

Lecture Notes in Physics

Volume 879

Founding Editors

W. Beiglböck
J. Ehlers
K. Hepp
H. Weidenmüller

Editorial Board

B.-G. Englert, Singapore, Singapore
U. Frisch, Nice, France
P. Hänggi, Augsburg, Germany
W. Hillebrandt, Garching, Germany
M. Hjorth-Jensen, Oslo, Norway
R.A.L. Jones, Sheffield, UK
M. Lewenstein, Barcelona, Spain
H. von Löhneysen, Karlsruhe, Germany
M. S. Longair, Cambridge, UK
J.-F. Pinton, Lyon, France
J.-M. Raimond, Paris, France
A. Rubio, Donostia, San Sebastian, Spain
M. Salmhofer, Heidelberg, Germany
D. Sornette, Zurich, Switzerland
S. Theisen, Potsdam, Germany
D. Vollhardt, Augsburg, Germany
W. Weise, Garching, Germany and Trento, Italy
J.D. Wells, Geneva, Switzerland

For further volumes:

www.springer.com/series/5304

The Lecture Notes in Physics

The series Lecture Notes in Physics (LNP), founded in 1969, reports new developments in physics research and teaching—quickly and informally, but with a high quality and the explicit aim to summarize and communicate current knowledge in an accessible way. Books published in this series are conceived as bridging material between advanced graduate textbooks and the forefront of research and to serve three purposes:

- to be a compact and modern up-to-date source of reference on a well-defined topic
- to serve as an accessible introduction to the field to postgraduate students and nonspecialist researchers from related areas
- to be a source of advanced teaching material for specialized seminars, courses and schools

Both monographs and multi-author volumes will be considered for publication. Edited volumes should, however, consist of a very limited number of contributions only. Proceedings will not be considered for LNP.

Volumes published in LNP are disseminated both in print and in electronic formats, the electronic archive being available at springerlink.com. The series content is indexed, abstracted and referenced by many abstracting and information services, bibliographic networks, subscription agencies, library networks, and consortia.

Proposals should be sent to a member of the Editorial Board, or directly to the managing editor at Springer:

Christian Caron
Springer Heidelberg
Physics Editorial Department I
Tiergartenstrasse 17
69121 Heidelberg/Germany
christian.caron@springer.com

Christoph Scheidenberger • Marek Pfützner
Editors

The Euroschool on Exotic Beams, Vol. IV

 Springer

Editors

Christoph Scheidenberger
NuSTAR department
GSI Helmholtzzentrum
für Schwerionenforschung GmbH
Darmstadt, Germany

Marek Pfützner
Faculty of Physics
University of Warsaw
Warsaw, Poland

ISSN 0075-8450

Lecture Notes in Physics

ISBN 978-3-642-45140-9

DOI 10.1007/978-3-642-45141-6

Springer Heidelberg New York Dordrecht London

ISSN 1616-6361 (electronic)

ISBN 978-3-642-45141-6 (eBook)

Library of Congress Control Number: 2014930224

© Springer-Verlag Berlin Heidelberg 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

We are pleased to present the continuation of the series Lecture Notes in Physics emerging from the Euroschool on Exotic Beams. This school, initiated in Leuven (Belgium) in 1993, has been running every year (with one exception in 1999). Based on lectures given at the Euroschool, the Lecture Notes provide an introduction for graduate students and young researchers to novel and exciting fields of physics with radioactive ion beams and their applications. The fourth volume in this series covers selected material presented in Euroschool lectures between 2007 and 2011.

Since the late 80s, the field of radioactive ion beams has been rapidly developing and substantially expanding. While many of its roots were founded in Europe, and also leadership of the field was for many years concentrated in Europe, there are meanwhile intense efforts worldwide to build and exploit dedicated second-generation radioactive beam facilities. The exciting physics of radioactive ions is mainly linked to the study of nuclear structure under extreme conditions of isospin, mass, spin and temperature. Radioactive ion beam science addresses problems in nuclear astrophysics, solid-state physics and fundamental interactions. Furthermore, important applications and spin-offs also originate from this basic research. The development of new production, acceleration and ion manipulation techniques and the construction of new detectors is also an important part of this science. A major aim is the development of a unified picture of the atomic nucleus, to understand the structure and dynamics of nuclei and to provide reliable predictions of nuclear structure properties within the “Terra Incognita”, the regions in the nuclear chart which cannot be explored with present experimental techniques.

