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研究課題名（和文）Skyrmionic LEGO- entangled skyrmion networks in chiral magnets and liquid crystals

研究課題名（英文）Skyrmionic LEGO- entangled skyrmion networks in chiral magnets and liquid crystals

研究代表者
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研究成果の概要（和文）：私は、カイラル磁性体や液晶中のホップフィオン、バイメロン、スキルミオニウムなどの多様な多次元ソリトンの特性を調査してきました。ホモトピー理論や結び目理論などの数学分野と偏微分方程式の方法論を組み合わせることで、次のような基本的な疑問に取り組みました。ソリトン間の許容される変換とその内部安定性の源は何か、ソリトンから形成される新しい拡張相にはどのようなものがあるかなど。研究の一部は、Katia Pappas の実験グループ（オランダ、デルフト）と共同で行われました。私たちは、傾斜スパイラルとスキルミオン状態の温度と磁場の依存性に注目しました。研究結果は 10 本以上の論文で発表されています。

研究成果の学術的意義や社会的意義
(i) I generalized mathematically the classes of chiral solitons; (ii) I revisited and designed experiments on visual observation of skyrmion networks; (iii) I suggested networks of entangled skyrmions as carriers of information in spintronic devices

研究成果の概要（英文）：I have investigated the properties of diverse multidimensional solitons, such as hopfions, bimerons, skyrmioniums etc., in chiral magnets and liquid crystals. By combining such mathematical disciplines as homotopy and knot theories as well as the methodology of partial differential equations I addressed such fundamental questions as: what are the allowed transformations between solitons and the source of their internal stability; what new extended phases formed from solitons are possible; how do solitons interact and/or collapse via formation of defects; what types of dynamics in spintronic devices can be realized etc.? Part of the research was done in collaboration with the experimental group of Katia Pappas (Delft, the Netherlands). We focused our attention on the temperature and field dependencies of the tilted spiral and skyrmion states. The results of the research have been published in more than 10 papers.

研究分野：Skyrmionics

キーワード：soliton　skyrmion　hopfion　DMI　chiral magnets

１．研究開始当初の背景

Chiral skyrmions are particle-like topological solitons with complex non-coplanar spin structures stabilized in noncentrosymmetric magnetic materials by specific Dzyaloshinskii-Moriya interaction (DMI). Skyrmions are considered as promising candidates for the next-generation memory and logic devices, in which the information is encoded by these countable nanometer scale solitons. The purpose of the current research project was to initiate a thorough experimental and theoretical search for novel classes of such two-dimensional solitons in chiral magnets and liquid crystals and extend the study towards other soliton varieties such as three-dimensional knotted hopfions. The research project also holds in mind fundamental aspects of the physics of chiral solitons and attempts to address the fundamental problem "What types of new physical behavior and properties can arise in condensed matter because of these nontrivial field configurations?

Skyrmionics is a very active and rapidly burgeoning field and many research teams all over the world intensively investigate chiral solitons and related phenomena in bulk noncentrosymmetric magnetic materials and recently synthesized nanomagnetic systems (nanolayers, multilayers, nanowires, nanodots). To remain competitive in this field, one needed new ideas and a set of interdisciplinary tools.

２．研究の目的

The aim of the project was by experimental and theoretical means to search for new classes of topological chiral solitons and examine their internal properties. I tried to address such fundamental questions as: what are the allowed transformations between solitons and the source of their internal stability; what new extended phases formed from solitons are possible; how do solitons interact and/or collapse via formation of defects; what types of dynamics in spintronic devices can be realized etc.? I aimed at thorough investigation of the reaction of topological solitons on external stimuli such as magnetic/electric field, surface anchoring and/or temperature. An additional goal was to come up with a logical design of future spintronic devices based on the current-driven dynamics of solitons as obtained by the numerical micromagnetic experiments.

３．研究の方法

The theoretical part of the project relied on the numerical experiment, for which I used high performance computer clusters at IFW Dresden. Up to 80 different spin states with millions of spins could be addressed simultaneously making statistics very prompt. In addition, I used open software such as mumax3 to double-check the results of self-written numerical routines. In addition, I combined such mathematical disciplines as homotopy and knot theories as well as the methodology of partial differential equations to enrich the systematics of the search.

The experimental part was done in collaboration with the group of Prof. Katia Pappas (Delft, the Netherlands). We used versatile indirect techniques such as neutron scattering, magnetization and ac magnetic susceptibility measurements.

