sci. Technol.* **35** (2022) 02LT01.

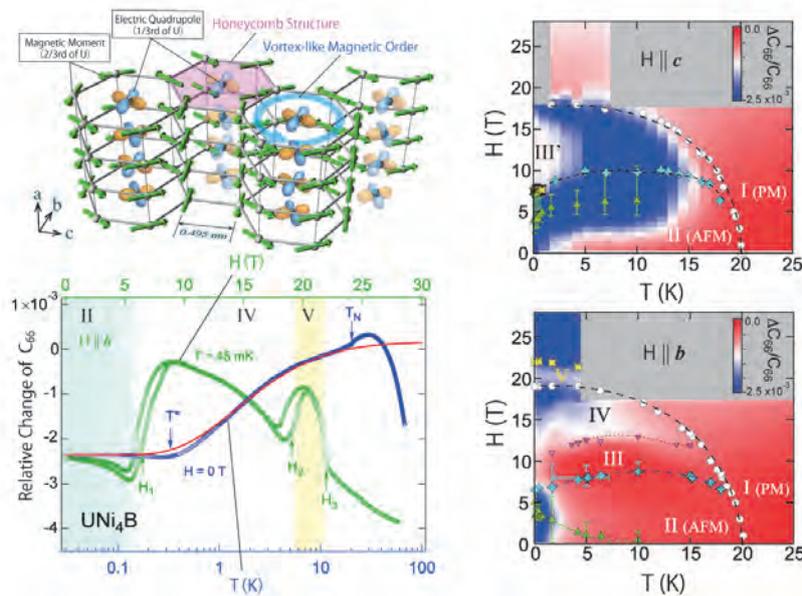
大きさ $\sim 12 \times 13 \times 11.7 \text{ mm}^3$ の積層マグネットの中心にこれまでの記録を超える 17.89 T の強磁場の捕捉に成功しました。積層マグネットは人工ピンである HfBaO_3 を内包した $\text{EuBa}_2\text{Cu}_3\text{O}_7$ コーテッド・コンダクター ($\sim 12 \times 13 \times 0.055 \text{ mm}^3$) 計 200 枚からなります。その中心に捕捉磁場測定用の 3 個の微小ホール素子を設置しています。磁場捕捉は 6.5 K で 75 分以内に行われました。これは、これまでのより大きな積層マグネットにおける $\sim 8 \text{ K}$ 、 $\sim 19 \text{ h}$ 、及び機械的な補強を行なった $\text{GdBaCu}_3\text{O}_7$ バルク体における $\sim 26 \text{ K}$ 、 $\sim 20 \text{ h}$ と対比されます。磁束ジャンプ抑制のため、 $\sim 10 \text{ K}$ 付近で大きな熱容量を持つ鉛を一部のコーテッド・コンダクターに蒸着しています。

陶山 正裕¹, 卞 舜生¹, 為ヶ井 強¹, 飯島 康裕², 淡路 智³

¹ 東大工物工, ² フジクラ, ³ 東北大金研

Electric Quadrupolar Fluctuation in the Center of Vortex-like Magnetic Structure of UNi₄B

UNi₄B の磁気渦の中で揺らぐ電気四極子



The international collaborative research group have succeeded in identifying that electric quadrupoles play an important role in the magnetic order of the honeycomb-layer compound UNi₄B. The group showed that these quadrupoles maintain their degrees of freedom without ordering at the center of a magnetic vortex arrangement. In this study, the cooperation partners combined ultrasound technique, which can sensitively detect orbital degrees of freedom, with the 28T-CHM and ³He-⁴He dilution refrigerator at the High Field Laboratory for Superconducting Materials at Tohoku University.

T. Yanagisawa¹, H. Matsumori¹, H. Saito¹, H. Hidaka¹, H. Amitsuka¹, S. Nakamura², S. Awaji², D. I. Gorbunov³, S. Zherlitsyn³, J. Wosnitza^{3,4}, K. Uhlířová⁵, M. Vališka⁵, and V. Sechovský⁵
¹ Hokkaido Univ., ² IMR, Tohoku Univ., ³ HLD-EMFL, HZDR, ⁴ TU Dresden, ⁵ Charles Univ.

