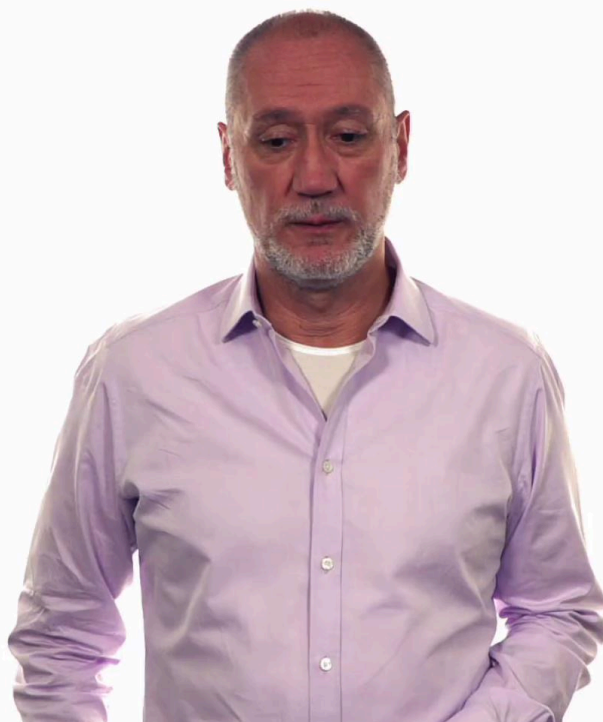


EPFL



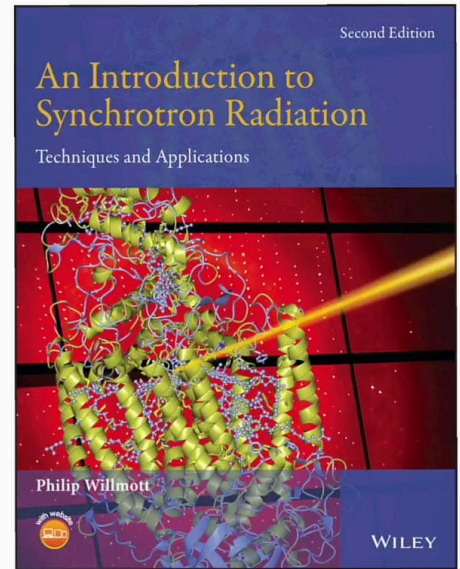
Hello and welcome. My name is Phil Willmott. I will be guiding you through the world of x-ray science and its applications in two introductory courses under the general title of Synchrotrons and X-ray Free-Electron Lasers Techniques and Applications. I'm a physicist by training, but I've been exposed to many other disciplines, both over the last decade and a half or two decades, working at synchrotrons, but also earlier in my academic career. Presently, in addition to be an adjunct professor at the University of Zurich, I'm responsible for the Photon Science Programme upgrade at the forthcoming upgrade of the Swiss Light Source to a so-called diffraction-limited storage ring at the Paul Scherrer Institute in Switzerland. In this first six-week course, I will introduce you first to the fields of x-ray and synchrotron science, followed by a detailed description of the nature of the interactions of x-rays with matter. We then continue with an overview of the generation of X-radiation, with particular reference to synchrotron or machine physics, and a summary of the architecture and operation of x-ray free-electron lasers detailing the properties that make them so desirable.

Notes

Summary



0m 05s



<https://www.wiley.com/en-us/An+Introduction+to+Synchrotron+Radiation%3A+Techniques+and+Applications%2C+2nd+Edition-p-9781119280392>

This first course then finishes with a detailed account of the components and construction of beamlines and x-ray instrumentation, including the manipulation of synchrotron light using x-ray optics. The second separate six-week course concentrates on the techniques and applications that utilise synchrotron radiation. These are divided into three broad themes of scattering techniques, spectroscopy methods, and imaging. Both this and its sister course are partly-based on the second edition of my introductory textbook on synchrotron radiation, which is available through most online bookstores or the publisher's website, John Wiley & Sons. For those who would like to review many of the concepts which are presented here at their own leisure using the more traditional medium of the written page, or read deeper into aspects of particular interest. The book also contains over 120 problems, plus their detailed solutions, which is provided in the appendices. The several hundred figures in the book are also freely available on the web.

