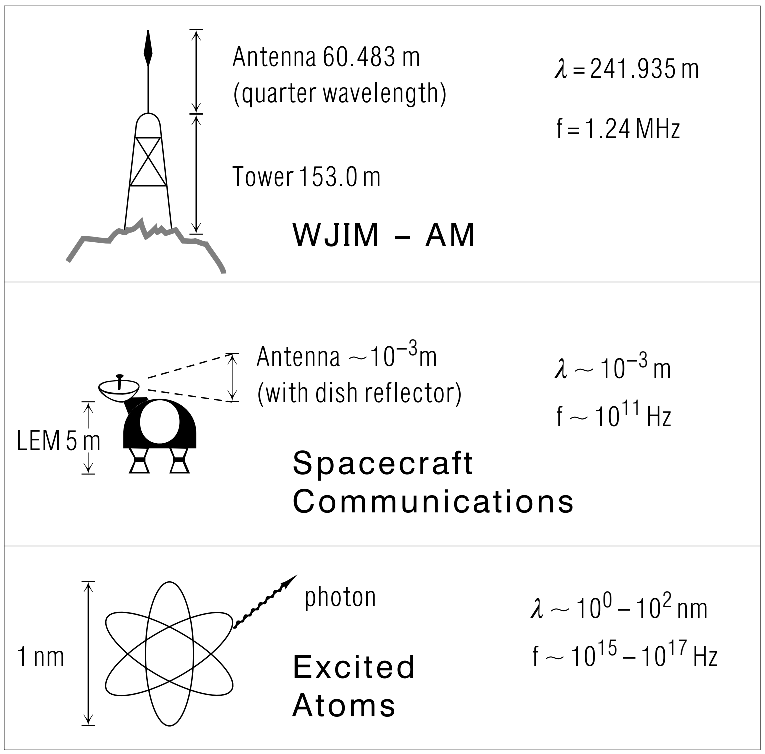
MISN-0-212

CHARACTERISTICS OF PHOTONS



Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

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by

Peter Signell and Ken Gilbert

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Title: **Characteristics of Photons**

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Input Skills:

1. Vocabulary: wavelength, frequency (MISN-0-201) or (MISN-0-430); energy, momentum, mass (MISN-0-15) or (MISN-0-413).
2. Solve simple collision problems (MISN-0-21) or (MISN-0-413).
3. Given two of the three basic wave parameters—phase velocity, wavelength, and frequency—calculate the third (MISN-0-201) or (MISN-0-430).

Output Skills (Knowledge):

K1. Name the seven major regions of the electromagnetic radiation spectrum on a chart that shows the frequency spread of each region.

K2. Name a characteristic photon source for each of the seven major frequency regions of the electromagnetic spectrum.

K3. State a very approximate relationship often found between photons, wavelengths and the dimensions of their sources.

K4. Locate the basic colors of the visible spectrum on a wavelength chart.

K5. Sketch a graph of normal eye sensitivity vs. wavelength.

Output Skills (Rule Application):

R1. Given information relevant to one of the four quantities associated with a photon - energy, momentum, wavelength, and frequency - calculate the other three, including in the context of particle scattering with N final-state particles.

External Resources (Optional):

1. Textbook: H. White, *Modern College Physics*, D. Van Nostrand and Co., Inc., Princeton, NJ (1956).

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1. Light as Photons

1a. Energy, Momentum, Speed, Non-Mass. What is the nature of light? Basically it consists of particle-like objects called "photons," each of which has energy and momentum. All photons travel at the single speed known as the speed of light, designated by the symbol c. This photon speed is incredibly large and has proved to be unalterable. Photons have no measurable mass but their observed energies and momenta still obey the relationships of relativistic mechanics, even in collisions with particles that do have mass.

