Stefan P. Hau-Riege

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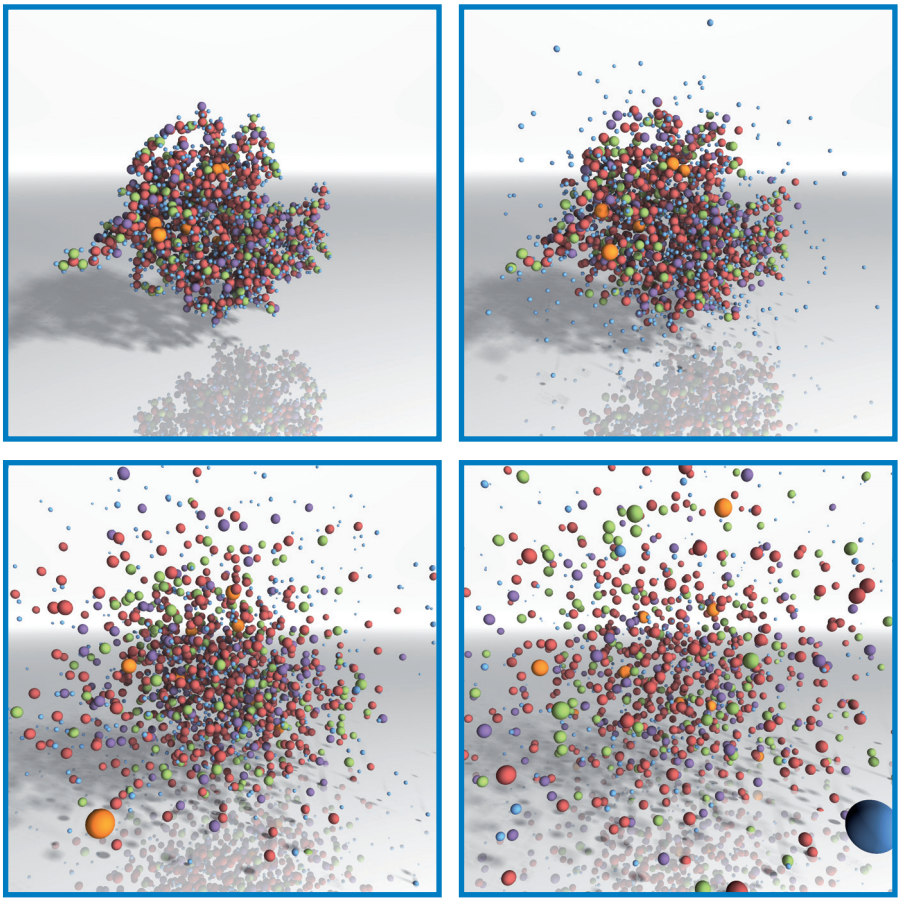
High-Intensity X-rays – Interaction with Matter

Processes in Plasmas, Clusters, Molecules, and Solids



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for Christine, Jamie, and Justin

Contents

Preface

This monograph provides a coherent and current overview of the interaction of x rays with matter, specifically focussing on high-intensity short-pulse radiation. We discuss the relevant physical processes, including the interaction of the x-ray field with electrons, the coupling of electrons and ions, the microscopic and macroscopic changes in materials, and the feedback of these processes. We conclude by providing several examples taken from the recent scientific literature.

There are many books available that treat the interaction of x-ray radiation with matter at intensities that are sufficiently low so that the materials do not change. On the other end of the spectrum are plasma-physics books that discuss the interaction of high-intensity photon beams with plasmas. This book bridges these two extremes by providing a comprehensive coverage of the full spectrum of interactions of low- to high-intensity x-ray radiation with materials. It discusses how x rays affect the state of matter, and, in turn, how these changes affect x-ray–matter interaction.

Similar books have been published for the optical wavelength regime. In contrast, x-ray wavelengths are on the order of interatomic distances, and x-ray energies are comparable to the transition and ionization energies of atoms and ions. Therefore, the relevant physical processes are very different.

X-ray–matter interaction draws from various disciplines, ranging from atomic physics, laser physics, plasma physics, astrophysics, computational physics, materials science, to chemistry. Most elements of this book are scattered throughout the scientific literature and have been published in scientific journals and the more introductory materials in book form. We aim at enabling the reader to gain an understanding of the fundamentals and to get an idea of the current state of research efficiently without being bogged down by either the scientific jargon specific to each discipline or by the sheer volume of publications. This will be especially useful for young researchers and occasional practitioners of this field who need to learn about the most relevant aspects of the various fields quickly.

