物性研究所セミナー

標題：New topological quantum order in 2D lattices from non-invertible symmetries
日時：2025 年 2 月 17 日(月) 午後 4 時～午後 5 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：Prof. Ayan Mukhopadhyay
所属：Pontificia Universidad Católica de Valparaíso, Chile
要旨：

I will introduce an exactly solvable 2D lattice model which reveals a large number of distinct topological phases with non-invertible (generalized) symmetries. In all these topological phases, which have topological ground state degeneracy, a commutative stabilizer monoid of Hermitian operators leave the ground state invariant and can also distinguish *all* local excitations, (These symmetries are indeed symmetry operations.) There exists novel confined fractonic excitations which change the nature of deconfined excitatons profoundly. The fusion rules form an associative but noncommutative. non-Abelian and non-unital category, and are distinct for each of these phases. A class of these phases are adiabatically connected to a limit which can be described in terms of generalized free field theories. I will describe systematic ways to construct such phases. I will also discuss phases which do not have generalized free field limits.These phases have novel forms of non-local entanglement as many of them share the same topological entanglement entropy. They also violate the entanglement bootstrap axioms. When the phases do not have a generalized free field limit, the violation of the entanglement bootstrap axioms can happen for arbitrary large subregions signifying new forms of long-range entanglement.

標題：パルス強磁場 ESR によるテラヘルツ一方向透過性の観測と定常強磁場角度回転比熱測定の開発
日時：2025 年 2 月 19 日(水) 午後 1 時 30 分～午後 2 時 30 分
場所：Online
講師：赤木暢 助教
所属：東北大学金属材料研究所
要旨：

近年、マルチフェロイック物質における電気磁気効果を反映した特殊なマグノンが注目されています。今回は、阪大先端強磁場のパルス強磁場電子スピン共鳴測定を用い、特殊なマグノン連続励起の観測と巨大な方向二色性の観測に成功し、それらの理論的解明を進めたのでその成果について紹介する。

また、最近開発した 25TCSM など定常強磁場下で使用できる 2 軸回転比熱測定についても、開発の詳細を中心に紹介した。

標題：Entanglement Entropy at Deconfined and Gross-Neveu Quantum Critical Points
日時：2025 年 2 月 20 日(木)午前 9 時～午前 10 時
場所：Online
講師：Jonathan D′Emidio
所属：University of Tennessee

要旨：

The structure of entanglement underpins much of our understanding of modern condensed matter physics. The most basic quantifier, the entanglement entropy, displays universal properties that offer a unique characterization of quantum many-body systems. In this talk I will introduce a technique for computing entanglement entropy in quantum Monte Carlo simulations, based on the concept of nonequilibrium work to compute free energy differences, which allows for precise calculations of unprecedented size. As an application of this approach, I will present results on a 2D quantum spin model for deconfined criticality, where emergent symmetry is observed at the critical point between two disparate ordered phases. Finally, I will show how this methodology can be successfully adapted to study 2D models of interacting fermions. This is applied to the Hubbard model on the honeycomb lattice, which realizes a Dirac semi-metal phase separated by a Gross-Neveu transition from an antiferromagnetic Mott insulator. I will present results throughout the phase diagram and at the critical point of this model, where universal logarithmic terms of the entanglement entropy are observed for the first time.

標題：動物の光受容タンパク質オプシンの歴史・特徴・応用
日時：2025 年 2 月 21 日(金) 午前 10 時～午後 0 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：塚本 寿夫
所属：神戸大学
要旨：

ヒトなどの動物は外界からの物理的刺激の代表である光を、主に眼で受容している。このような動物の光受容機能の「入口」となる、光情報を細胞内に伝えるプロセスはオプシンと呼ばれる光受容タンパク質によって担われている。本セミナーでは、種々の動物が持つオプシンの分子としての機能や特徴がどのような歴史的文脈で解明されてきたかを概説した上で、オプシンが示す多様な分子特性を紹介し、それらの分子特性が動物の光受容機能をどのように特徴づけているのかお話しする。さらに、動物のオプシンを、生物学研究を発展させるツールとして応用する取り組みについても紹介した。

標題：Spin and orbital angular momentum degrees of freedom in time-resolved XUV spectroscopies
日時：2025 年 2 月 25 日(火) 午後 3 時～午後 4 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：Mauro Fanciulli **氏**
所属：CY Cergy Paris Université
要旨：

Light-matter interaction comprehends a number of fundamental processes at the core of most condensed matter physics studies. While experimental challenging, it is of great importance to seek the combination of different degrees of freedom, in order to have a better insight of the particular process and at the same time to exploit it as an investigation technique.

In this seminar, I will present two separate case studies with the common thread of combining spin and orbital angular momentum degrees of freedom in time-resolved spectroscopic techniques in the extreme ultraviolet (XUV) range, with the aim of extracting qualitatively new type of information.

・Combining a high harmonic generation (HHG) XUV beamline at the Attolab facility [1] with a hemispherical analyzer equipped with a VLEED spin polarimeter, we are able to perform a complete spin-, time- and angle-resolved photoemission spectroscopy (STAR-PES) experiment, giving access not only to the charge but also to the spin dynamics in condensed matter systems. We have investigated two prototypical transition metal dichalcogenides (TMDC): WSe2 and WTe2. Our results in the inversion-symmetric 2H-WSe2 bulk crystal [2] reveal efficient chiroptical control of bright excitons’ hidden spin polarization. After the optical photoexcitation however, intervalley scattering between nonequivalent K-K’ valleys leads to a decay of bright excitons’ hidden spin polarization. Conversely, the ultrafast formation of momentum-forbidden dark excitons acts as a local spin polarization reservoir, which could be used for spin injection in van der Waals heterostructures involving multilayer transition metal dichalcogenides. In the case of dichalcogenide WTe2 [3], a precursor of Weyl type-II semimetal topological phase, the comparison of STARPES measurements with relativistic one-step photoemission calculations reveal a spin accumulation above the Weyl points region, which is consistent with a spin-selective bottleneck effect due to the presence of spin-polarized cone-like electronic structure.