1b. Creation and Annihilation: Seeing Objects. Photons are created in the sun, in light bulbs and at the surface of objects you are looking at. They are created by the electromagnetic interaction out of energy, momentum and angular momentum.[1] They travel at speed c, some going to your eye where they are annihilated (absorbed) in your retina. A photon's energy, released by its annihilation in your retina, triggers an electrochemical reaction that eventually reaches your brain and participates in the construction of a mental picture. The annihilated photon's momentum and angular momentum are absorbed by your body, the earth, etc.[2]

1c. Lower Speeds in Matter; Optical Devices. During the transit of a region containing atoms and molecules, such as air or your eye, a photon will sometimes be annihilated and then recreated as it passes within the region of influence of an atomic or molecular electron. The delay due to annihilation and creation gives the appearance of a lowered speed for photons traveling through matter. This appearance of lowered speed forms the basis for many optical instruments, from eyes to eye glasses to automobile headlights.

1d. Photons as Waves and Particles. In part because they travel at speed c, many photons readily display both wave-like and particle-like properties. Since waves and particles are mutually exclusive concepts in classical mechanics, we must resort to non-classical theories for a complete description of photons. Indeed, almost all of the technologically-important properties of photons can be derived from the non-classical Quantum Field Theory.[3] A detailed discussion of this theory is usually reserved for advanced graduate physics courses, but we can achieve considerable understanding of photon phenomena by straightforward application of the simple equations that connect the four basic wave and particle properties of individual photons: wavelength, frequency, momentum and energy.

[1] See "Fundamental Forces and Elementary Particle Classification" (MISN-0-255).
[2] See "Dynamics Laws in Everyday Life" (MISN-0-62).

2. The Photon Spectrum

2a. Seven Major Regions. Fig. 1a shows the usual groupings of the photon spectrum[4] into: gamma rays, x-rays, ultraviolet radiation, (visible) light,[5] infrared radiation, microwave radiation, and radio frequency waves. Typical sources and absorbers are shown in Table I. The unit used for wavelengths in the visible region is "nm," pronounced "nan′ oh meter." "Nano" is a metric system modifier meaning 10^{-9}, so $1\,\text{nm} = 10^{-9}\,\text{m}$.

2b. The Visible Region: Eye/Brain Response. Figure 1b shows the wavelength locations of common colors. There is a smooth transition from one color to another as one moves through the wavelengths, so that, for example, the wavelength half way between those labeled "blue" and "green" produces the color sensation we call "blue-green."[6] This sensation is a combined production of the eye and brain: the experimental details are amazing and are not yet fully understood. Figure 1b also shows the standard response curve of the human eye, peaking in the green-yellow. It would seem more than a coincidence that the energy spectrum of the sunlight that reaches the earth's surface also shows a lot of energy in the green and yellow regions. Fig. 2 shows the spectrum of sunlight, but it varies somewhat with the seasons, atmospheric conditions, and latitude.[7]

[3] See "Wave-Particle Duality for Light" (MISN-0-246).
[4] Usually referred to as "the electromagnetic spectrum."
[5] See, for example, H. White, *Modern College Physics*, D. Van Nostrand and Co., Inc., Princeton, NJ (1956), especially the color plate opposite page 445.
[6] See "Introduction to Color Physics" (MISN-0-227), "Land's Observations on Color Perception" (MISN-0-228) and "The Measure of Perceived Color" (MISN-0-229).
[7] For details see, for example, *Color in Business, Science, and Industry*, D. B. Judd and G. Wyszecki, John Wiley and Sons, New York (1975), esp. p. 108-111.

