Selected Topics in 2018
Research Highlight at HFLSM

Research

28T-CHM

25T-CSM

HFLSM

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

Selected Topics in 2018 – Research Highlight at HFLSM

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◇◆◇ Preface ◇◆◇

This booklet reports the highlights of researches and the new improvements during FY2018 performed in the HFLSM: High Field Laboratory for Superconducting Materials at Sendai. HFLSM has been developed numbers of new magnets technologies including cryogen-free hybrid magnet and cryogen-free superconducting magnets generating magnetic fields above 20 T. At HFLSM, the unique 25 T cryogen-free superconducting magnet has been operational for user program and has attracted many domestic and overseas users. Such cryogen-free superconducting magnets surely offer long-term stable and high-quality steady fields. HFLSM offers varieties of hybrid and superconducting magnets for researches in materials science, physics, applied superconductivity, chemistry and other pure and inter-disciplinary sciences performed in steady magnetic fields. It should be noted that HFLSM is now preparing for 30 T class superconducting magnet based on our original technologies.

In November, 2019, IMR has recognized as one of the six international collaboration centers by MEXT and has launched the new international user program named Global Institute for Materials Science Tohoku (GIMRT). In this program, the both domestic and overseas users are supported for their travel and staying expenses at HFLSM. Moreover, a collaboration among multiple institutions including IMR can be conducted in the "Bridge type" scheme. These new programs will enhance the diverse and strong collaboration in a global framework.

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.

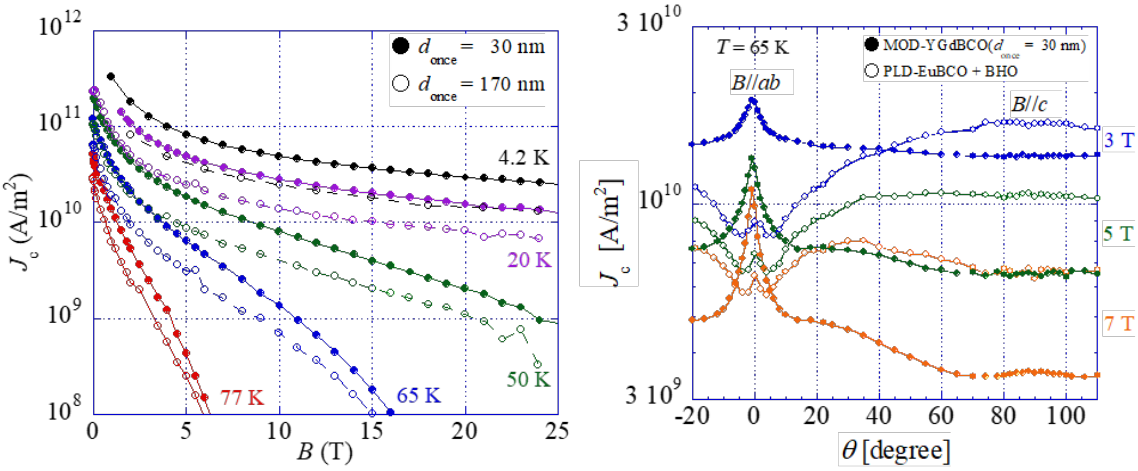
1 October 2019

Hiroyuki Nojiri

Director of HFLSM

Enhancement of In-Field Critical Current Density of $BaZrO_3$-Added (Y, Gd) BCO-Coated Conductors by UTOC-MOD Process

UTOC-MOD 法による BZO 導入(Y, Gd)BCO 線材の磁場中臨界電流密度の向上



The metal-organic decomposition (MOD) is a promising low-cost process for a production of coated conductors because of its non-vacuum process. However, critical current density, J_c, in the MOD processed tapes were generally inferior to that of PLD. In this study, we demonstrated that the ultra-thin once coating (UTOC) process using 30 nm once-coat-layer-thickness (d_{once}) shows superior in-field J_c down to 4.2 K than that of the previous standard coating using 170 nm layer thickness for each coating. Furthermore, the in-field J_c are even better than that of the $BaHfO_3$ added PLD process in a medium range of magnetic field; the minimum J_c, which is estimated from magnetic field angle dependence, shows higher value up to 5 T of magnetic field at 65 K. In short, the UTOC-MOD process is very promising especially for the practically important mid-field region such as 3 to 5 T.

T. Suzuki[1], S. Oomura[1], K. Imamura[1], M. Inoue[2], K. Higashikawa[1], S. Awaji[3], K, Nakaoka[4], T. Izumi[4], T. Kiss[1].

[1] Kyushu Univ., [2] Fukuoka Institute of Technology, [3] IMR, Tohoku Univ., [4] AIST.

Reference: T. Suzuki *et al.*, “Enhancement of in-field critical current density of $BaZrO_3$-added (Y, Gd)BCO-coated conductors by using a multi-coating TFA-MOD method”, IEEE Trans. Appl. Supercond. 28 (2018) 6600504.

