1
Introduction

When Wilhelm Conrad Röntgen discovered "a new kind of rays" in 1895 [1], they became famous very soon for their remarkable property of penetrating without deviation through almost any kind of matter. They get weakened depending on material, the lighter the material, the less the absorption, this was clear very soon. Almost immediately this penetrating power was used to look inside materials without the need to physically destroy them. More than a century after the discovery, X-rays (in German-speaking countries they are called "Röntgenstrahlen" after their discoverer, although W.C. Röntgen himself called them "X-Strahlen", X-rays) are still famous for the same reason. Their applications in medical and technical imaging are still mainly governed by looking into the interior of materials, be it a suitcase in an X-ray scanner at the airport, an engine part in quality control, or a human body in a hospital. X-rays play a vital role also in material science, as they provide precious information about the otherwise inaccessible material's interior.

1.1
X-ray Interaction with Matter

1.1.1
Transmission of X-ray

From a physical point of view, we nowadays understand a bit more than Mr. Röntgen did. The fact that X-rays go through matter without deviation means that the refractive index is very close to unity. A small imaginary part in the refractive index accounts for absorption. Looking very carefully reveals that even the real part of the refractive index is not exactly unity, but slightly smaller. This is the origin of the process of total external reflection: When X-rays hit a surface under very small angles, they may bounce off like from a mirror. This happens up to a certain critical angle for total external reflection, which depends on the density of the material and on the wavelength of the X-rays. Typical values of the difference between the refractive index of X-rays and vacuum (or air) are in the order of 10^{-5}, with the imaginary part of that difference about an order of magnitude smaller.

Nanobeam X-Ray Scattering, First Edition. Julian Stangl, Cristian Mocuta, Virginie Chamard, and Dina Carbone.

In modern X-ray science, the X-ray transmission as shown in Figure 1.1a is still used in the important field of X-ray imaging, with a spatial resolution limited mainly by the resolution of the detector. The traditionally used photographic films or image plates have mostly been replaced by two-dimensional (2D) detector arrays, which are based on different detection principles, but have in common that the image is obtained in the form of intensity values per pixel. To increase the image resolution, often optical detectors with magnifying optics are used, and resolutions down to about a micrometer are reached. In this case the X-rays are collected on a fluorescent screen placed at the focus of the objective. Such a transmission image, however, often does not contain enough information about the specimen, since the absorption information is roughly the projection (or the integration) of the absorption of the whole specimen along the X-ray beam direction. It is not possible to discern whether higher absorption detected in a certain part of the specimen is related to a heavier material or an increased thickness. In order to improve this technique, three major developments have demonstrated to be very effective: three-dimensional (3D) information can be obtained using tomographic approaches, where several 2D images recorded at different view angles are combined to obtain the full 3D distribution of the absorption contrast inside the sample. Taking measurements at different wavelengths allows distinguishing differences in thickness and absorption inside the specimen. Finally, not only using the absorption, that is, the imaginary part of the refractive index, but also exploiting the real part of the refractive index leads to what is know as "phase contrast imaging". Due to the real part of the refractive index, X-rays inside the material have a slightly different wavelength, and consequently the transmitted X-rays behind the sample experience a phase shift, which depends on the amount and density of traversed material for each lateral position, as shown in Figure 1.1b. These phase shifts lead to interference effects, which can produce a very significant imaging contrast even in cases where the absorption contrast is weak, especially for light materials such as biological tissue. Phase contrast imaging benefits from the fact that the deviation of the real part of the refractive index from unity is typically an order of magnitude larger than the imaginary part.

