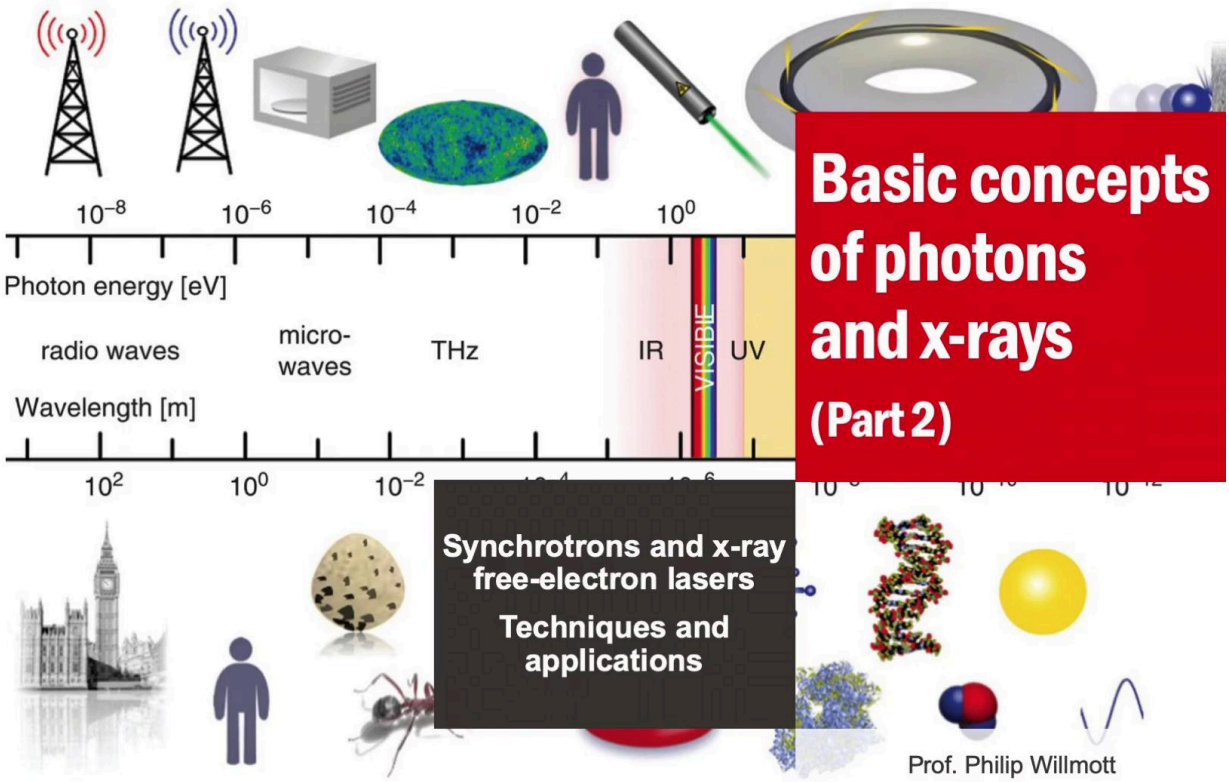


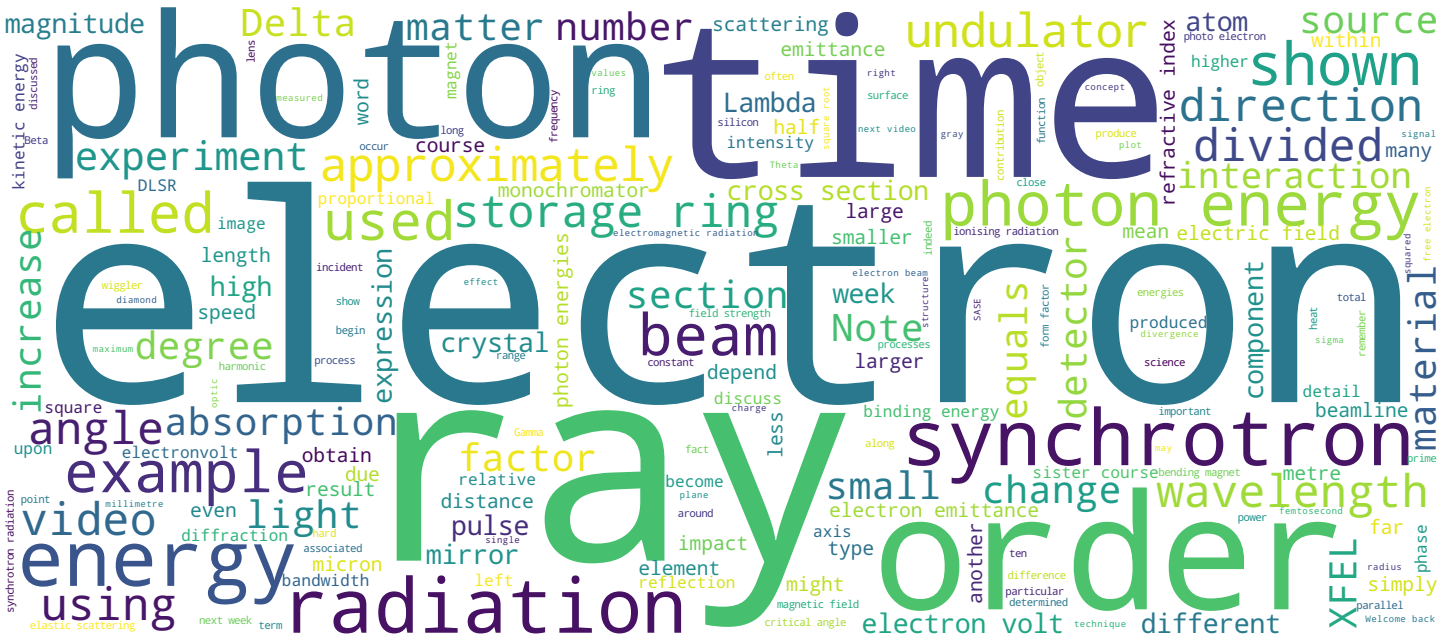
Basic concepts of photons and x-rays (Part 2)

Synchrotrons and x-ray free-electron lasers

