MA99 EDUCATION

The Nature of Light: Topic Notes 07

NSW PHYSICS STAGE 6 SYLLABUS 2017 FOR HSC 2027

Module 7 is partly about the history of an argument. Two models of light each explain what the other cannot, and the syllabus asks you to say which result belongs to which model and why. Questions here reward a student who can name the evidence, not one who can only calculate.

1. The two-minute diagnostic

Ten statements. Tick what is true of you now, then read the row you land in.

- ☐ I can say what Maxwell predicted and how it was confirmed.
- ☐ I can name four things a stellar spectrum reveals, and how.
- ☐ I can calculate a fringe spacing in a double slit experiment.
- ☐ I can explain why polarisation proves light is transverse.
- ☐ I can state what the wave model fails to explain, with three examples.
- ☐ I know the difference between what intensity changes and what frequency changes.
- ☐ I can calculate a maximum kinetic energy and a stopping voltage.
- ☐ I can state both postulates of special relativity in my own words.
- ☐ I can calculate a dilated time and a contracted length, and say in which frame.
- ☐ I can explain what $E = mc^2$ actually claims.

1.1 Interpreting your score

Count the ticks and read the matching row.

TICKS	WHAT IT MEANS	GO HERE FIRST
0 to 3	The content is not in place yet.	Sections 1 and 2, in order, with the worked examples covered.
4 to 6	You calculate well and lose marks on the explanation questions.	Sections 3 and 4, then every explain and assess question you can find.
7 to 9	The gap is precision about frames and models, not content.	The drill in section 6, then a full paper against the clock.
10	Nothing here will add a mark.	Past papers. Come back only to check a relationship.

Several statements here ask whether you can explain something rather than calculate it. That is deliberate, and it is where the marks in this module are.

Date this. Run the same statements again at the end of term and compare the result with this one to measure progress.

First run. Date: _____ **Score:** _____

End of term. Date: _____ **Score:** _____

2. The electromagnetic spectrum and spectroscopy

Maxwell's equations predicted that a changing electric field produces a changing magnetic field and the other way around, so the two can sustain each other and travel as a wave. The predicted speed came out of the equations as a combination of two constants, one electric and one magnetic, and it matched the measured speed of light. That match is what established light as an electromagnetic wave.

- Electromagnetic waves are transverse, with the electric and magnetic fields perpendicular to each other and to the direction of travel.
- They need no medium. This is what finally displaced the idea of a luminiferous aether.
- All of them travel at $c = 3.00 \times 10^8$ m/s in a vacuum, whatever the wavelength, and $c = f\lambda$ connects the frequency and the wavelength.

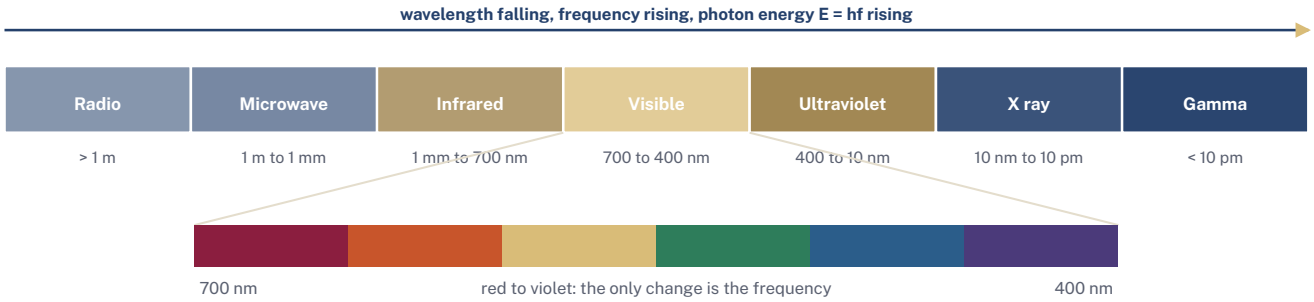


Figure 1 · The spectrum ordered by wavelength. The only physical difference along it is the frequency, and therefore the energy carried by each photon.

2.1 Measuring the speed of light

The speed of light was measured before it was explained. Roemer inferred it from the timing of the eclipses of Jupiter's moons, Fizeau used a toothed wheel and a distant mirror, and Michelson refined the rotating mirror method to a precision that stood for decades. The modern value is exact by definition, because the metre is now defined from it.

