High-Energy Nuclear Optics of Polarized Particles

This page intentionally left blank

High-Energy Nuclear Optics of Polarized Particles

Vladimir G. Baryshevsky

Research Institute for Nuclear Problems
Belarusian State University

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

HIGH-ENERGY NUCLEAR OPTICS OF POLARIZED PARTICLES

Copyright © 2012 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN-13 978-981-4324-83-0

ISBN-10 981-4324-83-3

Printed in Singapore.

Preface

The phenomena of interference, diffraction and refraction of light are well known even to lycee and college students. A great variety of their applications is described in school and university manuals and popular science books [Born and Wolf (1965); Purcell (1985); Crawford (1968); Wichman (1967); Agranovich and Gartstein (2006)]. Centuries-long argument about the nature of light: whether light is a wave or a particle, finally led to the creation of quantum mechanics and extension of the wave conception to the behavior of any particles of matter. As a result, optical concepts and notions were also introduced for describing interaction of particles with matter, nuclei, and one another [Landau and Lifshitz (1977); Fermi (1950); Feynman *et al.* (1965)]. In particular, widely used nowadays is diffraction of electrons and neutrons by crystals, which are in fact natural diffraction gratings. Neutron interferometers were designed [Greenberger and Overhauser (1979)]. It was found out that scattering of particles by nuclei (and by one another) is in many cases similar to scattering of light by a drop of water (the optical model of the nucleus).

A study of interaction between light and matter has shown that besides frequency and propagation direction, light waves are characterized by polarization.

The first experiment, which observed a phenomenon caused by the polarization of light, was carried out in 1669 by E. Bartholin, who discovered the double refraction of a light ray by Iceland spar (calcite). Today it is common knowledge that in the birefringence effect, the stationary states of light in a medium are the states with linear polarization parallel or perpendicular to the optic axis of a crystal. These states have different refractive indices and move at different velocities in a crystal. As a result, for example, circularly polarized light in crystals turns into linearly polarized and

vice versa [Born and Wolf (1965)].

Another series of experiments was performed by D.F. Arago in 1811 and J.B. Biot in 1812. They discovered the phenomenon of optical activity, in which the light polarization plane rotates as the light passes through a medium. In 1817, A. Fresnel established that in an optically active medium rotating the polarization plane, the stationary states are the waves with right-hand and left-hand circular polarizations, which, as he found out in 1823, move in a medium at different velocities (i.e., propagate with different refractive indices), thus causing the polarization plane to rotate. Let us also recall the effect of light polarization plane rotation in matter placed in a magnetic field, which was discovered by Faraday, and the birefringence effect in matter placed in an electric field (the Kerr effect).

The above-mentioned phenomena and various other effects caused by the presence of polarization of light and optical anisotropy of matter have become the subjects of intensive studies and found wide applications. The microscopic mechanism leading to the appearance of optical anisotropy of matter is, in the final analysis, due to the dependence of the process of electromagnetic wave scattering by an atom (or molecule) on the wave polarization (i.e., on the photon spin) and to bounds imposed on electrons in atoms and molecules. Beyond the optical spectrum, when the photon frequency appears to be much greater than the characteristic atomic frequencies, such bounds become negligible, and the electrons can be treated as free electrons. As a result, the effects caused by optical anisotropy of matter, which are studied in optics, rapidly diminish, becoming practically unobservable when the wavelengths are smaller than 10^{-8} cm.

Moreover, there is a widespread belief that it is only possible to speak of the refraction of light and to use the concept of the refraction index of light in matter because the wavelength of light ($\lambda \approx 10^{-4}$ cm) is much greater than the distance between the atoms of matter R_a ($R_a \approx 10^{-8}$ cm) since only in this case ($\lambda \gg R_a$) matter may be treated as a certain continuous medium. As a consequence, in a short-wave spectral range where the photon wavelength is much smaller than the distance between the atoms of matter, the effects similar to the Faraday effects and birefringence, which are due to refraction, should not occur. However, such a conclusion turned out to be incorrect. The existence of the refraction phenomena does not appear to be associated with the relation between the wavelength λ and the distance between atoms (between scatterers). Even at high photon energies when the wavelength is much smaller than R_a , the effects due to refraction of waves in matter can be quite appreciable. Thus, for example,