1.1.2
Diffraction of X-rays

Several years after the discovery of X-rays, Walter Friedrich and Paul Knippig under the supervision of Max von Laue proved that X-rays are diffracted from the regular arrangement of atoms in a crystal [2]. It was a rather remarkable experiment performed in 1912 that proved, at the same time, the wave nature of X-rays and the fact that crystals are built from atoms. Even more, the distances of the atoms and the wavelength of the X-rays used were shown to be of the same order of magnitude, around 1 Å (or, in SI unit, 0.1 nm; the Å-scale is, however, still largely used in the X-ray scattering community). Ever since, scattering of X-rays has been used for the analysis of crystalline materials. This is a rather different way of obtaining information on the interior of a material as compared to the ab-

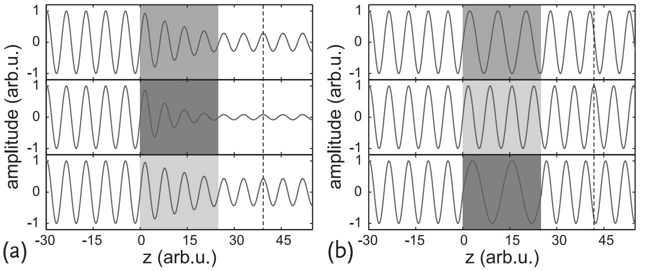

Figure 1.1 (a) X-rays travelling through matter (gray) is exponentially weakened due to the imaginary part of the refractive index. Different materials can be distinguished by different amplitudes and hence different intensities behind the sample. (b) The deviation from unity of the refractive index leads to a wavelength change inside matter (gray), even in the case of zero absorption. This leads to relative phase shifts of the X-rays after the sample, which can be exploited in phase contrast imaging, using the interference of waves transmitted through different parts of the sample.

sorption measurements mentioned above. There is no a priori resolution in real-space, since a beam of size typically ranging from few hundred micrometers to few millimeters is directed onto a crystal, and is diffracted under large angles. The detector collects the intensity diffracted by the whole illuminated volume, with no lateral resolution. Nevertheless, from the diffraction angle the distances between the atoms inside the specimen can be measured very accurately, up to 1/10 000 of the diameter of a single atom [3, 4]. This indeed represents a resolution far beyond any other microscopy technique, which, of course, comes at a price – it requires a crystalline specimen with a regular arrangement of atoms over very large distances. Therefore, this seems to be a technique with not too many applications, since large perfect crystals are rare. The opposite is true. Almost all solid state material is crystalline at least on a mesoscopic scale, that is, it consists of many small crystallites with size often in the micrometer or sometimes sub-micrometer range. This is still large compared to interatomic distances, and therefore diffraction can occur. By measuring accurately the diffraction patterns from a specimen, not only the distances between atoms but also the symmetry of the atomic arrangement can be determined. This provides a fingerprint of the material, and hence allows to determine the constituents of alloys, the nature of pigments in a painting, the constituents of compounds, to cite a few examples. The measurement of atomic distances also results in sensitivity to strain, for example due to distortions in the crystal lattice around defects or near interfaces.

The year this manuscript has been prepared coincides with the centenary of the first recorded X-ray diffraction image by von Laue in 1912, who was awarded the Nobel Prize in 1914. In the past 100 years, X-ray diffraction techniques have revolutionized our understanding of – amongst others – condensed matter. This is illustrated in Figure 1.2a, showing one of the first Laue images of a zinc-blende crystal and the rather simple unit cell structure, which required, however, quite some intuition to reveal at those days. For comparison a recent diffractogram of a crystal of the macromolecule collagenase G is shown as well, taken using monochromat-