2.2 What a spectrum tells you

A hot dense object gives a continuous spectrum. A hot low pressure gas gives an emission line spectrum, with bright lines at wavelengths characteristic of the element. A continuous source viewed through a cooler gas gives an absorption spectrum, with dark lines at those same wavelengths.



One piece of light, read four ways. A question that gives you a spectrum is asking which of these it wants.

Figure 2 · Four measurements on a single stellar spectrum, and the property each one yields.

Wien's displacement law

$\lambda_{max} = b / T$, with $b = 2.898 \times 10^{-3}$ m·K.

The hotter the object, the shorter the wavelength at which its continuous spectrum peaks. This is why a cooler star looks red and a hotter one looks blue-white.

The temperature must be in kelvin. Using degrees Celsius is the commonest error in this section, and it is not a small one.

Worked example · 1

Find the peak wavelength for Wyndarra A at 5800 K, Wyndarra B at 3200 K and Wyndarra C at 12 000 K.

Formula: $\lambda_{max} = b / T$

Wyndarra A: $\lambda = 2.898 \times 10^{-3} / 5800 = 5.00 \times 10^{-7}$ m, or 500 nm, in the green

Wyndarra B: $\lambda = 2.898 \times 10^{-3} / 3200 = 9.06 \times 10^{-7}$ m, or 906 nm, in the infrared

Wyndarra C: $\lambda = 2.898 \times 10^{-3} / 12\,000 = 2.42 \times 10^{-7}$ m, or 242 nm, in the ultraviolet

ANSWER Wyndarra B, the red giant, peaks in the infrared and Wyndarra C, the white dwarf, in the ultraviolet; only Wyndarra A, a main sequence star, peaks in visible light

> Kelvin, always. Celsius in Wien's law is a whole question thrown away.

3. Light as a wave

Three results establish the wave model, and each of them is impossible to explain if light is only a stream of particles.

3.1 Diffraction

Light spreads out after passing an edge or a narrow gap. The spreading is noticeable when the gap is comparable to the wavelength, which is why it is hard to see with visible light and easy with sound.

3.2 Young's double slit experiment

Light through two narrow slits produces a pattern of bright and dark fringes on a screen. Bright fringes fall where the two paths differ by a whole number of wavelengths, dark fringes where they differ by a half number. A particle model gives two bright bands and nothing else.

Key idea

Fringe spacing $y = \lambda L / d$, where L is the slit to screen distance and d the slit separation. A larger wavelength or a wider screen distance spreads the fringes out. Slits further apart bring them closer together.

For a diffraction grating, $d \sin\theta = m\lambda$, where m is the order of the maximum.

Worked example · 2

In Hut 7 a helium neon laser at 633 nm passes through slits 0.25 mm apart onto a screen 2.4 m away. Find the fringe spacing.

Formula: $y = \lambda L / d$

Substitute: $y = (633 \times 10^{-9} \times 2.4) / (0.25 \times 10^{-3})$

$y = 1.52 \times 10^{-6} / 2.5 \times 10^{-4}$

ANSWER $y = 6.08 \times 10^{-3}$ m, or 6.08 mm between adjacent bright fringes

Worked example · 3

The same laser passes through a grating of 600 lines each millimetre. Find the angle of the first order maximum.

Grating spacing: $d = 1 / 600\,000 = 1.67 \times 10^{-6}$ m

Formula: $d \sin\theta = m\lambda$, with $m = 1$

$\sin\theta = \lambda / d = 633 \times 10^{-9} / 1.67 \times 10^{-6} = 0.380$

ANSWER $\theta = 22.3$ degrees from the central maximum

3.3 Polarisation

Light can be polarised, meaning its electric field oscillations can be confined to one plane. Only a transverse wave can be polarised. A longitudinal wave such as sound cannot, because its oscillations are already along the direction of travel. Polarisation is therefore direct evidence that light is a transverse wave.

Malus's law

$I = I_0 \cos^2\theta$, where θ is the angle between the polariser and the analyser.

At $\theta = 0$ everything gets through. At $\theta = 90$ degrees nothing does. At 45 degrees, exactly half.

Unpolarised light passing a single polariser loses half its intensity, whatever the orientation, because the field directions are distributed evenly.

Worked example · 4

Polarised light of intensity I_0 meets an analyser at 35 degrees to its plane. Find the fraction transmitted.