when a beam of linearly polarized γ -quanta with the energies greater than tens of kiloelectronvolts (wavelengths smaller than 10^{-9} cm) passes through matter with polarized electrons, there appears rotation of the polarization plane of γ -quanta, which is kinematically analogous to the Faraday effect ([Baryshevskii and Lyuboshitz (1965); Baryshevskii *et al.* (1972); Lobashev *et al.* (1971); Lobashev *et al.* (1975); Bock and Luksch (1971)]). Moreover, with the growth of the energy of γ -quantum (the decrease in the γ -quantum wavelength) the effect increases, attaining its maximum in the megaelectronvolt energy range. Unlike the Faraday effect, which is due to the bounds imposed on electrons in atoms, for γ -quanta electrons may be treated as free electrons. The effect of polarization plane rotation in this case is due to the quantum-electrodynamic radiative corrections to the process of scattering of γ -quanta by an electron, which are lacking in classical electrodynamics.

Analogously, the propagation in matter of the de Broglie waves, which describe motion of massive particles, can be characterized by the refractive index [Goldberger and Watson (1984); Fermi (1950)]. In this case, the refractive index also characterizes particle motion in matter, even at high energies, for which the de Broglie wavelength $\hbar/mv$ (m is the particle mass, v is its velocity, in the case of relativistic velocities m stands for the relativistic mass $m\gamma$, γ is the Lorentz factor) is small in comparison with the distance between the atoms (scatterers). Furthermore, it turns out that for particles with nonzero spin, there exist the phenomena analogous to light polarization plane rotation and birefringence. In this case such phenomena of quasi-optical activity of matter ("optical" anisotropy of matter) are due not only to electromagnetic but also to strong and weak interactions.

The investigations in this field were initiated by V. Baryshevsky and M. Podgoretsky [Baryshevskii and Podgoretskii (1964)], who predicted the existence of the phenomenon of quasi-optical spin rotation of the neutron moving in matter with polarized nuclei, which is caused by strong interactions, and introduced the concept of a nuclear pseudomagnetic field (neutron spin precession in a pseudomagnetic field of matter with polarized nuclei). The concept of a nuclear pseudomagnetic field and the phenomenon of neutron spin precession in matter with polarized nuclei were experimentally verified by Abragam's group in France (1972) [Abragam *et al.* (1972)] and Forte in Italy (1973) [Forte (1973)].

Here we would also mention the paper by F. Curtis Michel [Michel (1964)], who predicted the existence of spin "optical rotation" due to parity nonconserving weak interactions (the phenomenon was experimentally revealed [Forte *et al.* (1980)] and is used for studying parity nonconserving

weak interactions between neutrons and nuclei).

Further analysis showed that the effects associated with the optical activity of matter, which we consider in optics, are, in fact, the particular case of coherent phenomena emerging when polarized particles pass through matter with nonpolarized and polarized electrons and nuclei [Baryshevsky (1982a); Baryshevskii (1976a); Baryshevsky (1995b)]. It was found out, in particular, that at high energies of particles (tens, hundreds and thousands of gigaelectronvolts), the effects of “optical anisotropy” are quite significant and they may become the basis of unique methods for the investigation of the structure of elementary particles and their interactions.

V. Baryshevsky

Acknowledgments

I would like to take the opportunity to express my thanks to the people who have contributed in a variety of ways to the completion of this book.

First of all, I cannot but heartily mention M.I. Podgoretskii, my teacher, who I was privileged to learn from and to work with.

I have always owed great thanks to him and V.L. Lyuboshitz for many happy years that we worked together in a most friendly and stimulating atmosphere.

My thanks and appreciations also go to my colleagues at the Research Institute for Nuclear Problems, Belarusian State University for years of dedicated work, enthusiasm, and professionalism. I would like to express my special gratitude to Alexandra Gurinovich, whose abilities and help contributed greatly to the appearance of this book.

Many thanks go to Victoria Mazurova for assisting in the English translation of the manuscript.

Finally, I am forever indebted to my wife Galina, whose understanding, endless patience, and encouragement have supported me for every trials that comes my way. Her taking all the burdens of daily cares off my shoulders enabled me to reach this far.