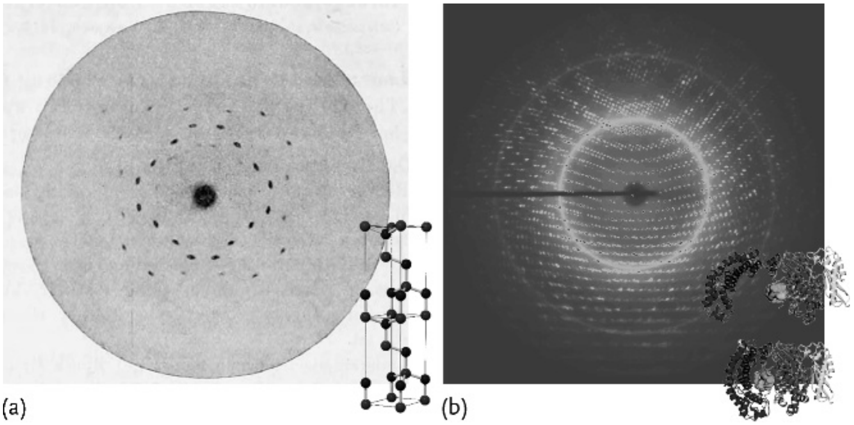

Figure 1.2 (a) One of the first Laue images of a zinc-blende crystal ([5]; image from [5]), the inset shows two unit cells of the according crystal structure. (b) Recent diffractogram of a crystal formed by a complex macromolecule collagenase G. The inset shows a simplified structural view of the molecule in two configurations, corresponding to two phases in the hydrolysis of a collagen triple-helix molecule. Image courtesy of H. Brandstetter, see also [6].

ic synchrotron radiation. From large series of such datasets, the structure of the molecule (consisting of many thousand atoms) can be determined, and even its biological functionality – in this case degeneration of collagen molecules – understood [6]. The inset of Figure 1.2b shows two according conformations (only the most important structural elements of the molecule are shown). Actually, X-ray diffraction has become an extremely important technique for such investigations of biological macromolecules and their function, which are nowadays performed on a routine basis. The first time X-ray diffraction helped to understand macromolecular structure might also be the most famous example of such investigations, namely the solution of the DNA molecule [7, 8], certainly one of the greatest contributions of X-rays to the understanding of nature.

A very important class of crystals in everyday life are semiconductors, which are actually the most perfect crystals surrounding us. The use of semiconductors in nanotechnology demands more and more detailed structural analysis at the nanoscale to correlate with physical properties and materials functionality. Diffraction techniques continue to develop at a rapid pace and strongly contribute to reveal the complex properties of materials also at the nanoscale, where crystal structure, morphology, chemical composition and crystalline defects and distortions (strain fields) all come into interplay.

Diffraction, however, is not limited to the investigation of atomic-scale distances, but can serve the investigation of nano- and microscale structures as well. Depending on the wavelength used, or the diffraction angles explored, one can access crystal structure at the atomic scale (including, crystallographic phases, strain fields, intermixing in alloys, etc.) but also order or periodicities at the mesoscale. Due to the fact that the interaction of X-rays with matter is mediated by electrons, and that the phenomenon of diffraction is based on a constructive interference of waves related to "some" periodicity of the electronic structure, any and all repeated distances in a specimen (thickness, lateral size, lateral ordering) can give rise to "diffraction". One can say that, qualitatively, the diffraction process picks up a "specific distance" in real-space, and transforms it into a defined "frequency" in reciprocal space. In other words, the diffraction from a real-space structure corresponds to measure its Fourier transform. Each observed frequency k corresponds to a periodicity $d \sim 1/k$ in real-space. Matter is often a patchwork of different lengthscales, especially so in nanostructured materials, both natural as well as technical ones. Important examples are tissues like wood or bone, or technical alloys with a strength depending on the constituent nanocrystalline particles and how they are interlinked. The surface of such particles and interfaces between them are often most important for the properties, and it is safe to say that sometimes the particular structure of a certain interface is even more important than the material on both sides of it. For the understanding of material properties out of its inner structure, the characterization of nanostructures, especially including the properties of surfaces and interfaces, is therefore a central task.

1.1.3
X-ray Elemental Sensitivity

By tuning the energy of the X-rays one can promote electrons from the atomic core levels to excited states. When these excited states decay, X-rays with a specific wavelength are emitted isotropically in the space. This "fluorescence" effect can be used to probe composition of materials, and can be exploited in imaging techniques to have an elemental map of the investigated specimen. Energy tunability is also exploited in other X-ray techniques, as anomalous scattering and resonant scattering. Often however, chemical sensitivity is obtained "indirectly", for example, by the relationship between chemical species and atomic distances in a diffraction experiment.