Notes

Summary



1m 28s

- 400+ figures from book
 - <https://wiley.mpstechnologies.com/wiley/BOBContent/searchLPBobContent.do>
Type "Willmott" into author field
- Center for x-ray optics CXRO: <http://www.cxro.lbl.gov>
 - Interactions of x-rays with matter – plots, databases, x-ray data booklet
 - Educational material on x-ray optics, nanofabrication, coatings, etc.
- X-ray cross-section database
 - <https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html>
- Atomic form factors
 - <http://lamp.tu-graz.ac.at/~hadley/ss1/crystaldiffraction/atomicformfactors/formfactors.php>
- Protein data bank
 - <https://www.rcsb.org>
- XAS data base
 - <http://cars.uchicago.edu/xaslib/search>
- EXAFS spectra
 - http://www.exafsmaterials.com/Ref_Spectra_0_4MB.pdf
- Anomalous structure factor calculator
 - <http://cars9.uchicago.edu/dafs/diffkk/>
- Darwin-width calculator
 - <https://www.chess.cornell.edu/users/calculators/x-ray-calculations-darwin-width>
- X-ray optics intro
 - <http://www.x-ray-optics.de/index.php/en/>



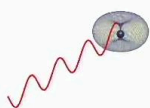
There are many invaluable online resources for x-ray science and disciplines exploiting synchrotrons and XFELs. Those I have found most useful and pertinent to this and its sister course are listed here, beginning with the link to all the freely-available images found in my textbook and to a large extent also used here. In addition, note that most of the animations that appear in these MOV videos can be downloaded as supplementary materials. Moreover, some topics are explained in greater detail in PDF format, covering aspects that are not 100 percent necessary for the core material given here, but can be read at leisure for the more curious of mind. The other three resources in the left-hand list are extremely useful for most all synchrotron and XFEL users in order to determine many properties of materials in the x-ray regime. The list on the right-hand side contains material from data banks plus more specialised online calculators. I recommend you visit all these websites to see what they have to offer at your earliest opportunity.

Notes

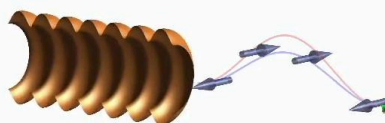
Summary



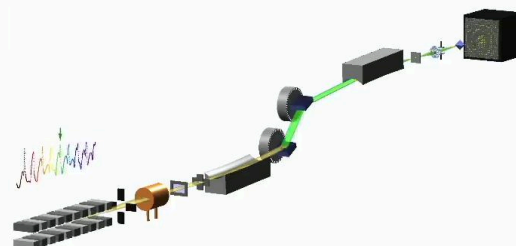
Online resources – synchrotronmovies.com



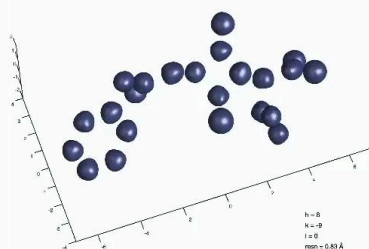
Interactions of x-rays with matter



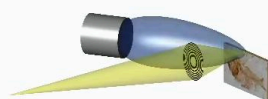
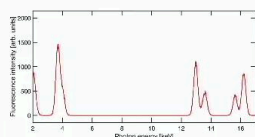
Machine physics



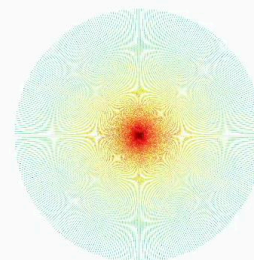
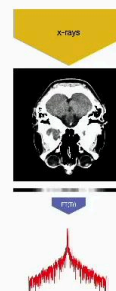
Beamlines and optics



Scattering techniques



Spectroscopic techniques



Imaging techniques

Lastly, many of the videos shown in both this and the sister course, plus many more besides on diverse aspects of x-ray and synchrotron science, can be downloaded at the website synchrotronmovies.com along with the MATLAB codes I wrote to generate them. There are six general headings of which some of the more attractive examples are shown here that follow the format of my textbook quite closely. Presently, there are over 70 animations, and more will surely follow soon. Feel free both to download the animations and improve upon my MATLAB code. I am a truly atrocious coder.