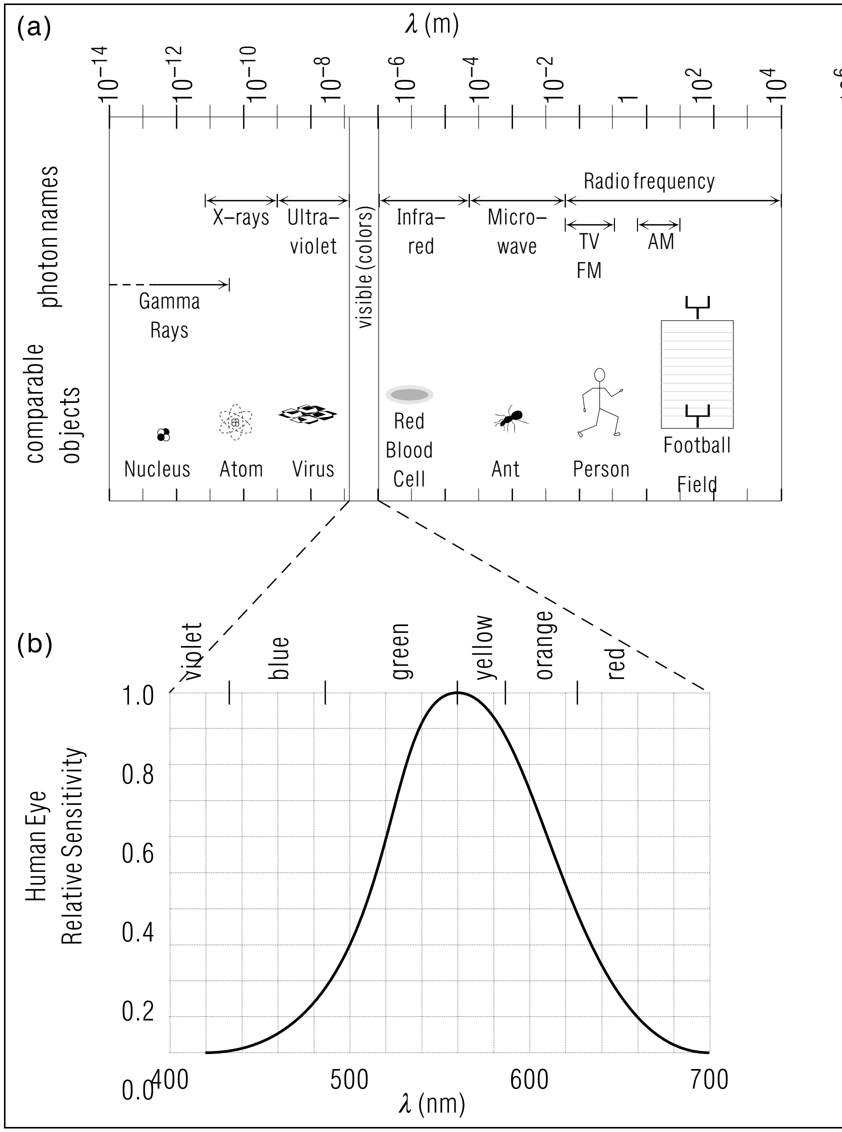


Figure 1. (a) The photon wavelength (λ) spectrum with size comparisons; (b) The standard response curve of the human eye. This figure is often reproduced in color.

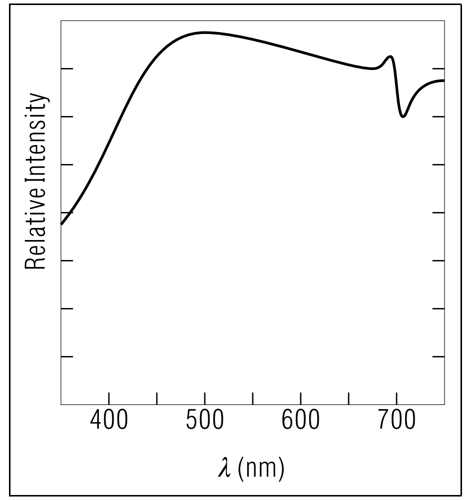


Figure 2. Relative energy vs. wavelength (λ) for the sun's radiation reaching the earth.

Table 1. Typical photon sources and absorbers for each region of the photon spectrum (Fig. 1).