The recent advent of new powerful x-ray sources such as x-ray free-electron lasers make the release of this book very timely. Within the context of large-scale facilities, the scientific community at large is currently shifting its focus away from particle physics toward photon science. The recent shutdown of the particle physics facility Barbar and the construction of the LCLS x-ray free-electron laser (FEL) in its

place at the SLAC National Accelerator Laboratory in the USA is a testimony to this change. Numerous large-scale photon-science facilities producing EUV (extreme ultraviolet) and x-ray radiation are being built all over the world: The first EUV FEL at DESY in Germany became operational in 2005, Japan demonstrated an EUV FEL in 2006, and others are planned, for example in Italy, Switzerland, and the USA. To access the shorter wavelength regime, an x-ray free-electron laser has been built in the USA (LCLS), and others are in progress, including in Germany (XFEL) and in Japan (SCSS). In addition to these facilities, new x-ray synchrotron sources such as PETRA III at DESY will also be available soon.

In light of these developments, this book has several target audiences: (i) Young scientists, postdoctoral researchers, graduate students, and senior undergraduate students who recognize the exciting field of x-ray–matter interaction science, and want to participate in it, (ii) more experienced scientists who want to change their research focus toward photon science, and (iii) scientists from various disciplines, such as life sciences, biology, materials science, physics, and chemistry, that plan on applying these new facilities in their respective fields. The interdisciplinary nature of the field of x-ray–matter interaction may make this book even interesting for the more casual reader.

The prerequisite for this book is a basic understanding of mechanics, electrodynamics, and quantum mechanics, even though most basic concepts are briefly explained whenever they are introduced, and relevant and introductory literature is cited. In that sense, the readership level is advanced. We hope that the book still has appeal to the more experienced research worker (specialist).

We have tried to make this monograph self-contained by including reviews of the basic aspects of atomic physics, electrodynamic wave propagation, and electron dynamics, with a specific focus on aspects relevant to high-intensity x-ray–matter interaction. An introduction to the field of x-ray–matter interaction is given in Chapter 1, in which we give an overview of available x-ray sources, summarize the processes relevant to x-ray–matter interaction, and point out the key aspects relevant to high-intensity pulses. In Chapter 2, we discuss the atomic physics relevant to x-ray-irradiated matter. This subject is essential in order to understand x-ray absorption processes and the subsequent electron dynamics. In Chapter 3, scattering of x-ray radiation from atoms, molecules, and other aggregates of atoms and different media is discussed. In Chapter 4, we discuss the propagation of electromagnetic waves in different media, and especially focus on the intensity distribution of the electromagnetic field since this determines the interaction of x rays with materials. In Chapter 5, we discuss the dynamics of the electrons in x-ray-irradiated materials.

The following chapters focus on high-intensity, short x-ray pulses, motivated by the recent advent of x-ray free-electron lasers. In Chapter 6, we discuss the characteristics of short x-ray pulses and describe instrumentation to create and diagnose such pulses. We also include the effects of the pulse duration on x-ray–matter interaction processes. In the related Chapter 7, we discuss aspects of the interaction of high-intensity x-ray pulses with matter. Since x rays modify matter, their interaction with the material changes with time. This aspect is discussed in Chapter 8. In Chapter 9, we present modeling approaches for x-ray–matter interaction. Finally,

in Chapter 10, we give some recent examples of high-intensity x-ray–matter interaction. This chapter is strongly biased by the research interests of the author.

I am deeply grateful to innumerable discussions with a large number of long-term colleagues, who over many years participated in carrying out calculations and experiments, and in interpreting the obtained results. It is a great pleasure to specifically mention valuable advice, help, and support from Elden Ables, Jennifer Alameda, John Arthur, Eduard Arzt, Sasa Bajt, Sherry Baker, Anton Barty, Brian Bennion, Karl Van Bibber, Richard Bionta, Michael Bogan, Sebastien Boutet, Carl Caleman, Jaromir Chalupksy, Henry Chapman, Rip Collins, Tilo Döppner, Paul Emma, James Evans, Gyula Faigel, Roger Falcone, Carsten Fortmann, Matthias Frank, Jerome Gaudin, Siegfried Glenzer, Jim Glosli, Bill Goldstein, Alexander Graf, Frank Graziani, Janos Hajdu, Rick Iverson, Verne Jacobs, Jacek Krzywinski, Jaroslav Kuba, Steve Lane, Dick Lee, Richard London, Stefano Marchesini, Marty Marinak, Dennis Matthews, Marc Messerschmidt, Paul Mirkarimi, Stefan Moeller, Michael Murillo, Michael Pivovaroff, Dave Richards, Dmitri Ryutov, Howard Scott, Marvin Seibert, Ryszard Sobierajski, Klaus Sokolowski-Tinten, Regina Soufli, John Spence, Eberhard Spiller, Fred Streitz, Hannah and Abraham Szöke, Michael Thomas, Nicusor Timneanu, Thomas Tschentscher, Jim Turner, and Chris Walton.

