

# Lecture Notes in Physics

## Editorial Board

R. Beig, Wien, Austria  
W. Domcke, Garching, Germany  
B.-G. Englert, Singapore  
U. Frisch, Nice, France  
P. Hänggi, Augsburg, Germany  
G. Hasinger, Garching, Germany  
K. Hepp, Zürich, Switzerland  
W. Hillebrandt, Garching, Germany  
D. Imboden, Zürich, Switzerland  
R. L. Jaffe, Cambridge, MA, USA  
R. Lipowsky, Golm, Germany  
H. v. Löhneysen, Karlsruhe, Germany  
I. Ojima, Kyoto, Japan  
D. Sornette, Nice, France, and Los Angeles, CA, USA  
S. Theisen, Golm, Germany  
W. Weise, Garching, Germany  
J. Wess, München, Germany  
J. Zittartz, Köln, Germany

## The Editorial Policy for Edited Volumes

The series *Lecture Notes in Physics* (LNP), founded in 1969, reports new developments in physics research and teaching - quickly, informally but with a high degree of quality. Manuscripts to be considered for publication are topical volumes consisting of a limited number of contributions, carefully edited and closely related to each other. Each contribution should contain at least partly original and previously unpublished material, be written in a clear, pedagogical style and aimed at a broader readership, especially graduate students and nonspecialist researchers wishing to familiarize themselves with the topic concerned. For this reason, traditional proceedings cannot be considered for this series though volumes to appear in this series are often based on material presented at conferences, workshops and schools.

## Acceptance

A project can only be accepted tentatively for publication, by both the editorial board and the publisher, following thorough examination of the material submitted. The book proposal sent to the publisher should consist at least of a preliminary table of contents outlining the structure of the book together with abstracts of all contributions to be included. Final acceptance is issued by the series editor in charge, in consultation with the publisher, only after receiving the complete manuscript. Final acceptance, possibly requiring minor corrections, usually follows the tentative acceptance unless the final manuscript differs significantly from expectations (project outline). In particular, the series editors are entitled to reject individual contributions if they do not meet the high quality standards of this series. The final manuscript must be ready to print, and should include both an informative introduction and a sufficiently detailed subject index.

## Contractual Aspects

Publication in LNP is free of charge. There is no formal contract, no royalties are paid, and no bulk orders are required, although special discounts are offered in this case. The volume editors receive jointly 30 free copies for their personal use and are entitled, as are the contributing authors, to purchase Springer books at a reduced rate. The publisher secures the copyright for each volume. As a rule, no reprints of individual contributions can be supplied.

## Manuscript Submission

The manuscript in its final and approved version must be submitted in ready to print form. The corresponding electronic source files are also required for the production process, in particular the online version. Technical assistance in compiling the final manuscript can be provided by the publisher's production editor(s), especially with regard to the publisher's own  $\text{\LaTeX}$  macro package which has been specially designed for this series.

## LNP Homepage ([springerlink.com](http://springerlink.com))

On the LNP homepage you will find:

- The LNP online archive. It contains the full texts (PDF) of all volumes published since 2000. Abstracts, table of contents and prefaces are accessible free of charge to everyone. Information about the availability of printed volumes can be obtained.
- The subscription information. The online archive is free of charge to all subscribers of the printed volumes.
- The editorial contacts, with respect to both scientific and technical matters.
- The author's / editor's instructions.

J. Al-Khalili E. Roeckl (Eds.)

# The Euroschool Lectures on Physics with Exotic Beams, Vol. I



Springer

## Editors

Jim Al-Khalili  
Department of Physics  
University of Surrey  
Guildford GU2 7XH  
Surrey, U.K.

Ernst Roeckl  
GSI Darmstadt  
Plankstr.1  
64291 Darmstadt, Germany

---

J. Al-Khalili, E. Roeckl (Eds.), *The Euroschool Lectures on Physics with Exotic Beams, Vol. I*,  
Lect. Notes Phys. 651 (Springer, Berlin Heidelberg 2004), DOI 10.1007/b98790

---

Library of Congress Control Number: 2004108216

ISSN 0075-8450  
ISBN 3-540-22255-3 Springer-Verlag Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable to prosecution under the German Copyright Law.