Region	**Sources/Absorbers**
gamma	radioactive nuclei, nuclear and elementary particle reactions
x-ray	tightly-bound electrons in atoms, decelerating electrons hitting metal surfaces
ultraviolet	atoms and molecules in gas discharges
visible	de-excitation/excitation of atoms, molecules
infrared	molecules, hot bodies
microwave	electronic devices, atomic/molecular fine structure
radio	electronic devices, lightning

3. Photon Origins

3a. Charged Particle Accelerations. Experimental evidence has shown that photons are emitted, absorbed, and scattered only by electrically charged particles and only while those charged particles are undergoing acceleration. Electrons and protons are examples of such charged

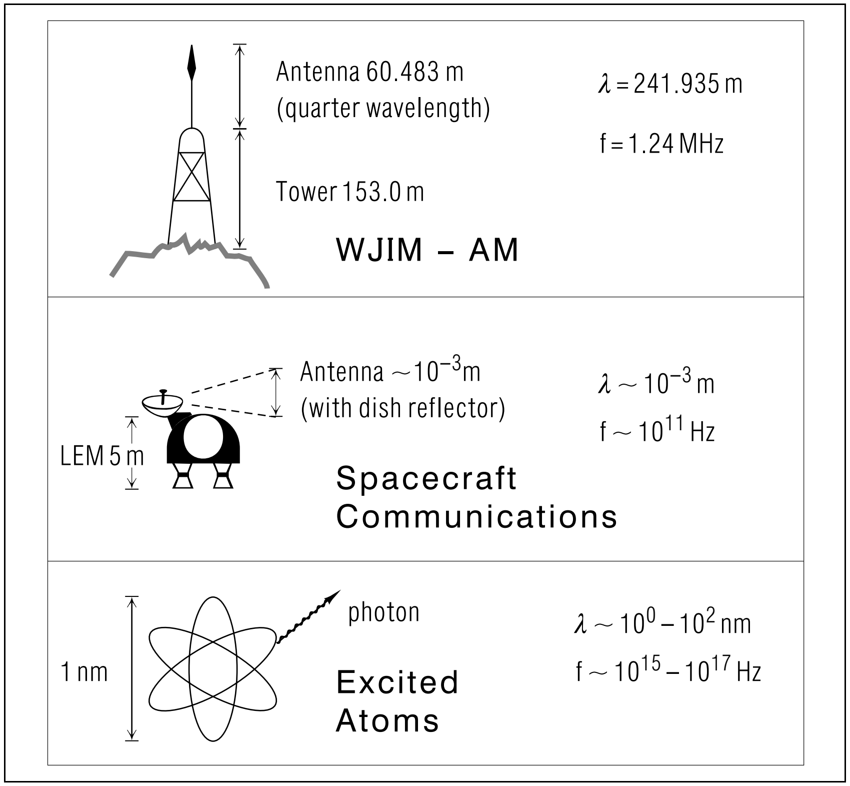


Figure 3. Source sizes and photon wavelengths for several emitters.

particles. So are neutrons, which are electrically neutral but which have internal circulating charges of both signs. The photons coming from an ordinary light bulb are produced when the electric current's electrons are decelerated in collisions with the filament's metallic lattice. The greater the deceleration, the higher the main frequencies of the emitted photons.

3b. Wavelength and Source Size. Comparing the diagrams in Fig. 3, it is evident that there is some kind of correspondence between photon wavelength and the dimensions of the photon source. This relation can be attributed to the coupling efficiency for emitting radiation into the surrounding region. For example, suppose you could vary the length of a radio station's antenna, like that of radio station WJIM in Fig. 3, while keeping its broadcast frequency fixed. You would find the greatest efficiency of radiation when the antenna was somewhere between one-fifth

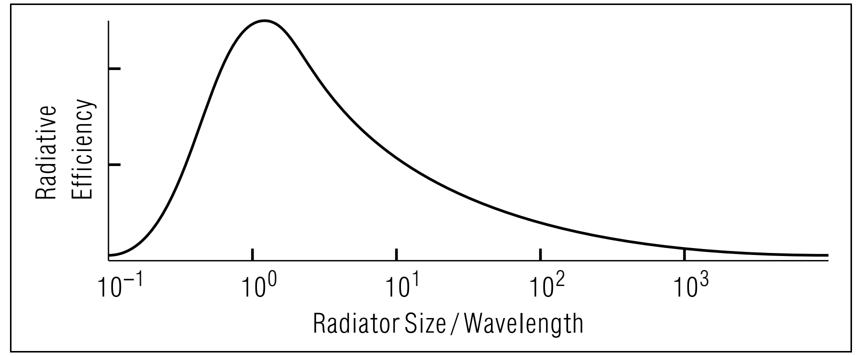


Figure 4. A sketch, not to be taken too literally, of radiation efficiency vs. ratio of radiator size to wavelength of radiation.

