Introduction

> Commonplace as such experiments have become in our laboratories, I have not yet lost that sense of wonder, and delight, that this delicate motion should reside in all ordinary things around us, revealing itself only to him who looks for it.
>
> E. M. Purcell, Nobel Lecture, 1952

In December 1945, Purcell, Torrey and Pound detected weak radio-frequency signals generated by the nuclei of atoms in ordinary matter (in fact, about 1 kg of paraffin wax). Almost simultaneously, Bloch, Hansen and Packard independently performed a different experiment in which they observed radio signals from the atomic nuclei in water. These two experiments were the birth of the field we now know as nuclear magnetic resonance (NMR).

Before then, physicists knew a lot about atomic nuclei, but only through experiments on exotic states of matter, such as found in particle beams or through energetic collisions in accelerators. How amazing to detect atomic nuclei using nothing more sophisticated than a few army surplus electronic components, a rather strong magnet, and a block of wax!

In his Nobel Prize address, Purcell was moved to a poetic description of his feeling of wonder, cited above. He went on to describe how

> in the winter of our first experiments... looking on snow with new eyes. There the snow lay around my doorstep – great heaps of protons quietly precessing in the Earth's magnetic field. To see the world for a moment as something rich and strange is the private reward of many a discovery.

In the years since then, NMR has become an incredible physical tool for investigating matter. Its range is staggering, encompassing such diverse areas as brains, bones, cells, ceramics, inorganic chemistry, chocolate, liquid crystals, laser-polarized gases, protein folding, surfaces, superconductors, zeolites, blood flow, quantum geometric phases, drug development, polymers, natural products, electrophoresis, geology, colloids, catalysis, food processing, metals, gyroscopic navigation, cement, paint, wood, quantum exchange, phase transitions, ionic conductors, membranes, plants, micelles, grains, antiferromagnets, soil, quantum dots, explosives detection, coal, quantum computing, cement, rubber, glasses, oil wells and Antarctic ice.

Two brief examples may suffice here to show the range and power of NMR.

The first example is taken from *functional NMR imaging*. As explained in Section 12.6, it is possible to use the radio-frequency (r.f.) signals from the nuclei to build up a detailed picture of the three-dimensional structure of an object. The grey image given in Plate 1 shows this method applied to a human head, revealing the lobes of the brain inside the skull. The red and yellow flashes superimposed on the picture reveal *differences* in the NMR signals when the subject is performing some mental task, in this case processing the memory

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of a face that has just been removed from view. NMR can map out such mental processes because the brain activity changes slightly the local oxygenation and flow of the blood, which affects the precession of the protons in that region of the brain.

The second example illustrates the determination of biomolecular structures by NMR. Plate 2 shows the structure of a protein molecule in solution, determined by a combination of multidimensional NMR techniques, including the COSY and NOESY experiments described in Chapters 16 and 20. The structure is colour coded to reveal the mobility of different parts of the molecule, as determined by NMR relaxation experiments.

In this book, I want to provide the basic theoretical and conceptual equipment for understanding these amazing experiments. At the same time, I want to reinforce Purcell's beautiful vision: the heaps of snow, concealing innumerable nuclear magnets, in constant precessional motion. The years since 1945 have shown us that Purcell was right. *Matter really is like that*. My aim in this book is to communicate the rigorous theory of NMR, which is necessary for *really* understanding NMR experiments, but without losing sight of Purcell's heaps of precessing protons.