1.2
Diffraction at Different Lengthscales and Real-Space Resolution

In this book we will review the use of X-ray nanobeams, provided at the moment almost exclusively at synchrotron facilities. In this context, it is often claimed that such facilities work as powerful microscopes to shed light into the inner structure of matter. As was mentioned above, it is important to distinguish two ways of getting spatial resolution: a *direct* one like in imaging, with resolution limits determined by detector pixel sizes, homogeneity, sample properties (in phase contrast). Another one is *indirect*: measured signals are in reciprocal space, that is, we measure the Fourier transform of an object. During data analysis, which is usually not a simple inverse Fourier transform as we shall see, the real-space properties are calculated rather than observed. Spatial resolution[1] can therefore be high and low at the same time: we see very small changes in atomic distances (strain), but we do not see where in the sample this special distance is located. Fluctuations, ensembles of defects or nanostructures need to be treated via a statistical analysis, which usually grabs the main features well, but loses information on particular details.

A new trend, triggered by the growing importance of inhomogeneous nanomaterials, tries to close this gap: making the investigated area smaller allows locating where a certain change happens, how a certain property is distributed. Tracking such inhomogeneities and correlating them to particular properties like mechanical strength or electronic structure is one prerequisite for the design of materials with certain properties. This tracking is possible by use of focused X-rays, which became available at modern synchrotron sources.

1.2.1
How to Produce an X-ray Nanobeam

In order to produce a nanofocused X-ray beam, several requirements need to be met. Of course some kind of X-ray lens is required. In addition, one needs a rather small source size and reasonable distances between source, lens, and focal spot to achieve sub-micron focus sizes. This is difficult to realize using conventional laboratory equipment, but actually available at many synchrotron sources. The availability of lenses is of course a problem by itself, and we will consider it in a moment. Source sizes are typically in the few 10 to few 100 μm range at synchrotrons, which is rather smaller than for a laboratory instrument, but not by far. Distances are, however, much larger at synchrotrons, and typically in the order of 50–100 m between source and sample, which is where the focal spot should be. Hence, if a lens of something around 10 cm focal length can be fabricated, demagnification ratios in the range of 500–1000 are feasible, and one may arrive at few 10 to few 100 nm focus diameters. Of course, the usually much lower divergence available at a synchrotron is in favor of realistic focusing considering the achievable resolution in reciprocal space, as we will see.

Now it is common wisdom that the refractive index of matter for hard X-rays in the 10 keV regime differs from unity only by around 10^{-5}, with an imaginary part responsible for absorption usually still an order of magnitude smaller. So refractive lenses require very small radii of curvature to deliver reasonably small focal lengths, but this is actually not possible. In practice a set of lenses from a rather light element like Be or Si can be used, so-called compound refractive lenses.

Since the refractive index is slightly smaller than one, total external reflection at grazing incidence angles offers another possibility to realize lenses. Such mirror lenses have the advantage of being achromatic, as long as the incidence angles are below the critical angle for the wavelength range under consideration, but have the disadvantage that they deflect the beam and require more effort during alignment or changes of the setup.

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1) The term “resolution” is used here in a sloppy way. An exact definition can be found in Section 8.1.

A third class of lenses uses diffraction effects, the most frequently used variant being Fresnel zone plates. The limit here lies in the fabrication, which requires very fine zone patterns with a high aspect ratio to allow for efficient contrast between the zones. Recently, aspect ratios of the absorbing zones around 10 can be routinely realized, and often heavy metals such as gold deposited on a lithographically patterned Si support are used. With thicknesses in the micron range, zone plates are actually not so much absorbing X-rays, but rather phase-shifting. As we will see in Chapter 3, each lens type has its advantages and disadvantages, but all concepts have successfully been used to demonstrate beam diameters (full width at half maximum; FWHM) well below 100 nm, and hence are feasible for the purpose of real-space separation of nanostructures and a selective investigation.