As with previous volumes, the present Lecture Notes do not comprise a complete overview of the field, but represent sample topics of theory and experiment. Since the appearance of the latest volume in 2009, and already before, many new subjects were covered in the lectures, and some of them are presented here. The topics have been selected by the editors to exhibit recent advances in the field and to complement previous Lecture Notes. None of them has been covered in previous volumes, all represent an active field of current research, and all authors are well known experts in their domains and are highly respected scientists. Their contributions to this book are not meant to be review-type articles rather they provide a

modern introduction to a specific subject in a didactic way, given by practitioners at the forefront of scientific research. This approach has proved to be successful and the Euroschool Lecture Notes are popular among both students and scientists. The content of volumes I, II and III of this series is available on the Euroschool website <http://www.euroschoolonexoticbeams.be>. We hope that the present volume will be no less successful than the previous editions.

The Euroschool concept began as a European initiative. From the start the intention was to gather original questions, methods and results from the field of radioactive beams and exotic nuclei, and to bring them to the attention of students and young researchers working in this domain both within Europe and overseas. The school has, at all times, been open for European and international participants. Since 2001 the Euroschool has traveled to various locations and countries throughout Europe. Events took place in Finland (2001, 2011), France (2002, 2007), Spain (2003, 2010), United Kingdom (2004), Germany (2005), Italy (2006), Poland (2008), Belgium (2009), Greece (2012), and most recently in Russia (2013). The evident success of the Euroschool on Exotic Beams originates to a large extent from the excellence of the lecturers invited to share their knowledge with the students and the pleasant, informal atmosphere which generates a valuable forum for discussions. Despite some organizational changes which occurred during this time, the scope, format, spirit, and popularity among young participants has been maintained. It is our pleasure—and debt—to thank the sponsors for their support, which makes the Euroschool events possible:

- Demokritos—National Center for Scientific Research, Athens (Greece)
- ECT*, European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Trento (Italy)
- GANIL—Grand Accélérateur National d’Ions Lourds, Caen (France)
- Gobierno de España—Ministerio de Economía y Competitividad—FNUC Network and CPAN Ingenio 2010, Madrid (Spain)
- GSI—Helmholtz Centre for Heavy Ion Research, Darmstadt (Germany)
- HIC-4-FAIR—Helmholtz International Center for FAIR, Darmstadt (Germany)
- IFIC-CSIC—Instituto de Física Corpuscular, Consejo Superior de Investigaciones Científicas, Madrid (Spain)
- INFN—Istituto Nazionale di Fisica Nucleare (Italy)
- ISOLDE-CERN, Geneva (Switzerland)
- JINR—Joint Institute for Nuclear Research, Dubna (Russia)
- JYFL—University of Jyväskylä (Finland)
- KU Leuven—Instituut voor Kern- en Stralingsfysica, Leuven (Belgium)
- RuG-KVI—Kernfysisch Versneller Instituut, Groningen (The Netherlands)
- UCL—Centre de Recherche du Cyclotron, Louvain-la-Neuve (Belgium)
- University of Warsaw (Poland)
- USC—University of Santiago de Compostela (Spain)

Finally, we would like to thank all who have contributed to this volume. First of all to the authors who have given excellent lectures for the Euroschool students, and who have invested time and effort in preparing the contributions to this book

in a comprehensive and pedagogical way. Secondly, we thank our colleagues on the Board of Directors of the Euroschool, who supported the development of this volume with interest and for their valuable ideas. Last, but not least, it is our pleasure to thank Dr. Chris Caron and his colleagues at Springer Verlag for the encouragement and continuous support in a fruitful collaboration.