and one-half of a wavelength long. Where it falls in that range depends on details of the station's design. Actually, WJIM's antenna was made to be close to one quarter of a wavelength long. As another example, consider space-craft communications with frequencies in the neighborhood of 100 GHz (S-band): their antennas are on the order of millimeters in length. Fig. 4 illustrates the frequently-found relationship between the radiation efficiency and the ratio of the radiator's size to the radiation's wavelength.

3c. Acoustic Analogy. The problem of efficient photon radiation or absorption is analogous to the problem of high fidelity sound reproduction. In order to reproduce low frequencies (large wavelengths) with good efficiency, a large loudspeaker is used to transfer energy to (couple with) the air. This large radiator, however, is inefficient in the upper frequency range; thus a small speaker is added to couple the high frequencies (small wavelengths) to the air mass.

4. Wave/Particle Properties

4a. Energy, Frequency, Wavelength, Momentum. The important equations relating photons' wave and particle properties are:

$$E = h\nu = \frac{hc}{\lambda} = pc \qquad (1)$$

where:

$$E = \text{energy of photon,}$$
$$h = \text{Planck's constant,}$$
$$\nu = \text{photon frequency,}$$
$$c = \text{speed of light,}$$
$$\lambda = \text{wavelength of photon,}$$
$$p = \text{momentum of photon.}$$

Planck's constant, h, is an experimentally determined number whose currently accepted value is: $(6.626075 \pm 0.000040) \times 10^{-34}\,\mathrm{J\,s}$. Note that the photon's energy and momentum are not given in terms of mass and velocity, as in classical mechanics, although Eq. (1) does agree with the relativistic equation, $E^2 = p^2\,c^2 + m^2\,c^4$, if we substitute the photon's true mass of zero for m.

4b. Units Choice Criteria. It is usually advantageous to use units which are on the scale of the phenomena being studied, not units set up for dealing with phenomena of a widely different scale. For example, when dealing with the momentum and kinetic energy of photons and electrons, "MKS" (meter-kilogram-second) units would usually involve factors of the order of 10^{-20} and would thus be unwieldy and contain too many symbols. Instead, for that case one uses the electron-volt (eV) as the basic unit: it is the energy lost or acquired by an electron traversing a one volt potential difference.

4c. Energy Units. The units usually considered appropriate for energies associated with atomic, nuclear, and particle phenomena are electron-volts (eV), kilo-electron-volts (KeV), mega-electron-volts (MeV) and giga-electron-volts (GeV).[8] These are pronounced "g-e-v's," etc.

4d. Momentum Units. Since a photon's momentum is equal to its energy divided by the speed of light, $p = E/c$, the widely used atomic- and nuclear-scale momentum units are eV/c, MeV/c and GeV/c. For example, a 5 eV photon ($E = 5\,\mathrm{eV}$) is quoted as having a momentum of $5\,\mathrm{eV}/c$, pronounced "five-e-v-over-c." Here the speed of light, c, is not put in as $3 \times 10^8\,\mathrm{m/s}$, but is just left as the symbol "c." Planck's constant, h, is usually used in combination with c: $hc = 1240\,\mathrm{eV\,nm}$.

4e. Mass Units. In working problems involving atomic and nuclear phenomena, we almost always quote masses of objects in energy units

[8]See the Appendix for a list of metric prefixes.

divided by c^2. Thus, for example:

$$\begin{aligned} \text{electron mass} &= 511\,\mathrm{KeV/c^2}\ (\text{"...k-e-v-over-}c\text{-square"}) \\ \text{proton mass} &= 938\,\mathrm{MeV/c^2} \end{aligned}$$

These masses can be readily converted to kilograms if and when a need arises.