This page intentionally left blank

Contents

<i>Preface</i>	v
<i>Acknowledgments</i>	ix
<i>Introduction</i>	1
Nuclear Optics of Polarized Matter. Nuclear Pseudomagnetism	3
1. Refraction and mirror reflection from a matter–vacuum plane boundary	5
1.1 Radiation and Scattering of Waves and Particles	5
1.2 Refraction and Mirror Reflection	14
1.3 The Optical Theorem	18
1.4 Scattering of Waves by a Set of Scatterers	20
2. Neutron spin “optical” rotation in matter with polarized nuclei. Nuclear pseudomagnetism	37
2.1 Polarized Beams and Polarized Targets	37
2.2 Phenomenon of Neutron Spin Precession in a Pseudomagnetic Field of Matter with Polarized Nuclei . .	41
2.3 Refraction of Neutrons in a Magnetized Medium	50
2.4 The Schrödinger Equation for a Coherent Neutron Wave Moving in a Polarized Nuclear Target	55
2.4.1 Paramagnetic resonance in a nuclear pseudomagnetic field	56

2.4.2	Spontaneous radiation of photons accompanying the passage of light through anisotropic matter . .	61
2.5	Neutron and Atomic-Spin Interferometry. Atom (Molecule) Spin Rotation and Oscillation under Refraction in a Constant Electric Field	63
2.5.1	Nonorthogonal Quasistationary States	70
3.	Gamma-optics of polarized matter	77
3.1	The Phenomenon of Rotation of the Polarization Plane of γ -Quanta in Matter with Polarized Electrons. Magnetic X-ray Scattering	77
3.2	Birefringence of γ -Quanta in a Target with Polarized Nuclei	85
4.	Diffraction of particles in polarized crystals	99
4.1	Refraction of a Coherent Wave in Polarized Crystals . . .	99
4.2	Multifrequency Nuclear Precession of Neutrons in Polarized Crystals with Ferromagnetic and Antiferromagnetic Ordering	104
4.3	Magnetic Diffraction of Neutrons	111
4.4	Multifrequency Precession of the Neutron Spin in a Uniform Magnetic Field	112
4.5	The Bragg Case of Neutron Diffraction in Nonmagnetic Crystals in a Magnetic Field	121
4.6	Neutron Spin Precession and Spin Dichroism in Nonmagnetic Nonpolarized Crystals	122
4.7	Mirror Reflection Under Diffraction Conditions (Grazing Incidence X-ray Diffraction)	126
5.	Diffraction of neutrons and γ -quanta in crystals exposed to variable external fields	131
5.1	Maxwell Equations and Dielectric Permittivity of Crystals Exposed to a Variable External Field	132
5.2	Diffraction of γ -Quanta in Crystals in a Variable External Field under Resonance Scattering by Nuclei	136
5.3	On Refraction in Crystals at $\alpha \gg g_0$	141
5.4	Scattering of a Monochromatic Plane Wave by a Plate of Matter Exposed to an Ultrasonic Wave	142

5.5	Coherent Acceleration and Polarization of Neutron in Magnetically-Ordered Crystals Illuminated by a Light Wave	149
5.6	Nuclear Reactions in a Light Wave	153
5.7	Optical Anisotropy of Matter in the Rotating Coordinate System	155
5.8	On Emission of Neutrons (γ -Quanta) by Nuclei from Crystals	158
6.	Positronium and muonium spin rotation and oscillations	163
6.1	Spin Rotation of an Electron (Atomic) Beam in Magnetized Matter	163
6.2	Exchange-Induced Shifts of Atomic Optical Lines in Polarized Gases	167
6.3	Positronium (Muonium) in Matter with Polarized Electrons	171
6.4	Phenomenon of Quantum Oscillations of the Positronium Decay γ -Quantum Angular Distribution in a Magnetic Field	177
6.4.1	Positronium spin rotation	177
6.4.2	Positronium three-quantum annihilation in a magnetic field	179
6.4.3	The spin matrix of positronium in a magnetic field	183
6.4.4	Time oscillation of the positronium decay γ -quantum angular distribution in a magnetic field	185
6.4.5	Oscillation cross section in the case of γ -quanta recording with three (one) detectors	186
6.4.6	Observation of time quantum oscillation in 3γ -annihilation of positronium in a magnetic field	191
6.5	The Quadrupole Moment in the Ground State of Hydrogen, Muonium, Mesoatoms and Other Hydrogen-like Atoms	192
6.5.1	The quadrupole moment of the ground state of muonium (hydrogen, Ps)	192
6.5.2	Quadrupole interaction of mesoatoms in matter	198