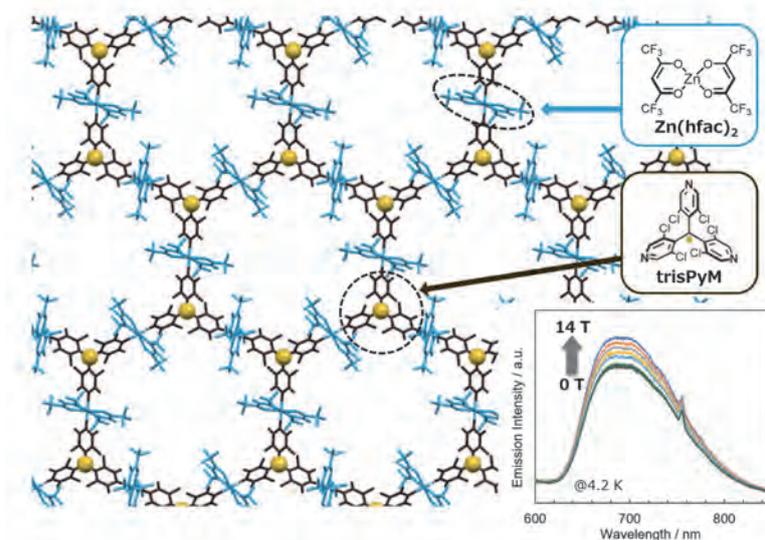
Reference: T. Yanagisawa *et al.*, “Electric quadrupolar contributions in the magnetic phases of UNi₄B”, Phys. Rev. Lett. **126** (2020) 157201.

日独捷(チェコ)の国際共同研究グループは蜂の巣構造を持つウラン化合物 UNi₄B が形成する磁気渦の中心で、秩序せず自由度を保ち続けて揺らぐ電気四極子の存在(図左上)を捉えることに成功しました。研究グループは東北大学金属材料研究所の 28 T 無冷媒ハイブリッド磁石に ³He-⁴He 希釈冷凍機を組み合わせ、軌道自由度を敏感に観測する超音波測定法を用いて、極低温・強磁場領域の横波弾性定数測定を行いました。得られた磁場-温度相図(図右)から、UNi₄B の秩序相において電気四極子が重要な役割を果たしていることを明らかにしました。

柳澤達也¹, 松盛泰明¹, 齋藤 開¹, 日高宏之¹, 網塚 浩¹, 中村慎太郎², 淡路 智², D. I. Gorbunov³, S. Zherlitsyn³, J. Wosnitza^{3,4}, K. Uhlířová⁵, M. Vališka⁵, V. Sechovský⁵
¹ 北大院理, ² 東北大金研, ³ ドレスデン強磁場研究所, ⁴ ドレスデン工科大, ⁵ カレル大

Radical-based Coordination Polymers Exhibiting Magnetoluminescence

磁場応答発光を示すラジカル性配位高分子



Magnetoluminescence (MagLum) of radicals (i.e. molecules possessing unpaired electrons) is a rare example of spin-correlated photofunctions, where the spin degree of freedom of materials is coupled strongly to the luminescence properties. MagLum has been observed to date only in radicals dispersed in host matrices. In this study, we revealed that radical-based 1D chain and 2D honeycomb lattice coordination polymers (CPs) demonstrate MagLum at 4.2 K. While the solid-state emissions of component radicals in their crystalline states were not affected significantly by external magnetic fields, those of CPs were greatly modulated. The results indicate that reducing radical-radical interactions via CP formation would be a key factor for achieving MagLum.

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¹ IMS, ² Dept. of Chem., Univ. of Tokyo, ³ IMR, Tohoku Univ., ⁴ Res. Inst. for Sci. and Tech., Tokyo Univ. of Sci., ⁵ JST-PRESTO

Reference: S. Kimura *et al.*, “Radical-Based Coordination Polymers as a Platform for Magnetoluminescence”, *J. Am. Chem. Soc.* **143** (2021) 5610.