Notes

Summary



4m 01s

Contents and objectives of this video



- Why x-rays?
 - Imaging
 - Scattering
 - Transparency
 - Resonant phenomena

This first introductory week concerns itself with a brief explanation of what synchrotrons and undulators are, and provides a historical perspective of x-ray science and the role of large-scale facilities and its development. In this first video, we consider the question, Why use x-rays at all? We take a brief look at what synchrotrons and XFELs actually, physically are, and of course, whether use is desirable. Now, just a small orthographic footnote before we proceed. As you can see, I've written x-ray with a small x. And I will continue to do so unless, of course, it's at the beginning of a sentence. The upper case X is certainly more common in English, though both are legitimate. I incline to the lowercase as I find that while reading, the sudden and unexpected uppercase makes me stumble in anticipation of a new sentence. Not a problem [inaudible 00:05:43], I guess.

Notes

Summary



4m 42s

EPFL X-rays, schmex-rays?



- Until turn of 20th century, visible light was only optical tool
- Lasers produce very intense visible radiation
- So what added value do x-rays offer?

X-rays are like visible light, radio waves, microwaves, ultraviolet radiation, etc., a form of electromagnetic radiation distinguished only by the magnitude of their wavelengths. So what are x-rays? And why would we want to use them over, say, visible light, which is, after all, visible? Indeed, optical microscopes were used famously by Antony van Leeuwenhoek to record for the first time in detail, and its resolutions below one micron, the appearance and sizes of unicellular organisms, bacteria, red blood cells, and spermatozoa towards the end of the 17th century. In the mid 20th century, lasers were invented producing hitherto, unforeseen light intensities, spectral purity, and collimation that would revolutionise chemical spectroscopy, industrial processes, medical procedures, and most importantly of all, the checkout at supermarkets. Why then use x-rays?

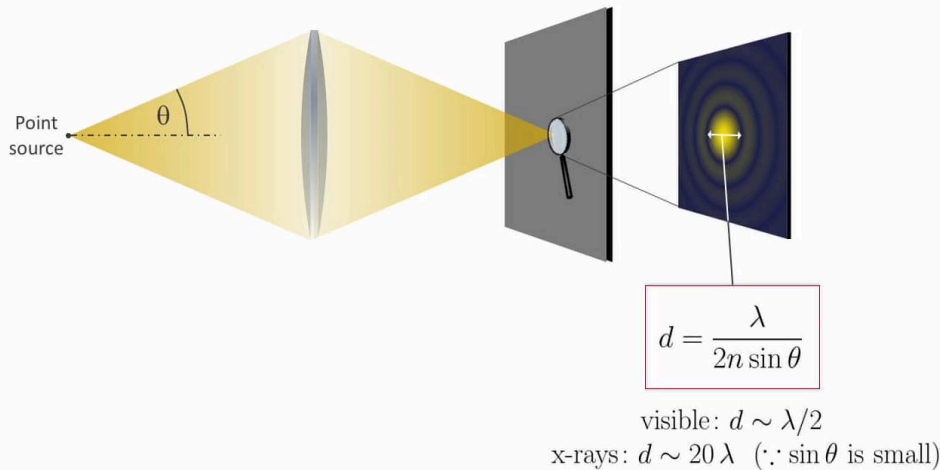
Notes

Summary



5m 44s

EPFL Argument for x-rays (1): the Abbe limit



The first reason is their wavelength and the ultimate resolution of an image one can obtain when using a given wavelength. As we will see in more detail in the second section of this week's videos, the typical wavelength of visible light is between approximately 100 times and 10,000 times longer than that associated with x-rays. Let us consider a truly point source that we would like to image using a perfect lens and electromagnetic radiation of wavelength λ . If we look closely at the created image in the image plane, we see that it is or not also a point, but instead it's a disc surrounded by concentric rings. This is due to the wavelight nature of light and associated diffraction phenomena. The diameter of this disc is given by d equals λ , upon $2n$, sine, θ , where N is the refractive index of the lens and θ is the half angle of the radiation collected by that lens. This is the so-called Abbe resolution limit, named after Ernst Karl Abbe who first arrived the equation in 1873. In the visible regime, N can assume values up to approximately three. Water has a value of 1.33, diamond 2.5. And the lens can capture light at half angles as large as 45 degrees or thereabout.