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Fremont, January 2011 *Stefan P. Hau-Riege*

1
Introduction

Wilhelm Conrad Röntgen discovered x rays at the University of Würzburg in 1895, and published his results in a groundbreaking report entitled *Über eine neue Art von Strahlen* (*On a new kind of rays*) [1]. In the twentieth century, x rays have played an important role in gaining an understanding of matter on the atomic scale and quantum mechanics in general. Table 1.1 shows some of the key events in this fast-paced journey of discoveries. The discovery of x rays sparked a new era of science. One of the major accomplishments, has been the exploration of the microscopic structural details of molecules, liquids and solids at length scales of interatomic distances.

X rays can penetrate thick objects that are opaque to visible light. On the basis of this property, atomic-resolution three-dimensional real-space imaging methods are used to obtain the at-first invisible interior structure of objects. Several x-ray imaging techniques have been developed for this purpose. For example, real-space x-ray microscopy is similar to visible light microscopy, except that traditional refractive lenses are replaced by x-ray lenses such as zone plates. Lensless imaging does away with lenses altogether [2], and instead reciprocal-space coherent diffraction patterns are recorded. They are subsequently inverted using computational algorithms to obtain a real-space image. These techniques allow the recording of high-resolution images that can be sensitive to elemental composition, chemical state, and state of magnetism.

With the advent of high-intensity short-pulse x-ray sources, ultrafast processes have become accessible for investigations. These sources will allow the study of materials on time scales comparable to the motion of electrons circling around atoms, on spatial scales of interatomic bonds, and on energy scales that hold electrons in correlated motion with their neighbors. Ultrashort electromagnetic radiation sources are a critical tool for studying material properties, with the ultimate outlook of recording femtosecond movies of atomic and chemical processes.

The earliest x-ray sources were x-ray tubes. Even though their light output is of relatively low brightness, x-ray tubes have enabled numerous important discoveries, as laid out in Table 1.1. The laser was invented about 50 years ago and has led to steep progress in the optical sciences. Similarly, the advent of dedicated synchrotron sources around 1970 has enabled enormous advances in the x-ray sciences. We are now witnessing the emergence of short-pulse high-intensity x-ray

High-Intensity X-rays – Interaction with Matter, First Edition. Stefan P. Hau-Riege.

Table 1.1 An abbreviated history of x-ray physics.

Year	Event
1895	Wilhelm Röntgen takes first medical x ray of his wife's hand
1901	Wilhelm Röntgen receives Nobel prize for producing and detecting x rays
1909	Charles Barkla and Charles Sadler observe characteristic x rays by electron bombardment of pure elements
around 1910	Discovery that x rays are electromagnetic waves of shorter wavelength and higher energy than normal light
1912	Discovery of x-ray diffraction by Max von Laue, Walter Friedrich, and E. Paul Knipping
1913	William H. and William L. Bragg build an x-ray spectrometer
1913	William L. Bragg observes the first x-ray spectrum
1913	Henry Moseley establishes the relation between atomic number and the specific x-ray wavelength of the elements
1914	Max von Laue receives Nobel prize for the discovery of diffraction of x rays by crystals
1915	William H. and William L. Bragg receive the Nobel prize for determining crystal structures with x rays
1916	Karl Siegbahn and W. Stenstroem observe x-ray emission satellites
1917	Charles Barkla receives the Nobel prize for the discovery of the characteristic x-ray radiation of the elements
around 1920	Wave–particle duality generally accepted
1922	Lise Meitner discovers Auger electrons
1924	Karl Siegbahn receives Nobel prize for his discoveries and research in the field of x-ray spectroscopy
1927	Arthur Compton receives the Nobel prize for demonstrating the particle concept of electromagnetic radiation
1936	Peter Debye receives the Nobel prize for his contributions to the study of molecular structure (by x-ray diffraction)
1962	Max Perutz and John Kendrew receive the Nobel prize for determining the structure of hemoglobin and myoglobin
1964	Dorothy Crowfoot Hodgkin receives the Nobel prize for determining the structure of penicillin and other important biochemical substances
1964	Synchrotron radiation available down to 0.1 Å
1976	William Lipscomb receives the Nobel prize for his studies on the structure of boranes illuminating problems of chemical bonding
1979	Allan Cormack and Godfrey Hounsfield receive the Nobel prize for the development of computerized tomography
1981	Kai Siegbahn receives the Nobel prize for his contributions to the development of high-resolution electron spectroscopy
1985	Herbert Hauptman and Jerome Karle receive the Nobel prize for developing direct methods for x-ray structure determination
1988	Johann Deisenhofer, Robert Huber, and Hartmut Michal receive the Nobel prize for the determination of the protein structures crucial to photosynthesis
1994	First soft x-ray scanning transmission microscope (STXM)
1999	Chandra x-ray observatory in use
2009	First hard-x-ray free-electron laser in use

