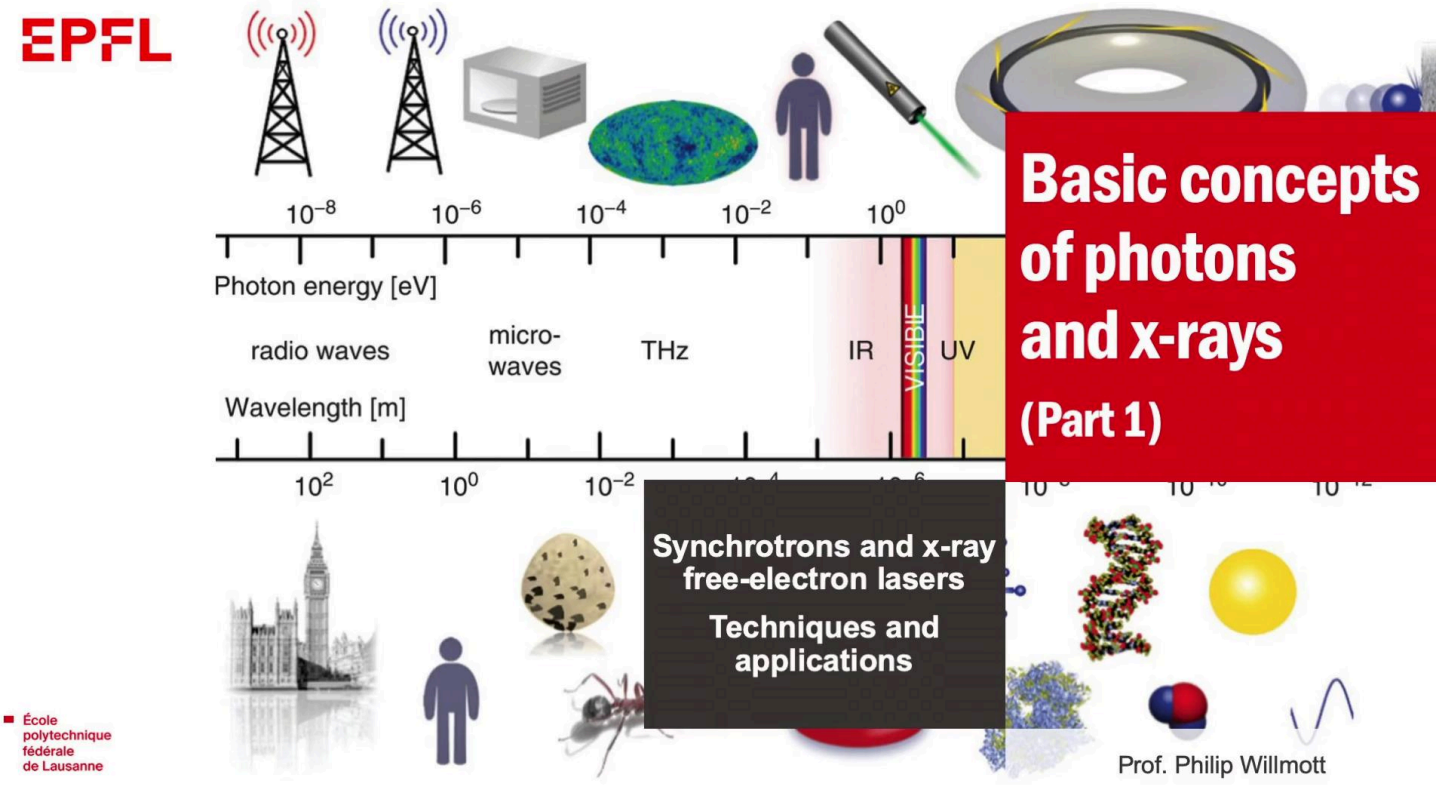

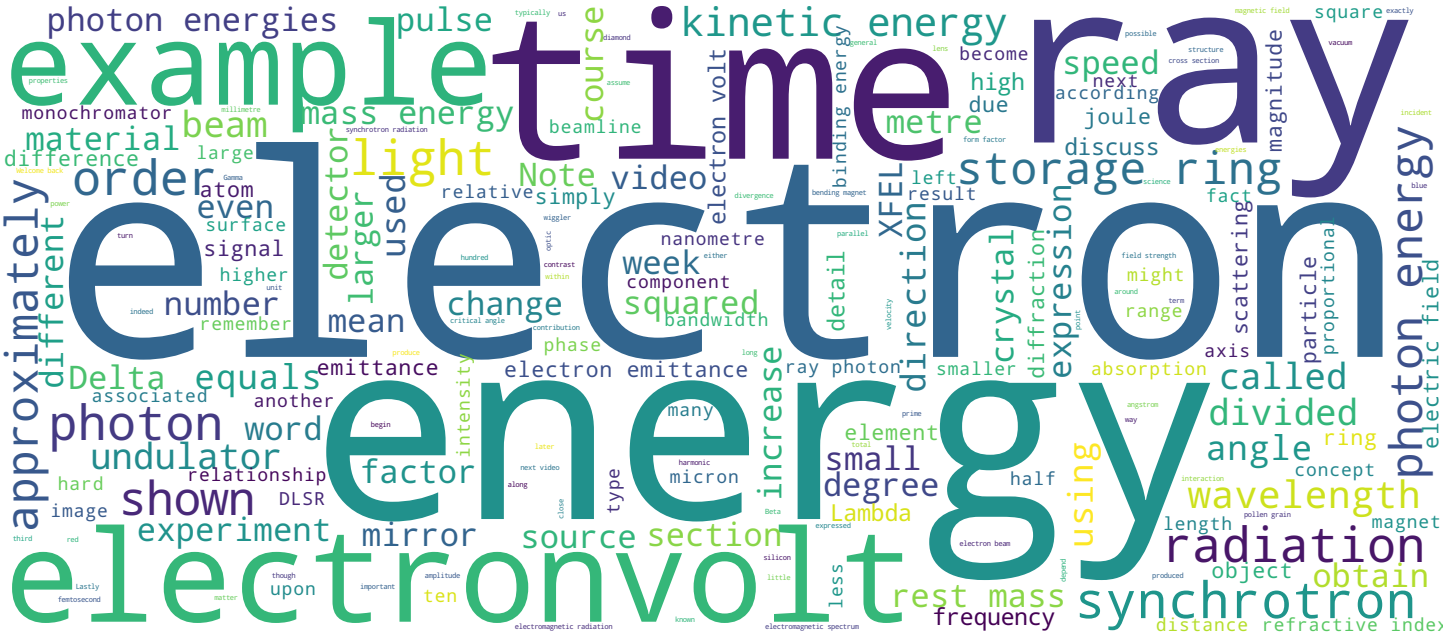

