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科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Non-axisymmetric skyrmions in chiral and frustrated magnets

研究課題名（英文）Non-axisymmetric skyrmions in chiral and frustrated magnets

研究代表者
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研究成果の概要（和文）：面異方性を持つ極性磁石に斜めに磁場をかけた時の強磁性相内に出現する新しいクラスの孤立した磁気スキルミオンを見出した。 これらのスキルミオンの非対称磁気構造はエネルギー密度の複雑なパターンと関連しており、それは極軸から傾いた強磁性モーメントを伴う周囲の状態に関して正および負の磁化を示す。 それに対応して、スキルミオン - スキルミオン相互作用は異方性の性質を持ち、ペアの相対的な向きに応じて引力的にも反発的にもなり得る。 私はこれらの非対称スキルミオンの楕円錐状状態に対する安定性を調べた。 私の理論的な結果は、孤立した非対称スキルミオンとそれらのクラスターの実験的研究に明確な方向性を与えた。

研究成果の学術的意義や社会的意義
My research had a strong impact on the skyrmionic community: a) mathematical generalization of skyrmion classes; b) revision of experimental data on the visual skyrmion observation c) numerical simulation on the current-driven skyrmion motion, new prototypes of spintronic devices.

研究成果の概要（英文）：I introduced a new class of isolated magnetic skyrmions emerging within tilted ferromagnetic phases of polar magnets with easy-plane anisotropy. The asymmetric magnetic structure of these skyrmions is associated with an intricate pattern of the energy density, which exhibits positive and negative asymptotics with respect to the surrounding state with a ferromagnetic moment tilted away from the polar axis. Correspondingly, the skyrmion-skyrmion interaction has an anisotropic character and can be either attractive or repulsive depending on the relative orientation of the skyrmion pair. I investigated the stability of these asymmetric skyrmions against the elliptical cone state and followed their transformation into axisymmetric skyrmions, when the tilted ferromagnetic
moment of the host phase was reduced. My theoretical results gave clear directions for experimental studies of isolated asymmetric skyrmions and their clusters embedded in tilted ferromagnetic phases.

研究分野：spintronics

キーワード：skyrmion　DM interaction　current-drive dynamics　micromagnetism

１．研究開始当初の背景

The magnetic skyrmion (Fig. 1a) is a topological defect with a complex non-coplanar spin structure recently found in a handful of non-centrosymmetric materials with the *Dzyaloshinskii–Moriya interaction*. Together with Prof. Maxim Mostovoy (Groningen) we also suggested that skyrmions with additional degrees of freedom can exist in magnetically frustrated materials.

To date, the full attention of *skyrmionics* is riveted on the **axisymmetric skyrmions** (Fig. 1). Such skyrmions exist as ensembles of weakly *repulsive* particles in the *saturated* phase of noncentrosymmetric magnets.

Recently, in collaboration with the group from Department of Materials Science and Metallurgy (Cambridge, United Kingdom), I and Prof. Alex Bogdanov (IFW, Dresden) have introduced a new class of **non-axisymmetric skyrmions** emerging in the *conical phase* of chiral magnets (Fig. 2). These skyrmions are mutually *attractive* and tend to produce multi-skyrmion bound states. They are predicted to underlie precursor phenomena (e.g., A-phase in B20 magnets) and have prospects of being used in spintronics as *an effective alternative* to the common axisymmetric skyrmions. We also succeeded in the first experimental discovery of skyrmion clusters in thin (≈70 nm) single-crystal samples of Cu_2OSeO_3.

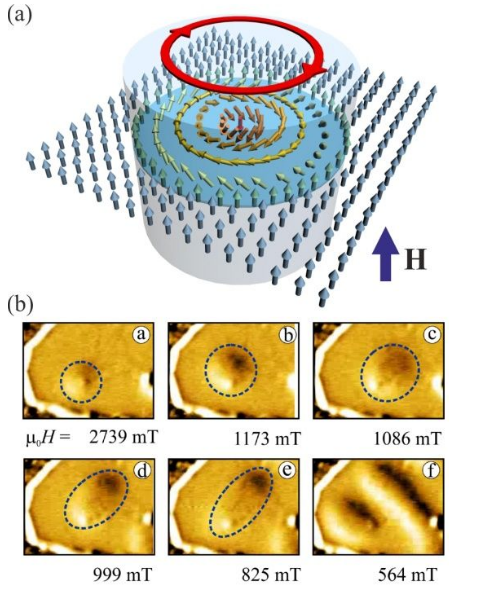

Fig. 1. (a) Schematic of an **axisymmetric isolated skyrmion.** (b) Detailed view of an isolated skyrmion in PdFe/Ir(111).

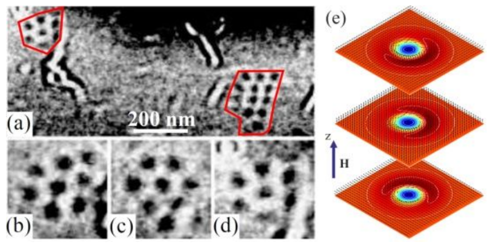

Fig. 2. **Non-axisymmetric skyrmions in the conical phase of Cu_2OSeO_3.** (a) - (d) Skyrmion clusters at T = 11 K and H = 116 mT. (e) a stack of the magnetization planes for different fixed values of z.