University of Warsaw, Poland

GSI Darmstadt and University of Giessen, Germany

Marek Pfützner

Christoph Scheidenberger

Contents

1	Clustering in Light Nuclei; from the Stable to the Exotic	1
	Martin Freer	
1.1	Clusters and Correlations in Context	1
1.2	Clusters in First Principles Models	2
1.3	Appearance of the Nuclear Cluster from the Mean-Field	3
1.4	More Sophisticated Models of Clustering	11
1.4.1	Bloch-Brink Alpha Cluster Model (ACM)	11
1.4.2	Condensates and the THSR Wave-Function	13
1.4.3	Microscopic Cluster Models	14
1.4.4	Antisymmetrised Molecular Dynamics (AMD) and Fermionic Molecular Dynamics (FMD)	16
1.4.5	Ab Initio Type Models	18
1.5	Experimental Examples of Clustering	19
1.5.1	The Example ^8Be	19
1.5.2	The Structure of ^{12}C	20
1.6	Experimental Techniques—Break-up and Resonant Scattering Reactions	22
1.6.1	Resonant Scattering	22
1.6.2	Break-up Measurements	24
1.7	Beyond α -Clusters—Valence Neutrons and Molecules	26
1.7.1	The Neutron-Rich Nucleus ^{10}Be	30
1.7.2	More Complex Molecular States and the Extended Ikeda Diagram	32
1.8	Summary and Conclusions	34
	References	35
2	A Pedestrian Approach to the Theory of Transfer Reactions: Application to Weakly-Bound and Unbound Exotic Nuclei	39
	Joaquín Gómez Camacho and Antonio M. Moro	
2.1	Introduction	39
2.2	Theoretical Formalism	41

2.2.1	Distorted Wave Born Approximation DWBA	43
2.2.2	Adiabatic Distorted Wave Approximation ADWA	46
2.2.3	Continuum Discretized Coupled Channels Born Approximation CDCC-BA	49
2.2.4	Coupled Reaction Channels CRC	51
2.2.5	Connection with the Faddeev Formalism	55
2.3	Transfer to Unbound States	58
2.3.1	Recent Applications to Weakly Bound Halo Nuclei	60
2.4	Summary and Conclusions	62
	References	64
3	What Can We Learn from Transfer, and How Is Best to Do It?	67
	Wilton N. Catford	
3.1	Motivation to Study Single-Nucleon Transfer Using Radioactive Beams	67
3.1.1	Migration of Shell Gaps and Magic Numbers, Far from Stability	68
3.1.2	Coexistence of Single Particle Structure and Other Structures	70
3.1.3	Description of Single Particle Structure Using Spectroscopic Factors	70
3.1.4	Disclaimer: What This Article Is, and Is Not, About	71
3.2	Choice of the Reaction and the Bombarding Energy	72
3.2.1	Kinematics and Measurements Using Normal Kinematics	72
3.2.2	Differential Cross Sections: Dependence on Beam Energy and ℓ Transfer	73
3.2.3	Choice of a Theoretical Reaction Model: The ADWA Description	77
3.2.4	Comparisons: Other Transfer Reactions and Knockout Reactions	78
3.3	Experimental Features of Transfer Reactions in Inverse Kinematics	80
3.3.1	Characteristic Kinematics for Stripping, Pickup and Elastic Scattering	81
3.3.2	Laboratory to Centre of Mass Transformation	85
3.3.3	Strategies to Combat Limitations in Excitation Energy Resolution	86
3.4	Examples of Light Ion Transfer Experiments with Radioactive Beams	89
3.4.1	Using a Spectrometer to Detect the Beam-like Fragment	89
3.4.2	Using a Silicon Array to Detect the Light (Target-like) Ejectile	90
3.4.3	Choosing the Right Experimental Approach to Match the Experimental Requirements	94
3.4.4	Using (d, p) with Gamma-Rays, to Study Bound States	97

3.4.5	The Use of a Zero-Degree Detector in (d, p) and Related Experiments	102
3.4.6	Simultaneous Measurements of Elastic Scattering Distributions	105
3.4.7	Extending (d, p) Studies to Unbound States	106
3.4.8	Simultaneous Measurement of Other Reactions Such as (d, t)	107
3.4.9	Taking into Account Gamma-Ray Angular Correlations in (d, p)	108
3.4.10	Summary	114
3.5	Heavy Ion Transfer Reactions	115
3.5.1	Selectivity According to $j_>$ and $j_<$ in a Semi-classical Model	115
3.5.2	Examples of Selectivity Observed in Experiments	117
3.6	Perspectives	118
	References	120
4	Effective Field Theories of Loosely Bound Nuclei	123
	U. van Kolck	
4.1	Introduction	123
4.2	Nuclear Physics Scales and Effective Field Theories	124
4.2.1	Basic Ideas	126
4.2.2	An Example: NRQED	133
4.2.3	Summary	141
4.3	QCD at Low Energies	141
4.3.1	Building Blocks	141
4.3.2	Chiral EFT	147
4.3.3	Renormalization of Singular Potentials and Power Counting	158
4.3.4	Summary	162
4.4	Loosely Bound Systems	162
4.4.1	Fine-Tuning	163
4.4.2	Contact EFT	164
4.4.3	Halo/Cluster EFT	173
4.4.4	Summary	178
4.5	Conclusions and Outlook	178
	References	179
5	Direct Reactions at Relativistic Energies: A New Insight into the Single-Particle Structure of Exotic Nuclei	183
	Dolores Cortina-Gil	
5.1	Introduction	183
5.1.1	First Experiments	186
5.2	Knockout Reactions	189
5.2.1	Extraction of Information in Knockout Reactions	189
5.2.2	Experimental Needs and Relevant Observables	193