・The spin angular momentum (SAM) of a photon is associated to the circular polarization of electromagnetic radiation in the wave picture. Like other quantum particles, photons can carry also orbital angular momentum (OAM), which corresponds to a helicoidal wavefront of light instead of a plane wave. While the SAM of light is extensively used for dichroic studies, e.g. in X-ray magnetic circular dichroism (XMCD), the OAM degree of freedom has been much less exploited. I will present the classical electromagnetic theory for the case of scattering of light carrying OAM by a non-uniform magnetic material, an extension of the magneto-optic Kerr effect, leading to a differential signal associated to the so-called magnetic helicoidal dichroism (MHD) [4]. It is found that MHD can give information about the overall topology of the magnetic structure under the probing helicoidal beam. I will also present the first experimental observation of MHD measured at the FERMI free electron laser on a permalloy magnetic vortex with an XUV beam at the Fe 3p resonance [5]. The agreement of the experimental results with the theoretical predictions opens up two directions: on one hand, the extension of MHD to the time domain, allowing to track the ultrafast demagnetization and remagnetization dynamics and the transient modification of magnetic topology after a femtosecond infrared pulse [6]; on the other hand, the possibility to explore fundamental properties of light such as photon spin-orbit interaction [7].

References

[1] D. Bresteau et al., European Physical Journal Special Topics 1 (2023).
[2] M. Fanciulli et al., Physical Review Letters 131, 066402 (2023).
[3] M. Fanciulli et al., Physical Review Research 2, 013261 (2020).
[4] M. Fanciulli et al., Physical Review A 103, 013501 (2021).
[5] M. Fanciulli et al., Physical Review Letters 128, 077401 (2022).
[6-7] M. Fanciulli et al., submitted

標題：Adsorption-desorption phase transition and dynamical scaling in a soft porous crystal
日時：2025 年 3 月 4 日(火) 午後 4 時～午後 5 時
場所：物性研究所 本館 6 階第 2 セミナー室(A612 号室)及び Online
講師：光元 亨汰
所属：東京大学 総合文化研究科
要旨：

Metal-organic frameworks (MOFs), which possess a high degree of crystallinity and a large surface area with tunable inorganic nodes and organic linkers, often exhibit soft mechanics upon molecular adsorption [1]. When guest molecules are adsorbed heterogeneously, heterogeneity in the lattice structure and stiffness of host frameworks‐‐elastic heterogeneity‐‐emerges due to the interaction between guest molecules and host matrices. However, the role of elastic heterogeneity in soft MOFs remains elusive.

We first show the asymmetric role of elastic heterogeneity in the adsorption-desorption transition[2]. We construct a minimal model incorporating adsorption-induced lattice expansion/contraction and an increase/decrease in the elastic moduli. By using Monte Carlo simulations, we find that the transition is hindered by the entropic and energetic effects, which become asymmetric in the adsorption and desorption processes, leading to the strong hysteretic nature of the transition. Furthermore, we find that elastic heterogeneity can stabilize a superlattice of the guest molecules[3]. Our results provide a theoretical guideline for designing MOFs with tunable adsorption hysteresis and patterns of adsorbates using elastic heterogeneity.

Elastic heterogeneity also plays an essential role in non-equilibrium dynamics in MOFs. In the adsorption process, the adsorption domain growth occurs from the boundary in contact with the guest particle bath. A rough surface of the adsorption domain emerges due to elastic heterogeneity. The roughness shows a dynamic scaling behavior called Family-Vicsek scaling.

[1] S. Horike, S. Shimomura and S. Kitagawa, Nat. Chem. 1, 695 (2009).
[2] KM and K. Takae, Proc. Natl. Acad. Sci. 6, e2302561120 (2023).
[3] KM and K. Takae, Phys. Rev. Res. 6, L012029 (2024).

標題：トポロジカル秩序の理論的性質の理解とフィボナッチ・エニオンの実現
日時：2025 年 3 月 10 日(月) 午前 10 時 30 分～2025 年 3 月 11 日(火) 午後 5 時
場所：東京大学柏キャンパス 新領域基盤棟 2F 大講義室（2C0）
講師：戎　弘実
所属：京都大学基礎物理学研究所
要旨：

通例、物理学において相という概念は非常に重要であり、これまで系の局所的な秩序変数を調べることで分類されてきました。しかし分数量子ホール系、スピン液体など、今までの相分類の枠組みでは収まらないトポロジカル秩序と呼ばれる新しい相が提唱され、現代の物理学において重要なテーマの 1 つとなっています。この相は局所的でなく、系の大域的な情報（系のトポロジー）によって分類されます。この相の重要な性質の 1 つとして、分数電荷の励起・エニオンを持つことが挙げられます。

本セミナーは 6 回に分けて実施し、トポロジカル秩序に関する重要な性質・概念−具体的には相の有効理論（Chern-Simons 理論）、エッジ状態を記述する共形場理論、パラフェルミオンの励起、量子もつれと分数統計性との関連、エニオン凝縮など−について理解することを目指します。これらの知見を基に、R. Mong らによる $\nu = 2/3$ の分数量子ホール系やスピン液体からフィボナッチ・エニオン（トポロジカル量子コンピュータに有用とされるエニオンの 1 つ）を創成する画期的な提案[1]について議論しました。

[1] R. Mong, D. Clarke, J. Alicea, N. Lindner, P. Fendley, C. Nayak, Y. Oreg, A. Stern, E. Berg, K. Shtengel, and M. Fisher, “Universal Topological Quantum Computation from a Superconductor-Abelian Quantum Hall Heterostructure” Phys. Rev. X 4, 011036 (2014).

標題：Exotic flux phases of quantum spin ice
日時：2025 年 3 月 13 日(木) 午後 2 時〜午後 3 時
場所：物性研究所本館 6 階 第 4 セミナー室 (A614)
講師：Alaric Sanders
所属：The University of Cambrdige
要旨：

Recent excitement in the quantum spin ice community has come from the experimental discovery of pseudospin-1/2breathing pyrochlores, including Ba3Yb2Zn5O11, in which inversion symmetry is broken by the 'up' and 'down' tetrahedra taking different physical sizes. We show here that the often-neglected Jz± coupling between Kramers ions, in combination with the breathing nature of the lattice, can produce an imaginary ring flip term. This can lead to an unconventional 'U(1) π/2 phase', corresponding to a maximally dense packing of visons on the lattice. Coherent dynamics persist in all phases, together with an emergent QED description, in a manner reminiscent of fragmentation in spinon crystals. We characterize the enlarged QSI phase diagram and its excitations, showing that the imaginary ring flip acts both as a chemical potential for visons and as an effective three-photon vertex akin to strong light-matter coupling. The novel coupling causes a structured high-energy continuum to emerge above the photon dispersion, which is naturally interpreted as three photon up-conversion in a nonlinear optical crystal.