Techniques and applications

Prof. Philip Willmott

École polytechnique fédérale de Lausanne



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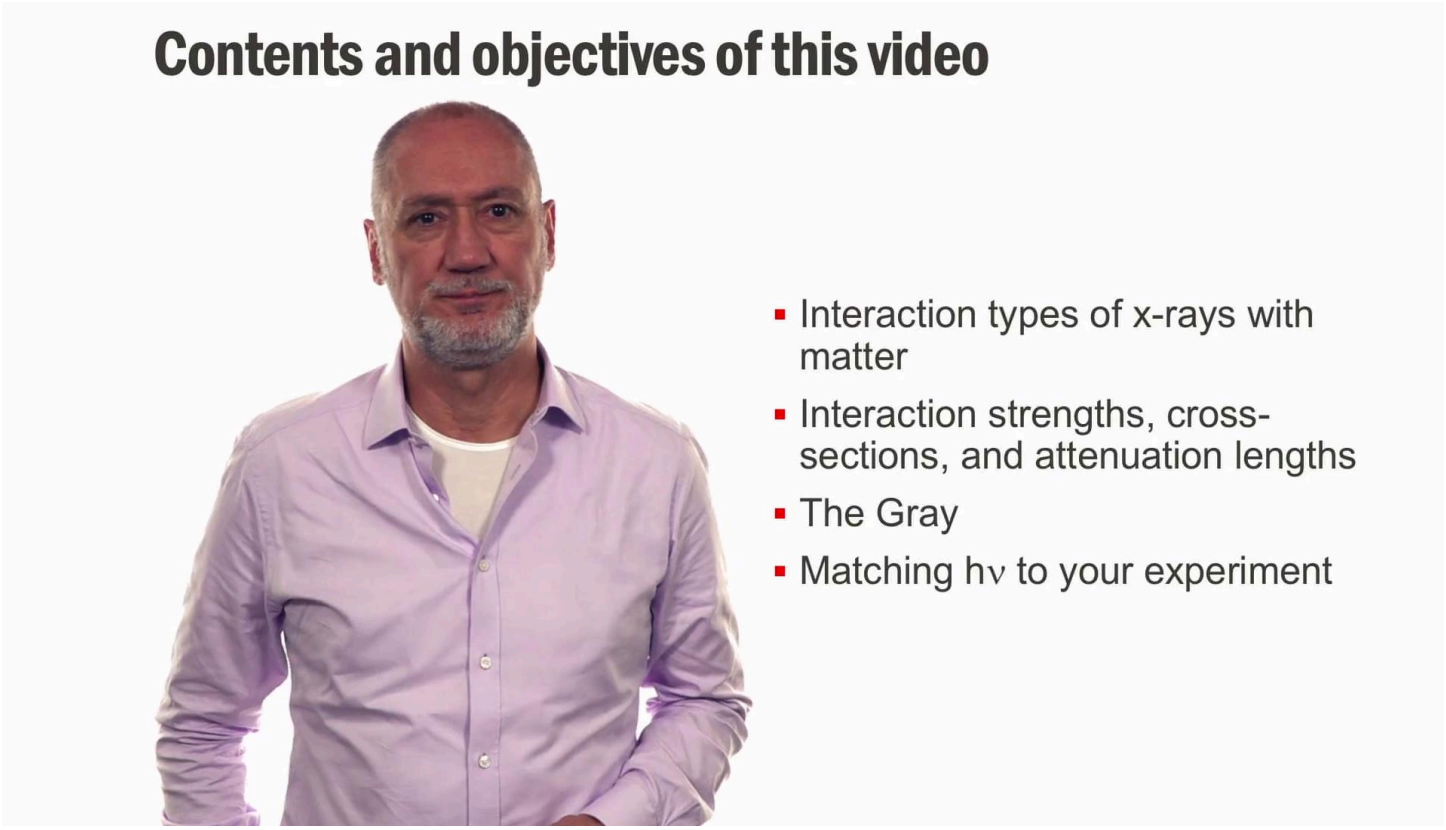
Video