Springer-Verlag is a part of Springer Science+Business Media  
springeronline.com

© Springer-Verlag Berlin Heidelberg 2004  
Printed in Germany

The use of general descriptive names, registered names, trademarks, 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.

Typesetting: Camera-ready by the authors/editor  
Data conversion: PTP-Berlin Protago-TeX-Production GmbH  
Cover design: *design & production*, Heidelberg

Printed on acid-free paper  
54/3141/ts - 5 4 3 2 1 0

# Lecture Notes in Physics

For information about Vols. 1–604

please contact your bookseller or Springer-Verlag

LNP Online archive: [springerlink.com](http://springerlink.com)

Vol.605: G. Ciccotti, M. Mareschal, P. Nielaba (Eds.), *Bridging Time Scales: Molecular Simulations for the Next Decade*.

Vol.606: J.-U. Sommer, G. Reiter (Eds.), *Polymer Crystallization. Observations, Concepts and Interpretations*.

Vol.607: R. Guzzi (Ed.), *Exploring the Atmosphere by Remote Sensing Techniques*.

Vol.608: F. Courbin, D. Minniti (Eds.), *Gravitational Lensing: An Astrophysical Tool*.

Vol.609: T. Henning (Ed.), *Astromineralogy*.

Vol.610: M. Ristig, K. Gernoth (Eds.), *Particle Scattering, X-Ray Diffraction, and Microstructure of Solids and Liquids*.

Vol.611: A. Buchleitner, K. Hornberger (Eds.), *Coherent Evolution in Noisy Environments*.

Vol.612: L. Klein, (Ed.), *Energy Conversion and Particle Acceleration in the Solar Corona*.

Vol.613: K. Porsezian, V.C. Kuriakose (Eds.), *Optical Solitons. Theoretical and Experimental Challenges*.

Vol.614: E. Falgarone, T. Passot (Eds.), *Turbulence and Magnetic Fields in Astrophysics*.

Vol.615: J. Büchner, C.T. Dum, M. Scholer (Eds.), *Space Plasma Simulation*.

Vol.616: J. Trampetic, J. Wess (Eds.), *Particle Physics in the New Millennium*.

Vol.617: L. Fernández-Jambrina, L. M. González-Romero (Eds.), *Current Trends in Relativistic Astrophysics, Theoretical, Numerical, Observational*

Vol.618: M.D. Esposti, S. Graffi (Eds.), *The Mathematical Aspects of Quantum Maps*

Vol.619: H.M. Antia, A. Bhatnagar, P. Ulmschneider (Eds.), *Lectures on Solar Physics*

Vol.620: C. Fiolhais, F. Nogueira, M. Marques (Eds.), *A Primer in Density Functional Theory*

Vol.621: G. Rangarajan, M. Ding (Eds.), *Processes with Long-Range Correlations*

Vol.622: F. Benatti, R. Floreanini (Eds.), *Irreversible Quantum Dynamics*

Vol.623: M. Falcke, D. Malchow (Eds.), *Understanding Calcium Dynamics, Experiments and Theory*

Vol.624: T. Pöschel (Ed.), *Granular Gas Dynamics*

Vol.625: R. Pastor-Satorras, M. Rubi, A. Diaz-Guilera (Eds.), *Statistical Mechanics of Complex Networks*

Vol.626: G. Contopoulos, N. Voglis (Eds.), *Galaxies and Chaos*

Vol.627: S.G. Karshenboim, V.B. Smirnov (Eds.), *Precision Physics of Simple Atomic Systems*

Vol.628: R. Narayanan, D. Schwabe (Eds.), *Interfacial Fluid Dynamics and Transport Processes*

Vol.629: U.-G. Meißner, W. Plessas (Eds.), *Lectures on Flavor Physics*

Vol.630: T. Brandes, S. Kettemann (Eds.), *Anderson Localization and Its Ramifications*

Vol.631: D. J. W. Giulini, C. Kiefer, C. Lämmerzahl (Eds.), *Quantum Gravity, From Theory to Experimental Search*

Vol.632: A. M. Greco (Ed.), *Direct and Inverse Methods in Nonlinear Evolution Equations*

Vol.633: H.-T. Elze (Ed.), *Decoherence and Entropy in Complex Systems, Based on Selected Lectures from DICE 2002*

Vol.634: R. Haberlandt, D. Michel, A. Pöpl, R. Stannarius (Eds.), *Molecules in Interaction with Surfaces and Interfaces*