1.2.2
Experiments with Nanobeams

Considering an experiment using a focused beam more closely, we realize that there is always a certain tradeoff: Regardless of whether we consider small-angle scattering or high-angle diffraction, we will be working essentially in reciprocal space as a Fourier space. In the commonly used kinematic approximation, we implicitly assume that the sample is illuminated by a plane wave, but a focused beam is actually not a plane wave. The basic principle and the tradeoff is sketched in an idealized way in Figure 1.3. Focusing leads to a concentration of intensity in the focal spot, but *always* introduces an angular spread of the beam, coupled to the curvature of the wavefront. In practice, a beam of finite size never is a plane wave, but while the beam divergence delivered from synchrotron sources may in most cases be neglected, the convergence introduced after the lens is finite and not negligible. The result is that we loose resolution in reciprocal space compared to the unfocused beam, while direct space resolution is enhanced. This somehow sounds like a tradeoff with no net effect, but it is not; beam divergence can be increased up to a certain limit determined by the sample, that is, the peak width following

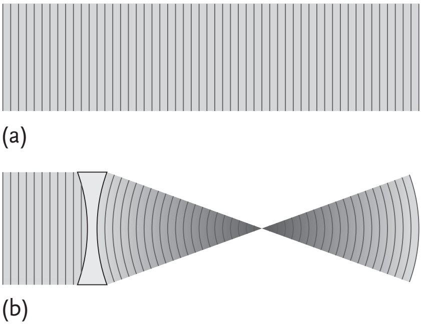

Figure 1.3 (a) Sketch of a parallel beam used in many experiments; wavefronts are plane, intensity is constant in space. (b) Focused beam; wavefronts are curved, and hence a certain angular spread is introduced; intensity is concentrated in the focal spot.

from typical feature sizes, without loss of resolution there, while at the same time real-space resolution gets better. Nanoscience is a good field for these new X-ray probes: small structures inherently produce spread-out diffraction patterns, which allow considerable focusing without actually loosing information.

Nanoscience is at the same time a field often requiring to obtain very local information. Both technical as well as natural nanostructures obtain many properties from a particular, in most cases, rather inhomogeneous structure at the nanoscale, even if the macroscopic structure appears to be homogenous; which is often true for technological samples like alloys or ceramics, while biological specimen are more often inhomogeneous at almost any lengthscale – we already mentioned wood as a typical example. Hence, the combination of focused beams as probes and nanoscale specimen turns out to match very well in many cases.

Considering the prospects of these combinations, we may just consider some basic facts. Nanobeam developments have been around for roughly one decade. Focus diameters decreased from few micrometers down to the few 10 nm range, that is, by about two orders of magnitude. More and more beamlines have become available world wide, the main developments include two directions; many synchrotron centers go for rather long beamlines to get a better demagnification ratio. On the other hand, keeping a 100 nm diameter beam stable within few 10 nm or better over a distance of 100 m is not trivial. Any vibration leads to an increase of the effective focus size (time-averaged), and there are a bunch of sources of vibration at large scale facilities, like vacuum pumps, air conditioning, heavy machinery, and so on. Vibration management is therefore an important part of further developments. But where, besides the principal tradeoff between real and reciprocal space resolution, are the limits? Compared to conventional optical microscopy it is rather clear that all angles remain comparatively small, that is, numerical apertures will not be approaching unity easily. Hence, the resolution limit will be one or two orders of magnitude away from the wavelength, that is, somewhere in the nm range. What can in principle be achieved depends, however, not only on the optics, the lens, but quite a lot also on other experimental restrictions.

As one example, we may consider a forward scattering or imaging experiment compared to a diffraction experiment. The former does not need a lot of sample alignment. In a very simplified way we may guess that one rotation to set the sample azimuth and two translations to bring the spot of interest into the X-ray focus will be enough. Consequently, the experiment can be rather compact, the focal length can be small and the demagnification accordingly large. The diffraction experiment, on the other hand, requires several rather precise rotation and translation stages to align at least the incidence angle of the beam with respect to the sample and the tilt of the sample perpendicular to the scattering plane, in addition to the sample azimuth and the translation stages. As a result, an optics with a larger "working distance", that is, larger focal length, and hence a smaller demagnification, is required. Similar considerations apply for experiments where the sample needs to be kept in a particular environment, for instance to pursue *in situ* experiment during fabrication of nanostructures or during operation of nanodevices.