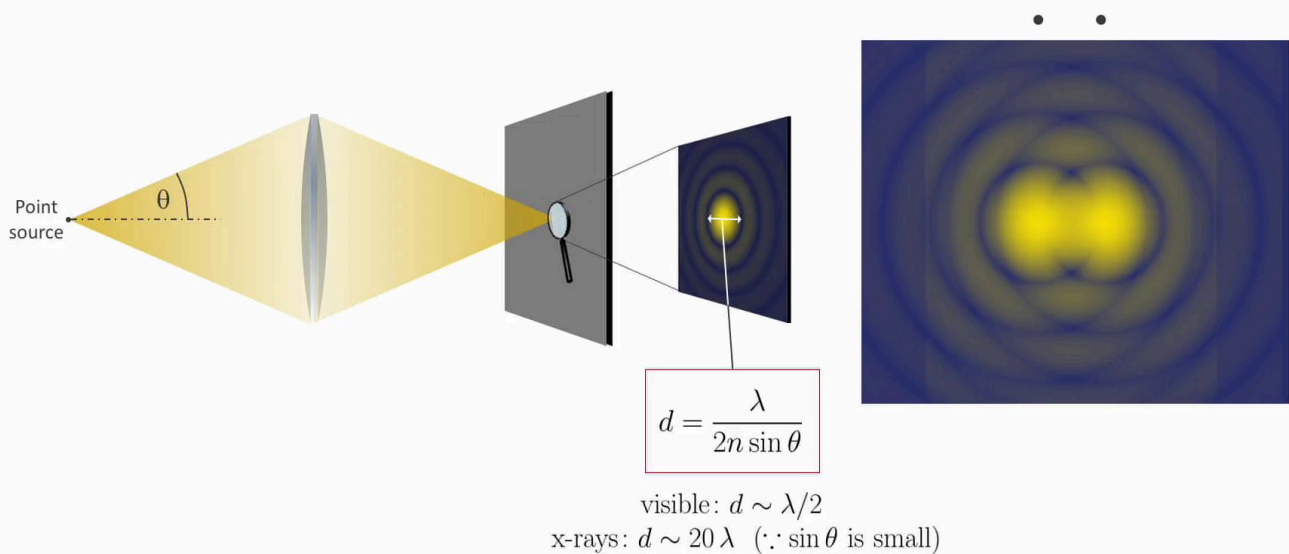
Notes

Summary



6m 57s

EPFL Argument for x-rays (1): the Abbe limit



This means that the ultimate resolution in the visible lies at around Lambda upon 2 or about 250 nanometers. In the x-ray regime, and is only very slightly different [inaudible 00:08:53]. That is, x-rays are only very weakly refracted by matter, and this subtended angle of x-ray lenses, maybe only a few degrees at best. Thus, the ultimate resolution is a few times of Lambda, depending quite strongly on the wavelength and lens used. Two objects must therefore be separated by d or greater for them to be resolved in the image.

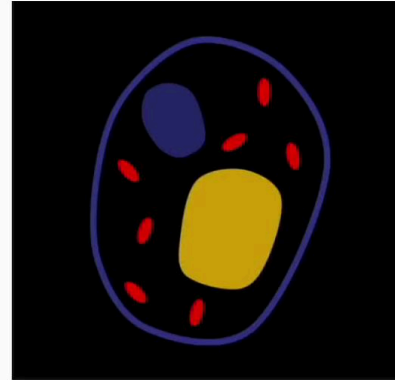
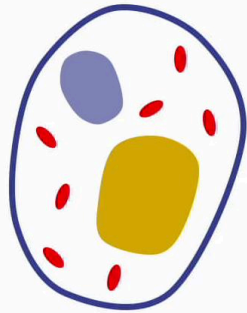
Notes

Summary



8m 40s

EPFL Argument for x-rays (1): the Abbe limit



Decreasing wavelength



An object may, thus, appear to be blurred beyond recognition if the wavelength is too long, and only becomes distinguishable once the wavelength becomes similar to or smaller than the features of interest.