7.	Particle “optical” spin rotation at violation of space-reflection symmetry (P) and time reversal invariance (T)	203
7.1	P- and T-Noninvariant Phenomena in Neutrons Transmission Through Matter with Polarized Nuclei . . .	203
7.2	T-Violating Neutron Spin Rotation and Spin Dichroism in Crystals	210
7.3	P- and T-Noninvariant Phenomena in Atoms (Particles, Nuclei) Passing Through a Photon Target . . .	222
7.3.1	Refraction of light in a medium with polarized atoms (molecules) under P- and T-noninvariance	230
7.3.2	Spin rotation and spin dichroism under P- and T-noninvariance	231
8.	Time-reversal violating optical gyrotropy and birefringence of matter	235
8.1	Tensor of Dielectric Permittivity of a Medium in the Presence of T-, P-Odd Weak Interactions	238
8.2	T-, P-Odd Polarizabilities of Atoms and Molecules	243
8.3	The Possibility to Experimentally Observe the Time-Reversal Violating Optical Phenomena	250
8.4	The P-, T-Violating Diffraction of Electromagnetic Waves by a Diffraction Grating	255
9.	Phenomenon of time-reversal violating magnetic field generation by a static electric field and electric field generation by a static magnetic field	269
9.1	Time-Reversal Violating Generation of Electric and Magnetic Fields	269
9.2	About a Possibility to Search for the Electron EDM at the Level $10^{-28} \div 10^{-30}$ e·cm and the Constant of T-odd, P-odd Scalar Weak Interaction of an Electron with a Nucleus at the Level $10^{-5} \div 10^{-7}$ in Heavy Atoms and Ferroelectrics	283
9.2.1	Possible limit for d_e and k_1^{nuc} that could be obtained in the ferroelectric PbTiO_3	286

9.3	About the Possibility to Measure an Electric Dipole Moment (EDM) of Nuclei in the Range $10^{-27} \div 10^{-32}$ e · cm in Experiments for Search of Time-reversal Violating Generation of Magnetic and Electric Fields . . .	287
9.3.1	Nuclei in an electric field at low temperatures . .	288
9.3.2	Nuclei in a magnetic field at low temperatures . .	291
9.3.3	About the contribution of the electromagnetic interaction to the electric dipole moment of nuclei	293

“Optical” Spin Rotation and Birefringence Effect of High-Energy Particles 299

10.	“Optical” spin rotation of high-energy particles in a nuclear pseudomagnetic field	301
10.1	Spin Precession of Relativistic Particles in Polarized Matter	301
10.2	Spin Rotation and Spin Dichroism	304
10.3	Proton (Antiproton) Spin Rotation in a Thick Polarized Target and Spin Filtering of Particle Beams in a Nuclear Pseudomagnetic Field	307
10.4	Influence of Multiple Coulomb Scattering and Energy Losses on “Optical” Spin Precession and Dichroism of Charged Particles in Pseudomagnetic Fields of a Polarized Target	310
11.	The phenomenon of birefringence (spin oscillation and spin dichroism) of particles with spin $S \geq 1$	321
11.1	Rotation and Oscillation of Deuteron Spin in Nonpolarized Matter and Spin Dichroism (Birefringence Phenomenon)	325
11.2	The Effect of Tensor Polarization Emerging in Nonpolarized Beams Moving in Nonpolarized Matter . . .	329
11.3	The Amplitude of Zero-Angle Elastic Scattering of a Deuteron by a Nucleus	332
11.4	First Observation of Spin Dichroism with Deuterons in a Carbon Target	337

11.5	About Possible Influence of Birefringence Effect on the Processes of Production (Photoproduction, Electroproduction) of Vector Mesons in Nuclei	339
12.	Ω^- -hyperon spin birefringence and quark rescattering	343
13.	“Optical” spin rotation and birefringence of particles in a storage ring and measurement of the particle EDM, tensor electric and magnetic polarizabilities	347
13.1	Particle Spin Rotation in an Electromagnetic Field in a Storage Ring	349
13.2	Deuteron Spin Rotation in Electromagnetic Fields of a Storage Ring	354
13.3	Deuteron Spin Oscillation in a Storage Ring and Measurement of the Deuteron Tensor Magnetic Polarizability	361
13.4	Deuteron Spin Oscillation in a Storage Ring and Measurement of the Deuteron Tensor Electric Polarizability	362
13.5	The Index of Refraction and Effective Potential Energy of Particles in a Moving Relativistic Beam	365
13.6	Spin Rotation of the Proton (Antiproton, Deuteron) in a Storage Ring with a Polarized Target	369
13.7	Equations Describing Spin Motion for a Particle in a Storage Ring	371
13.8	Phenomena of Spin Rotation and Oscillation of Particles (Atoms, Molecules) Captured to a Trap Blown by a Flow of High-Energy Particles in a Storage Ring	375
14.	On the influence of a weak pseudomagnetic field on neutrino oscillations and collective processes in the matter of a supernova (neutron stars) and neutrino gas	381

