Cold and Ultracold Collisions in Quantum Microscopic and Mesoscopic Systems

Cold and ultracold collisions occupy a strategic position at the intersection of several powerful themes of current research in chemical physics; in atomic, molecular, and optical physics; and even in condensed matter. The nature of these collisions has important consequences for optical manipulation of inelastic and reactive processes, precision measurement of molecular and atomic properties, matter–wave coherences, and quantum-statistical condensates of dilute, weakly interacting atoms. This crucial position explains the wide interest and explosive growth of the field since its inception in 1987. The author reviews elements of quantum scattering theory, collisions taking place in the presence of one or more light fields, and collisions in the dark, below the photon recoil limit imposed by the presence of any light field. Finally, it reviews the essential properties of these mesoscopic quantum systems, and describes the key importance of the scattering length to condensate stability.

JOHN WEINER graduated from the Pennsylvania State University with high distinction and received his Ph.D. from the University of Chicago. He is a Fellow of the American Physical Society and the Washington Academy of Sciences. He is a member of numerous professional societies in the USA and in France. He has held lectureships and professorships at Yale University, Dartmouth College, and the University of Maryland in the USA. He is presently a professor of chemical physics at the Université Paul Sabatier in Toulouse, France.

Cold and Ultracold Collisions in Quantum Microscopic and Mesoscopic Systems

JOHN WEINER
Université Paul Sabatier

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011–4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2003

Printed in the United Kingdom at the University Press, Cambridge

Typefaces Times 10/13 pt and Helvetica Neue   *System* LaTeX 2_ε [TB]

A catalog record for this book is available from the British Library

Library of Congress Cataloging in Publication data

Weiner, John, 1943–
Cold and ultracold collisions in quantum microscopic and mesoscopic systems / John Weiner.
p. cm.
Includes bibliographical references and index.
ISBN 0 521 78121 3
1. Collisions (Nuclear physics) 2. Materials at low temperatures. I. Title.
QC794.6.C6W45 2003
539.7′57–dc21 2003044033

ISBN 0 521 78121 3 hardback

Cambridge University Press
0521781213 - Cold and Ultracold Collisions in Quantum Microscopic and Mesoscopic Systems
John Weiner
Frontmatter
More information

Contents

Preface

Cold and ultracold collisions occupy a strategic position at the intersection of several powerful themes of current research in chemical physics, in atomic, molecular and optical physics, and even in condensed matter. The nature of these collisions has important consequences for optical manipulation of inelastic and reactive processes, precision measurement of molecular and atomic properties, matter–wave coherence and quantum-statistical condensates of dilute, weakly interacting atoms. This crucial position explains the wide interest and explosive growth of the field since its inception in 1987. Obviously due to continuing rapid developments the very latest new results cannot appear in book form, but the field is sufficiently mature that a fairly comprehensive account of the principal research themes can now be undertaken. The hope is that this account will prove useful to newcomers seeking a point of entry and as a reference for those already initiated.

After a general introduction and a brief review of the elements of scattering theory in Chapters 1 and 2, the next four chapters treat collisions taking place in the presence of one or more light fields. The reason for this is simply historical. After the development of the physics of optical cooling and trapping from the early to mid 1980s, the first generation of collisions experiments applied this light-force physics to cool and confine atoms in traps and beams. The dipole force trap, the magneto-optical trap, and "brightened" atom beams, described in Chapter 3, became the experimentalists' tools of the trade. Light fields from the radiation pressure force and the dipole gradient potential, needed to cool atoms to submillikelvin temperatures, also play an active role in the collision processes themselves. Chapter 4 describes how inelastic, energy-releasing collisions can be detected and studied by losses from atom traps, and Chapter 5 reviews the important advances derived from precision photoassociation spectroscopy. Chapter 6 recounts how light not only directs scattering flux into inelastic and reactive channels, but also prevents close atom encounters from occurring – atoms can be "shielded" from collisions and the scattering flux redirected to elastic channels.

Although cooling and trapping with light fields opened the way to the study submillikelvin collisions, these fields themselves posed a barrier to the lower temperatures and higher densities required to reach the quantum-degenerate regime. Evaporative cooling of ground-state atoms and confinement in dark magnetic traps provided the pathway to breach this light-field barrier. The physics of binary collisions in this regime reduces to s-wave scattering, which is much simpler than the inelastic and reactive processes at higher temperatures, but critically important for the structure and dynamics of Bose–Einstein condensates. Chapter 7 reviews the essential properties of these mesoscopic quantum systems, and describes the key importance of the scattering length to condensate stability. A vital area of current research focuses on the active manipulation of the scattering length by external fields and the search for quantum-degenerate molecular species. This story is far from complete, but enough has already been accomplished to point the reader toward those areas likely to yield exciting developments for some time to come.

The last topic treated in Chapter 7 concerns the role of collisions in quantum computation. Quantum information science is in its infancy, and it is too early to predict in which direction it will ultimately evolve. Nevertheless, the realization of quantum gate operations through the use of entangled atom states in optical lattices provides an instructive lesson on how to think about the nature of "information" and what must be the essential features of a quantum computer. Collisions provide the entangled states, and therefore their importance to future developments will remain crucial.

The starting point for this book was a *Review of Modern Physics* article (*Rev. Mod. Phys.*, 71: 1–85, 1999) co-authored by Paul Julienne, Vanderlei Bagnato, Sergio Zilio and me. That article reviewed developments in cold collisions through to the end of 1997, at the point where the Bose–Einstein condensate, first achieved in 1995, was just beginning to reveal its fascinating properties. Since then there has been an explosion of new physics in the control and manipulation of quantum-degenerate condensates (including literally exploding condensates!). The purpose of this book then is to not only update developments in the more established lines of cold collision research since the appearance of that article, but also to describe the important new role of collisions in the quantum-degenerate gases.

The author of this book owes a great debt of gratitude to his former co-authors of the *Review of Modern Physics* article mentioned above. Much of the theory presentation in Chapters 2 and 7 of this book is drawn from the contributions of Paul Julienne to that article, and the author has benefitted from many enlightening discussions with his colleagues at the Instituto de Física at the Universidade de São Paulo in São Carlos, Brazil and at the Université Paul Sabatier here in Toulouse. Whatever errors remain here are of course the sole responsibility of the present author.