sources such as x-ray free-electron lasers (XFELs), high-harmonic generators, x-ray lasers, and laser-plasma sources. With these new sources we are at the dawn of a very exciting time in x-ray science. One can expect progress of similar grandeur as resulted from the introduction of lasers and synchrotrons.

Reversible interaction mechanisms of x rays with matter, such as elastic x-ray scattering, are often used to probe materials. Since these interactions are usually relatively weak, large photon fluxes are required to obtain sufficiently intense probe signals. Since the absorption of x rays is typically much stronger than the elastic scattering strength, high-intensity x-ray radiation also modifies the structure of materials, and this is the main topic of this book: How x rays can be used to probe *and modify* matter.

We will now provide examples for the application of x-ray–matter interaction and discuss methods to produce x-ray radiation. We will then summarize fundamental models to describe x-ray–matter interaction, such as the Maxwell equations, semiclassical methods, and quantum electrodynamics. Subsequently, we will discuss x-ray–matter interaction processes in materials. Finally, we will point to some databases with information relevant to x-ray–matter interaction.

1.1 Examples for the Application of X-Ray–Matter Interaction

X rays find their application in diverse disciplines, including the life sciences, crystallography, atomic physics, plasma physics, materials science, chemistry, and astronomy. We will now discuss some of the key applications of x rays that highlight their versatility and that draw on their various unique properties, including their high penetrating power in materials and their short wavelengths that are comparable to interatomic distances. In addition, x-ray radiation can be prepared to have a high spectral purity, which is useful for x-ray spectroscopy, a very short pulse duration, which enables time-resolved studies, and high intensity, which can lead to nonlinear x-ray–matter interaction phenomena.

X-ray astronomy has enabled detailed studies of supernovae, pulsars, and black holes. Since the Earth's atmosphere is opaque to x-ray radiation, x rays can only be observed from outer space. The first rocket launch carrying a scientific payload that detected a cosmic x-ray source was performed in 1962 by American Science and Engineering (AS&E) and led to the detection of Scorpius X-1, the brightest x-ray source in the sky [3]. By today, numerous satellite missions have been carried out to study high-energy astrophysics with x rays.

In the laboratory, we can build x-ray sources and study the interaction of x rays with materials systematically. Since the first man-made x-ray sources were relatively weak, x rays were initially used primarily as a probe, and the modification of materials by x-ray beams was less common. One notable exception is medical x-ray imaging, which is the earliest application of laboratory x-ray sources, and which had a phenomenal commercial success. Medical x-ray imaging takes advantage of the high penetrating power of x rays, as we will discuss in the next section. In or-

der to minimize damage to the human tissue, the x-ray dose has to be kept low and the exposure time long, but medical x-ray imaging still increases the cancer risk through modification of biological molecules by x-ray radiation.