Hi. In this video, I will introduce you to the three relevant processes that we need to consider in this course regarding the interactions of X-rays with matter. We look at these in detail only next week. This very basic information will assist in guiding us as to the choice of the most appropriate photon energies that should be used for a given experimental goal.

Notes

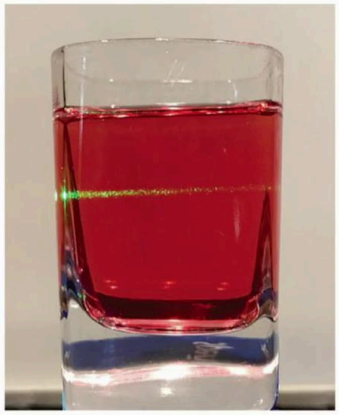
Summary

0m 05s

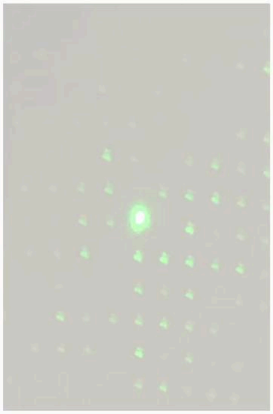
Familiar phenomena with visible light

Reflection

Refraction



Absorption



Diffraction

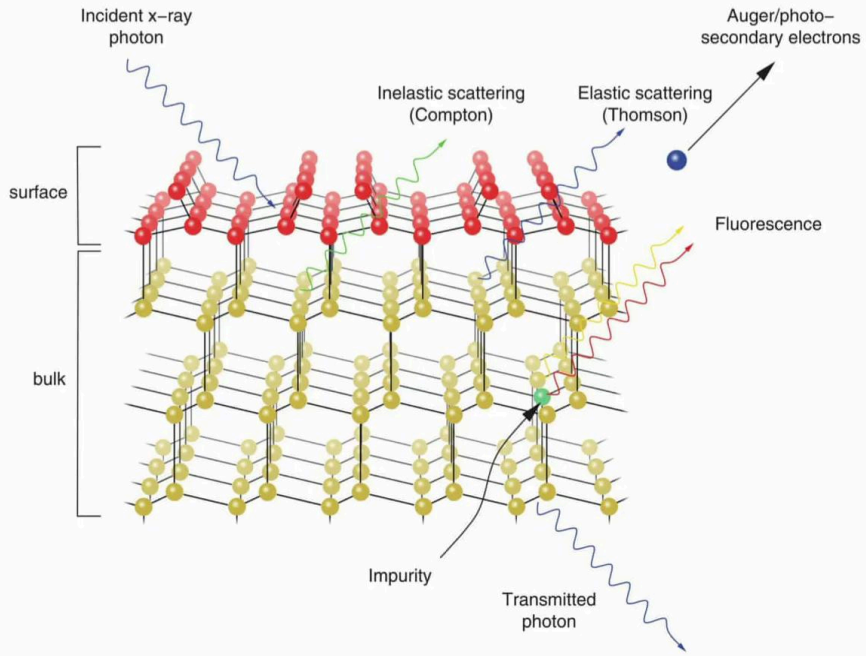
We're all familiar with the optical phenomena of reflection, refraction and absorption in the visible regime. Exemplified here by reflection off a chrome-plated surface, refraction of a lime twist in water, and absorption of green laser light by cranberry juice. Most of you watching this video will have at some point encountered diffraction as well. Such as the pattern shown here by shining a laser pointer onto a generic [inaudible 00:01:04] based smartphone screen. We'll consider separately diffraction phenomena in the sister course. But I would like to take this opportunity to say hello to Jason Isaacs as inspiration for this image.

Notes

Summary

0m 32s

Interaction types of UV and x-rays with matter