Formula: $I = I_0 \cos^2\theta$

Substitute: $I / I_0 = \cos^2 35 = (0.819)^2 = 0.671$

ANSWER $I / I_0 = 0.671$, so 67.1 per cent of the intensity is transmitted

4. Light as a quantum

The wave model runs out at two points, and both of them involve light exchanging energy with matter rather than travelling through space.

4.1 Black body radiation

The curve of intensity against wavelength for a hot object rises to a peak and falls away at short wavelengths. Classical physics predicted the opposite: intensity rising without limit as the wavelength shortened, the result later called the ultraviolet catastrophe. Planck fitted the real curve by assuming energy is exchanged in discrete packets of size $E = hf$, and treated that as a mathematical device rather than a physical claim.

4.2 The photoelectric effect

Light falling on a metal surface ejects electrons, but only above a threshold frequency, and the maximum kinetic energy of those electrons depends on the frequency and not on the intensity. Einstein explained this by taking Planck's packets literally: light arrives as photons, one photon is absorbed by one electron, and the energy is not shared.

The photoelectric equation

Kmax = hf − φ, where φ is the work function, the minimum energy needed to free an electron from that surface.

Below the threshold frequency $f_0 = \varphi / h$, no electrons are emitted at all, however intense the light and however long you wait.

Above it, emission is immediate even at very low intensity, because a single photon carries enough energy on its own.

Intensity changes how MANY electrons are emitted. Frequency changes how much ENERGY each one has. Confusing those two is the single most expensive error in the module.

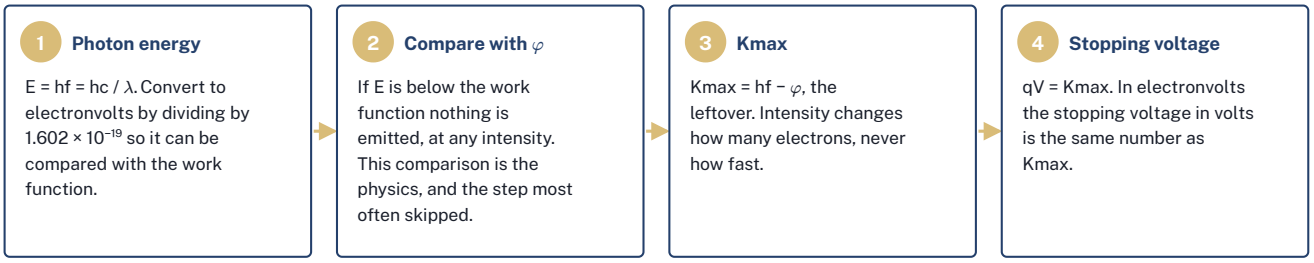


Figure 3 · The photoelectric method. The comparison in step two is where the physics is, and it is the step most often skipped.

Worked example · 5

Light of wavelength 420 nm falls on a metal with a work function of 1.95 eV. Find the photon energy, the maximum kinetic energy of the emitted electrons and the stopping voltage.

Photon energy: $E = hc / \lambda = (6.626 \times 10^{-34} \times 3.00 \times 10^{8}) / (420 \times 10^{-9})$

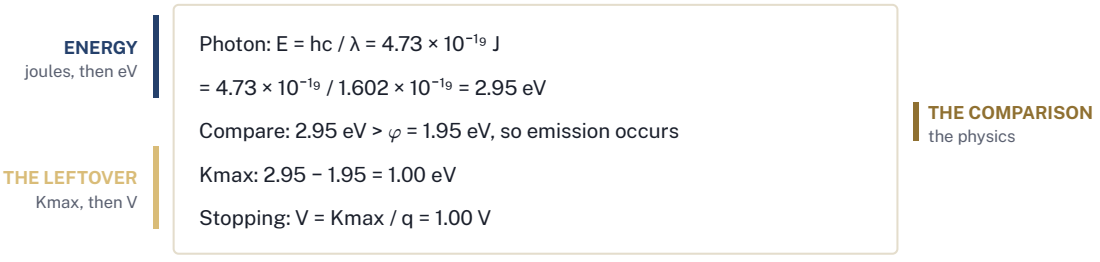
$E = 4.73 \times 10^{-19}$ J, which is $4.73 \times 10^{-19} / 1.602 \times 10^{-19} = 2.95$ eV

Compare: 2.95 eV is above the work function of 1.95 eV, so emission occurs

Maximum kinetic energy: Kmax = 2.95 − 1.95 = 1.00 eV = 1.60×10^{-19} J

Stopping voltage: $V = Kmax / q = 1.60 \times 10^{-19} / 1.602 \times 10^{-19} = 1.00$ V

ANSWER E = 2.95 eV, Kmax = 1.00 eV and the stopping voltage is 1.00 V



Five lines. Every photoelectric question in the course is a rearrangement of them.