標題：X 線自由電子レーザーによるタンパク質の動的構造と反応可視化
日時：2025 年 3 月 13 日(木) 午前 10 時〜午前 11 時 30 分
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：南後 恵理子
所属：東北大学多元物質科学研究所
要旨：

我々は、SACLA においてタンパク質構造解析手法の一つであるシリアルフェムト秒結晶構造解析の技術開発に取り組み、X 線自由電子レーザーと光励起による反応開始とを組み合わせることにより、光励起性タンパク質がプロトン輸送する過程を原子レベルで“動画”のように捉えることに成功した。この手法はその時間分解能から、これまで原子分解能で追うことのできなかった化学反応などの早い反応の追跡に適している。本発表では、我々が取り組んできた分子動画解析の技術開発と実際の解析例について紹介すると共に、東北大学キャンパス内に設立された次世代放射光施設 NanoTerasu における生命科学系利用についてもご紹介した。

標題：Architectures and algorithms for early FTQC
日時：2025 年 3 月 14 日(金) 午後 1 時〜2025 年 3 月 17 日(月) 午後 1 時
場所：First Session: ISSP A614, second session: ISSP A615
講師：Dr. Andreas Thomasen
所属：QunaSys Inc
要旨：

Theory session: The Noisy Intermediate-Scale Quantum (NISQ) era of quantum computing is characterized by quantum devices that have low error rates, but no error correction and typically on the order of 100 qubits, whereas the era of fault-tolerant quantum computing (FTQC) requires devices with full error correction facilitated by hundreds of thousands to millions of qubits for every logical qubit. Due to the distinct requirements and operating characteristics of these devices, algorithms and applications supported by NISQ and FTQC respectively are highly distinct as well.

However, this leaves a large gap, both in terms of devices, algorithms and applications which exist in the intermediate regime where partial error correction is possible and the devices support on the order of tens of thousands of qubits. In this seminar we will give a brief introduction to quantum computing for a non-specialist audience. We will then describe device architectures and algorithms that are specifically designed to fill this gap during the so-called early FTQC era. We will present the space-time efficient analogue rotation (STAR) architecture together with some algorithms that are well supported by it, namely quantum selected configuration interaction (QSCI) and statistical phase estimation (SPE). This seminar serves as theoretical background for our hands-on session on QURI SDK. The algorithms introduced are directly available as OSS as described in https://quri-sdk.qunasys.com/

Hands-on workshop: This workshop will be a hands-on session on QURI SDK, following the seminar by March 14th. Even if you did not attend the previous seminar, please join us if you would like to learn how to use QURI SDK. The workshop outline is as follows:

1) General introduction to QURI SDK and its intended workflow
2) Introduction to QURI VM with various virtual devices introduced
3) Experimenting with surface code parameters in QURI VM
4) Introduction to QURI Algo and algorithm components
5) Introduction to various algorithms for early FTQC

The learning objectives for this workshop is for the participants to be able to write quantum algorithms for their own research problems and simulate their performance on quantum hardware.

About the speaker: Dr. Andreas M. D. Thomasen is a research and development engineer at QunaSys with wide experience in NISQ algorithm development, software development and theoretical physics. His current research work focuses on benchmarking algorithms and developing industry applications using real quantum computing systems. Dr. Thomasen received his Ph.D. in Physics from the Okinawa Institute of Science and Technology focused in Topology in Condensed Matter. He holds a Master of Engineering in Optics and Electronics from Aarhus University in Denmark focused on Quantum cryptography.

About the company: QunaSys is advancing the industrial application of quantum computing through collaborations with numerous companies and research institutions. Through joint research with these partners, they are developing new technologies to help businesses build a competitive edge, exemplified by the creation of our quantum chemistry calculation method, “QSCI” (Quantum-Selected Configuration Interaction). Looking ahead to the era of fault-tolerant quantum computers (FTQC), we are also working to expand applications in new fields like Computer-Aided Engineering (CAE) and offering tools like QURI SDK to maximize quantum computing capabilities and improve algorithm development efficiency.

標題：Purely electronic chirality orders in achiral systems
日時：2025 年 3 月 17 日(月) 午後４時～午後５時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：服部 一匡 氏
所属：東京都立大学
要旨：

We construct purely electronic chirality (pEC) in achiral systems i.e., in the absence of structural chirality. In condensed matter physics and chemistry, chirality has conventionally been understood as a mirror-image asymmetry in crystal or molecular structures [1]. We demonstrate that simple electric quadrupole orders exhibit chirality-related properties without atomic displacement [2]. We point out that their chirality handedness can be controlled by magnetic fields, opening a simple way to manipulate the chirality domain. As a representative example, we analyze a model featuring 120-degree antiferro quadrupole orders on a distorted kagome system, predicting various chirality-related responses in the nonmagnetic ordered phase of URhSn [3]. We also briefly discuss that chiral phonons can emerge in achiral crystals through coupling with the pEC order. Our results provide a distinct origin of chirality and a fundamental basis for exploring the interplay between electronic and structural chirality.

Refs.
[1] L. D. Barron, Chirality 24, 879 (2012).
[2] T. Ishitobi and K. Hattori, arXiv:2502.13977.
[3] Y. Shimizu et al., Phys. Rev. B, 102, 134411 (2020).

標題：Ab initio extended Hubbard interactions
日時：2025 年 3 月 27 日(木) 午後 4 時～午後 5 時
場所：物性研究所 6 階第 5 セミナー室（A615）及び Online
講師：Young-Woo Son **氏**
所属：Korea Institute for Advanced Study
要旨：

In this talk, I will present my group and coworkers' recent efforts to develop an efficient first-principles calculation method to compute electronic structures, phonon dispersions, and electron-phonon interactions of correlated materials [1-10]. The method can obtain self-consistent on-site and inter-site Hubbard interactions using newly developed position-dependent pseudohybrid functionals [1]. All the interactions can be evaluated within self-consistent loops without serious additional costs such that the method can be as fast as conventional ab initio methods with (semi)local density approximations while its accuracy is comparable to sophisticated methods such as GW approximation [1,3,5-7].