Another way to probe materials with x rays is scattering. In x-ray crystallography, x rays are scattered from atoms that are arranged in repeating unit cells, leading to strong interference peaks called Bragg spots. Since the wavelength of x-ray light is on the order of interatomic distances, x-ray crystallography allows structure determination at atomic resolution. This technique has led to major advances in structural biology. When x-ray crystallography is performed using short-duration x-ray pulses, time-resolved x-ray studies become possible, allowing us to probe the evolution of materials at atomic resolution. Whereas x-ray crystallography is used primarily to determine the spatial arrangement of the ions, x-ray spectroscopy provides information about the electronic structure and chemical state of the materials. X-ray spectroscopy requires x-ray beams with high spectral purity. Finally, high-intensity x rays can be used to modify matter so strongly that the interaction becomes nonlinear. This has become a very active area of research since x-ray lasers have become available. We will now discuss some of these applications in more detail.

1.1.1 Medical Imaging with X Rays

Shortly after the discovery of x rays, Röntgen imaged the interior of his wife's hand on photographic plates, which was the very first picture obtained using x rays. This experiment was the first example of radiography, the most commonly used medical imaging technique to date. In radiography, an x-ray shadow graph is recorded, which is a two-dimensional projection of the imaged object. X-ray tomography is an extension of this technique and is used to generate three-dimensional medical images by measuring multiple one- or two-dimensional projections.

Both these imaging techniques are based on the variation of x-ray absorption in different types of body tissues. Figure 1.1 shows the linear attenuation coefficient μ of biological materials as a function of x-ray energy. The quantity μ is defined through

$$I = I_0 \exp(-\mu t), \tag{1.1}$$

where I_0 is the intensity of a monoenergetic incoming beam, I the intensity of the emerging radiation, and t is the material thickness. Relevant biological tissues, listed in order of decreasing linear absorption coefficient, are bones, muscles, and fat. X-ray absorption in water is similar to muscle tissue. Typically, x-ray energies in the range of 15–30 keV are used for imaging soft tissue, such as in mammography, and larger energies are used to image bones. Sometimes, opaque contrast materials are used, such as barium compounds, to visualize certain structures of the human body.

X rays are ionizing radiation since they ionize and dissociate molecules. These kinds of modifications can cause biological damage, including mutation and genet-

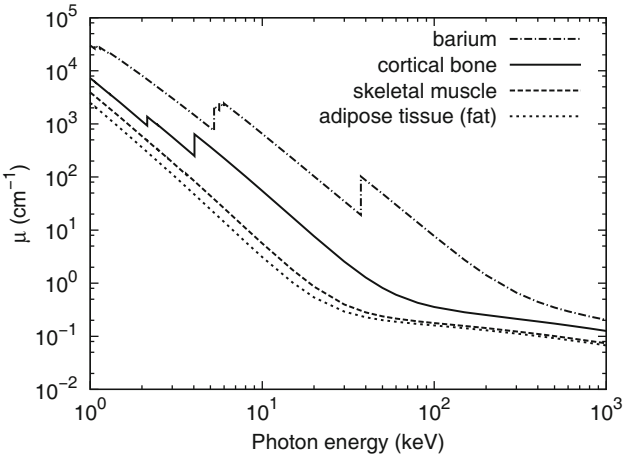

Figure 1.1 Linear absorption coefficient μ of human body tissue as a function of x-ray energy. For comparison, the data for barium, a common constituent of contrast enhancers, is also shown. The linear absorption coefficients of water and muscle tissue are very similar. Data were taken from [4].

ic modifications due to changes in the genetic sequence, radiation sickness caused by a too large x-ray dose over a short period of time, and an increase in the probability of cancer occurrence. The radiation exposure a patient receives from a full-body computer-tomography scan, often referred to as a CT or CAT scan, is often 500 times larger than for a conventional x-ray radiograph.

1.1.2 X-Ray Scattering and Spectroscopy

Most x-ray photons that interact with materials are absorbed through photoionization or are inelastically or elastically scattered. Figure 1.2 shows the interaction cross sections of 10-keV x rays as a function of the atomic charge number Z. The scattered x-ray photons are valuable in material diagnostics to obtain information about the crystal structure, chemical composition, and physical properties. For applications of structure determination, a short wavelength is required in order to resolve interatomic distances, whereas for spectroscopy applications, a narrow bandwidth and a tunable x-ray source, preferably near an absorption resonance, are desirable.