Notes

Summary



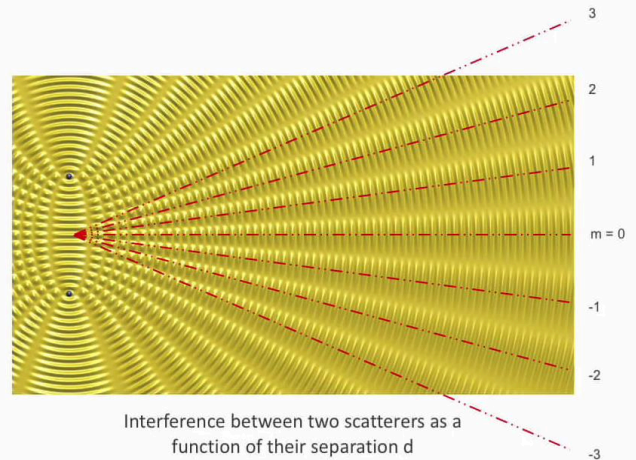
9m 21s

EPFL Argument for x-rays (2): diffraction

- Bragg's law
 - Describes interference/diffraction
 - "Imaging without lenses"

$$m\lambda = 2d \sin \theta$$

- Minimum $d = \lambda/2$
- Interatomic spacings $\sim 1 - 3 \text{ \AA}$
 - Hard x-rays: $\lambda \sim 0.1 - 5 \text{ \AA}$



The second argument in favour of x-rays is, in principle, based on an alternative expression to the Abbe limit universally used in direction phenomena, namely the Bragg law. Note the similarity of the Bragg law to the expression for the Abbe limit just shown before. Because no lenses are being used, large angles, even for x-rays, can be recorded and distances as small as $\lambda/2$ can be recorded. Here, 2θ , actually 2 times θ , describes the scattering angle of x-radiation of an object. Consider a plane wave of radiation incident on a small object. This will scatter in all directions. If we now imagine two objects and increase their separation, the scattered waves will overlap and interfere with one another, resulting in diffraction maxima of different order given by the integer m shown here. The larger the value of m , the better spatial resolution we can achieve from the real space model we can derive from the information coded in the diffraction pattern. We will discuss this phenomenon in detail in the sister course.

Notes

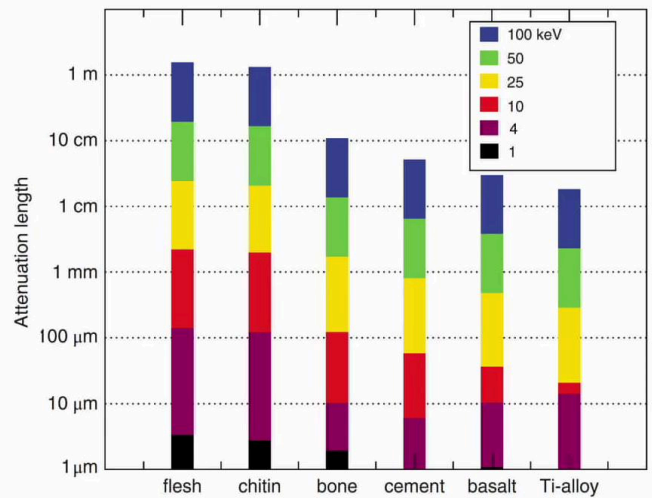
Summary



9m 36s

EPFL Argument for x-rays (3): transparency

- Hard x-rays more or less transparent to condensed matter
 - Degree of transparency depends on
 - Energy of x-ray
 - Density of elements in sample
 - Investigate nondestructively internal 3D architecture of heterogeneous samples



Attenuation lengths of different materials over two orders of magnitude x-ray photon energy

Thirdly, and famously, x-rays are partially transparent to condensed matter. The bread and butter diagnostic tool in hospital radiology departments depends on this phenomenon. Just how transparent and object is depends on the wavelength or photon energy of the x-rays, the object's size, and on the density and types of atoms that make up the object being irradiated. Once the correct x-ray energy has been chosen, a different centi degree of transparency in differing components of an object can be exploited to investigate the internal architecture of that object. As a rule of thumb, the denser the material, the less transparent it will be to x-rays of a given energy as shown here.