Vol.635: D. Alloin, W. Gieren (Eds.), *Stellar Candles for the Extragalactic Distance Scale*

Vol.636: R. Livi, A. Vulpiani (Eds.), *The Kolmogorov Legacy in Physics, A Century of Turbulence and Complexity*

Vol.637: I. Müller, P. Strehlow, Rubber and Rubber Balloons, *Paradigms of Thermodynamics*

Vol.638: Y. Kosmann-Schwarzbach, B. Grammaticos, K.M. Tamizhmani (Eds.), *Integrability of Nonlinear Systems*

Vol.639: G. Ripka, *Dual Superconductor Models of Color Confinement*

Vol.640: M. Karttunen, I. Vattulainen, A. Lukkarinen (Eds.), *Novel Methods in Soft Matter Simulations*

Vol.641: A. Lalazisis, P. Ring, D. Vretenar (Eds.), *Extended Density Functionals in Nuclear Structure Physics*

Vol.642: W. Hergert, A. Ernst, M. Däne (Eds.), *Computational Materials Science*

Vol.643: F. Strocchi, *Symmetry Breaking*

Vol.644: B. Grammaticos, Y. Kosmann-Schwarzbach, T. Tamizhmani (Eds.) *Discrete Integrable Systems*

Vol.645: U. Schollwöck, J. Richter, D.J.J. Farnell, R.F. Bishop (Eds.), *Quantum Magnetism*

Vol.646: N. Bretón, J. L. Cervantes-Cota, M. Salgado (Eds.), *The Early Universe and Observational Cosmology*

Vol.647: D. Blaschke, M. A. Ivanov, T. Mannel (Eds.), *Heavy Quark Physics*

Vol.648: S. G. Karshenboim, E. Peik (Eds.), *Astrophysics, Clocks and Fundamental Constants*

Vol.649: M. Paris, J. Rehacek (Eds.), *Quantum State Estimation*

Vol.650: E. Ben-Naim, H. Frauenfelder, Z. Toroczkai (Eds.), *Complex Networks*

Vol.651: J.S. Al-Khalili, E. Roeckl (Eds.), *The Euroschool Lectures of Physics with Exotic Beams, Vol.I*

# Preface

In recent years a new scientific discipline has emerged in nuclear physics research worldwide: the production and use of energetic radioactive beams. The study of the atomic nucleus, the tiny core of the atom and carrier of essentially all of the visible mass in the Universe, has undergone a major re-orientation in the past two decades and has seen the emergence of a new frontier. The availability of energetic beams of short-lived (radioactive) nuclei, referred to as ‘radioactive ion beams (RIB) or exotic nuclear beams’, has opened the way to the study of the structure and dynamics of thousands of nuclear species never before studied in the laboratory. These exotic beams, produced by two complementary techniques (in-flight separation and post-acceleration of low-energy radioactive beams), have been developed in a number of European Large-Scale Facilities. A very promising way towards establishing an accurate and globally applicable description of the inner workings of atomic nucleus is the study of exotic nuclei. Pioneering experiments and vigorous development programmes are ongoing in Europe, North America and Japan on existing facilities. In addition, a new generation of large-scale RIB facilities is being built.

While the field of RIB physics is linked mainly to the study of nuclear structure under extreme conditions of isospin, mass, spin and temperature, it also addresses problems in nuclear astrophysics, solid-state physics and the study of fundamental interactions. Furthermore important applications and spin-offs also originate from this basic research. There is hence little doubt that RIB physics has transformed not only nuclear science but many related areas too.

Due to the fact that one is not limited anymore to the proton/neutron ratio of stable-isotope beams, virtually the whole chart of the nuclides opens up for research. Theoretical models can be verified up to the limits of the existence of nuclear matter: it is clear that the focus on this isospin degree of freedom will lead to better insights into the validity of present models and eventually to a new and more complete description of the atomic nucleus.

It has been the aim of the series of Euro (Summer) Schools on which the lectures in this volume are based to train PhD students and young post-docs starting to work in the field of RIB physics. The series first started in 1993 under the name Euroschools on Exotic Beams, an EU supported initiative started by Mark Huyse and Piet Van Duppen, and continued in 2002-2006 as the EU funded EURO SUMMER SCHOOLS ON EXOTIC BEAMS. At each of these Schools, six leading researchers in the field from around the world are invited to lecture on their topic. The lectures range over the subjects of nuclear theory, experiment, technical developments (in accelerator and detec-

tor design) as well as wider applications in related fields such as astrophysics and nuclear medicine.