I will demonstrate that the newly developed method can compute accurate quasiparticle bands structures of various materials [1-4], phonon dispersions of correlated insulators [5] and charge-ordered materials [6], energy band splitting owing to spin-orbit coupling [7], charged defects states in oxides [8], ferroelectric properties of perovskite oxides [9] and electron-phonon interactions in transparent oxides [10]. Considering its improved accuracy with low computational costs, our new computational method is expected to contribute massive database-driven high-throughput quantum materials researches.

[1] S.-H. Lee and Y.-W. Son, Phys. Rev. Research 2, 043410 (2020).
[2] J. Huang et al., Phys. Rev. B 102, 165157 (2020).
[3] W. Yang et al., Phys. Rev. B 104, 104313 (2021).
[4] Y.-W. Son et al., Nano Lett. 22, 3112 (2022).
[5] W. Yang et al., J. Phys.: Condens. Matter 34 295601 (2022).
[6] B. G. Jang et al., Phys. Rev. Lett. 130, 136401 (2023).
[7] W. Yang et al., Phys. Rev. B 110, 155133 (2024).
[8] Y. Yang et al., arXiv:2409.01795
[9] M. C. Choi et al, arXiv:2502.00391
[10] W. Yang et al., in preparation (2025).

標題：Ultra-low friction of gold nanocrystals on graphene
日時：2025 年 4 月 16 日(水) 午後 2 時～午後 3 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)及び Online
講師：Prof. Masa Ishigami
所属：Department of Physics, University of Central Florida
要旨：Abstract:

Previous calculation [Guerra et al, Nature Materials, 9 634 (2010).] has predicted that gold nanocrystals slide on graphite with two radically different friction coefficients depending on their speeds. At low speeds (~µm/sec), nanocrystals on graphite are expected to possess higher friction, consistent with previous studies of thermal diffusion of gold on graphite and on graphene. At high sliding speeds in the range of 100 m/sec, nanocrystals are expected to behave radically differently, with a vanishing drag and, therefore, minimal friction. Such high speeds are not easily accessible by atomic force microscopy (AFM), a commonly used to measure nanoscale friction.

My research group has measured friction of gold nanocrystals with diameter ranging from 3 to 5 nm on graphene at speeds up to 35.6 cm/sec. We find the friction at high speeds to be an order of magnitude lower (!) than predicted previously by Guerra et al. I will discuss our measurement technique, the experimental results, and the origin of the observed friction (which is even lower than expected!) as well as recently ongoing efforts to understand this phenomenon further at individual nanocrystal levels. I will also briefly discuss other projects going on in my lab which includes magic angle graphene-based photodetectors, and application of machine learning to achieve high throughput scanning tunneling microscopy.

標題：パルス磁場中での磁気光学カー効果測定技術の開発と展望
日時：2025 年 4 月 18 日(金) 午前 11 時～午前 0 時
場所：Online
講師：米澤 進吾 教授
所属：京都大学工学研究科 電子工学専攻
要旨：

磁気光学カー効果とは物質表面における光の反射に伴って偏光状態が変化する効果である。これは光学領域でのホール効果ととらえることもでき、異常ホール効果と同様、磁化やバンドトポロジーのプローブである。類似の効果として、光の透過に伴う偏光の変化である磁気光学ファラデー効果が知られており、パルス磁場下での実験に既に使われている。

一方、磁気光学カー効果は、偏光の角度変化が最大でもミリラジアンのオーダーであり、ファラデー効果に比べて桁違いに小さくパルス磁場下での測定は挑戦的である。しかし、カー効果測定は、不透明な物質や薄膜などに適用できるという重要なメリットを持っているため、カー効果のパルス磁場下での測定が可能になれば、多くの対象物質に適用可能なパルス磁場下の有力な測定手法となりえる。

我々のグループでは、カイラル超伝導などの非自明な時間反転対称性破れ状態の検出を目指した超高感度の磁気光学カー効果の測定手法を導入してきたが、現在この手法をパルス磁場下の測定に拡張する研究を行っている。最近、2msec 程度のパルス磁場下において強磁性体の磁気光学カー効果の測定に成功した。本発表ではその現状を紹介するとともに将来展望を議論したい。

標題：Chiral effects and turbulence in supernovae
日時：2025 年 4 月 18 日(金) 午後 4 時 ～
場所：Online and Lecture Room A612 (Hybrid)
講師：Prof. Naoki Yamamoto
所属：Keio University
要旨：

Systems with Dirac or Weyl fermions exhibit quantum chiral transport phenomena induced by magnetic field and vorticity. These transport phenomena have a close connection to the chiral anomaly in quantum field theory and are considered to manifest in a variety of systems, such as Weyl/Dirac semimetals, quark-gluon plasma in relativistic heavy-ion collisions, electroweak plasma in the early universe, and neutrino matter in supernovae. In this talk, we focus on high-density lepton matter in supernovae and discuss how chiral transport phenomena can significantly alter the hydrodynamics evolution, including turbulence, with potential implications for magnetars, pulsar kicks, and supernova explosions.

標題：Surface acoustic waves-driven magnon spin Hall effect in atomically thin van der Waals antiferromagnets
日時：2025 年 5 月 2 日(金) 午後 4 時～午後 5 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：佐野 涼太郎
所属：東京大学物性研究所
要旨：

Intrinsic magnetism in two-dimensional (2D) materials had long been believed to hardly survive due to the enhanced thermal fluctuations. However, the recent discovery of exfoliated van der Waals (vdW) magnets has opened up a new avenue for 2D magnetism at finite temperatures [1,2]. Especially, transition metal phosphorus trichalcogenides are a family of easily exfoliatable vdW antiferromagnets [3]. These materials share the same honeycomb structure, but the bulk antiferromagnetic (AFM) phase varies depending on the magnetic elements. Furthermore, antiferromagnets exhibit ultrafast dynamics, null stray field, and robustness against external fields. Therefore, the investigation of these materials paves the way toward not only the understanding of 2D magnetism, but also future AFM spintronic devices.

Standard methods such as magnetization measurements and neutron diffraction, which could only access macroscopic magnetic properties, are not suitable for the study of atomically thin magnets. Especially, antiferromagnets do not have net magnetization, magneto-optical Kerr effect is not available either. Although recent studies have focused on Raman spectroscopy [4] and second-harmonic generation [5] to detect crystal symmetry lowering associated with the AFM transition, these signals do not provide clear identification in the monolayer limit. Therefore, an inclusive method which suits for exploring 2D antiferromagnets is highly desired.