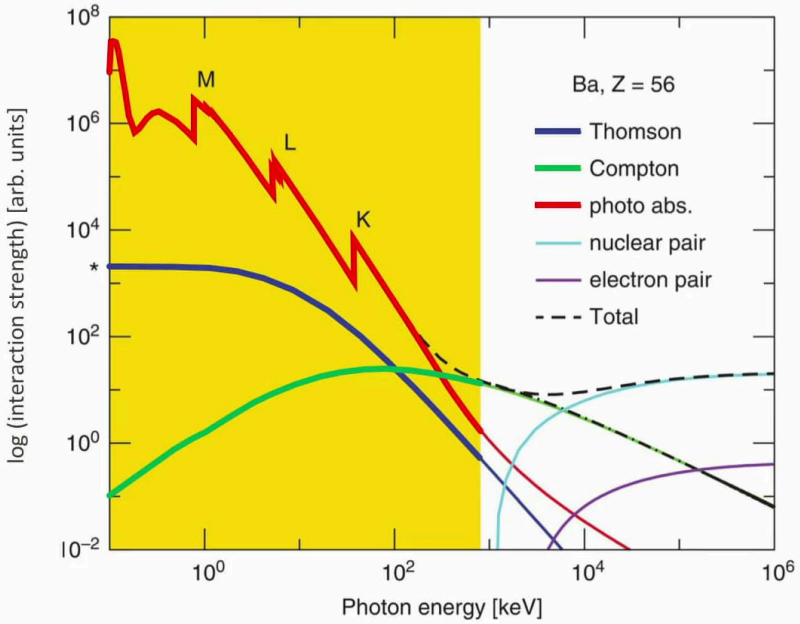
Now, shown, here is a cartoon of the interaction of X-rays with matter. Surface, and actually also interface regions of a solid or a liquid material are characterised, and in fact even defined by physical properties, structure and symmetries that may differ significantly from those of the bulk structure. X-rays impinging on the material may be elastically, Thomson scattered or inelastically, Compton scattered. They may be absorbed, in which case electrons or lower energy fluorescent photons can be subsequently emitted. If none of the above occur, the photon is transmitted through the sample.

Notes

Summary

1m 18s

Interaction strengths of UV and x-rays with matter



Now, what are the relative contributions of these processes? We show in this graph the cross sections for Thomson and Compton scattering and photo absorbtion for the element barium. How you work with cross sections and salient features of each type of interaction will be discussed in detail next week.

Notes

Summary

2m 06s

Important!

The electron is the only important particle describing the interaction of UV light and x-rays with matter

For the time being, it is sufficient to say that as far as radiation produced by synchrotrons and X-ray is concerned, the electron is the only important particle that we need to consider.

