# Springer Series in Solid-State Sciences

Volume 192

The Springer Series in Solid-State Sciences consists of fundamental scientific books prepared by leading researchers in the field. They strive to communicate, in a systematic and comprehensive way, the basic principles as well as new developments in theoretical and experimental solid-state physics.

More information about this series at http://www.springer.com/series/682

Jiadong Zang · Vincent Cros
Axel Hoffmann
Editors

# Topology in Magnetism

Springer

*Editors*
Jiadong Zang
University of New Hampshire
Durham, NH, USA

Axel Hoffmann
Materials Science Division
Argonne National Laboratory
Lemont, IL, USA

Vincent Cros
Unité Mixte de Physique CNRS/Thales
Palaiseau, France

ISSN 0171-1873 ISSN 2197-4179 (electronic)
Springer Series in Solid-State Sciences
ISBN 978-3-319-97333-3 ISBN 978-3-319-97334-0 (eBook)
https://doi.org/10.1007/978-3-319-97334-0

Library of Congress Control Number: 2018949638



This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Preface

The purpose of this collective book is to present selected topics of modern magnetism research, where the physical phenomena are directly related to topological properties. As was highlighted by the Nobel Prize in Physics in 2016 for the work of David J. Thouless, F. Duncan M. Haldane, and J. Michael Kosterlitz, concepts of topology have provided recently a powerful approach toward understanding a wide variety of contemporary condensed matter physics. Toward this end, combining topology with magnetism has given rise to numerous vibrant new topics, such as skyrmions and topological insulators. These are not only fundamentally interesting, but also are promising for a transformative revolution of information technology using topological charge as a new state variable.

We organized the book in roughly three parts. The first part focuses on phenomena that are governed by spin textures with non-trivial topology in real space. Chapter 1 (H.-B. Braun) provides a general overview of real space topological solitons in magnetic systems. Subsequently, Chap. 2 (A. Thiaville and J. Miltat) discusses to what extent magnetic domain walls are related to topology of spin textures and how this influences their dynamics. Related concepts are further explored in Chap. 3 (C. Behncke, C. F. Adolff, and G. Meier) for a specific type of topological solitons, namely magnetic vortices, that form in geometrically confined magnetic structures. Another type of topological soliton, magnetic skyrmions, is discussed in Chap. 4 (G. Chen), which focuses on skyrmions, a new magnetic state that can exist in magnetic multilayers where they have been considered as data carriers for information technologies, and in Chap. 5 (A. Bauer, A. Chacon, M. Halder, and C. Pfleiderer), which describes non-equilibrium behaviors of skyrmion lattices in bulk materials with lack of inversion symmetry.

The second part of the book is dedicated to physical phenomena, where the topology of the electronic band structure results in effective coupling between spin and charge transport. Toward this end, Chap. 6 (Y. Mokrousov) discusses the theoretical understanding of anomalous Hall effects, which despite their experimental discovery more than one hundred years ago, just very recently have been understood as fundamentally connected to the topology in momentum space and the related Berry phase physics. Chapter 7 (M. Althammer) discusses the closely

related spin Hall effect and focuses on how this effect can be experimentally explored via many different measurement approaches. This is followed by Chap. 8 (B. Wan, H.-Z. Lu, and X. Wan) by an introduction to Weyl semimetals, where the topology generates non-trivial surface and bulk electronic states. Lastly, Chap. 9 (L. Šmejkal and T. Jungwirth) discusses how the new field of antiferromagnetic spintronics provides interesting connections to topology in particular for Weyl and Dirac semimetals.

The last part of the book explores how topology may affect dynamics phenomena and excitations in magnetic systems. Chapter 10 (S. Demokritov) provides a detailed overview of spin waves, or magnons, and how their properties are influenced by geometric confinement of ferromagnets. This discussion is complemented by Chap. 11 (J. Åkerman), which focuses on localized magnetic excitations that are driven by spin transfer torques and how their dynamics relates to their topological properties. Finally, Chap. 12 (J. C. Y. Teo) describes how the antagonistic interplay between magnetism and superconductivity can give rise to novel quasiparticle excitations, Majorana fermions, whose unique topological properties are envisioned to be beneficial for robust quantum computation development.

Our hope is that the readers will find this a stimulating collection of concepts with intriguing connections between them. Our aim was to make the presentation of these concepts accessible to graduate students and researchers new to the field, while also providing a useful snapshot of the most recent developments that can serve as a reference for the expert. Through this effort, and together with the rapid pace of developments in many of the topics discussed in this book, we hope to contribute to the multitude of new exciting developments in the coming years resulting from exploiting topological concepts in the vast range of available magnetism-related materials systems.

Durham, NH, USA — Jiadong Zang
Lemont, IL, USA — Axel Hoffmann
Paris, France — Vincent Cros

# Contents

# Contributors

**Christian F. Adolff** Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Hamburg, Germany

**Johan Åkerman** Department of Physics, University of Gothenburg, Gothenburg, Sweden; Materials and Nanophysics, KTH Royal Institute of Technology, Kista, Sweden

**Matthias Althammer** Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany

**Andreas Bauer** Physik-Department, Technische Universität München, Garching, Germany

**Carolin Behncke** Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Hamburg, Germany

**Hans-Benjamin Braun** School of Physics, University College Dublin, Dublin, Ireland; School of Theoretical Physics, Dublin Institute of Advanced Studies, Dublin, Ireland

**Alfonso Chacon** Physik-Department, Technische Universität München, Garching, Germany

**Gong Chen** Physics Department, University of California, Davis, CA, USA

**Sergej O. Demokritov** Institute for Applied Physics and Center for Nanotechnology, University of Münster, Münster, Germany

**Marco Halder** Physik-Department, Technische Universität München, Garching, Germany

**Tomáš Jungwirth** Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic; School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, UK

**Hai-Zhou Lu** Department of Physics, Institute for Quantum Science and Engineering, South University of Science and Technology of China, Shenzhen, China; Shenzhen Key Laboratory of Quantum Science and Engineering, Shenzhen, China

**Guido Meier** Max-Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany

**Jacques Miltat** Laboratoire de Physique des Solides, Université Paris-Sud, Orsay, France

**Yuriy Mokrousov** Institute for Advanced Simulation, Forschungszentrum Jülich GmbH, Jülich, Germany; Institute of Physics, Johannes Gutenberg-University Mainz, Mainz, Germany

**Christian Pfleiderer** Physik-Department, Technische Universität München, Garching, Germany

**Libor Šmejkal** Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany; Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic; Faculty of Mathematics and Physics, Department of Condensed Matter Physics, Charles University, Prague, Czech Republic

**Jeffrey C. Y. Teo** Department of Physics, University of Virginia, Charlottesville, VA, USA

**André Thiaville** Laboratoire de Physique des Solides, Université Paris-Sud, Orsay, France

**Bo Wan** National Laboratory of Solid State Microstructures, School of Physics, Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing, China; Department of Physics, Institute for Quantum Science and Engineering, South University of Science and Technology of China, Shenzhen, China

**Xiangang Wan** National Laboratory of Solid State Microstructures, School of Physics, Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing, China