

# Lecture Notes in Physics

## Volume 842

### *Founding Editors*

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

### *Editorial Board*

B.-G. Englert, Singapore  
U. Frisch, Nice, France  
F. Guinea, Madrid, Spain  
P. Hänggi, Augsburg, Germany  
W. Hillebrandt, Garching, Germany  
M. Hjorth-Jensen, Oslo, Norway  
R. A. L. Jones, Sheffield, UK  
H. v. Löhneysen, Karlsruhe, Germany  
M. S. Longair, Cambridge, UK  
M. Mangano, Geneva, Switzerland  
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

For further volumes:

<http://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](http://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](mailto:christian.caron@springer.com)

Hans Paetz gen. Schieck

# Nuclear Physics with Polarized Particles

 Springer

Hans Paetz gen. Schieck  
Institut für Kernphysik  
Universität zu Köln  
Zülpicher Straße 77  
50937 Cologne  
Germany  
e-mail: h.schieck@t-online.de

ISSN 0075-8450  
ISBN 978-3-642-24225-0  
DOI 10.1007/978-3-642-24226-7  
Springer Heidelberg Dordrecht London New York

e-ISSN 1616-6361  
e-ISBN 978-3-642-24226-7

Library of Congress Control Number: 2011938361

© Springer-Verlag Berlin Heidelberg 2012

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. Violations are liable to prosecution under the German Copyright Law.

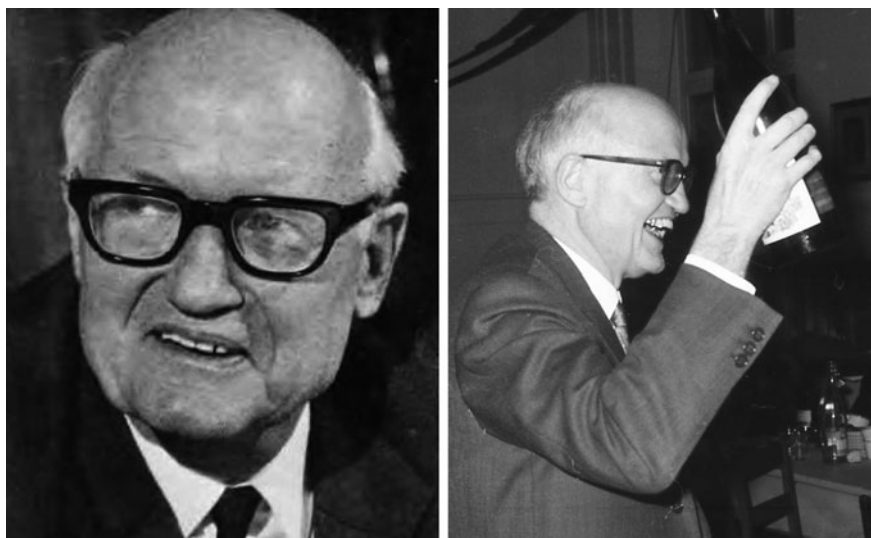
The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

*Cover design:* eStudio Calamar, Berlin/Figueras

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

## In memoriam



This book is dedicated to the memory of **Paul Huber** (1910–1971) who—at the University of Basel—pioneered an entire new field of nuclear physics: polarization phenomena, and with it the series of spin-physics (or polarization-phenomena) conferences and workshops. He was a brilliant teacher of physics, wrote a four-volume physics textbook, and worked in many international organizations such as IUPAP. Many of his former Ph.D. students became internationally renowned researchers and university teachers. Left photo reprinted with permission from AIP, New York. Copyright *Physics Today* 24(6) p. 71 (1971). Right photo by the author.

# Preface

Over 30 years a nuclear spin-polarization program has been maintained at the Institut für Kernphysik of the University of Cologne. The successful implementation of such a program requires not only the necessary equipment much of which has to be developed in-house but it rests on specially instructed and trained collaborators. These come about from undergraduate and graduate students who often start to work in experimental groups already as “mini-researchers”, develop into diploma or masters and later into Ph.D. students. Besides the standard education in physics, then by specializing in nuclear physics, and finally in specialized lectures and seminars they may become involved in fields like spin physics. In order to give them a knowledge basis in view of a lack of literature different scripts were written to accompany the lecture topics. One of the scripts was on the formal description of spin polarization, another on polarized-ion sources. It seems worthwhile to collect and conserve this knowledge in the form of a printed lecture note.

This lecture note consists of several parts. A large part is devoted to introducing the formal theory, the description of polarization and of nuclear reactions with polarized particles. Another part describes the physical basis of methods and devices necessary to perform experiments with polarized particles and to measure polarization and polarizing effects in nuclear reactions. A brief review of modern applications in medicine and fusion-energy research will conclude the lecture note. However, the many contributions of polarization to the widespread field of nuclear physics, especially nuclear reactions, i.e. its results and achievements in that context can only be touched upon within this more methodical survey.