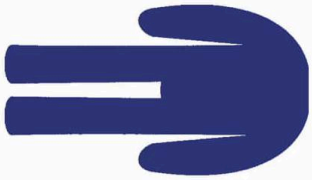
Notes

Summary

2m 30s

The Gray

- Gray: SI unit for absorption of ionizing radiation
  - J/kg
- 5 Gy (ca. 400 J for adult) typically lethal



As I have already mooted, although X-rays are partially transparent to matter, they do interact with it. And because they have energies, typically larger than the binding energy of valence electrons, and often also in excess of core electrons, X-rays are classified as ionising radiation. The SI unit for dosage of ionising radiation is the gray. One gray is equal to one joule of absorbed ionising radiation per kilogram. Five gray, or about 400 joules of absorbed X-rays is enough to put pay to a typical adult. A back of the envelope calculation reveals that such a dose results in the photo-ionisation of only approximately four in every billion molecules within the body for the case of five nanometre radiation.

Notes

Summary

2m 44s

The deadliness of ionizing radiation

+ 0.5°C

It is a salutary insight to note that if non-ionizing radiation is used, its impact is utterly negligible. Depositing 400 joules of Infra-Red radiation or heat into a cup of tea will heat it by about half a degree centigrade.

Notes

Summary

3m 44s

The deadliness of ionizing radiation

+ 0.5°C

0.5 s

Equally, even the most sunshine averse person can easily tolerate 400 joules of sunshine, as this equates to only about a half second exposure of equatorial midday sun. Thus, investing the available energy into a process that can eject electrons from just a small fraction of the radiated atoms is far more effective in wreaking havoc than jiggling all the atoms around by depositing non-ionizing radiation that is immediately converted into heat.

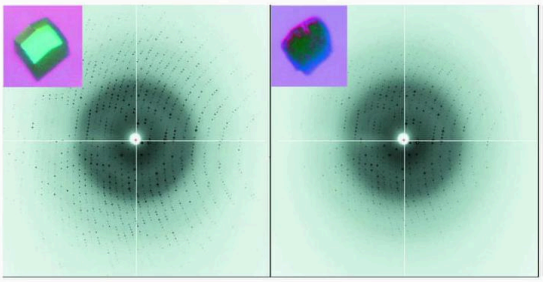
Notes

Summary

4m 03s

Typical sample dosage @ synchrotrons

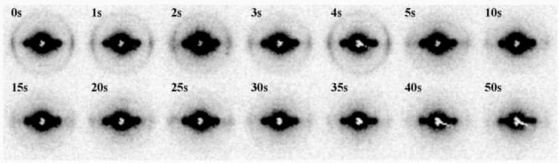
Protein crystallography



0 – 1.2 x 10^4 Gy 1.6 x 10^7 Gy

Teng and Moffat, J. Synchrotron Rad. **7** 313 (2000) doi: 10.1107/S0909049500008694
Owen *et al.*, PNAS **103** 4912 (2006) doi: 10.1073/pnas.0600973103

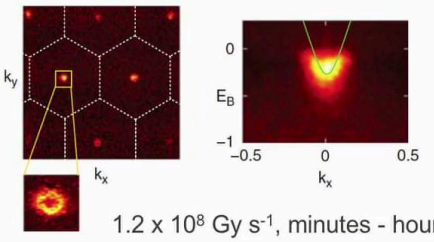
SAXS of keratin



1.7 x 10^7 Gy s^{-1} up to 50 s

Leccia *et al.*, J. Struct. Biol. **170** 69 (2010) doi: 10.1016/j.jsb.2009.11.006