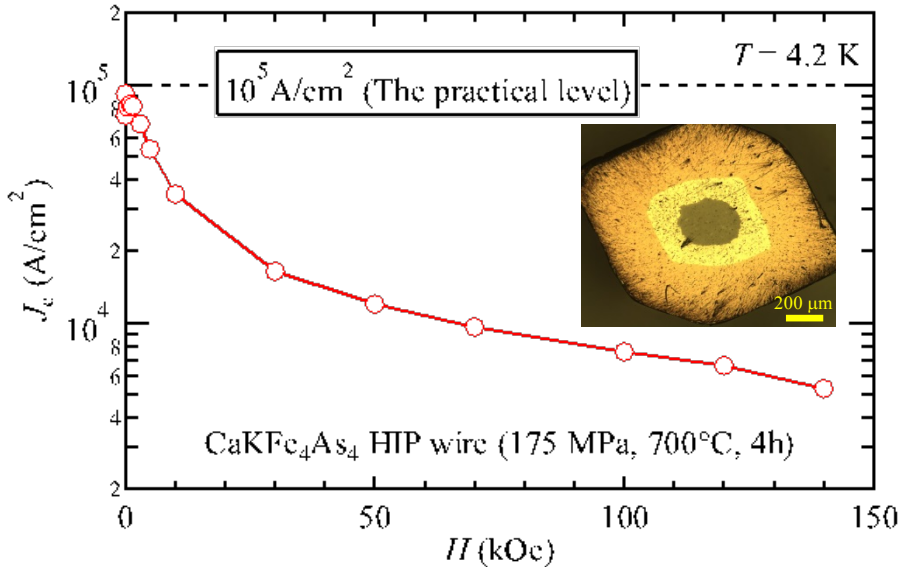
MOD 法は非真空プロセスで低コストな成膜法である。1 回塗布厚が 30 nm の UTOC-MOD 線材は 77 K から 4.2 K までの幅広い温度領域で従来の 170 nm の線材より優れた J_c 特性を示し、PLD 法による BHO 導入 EuBCO 線材と比較しても、J_c の最小値は 65 K において 5 T 以下で高い値となった。UTOC-MOD 法は実用上重要となる 3 – 5 T などの領域で非常に有用であることが分かった。

鈴木　匠[1], 大村　俊介[1], 今村　和孝[1], 井上　昌睦[2], 東川　甲平[1], 淡路　智[3], 中岡　晃一[4], 和泉　輝郎[4], 木須　隆暢[1]

[1] 九大, [2] 福工大, [3] 東北大金研, [4] 産総研

Development of $CaKFe_4As_4$ superconducting PIT-HIP round wires

$CaKFe_4As_4$超伝導 PIT-HIP 丸型線材の開発



We fabricated $CaKFe_4As_4$ round wires through a powder-in-tube (PIT) method followed by hot isostatic pressing (HIP) up to 175 MPa. The transport critical current density, J_c, at 4.2 K almost reached the level for practical applications (100 $kAcm^{-2}$) under self-field and reached 7.6 $kAcm^{-2}$ at 100 kOe. These values of J_c are the second largest J_c among those of iron-based superconducting (IBS) wires, only after wires of 122-system such as $(Ba,K)Fe_2As_2$, and $CaKFe_4As_4$ is expected as a new candidate for the raw material of IBS wires. On the other hand, X-ray diffraction analysis indicated that impurity phases were present in the core of the wire. Further enhancement of J_c by purification of the sample is demanded.

S. Pyon[1], D. Miyawaki[1], I. Veshchunov[1], T. Tamegai[1], K. Takano[2], H. Kajitani[2],
N. Koizumi[2] and S. Awaji[3]
[1] Dept. of Appl. Phys. Univ. Tokyo, [2] QST, [3] IMR, Tohoku Univ.

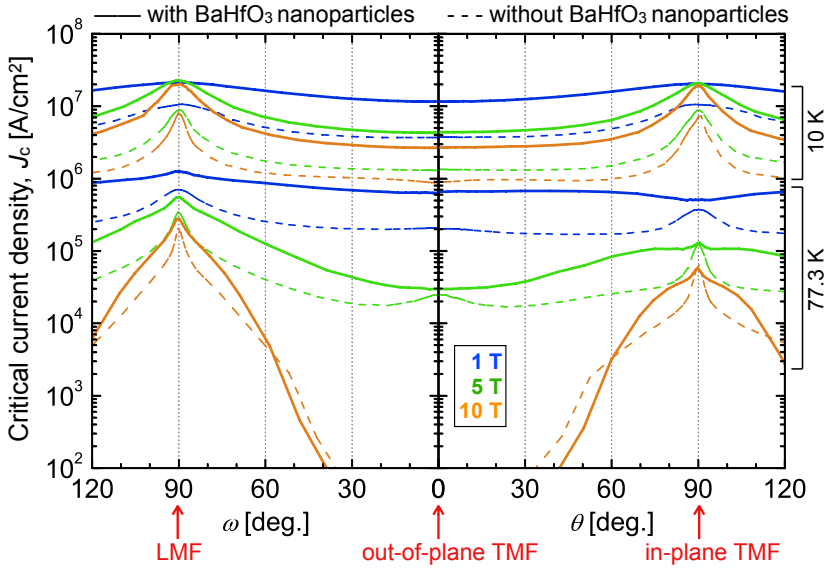
Reference: S. Pyon *et al.*, "Fabrication and characterization of $CaKFe_4As_4$ round wires sintered at high pressure", Appl. Phys. Express. **11** (2018) 122101.