This volume of *Lecture Notes in Physics* is the first in the series of a collection of lectures from recent Schools. It is aimed at a readership similar to those attending the Schools and should provide a helpful reference for young researchers entering the field and wishing to get a feel for contemporary research in a number of areas. The contributions are in the style of lecture notes that might be provided to new PhD students and which therefore have a reasonably long shelf-life. Unlike research papers or review articles, they are not meant to contain all the latest results or to provide an exhaustive coverage of the field but pedagogical introductions to the subject with examples.

We wish to point out that the contributions in this first volume are by lecturers chosen from among all previous Schools who have updated their material to incorporate recent advances and results. They were chosen by the editors in order to cover a selection of topics that span the field of RIB physics, from theory and experiment to techniques, applications and related areas. Naturally, since this is only the first volume of the *Lecture Notes in Physics* series for the School it is anticipated that the ‘backlog’ of lectures will eventually be dealt with, as each volume will contain roughly two years worth of School lectures.

Finally, we would like to thank our co-lecturers for their valuable contributions to this volume and Dr Chris Caron and his colleagues at Springer-Verlag for their help and fruitful collaboration in this matter.

J.S. Al-Khalili and E. Roeckl (Editors)

# Contents

## The Why and How of Radioactive-Beam Research

<i>Mark Huyse</i> .....	1
1 Introduction: The Structure of the Nucleus, How Deeply Is It Understood? .....	1
2 The Nuclear Chart, Our Road Map from Stable to Exotic Nuclei ..	2
2.1 Milestones in the Exploration of the Nuclear Chart .....	5
2.2 Important Discoveries .....	10
3 Radioactive Beams for Other Fields .....	26
3.1 Fundamental Interactions .....	27
3.2 Nuclear Astrophysics .....	27
3.3 Solid-State Physics .....	27
3.4 Nuclear Medicine .....	28
4 Outlook: The Next Generation .....	29

## Shell Model from a Practitioner's Point of View

<i>Hubert Grawe</i> .....	33
1 The Nuclear Shell Model .....	33
1.1 Independent Particle Motion, Nuclear Mean Field Potential and Single Particle Energies ...	34
1.2 Empirical, Schematic and Realistic Interactions .....	36
1.3 Observables and Effective Operators .....	38
1.4 Model Space, Truncation, Codes .....	40
2 Empirical Shell Model .....	41
2.1 Seniority in $j^n$ Configurations .....	42
2.2 Three and More Particles in Non-equivalent Orbitals .....	45
2.3 Particle-Hole Conjugation .....	48
3 Shell Model Applications .....	49
3.1 The N=2 (1s,0d) Shell: $^{16}\text{O}$ - $^{40}\text{Ca}$ .....	50
3.2 The N=3 (1p,0f) Shell: $^{40}\text{Ca}$ - $^{48}\text{Ca}$ - $^{56}\text{Ni}$ .....	50
3.3 The N=3 Plus Intruder Shell: $^{48}\text{Ca}$ - $^{56}\text{Ni}$ - $^{78}\text{Ni}$ .....	52
3.4 The N=4 Plus Intruder Shell: $^{80}\text{Zr}$ - $^{100}\text{Sn}$ - $^{132}\text{Sn}$ .....	53
3.5 The N=5 Plus Intruder Shell: $^{132}\text{Sn}$ - $^{146}\text{Gd}$ - $^{208}\text{Pb}$ .....	57
3.6 The Z=82-126 Shell: Beyond $^{208}\text{Pb}$ .....	58
4 Quadrupole Deformation in Light and Medium-Heavy Nuclei .....	59
4.1 The 1s,0d,0f Shell: $^{24}\text{Mg}$ and $^{32}\text{Mg}$ .....	60

4.2	The $0f, 1p, 0g$ Shell: $^{48}\text{Cr}$ and $^{56}\text{Ni}$ .....	62
5	Evolution of Shell Structure .....	63
5.1	Monopole Shift of SPE .....	63
5.2	Shell Quenching and Stabilisation at $N \gg Z$ .....	64
5.3	Experimental Evidence for $N=6, 16(14)$ and $34(32)$ Shells....	68
6	Status and Future .....	70

