Phys106, II-Semester 2018/19, Tutorial 3 solution

Stage 1 (i) For the following photon frequencies, determine the name of their part of spectrum (radio, visible....), their energy in Joule and their energy in electron Volts (eV).

- $\nu = 30$ THz
- $\nu = 2$ PHz
- $\nu = 10^{21}$ Hz
- $\nu = 10$ kHz
- $\nu = 4 \times 10^{18}$Hz

(ii) Compare the energies you found in (i) with the following table of energy *scales* associated with physical processes/objects. For which combinations does the *order of magnitude* match (best)?

- Energy scale of changing the excitation state of an atomic nucleus $E_{nuc} \approx 1$ MeV.
- Ionising an inner shell electron from a heavy atom $E_{ion} \approx 30$ keV. (XRAY)
- Exciting an electron in a dye-biomolecule to its lowest excited state $E_{dye} \approx 2$ eV.
- Energy of vibrations of molecular bonds, $E_{vib} \approx 2 \times 10^{-20}$ J.
- Resonance energy of a large linear antenna $E \approx 1 \times 10^{-30}$ J.

(iii) For the matching pairs, find the wave length of the photon and the sizescale associated with the matching physical process/object in list (ii). What common fact do you see. It turns out, which object elm waves interact with most strongly is mostly determined by the match in energy, not so much match between size/wavelength. Discuss. Why could that be like this?

<u>*Solution:*</u>

(i)

ν	**Spectrum**	**E[J]**	**E[eV]**
30 THz	Near infrared	1.98×10^{-20}	0.124
2 PHz	Near ultraviolet	1.32×10^{-18}	8.27
10^{21} Hz	Gamma	6.63×10^{-13}	4.14 MeV
10 kHz	Radio waves	6.63×10^{-30}	41.4 peV
4×10^{18} Hz	Hard X-rays	2.65×10^{-15}	1.65×10^{4}eV

(ii)

- *Excitation state of an atomic nucleus - Gamma ray ($\approx 10^{20}$ Hz)*
- *X-ray from an inner shell electron from a heavy atom - Hrad X-rays ($\approx 7 \times 10^{18} Hz$).*
- *Exciting an electron in a dye-biomolecule to its lowest excited state - Near ultraviolet ($\approx 500 THz$)*

- *Vibrational excitations of molecular bonds - Near infrared ($\approx 10^2 THz$).*
- *Resonance energy of a large linear antenna - Radio wave ($\approx 10kHz$).*

(iii)

ν	**Spectrum**	**Wavelength [m]**	**Physical object**	**size of that**
30 THz	Near infrared	9.99×10^{-6}	Water molecule	$2.75\AA$
2 PHz	Near ultraviolet	1.49×10^{-7}	Molecules	1×10^{-8}m
10^{21} Hz	Gamma	2.99×10^{-13}	Atomic nucleus	5 fm
10 kHz	Radio waves	2.99×10^{4}	Large antenna	100 m
4×10^{18} Hz	Hard X-rays	7.49×10^{-11}	Atoms	1.75×10^{-9}m

As written in the questions, electro-magnetic waves mainly interact with objects that have a matching resonance energy/ frequency. Here "interact" means, are emitted absorbed or modified by the object in question. For example gamma rays are created during processes involving dynamics of nucleons (protons/neutrons). They essentially do not interact with electrons in atoms etc. So in the list above, the "matches in energy" you found were chosen to illustrate the type of object/process a given elm wave typically interacts with.
We could also be tempted to make that association based on wavelength, but see with the examples above that this generally does not work so well. The processes listed all mainly respond to the temporal change of electric fields within the light wave, and don't care much about the spatial change associated with the wavelength.

Stage 2 **Wien's displacement law** says that the peak of the black body spectrum is at $h\nu_{max} = 2.8214 k_B T$ (you can derive this later using mathematica). Now only find the temperature ranges for which the peak of the BB spectrum is within a certain part of the elm spectrum (radio, visible....), for all those parts.

Solution:

(i)

ν	**Spectrum**	**T[K]**
$3 \times 10^{3} - 3 \times 10^{9}$ Hz	Radio wave	$5.1 \times 10^{-8} - 5.1 \times 10^{-2}$
$3 \times 10^{9} - 3 \times 10^{11}$ Hz	Microwave	$5.1 \times 10^{-2} - 5.1$
$3 \times 10^{11} - 1 \times 10^{13}$ Hz	Far infrared	$5.1 - 170$
$1 \times 10^{13} - 4 \times 10^{14}$ Hz	Near infrared	$170 - 6804$
$4 \times 10^{14} - 7 \times 10^{14}$ Hz	Visible	$6804 - 11907$
$7 \times 10^{14} - 3 \times 10^{16}$ Hz	Ultraviolet	$11907 - 510305$
$3 \times 10^{16} - 3 \times 10^{19}$ Hz	X-rays	$510305 - 5.1 \times 10^{8}$
$3 \times 10^{19} - \infty$ Hz	Gamma rays	$5.1 \times 10^{8} - \infty$

Stage 3 Discuss on your table how Planck's calculation trick [that energy must have discrete quanta Eq. (23)], can be understood once we know about photons.

Solution: We know now that lectromagnetic (EM) radiation is made of photons. Thus the quantization of the energy of EM radiation is due to the fact that each mode of the elm field (each standing wave, say), can only be occupied by an integer number of photons n. Since each photon carries energy $h\nu$, the total energy in an electro-magnetic wave of frequency ν must be $E_n(\nu) = nh\nu$.

Stage 4 (i) Answer the following questions on the photo-effect:

- The work function forsodium is 2.3 eV. What is the maximum kinetic energy of electrons you can get when shining blue light on it?
- Using UV light ($\lambda = 150$ nm) on silver, you have to apply a counter voltage of at least 4 V to stop any electrons from arriving. Infer the work function of silver.
- Calcium has a workfunction of 3.2 eV, if you shine light with intensity $1W/cm^2$ and frequency $\nu = 6 \times 10^{14}$ Hz do you see photo electrons? What happens if you increase the intensity?
- What if instead you shine light with intensity $1W/cm^2$ and frequency $\nu = 1 \times 10^{15}$ Hz, do you see photo electrons? What happens now if you increase the intensity?

(ii) Use the online simulator at: http://vlab.amrita.edu/. For simulator use the login and password provided by TAs. Perform the virtual measurements described there and interpret them in the context of the lecture.

Solution:

(i)

- *The maximus kinetic energy of electrons by shining blue light (670 THz) is 0.47 eV.*
- *The workfunction of silver is 4.26 eV.*
- *The total energy of incoming light of frequency 6.0×10^{14} Hz is 2.48 eV which is less than the work function of Calcium hence we can not see the photoelectrons. There will be no effect of increasing the intensity.*
- *Now the photoelectrons can be seen because the total energy of incoming light is 4.135 eV. Photocurrent will increase if we increase the intensity.*