２．研究の目的

The current research project focuses on the further investigation of non-axisymmetric skyrmions in the conical phase as well as on the search for other classes of skyrmions in chiral magnets. The theoretical results from micromagnetic models which demonstrate distinct properties of such skyrmions are backed experimentally by the groups from Germany, Japan, and United Kingdom.

A. The internal structure of the non-axisymmetric skyrmions within the conical phase and underlying experimental effects in chiral magnets FeGe and Cu_2OSeO_3: a) the stability region of non-axisymmetric skyrmions and their reversible transformation into axisymmetric skyrmions; b) the principles of skyrmion cluster formation; c) field- and temperature-driven evolution of skyrmion clusters and skyrmion shells – domain walls between skyrmions and cones;
B. The internal structure of the non-axisymmetric skyrmions within the tilted ferromagnetic phases in chiral magnets with the easy-plane anisotropy: a) anisotropic character of the inter-skyrmion potential; b) instability toward one-dimensional modulated states; c) possible experimental effects in GaV_4Se_8;
C. Systematic generalization of the skyrmion solutions stabilized within the Dzyaloshinskii theory of helimagnetism and the theory of frustrated magnets;

Logical design of future spintronic devices based on the current-driven dynamics of non-centrosymmetric skyrmions in nanostructures with different geometries as obtained by the numerical micromagnetic experiments.

３．研究の方法

By the means of *micromagnetic simulations* (self-written numerical codes) and *experimental imaging techniques* (e.g., Lorentz and scanning transmission electron microscopy), the research project introduces new classes of two- and three-dimensional skyrmions emerging in chiral and frustrated magnets. The investigation has proceeded in the following main steps:

A. Study of the compatibility problem of isolated skyrmions with the encompassing homogeneous and modulated states; selection of phases suitable for hosting the isolated skyrmions (theory)

B. Scrutiny of the internal structure of the biskyrmion molecules and cluster shape tuning by the external control parameters (theory&experiment)
C. Design modeling of the spintronic devices based on non-axisymmetric skyrmions (numerical experiments)

Within the standard micromagnetic theory of helimagnetism, I derived rigorous solutions for non-axisymmetric skyrmions in broad ranges of the thermodynamic parameters. These results were applied to devise experiments in thin films (and wedges) of FeGe and Cu_2OSeO_3 and to elucidate the non-trivial topological structure and magnetization behavior of non-axisymmetric skyrmions. The results also provided the theoretical basis for the emerging spintronics via non-centrosymmetric skyrmions and supply practical recommendations for future investigations.

４．研究成果

I focused on a comprehensive study of two classes of non-axisymmetric skyrmions in chiral magnets – skyrmions within the conical phase and skyrmions in the tilted ferromagnetic phase.

1. I introduced **a new class of isolated chiral skyrmions** that can occur within the tilted ferromagnetic phases in chiral magnets with the easy-plane anisotropy. I derived solutions for these skyrmions and investigated their transformation into regular axisymmetric skyrmions within polarized ferromagnetic states and instability toward other phases. The asymmetric magnetization distribution in these skyrmions leads to the intricate pattern of the energy density with positive and negative asymptotics with respect to the surrounding tilted phase and thus infers an anisotropic character of skyrmion-skyrmion interaction. My theory formulated clear directions for experimental studies of such angular skyrmions. In particular, bulk polar magnetic semiconductors GaV_4Se_8 with the C_{3v} symmetry and easy-plane uniaxial anisotropy gave an ideal opportunity for the experimental proof of our theory. Together with colleagues from Budapest (Hungary) and Augsburg (Germany) we devised experimental strategy to investigate this type of isolated skyrmions.

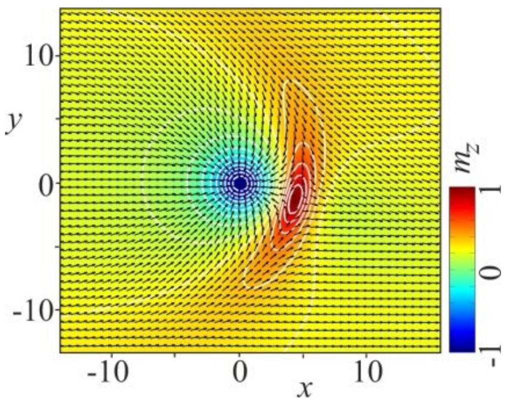

Fig. 3. Non-axisymmetric skyrmions within the tilted ferromagnetic phase

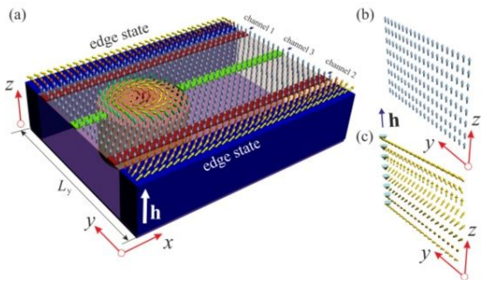

Fig. 4. Schematic of motion of a non-axisymmetric skyrmion confined by the edge states in a racetrack with the conical phase