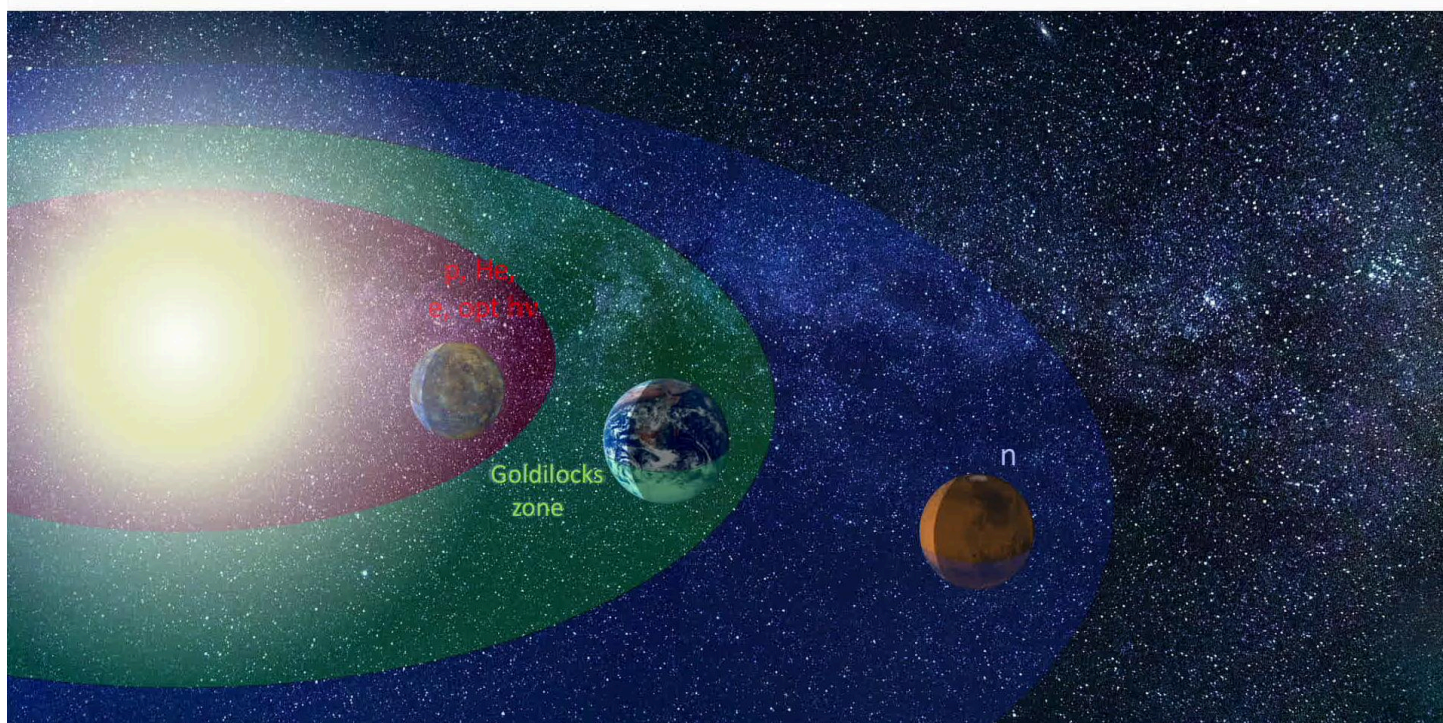
Notes

Summary

10m 56s



EPFL Argument for x-rays (3): transparency... but not too much!