我々は鉄系超伝導体 $CaKFe_4As_4$ を用いた丸型線材を PIT 法および 175 MPa での熱間等方加圧 (HIP) 法によって初めて作製した。その臨界電流密度 J_c は 4.2 K・自己磁場下において実用レベル 100 $kAcm^{-2}$ に匹敵する値であり、100 kOe の高磁場でも 7.6 $kAcm^{-2}$ に達した。これらの J_c の値は、鉄系超伝導体を用いた丸型線材の中では、$(Ba,K)Fe_2As_2$ 等の 122 系を用いた線材の J_c に次ぐ値であり、$CaKFe_4As_4$ は新しい鉄系超伝導線材の材料候補として期待される。一方、X 線回折等の分析から線材コアの不純物の存在が示されており、今後の試料の純良化により更なる J_c 向上が望まれる。

卞 舜生[1], 宮脇 大輔[1], Ivan Veshchunov[1], 為ヶ井 強[1],
高野 克敏[2], 梶谷 秀樹[2], 小泉 徳潔[2], 淡路 智[3]
[1] 東大工, [2] 量研機構, [3] 東北大金研

Longitudinal Magnetic Field Effects on UTOC-MOD-*RE*BCO Coated Conductors under High Magnetic Fields

極薄一回塗布膜 MOD コート線材における強磁場下での縦磁界効果



To clarify longitudinal magnetic field (LMF) effects on REBa$_2$Cu$_3$O$_{7-\delta}$ (RE: rare-earth) coated conductors which is expected to utilize for DC power cable application, we carried out critical current density (J_c) measurements under various temperature, magnetic field, and field orientation conditions. We found that introduction of artificial pinning centers is effective for J_c under LMFs as well as usual transverse magnetic fields (TMFs). We also found that J_c in LMF configuration converges to those in TMF configuration at lower temperature and magnetic fields where J_c in TMF are large. We hope that our findings give insight to understand the nature of magnetic vortices in LMF configuration.

T. Okada[1], H. Misaizu[1], S. Awaji[1], K. Nakaoka[2], T. Machi[2], T. Izumi[2], and M. Miura[3]

[1] IMR, Tohoku Univ., [2] AIST, [3] Dept. of Sci. and Technol., Seikei Univ.

Reference: T. Okada *et al.*, "Longitudinal Magnetic Field Effects on (Y,Gd)Ba$_2$Cu$_3$O$_{7-\delta}$ Coated Conductor with BaHfO$_3$ Nanoparticles Fabricated by UTOC-MOD Method", IEEE Trans. Appl. Supercond. **29** (2019) 8002705.

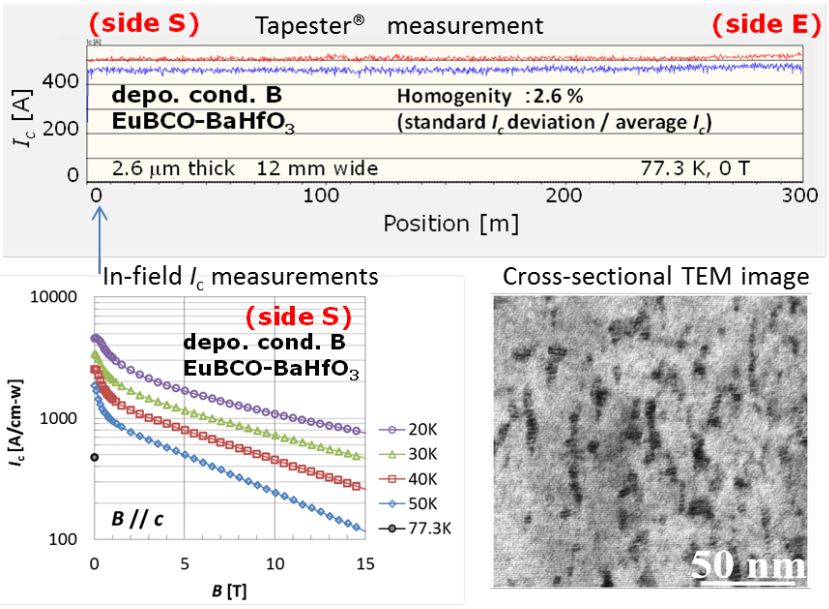
直流送電ケーブル応用が期待される希土類系銅酸化物超伝導コート線材の縦磁界効果を解明すべく，広範な温度・磁場・角度条件下での臨界電流測定を行なった．結果，人工ピンの導入は通常の横磁場臨界電流と同様に縦磁場臨界電流にも有効であることがわかった．また，低温・低磁場（横磁場臨界電流が大きい）領域で縦磁場臨界電流が横磁場臨界電流に収束する振舞いが見られた．未だ解明されていない縦磁界配置での磁束量子の描像に迫る足がかりになるものと期待している．

岡田 達典[1], 美齊津 英典[1], 淡路 智[1], 中岡 晃一[2], 町 敬人[2], 和泉 輝郎[2], 三浦 正志[3]

[1] 東北大金研, [2] 産総研, [3] 成蹊大理工

Development of Long-Length BMO-Doped REBCO Coated Conductors by Hot-Wall PLD Process

Hot-wall PLD による長尺人工ピン REBCO 線材の開発



Fujikura Ltd. has developed the artificial pinning center doped REBCO coated conductors by using hot-wall type pulsed-laser-deposition (PLD) system in order to enhance in-field critical current (I_c). By using a high growth rate condition which is obtained by optimizing the PLD deposition conditions, we succeeded in fabricating a 300 m long $BaHfO_3$-doped EuBCO coated conductor with uniform I_c distribution and high in-field I_c.