## **An Introduction to Halo Nuclei**

	<i>Jim Al-Khalili</i> .....	77
1	What Is a Halo? .....	77
1.1	Examples of Halo Nuclei .....	78
1.2	Experimental Evidence for Halos .....	79
2	Structure Models .....	81
2.1	Two-Body Systems .....	81
2.2	Three-Body Systems – The Borromean .....	83
2.3	Microscopic Models .....	85
3	Reaction Models .....	86
3.1	The Glauber Model .....	89
3.2	The Optical Limit of the Glauber Model .....	93
3.3	Cross Sections in Glauber Theory .....	94
3.4	The Binary Cluster Model .....	96
3.5	More General Few-Body Reaction Models .....	100
3.6	The CDCC Method .....	101
3.7	The Adiabatic Model .....	102
3.8	The Recoil Limit Approximation .....	104
3.9	Other Models .....	105
4	Results from Reaction Studies .....	106
4.1	Reaction Cross Sections .....	106
4.2	Elastic and Inelastic Scattering .....	107
4.3	Breakup Reactions .....	108
4.4	Momentum Distributions .....	108
5	Summary .....	110

## **In-Flight Separation of Projectile Fragments**

	<i>David J. Morrissey, Brad M. Sherrill</i> .....	113
1	Introduction .....	113
2	Useful Nuclear Reaction Mechanisms .....	116
2.1	Projectile Fragmentation .....	116
2.2	Projectile Fission .....	121
2.3	Nuclear Fusion .....	122
2.4	Target Considerations .....	122
3	In-Flight Separation with Profiled Degraders .....	123
3.1	General Characteristics .....	123
3.2	Computer Simulation of In-Flight Separation .....	128
3.3	Transverse Beam Emittance .....	128

4 Energy Degraders and Range Compression ..... 129  
 5 Summary of Existing Capabilities and Outlook ..... 133

**Measurement of Mass and Beta-Lifetime of Stored Exotic Nuclei**

*Fritz Bosch* ..... 137  
 1 Introduction ..... 137  
 2 Basics of Ion Storage-Cooler Rings ..... 138  
   2.1 Hill’s Equations, Betatron Oscillations, Tunes, and Space-Charge Limits ..... 138  
   2.2 Beam Cooling ..... 142  
 3 Mass Measurement of Stored Exotic Nuclei – ‘Schottky’- and ‘Isochronous’ Mass Spectrometry ..... 146  
   3.1 The Deep Entanglement of Nuclear Structure and Stellar Nucleosynthesis ..... 147  
   3.2 In-Flight Production, Storage and Cooling of Exotic Nuclei at the GSI Fragment Separator and Storage Ring ..... 149  
   3.3 ‘Schottky’ and ‘Isochronous’ Mass-Spectrometry of Exotic, Highly-Charged Ions ..... 151  
   3.4 Summary of Schottky and Isochronous Mass Spectrometry ... 154  
 4 Measurement of Beta-Lifetimes of Stored, Highly Charged Ions ... 155  
   4.1 Basics of Bound-State Beta Decay ..... 158  
   4.2 Bound-State Beta Decay of Bare <sup>187</sup>Re and the Age of the Universe ..... 160  
   4.3 Measurement of a Continuum and Bound-State Branching Ratio ..... 165  
 5 Summary and Outlook ..... 165

**Traps for Rare Isotopes**

*Georg Bollen* ..... 169  
 1 Introduction ..... 169  
 2 Challenges in the Application of Traps to Rare Isotopes ..... 170  
 3 Basics of Ion Traps ..... 172  
   3.1 Generation of the Electric Trapping Potential ..... 172  
   3.2 Ion Confinement in Paul or RFQ Traps ..... 174  
   3.3 Penning Traps ..... 182  
   3.4 Ion Motion Excitation in Penning Traps ..... 186  
   3.5 Frequency Measurements in Penning Traps ..... 191  
   3.6 Cooling in Penning and Paul Traps ..... 192  
   3.7 Injection of Ions into Traps ..... 196  
   3.8 Mass Determination in Penning Traps ..... 196  
 4 Application of Ion Traps to Rare Isotopes ..... 197  
   4.1 Ideal Decay Studies ..... 197  
   4.2 Radioactive Ion Beam Manipulation ..... 198