5.2.3	Results of Knockout Measurements	201
5.3	Quasi-Free Scattering Reactions with Rare Isotope Beams	220
5.3.1	Status of the QFS Program with Exotic Rare Isotopes at R^3B	222
5.4	Summary and Conclusions	226
	References	227
6	Nuclear Charge Radii of Light Elements and Recent Developments in Collinear Laser Spectroscopy	233
	Wilfried Nörtershäuser and Christopher Geppert	
6.1	Introduction	233
6.2	Atomic Theory: Isotope Shift and Charge Radii	234
6.2.1	Mass Shift	235
6.2.2	Field Shift	236
6.2.3	Evaluation of Mass Shift and Field Shift Constants	239
6.3	Nuclear Theory: Charge Radii Variations Along Isotopic Chains	248
6.3.1	Spherical Nuclei	248
6.3.2	Nuclear Deformation	249
6.3.3	Clustering and Halos in Light Nuclei	251
6.4	Measuring Charge Radii of Halo Isotopes	254
6.4.1	The Challenge of Halo Nuclei	254
6.4.2	Helium: Spectroscopy on Cold and Trapped Atoms	255
6.4.3	Lithium: Doppler-Free Two-Photon Spectroscopy on Thermal Atoms	259
6.4.4	Beryllium and Neon: High-Accuracy Measurements with Fast Beams of Ions	264
6.5	Further Developments in Collinear Laser Spectroscopy	272
6.5.1	Isotope Shift Determinations Using β -Asymmetry Detection	272
6.5.2	Photon-Ion Coincidence Detection	275
6.6	Towards the Limits: Improving Sensitivity with Cooled and Bunched Ion Beams	276
6.6.1	Principle of a Radio-Frequency Quadrupole	276
6.6.2	Applications of Ion Bunchers in CLS	278
6.6.3	Optical Pumping in the Cooler and Buncher	282
6.7	Future Prospects	285
6.8	Conclusion	287
	References	288
7	The Nuclear Energy Density Functional Formalism	293
	T. Duguet	
7.1	Introduction	293
7.1.1	Generalities	293
7.1.2	Nuclear Structure Theory	295
7.1.3	Goal of the Present Lecture Notes	299
7.2	Prelude	300

- 7.2.1 Reference States and Bogoliubov Transformation 300
- 7.2.2 Elements of Group Theory 301
- 7.2.3 Collective Variable and Symmetry Breaking 303
- 7.3 Energy and Norm Kernels 304
 - 7.3.1 Norm Kernel 304
 - 7.3.2 Energy Kernel 305
 - 7.3.3 Pseudo-potential-based Energy Kernel 306
 - 7.3.4 Skyrme Parametrization 307
- 7.4 Single-Reference Implementation 315
 - 7.4.1 Equation of Motion 316
 - 7.4.2 One-Nucleon Addition and Removal Processes 318
 - 7.4.3 Effective Single-Particle Energies 320
 - 7.4.4 Equation of State of Infinite Nuclear Matter 323
 - 7.4.5 Symmetry Breaking and “Deformation” 327
 - 7.4.6 Connection to Density Functional Theory? 329
- 7.5 Multi-reference Implementation 330
 - 7.5.1 Symmetry-Restored Kernels 331
 - 7.5.2 Full Fledged MR Mixing 334
 - 7.5.3 Pseudo-potential-based Energy Kernel 335
 - 7.5.4 Other Observables 336
 - 7.5.5 Dynamical Correlations 336
 - 7.5.6 State-of-the Art Calculations 339
 - 7.5.7 Approximations to Full Fledged MR-EDF 339
 - 7.5.8 Pathologies of MR-EDF Calculations 340
 - 7.5.9 Towards Pseudo-potential-based Energy Kernels 343
 - 7.5.10 Towards Non-empirical Energy Kernels 344
- 7.6 Conclusions 345
- References 347