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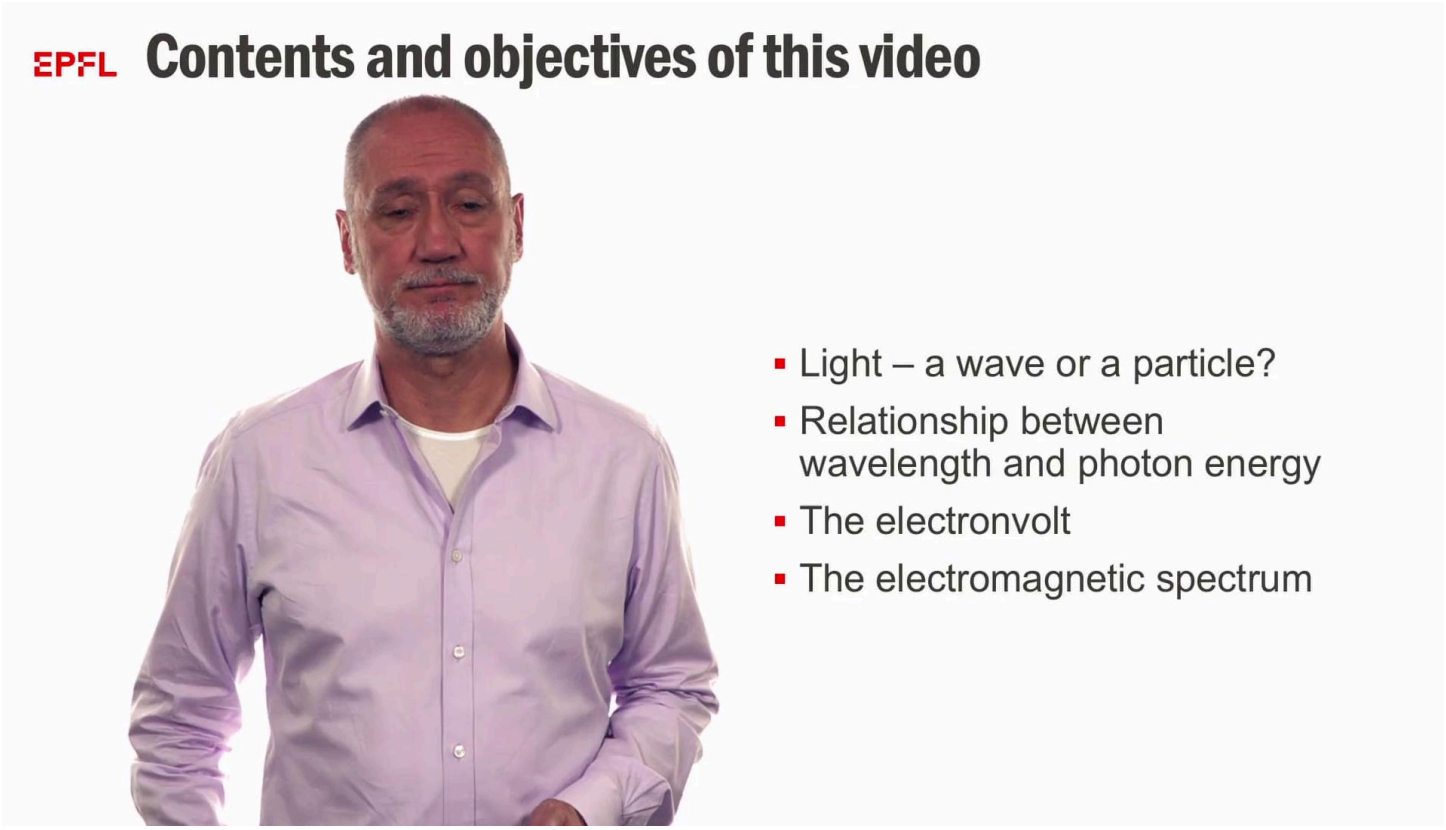