4.3	Rare Isotope Penning Trap Mass Spectrometry (RI-PTMS) . . .	200
4.4	PTMS Projects at Rare Isotope Beam Facilities . . . . .	203
5	Conclusions . . . . .	207

## Colour Section

<b>Volume 1</b> . . . . .	211
---------------------------	-----

## Decay Studies of $N \simeq Z$ Nuclei

<i>Ernst Roeckl</i> . . . . .	223	
1	Introduction . . . . .	223
2	Experimental Observables and Their Links to Nuclear–Structure Phenomena . . . . .	224
2.1	Introductory Remarks on Decay Modes of $N \simeq Z$ Nuclei . . . . .	224
2.2	Direct Charged–Particle Radioactivity . . . . .	225
2.3	Beta Decay . . . . .	230
2.4	Link to Astrophysics . . . . .	237
3	Experimental Techniques . . . . .	237
3.1	The GSI–ISOL Facility . . . . .	237
3.2	Charged–Particle Detection . . . . .	238
3.3	High–Resolution $\gamma$ –Ray Detection . . . . .	238
3.4	Total Absorption Spectroscopy . . . . .	238
4	Isotope Hunting . . . . .	239
5	Determination of Nuclear Masses . . . . .	240
6	Experiments on Direct Charged–Particle Emission . . . . .	241
6.1	Experiments on Direct $\alpha$ Emission Above $^{100}\text{Sn}$ . . . . .	241
6.2	Experiments on Direct One–Proton Radioactivity . . . . .	243
6.3	Discovery of Direct Two–Proton Radioactivity . . . . .	245
7	Experiments on $\beta$ Decay . . . . .	245
7.1	Precision Studies of $0^+$ to $0^+$ Fermi $\beta$ Decay: The Link to Fundamental Physics . . . . .	245
7.2	Beta Decay near $^{100}\text{Sn}$ : Observation of the GT Resonance . . .	248
7.3	Beta-Delayed Proton Emission of $^{57}\text{Zn}$ . . . . .	250
8	Experiments on $\gamma$ -Delayed Charged–Particle Emission: A Novel Tool of In–Beam Spectroscopy . . . . .	253
9	Isomer Spectroscopy . . . . .	254
9.1	Shape Isomer in $^{74}\text{Kr}$ . . . . .	254
9.2	Spin–Gap Isomer in $^{94}\text{Ag}$ . . . . .	255
10	Summary and Outlook . . . . .	257

## Gamma-Ray and Conversion-Electron Spectroscopy of Exotic Heavy Nuclei

<i>Rauno Julin</i> . . . . .	263	
1	Introduction . . . . .	263
2	Production of Nuclear Excited States . . . . .	264
3	Gamma-Ray Spectrometers . . . . .	266
3.1	Detector . . . . .	266

3.2	Principles of Gamma-Ray Detection . . . . .	267
3.3	Gamma-Ray Detector Arrays . . . . .	270
4	Conversion-Electron Spectrometers . . . . .	273
4.1	Internal Conversion . . . . .	273
4.2	Types of Electron Spectrometers . . . . .	273
4.3	SACRED – A Magnetic Solenoid Electron Spectrometer for In-Beam Measurements . . . . .	275
5	Combined Systems . . . . .	276
5.1	Decay Spectroscopy . . . . .	276
5.2	In-Beam Spectroscopy with Ancillary Detectors . . . . .	277
5.3	Recoil-Gating and Recoil-Decay-Tagging Methods . . . . .	278
6	In-Beam Spectroscopic Studies of Very Neutron Deficient $Z \approx 82$ Nuclei at JYFL . . . . .	282
6.1	Coexistence in Even- $A$ Pb Nuclei Beyond the $N = 104$ Neutron Mid-Shell . . . . .	282
6.2	Towards Prolate Po Isotopes . . . . .	284
7	In-Beam Spectroscopic Studies of Transfermium Nuclei at JYFL . . . . .	286
7.1	Production Cross-Sections . . . . .	287
7.2	Prompt Gamma Rays from $^{254}\text{No}$ , $^{252}\text{No}$ and $^{250}\text{Fm}$ . . . . .	288
7.3	Conversion Electrons from $^{254}\text{No}$ . . . . .	290
8	Summary and Outlook . . . . .	292