S. Fujita[1], S. Muto[1], W. Hirata[1], Y. Adachi[1], T. Yoshida[1], M. Igarashi[1], K. Kakimoto[1], Y. Iijima[1], K. Naoe[1], T. Kiss[2], T. Okada[3] and S. Awaji[3]

[1] Fujikura Ltd., [2] Kyushu Univ., [3] IMR, Tohoku Univ.

Reference: S. Fujita *et al.*, "Development of Long-Length BMO-Doped REBCO Coated Conductors by Hot-Wall PLD Process", IEEE Trans. Appl. Supercond. 28 (2018) 6600604.

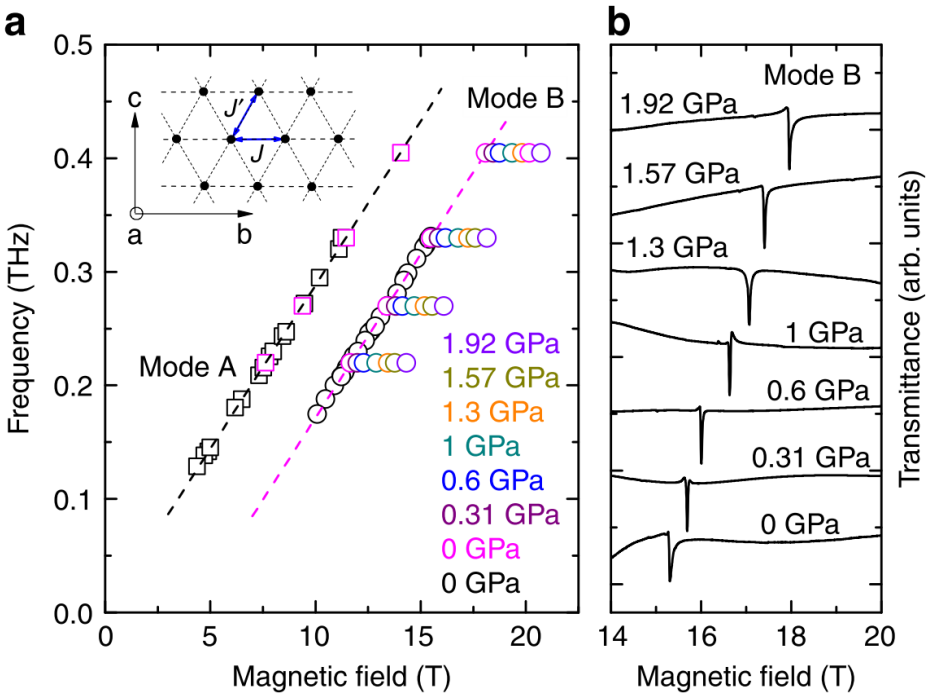
フジクラでは磁場中での臨界電流特性向上を目的として，Hot-wall-PLD を用いて人工ピンを導入した REBCO 線材の開発を行ってきた．REBCO の蒸着速度に着目し，低蒸着速度において臨界電流密度（J_c）が非常に高い成膜条件(A)と，高蒸着速度において厚膜化による高い臨界電流（I_c）が高速で得られる条件(B)を見出した．その結果，高蒸着速度条件を適用することで均一な長手 I_c 分布と高い磁場中 I_c を有する 300 m もの長尺人工ピン REBCO 線材の作製に成功した．

藤田　真司[1], 武藤　翔吾[1], 平田　渉[1], 足立　泰[1], 吉田　朋[1], 五十嵐　光則[1], 柿本　一臣[1], 飯島　康裕[1], 直江　邦浩[1], 木須　隆暢[2], 岡田　達典[3], 淡路　智[3]

[1]フジクラ, [2]九大, [3]東北大金研

Pressure-tuning the quantum spin Hamiltonian of the triangular lattice antiferromagnet Cs_2CuCl_4

