Preface

The first successful experiments in Neutron Radiography were carried out (to our knowledge) in 1935, just a few years after the discovery of the neutron, by H. Kallmann and E. Kuhn using a small neutron generator [1]. Not surprisingly, the field has developed and diversified over the last 70 years so that neutron imaging, in the broad sense, is now routinely used in a wide range of applications. The aim of this book (one of a series on the applications of neutron scattering [2]) is to introduce to the reader, whether novice or experienced researcher, the basic techniques used to image objects using neutron beams and to give a flavor of the vast range of applications where these imaging capabilities provide unique insight (Fig. 1).

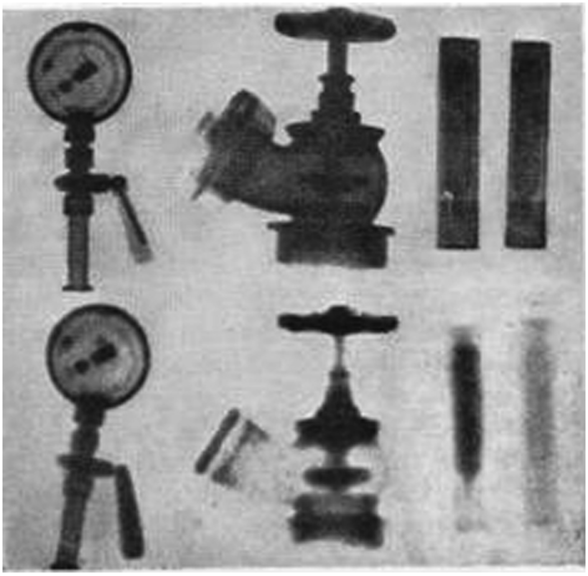

Fig. 1 Left to right: Pressure gauge with metal backplate; fire hydrant and test tubes filled with H_2O and D_2O imaged with gamma-rays (*top*) and neutrons (*bottom*) [3]

Traditionally, "neutron imaging" is used to describe the direct production of images by transmitting a beam of neutrons through an object onto a detector (e.g., film), i.e., exactly the same as is done with X-rays to image broken bones. An extension of this two-dimensional method (radiography) is to take many images of the same object in different orientations, and then to use the set of images to reconstruct a three-dimensional image (tomography). Although this may still seem to be "direct" imaging, in fact the image is "re-constructed" by software in a computer and sophisticated mathematical processes can be used to enhance particular features or generate virtual slices of the imaged object. We refer to such approaches as "constructed" or indirect imaging methods.

There are many other ways in which virtual pictures or images of an object can be rendered from more indirect measurements. Ultrasound imaging of an unborn baby involves the reconstruction of an image from scattered sound waves. As the size of the object being imaged decreases then simple direct imaging becomes effectively impossible, as the wavelength of the radiation being used becomes of comparable size. "Indirect" imaging methods such as electron diffraction can produce essentially the same "images" of crystal structures as those produced by an apparently "direct" method such as transmission electron microscopy, and indeed it is common to use the combination of these two techniques to enhance the images.

For example Fig. 2 shows a TEM/STEM image of Si_3N_4. The sample progresses from crystalline at the bottom to amorphous structure at the top. In addition there is a layer of lanthanum atoms on top of the crystalline part of the sample. The crystalline structure is overlaid with a ball-and-stick image obtained by diffraction from the crystal. Direct imaging resolves the crystal structure the same way that diffraction (indirect imaging) does; it does not resolve the amorphous structure, but amorphous structure can be determined by diffraction [4].

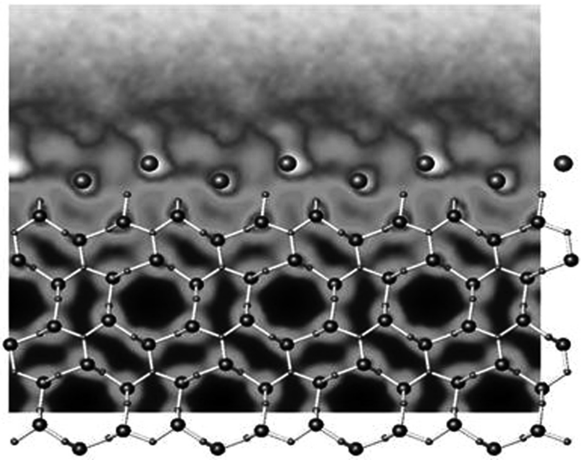

Fig. 2 Image courtesy of David Cockayne (Oxford University)

The current extreme example of indirect imaging is probably the reconstruction of three-dimensional images of single nanoparticles from coherent X-ray diffraction.