Acknowledgments

Preparation of this module was aided by discussions with Frank Zerilli. Dennis Nyquist helped with the discussion of antennas. Mike Brandl supplied the problems. Preparation of this module was supported in part by the National Science Foundation, Division of Science Education Development and Research, through Grant #SED 74-20088 to Michigan State University.

A. Metric-Unit Powers of Ten

(Illustrated for the Meter)

10^{-15} m	fm	femtometer ≡ fermi
10^{-12} m	pm	picometer
10^{-9} m	nm	nanometer
10^{-6} m	μm	micrometer ≡ micron
10^{-3} m	mm	millimeter
10^{0} m	m	meter
10^{3} m	km	kilometer
10^{6} m	Mm	megameter
10^{9} m	Gm	gigameter
10^{12} m	Tm	terameter
10^{15} m	Pm	petameter

PROBLEM SUPPLEMENT

$$hc = 1240\,\text{eV nm} = 1.240 \times 10^{-6}\,\text{eV m}$$
$$c = 2.998 \times 10^{8}\,\text{m/s}; \qquad \text{J} = 6.241 \times 10^{18}\,\text{eV}$$

Note 1: The constant quantity "hc" quoted above is the product of two constants: "h" is Plank's constant and "c" is the speed of light. The unit "eV" is an energy unit, while h has units of $energy \times time$ and c has units of $length/time$. The product of h and c thus has units of $energy \times length$, as you can see above.

Note 2: To understand units like MeV, see the chart of metric prefixes for lengths in the module's *Appendix*. The other metric quantities have the same prefixes, so 1 KeV$= 10^3$ eV, 1 MeV$= 10^6$ eV, etc.

Note 3: If you really become stuck on a problem, use the notations [S-1], [S-2], etc., to find help in this module's *Special Assistance Supplement*.

Note 4: Problems 1-4 also occur in this module's *Model Exam*.

1. Compute the energy, momentum, and wavelength (in miles) of a WMSN photon. WMSN is a radio station at 6.4 on the AM radio dial, which means that its frequency is 6.4×10^2 KHz. *Help: [S-9]*

2. How many WMSN photons (see Problem 1 above) would equal the kinetic energy of a flying mosquito ($\approx$1 GeV)? *Help: [S-8]*

3. If all parts of you were 850 million times as large, what color would WMSN photons appear to you? Note: assume everything else, including WMSN photons, are the same size as now. *Help: [S-2]*

4. A proton traveling at speed 0.1 c is completely stopped by collision with a heavy nucleus and with the emission of a photon. The mass of the proton is 938 MeV$/c^2$.

   What is the minimum wavelength possible for the photon, when all of the kinetic energy of the proton goes into the photon's energy? *Help: [S-7]* What is this kind of photon called?

5. The electron in an isolated hydrogen atom can flip from a state in which its spin is parallel to the spin of the proton to one in which the spins are anti-parallel. The difference in energy between these two

states is only 5.9×10^{-6} eV. What are the wavelength and frequency of a photon emitted in such a transition? *Help: [S-3]* In what part of the electromagnetic spectrum does this radiation fall?

6. Ultraviolet light with a wavelength shorter than 57.7 nm can knock the outermost electron free from a neon atom. By how much energy is the outermost electron bound to a neon atom? *Help: [S-4]*

7. It takes 5.16 eV of energy to separate a water molecule into H^+ and OH^- ions. What is the longest wavelength of electromagnetic radiation that will break up water molecules? *Help: [S-5]* What part of the electromagnetic spectrum does this lie in?

8. A short-wave radio station broadcasts on a wavelength of 4.0×10^1 meters with a total radiated power of 1.00×10^2 watts. How many photons is the transmitter putting out per second? *Help: [S-6]*

9. A proton captures a stationary electron to form a hydrogen atom in its ground state (the binding energy of a hydrogen atom is 13.6 eV). During the process a single photon is emitted. What is the wavelength of the photon? *Help: [S-1]* Is the photon visible?