三角格子磁性体の量子相のハミルトニアンの圧力制御



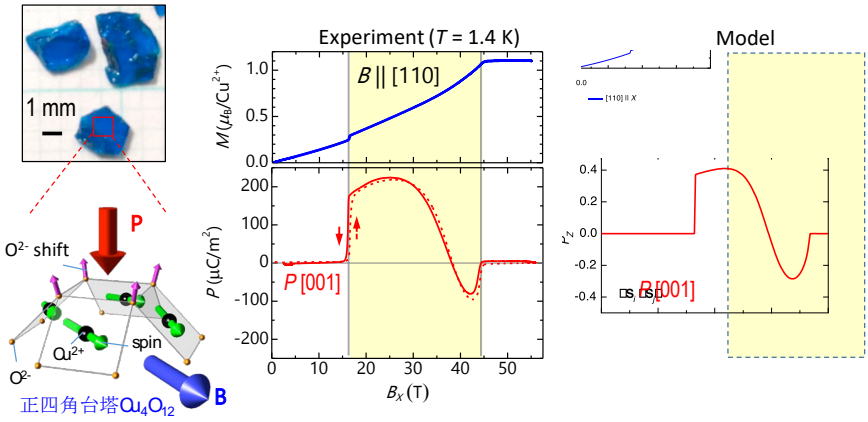
Quantum triangular-lattice antiferromagnets are important prototype systems to investigate numerous phenomena of the geometrical frustration in condensed matter. Apart from highly unusual magnetic properties, such systems possess a very rich phase diagram, determined by the spin-Hamiltonian parameters and with ground states, ranging from an unfrustrated square lattice to a quantum spin liquid. Using Cs_2CuCl_4 as a model system, we demonstrate a novel approach, where the exchange coupling parameters are altered by hydrostatic pressure. The approach combines high-pressure electron spin resonance and magnetization measurements, allowing us not only to quasi-continuously tune the exchange parameters, but also to accurately monitor them. Our experiments indicate a substantial increase of the exchange coupling ratio J'/J from 0.3 to 0.42 at a pressure of 1.8 GPa, revealing a number of emergent field-induced phases.

S.A. Zvyagin[1], D. Graf[2], T. Sakurai[3], S. Kimura[4], H. Nojiri[4], J. Wosnitza[1,5], H. Ohta[6], T. Ono[7], H. Tanaka[8]

[1]HLD-EMFL, Helmholtz-Zentrum Dresden-Rossendorf, [2]NHMFL, Florida State Univ., [3]RFCST, Kobe Univ., [4]IMR, Tohoku Univ., [5]IFMP, TU Dresden, [6]MPRC, Kobe Univ., [7]Dept. of Phys. Sci, Osaka Prefecture Univ., [8]Dept. of Phys. Tokyo Inst. of Tech.

Reference: S.A. Zvyagin *et al.*, “Pressure-tuning the quantum spin Hamiltonian of the triangular lattice antiferromagnet Cs2CuCl4”, Nature Comm. **10** (2019) 1064.

Exchange-Striction-Driven Magnetoelectric Coupling in Convex-Shaped Magnetic Structural Unit
凸形状磁気ユニットの示す交換歪誘起電気磁気結合



We study magnetoelectric properties of antiferromagnet $Pb(TiO)Cu_4(PO_4)_4$ which consists of convex-shaped Cu_4O_{12} magnetic units. We observe an emergence of ferroelectricity accompanied by a field-induced metamagnetic transition at 16.4 T. Moreover, we find that the electric polarization exhibits a peculiar field dependence including a sign reversal at around 35 T, where no marked magnetization anomaly is observed. To understand the origin of this behavior, we construct and analyze an effective spin model, in which a Dzyaloshinskii–Moriya interaction between neighboring spins due to convex geometry is taken into account. We find that a calculated electric polarization induced by an exchange striction agrees well with the experimental result, indicating that the exchange striction plays a prime role for the peculiar magnetoelectric coupling in this system.

K. Kimura[1], Y. Kato[2], K. Yamauchi[3], A. Miyake[4], M. Akaki[5], S. Kimura[6], M. Toyoda[7] *et al.*,
[1] GSFS, Univ. of Tokyo, [2] Dept. of Appl. Phys., Univ. of Tokyo, [3] ISIR-SANKEN, Osaka Univ.,
[4] ISSP, Univ. of Tokyo, [5]AHMF, Osaka Univ., [6] IMR, Tohoku Univ., [7] Dept. of Phys. Tokyo. Tech.

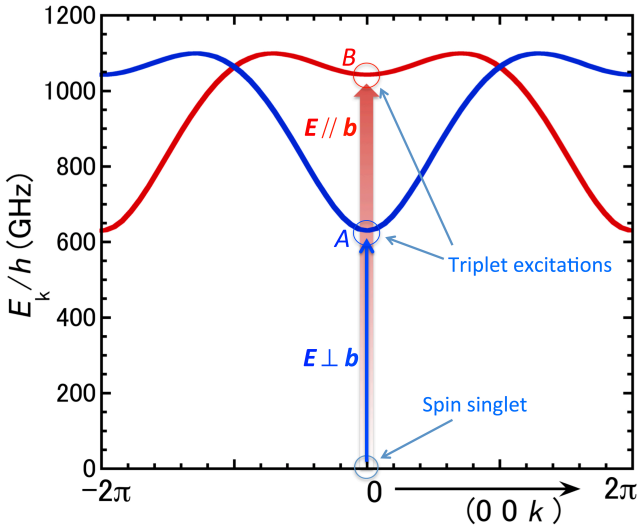
Reference: K. Kimura *et al.*, “Magnetic Structural Unit with Convex Geometry: A Building Block Hosting an Exchange-Striction-Driven Magnetoelectric Coupling”, Phys. Rev. Mater. **2** (2018) 104415.