In this book we have intentionally taken a broad view of neutron imaging to include any process by which a picture or image of an object, or part of an object, can be produced based on the interaction with a neutron beam. These methods and their applications include

- Direct imaging methods such as neutron radiography being used to study operating fuel cells
- Three-dimensional tomographical reconstructions of mechanical objects
- The use of indirect methods such as diffraction or small-angle scattering to image strain patterns in materials
- Indirect imaging of the shapes of biological molecules by reconstruction from small-angle neutron scattering data.

Clearly, neutron imaging is a less well-known technique than X-ray imaging; most people know of the simple medical applications of X-ray radiography and the more recent extension to tomography (CAT or computed axial tomography scanning). This is largely due to the fact that it is simpler, and less costly, to generate and manipulate high-intensity sources of X rays than of neutrons. Hence the applications highlighted in this book rely heavily on the distinctive properties of neutron beams, which allow useful and often unique information to be derived from the image.

- Neutrons are weakly interacting neutral particles that penetrate deeply into most materials, so they can be used to internally image large objects, e.g., a full-size operating internal combustion engine, non-destructively.
- The amount of scattering or absorption of neutrons by atomic nuclei varies in an apparently random fashion through the periodic table. Hydrogen in particular has a very large scattering cross-section. Neutrons can therefore provide good contrast for light atoms in the presence of heavy atoms, e.g., the "classical" neutron image of a rose inside a lead flask (Fig. 3). This makes neutron imaging highly complementary to X-ray imaging (Fig. 1).
- The amount of scattering or absorption can also vary significantly between isotopes of the same chemical element; e.g., hydrogen has a very different scattering cross-section from that of its isotope deuterium. The contrast of particular elements/materials in an image can therefore be enhanced by substituting one isotope for another (Fig. 1).
- "Thermal" neutrons have wavelengths similar to inter-atomic distances, so mechanisms such as refraction or diffraction can be used to enhance images or to produce indirect images.
- Neutrons have a magnetic moment and a magnetic scattering cross-section that is comparable to the nuclear cross-section for many atoms. They can therefore be used to image magnetic structures.

Fig. 3 Neutron radiograph of a rose in a lead flask [5]

Hence the intrinsic properties of neutrons allow a wide range of objects to be imaged, ranging from massive structures such as helicopter blades to the fine details of crystal structures and passing through the delicate composition of biological organisms and plants. Furthermore, these intrinsic properties provide for an extensive range of contrast enhancement mechanisms including absorption, scattering, diffraction, refraction, magnetic interactions, and, potentially, vibrations. These mechanisms can be used to determine the elemental compositions of objects, which may even be hidden, buried, or encapsulated within an impenetrable environment. The possibility of studying objects in situ, or in real operational environments, is promising for a range of industrial and academic applications.

Neutron imaging techniques have a huge potential but in the past, applications have been slow to develop, mainly because of the weakness of the source itself. Even the most powerful neutron sources in existence today have a source brightness that is comparable to a simple X-ray tube and many orders of magnitude lower than a third-generation synchrotron X-ray source. Hence, while synchrotron X-ray sources provide the capability of imaging single nanoparticles with nanometer resolution, or dynamic images of larger objects with micrometer spatial resolution and microsecond time resolution, neutrons are presently limited to static images with spatial resolutions of the order of tens of microns, or dynamic images of 100 microns and microsecond exposure times for stroboscopic processes. Neutron imaging of smaller objects can only be achieved indirectly, using scattering techniques from an ensemble of particles.

Despite these limitations, the following chapters give a flavor of the wide range of applications that presently (or will potentially) benefit from neutron imaging techniques. The book is organized into three major sections.

Section A provides a comprehensive overview of basic neutron techniques aimed more specifically at a non-specialist audience. Frequent reference is made to the two introductory chapters in the first book of this series [2] by Roger Pynn (Neutron Scattering – a Non-Destructive Microscope for Seeing Inside Matter), and Helmut Schober (Neutron Scattering Instrumentation). Both these chapters are freely available at www.springerlink.com. In Chapter 1 Kenneth Herwig summarizes the essential neutron properties and techniques which are relevant to the majority of neutron imaging applications. Masatoshi Arai and Kent Crawford provide, in Chapter 2, an excellent survey of the different types and characteristics of neutron sources, including nuclear reactors, high-power spallation sources, and portable generators, which are typically used nowadays for neutron imaging. Although there is considerable overlap in the use of these sources, each type of source has specific advantages for certain types of applications. Due to the low-intrinsic brightness of neutron sources, efficient optical systems are imperative, so Ken Andersen's chapter (Chapter 3) presents the basic concepts of the neutron optics that are typically used on imaging beam lines. Finally in this section, Lowell Crow (Chapter 4) examines modern neutron detection methods for imaging. The first section reviews neutron capture converters which form the basis for thermal neutron detection, and the following sections examine detector systems with an emphasis on imaging applications.