Brief Answers:

1. 2.6 neV, 2.6 neV$/c$, 0.30 miles.
2. 4×10^{17} photons.
3. Green.
4. 0.264 pm, gamma ray.
5. $\lambda = 0.21$ m, $\nu = 1.4$ GHz. This is in the very high radio frequency range, nearly in the microwave range.
6. 21.5 eV
7. $\lambda = 240$ nm, in the ultraviolet region.
8. 2.02×10^{28} photons/sec.
9. $\lambda = 91.2$ nm. No, it is in the ultraviolet region.

SPECIAL ASSISTANCE SUPPLEMENT

S-1 *(from PS-Problem 9)*

The system of electron plus proton, before the capture, was stated to have zero kinetic energy. After the capture/emission, the atom had an energy of $-13.6\,\text{eV}$. Therefore the photon had an energy of $+13.6\,\text{eV}$.

S-2 *(from PS-Problem 3)*

$\lambda(\text{WMSN}) = c/\nu = (3.0 \times 10^8\,\text{m/s})/(640 \times 10^3\,\text{Hz})$
Making the eye 850×10^6 times larger would presumably be the same as keeping the eye as it is and making the wavelength 850×10^6 times smaller:
$\lambda' = \lambda/850 \times 10^6 = 550\,\text{nm}$.

S-3 *(from PS-Problem 5)*

Assume the energy change, $5.9 \times 10^{-6}\,\text{eV}$, all goes into the photon (nothing else is mentioned), so that is the photon's energy.

S-4 *(from PS-Problem 6)*

The binding energy of an electron is defined as the minimum energy it takes to knock it out of the atom. Thus $BE = E(\text{minimum photon}) = h\nu(\text{min}) = hc/\lambda(\text{max})$.

S-5 *(from PS-Problem 7)*

Long wavelength photons have smaller energies than those of shorter wavelength. Thus the longest wavelength photon would be the least energetic. It would just dissociate the water molecule, leaving nothing left over for kinetic energy. Then $\lambda = hc/E$, obtained by combining other equations in the text.

S-6 *(from PS-Problem 8)*

Recall from mechanics and from electricity and magnetism that: average power $= \Delta E/\Delta t$ and W = J/s.

S-7 *(from PS-Problem 4)*

$$E_k = \frac{1}{2}mv^2 = \frac{1}{2}\left(938\frac{MeV}{c^2}\right)\cdot(0.1\,c)^2 = 469 \times 10^4\,\text{eV}$$

Note that the c^2's cancel.

S-8 *(from PS-Problem 2)*

(energy/photon) × (total no. of photons) = (total energy)
⇒ (total no. photons) = (total energy) / (energy/photon)
where "energy per photon" is the energy in each photon.

S-9 *(from PS-Problem 1)*

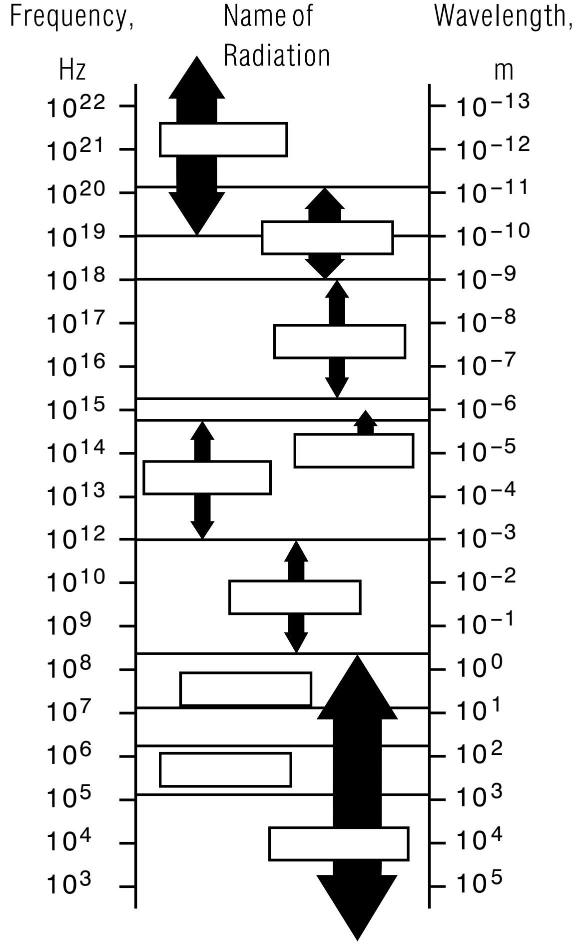
$\lambda = 4.69 \times 10^2\,\text{m}$
For the conversion to miles, we hope you learn to quickly make the conversion using a remembered English-metric relationship. Many science/technology professionals remember 2.54 cm = 1.00 inch (see the Conversion Factors in Appendix A8 just before the Index in this volume), and then they use their remembered number of inches in a foot and feet in a mile to make the conversion. Many also find it convenient to remember 62 miles/hr = 100 km/hr, which can be seen on the speedometer of any recently made car.