This transparency of objects to x-rays obviously implies that x-rays do not interact very strongly with matter. But if we want to use them as a probe to the structure and physical properties of matter, we really do want them to interact to a degree. A neutrino microscope, for example, would have an absurdly large expense to effectiveness ratio. Now, I like to draw an analogy here, that of the solar system. The interaction of, for example, Mercury or Venus with solar radiation is so strong that the possibility of life there is extinguished. Pluto, in contrast, is so far from the Sun and so frigidly cold that life here is equally improbable. It is in between these two limits in a so-called Goldilocks zone that life can prosper. In analogy, the interaction, for example, of protons, Alpha particles, or optical light with matter is so strong that analysis of this interaction can become problematic. In contrast, because neutrons contain no charge, they pass through matter with annoying facility, limiting the smallest objects that can be investigated with them.

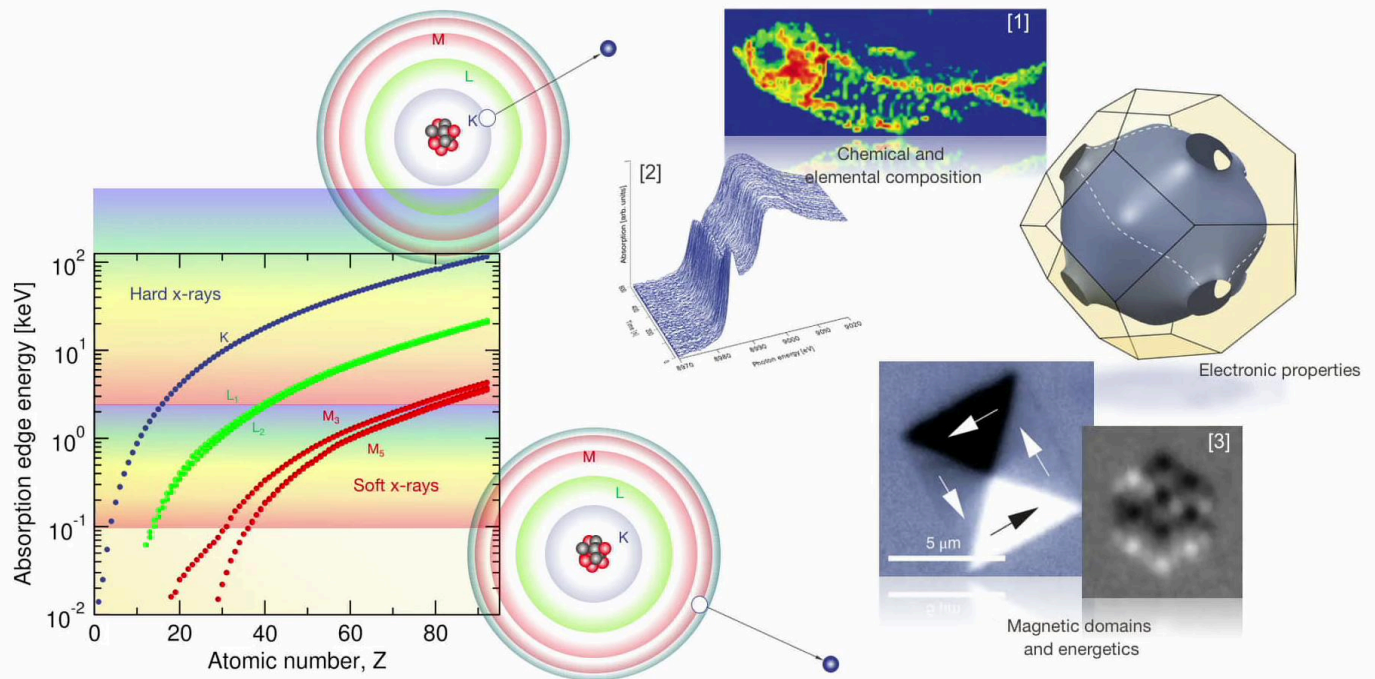
Notes

Summary



11m 50s

EPFL Argument for x-rays (4): interactions with specific electrons



X-rays, on the other hand, have cross sections that are large enough to provide easily measurable effects while being sufficiently small that they pass through significant volumes of material, which is, itself, only mildly impacted by the weak interactions and thus not rapidly destroyed. Lastly, most electrons in the naturally-occurring elements have binding energies to the positively-charged nuclear core in a range covered by x-radiation. We will look more closely at these in the next section and also in next week's videos. If one tunes the x-ray energy to be close to that of the binding energy of a particular electron in a particular element, the x-ray is said to be resonant with that electron, and the interaction strength between the x-ray and electron is much enhanced. In this manner, one can probe a certain electron type. For example, an L-electron in ion provides invaluable information on the magnetic properties of the material that contain the ion atom. Depending on the electron that interacts with the x-rays, different physical chemical properties can be investigated from the chemical binding and elemental composition of a sample through magnetic properties to the electronic structure of novel materials such as high temperature superconductors.

