THE PHYSICS OF POLARIZED TARGETS

Magnetic resonance is a field that has expanded to a wide range of disciplines, both in basic research and in its applications, and polarized targets have played an important role in this growth. This volume covers the range of disciplines required for understanding polarized targets, focusing in particular on the theoretical and technical developments made in dynamic nuclear polarization (DNP), nuclear magnetic resonance (NMR) polarization measurement, high-power refrigeration and magnet technology. Beyond particle and nuclear physics experiments, dynamically polarized nuclei have been used for experiments involving structural studies of biomolecules by neutron scattering and by NMR spectroscopy. Emerging applications in magnetic resonance imaging (MRI) are also benefiting from the sensitivity and contrast enhancements made possible by DNP or other hyperpolarization techniques. Topics are introduced theoretically using language and terminology suitable for scientists and advanced students from a range of disciplines, making this an accessible resource to this interdisciplinary field.

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Preface

Spin is the Rosetta stone of physics. It has proved many theoretical models and disproved others; it is inconceivable to study and explain matter, radiation and interactions without including the spin of the constituent particles and structures. For example, the Pauli exclusion principle is needed to understand the structure of atoms, and this is based on the knowledge that electrons are spin ½ fermions of which only one can occupy a given quantum state. Atomic electrons pair with opposite spins so as to build magnetically neutral matter, the most common state of solids and fluids. Also the conduction electrons in metals may form Cooper pairs with opposite spins, which explains superconductivity. These pairs behave as bosons with zero or integer spin. Quantum statistics of these half-integer or integer spin particles is the basis of low-temperature properties of quantum fluids and solids.

The Pauli exclusion principle is also seen in the electron degeneracy pressure of white dwarfs and in the neutron degeneracy pressure of the neutron stars that stabilize these astronomical objects. The degeneracy pressure generates the repulsive magnetic force due to the exchange interaction. It is only the gravity force that makes the neutron star collapse into a black hole.

Going deeper into matter, the understanding of nuclear structures requires the introduction of the spin for their constituent protons and neutrons, the nucleons. These, in turn, are built of quarks and gluons which are spin ½ fermions for the first and spin 1 bosons for the latter; this knowledge is vital for the understanding of the structure and interactions of nucleons in nuclear matter.

In the Foreword of his book *Spin in Particle Physics*, Elliott Leader states that ‘spin is an essential and fascinating complication in the physics of elementary particles’, a reversal of the slogan of the 1960s that ‘spin is an inessential complication of particle physics’. The slogan, an anecdote, can be understood from the historic fact that in the 1960s new particles were discovered almost on a monthly basis by analyzing bubble chamber pictures from which the particle masses could be determined. This was clearly more rewarding than wrestling with the complicated equipment and enormous statistics required for the study of the interactions of these particles in fine detail.

Spin polarized targets, the subject of this book, are an important tool and part of such complicated equipment. Other tools include polarized sources and polarized secondary beams, and the acceleration, storage and polarimetry of such beams. Our focus here is on the polarized solid targets that are particularly suitable for scattering experiments in secondary beams, but also important for the experiments in intense primary beams of protons and electrons; their intensity has developed steadily to reach now levels close to that of unpolarized beams.

In the course of the development of the polarized target techniques in the 1960s and 1970s, many disciplines were brought together: solid state physics and chemistry, electron spin spectroscopy, NMR spectroscopy, cryogenics, microwave, magnet and radiofrequency techniques. All of these needed to be pushed beyond their known limits in order to satisfy the growing needs of the particle physics experiments. Truly multidisciplinary skills were required.

The techniques developed for polarized targets helped also these scientists, in turn, in their own specialized disciplines. Among their achievements are the studies of nuclear magnetism and pseudomagnetism started in the 1970s, of large biomolecules by spin contrast variation started in the 1980s and of high-resolution NMR spectroscopy using DNP of rare spins more recently. Also, dissolution DNP was invented for the signal enhancement in MRI. These are good examples of the cross-fertilization and spin-offs resulting from the multidisciplinary collaborations.

The book is organized in the following way. The first two chapters describe the generic spin and its resonance in a high magnetic field, first without other interactions and then including interactions among themselves and with the constituents of the solid lattice. These chapters can be skipped by those who are already experts in magnetic resonance. Chapter 3 then focuses on the behavior of paramagnetic (unpaired) electron spins as is needed for the understanding of dynamic nuclear polarization in solids, which is the topic of Chapter 4.

Nuclear spins and their resonance in the solid lattice are discussed in Chapter 5, before describing the measurement of nuclear spin polarization in Chapter 6. Chapter 7 deals with the preparation and handling of the solid polarized target materials, and Chapter 8 focuses on the refrigeration of such materials during dynamic polarization using microwave irradiation. The required magnet and microwave techniques are the topics of Chapter 9.

Chapter 10 lists briefly other methods of generating high nuclear spin polarization, also used in particle physics experiments but, in particular, as used in new chemical and biomedical applications. Finally, the design and optimization of experiments with polarized targets are discussed in Chapter 11, focusing specifically on high-energy particle scattering experiments.

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