NOTE: The value of h alone, by itself, is not needed in this problem: do not waste time computing it. All that is needed is the value of the combination hc.

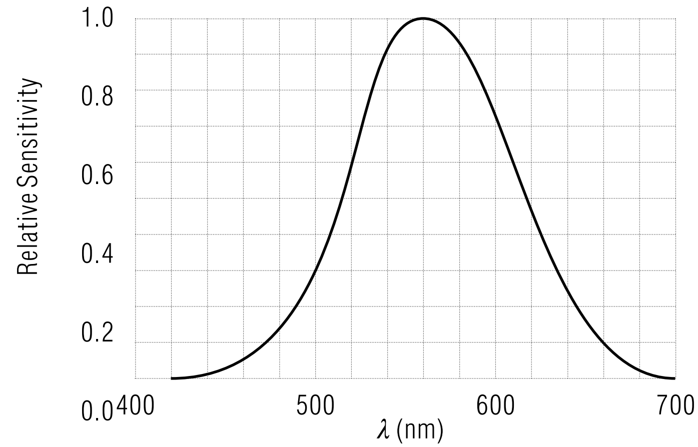
MODEL EXAM

$$hc = 1240\,\text{eV nm} = 1.240 \times 10^{-6}\,\text{eV m}$$
$$c = 2.998 \times 10^{8}\,\text{m/s}; \qquad \text{J} = 6.241 \times 10^{18}\,\text{eV}$$

1. Fill in the nine missing names:



2. Mark the various colors in their proper places and explain the meaning of the curve:



3. For each of five of the seven major regions of the electromagnetic spectrum, give a different source of photons.

4. See Output Skills K3 and K5 in this module's *ID Sheet.* Neither, either, or both of them may be included on the exam.

5. Compute the energy, momentum, and wavelength (in miles) of a WMSN photon. WMSN is at 6.40 on the radio dial, which means that its frequency is 640 KHz.

6. How many WMSN photons would equal the kinetic energy of a flying mosquito ($\approx$1 GeV)?

7. If all parts of you were 850 million times as large, what color would WMSN photons appear to you? Note: assume everything else, including WMSN photons, are the same size as now.

8. A proton traveling at speed $0.1\,c$ is completely stopped by collision with a heavy nucleus and with the emission of a photon. What is the minimum wavelength possible for the photon, when all of the kinetic energy of the proton goes into the photon's energy? The mass of the proton is $938\,\text{MeV}/c^2$ and $hc = 1240\,\text{eV nm}$. What is this kind of photon called?

Brief Answers:

1. See this module's *text*.
2. See this module's *text*.
3. See this module's *text*.
4. See this module's *text*.
5. See Problem 1 in this module's *Problem Supplement*.
6. See Problem 2 in this module's *Problem Supplement*.
7. See Problem 3 in this module's *Problem Supplement*.
8. See Problem 4 in this module's *Problem Supplement*.