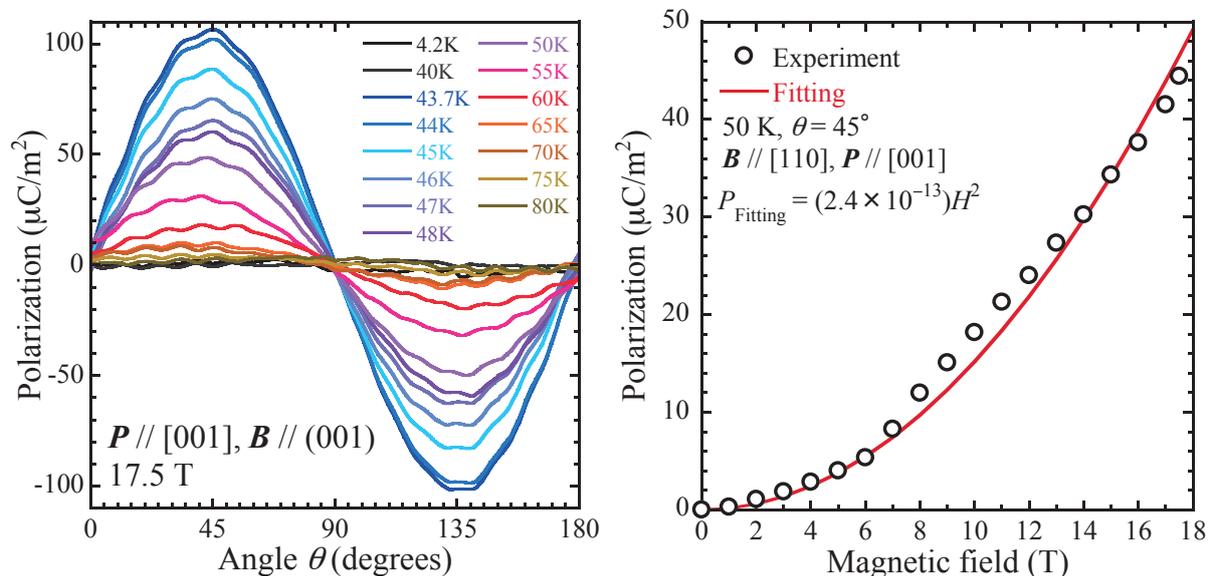
ラジカルが示す磁場応答発光 (MagLum) は、物質のスピン自由度と発光特性が強くカップルしたスピン相関光機能の稀有な例である。これまで MagLum はラジカルを固体担体にドープした試料においてのみ実現されてきた。本研究では、我々はラジカルからなる1次元鎖および2次元ハニカム格子構造を有する配位高分子が、4.2 K において MagLum を示すことを明らかにした。配位高分子の構成要素であるラジカル単体の結晶は有意な MagLum を示さない一方、これらを構成要素とする配位高分子の固体発光は磁場により大きく変調される。これらの結果は、「配位高分子化」がラジカルの MagLum を実現するための良い手法となり得ることを示している。

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Enhancement of the Magnetoelectric Effect Using the Dynamic Jahn-Teller Effect in the Transition-Metal Complex [Mn^{III}(taa)]

遷移金属錯体[Mn^{III}(taa)]の動的 Jahn-Teller 効果による電気磁気効果の増強



We have found an enhancement of the magnetic-field-induced electric polarization by the dynamic Jahn-Teller effect in the noncentrosymmetric paramagnetic transition metal complex [Mn^{III}(taa)]. The electric polarization of over 100 $\mu\text{C}/\text{m}^2$ is observed owing to the second order magnetoelectric effect in this compound. Fluctuating electric dipole moments, which are generated from the Jahn-Teller effect in [Mn^{III}(taa)] molecules are aligned by magnetic fields. This alignment results in the relatively large field-induced electric polarization in [Mn^{III}(taa)].

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Reference: Y. Otsuki *et al.*, “Enhancement of the Magnetoelectric Effect Using the Dynamic Jahn-Teller Effect in a Transition-Metal Complex”, Phys. Rev. Lett. **128** (2022) 117601.

空間反転中心を持たない点群 T_d に属する遷移金属錯体[Mn^{III}(taa)]は、 $T_c \sim 47$ K 以上で d 軌道の二重縮退を反映した動的 Jahn-Teller 効果による分子歪みを示す。この Jahn-Teller 歪みは、向きの自由度を持った電気双極子を分子に発生させ、またスピン軌道相互作用を介して磁場と結合する。我々は Jahn-Teller 歪みの磁場整列に由来して起こる電気双極子の配向を利用することによって、二次の電気磁気効果による 100 $\mu\text{C}/\text{m}^2$ を超す磁場誘起電気分極を観測した。

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