For elastic scattering, the phase relationship and the energy of the incoming and outgoing photons are preserved. In crystallography, the periodic arrangement of atoms or molecules leads to sharp Bragg peaks in the scattering pattern, from which the structure of crystals can be determined. For example, protein crystallography can be used to investigate complex biological macromolecules. Typically, x rays in the 3.5–20-keV energy range are used for atomic-resolution structure determination of matter. Currently, about 80% of new macromolecular structures

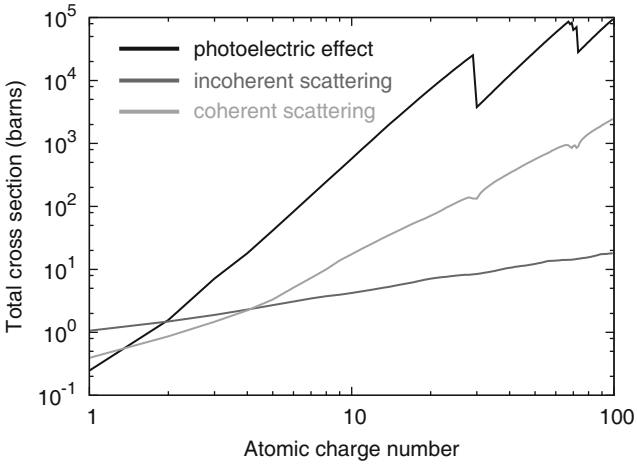

Figure 1.2 Atomic photoionization, incoherent scattering, and elastic scattering cross sections of 10-keV x rays as a function of the atomic charge number Z [5].

are determined through x-ray crystallography at synchrotron facilities. For higher-Z materials, x rays in the energy range from 20 to 100 keV are used to increase penetration and to reduce absorption and damage. X-ray scattering also allows the measurement of the grain size in materials, the thickness and roughness of layers and films, and the mechanical state. Now that high-intensity x-ray sources have become available, x-ray diffractive imaging of single nanoparticles has become possible. In the small-angle-x-ray scattering (SAXS) technique, the structure of matter is probed with a resolution down to a μm or nm. In wide-angle-x-ray scattering (WAXS), the diffracted light is measured at higher (sub-nm) resolution.

For inelastic scattering events, the energy of the photon changes due to interaction with the electron system. By measuring the spectrum of the scattered photons, we can obtain information about the electronic structure. Multiple techniques have been developed for this purpose, including x-ray Thomson scattering as a plasma diagnostic. By measuring the spectrum of the scattered photons, we obtain fundamental information about the plasma, such as density, temperature, and collective properties [6]. Resonant inelastic scattering (RIXS) is an x-ray spectroscopy technique to obtain information about the electronic structure by measuring the momentum transfer near intrinsic excitations. By operating near the resonance of the system, the x-ray interaction cross sections are relatively large. Another important class of x-ray analysis techniques are x-ray absorption spectroscopy (XAS) methods. By tuning the x-ray radiation, the absorption edges of materials can be mapped out. Similar to the optical regime, the most intense features in the spectrum are related to electric-dipole transitions. When specific absorption edges are studied in detail, the technique is called x-ray absorption fine-structure spectroscopy (XAFS), which encompasses two techniques: (i) Studying the rising edge of the absorption spectrum is called extended x-ray absorption near-

edge structure (XANES) or near-edge x-ray absorption fine structure (NEXAFS). (ii) When the region above the edge is studied, the ejected photoelectron scatters off neighboring ions, so that the absorption spectrum is sensitive to the chemical environment. This technique is called extended x-ray absorption fine structure (EXAFS).

1.1.3 Short-Pulse X-Ray Probing of Matter

Short x-ray pulses can be used to obtain snapshots of material properties, thereby enabling the study of the dynamics of material processes. X-ray pulses with femtosecond duration potentially allow probing the evolution of chemical reactions through x-ray spectroscopy, which holds the promise of detecting the formation and breaking of molecular bonds, and the identification of intermediate transition states. X rays can also be used to generate and probe the evolution of excited states. Short-pulse optical lasers have enabled time-resolved studies of chemical reaction. Short-pulse x-ray radiation additionally promises to provide spatial resolution of the chemical reaction process.

In the field of time-resolved macromolecular x-ray crystallography, short optical and x-ray pulses are used to obtain information about the function of molecules, specifically transient structures and reaction mechanism. Reactions are typically initiated with short pulses from an optical laser with a duration ranging from a few femtoseconds to 100 ns, and then the crystal is probed with short x-ray pulses from a synchrotron light source with pulse length as short as 10 ps. A major concern is x-ray radiation damage to the crystals, since when short-duration x-ray pulses are used to probe materials, the photon flux is often increased in order to maintain required signal levels.[1)] A larger photon flux may lead to modification of materials through x-ray-induced ionization and subsequent atomic motion which, in turn, can lead to changes in the optical properties and the x-ray–matter interaction mechanism. In recent experiments using free-electron lasers it has been demonstrated that atomic motion can be delayed on the time scale of tens of femtoseconds due to the inertia of the atomic nuclei [7], whereas the optical properties are determined by the evolution of the electron system which occurs much faster. For example, materials may become transparent due to the depletion of electrons from resonance states [8].