SX-ARPES of GaN QW structure



1.2 x 10^8 Gy s^{-1}, minutes - hours

Lev *et al.*, Nature Comms. **9** 2653 (2018) doi: 10.1038/s41467-018-04354-x

So why is ionising radiation so harmful? The photo-electron initially released by photo ionisation has an energy equal to the absorbed photon energy, minus the binding energy of that electron. Depending on the shell from which the electron was emitted, the binding energy is usually much smaller than the photon energy. Meaning that the photo-electron will have a large kinetic energy. This high energy electron interacts very strongly with other electrons in the material, causing them too to be ejected from their atoms. Which therefore results in a cascade effect of ionisation and the production of harmful radicals such as oxygen atoms and ions. The impact this has on the sample depends to a large degree on the typical bond strengths. Soft organic matter, such as found in proteins, is much more easily damaged than strongly bound covalent or ionic inorganic compounds. In the example shown here, the protein crystal on the left is clearly impacted by the time it has absorbed approximately 10 million gray. While the keratin, on the right, requires an order of magnitude more dose before the elastic scattering signal begins to be affected. Look at the outer ring in each of the images carefully, and you see how they change. In contrast, gallium nitride, a robust compound semiconductor showed no measurable degradation after doses in excess of 10 billion gray.

Notes

Summary

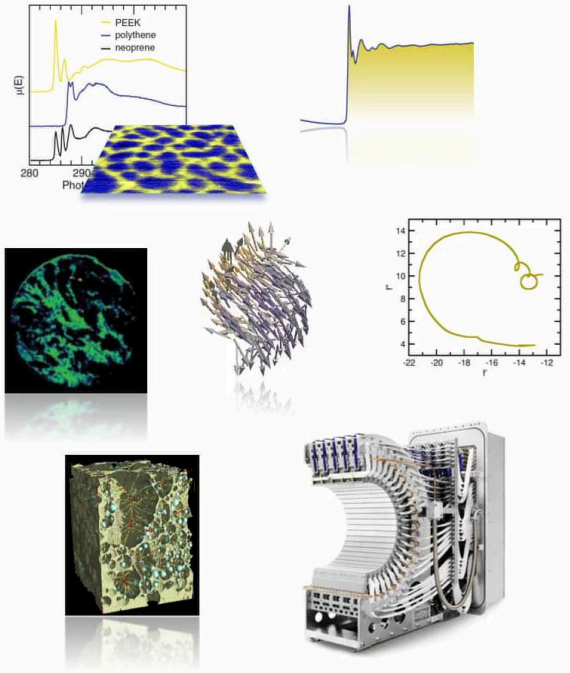
4m 40s

Matching the photon energy to your experiment

- Consider
  - Absorption edges
    - e.g.
      - Carbon K-edge @ 285 eV: soft x-rays (STXM)
      - Co L-edge @ 780 eV: soft x-rays (PEEM)
      - Sulfur K-edge @ 2.472 keV: “tender“ x-rays (XANES)
      - Selenium K-edge @ 12.66 keV: hard x-rays (MX)
    - Spectroscopy: chemical information
    - Imaging: elemental/chemical/magnetic contrast
    - Imaging: photoabsorption length ≷ sample size
    - Diffraction: help in structure determination
    - Diffraction: photoabsorption length ≫ sample size
  - Resolution
    - Diffraction: wavelength/scattering angles