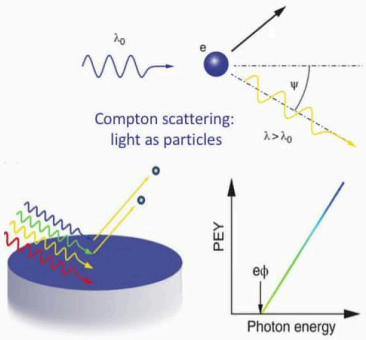
Welcome back. In this second section of the first week of this course, we discuss the particle wave duality of electromagnetic radiation first posited by Max Planck and further developed by Einstein and de Broglie. We then discuss the relationship between the energy of a photon and the wavelength, or frequency, of the associated electromagnetic wave and the most convenient unit with which to quantify this. Providing typical values for the different classifications within the electromagnetic spectrum.

Notes

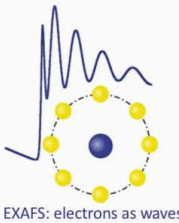
Summary

0m 05s

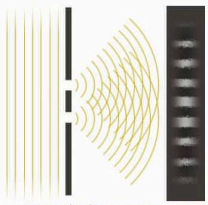
Light and particle-wave duality



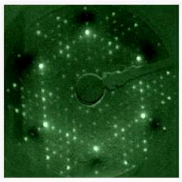
Photoelectric effect: light as particles



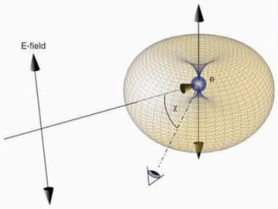
EXAFS: electrons as waves



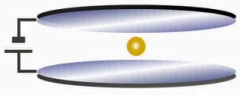
Young's slit experiment:
light as waves



LEED: electrons as waves



Dipole radiation: light as waves,
electrons as particles



Millikan's experiment:
electrons as particles

- In this lecture series:
  - "Light" ⟺ electromagnetic (EM) radiation
  - "Visible light" only small part of EM spectrum
- Particle-wave duality
  - Single model (i.e., wave *or* particle) inadequate to explain all observations of microscopic systems
  - e.g. electron diffraction (de Broglie wavelength) v Millikan's experiment (particle)
  - Photoelectric effect (particle = "photon") v Young's slit experiment (wave)

In this course I will use the terms 'electromagnetic radiation' and 'light' interchangeably. Whereby with light, I mean any part of the electromagnetic spectrum and not just the very narrow, visible regime that we detect with our eyes. Without going into a long historical narrative, suffice it here to state that at the turn of the 20th century, the concept of the photon was introduced by Max Planck as a convenient artifice to resolve contradictions in separate aspects of classical electromagnetic theory. It was Einstein who first actually proposed that the photon was, in fact, a real entity in his explanation of the photoelectric effect. He would later write: It seems as though we must use sometimes the one theory and sometimes the other. While at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality. Separately, neither of them fully explains the phenomena of light, but together they do. Here just some of the most well-known examples are given of not only light interpreted as either a wave or a particle, but also, importantly, the same duality for electrons. The concept of particle wave duality is not confined to light, but can be applied in principle to all objects, even if the wavelike nature of these objects rapidly becomes insignificant with an increase in that object's size.