Section B focuses on the neutron beam implementation of some well-known imaging techniques. Arthur Heller and Jack Brenizer (Chapter 5) present a summary of the history, methods, and related variations of neutron radiography techniques including a section on the application of standards. Even today, conventional film radiography remains the mainstay of high-resolution, large field-of-view, neutron imaging. In Chapter 6, Wolfgang Treimer extends the basic theories and applications to include three-dimensional tomography and introduces some of the newer methods for enhancing contrast such as wavelength dependent ("Bragg edge") imaging and small-angle scattering. Kenneth Tobin et al. (Chapter 7) provide a review of neutron image formation, resolution analysis concepts, and methods for both the design and characterization of radiography systems and conclude with a discussion of volumetric reconstruction techniques using analytic or iterative computed tomography algorithms.

The next two chapters describe techniques that depend intrinsically on the wave nature of the neutron. Franz Pfeiffer (Chapter 8) provides a fascinating overview of neutron phase imaging and its natural extension to neutron phase tomography. This technique offers the potential to image fundamental quantum mechanical interactions. Bhaskar Sur et al. (Chapter 9) show initial results from neutron holography experiments using both the internal and the external source approaches. Although in its infancy, neutron holography has the potential to resolve to atomic resolution the structures of materials, which are difficult to crystallize. Finally in this section Nikolay Kardjilov et al. (Chapter 10) describe some novel imaging techniques using the magnetic properties of the neutron. After demonstrating the power of neutrons to image magnetic fields in and around objects, they go on to describe theoretically some tantalizing but challenging potential applications of spin contrast imaging and neutron-based magnetic resonance imaging.

Section C provides the reader with an excellent, though non-exhaustive, overview of some specific applications of neutron imaging in diverse fields of research. Muhammad Arif et al. (Chapter 11) describe in situ neutron radiography and tomography studies of operating fuel cells and hydrogen storage systems, undoubtedly a high priority global research field for the foreseeable future, where the ability of neutrons to "see" hydrogen provides essential information to improve the practical chemical and mechanical engineering design.

Dayakar Penumadu (Chapter 12) provides an overview of some recent applications of neutron imaging methods to broad classes of materials science and engineering studies including metal casting, strain imaging, and characterization of discrete particle systems.

Carla Andreani et al. (Chapter 13) discuss the growing use of neutrons to image artifacts of interest in the domain of cultural heritage. Novel characterization methods allow determination of the provenance of ancient objects and can shed light on the methods and tools used at the time of manufacture.

In Chapter 14 Kenneth Watkin et al. summarize past and recent research efforts to apply neutron radiography to biological specimens, in the expectation that clinical and medical research, as well as forensic science, may benefit from advanced neutron imaging methods.

Moving on to prospective techniques for live imaging, Anuj Kapadia describes (in Chapter 15) the development of a tomographic technique that uses neutron inelastic scatter interactions to quantitatively identify the spatial distribution of elements in the body. The technique, called Neutron Stimulated Emission Computed Tomography (NSECT), uses a beam of fast neutrons to excite stable isotopes of elements in the body to determine their concentration and spatial distribution within the body. It has the potential to diagnose several element-related disorders in humans that are characterized by a change in element concentration in the diseased tissue.

In Chapter 16 William Heller and Gary Baker describe how small-angle neutron scattering measurements when combined with advanced computer modeling and contrast variation methods enable visualization of the structure and function of biological macromolecules.

Chapter 17 by Tomoko Nakanishi shows some fascinating examples of neutron imaging applied to plant physiology which allow in situ studies of vital processes in plant growth to be visualized.

Finally in Chapter 18 Dick Lanza summarizes security-related applications of neutron imaging, e.g., for the detection of illicit materials such as explosives or nuclear materials. One particular technique, neutron resonance radiography, is discussed in detail, as it illustrates many of the issues connected with imaging and detection.

We have attempted to provide a broad overview of the potential of neutron imaging methods. It is evident that in the process we will have omitted some important areas of application. Nevertheless we hope that you enjoy this edition and will be stimulated to read further.

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