凸形状磁気構造ユニットCu_4O_{12}を内包する反強磁性体$Pb(TiO)Cu_4(PO_4)_4$において、16.4 T で生じる磁場誘起メタ磁性転移に伴って強誘電性が発現すること発見し、さらには、磁化には異常の見られない35 T付近において電気分極の符号が反転するという特異な振る舞いを観測した。スピンクラスターの凸面形状に由来する Dzyaloshinskii–Moriya 相互作用を考慮した有効モデルを構築し、これに基づく磁化および電気分極の解析から、本系の特異な電気磁気結合が交換歪みによって引き起こされていることを明らかにした。

木村健太 [1], 加藤康之 [2], 山内邦彦 [3], 三宅厚志 [4], 赤木 暢 [5], 木村尚次郎 [6], 豊田雅之 [7] 他
[1] 東大新領域, [2] 東大工, [3] 阪大産研, [4] 東大物性研, [5] 阪大先端強磁場, [6] 東北大金研, [7] 東工大

Electric dipole spin resonance in a quantum spin dimer system driven by magnetoelectric coupling

電気磁気結合による量子スピンダイマー系の振動電場 ESR



From the high field electron spin resonance measurements with linearly polarized electromagnetic wave, we have clarified that the optical transition between the spin singlet and triplet states in the quantum spin S = 1/2 dimer system $KCuCl_3$ occurs owing to the electric dipole transition. Coupling between the electric polarization, generated from the vector spin chirality, and the oscillating electric fields causes this electric dipole transition.

S. Kimura[1], M. Matsumoto[2], M. Akaki[3], M. Hagiwara[3], H. Tanaka[4]

[1] IMR, Tohoku University, [2] Dept. of Phys., Shizuoka University,

[3] AHMF, Osaka University, [4] Dept. of Phys., Tokyo Institute of Technology

References: S. Kimura *et al*.: "Electric dipole spin resonance in a quantum spin dimer system", Phys. Rev. B **97** (2018) 140406(R).

偏光を用いた強磁場ESR測定によって、S = 1/2反強磁性ダイマー系$KCuCl_3$の本来禁制なスピンシングレットからトリプレット状態への光学遷移が電気双極子遷移によって生じることを明らかにした。この遷移は、ベクトルスピンカイラリティーに由来するスピンに依存した電気分極と振動電場との相互作用によって実効的に発生する動的Dzyloshinskii-Moriya相互作用の働きのため起こる。

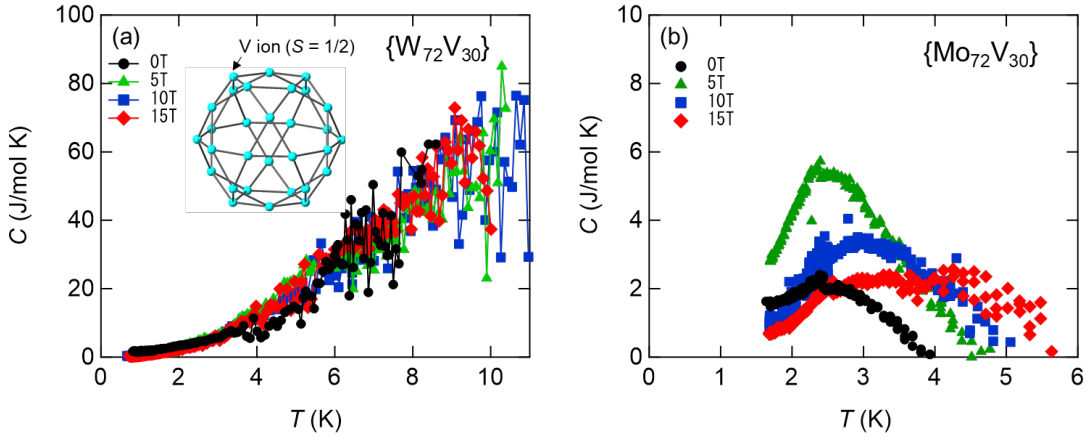
木村尚次郎[1], 松本正茂[2], 赤木暢[3], 萩原政幸[3], 田中秀数[4]

[1] 東北大学金属材料研究所, [2] 静岡大学理学部,

[2] 大阪大学先端強磁場科学研究センター, [4] 東京工業大学理学院

Observation of low-energy singlet excited states in the spin-1/2 spherical kagome clusters $\{Mo_{72}V_{30}\}$ and $\{W_{72}V_{30}\}$

スピン 1/2 球状カゴメクラスター$\{Mo_{72}V_{30}\}$および$\{W_{72}V_{30}\}$における低エネルギー一重項励起状態の観測



The spherical clusters $\{Mo_{72}V_{30}\}$ and $\{Mo_{72}V_{30}\}$, in which the S = 1/2 spins of V ions form an icosidodecahedron, can be regarded as zero-dimensional analog of the kagome lattice. The ground state and the low-energy excited states of these clusters consisting of 20 corner sharing triangles have attracted much interest in the field of geometrically frustrated spin systems. We elucidate in this study the existence of numerous low-energy singlet excited states by the specific heat measurements at low temperatures and in magnetic fields. In addition, it has been revealed that these singlet excited states are partially lifted by the slight distortion of the cluster, and triplet excited states are dominant at low temperatures.

T. Kihara[1], H. Nojiri[1], Y. Narumi[2], Y. Oshima[3], K. Kindo[4], C. Heesing[5], J. Schnack[5], and A. Müller[5]

[1] IMR, Tohoku Univ., [2] AHMF, Osaka Univ., [3] RIKEN, [4] ISSP, The Univ. of Tokyo, [5] Bielefeld Univ.