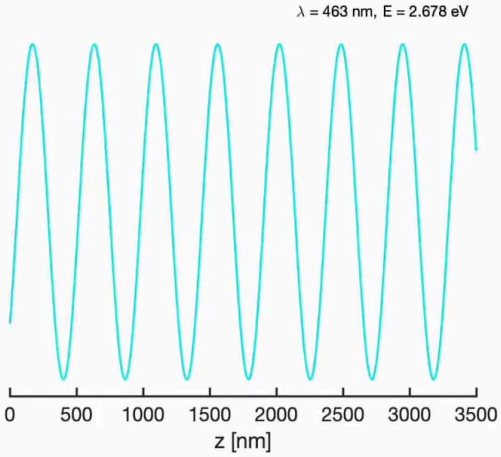
Notes

Summary

0m 40s

Light – speed, wavelengths, and frequencies

$$c = \nu\lambda$$



Red (700 nm) to blue (400 nm) visible light

- Velocity of light c = constant in vacuum
  - c = 2.9979 x 10^8 m s^{-1}
- Light is a transverse electromagnetic wave
- As wavelength decreases, frequency increases

The relationship between the wavelength, velocity, and frequency of waves is well known. In the case of light waves in a vacuum, they travel at nature's speed limit of just under 300,000 kilometres per second. Note that all electromagnetic radiation is a transverse wave. That is, the changes in amplitude are at right angles to the direction of propagation. From the relationship that the velocity of light C equals the frequency Mu times the wavelength Lambda, it is immediately apparent that as the wavelength decreases, the frequency must increase as shown here.

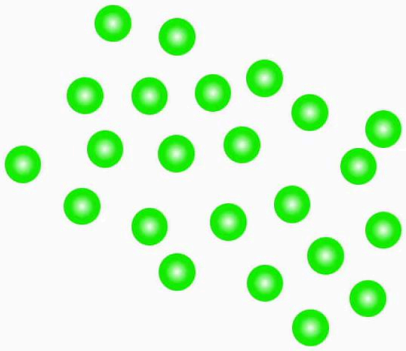
Notes

Summary

2m 22s

Photons – particles of light

$$E = h\nu = hc/\lambda$$



- E = energy of photon
- For a given frequency ν, E = the smallest possible energy packet of EM radiation
- h = Planck's constant
  - h = 6.626 x 10^{-34} J s
  - ħ = h/2π = 1.055 x 10^{-34} J s
- Visible light
  - E = 1.774 eV @ 700 nm
    = 3.100 eV @ 400 nm

When viewed from a corpuscular perspective, that is, light as a collection of photons, the relationship between energy of a photon on an wavelength is given by the Planck-Einstein relationship E equals H C upon Lambda. Where H is Planck's constant, which is equal to 6.63 times 10 to the minus 34 joule-seconds. And C is the speed of light in vacuum. See also the supplementary table for a list of physical constants used in this course. Inserting typical values into this equation, one sees that even for the hardest, that is, the most energetic X-rays used in synchrotron science, which have wavelengths of the order of a picometre, photon energies are of the order of a tenth of a thousandth of a billionth of a joule. In other words, 10 to the minus 13 of a joule. The joule is therefore obviously not a convenient energy unit to use when discussing X-ray photon energies. I would never tell my doctor, for example, that I weigh 4.27 times 10 to the minus 29 solar masses. Or indeed, 9.33 times 10 to the 31 electron masses.