**Selected Topics in Reaction Studies with Exotic Nuclei**

	<i>Nicolas Alamanos, Alain Gillibert</i> . . . . .	295
1	Introduction . . . . .	295
2	Elastic Scattering . . . . .	295
2.1	Proton Plus Nucleus Elastic Scattering . . . . .	296
2.2	The MUST Detector . . . . .	302
2.3	Weakly Bound Nucleus-Nucleus Elastic Scattering . . . . .	305
3	Inelastic Scattering and Magic Numbers . . . . .	310
3.1	Highlights . . . . .	310
3.2	Selected Examples of Proton Inelastic Scattering . . . . .	315
3.3	Proton Inelastic Scattering on S Isotopes . . . . .	316
4	Transfer Reactions . . . . .	328
5	Sub-barrier Fusion . . . . .	330

**Weak Interaction Studies**

**by Precision Experiments in Nuclear Beta Decay**

	<i>Nathal Severijns</i> . . . . .	339
1	Introduction . . . . .	339
2	The Standard Model of Particles and Forces . . . . .	340
2.1	Elementary Particles, Intermediate Bosons and Forces . . . . .	340
2.2	The Standard Model . . . . .	345
2.3	The Cabibbo-Kobayashi-Maskawa Quark-Mixing Matrix . . . . .	348
2.4	Not the Ultimate Theory . . . . .	350

3	Nuclear Beta Decay .....	352
3.1	Selection Rules .....	352
3.2	The Beta Decay Interaction Hamiltonian .....	352
3.3	Angular Distribution and Correlations in Beta Decay .....	357
4	Searching for Non-standard Model Physics in Nuclear $\beta$ -Decay ....	362
4.1	Unitarity of the Cabibbo-Kobayashi-Maskawa Quark-Mixing Matrix .....	362
4.2	Right-Handed V-, A-currents .....	366
4.3	Exotic Interactions .....	370
4.4	Time Reversal Violation .....	375
5	Summary and Outlook .....	377

## **Nuclear Astrophysics and Nuclei Far from Stability**

*Karlheinz Langanke, Friedrich-Karl Thielemann, Michael Wiescher* ... 383

1	Thermonuclear Rates and Reaction Networks .....	383
1.1	Thermonuclear Reaction Rates .....	383
1.2	Nuclear Reaction Networks .....	386
1.3	Burning Processes in Stellar Environments .....	388
2	Experimental Nuclear Astrophysics with Radioactive Beams .....	391
2.1	Relevant Energy Ranges for Cross Section Measurements ....	392
2.2	Radioactive Beams .....	393
3	Cross Section Predictions and Reaction Rates .....	397
3.1	Thermonuclear Rates from Statistical Model Calculations ....	399
4	Weak-Interaction Rates .....	409
4.1	Electron Capture and Beta-Decay .....	409
4.2	Neutrino-Induced Reactions .....	411
5	Explosive Burning Processes .....	413
5.1	Explosive H-Burning .....	415
5.2	Explosive He-Burning .....	416
5.3	Explosive C- and Ne-Burning .....	418
5.4	Explosive O-Burning .....	418
5.5	Explosive Si-Burning .....	419
5.6	The r-Process .....	421
6	Core Collapse Supernovae .....	422
6.1	General Picture .....	423
6.2	Weak-Interaction Rates and Presupernova Evolution .....	425
6.3	The Role of Electron Capture During Collapse .....	427
6.4	Neutrino-Induced Processes During a Supernova Collapse ....	431
6.5	Type II Supernovae Nucleosynthesis .....	432
7	The r-Process .....	437
7.1	The Role of Nuclear Physics .....	438
7.2	Working of the r-Process and Required Environment Properties .....	440
7.3	r-Process Sites .....	441
8	Nuclear Processes in Explosive Binary Systems .....	444

8.1	Nova Explosions .....	445
8.2	X-Ray Bursts .....	447
8.3	X-Ray Pulsars .....	452
8.4	Black Hole and Neutron Star Accretion Disks .....	453
9	Outlook .....	453