1.2 Electromagnetic Spectrum

X rays can be described as electromagnetic waves, just like optical and ultraviolet radiation. A portion of the spectrum of electromagnetic waves is shown in Figure 1.3,

1) The photon flux is defined as the number of photons per unit area per unit time, and the photon fluence of an x-ray pulse is defined as the number of photons per unit area.

along with the names of the energy regimes. The boundaries of these regimes are not very well defined.

For x rays, it is often convenient to express the wavelength λ in units of Ångströms, abbreviated by the symbol Å. One Ångström equals 0.1 nm, 10^{-8} cm, or 10^{-10} m. X rays lie approximately in the wavelength regime between 200 and 0.1 Å. Wavelengths are also often given in energy units, hc/λ, where h is the Planck constant, and c is the speed of light. In convenient units,

$$\lambda\,[\mathrm{eV}] \approx \frac{12\,398.417}{\lambda\,[\mathrm{Å}]}\ . \tag{1.2}$$

In this book, we consider photons in the soft and hard x-ray regime, ranging from 250 eV to 100 keV.

Also shown in Figure 1.3 are liner absorption coefficients for different kinds of materials. Whereas for energies below 100 eV the linear absorption coefficient

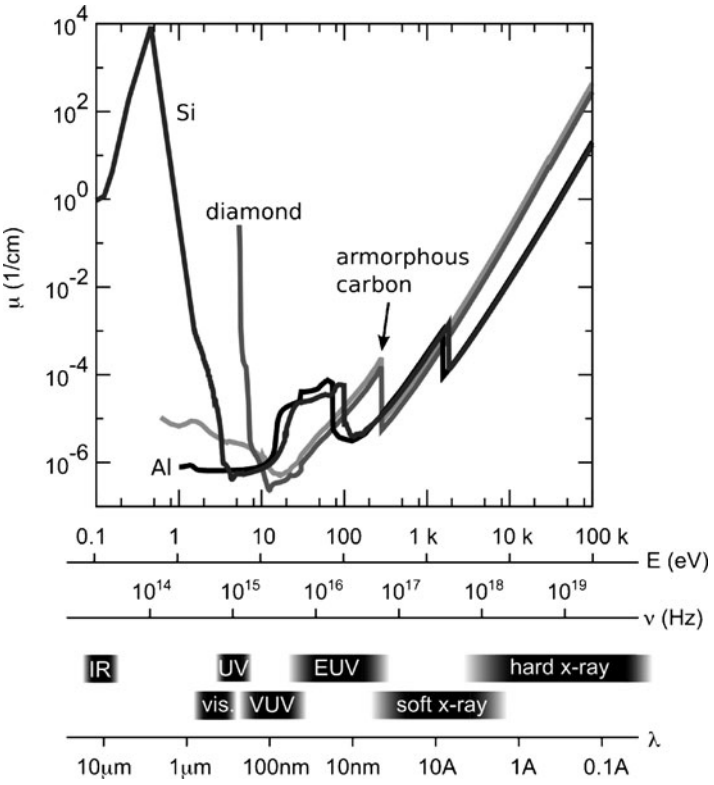

Figure 1.3 Overview of the electromagnetic spectrum. IR = infrared, vis. = visible, UV = ultraviolet, VUV = vacuum ultraviolet, and EUV = extreme ultraviolet. The top graph shows the linear absorption coefficient μ for different material types [9].

shows a complex dependence on the photon energy since it is determined by the valence and bonding environment of the atoms, in the x-ray regime this dependence is much more straight-forward since inner-shell isolated-atom response is dominant.

1.3 X-Ray Light Sources

Progress in x-ray physics has been tightly coupled to the advancement of light sources. Since the discovery of x rays in 1895, the average brightness of x-ray sources has been increasing steadily over three orders of magnitude every ten years. The brightness B is defined as the number of photons N divided by the product of the beam area A, the divergence ϵ, the pulse length τ, and the fractional bandwidth of energy $\Delta E/E$,

$$B = \frac{N}{A\epsilon\tau\frac{\Delta E}{E}} \,. \tag{1.3}$$

The divergence is the opening solid angle of the radiation beam. A typical unit for the brightness is number of photons/(s mm^2 mrad^2 0.1% bandwidth).