４．研究成果

The results of the research project have been published in 13 papers in international refereed journals with an impact factor not less than 3.5. 70% of the budget was spent to buy computational computers for students and textbooks, since there was no support from Hiroshima university. As a result, 3 papers were published with master students being the first authors.

The papers include new findings on two- and three-dimensional solitons as well as several experimental papers.

First of all, together with the master student N. Mukai (2 published papers), we found two varieties of 2D bimerons in easy-axis and easy-plane chiral magnets. Remarkably, easy-plane bimerons attract each other and thus give an excellent opportunity to construct clusters with diverse arrangement of constituent bimerons, e.g., one may form round “supermolecules” – “roundabouts” and “crossings” - or create polymer-like networks with branching. Bimeron “polymers” are believed to have non-trivial magnonic properties and current-driven dynamics.

Three-dimensional skyrmions were investigated together with the master student T. Shigenaga (1 published paper). Many unique properties of skyrmions in wedge-shaped samples were revealed what makes them more attractive candidates for spintronics as compared with skyrmions in thin films.

Four papers were published in collaboration with Prof. Katia Pappas, which include theoretical explanation of the experimental results on high- and low-temperature skyrmion states in a Mott insulator Cu2OSeO3.

Four papers were published as a single-author paper. Here I touched many aspects of such chiral solitons as hopfions, torons, bobbers or skyrmions with “soft” modulus.

Unfortunately, due to the lack of the budget, I could not attend conferences. I did only 4 invited talks at local conferences and 1 invited lecture.

５．主な発表論文等

〔雑誌論文〕　計7件（うち査読付論文　7件／うちオープンアクセス　3件）

１．著者名 Natsuki Mukai and Andrey O. Leonov	４．巻 106
２．論文標題 Skyrmion and meron ordering in quasi-two-dimensional chiral magnets	５．発行年 2022年
３．雑誌名 Phys Rev B	６．最初と最後の頁 224428
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.106.224428	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Andrey O. Leonov and Catherine Pappas	４．巻 11
２．論文標題 Reorientation processes of tilted skyrmion and spiral states in a bulk cubic helimagnet Cu2OSeO3	５．発行年 2023年
３．雑誌名 Frontiers in Physics	６．最初と最後の頁 1105784
掲載論文のDOI（デジタルオブジェクト識別子） 10.3389/fphy.2023.1105784	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Andrey O. Leonov and Ulrich K. Roessler	４．巻 13
２．論文標題 Mechanism of Skyrmion Attraction in Chiral Magnets near the Ordering Temperatures	５．発行年 2023年
３．雑誌名 nanomaterials	６．最初と最後の頁 891
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/nano13050891	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 A. O. Leonov and C. Pappas	４．巻 4
２．論文標題 Topological boundaries between helical domains as a nucleation source of skyrmions in the bulk cubic helimagnet Cu2OSeO3	５．発行年 2022年
３．雑誌名 Phys. Rev. Research	６．最初と最後の頁 43137
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevResearch.4.043137	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名	4．巻
Andrey O. Leonov	105
2．論文標題	5．発行年
Skyrmion clusters and chains in bulk and thin-layered cubic helimagnets	2022年
3．雑誌名	6．最初と最後の頁
Phys. Rev. B 105, 094404 (2022)	1-12
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1103/PhysRevB.105.094404	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

1．著者名	4．巻
Andrey O. Leonov	104
2．論文標題	5．発行年
Surface anchoring as a control parameter for shaping skyrmion or toron properties in thin layers of chiral nematic liquid crystals and noncentrosymmetric magnets	2021年
3．雑誌名	6．最初と最後の頁
Phys. Rev. E 104, 044701	1-15
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1103/PhysRevE.104.044701	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

1．著者名	4．巻
Andrey O. Leonov, C. Pappas, and Ivan I. Smalyukh	104
2．論文標題	5．発行年
Field-driven metamorphoses of isolated skyrmions within the conical state of cubic helimagnets	2021年
3．雑誌名	6．最初と最後の頁
Phys. Rev. B 104, 064432	1-13
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1103/PhysRevB.104.064432	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

〔学会発表〕　計2件（うち招待講演　2件／うち国際学会　2件）

1．発表者名
Andrey Leonov
2．発表標題
3D chiral skyrmions
3．学会等名
SKCm2 Kickoff symposium（招待講演）（国際学会）
4．発表年
2023年

1．発表者名 Andrey O. Leonov
2．発表標題 Frustration of skyrmion tubes in cubic helimagnets and chiral liquid crystals
3．学会等名 Invited talk at The International Conference on Frustration, Topology and Spin Textures (ICFTS)（招待講演）（国際学会）
4．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関