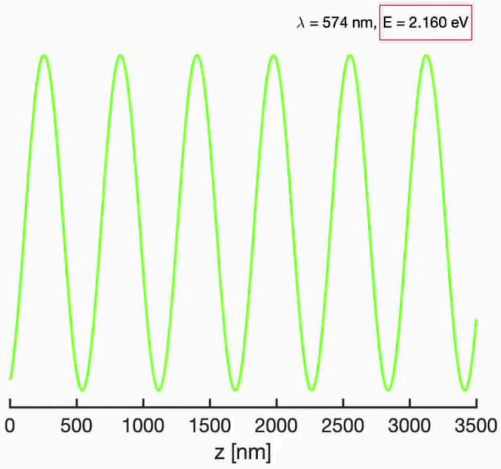
Notes

Summary

3m 09s

Photons – particles of light

$$E = h\nu = hc/\lambda$$



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- h = Planck's constant
  - h = 6.626 x 10^{-34} J s
  - ħ = h/2p = 1.055 x 10^{-34} J s
- Visible light
  - E = 1.774 eV @ 700 nm
    = 3.100 eV @ 400 nm
- What is an "eV"??

Instead, we use the electronvolt. If we look at our animation of the changing wavelength and frequency again, we see the energy expressed in electronvolts increases from approximately 1.8 electronvolts to 3.1 electronvolts from red to blue in the visible. So what exactly is an electronvolt?

Notes

Summary

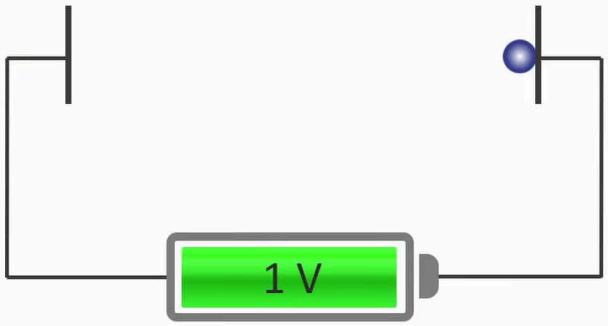
4m 27s

The electronvolt

- Electronvolt = eV
- Energy of an electron after being accelerated from rest in a potential of 1 V
- Energy = qV = $1.6022 \times 10^{-19} \times 1$ J

- 1 eV = 1.6022×10^{-19} J
- 6.24×10^{18} eV/J
- v_e @ 1 eV = 593 km s^{-1}!!

The eV is a very small amount of energy!



For fun: https://www.youtube.com/watch?v=6JAkyaEljSA&t=16s

An electronvolt is the gain in kinetic energy of an electron when it is accelerated across an electric potential of one volt and is equal to 1.6022 times 10 to the minus 19 joules. Compared to the SI unit for energy, the joule, an electronvolt is a very tiny amount of energy. Even at this very small energy, however, small objects can become very fast. An electron with the kinetic energy of 1eV attains a velocity of nearly 600 kilometres per second.

Notes

Summary

4m 50s

Electronvolts, bees, and pollen

- Example: pollen grain
  - 50 μm diameter
  - 1.4 g cm^{-3} density
  - m = 9.16 x 10^{-11} kg
  - Settling velocity = 3 cm s^{-1}
  - KE = ½ mv^2 = 4.12 x 10^{-14} J = 257.3 keV
  - "Rest-mass energy" = m_0c^2 = 8.24 MJ ≡ daily calorific needs of an adult

But how small exactly? Let us consider some examples. Very few macroscopic phenomena can be conveniently expressed in electronvolts. And the best I could muster was the kinetic energy of a typical grain of pollen dislodged from a flower by a bee. From data gleaned on the web, I determined, using the expression equals 1/2 M V squared, that the kinetic energy of this pollen grain is approximately 250 kiloelectronvolts. Larger than all but the most energetic X-ray photons produced at synchrotrons. In contrast, the bee, once it takes flight, may have a kinetic energy of 200 million billion electronvolts. That's two times 10 to the 17 electronvolts. Now comes an important fact. While the kinetic energy of the pollen grain is extremely small for macroscopic phenomena, it also has in addition, a so-called rest mass energy. Which, according to Einstein's famous equation, is the energy that would be released if all the pollen's mass were converted into pure energy. According to this equation E equals M C squared, this turns out, rather thrillingly, to be over eight megajoules for a pollen grain. About the energy in an average lightning bolt, for example. Or, the daily calorific needs for an adult human.