Here, we propose a magnon spin Hall current driven by the surface-acoustic waves (SAWs) as a novel probe for such 2D vdW antiferromagnets [6]. Owing to extremely large mechanical flexibility of 2D materials, SAWs are ideally suited for fundamental research of them. A modulation of exchange energies due to strain mimics the role of gauge fields for magnons. The strain gauge fields work at two valley points in the opposite direction, leading to the activation of the valley degrees of freedom (DOF). Therefore, the valley DOF with the use of SAWs is a promising concept for detection of the magnetic order in 2D vdW antiferromagnets.

[1] C. Gong et al., Nature 546, 265 (2017).
[2] B. Huang et al., Nature 546, 270 (2017).
[3] K. Du et al., ACS Nano 10, 1738 (2016).
[4] J. Lee et al., Nano Lett. 16, 7433 (2016).
[5] H. Chu et al., PRL 124, 027601 (2020).
[6] R. Sano et al., PRL 132. 236302(2024).

標題：Orientational ordering in a two-dimensional active model for dense bacterial suspension
日時：2025 年 5 月 7 日(水) 午後 2 時～午後 3 時
場所：物性研究所本館 6 階 第 5 セミナー室（A615）
講師：Yoshihiko Nishikawa
所属：Kitasato University
要旨：

Active matter systems often exhibit dynamic and static properties that are highly distinct from thermal equilibrium, including motility-induced phase separation, active turbulence, and crystallization in low dimensions. Bacterial suspension is one typical example, in which self-propelled bacteria move and interact with others, leading to complex, emergent behaviors. Recently, H. Lama et al. (2024) experimentally showed that two-dimensional dense suspension of E. Coli has two glassy transitions at different densities, where the orientational and translational degrees of freedom become dynamically arrested, respectively. They further found that the exponent for the critical divergence of the relaxation time is smaller than the lower-bound of the mode-coupling theory for equilibrium glassy systems. While this suggests the glassy transition to be qualitatively different from the equilibrium counterpart, the origin of the small exponent remains unclear.

Here, we propose a minimal active model for dense bacterial suspension in two dimensions and numerically study its dynamics and statics. In our model, each bacterium is represented by a spherocylinder of fixed length, with its state specified by position of the center of mass and orientation. Bacteria interact with each other via a short-range repulsive interaction and actively move in the direction of its orientation. To mimic the tumbling motion of bacteria in a crowded environment, we further incorporate in the model stochastic velocity reversal with a fixed rate per unit time.

With increasing density, the orientational dynamics of the system drastically slows down and its relaxation time shows a rapid growth, suggesting the critical divergence at a finite density ¥phi_c. On the other hand, even at ¥phi_c, the translational dynamics has a short relaxation time and bacteria can easily change their positions, with their orientations virtually fixed for a very long time. These dynamical properties are consistent with the experiment. Despite the long time scale for the bacterial orientation, the nematic order remains short ranged, again consistent with the experimental results. However, we find that the length scale of the ‘tetratic’ fourfold orientational order grows much faster than that of the nematic order when approaching ¥phi_c, indicating that the slow orientational dynamics is controlled by this orientational order. We will also discuss the collective orientational and translational dynamics near ¥phi_c.

標題：Estimation of continuum models for soft material self-assembly and data-driven coarse-graining

日時：2025 年 5 月 14 日(水) 午後 4 時～午後 5 時

場所：Online and Seminar Room 5 (A615), ISSP

講師：義永 那津人 教授

所属：公立はこだて未来大学

要旨：

The design of structures of materials is one of the most important issues in various fields of physical science, as their structures are related to their physical properties. The structures are often characterized by periodic or quasiperiodic order. These ordered structures, which we call a pattern, are ubiquitous in nature ranging from fluid convection to the microphase separation of block copolymers and atomic and molecular crystals. Surprisingly, the same pattern appears in different systems with completely different length scales. Recently, we have been working on estimating a model and non-equilibrium process to reproduce a desired structure[1,2].

Continuum models described by partial differential equations (PDE) have been widely used to reproduce patterns in nature and to give insight into the mechanism underlying pattern formation. Although many PDE models have been proposed, they rely on the pre-request knowledge of physical laws and symmetries, and developing a model to reproduce a given desired pattern remains difficult. We propose a method to estimate the best dynamical PDE for one snapshot of a target pattern under the stationary state without ground truth[3]. We apply our method to nontrivial patterns, such as quasi-crystals (QCs), a double gyroid and Frank Kasper structures recently found in soft materials. Our method works for noisy patterns and the pattern synthesised without the ground truth parameters, which are required for the application toward experimental data.

We also discuss our recent efforts to estimate a coarse-grained model from data of microscopic dynamics in a data-driven manner[4]. Specifically, we consider a hydrodynamic description of active matter systems from their particle dynamics.

References:

[1] U. Tu Lieu and N. Yoshinaga, J. Chem. Phys. 156 (2022) 054901.

[2] U. Tu Lieu and N. Yoshinaga, Soft Matter 21 (2025) 514.

[3] N. Yoshinaga and S. Tokuda, Phys. Rev. E 106 (2022) 065301.

[4] B. Roy and N. Yoshinaga, arXiv:2411.03783 (2024).

標題：A free probability approach to quantum chaos in random matrix ensembles

日時：2025 年 5 月 16 日(金) 午後 1 時 30 分～午後 2 時 30 分

場所：物性研究所本館 6 階 第 5 セミナー室 (A615)

講師：Pratik Nandy

所属：Yukawa Institute, Kyoto University

要旨：

A quantum dynamical system can be described as an algebra of bounded operators in a non-commutative probability space equipped with a time evolution map. In free probability theory, quantum chaos is marked by “free independence” between observables at early and late times, causing certain statistical measures (cumulants) to vanish. Motivated by this, we study the statistics of a time-evolved operator in the Rosenzweig-Porter (RP) random matrix ensembles. The RP model displays a complex phase structure, namely the ergodic, fractal, and localized regimes, featuring two phase transitions. We show that the free probability approach is powerful enough to distinguish these three phases. The numerical results in the ergodic regime can be verified analytically using complex algebra tools such as the Cauchy transform and Stieltjes inversion methods. This talk is based on an ongoing work.