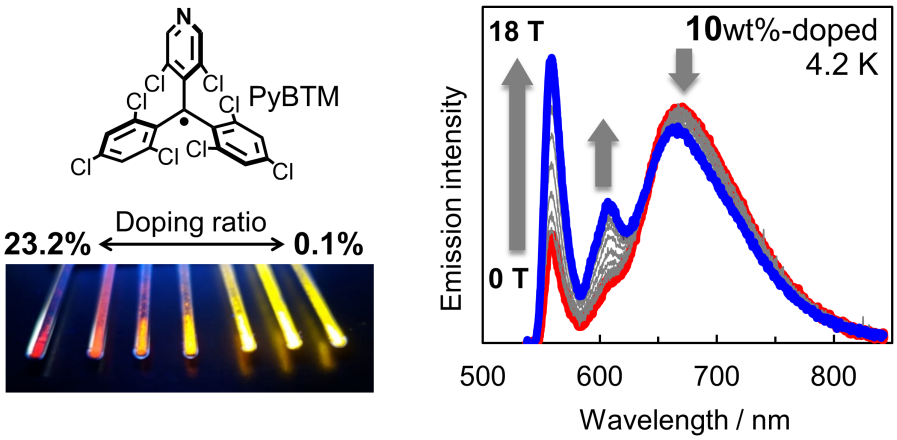
Reference: T. Kihara *et al.*, “Evidence of low-energy singlet excited states in the spin-1/2 polyhedral clusters $\{Mo_{72}V_{30}\}$ and $\{Wo_{72}V_{30}\}$ with strongly frustrated kagome networks”, Phys. Rev. B. **99** 064430 (2019).

球状クラスター{Mo72V30}および{Mo72V30}は、スピン 1/2 を持つ V イオンが 20･12 面体を形成しており、カゴメ格子の類似物質と見なすことができる。頂点共有した 20 個の三角形から成るこの系で、どのような基底状態および低エネルギー励起が実現するかに興味が持たれている。我々は、低温磁場中の比熱測定によって、最低エネルギー近傍に多数の一重項励起状態が存在していることを明らかにした。また、この一重項励起状態はクラスターを僅かに歪ませることで消失し、低温では三重項励起が支配的となることを見出した。

木原　工 [1], 野尻　浩之 [1], 鳴海　康雄 [2], 大島　勇吾 [3]　金道　浩一 [4], C. Heesing[5], J. Schnack[5], A. Müller[5]

[1] 東北大学金属材料研究所, [2] 大阪大学先端強磁場科学研究センター, [3] 理化学研究所, [4] 東京大学物性研究所, [5] Bielefeld Univ.

Magnetoluminescence of a stable organic radical
安定有機ラジカルが示す磁場応答発光



Organic radicals possessing open-shell electronic states are expected to show unique optical properties resulted from interplay between electron spin and luminescence. We investigated the magnetic field dependence of the emission spectra of a stable organic radical PyBTM that was doped into host molecular crystals. The 10 wt%-doped crystals exhibited both PyBTM monomer- and excimer-centered emission bands, and the intensity ratio of these two bands was modulated drastically by applying a magnetic field of up to 18 T at 4.2 K. This is the first observation of a magnetic field effect on the luminescence (magnetoluminescence) of organic radicals. We proposed that a radical-pair state (R* + R) generated in the excites states is a key for realizing this phenomenon.

S. Kimura[1], T. Kusamoto[1], S. Kimura[2], K. Kato[3], Y. Teki[3], H. Nishihara[1]
[1] Dept. of Chem., Univ. of Tokyo, [2] IMR, Tohoku Univ.
[3] Div. of Mol. Mat. Sci., Osaka City Univ.

Reference: T. Kusamoto *et al.*, "Magnetoluminescence in a Photostable, Brightly Luminescent Organic Radical in a Rigid Environment" Angew. Chem. Int. Ed. **57** (2018) 12711.

開殻電子構造を有する有機ラジカルでは、電子スピンと発光特性の協奏に基づく光物性が期待できる。我々は安定有機ラジカル PyBTM をドープした分子結晶の発光スペクトルの磁場依存性を調べた。4.2 K における測定の結果、10wt%ドープ量の試料は PyBTM のモノマーとエキシマーに由来する発光帯を示し、この二つの発光帯の強度比が磁場印加とともに大きく変化する（発光スペクトルが大きく変化する）ことを明らかにした。これはラジカルの発光の磁場効果の初観測である。我々は励起状態において生成するラジカルペアが磁場効果発現の鍵となることを提案した。