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

    - Scanning imaging: size of beam passing through sample

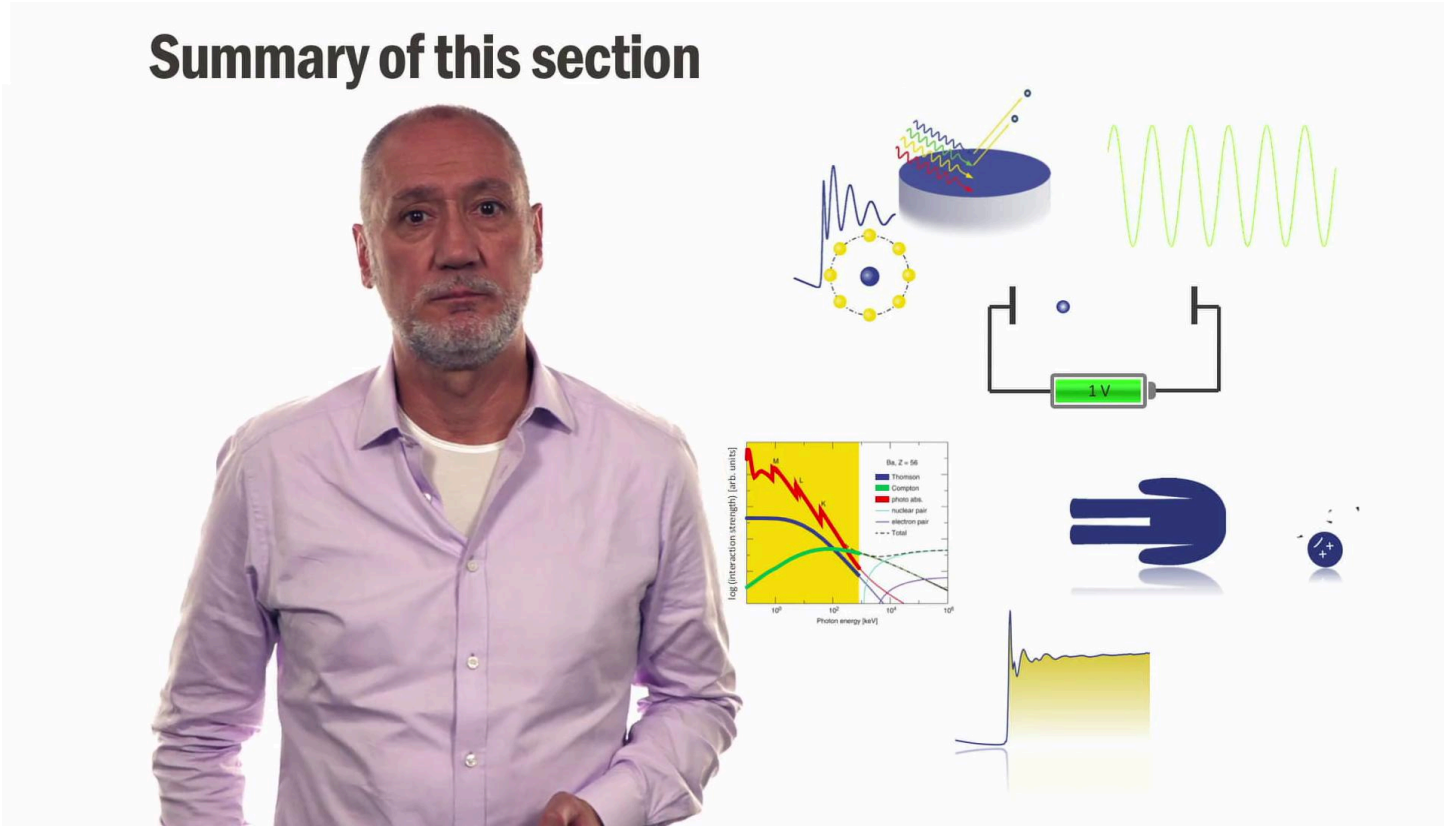


When planning an experiment, what factors should one consider in the choice of photon energy? Many X-ray spectroscopic measurements require the photon energy to be scanned over an energy range that includes the ionisation energy of one or more of the constituent atoms. In common parlance, you say you have scanned over an absorption edge. The change in response of the system as a function of photon on energy, whether that be the degree of absorption, the production of fluorescent signal, changes in the amount of elastic scattering or the kinetic energy and direction of photo electrons which are produced through absorption, can be used to determine that system's physical-chemical properties. Moreover, the spatial resolution is determined by the wavelength chosen, and in many scanning techniques, also by the width of the beam at the sample. Which, as we have already discussed, has a lower limit determined by diffraction phenomena. The so-called Abbe limit. In this, and even more so in the sister course, we'll consider such boundary conditions case for case.

Notes

Summary

6m 22s



Summarising this section, we have touched on the need to embrace particle wave duality, not only for electromagnetic radiation, where we either talk of photons or waves, but also for electrons, which demonstrate both wavelike and corpuscular natures too. We looked at the relationship between wavelength and frequency in electromagnetic waves and how these relate to the energy of photons. I introduce you to the convenient energy unit of the electronvolt before showing the interaction strengths of X-rays with matter in particular, for the three processes of photo absorption, elastic scattering and Compton scattering. We then considered the impact of the interaction of X-rays with matter on the perishability of a given sample. Lastly, general guidelines were listed for choosing a particular X-ray energy for the experiment in mind.

Notes

Summary

7m 39s

In the final short section of this week, we close off by taking a closer look at the architecture and components of synchrotrons and X-rays.

Notes

Summary

8m 42s