Especially in the more experimental parts of the lecture note it appears impossible to cite all relevant references completely. Therefore, only original references to important developments of the field or selected references to the more recent literature, preferably containing further more complete references, can be cited here. They have been selected in view of their exemplary (not necessarily priority) value or, when discussing devices of polarization physics, the author will show examples with which he is acquainted in order to introduce the principles and more recent developments. Therefore, the examples are mainly taken from low-energy installations such as tandem-Van-de-Graaff laboratories although the

emphasis of present research is shifting to medium- and high-energy nuclear physics and the number of low-energy installations is waning. Consequently the description is entirely non-relativistic and focussed on the energy range from astrophysical energies ( $\approx 10$  keV) to tens of MeV. Also it is restricted to polarization of hadronic particles i.e. the polarization effects of electrons or  $\gamma$  radiation are not treated.

# Acknowledgments

It is a pleasure for me to thank all colleagues and especially my students over many years who not only have worked on improving the theoretical understanding of polarization phenomena but also on developing and improving the technical means and relevant devices which were used successfully for nuclear physics, especially in the field of low-energy few-body reactions.



# Contents

## Part I Formalism: Description of Spin Polarization

<b>1</b>	<b>Introduction</b> . . . . .	3
	References . . . . .	6
<b>2</b>	<b>Spin States and Spin Polarization</b> . . . . .	9
2.1	Measurement Process, Pure and Mixed States, Polarization . . .	10
2.2	Expectation Value and Average of Observables in Measurements . . . . .	11
	References . . . . .	12
<b>3</b>	<b>Density Operator, Density Matrix</b> . . . . .	13
3.1	General Properties of $\rho$ . . . . .	13
3.2	Distinction Between Pure and Mixed States . . . . .	14
	3.2.1 Pure State . . . . .	14
	3.2.2 Mixed State . . . . .	15
3.3	Other General Properties of $\rho$ . . . . .	16
3.4	Examples for Density Matrices . . . . .	17
	3.4.1 Spin $S = 1/2$ . . . . .	17
	3.4.2 Spin $S = 1$ . . . . .	20
	3.4.3 Rotation of a Pure $S = 1$ State . . . . .	22
3.5	Complete Description of Spin Systems . . . . .	23
3.6	Expansions of the Density Matrix, Spin Tensor Moments . . . . .	24
	3.6.1 Expansion of $\rho$ in a Cartesian Basis for Spin $S = 1/2$ . . . . .	25
	3.6.2 Spin $S = 1$ . . . . .	26
	3.6.3 Limiting Values of the Polarization Components . . . . .	29
	3.6.4 Expansion Into Spherical Tensors . . . . .	29
	3.6.5 Example for the Construction of a Set of Spherical Tensors for $S = 1$ . . . . .	32
	3.6.6 Spin Tensor Moments . . . . .	34

3.6.7	Spherical Tensors, Density Matrix, and Tensor Moments for Spin $S = 1/2$ . . . . .	34
3.6.8	Density Matrix and Tensor Moments for Spin $S = 1$ . . . . .	35
3.6.9	Polarization of Particles with Higher Spin . . . . .	37
References	. . . . .	38
<b>4</b>	<b>Rotations, Angular Dependence of the Tensor Moments</b> . . . . .	<b>39</b>
4.1	Generalities . . . . .	39
4.2	The Description of Rotations by Rotation Operators . . . . .	39
4.3	Rotation of the Density Matrix and of the Tensor Moments . . . . .	41
4.4	Practical Realization of Rotations . . . . .	43
4.5	Coordinate System . . . . .	43
References	. . . . .	44

**Part II Nuclear Reactions**

<b>5</b>	<b>Description of Nuclear Reactions of Particles with Spin</b> . . . . .	<b>47</b>
5.1	General . . . . .	47
5.2	The M Matrix . . . . .	48
5.3	Types of Polarization Observables . . . . .	50
5.4	Coordinate Systems . . . . .	52
5.4.1	Coordinate Systems for Analyzing Powers . . . . .	52
5.4.2	Coordinate Systems for Polarization Transfer . . . . .	53
5.4.3	Coordinate Systems for Spin Correlations . . . . .	54
5.5	Structure of the M Matrix and Number of “Necessary” Experiments . . . . .	57
5.6	Examples . . . . .	60
5.6.1	Systems with Spin Structure $1/2 + 0 \rightarrow 1/2 + 0$ . . . . .	60
5.6.2	Systems with the Spin Structure $1/2 + 1/2 \rightarrow 1/2 + 1/2$ . . . . .	61
5.6.3	The Systems with Spin Structure $\frac{1}{2} + \vec{1}$ and Three-Nucleon Studies . . . . .	62
5.6.4	The Systems with Spin Structures $\vec{1} + \vec{1}$ and $\frac{1}{2} + \frac{1}{2}$ and the Four-Nucleon Systems . . . . .	62
5.6.5	Practical Criteria for the Choice of Observables . . . . .	63
References	. . . . .	64
<b>6</b>	<b>Partial Wave Expansion</b> . . . . .	<b>65</b>
6.1	Neutral Particles . . . . .	65
6.2	Charged Particles . . . . .	68
6.3	Computer Codes . . . . .	69
References	. . . . .	70