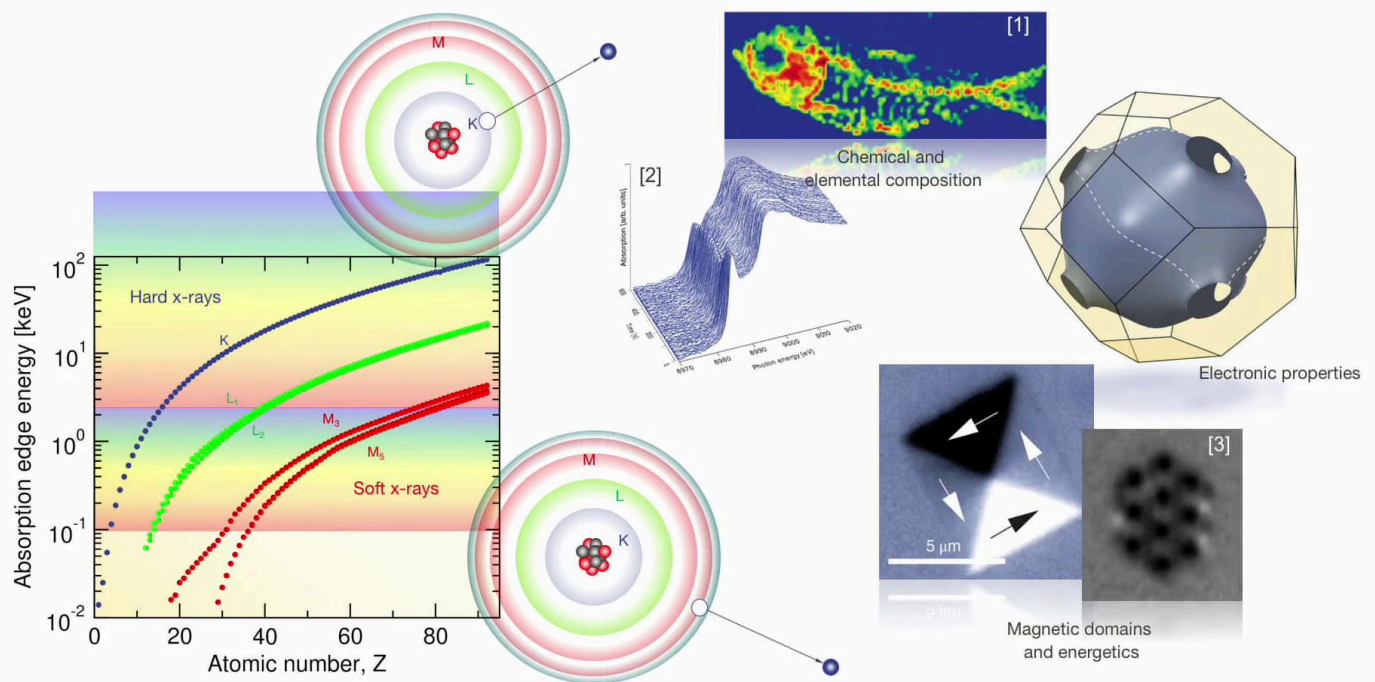
Notes

Summary



13m 14s

Argument for x-rays (4): interactions with specific electrons



We will investigate the fundamental interaction types of matter with x-rays in next week's videos, while the detailed techniques and applications are covered in the sister course. In the next video, we will see what synchrotrons and XFELs actually look like, compare and contrast the type of radiation they produce, and encapsulate this in the figure of merit known as brightness or brilliance.

Notes

Summary



14m 47s