We will now give an overview of the various x-ray sources and their output characteristics. Specifically, *short*-pulse x-ray sources that are required for time-resolved studies are described in more detail in Section 6.2.1.

1.3.1 X-Ray Tubes

X-ray tubes are the oldest kind of laboratory x-ray source. In an x-ray tube, electrons are extracted from a cathode and then accelerated toward an anode in vacuum by applying a voltage ranging from a few to 100 kV. Typical cathode and anode materials are aluminum and platinum, respectively. When the electrons hit the anode, x rays are generated. A special kind of x-ray tube is the Crookes tube, in which the number of x rays is increased by replacing the vacuum environment with a dilute gas. In the gas, additional secondary electrons are generated through electron impact ionization and accelerated toward the anode, leading to the emission of a larger number of x rays. The anode is angled to make it easier for the x rays to escape. It is often desirable to make the electron beam as small as possible to create an x-ray point source, but then heating is a concern and the anode needs to be cooled since the x-ray power is limited by heat dissipation from the focal spot on the anode. This limit can be substantially improved by rotating the anode, and letting the electron beam sweep over it. A schematic of this rotating-anode x-ray source is shown in Figure 1.4. This setup requires an anode made out of high-temperature materials, and cooling of the anode in vacuum, which is a challenging task.

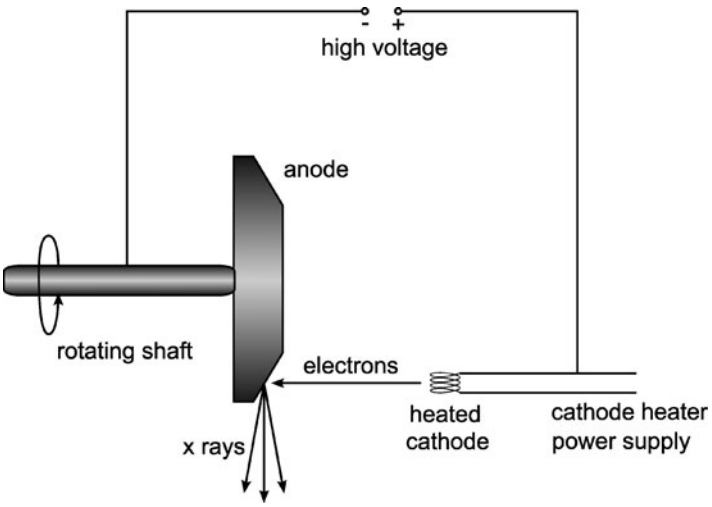

Figure 1.4 Schematic of a rotating-anode x-ray source.

1.3.2
Laser-Produced X-Ray Sources

By irradiating solid and gas targets with high-power optical lasers, high-energy density plasmas are generated that emit photon radiation in the x-ray regime. As shown in Table 1.2, various methods have been proposed to use this radiation as x-ray sources, which we will summarize now. For more details, the reader is referred to [10].

Two very large laser facilities are currently being constructed, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in the USA, and the Laser Megajoule (LMJ) at the Commissariat a l'Energy Atomique (CEA) in France. These lasers produce visible-light pulses with energies of more than 1 MJ. Focusing them onto a high-Z target leads to the creation of a hot plasma with electron temperatures of several keV. These electrons emit x rays as line radiation (characteristic x rays) and in the continuum through bremsstrahlung.

More readily accessible are table-top solid-state lasers with TW (10^{12} W) pulse powers, which can reach PW (10^{15} W) power in larger-scale facilities. Ti-doped sapphire lasers with a wavelength around 806 nm are commonly used. These lasers can produce visible-light pulses with a pulse energy of up to 1 J that are only a few wave cycles in duration. Large pulse intensities of 10^{17}–10^{21} W/cm^2 can be achieved using the technique of chirped-pulse amplification (CPA), where short optical pulses are dispersively stretched, amplified, and then compressed again [11], coupled with techniques for diffraction-limited focusing. When matter is irradiated with such laser light, electrons in the material quiver (oscillate) with quiver energies of up to 1 MeV, which is comparable to the rest mass of an electron. When these electrons hit a target, line emission by inner-shell ionization and continuous hard-