**7 Charged-Particle Versus Neutron-Induced Reactions . . . . . 71**  
 References . . . . . 72

**Part III Devices**

**8 Sources and Targets of Polarized H and D Ions . . . . . 75**

8.1 Physical Basics: General Introduction . . . . . 75

8.2 Hyperfine Structure . . . . . 77

8.2.1 HFS of the H Atom . . . . . 77

8.2.2 HFS in a Magnetic Field (Zeeman Effect). . . . . 78

8.2.3 Zeeman Splitting of the H Atom . . . . . 81

8.2.4 Zeeman Splitting of the D Atom . . . . . 82

8.2.5 Calculation of Polarization . . . . . 83

8.3 Physics and Techniques of the Ground-State Atomic  
 Beam Sources ABS . . . . . 88

8.3.1 Production of H and D Ground-State  
 Atomic Beams . . . . . 88

8.3.2 Dissociators, Beam Formation and Accomodation . . . . . 88

8.3.3 State-Separation Magnets: Classical and Modern  
 Designs . . . . . 90

8.3.4 RF Transitions . . . . . 93

8.4 Ionizers . . . . . 102

8.4.1 Ionizers: Electron-Bombardment and CBS Designs. . . . . 102

8.4.2 Sources for Polarized  ${}^6,7\text{Li}$  and  ${}^{23}\text{Na}$  Beams . . . . . 106

8.4.3 Optically Pumped Polarized Ion Sources (OPPIS) . . . . . 107

8.5 Physics of the Lambshift Source LSS . . . . . 107

8.5.1 The Lambshift . . . . . 107

8.5.2 Level Crossings and Quench Effect . . . . . 108

8.5.3 Enhancement of Polarization . . . . . 109

8.5.4 Examples of the Polarization Calculation  
 for Different Modes of the LSS . . . . . 109

8.5.5 Hydrogen . . . . . 110

8.5.6 Deuterium . . . . . 111

8.5.7 Production and Maximization of the  
 Beam Polarization . . . . . 114

8.6 Spin Rotation in Beamlines and Precession in a Wien Filter. . . . . 121

8.6.1 Spin Rotation in Beamlines . . . . . 121

8.6.2 Spin Rotation in a Wien Filter . . . . . 123

8.7 Polarized (Gas) Targets and Storage Cells. . . . . 126

References . . . . . 128

<b>9</b>	<b>Polarization by Optical Pumping</b> . . . . .	131
9.1	Principles . . . . .	131
9.2	Polarization of $^3\text{He}$ . . . . .	131
9.2.1	Polarization by Metastability Exchange. . . . .	132
9.2.2	Spin Exchange . . . . .	133
9.3	Ion Sources for Polarized $^3\text{He}$ Beams . . . . .	135
	References . . . . .	135

## Part IV Methods

<b>10</b>	<b>Production of Polarization by Other Methods</b> . . . . .	139
10.1	Polarized Charged-Particle Beams from Nuclear Reactions . . . . .	139
10.2	Polarized Neutrons from Nuclear Reactions. . . . .	139
10.3	Spin Filtering: Interaction of Low-Energy Neutrons with Hyperpolarized $^3\text{He}$ . . . . .	140
10.4	Spin Filtering for Polarized Antiprotons . . . . .	141
	References . . . . .	141
<b>11</b>	<b>Measurement of Polarization Observables</b> . . . . .	143
	Reference . . . . .	144
<b>12</b>	<b>Polarimetry</b> . . . . .	145
12.1	Absolute Methods. . . . .	145
12.1.1	Time Reversal and Double Scattering. . . . .	145
12.1.2	Analytical Behavior of the Scattering Amplitudes . . . . .	146
12.1.3	Calibration Points Due to a Special Spin Structure . . . . .	147
12.1.4	Calibration Due to Special Conditions . . . . .	149
12.1.5	Typical Low-Energy Analyzer Reactions. . . . .	150
12.1.6	Polarimetry in Polarization-Transfer Experiments. . . . .	153
12.2	Polarimetry of Atomic (and Molecular) Beams . . . . .	154
12.2.1	Breit-Rabi Polarimeters. . . . .	154
12.2.2	Lambshift Polarimeters LSP . . . . .	156
	References . . . . .	157

## Part V Applications

<b>13</b>	<b>Medical Applications</b> . . . . .	161
13.1	Hyperpolarized $^3\text{He}$ and $^{129}\text{Xe}$ . . . . .	161
	References . . . . .	163

- 14 “Polarized” Fusion** . . . . . 165
  - 14.1 Five-Nucleon Fusion Reactions . . . . . 166
  - 14.2 Four-Nucleon Reactions . . . . . 167
    - 14.2.1 Suppression of Unwanted DD Neutrons . . . . . 168
  - 14.3 Status of ‘Polarized’ Fusion. . . . . 170
  - References . . . . . 172
  
- 15 Outlook** . . . . . 175
  - References . . . . . 176
  
- Index** . . . . . 179