2. I proceeded with the investigation of non-axisymmetric skyrmions in the conical phase of chiral magnets. Recently, I introduced such skyrmions mathematically as solutions of the field equations of the Dzyaloshinskii's theory. I also imaged the clusters of such skyrmions by the transmission electron microscopy in Cu_2OSeO_3. The special emphasis was put on the structure of the skyrmion shell – the domain boundary between skyrmions and the conical phases – as well as on the impact of specific surface twists which were recently shown to stabilize skyrmions in thin layers.

3．By the tools of micromagnetics, I also investigated the dynamical properties of non-centrosymmetric skyrmions and provided a basis for future experimental attempts. In particular, the following tasks were undertaken: (a) the current-driven dynamics of non-centrosymmetric skyrmions in chiral magnets. (b) the structure of the edge modulations in confined magnets and their interaction with non-axisymmetric skyrmions (Fig. 4). We carried out a detailed analysis of the skyrmion solutions for different types of boundary conditions and in a broad range of the material parameters of the system. (c) I suggested different designs of spintronic devices which could effectively utilize non-axisymmetric skyrmions.

５．主な発表論文等

〔雑誌論文〕（計７件）(7 Papers)

1. R. Murooka, A. O. Leonov, K. Inoue, and Jun-ichiro Ohe, Phys. Rev. Lett. in press

(2019). *"Current-induced shuttlecock-like movement of non-axisymmetric chiral skyrmions"*

2. A. O. Leonov, A. N. Bogdanov, and K. Inoue, Phys. Rev. B **98**, 060411(R) (2018). *„Toggle-switch-like crossover between two types of isolated skyrmions within the conical phase of cubic helimagnets"* (peer-reviewed)

3. A. O. Leonov and K. Inoue, Phys. Rev. B **98**, 054404 (2018). *"Homogeneous and heterogeneous nucleation of skyrmions in thin layers of cubic helimagnets"* (peer-reviewed)

4. J. C. Loudon, A. O. Leonov, A. N. Bogdanov, M. Ciomaga Hatnean, and G. Balakrishnan, Phys. Rev. B **97**, 134403 (2018). *"Direct observation of attractive skyrmions and skyrmion clusters in the cubic helimagnet Cu2OSeO3"* (peer-reviewed)

5. A. O. Leonov and I. Kézsmárki, *Phys. Rev. B* ***96***, 214413 (2017). *"Skyrmion robustness in noncentrosymmetric magnets with axial symmetry: The role of anisotropy and tilted magnetic fields"* (peer-reviewed)

6. A. O. Leonov and I. Kézsmárki, Phys. Rev. B, **96**, 014423 (2017). *„Asymmetric isolated skyrmions in polar magnets with easy-plane anisotropy "*(peer-reviewed)

7. S. Bordács, A. Butykai, B. G. Szigeti, J. S. White, R. Cubitt, A. O. Leonov, S. Widmann, D. Ehlers, H.-A. Krug von Nidda, V. Tsurkan, A. Loidl & I. Kézsmárki, Sci. Rep. **7**: 7584 (2017) *„Equilibrium Skyrmion Lattice Ground State in a Polar Easy-plane Magnet"*(peer-reviewed)

〔学会発表〕（計 6 件）(6 presentations)

1. A. O. Leonov, invited talk at International Symposium on Chiral Magnetism (χ-mag 2018), Nara-2018, July 25th to 28th, Nara (Japan) – *Chiral skyrmions: overview of perspectives*

2. A. O. Leonov, invited talk at 14th International Workshop on Magnetism & Superconductivity at the Nanoscale, Comaruga-2018, Sun 1nd - Fri 6th, July, Comaruga (Spain) - *Homogeneous and heterogeneous nucleation of skyrmions in thin layers of cubic helimagnets and liquid crystals*

3. A. O. Leonov, invited talk at International Conference of Magnetism and Spintronics, SolSkyMag-2018, June 18 – June 22, San Sebastian (Spain) – *Non-axisymmetric chiral skyrmions*

4. A. O. Leonov, invited talk at 6th International Conference on Superconductivity and Magnetism, ICSM-2018, 29th April – 4 May, Antalya (Turkey) - *The Properties of Isolated Skyrmions in Chiral Magnets and Liquid Crystals*

5. A. O. Leonov, invited talk at SkyMag "Challenges for Magnetic Skyrmions", 2017, May 02-05, Paris (France) - *The properties of isolated skyrmions in chiral and frustrated magnets*

6. A. O. Leonov, Research Progress Meeting on Chiral Magnet, 2017, 01 Feb -04 Feb, Takeo, Japan - *Theoretical studies on H-T phase diagrams of chiral magnets*

〔図書〕（計 0 件）

〔産業財産権〕
○出願状況（計 0 件）

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ホームページ等

６．研究組織

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