Notes

Summary

5m 28s

Electronvolts, bees, and pollen

- Example: pollen grain
  - 50 μm diameter
  - 1.4 g cm^{-3} density
  - m = 9.16 x 10^{-11} kg
  - Settling velocity = 3 cm s^{-1}
  - KE = ½ mv^2 = 4.12 x 10^{-14} J = 257.3 keV
  - "Rest-mass energy" = m_0c^2 = 8.24 MJ ≡ daily calorific needs of an adult

Personally, I also find it rather exciting to realise that pottering around for a day expends the same sort of energy as that which results in a huge flash of light and a colossal bang. So I guess, at one level, we're all explosively dynamic. Anyway, anyway, anyway. I mention this not only as a curious and fun fact, but also to highlight the energy distribution of electrons within storage rings of synchrotrons. While for the pollen grain, nearly all of its total energy is in the form of its rest mass energy, for the storage ring electrons it is nearly all in their kinetic energy because it is travelling so close to the speed of light. An electron in a storage ring has a kinetic energy typically 10,000 times larger than its rest mass energy. We will look into this aspect and its relativistic consequences in more detail in week three.

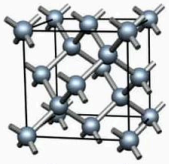
Notes

Summary

7m 01s

Electronvolts and the atomic world

- Chemical reactions
  - Imagine a chemical reaction resulting in a 1 eV difference in energy per involved molecule
  - 1 eV/molecule x 6.022 x 10^{23} molecules/mole = 1.6022 x 10^{-19} x 6.022 x 10^{23} = 96.5 kJ/mol
  - 100 kJ/mol IS TYPICAL FOR REACTION ENTHALPIES
- Chemical bonds
  - Graphite interplanar van-der-Waals bond = 0.05 eV
  - Diamond C-C bond = 3.5 eV
- Ionization energy of H-atom = 13.6 eV



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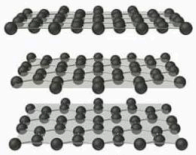

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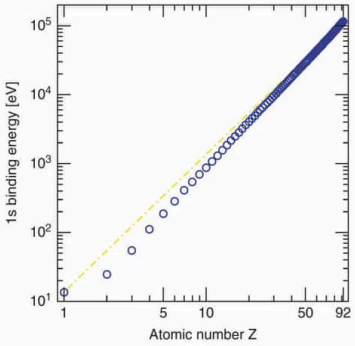
- Core-electron binding energies
  - 0th approximation: 1s B.E. = 13.6 x Z^2 eV



- Thermal energy = $3k_BT/2$ = 0.04 eV @ RT
- Rest-mass energy of an electron = m_0c^2 = 511 keV
- Energy of electrons in a synchrotron storage ring ~ GeV

In the microscopic world of atoms, electronvolts are the natural unit of choice for energy. For example, the large majority of chemical reactions have enthalpies, in other words, the difference in energy between the starting material and the end products, of between a few tens and a few hundreds of kilojoules per mole. But we know that there is Avogadro's number. That is, approximately six times 10 to the 23 particles in a mole. From which we can readily calculate that, for example, a 100 kilojoule per mole reaction equates to an energy difference between the educts and the products of one electronvolt for each individual molecular reaction. Chemical bonds expressed in electronvolts also yield sensible numbers. The weak Van der Waals bond between graphite layers has a bond strength equal to approximately a 20th of an electronvolt. While that between carbon atoms in diamond is about 3.5 electronvolts, some 70 times stronger. The ionisation energy of a hydrogen atom, that is, the binding energy of its single electron is famously equal to 13.6 electronvolts and is also referred to as the Rydberg Energy.

Notes

Summary

8m 01s

Electronvolts and the atomic world

- Chemical reactions
  - Imagine a chemical reaction resulting in a 1 eV difference in energy per involved molecule
  - 1 eV/molecule x 6.022 x 10^{23} molecules/mole = 1.6022 x 10^{-19} x 6.022 x 10^{23} = 96.5 kJ/mol
  - 100 kJ/mol IS TYPICAL FOR REACTION ENTHALPIES
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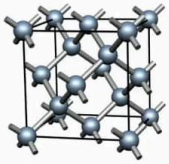
  - Graphite interplanar van-der-Waals bond = 0.05 eV
  - Diamond C-C bond = 3.5 eV
- Ionization energy of H-atom = 13.6 eV



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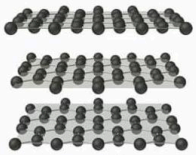

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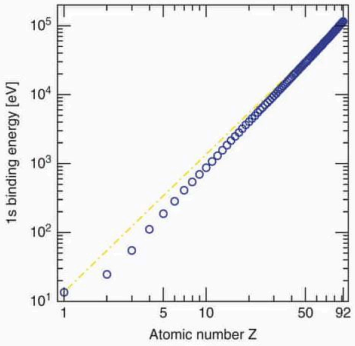
- Core-electron binding energies
  - 0th approximation: 1s B.E. = 13.6 x Z^2 eV