標題：Pushing the Limits: How New Materials Are Powering the Future of Chips
日時：2025 年 5 月 16 日(金) 午後 2 時～午後 3 時
場所：物性研究所本館 6 階 第 2 セミナー室（A612）
講師：Dr. Johan Swerts
所属：imec
要旨：

To sustain CMOS transistor density scaling in accordance with Moore’s Law, the semiconductor industry has undergone a series of architectural transformations−from the 2D planar transistor to the FINFET architecture, and now toward nanosheet-based gate-all-around (GAA) transistors at the 3nm technology node. Looking ahead, complementary FET (CFET) architectures, which involve the vertical stacking of n-type and p-type transistors, are expected to emerge around 2030. These transitions are increasingly depending on the integration of novel materials, as traditional scaling approaches reach their physical and performance limits. For example, the increasing resistance-capacitance (RC) delay associated with scaled interconnects necessitates the exploration of copper replacement materials and alternative metallization schemes that can provide lower resistivity. Beyond the CFET era, the transistor channel might undergo a fundamental shift, with 2D-grown materials being actively investigated for their potential to enhance electrostatics and carrier transport in ultra-scaled nodes.

In parallel, memory technologies face their own scaling challenges. Traditional DRAM is approaching fundamental limits in capacitor and access transistor scaling, prompting the exploration of 3D DRAM architectures and new channel materials such as deposited semiconductor oxides. These approaches aim to enable higher density without sacrificing retention or speed. The field of emerging non-volatile memories−including ferroelectric RAM, and magnetoresistive RAM (MRAM)−is particularly dependent on material innovation.

This presentation will provide an insight in key materials innovations shaping the future of semiconductor devices. We will discuss both the opportunities and the integration challenges that must be addressed to translate these materials from laboratory research into manufacturable technologies.

Johan Swerts is currently serving as the director of the Materials-Interfaces and Deposition-Analysis (MIDA) department at imec since 2022. His department, comprising around 100 researchers and R&D engineers, focuses on developing novel materials and deposition processes for imec’s advanced 300mm silicon pilot line.
imec (Interuniversity Microelectronics Centre) is a leading international research and development organization specializing in nanoelectronics and digital technologies. Headquartered in Leuven, Belgium, imec was founded in 1984 and has since expanded globally. imec’s contributions are pivotal in advancing semiconductor technology, making chips more efficient and supporting applications across healthcare, automotive, and energy sectors. The organization continues to play a crucial role in Europe’s technological ecosystem, including leading initiatives under the European Chips Act.

標題：Regional chemical potential analysis for material surfaces
日時：2025 年 5 月 23 日(金) 午後 4 時～午後 5 時
場所：物性研究所 6 階第 5 セミナー室（A615）及び online（Hybrid）
講師：福田 将大
所属：東京大学物性研究所
要旨：

Whether a molecular or crystal surface is chemically active plays a crucial role in evaluating both the selectivity of molecular adsorption and the interatomic forces observed in atomic force microscopy (AFM). In this study, we propose a local regional chemical potential (RCP) analysis method based on an energy window scheme [1] to quantitatively estimate the selectivity of atomic and molecular adsorption on surfaces, as well as the strength of chemical bonding forces between a probe tip and a surface in AFM measurements [2,3].

In particular, focusing on the local picture of covalent bonding, we use a simple H2 molecular model to demonstrate a clear relationship between chemical bonding forces and the local RCP. Moreover, for molecular systems and diamond C(001) surfaces, we perform density functional theory calculations and reveal that the local RCP at the surfaces successfully visualizes electron-donating regions such as dangling bonds and double bonds. These results suggest that the local RCP can serve as an effective measure to analyze high-resolution non-contact or near-contact AFM images enhanced by chemical bonding forces.

[1] M. Fukuda, M. Senami, Y. Sugimoto, and T. Ozaki, arXiv:2505.04053.
[2] R. Zhang, Y. Yasui, M. Fukuda, T. Ozaki, M. Ogura, T. Makino, D. Takeuchi, and Y. Sugimoto, Nano Letters 25, 1101 (2025).
[3] R. Zhang, Y. Yasui, M. Fukuda, M. Ogura, T. Makino, D. Takeuchi, T. Ozaki, and Y. Sugimoto, Phys. Rev. Res. 7, 023036 (2025).

標題：Nonlinear dynamics at the fractional quantum Hall edge
日時：2025 年 5 月 26 日(月) 午後 3 時～午後 4 時
場所：物性研究所本館 6 階 第 5 セミナー室（A615）
講師：Dr. Alberto Nardin
所属：LPTMS, Paris-Saclay University
要旨：

One of the hallmark features of fractional quantum Hall liquids is the existence of chirally propagating edge modes at their boundary, whose presence has been an invaluable tool for probing the system’s exotic properties, most notably the presence of fractionally charged quasiparticles with anyonic exchange statistics. During this talk, I’ll describe how corrections to Wen’s chiral Luttinger liquid, the golden-standard for the description of these edge modes, emerge in systems such as anharmonically confined quantum Hall fluids or small atomic fractional quantum Hall states on a lattice. In particular, mode dispersion and non-linearities give rise to intriguing new features, such as solitons propagating along the boundary, quantum blockaded dynamics leading to the possibility of generating non-classical states of the edge, and bistable behaviors.

標題：Analog Control of Ferromagnetic Magnetization Through Spin-Orbit Torque for Neuromorphic Computing

日時：2025年5月27日(火) 午後2時～午後3時

場所：物性研究所本館6階 第5セミナー室（A615）

講師：Dr. Aurelien Lagarrigue

所属：東北大学電気通信研究所

要旨：

As conventional computing struggles to address several tasks with high energy efficiency, significant efforts have been devoted to neuromorphic computing. This promising alternative aims to mimic the physiological behavior of biological neurons and synapses using solid-state components. Analog-like behavior was observed in spin-orbit torque (SOT) based devices with antiferromagnet/ferromagnet heterostructures [1,2]. However, the small anomalous Hall resistance variations and the 4-terminal Hall bar geometry are not optimal for practical applications, motivating the present studies.