Channeling and High-Energy Nuclear Optics in Crystals **387**

15.	Channeling of high-energy particles in crystals	389
15.1	Channeling of High-Energy Particles in Crystals	389

15.1.1	Channeling and diffraction of particles	389
15.1.2	Principles of the quantum theory of channeling	394
15.1.3	The energy–band spectrum of electrons and positrons channeled in a single crystal	398
15.2	Quantum Theory of Reactions Induced by Channeled Particles	409
15.3	Channeling (Diffraction) in Crystals in the Presence of Variable Fields	419
16.	The phenomenon of spin rotation of particles moving in bent crystals and measurement of the magnetic moment of short–lived particles and nuclei	423
16.1	Spin Rotation of Relativistic Particles Passing Through a Bent Crystal and Measurement of the Magnitude of ($g - 2$)	423
16.2	Spin Rotation and Depolarization of Relativistic Particles Traveling Through a Crystal	431
16.3	Oscillations in the Polarization of a Fast Channeled Particle Caused by its Quadrupole Moment	434
16.4	Spin Oscillation and the Possibility of Quadrupole Moment Measurement for Ω^- -hyperons Moving in a Crystal	436
16.5	Spin Rotation and Oscillations of High Energy Channeled Particles in the Effective Nuclear Potential of a Crystal as one of the Possibilities to Obtain and Analyze the Polarization of High Energy Particles	438
17.	A channeled fast particle as a two–dimensional (one–dimensional) relativistic atom	445
17.1	Spontaneous Photon Radiation in Radiation Transitions Between the Bands of Transverse Energy of Channeled Particles	445
17.2	Diffacted X-ray Radiation from a Relativistic Oscillator in a Crystal (DRO) (Diffacted Channeling Radiation (DCR))	451
17.2.1	General expression for spectral–angular distribution of radiation generated by a particle in a crystal	453

17.3	Parametric X-ray Radiation (PXR)	455
17.4	Diffacted X-ray Radiation from a Channeled Particle (DCR)	462
17.5	Surface Parametric X-ray (Quasi-Cherenkov) Radiation (SPXR) and DRO	464
17.6	Generation of γ -Quanta by Channeled Particles in a Crystal Undulator	466
17.7	Spectral-Angular Characteristics of Parametric X-ray Radiation (PXR) and Diffacted Radiation of Oscillator (DRO)	470
17.8	X-ray Radiation from a Spatially Modulated Relativistic Beam in a Crystal	474
17.9	Time Dependence of the Intensity of Radiation Produced by a Particle Transmitted Through a Crystal	481
18.	Interference of independently generated beams of γ -quanta	491
19.	Influence of multiple scattering and energy losses on emission of γ -quanta by high-energy particles in a medium	499
19.1	Spectral-Angular Distribution of Radiation Under the Conditions of Multiple Scattering and Energy Losses	499
19.2	Bremsstrahlung, Transition and Cherenkov Radiation of High-Energy γ -quanta in the Absence of Energy Losses	506
20.	Principles of the quantum theory of emission of γ -quanta in crystals	519
20.1	The Cross Section of Photon Generation by Particles in an External Field	519
20.2	Photon Generation in Crystals under Channeling Conditions	525
20.3	Spectral and Angular Distributions of Photons in the Dipole Approximation	531
20.4	The Influence of Refraction and Diffraction of γ -Quanta on Angular and Spectral Characteristics of Radiation Produced by Particles in Crystals	533
20.5	Optical Radiation Produced by Channeled Particles	536
20.6	Angular Distribution of Radiation Produced by Particles in a Crystal Under Refraction	539

20.7	Radiation Spectrum in the Quasiclassical Approximation	543
20.8	The Relation Between the Theory of Pair Formation in Crystals and the Quantum Electrodynamics of a Homogeneous Intense Field	548
21.	Synchrotron-type radiation processes in crystals and polarization phenomena accompanying them	557
21.1	Synchrotron-type Dichroism of Crystals	559
21.2	Synchrotron-type Birefringence of γ -quanta in Crystals .	564
21.3	Absorption Anisotropy of High-Energy Photons in a Crystal	569
21.4	Effects with Participation of Polarized $e^\pm$	571
21.5	Radiative Self-Polarization of $e^\pm$ in the Intense Fields of Crystals	572
21.6	Effect of Variation of the Anomalous Magnetic Moment of $e^\pm$	577
	<i>Bibliography</i>	581
	<i>Index</i>	619