- Thermal energy = $3k_BT/2$ = 0.04 eV @ RT
- Rest-mass energy of an electron = m_0c^2 = 511 keV
- Energy of electrons in a synchrotron storage ring ~ GeV

Indeed, the Rydberg energy, because it is associated with the simplest atomic system of just one electron bound to a single proton, can be used to make a quick back-of-the-envelope calculation of the bond strength of the most strongly bound core electrons in all the elements. This assumes that the bound electron is only influenced by the positive charge of the nucleus and ignores the repelling action of the other electrons, which are also bound to the atom. In this approximation, then, classical electrostatics predicts that the binding energy of these so-called 1S electrons is simply 13.6 electronvolts times Z squared. Thus four neon, for which Z is equal to 10, one would predict that the 1S electron has a binding energy of 1360 electronvolts. In reality, the other nine electrons in the neon atom encourage the light charged core electron to leave and the experimentally determined value is, in fact, only 870 electronvolts. A graphical comparison between the actual and zeroth order approximation is shown here. I now mention three more energies expressed in electronvolts as they are highly pertinent to this course. First, the thermal kinetic energy of a free moving particle is three halves KB times T.

Notes

Summary

9m 26s

Electronvolts and the atomic world

- Chemical reactions
  - Imagine a chemical reaction resulting in a 1 eV difference in energy per involved molecule
  - 1 eV/molecule x 6.022 x 10^{23} molecules/mole = 1.6022 x 10^{-19} x 6.022 x 10^{23} = 96.5 kJ/mol
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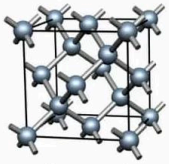

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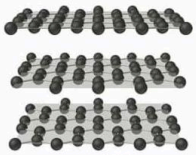

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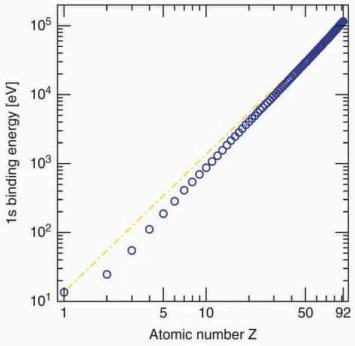


- Thermal energy = $3k_BT/2$ = 0.04 eV @ RT
- Rest-mass energy of an electron = m_0c^2 = 511 keV
- Energy of electrons in a synchrotron storage ring ~ GeV

Where KB is Boltzmann's constant and is equal to 1.38 times 10 to the minus 23 joules per kelvin. At room temperature, therefore, gas particles have a mean kinetic energy of approximately 1/25 of an electronvolt. The rest mass energy of any object with mass is, according to Einstein's special theory of relativity, the energy created by converting a body's mass to energy and is equal to M C squared, as we have just mentioned before. That is, its mass measured in the same inertial frame as that particle multiplied by the speed of light C squared. For an electron, this equates to a little over half a million electronvolts, or about twice the classical kinetic energy of the dislodged grain of pollen we've just encountered. If possible, try to remember the rest mass energy of an electron, 511 kiloelectronvolts. As we will use it repeatedly in the third and fourth week of this course. Lastly, the relativistic energy of electrons travelling around the storage rings of synchrotrons is typically measured in billions of electronvolts or gigaelectronvolts. This is much larger than the electrons' rest mass energy. Indeed, a good definition of a particle being relativistic is if its total energy exceeds its rest mass energy. We will return to this in detail in the next two weeks.

Notes

Summary

11m 00s

Electronvolts and photons

$$E = h\nu = hc/\lambda$$

- Photon energies expressed in Joules
  - h = 6.626 x 10^{-34} J s
  - c = 2.9979 x 10^{8} m s^{-1}
  - If we express λ in nm

    = 1.986 x 10^{-16}/ λ [nm]

  - e.g. λ = 500 nm (visible), E = 3.97 x 10^{-19} J
    λ = 0.1 nm (x-rays), E = 1.986 x 10^{-15} J

- Photon energies expressed in eV
  - h = 6.626 x 10^{-34} J s
  - c = 2.9979 x 10^{8} m s^{-1}
  - If we express λ in nm

    = 1239.84/ λ [nm]