In the first part, I will present a study of 3- terminal perpendicular magnetic tunnel junctions (MTJs) with diameter DMTJ ranging from 200 nm to 10 μm, patterned on top of an antiferromagnetic PtMn channel. The write operation is performed by applying a current pulse ICH through the channel, while the read operation is conducted through tunnelling magnetoresistance (TMR) measurements. The MTJ's stack structure is shown in Fig. (a), alongside the hysteresis magnetic loops, microscope pictures and measuring set-up. We demonstrate analog and field-free SOT switching of the MTJ's resistance. Figure (e) shows RMTJ (ICH) with several intermediate non-volatile resistive states and a resistance variation of > 1 kΩ. In- depth measurements with magnetic field reveal the potential to achieve even higher resistance change with TMR > 100%.

In the second part, I will focus on a secondary project involving nanocomposite ferromagnetic heterostructures (CoPtCrB), characterized by significantly smaller magnetic domains. This feature enables further miniaturization of the devices. Hall effect measurements revealed field- and current-induced switching in nanodots, with diameters reduced to as little as 50 nm. The intermediate states observed are clearly distinguishable and can be reliably controlled–an essential characteristic for synaptic devices.

These results pave the way for energy-efficient artificial synapses for neuromorphic applications.

[1] S. Fukami et al., Nat. Mater. 15, 535 (2016).
[2] A. Kurenkov et al., Appl. Phys. Lett. 110, (2017).

標題：Development of Capacitance Measurements in Pulsed Fields to Probe the Microscopic Origin of Magnetic Anisotropy in Kitaev Candidates

日時：2025年5月27日(火) 午前9時30分～午前10時30分

場所：Online

講師：Dr. Minseong Lee

所属：National High Magnetic Field Laboratory

要旨：

The Kitaev quantum spin liquid is a highly entangled state with fractionalized excitations–Majorana fermions–that are promising for fault-tolerant quantum computing. Honeycomb cobaltites are proposed to realize Kitaev-type exchange interactions due to a distinct hierarchy among crystal electric field effects, spin-orbit coupling, and lattice geometry. However, whether these materials truly support significant Kitaev interactions remains under debate. In this talk, I will present an approach using high-field torque magnetometry to probe magnetic anisotropy as a signature of these interactions. By scaling the torque data, we can uncover the microscopic origin of the anisotropy. To measure torque in bulk samples, capacitive torque magnetometry is preferred. As a first step toward this, I will also present a method for implementing capacitance measurements in pulsed magnetic fields.

標題：Entanglement area law in interacting bosons: from Bose-Hubbard, φ^4, and beyond
日時：2025 年 5 月 30 日(金) 午後 4 時～午後 5 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：Dr. Donghoon Kim
所属：RIKEN
要旨：

The entanglement area law is a fundamental principle that shapes the informational structure of quantum many-body systems and is critical for algorithms based on tensor networks. Traditionally, this law has been established under two key assumptions: the system must have bounded local energy and exhibit short-range interactions. However, extending the area law to scenarios with unbounded local energy and long-range interactions remains a significant challenge, particularly in bosonic systems where these standard assumptions do not hold. In this work, we affirm the validity of the entanglement area law across a broad class of one-dimensional interacting bosonic systems, including models such as the Bose-Hubbard and ϕ^4 models, as well as systems with long-range interactions. Our approach overcomes the limitations of conventional assumptions by showing subexponential decay in the boson number distribution due to repulsive interactions. Consequently, we establish that it is possible to approximate ground states using Matrix Product States (MPS) with quasipolynomial bond dimensions. These findings provide crucial insights for simulating bosonic systems with long-range interactions and advancing quantum simulation methodologies.

標題：最先端レーザー技術による光量子情報処理・超精密計測分野の開拓
日時：2025 年 6 月 3 日(火) 午後 1 時～午後 3 時
場所：物性研究所本館 6 階 第 5 セミナー室および Online (Hybrid)
講師：遠藤 護 氏
所属：東京大学大学院工学系研究科物理工学専攻 古澤・遠藤研究室
要旨：

レーザー技術の発展は、基礎物理学から精密レーザー加工まで幅広い分野に大きな恩恵をもたらしている。我々は光周波数コムや、それに関連するレーザー技術を基盤として、精密分光、超低雑音マイクロ波生成、光量子情報処理などを展開してきた。例えば、繰り返し周波数が 10 GHz を超えるレーザーダイオード励起型モード同期固体レーザーを開発し[1]、その高い繰り返しを活かした応用研究を推進した[2]。また、レーザー光源や制御回路の最適化により一般的な雑音フロアより 30 dB 以上低い位相雑音を持つマイクロ波の生成および新たな測定技術を確立した[3-5]。特に最近行っている光量子情報処理の研究では、誤り耐性型量子コンピュータ実現に不可欠な量子状態を生成する際にレーザー技術が決定的な役割を果たしている[6-8]。本講演では、これら多岐にわたる研究成果を、レーザーやその周辺技術を軸にして紹介した。

1. M. Endo, I. Ito, Y. Kobayashi, Optics Express 23, 1276-1282 (2015).
2. M. Endo, S. Kimura, S. Tani, Y. Kobayashi, Communications Physics 4, (2021).
3. M. Endo, T. D. Shoji, T. R. Schibli, IEEE Journal of Selected Topics in Quantum Electronics 24, 1-13 (2018).
4. M. Endo, T. D. Shoji, T. R. Schibli, Scientific Reports 8, 4388 (2018).

5. M. Kalubovilage, M. Endo, T. R. Schibli, Optics Express 28, 25400-25409 (2020).
6. M. Endo et al., Optics Express 31, 12865 (2023).
7. S. Konno et al., Science 383, 289-293 (2024).
8. M. Endo et al., arXiv:2502.08952 (2025).

標題：Anomalous Hall Crystals: Stability and dynamics
日時：2025 年 6 月 6 日(金) 午前 10 時 30 分～午前 11 時 30 分
場所：Online
講師：Tomohiro Soejima
所属：Department of Physics, Harvard University
要旨：

When electrons are interacting strongly, they can form a strongly-correlated phase. A classic example is the Wigner crystal phase, where electrostatic energy localizes electrons into a crystalline lattice.

In this work, we propose a topological variant of the Wigner crystal, which we dub an Anomalous Hall Crystal (AHC). The AHC has nonzero Chern number, distinguishing it from classical Wigner crystals.

We first use mean-field Hartree-Fock calculation to show that the AHC phase can be stable in rhombohedral pentalayer graphene, which has recently been shown to host integer/fractional Chern insulators.

Next, we consider a generalization of the two dimensional electron gas, which we dub “lambda-jellium”, and show its Hartree-Fock phase diagram hosts a stable AHC phase. These two findings confirm the important role played by nontrivial band geometry in stabilizing the novel AHC phase.