木村　舜[1], 草本　哲郎[1], 木村　尚次郎[2], 加藤　賢[3], 手木　芳男[3], 西原　寛[1]
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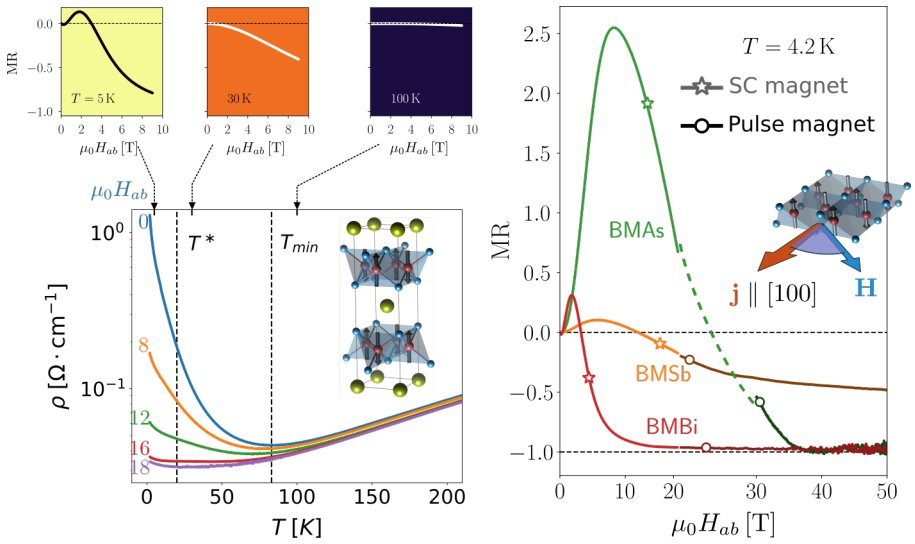
Large magnetoresistance in $BaMn_2Pn_2$ antiferromagnets



LMR as seen in temperature and (left) and H_{ab} scans at low temperature (right). The crystal structure of $BaMn_2Pn_2$ is shown the inset of the left.

A new kind of large magnetoresistance (LMR) phenomenon was found in a family of $BaMn_2Pn_2$ antiferromagnets (Pn = P, As, Sb, and Bi) with parity-time symmetry. Under magnetic fields ($\mathbf{H}_{ab}$) perpendicular to the antiferromagnetic axis, the resistivities of these materials are reduced by 60 times, thus yielding a LMR of about -98%. The anisotropy of the LMR reveals that the electrical conductivity is extremely sensitive to the minute changes in the direction of the antiferromagnetic moments induced by the parity-time symmetry-breaking $\mathbf{H}_{ab}$. The observed LMR arises from the nontrivial low-energy bands of $BaMn_2Pn_2$ antiferromagnets, which are governed by the parity-time symmetry.

K-K. Huynh[1], T. Ogasawara [2], K. Kitahara[2], Y. Tanabe[2], S. Y. Matsushita[2], T. Tahara[3], T. Kida[3], M. Hagiwara[3], D. Arčon[4,5], K. Tanigaki[1,2]

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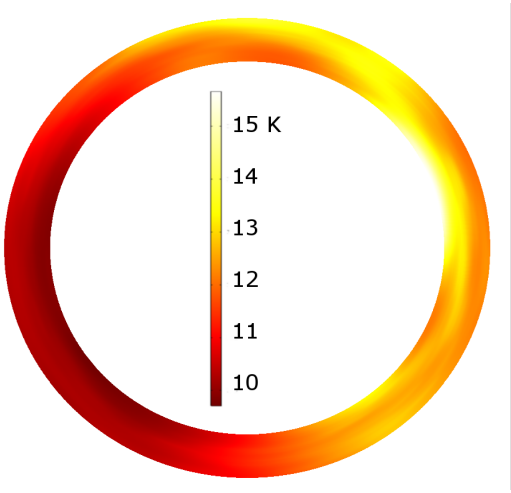
Reference: K.-K. Huynh *et al.,* Negative and positive magnetoresistance in the itinerant antiferromagnet $BaMn_2Pn_2$ (Pn = P, As, Sb, and Bi), Phys. Rev. B 99, 195111 (2019)

Simulation of local dissipation phenomena in high field REBCO HTS inserts



Simulated temperature distribution in a REBCO pancake at the beginning of thermal runaway, assuming 7.5 % variations of performance along the tape

Rare-Earth BaCuO (REBCO) High Temperature Superconductors (HTS) are attractive for very high field inserts due to their large engineering current densities under high magnetic fields when operating close to 4.2 K and their good mechanical strength. REBCO tapes display performance inhomogeneity along their lengths, with mm-scale variations of the local critical current. Combined with their very good thermal stability, it leads to a high risk of damaging hot spots when operating close to the estimated critical current. We developped a model to study the occurrence and evolution of dissipative zones in REBCO HTS magnets and the resulting thermal runway phenomenon, taking into account the local inhomogeneity of REBCO tapes performances. This model was used to investigate the destructive thermal runway that occurred in the REBCO insert of the 25 T CSM magnet developed at the HFLSM. Although imperfectly, we could reproduce such event and demonstrate that a more sensitive detection system, with threshold value in the mV range, could have been used to protect such insert effectively from sharp local defects, while detection system in the tens of mV range would be sufficient if the REBCO tape used in the insert have typical inhomogeneity.

A. Badel[1, 2], B. Rozier[2], K. Takahashi[1], S. Awaji[1]
[1] IMR, Tohoku Univ., Japan [2] University Grenoble Alpes, France

Reference: A. Badel *et al.*, “Simulation of local dissipation phenomena in the REBCO insert of the 25 T CSM magnet: Understanding and Preventing destructive thermal runaway”, *IEEE Trans. Appl. Supercond.* **25(5)** 4600605, 2019.