  - e.g. λ = 500 nm (visible), E = 2.48 eV
    λ = 0.1 nm (x-rays), E = 12398.4 eV

Take-home message:
eV are much more suitable units to express photon energies

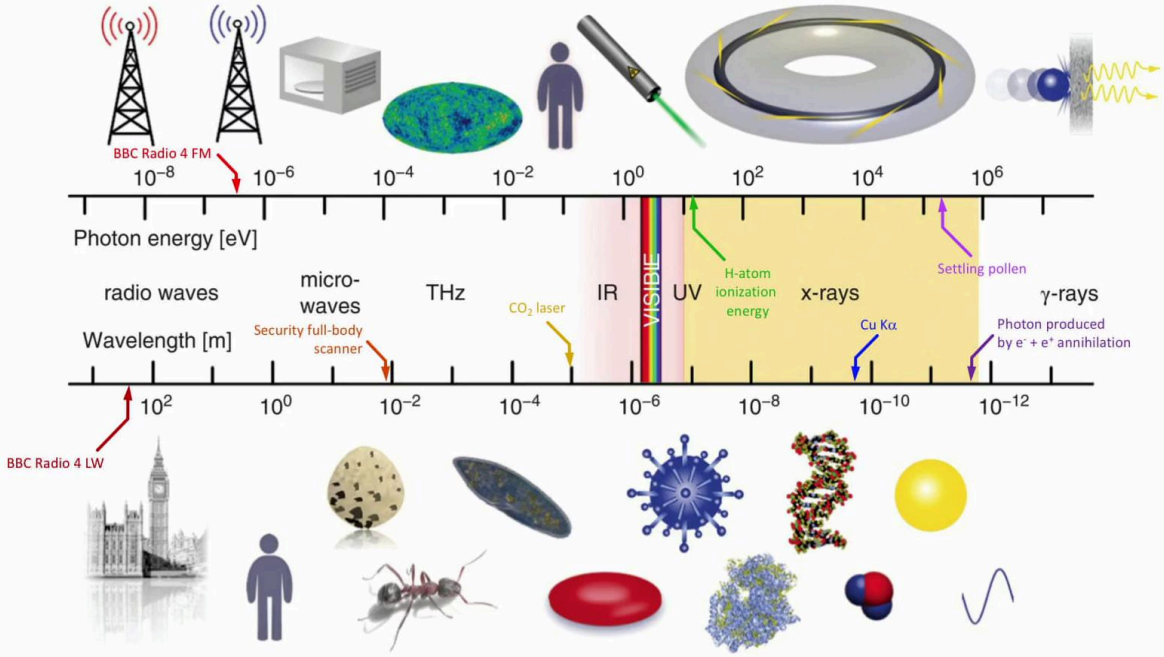
So in summary, we can derive practical expressions for photon energies using the known values for H and C. For completeness, I showed the expression for photon energies given in joules, [inaudible 00:12:48] that we obtain unwieldy numbers. However, in electronvolts, we obtain the relatively straightforward expression that the photon energy is approximately equal to 1240 divided by the wavelength if the latter is expressed in nanometres. A green photon in the visible thus has an energy of approximately 2.5 electronvolts. While a hard X-ray photon with a wavelength of one angstrom or 0.1 nanometres, has an energy of 12.4 kiloelectronvolts. We will use this expression many times in this course. So I recommend you become familiar with it. The take-home message is, therefore, that electronvolts are a much more convenient unit of energy to work with when expressing photon energies.

Notes

Summary

12m 36s

From radio to gamma rays – the electromagnetic spectrum



We finish this video by taking a glance at an overview of the electromagnetic spectrum from one long wavelength, radio waves, all the way through to high energy gamma rays. The upper scale shows the photon energy in electronvolts. The lower, the wavelength in metres. The images at the top are examples of sources of the radiation where they sit along the energy axis while objects with length scales corresponding to the different wavelengths are given at the bottom. Note also the wide golden band corresponding to energies provided by synchrotrons. Actually, this extends further to the left, down to the infrared. But much below a few electronvolts, laser sources do tend to dominate down to approximately 10 microns in any case. Lastly, some specific radiation sources, plus the kinetic energy of our settling pollen are also highlighted. In the next video, we take a brief introductory look at the different interactions of X-rays with matter. Including their relative strengths and how these change according to the X-ray photon energy and the chemical elements involved. Based on these rules of thumb, we can then judge which photon energy, or energies might be most appropriate for a planned investigation.

Notes

Summary

13m 42s