**Medical Applications of Accelerated Ions**

	<i>Wilma K. Weyrather</i> .....	469
1	Introduction .....	469
2	The Physical Basis of Ion Beam Therapy .....	470
	2.1 Depth Dose Distribution of Photons .....	470
	2.2 Inverse Dose Distribution of Ions .....	472
	2.3 Lateral Scattering .....	474
	2.4 Nuclear Fragmentation .....	475
3	The Enhanced Relative Biological Effectiveness (RBE) .....	476
	3.1 Molecular Mechanisms Yielding Increased RBE .....	476
	3.2 RBE and Energy and Atomic Number of the Particle .....	478
	3.3 RBE and Repair Capacity of the Irradiated Tissue .....	479
	3.4 RBE Calculation for Therapy .....	481
4	Tumorconform Treatment .....	483
	4.1 Active Energy Variation .....	483
	4.2 Magnetic Beam Scanning .....	484
	4.3 Treatment Planning .....	484
	4.4 In Vivo Dose Localisation by PET .....	485
	4.5 Patient Treatment .....	486
	4.6 Planned Facilities .....	488
	4.7 Conclusions .....	488

# List of Contributors

**Nicolas Alamanos,**  
CEA/DSM/DAPNIA/SPhN Saclay,  
91191 Gif-sur-Yvette Cedex, France  
nalamanos@cea.fr

**Jim Al-Khalili,**  
Department of Physics,  
University of Surrey,  
Guildford, GU2 7XH, UK  
J.Al-Khalili@surrey.ac.uk

**Georg Bollen,**  
National Superconducting Cyclotron  
Laboratory and Department for  
Physics and Astronomy,  
Michigan State University,  
East Lansing, MI 48824, USA,  
bollen@nscl.msu.edu

**Fritz Bosch,**  
Gesellschaft für  
Schwerionenforschung (GSI),  
PO Box 64220,  
Darmstadt, Germany,  
f.bosch@gsi.de

**Alain Gillibert,**  
CEA/DSM/DAPNIA/SPhN Saclay,  
91191 Gif-sur-Yvette Cedex, France  
gillili@hep.saclay.cea.fr

**Hubert Grawe,**  
Gesellschaft für  
Schwerionenforschung,  
Planckstr. 1,  
64291 Darmstadt, Germany  
h.grawe@gsi.de

**Mark Huyse,**  
University of Leuven,  
Instituut voor  
Kern- en Stralingsfysica,  
Celestijnenlaan 200 D,  
3001 Leuven, Belgium  
Mark.Huyse@fys.kuleuven.ac.be

**Rauno Julin,**  
Department of Physics,  
University of Jyväskylä,  
P.O.B. 35 (JYFL),  
40351 Jyväskylä, Finland  
rauno.julin@phys.jyu.fi

**Karlheinz Langanke,**  
Institute for Physics and Astronomy,  
University of Aarhus,  
8000 Aarhus, Denmark  
langanke@phys.au.dk

**David J. Morrissey**,  
National Superconducting Cyclotron  
Laboratory,  
Michigan State University,  
East Lansing, MI 48824, USA  
morrissey@nscl.msu.edu

**Ernst Roeckl**,  
Gesellschaft für  
Schwerionenforschung,  
Planckstr. 1,  
64291 Darmstadt, Germany,  
and Institute of Experimental  
Physics,  
University of Warsaw,  
ul. Hoża,  
00-681 Warsaw, Poland  
E.Roeckl@gsi.de

**Nathal Severijns**,  
Instituut voor  
Kern- en Stralingsfysica,  
Katholieke Universiteit Leuven,  
3001 Leuven, Belgium  
Nathal.Severijns  
@fys.kuleuven.ac.be

**Brad M. Sherrill**,  
National Superconducting Cyclotron  
Laboratory,  
Michigan State University,  
East Lansing, MI 48824, USA  
sherrill@nscl.msu.edu

**Friedrich-Karl Thielemann**,  
Department of Physics and  
Astronomy,  
University of Basel,  
4056 Basel, Switzerland  
Friedrich-Karl.Thielemann  
@unibas.ch

**Wilma K. Weyrather**  
Gesellschaft für  
Schwerionenforschung,  
Planckstr. 1,  
64291 Darmstadt, Germany  
W.Kraft-Weyrather@gsi.de

**Michael Wiescher**,  
Department of Physics,  
University of Notre Dame,  
IN 46556, USA  
Michael.C.Wiescher.1@nd.edu