In the final part of the talk, I will discuss the phonon dynamics of the AHC phase, both with and without magnetic field, and show how it can be extracted from numerics.

標題：Chemically Resolved IR-AFM Metro logy of Sub-25 nm Half-Pitch Patterns in Self-Assembled (SA) Block Co-Polymers
日時： 2025 年 6 月 17 日(火) 午後 3 時～午後 4 時
場所：物性研究所本館 6 階 第一会議室 (A636)
講師：ディードリック・マース 氏
所属：TNO Industry (NL) and Hitachi High-tech Corporation Europe (D)
要旨：

Resist stochastics ultimately limit patterning, a result of the interplay of resist composition, exposure, bake and development. Metrologies like OCD and CD-SEM only measure critical dimension (CD) and uniformity after development, offering limited process control. Each step modifies molecular bonds, leaving infrared (IR, 5-20 μm) fingerprints in activated chemical structures. When combining IR with AFM, nearfield effects resolve chemical alterations at the nm scale. This seminar presents how IR-AFM offers both chemical selectivity ánd lateral resolution to resolve modifications in latent (D)SA and EUVL images, even before post-expose-bake (PEB) and development. Metrology data from these images yield deeper insights in SA, thus facilitating improvement of DSA materials and processes. Ultimately, chemical metrology by IR-AFM can contribute to process control in Semicon manufacturing.

標題：真空紫外域の周波数コム開発とその応用

日時： 2025年6月19日(木) 午前10時～午後0時

場所： A棟6F 第一会議室＆Online（ハイブリッド）

講師：小澤 陽 氏

所属：横浜国立大学 総合学術高等研究院、マックスプランク量子光学研究所

要旨：【概要】

光周波数コム技術は基礎物理の探求から医療応用に至るまで幅広い展開がなされている一方で、波長200 nm 以下の真空紫外波長域における応用は困難であった。本講演では、高出力かつ低ノイズなレーザー光源の開発と、それを用いた真空紫外周波数コムの発生手法について紹介する[1,2]。本技術を用いることで、量子力学の検証のための精密原子・分子分光、レーザー冷却、高安定光周波数標準、高感度分子検出、量子光学実験といった様々な応用を真空紫外波長域で展開することが可能になる。このような応用実験の現状と今後の展望についても述べる。

[1] F. Schmid et al., APL Photon. 9, 026105 (2024).

[2] F. Canella et al., Optica 11, 1 (2024).

標題：Topological defects in magnetic systems and their quantum applications

日時：2025年6月27日(金) 午後4時～午後5時

場所：物性研究所本館6階 第5セミナー室 (A615)

講師：廣澤 智紀 氏

所属：青山学院大学 理工学部 物理科学科

要旨：

In this talk, we first introduce the gauge field induced by topological spin textures. We briefly review how this emergent gauge field leads to topological phenomena in magnetic skyrmions, which are microscopic magnetic vortices with an integer topological charge. We then consider topological spin textures in triangular lattice antiferromagnets, where the ground state has SO(3) symmetry, such as the 120-degree order and the four-sublattice tetrahedral order. The SO(3) order parameter is known to host a Z2 vortex as a topological defect. We present our recent work on the formation of the Z2 vortex crystal within the tetrahedral order [1]. We also discuss the possibility of fractional bound charges and their fractional statistics. In the second topic, we discuss quantum applications of topological defects with a focus on domain walls. Employing the density-matrix renormalization group method, we discuss the domain wall qubits and their single-qubit and two-qubit gate operations [2].

[1] “Z2 Vortex Crystals and Topological Magnons in a Tetrahedral Antiferromagnet”, T. Hirosawa, A. Mook, M. Azhar, arXiv:2503.06008.

[2] “Density Matrix Renormalization Group Study of Domain Wall Qubits”, G. Qu, J. Zou, D. Loss, and T. Hirosawa, arXiv:2412.11585.

標題：Enhancing efficiency of local-information time evolution
日時：2025 年 6 月 27 日(金) 午前 10 時～午前 11 時
場所：物性研究所本館 6 階 第 5 セミナー室 (A615)
講師：Moksh Bhateja
所属：Max Planck Institute PKS
要旨：

The time evolution of an initially unentangled system under the von Neumann equation generally leads to rapid entanglement growth. This poses challenges for numerical tractability. The Information Lattice framework addresses this by systematically discarding accumulated non-local information (i.e., entanglement) to maintain computational feasibility. Within the local-information time evolution (LITE) approach, we propose Renyi-2 entropy as a measure of information, eliminating the need for matrix decomposition. When combined with additional approximations, this approach significantly enhances the efficiency and scalability of simulations in terms of both system size and duration of time evolution. We demonstrate the accuracy of this method by computing high-quality diffusion coefficients and local observables for a large non-integrable system.

標題：PFNMR and other RF techniques in pulsed high magnetic fields at LNCMI
日時：2025 年 6 月 27 日(金) 午後 3 時 30 分～午後 4 時 30 分
場所：Online
講師：Dr. Nicolas Bruyant
所属：LNCMI-Toulouse CNRS, France
要旨：

In this talk, I will introduce the specificities of nuclear magnetic resonance spectroscopy in pulsed magnetic fields (PFNMR) above 45 T using non-destructive pulsed magnets [1]. These techniques require specific developments of custom pulsed magnets [2] and experimental setups. Due to the challenging conditions of pulsed magnetic fields, the measurable physical parameters are limited. I will explain the possible studies [3,4] and limitations of pulsed fields for NMR studies. These limits are due to both the short experiment duration and the limitations of RF techniques.

References:

[1] H. Kühne et al.,“Nuclear magnetic resonance spectroscopy in pulsed magnetic fields.”Contemporary Physics 65, 40 (2024).

[2] A. Orlova et al.,“New high homogeneity 55 T pulsed magnet for high field NMR.”Journal of Magnetic Resonance 268, 82 (2016).

[3] Y. Tokunaga et al.,“High-field phase diagram of the heavy-fermion metal CeIn3: Pulsed-field NMR study on single crystals up to 56 T.”Physical Review B 99, 085142 (2019).

[4] A. Orlova et al.,“Nuclear magnetic resonance signature of the spin-nematic phase in LiCuVO4 at high magnetic fields.”Physical Review Letters 118, 247201 (2017).