Very often, different demands for an experiment contradict each other. Absence of vibrations and the need to have a sample in a vacuum environment, for instance, are hardly compatible. A sample chamber will also mostly be an annoyance if one needs to view the sample through a microscope during alignment of a particular region into the beam, like a certain device on an integrated circuit, or a particular point inside a biological cell. The chamber might, however, be mandatory to avoid beam damage by the intense beam, which is again an issue on its own, as we will see below. It will therefore require many years of development to optimize various experimental concepts, and we are certainly entering into an interesting area considering developments in the field of X-ray nanofocusing.

1.2.3
Coherence Properties of Small Beams

Due to the restrictions on optical elements, beam diameters in front of the lens are often in the range of few 10 to few 100 μm. For the brilliant and hence, well collimated synchrotron beams, this is close to or within the lateral coherence lengths of the beam. As a consequence, the beams used in nanofocusing are often highly coherent, and this is something that can be and is exploited in different ways. So far, most experiments rather demonstrate the potential than actually present widely usable analysis schemes, but they hold a considerable promise to overcome an old problem inherent to X-ray scattering experiments – the *phase problem*. X-ray wavefields oscillate at frequencies way too high for any available detector to be followed directly. Hence, what is measured is always the intensity of the scattered beam, which is proportional to the square modulus of the scattering amplitude in the classical wave picture, and manifested by counting the number of photons per time and area in a particle description. The scattering amplitude is, to some approximation, proportional to the Fourier transform of the electron density within the specimen, and hence contains – in principle – more or less all information about the sample. However, the measured intensity has "lost" the phase information of the scattering amplitude, and we cannot easily calculate the real-space structure from the intensity distribution in reciprocal space. The problem is even more severe since very often the illuminated sample area contains many coherence volumes and what we get is the real-space average of the actual structure. The latter point can be resolved using a coherent focused beam. What about the former? While the phase problem cannot be circumvented in all cases, under certain circumstances, this is actually possible. What we need is some, but not very detailed information about the sample, for instance an upper limit of the size. This results in a lower limit of the oscillation periods in the reciprocal space structure. Now if we are able to measure this structure (our resolution issue discussed above gets important again, but there are many cases where resolution is good enough) at a rate in reciprocal space finer than this period, we obtain an oversampled data set, which allows in principle to retrieve the lost phase. If we can retrieve it, we may directly calculate the real-space structure from our measured data. Several different approaches have been developed to tackle this problem, and very often the situation is not at all as simple as sketched above. But nevertheless it has been shown that at least the shape of nanoscale objects can be obtained in a rather straight forward manner if the constituting materials are not too light. Retrieving strain fields is still rather problematic, but progress has also been made to this end. Most approaches use iterative algorithms, which tend to run into the problem of being trapped within local minima of the error metric, and a complete scientific field emerged treating this problem and solutions to it. Another route uses a reference object to create a reference wave to encode the phase in a holographic way into the measured intensity signal. Also this approach is so far feasible only for a rather small class of samples, sometimes they have to be actually designed for the particular experiment, so that we are not currently in a state of mature analysis schemes for a wide range of problems and applications. Many efforts will be required, and a lot of developments are possible.

1.2.4
Side Issues ?

Even on a very practical level, most nanobeam experiments suffer from rather fundamental problems not routinely discussed in publications. For instance, if we want to illuminate a certain 100 nm area on a 10 mm large specimen, how do we detect where our X-ray beam hits the sample? Of course we will construct the whole setup as good as we can, but this means that usually we will know the place we hit within a precision of a few micrometers at best. Once we have aligned our goniometer, but now need to rotate a stage by several degrees, this spot is very likely to move a little bit. So we need to realign, which means we first need to find a signal, often a particular feature of the scattering signal in reciprocal space, which allows us to identify the position we hit. Then we need to scan a micron-sized area with 10 nm steps, which may take a while. The authors experienced that very often this alignment process requires much more time than the actual measurement. Sometimes, one finds oneself in a situation similar to early stage electron microscopists, namely that drifts that may be caused by temperature gradients or other reasons happen on a timescale very comparable to the time needed for alignment, and hence perfect alignment is very hard to reach. Therefore, software developments like improving detector readout time or being able to measure during a scan instead of step-by-step can be as important for the success of a nanobeam experiment as the focus diameter itself.

