TOPOLOGICAL PHASES OF MATTER

Topological phases of matter are an exceptionally dynamic field of research: several of the most exciting recent experimental discoveries and conceptual advances in modern physics have their origins in this field. These have generated new – topological – notions of order, interactions, and excitations. This text provides an accessible, unified, and comprehensive introduction to the phenomena surrounding topological matter, with detailed expositions of the underlying theoretical tools and conceptual framework, alongside accounts of the central experimental breakthroughs. Among the systems covered are topological insulators, magnets, semimetals, and superconductors. The emergence of new particles with remarkable properties such as fractional charge and statistics is discussed alongside possible applications such as fault-tolerant topological quantum computing. Suitable as a textbook for graduate or advanced undergraduate students, or as a reference for more experienced researchers, the book assumes little prior background, providing self-contained introductions to topics as varied as phase transitions, superconductivity, and localization.

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Contents

Tables

Boxes

Preface

Topological condensed matter physics presents an embarrassment of riches, both in the bewildering variety of phenomena that fall under this heading and in the sheer volume of publications in the field. In addition, the breadth of the field is reflected in a diversity of backgrounds of its practitioners: it is a place where immigrants from high-energy physics collaborate with materials chemists. This poses the twin challenges of selection and organization of material for a book.

Against this backdrop, the content of this book reflects our vision of the field, in particular what we feel might in the long run form part of the canon of many-body physics. We have tried to emphasize conceptual and historical milestones. We focus on topological phases in solids, rather than on similar phases of neutral atoms in either helium or ultra-low-density atomic gases, which couple very differently to electromagnetic fields, even though these have certainly contributed to central developments of the field.

We have limited ourselves to a relatively small number of references. Given that the material of the book corresponds to such a vast body of work, we would otherwise have ended up with an unpalatably long but necessarily still woefully incomplete list of references. We have tried to include scholarly review articles where hundreds more references can be found in a more structured fashion. We apologize to those objecting to this or any other aspect of the presentation for our shortcomings; they are warmly encouraged to contribute their own versions, as condensed matter physics does not have the literature it deserves.

Few are the book projects that are swiftly concluded, and ours is not one of them. Without the collapse of our travel schedules due to the present pandemic, perhaps this manuscript would still not be finished. Of course, had we completed the book more swiftly, we would have missed a number of exciting developments, such as the discoveries of Floquet time crystals and Weyl and Dirac semimetals. At any rate, we do not expect a letup of the sequence of discoveries any time soon.

Indeed, overall condensed matter physics continues to have a refreshingly unmodern flavor to it. Most of its discoveries are made by small collaborations of creative individuals, often entirely serendipitously – just think of the integer quantum Hall effect, the cuprate superconductors, the isolation of graphene, or the prediction of topological insulators. This is a far cry from purportedly goal-oriented large-scale research programs, the organization of which both of us are admittedly also guilty of. At the same time, it is undeniably true that the use of large-scale facilities like modern neutron and light sources has advanced the field tremendously.

The passage of time has also asserted itself in several other ways. Topological condensed matter physics has in the meantime been recognized by the 2016 Nobel Prize for Duncan Haldane, Michael Kosterlitz, and David Thouless. Neither was sad news in short supply, with Thouless passing away only a few months after the untimely death of Shoucheng Zhang. The passing of Phil Anderson in March 2020 concluded the extraordinary career of arguably the most influential scientist of the second half of the twentieth century.

Finally, it might be useful to explain our approach to pedagogy, since it is intended that this book will be useful also for courses of self-study. Our feeling is that an encyclopedic list of results without derivations is unlikely to help readers understand the material for themselves, while too detailed a presentation tends to obscure the underlying conceptual structure of the material. In compromise, we have tried to explain a moderate number of central results, with a key example where appropriate; most of these do not require a great deal of technical background or impose greatly on the reader's patience. We would like to think, of course, that the book can thus also be useful as an initial reference that can be consulted for the basics of a subject and as a source for more comprehensive reading.

For the nonexpert reader, although much interesting material has had to be omitted, what has been included may still be hard to navigate initially. To lower the entry bar, besides providing background in Chapter 2 to make the book reasonably self-contained, we have collated the most fundamental material in two chapters, which we recommend as an entry point. These are Chapter 3, on integer topological phases, and Chapter 5, on fractionalization.

Ideally, the book will be useful for active practitioners in the field as well as for newcomers, to whom we would like to extend a heartfelt welcome.

Acknowledgments

The embarrassment of riches of topological condensed matter physics mentioned in the preface is matched by the number and generosity of the people to whom we are indebted on our scientific journey to date. The first mention should be of those scientists who guided our steps during our scientific childhood and adolescence. Added to this are the collaborators with whom we began and sustained a research effort in the field.

In this spirit, J.E.M. thanks Duncan Haldane and Xiao-Gang Wen for explaining the beauty of topological order; Leon Balents and Cenke Xu for collaborations in the early days of topological materials; and Joseph Orenstein and David Vanderbilt for adding a dose of realism, in their distinct ways, later on. Similarly, R.M. is grateful to John Chalker and Shivaji Sondhi, especially for the early work on frustrated magnetism that was finding its place in the fabric of topological condensed matter physics as it was being woven. Since then, he has benefited greatly from the time and enthusiasm of many collaborators. Feeling distinctly uncomfortable singling out any individually, he would like to hide behind the Europhysics Prize Committee to signal his gratitude for satisfying theory–experiment collaborations like the one involving the discovery of emergent magnetic monopoles with Claudio Castelnovo and the groups of Alan Tennant and Santiago Grigera.

Both of us have had the privilege of watching junior scientists from our research groups develop into independent contributors to the field of topological physics. We particularly thank our students and postdocs, too many to list, not just for their collaboration on research but for making the job of professor a worthwhile one. Early versions of this material were inflicted upon students, and refined based on their questions, not just at our institutions but at a number of advanced schools. J.E.M. acknowledges Oxford University Press for permission to reuse material in Section 2.7, Chapter 4 and Section 6.6.1 from his Les Houches lecture notes (Chamon et al., 2017).

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R.M. dedicates this book to the memory of Philip W. Anderson. As the founding pioneer of much of condensed matter physics, his intellectual influence pervades this field, and this book, on many levels. We mourn the loss of an outstanding person who was a role model for many of us, not just as a scientist, and feel privileged to have known him.

J.E.M. dedicates this book to another native of Illinois, William Moore, for his contributions in other spheres, including as a father.