There are additional issues, where systematic investigations are only being started, one of them is beam damage. Moving to smaller focus sizes requires squeezing more photons into smaller areas in order to keep integrated intensities at a useful level. Estimations show that absorbed power amounts to something like one 10 keV photon per atom and second. Or in other terms, radiation doses in the megagray range are deposited within seconds at third-generation synchrotrons. While hard condensed matter samples can often tolerate such radiation levels, this is certainly critical for organic material. And still the number of photons reaching the detector is at the lowest limit for detection, for instance in coherent scattering experiments.

1.3
Future Developments

Free electron lasers in the hard X-ray regime were only available very recently, and are partly still under construction. For these facilities, the number of photons in a single pulse is many orders of magnitudes higher than for a synchrotron, and many samples will be destroyed in a single pulse. In this respect, free electron lasers may seem the very limit of usable brilliance. Still, destroying the sample in a single shot need not be the end of a diffraction experiment. The scattering process is happening at a much faster time scale than the disintegration of the sample, which is mainly caused by electrostatic forces due to the large number of electrons removed by the intense photon pulse. If the observed scattered intensity is sufficient for a single pulse, the experiment is still feasible; this will be the case only for certain samples. Otherwise we can still obtain useful data if the experiment can be repeated for a large number of identical structures, which is the concept followed for the investigation of macromolecules [10]. Instead of forming crystals of molecules to enhance the total scattered intensity, the scattering from individual molecules can be integrated. While this is not an easy task, since each molecule will be hit by the X-rays in a different orientation, and summing the scattered intensities from subsequent molecules is only feasible if this orientation can be identified, it can eliminate the crystallization process, which at the moment is the fundamental bottleneck of protein crystallography. For material science, concepts still have to be developed to exploit the extremely brilliant X-ray pulses from free electron lasers. Most probably, they will not replace synchrotron sources for the investigation of static nanostructures, where only the integrated number of photons matters and sample damage can be more easily avoided for lower photon densities. But for the study of dynamic processes, where time averaging is less of an option, free electron lasers will likely lead to completely new insights.

From what was said above, it is obvious that X-ray diffraction using nanofocused beams is a scientific field in its early stages. Many fundamental demonstrations and first pioneering experiments have been performed, but many issues are still problematic or less investigated, and the techniques are not yet mature enough for standardized experiments for the characterization of nanostructures. This book will therefore try to review the present state, highlight the potentials as well as the problems to be solved. It is intended as a guidebook to give an impression on the various topics relevant for experiments with focused radiation in the hard X-ray regime. While we tried to put together knowledge from literature as well as own experience into a common framework, some aspects seem to be better discussed considering particular examples. In order to be reasonably self-contained, a brief introduction to scattering theory will be given in Chapter 2 in the beginning, which is, however, rather intended to set the nomenclature than to thoroughly introduce theoretical scattering concepts, for which purpose the reader is referred to other textbooks. More detailed discussions will be devoted to the different focusing techniques available in Chapter 3, their physical principles and limits as well as their more practical advantages and disadvantages. We will discuss typical experimental setups and review the results that have been obtained using them in Chapters 4 to 6. This cannot be a comprehensive list of what can be done, since many possible experiments have not yet been done; but the reader should get an impression of the possibilities, and hopefully be able to devise his or her own nanobeam experiment.

Chapters 7 and 8 are devoted to coherent diffraction experiments. They are not inherently bound to the use of focused beams, but very often focused beams are used for such experiments, simply to obtain enough photon flux. Then, the particular boundary conditions of such experiments deserve detailed considerations. Towards the end of the book, we also try to give an outlook on future developments, in order to sensibilize readers for certain topics and aspects. Of course such an outlook cannot be complete. Hence, if we fail to mention a development, this just means that we are not aware of it, but not that it is not possible; we certainly do not want to discourage anybody in trying out a "crazy" idea.

Giving an overview of the field in its present state, we hope to contribute to the further development, and we are looking forward to a number of exciting experiments to become possible using focused X-rays.