Figure 4 · The same calculation with each line named. Every photoelectric question in the course is a rearrangement of these five lines.

Worked example · 6

Find the threshold frequency and threshold wavelength for the same metal.

Work function in joules: $\varphi = 1.95 \times 1.602 \times 10^{-19} = 3.124 \times 10^{-19}$ J

Threshold frequency: $f_0 = \varphi / h = 3.124 \times 10^{-19} / 6.626 \times 10^{-34} = 4.715 \times 10^{14}$ Hz

Threshold wavelength: $\lambda_0 = c / f_0 = 3.00 \times 10^{8} / 4.715 \times 10^{14} = 6.363 \times 10^{-7}$ m

ANSWER $f_0 = 4.71 \times 10^{14}$ Hz and $\lambda_0 = 636$ nm, in the red

Light of longer wavelength than 636 nm ejects nothing from this metal, at any intensity

WAVE MODEL	PARTICLE MODEL
Huygens, Young, Maxwell	Newton, then Planck and Einstein
Interference and diffraction	Photoelectric effect: threshold frequency and Kmax = hf − φ
Polarisation	Black body spectrum, E = hf
Refraction with a speed change	Fails: interference, diffraction and polarisation
Electromagnetic waves, c = 1 / √(μ0 ε0)	Each photon carries E = hf
Fails: photoelectric threshold and the instant emission of electrons	

Assess means: what each explains, what each cannot, and that both are needed

Figure 5 · What each model explains. A question asking you to assess the models is asking for this table in sentences.

5. Light and special relativity

The Michelson Morley experiment set out to detect the Earth's motion through the aether by comparing the speed of light along two perpendicular arms. It found no difference, and repeated attempts at higher precision found none either. The result is a famous null result: the experiment worked, and what it showed was that the effect being looked for was not there.

The two postulates

One. The laws of physics are the same in all inertial frames of reference. No experiment inside a frame can tell you whether that frame is moving.

Two. The speed of light in a vacuum is the same for every observer, regardless of the motion of the source or of the observer.

Everything else in special relativity follows from those two statements. They are not derived from anything; they are the starting point.

5.1 Time dilation

Proper time, written t_0, is the time between two events measured in the frame where they happen at the same place. Any observer moving relative to that frame measures a longer interval. Naming the frame is not a formality: half the marks in a relativity question are for saying which time is which.

Worked example · 7

A particle with a proper lifetime of 2.20 microseconds travels at 0.980c. Find its lifetime in the laboratory frame and the distance it covers.

Lorentz factor: $\gamma = 1 / \sqrt{(1 - 0.980^2)} = 1 / \sqrt{0.0396} = 5.025$

Laboratory lifetime: $t = \gamma t_0 = 5.025 \times 2.20 = 11.06$ microseconds

Distance: $d = vt = 0.980 \times 3.00 \times 10^8 \times 11.06 \times 10^{-6} = 3.25 \times 10^3$ m

Without time dilation it would cover only $0.980 \times 3.00 \times 10^8 \times 2.20 \times 10^{-6} = 647$ m

ANSWER $t = 11.1$ microseconds and $d = 3.25 \times 10^3$ m, five times further than classical physics allows

5.2 Length contraction

Proper length, L_0, is the length measured in the frame where the object is at rest. An observer moving relative to it measures a shorter length, contracted only along the direction of motion.

Worked example · 8

A structure of proper length 120 m moves past an observer at 0.800c. Find the length that observer measures.

Lorentz factor: $\gamma = 1 / \sqrt{(1 - 0.800^2)} = 1 / \sqrt{0.36} = 1.67$

Contracted length: $L = L_0 / \gamma = 120 / 1.667$

ANSWER $L = 72.0$ m, measured along the direction of motion only

The part that is not optional

Neither observer is wrong, and neither is privileged. Each measures the other's clock running slow and the other's lengths contracted, and both are correct within their own frame.

The effects are reciprocal because the postulates make no frame special. A response that says one observer really is moving has missed the first postulate.

5.3 Relativistic momentum and mass energy

Momentum is $p = \gamma mv$, which grows without limit as v approaches c. That is why no massive object can reach the speed of light: the momentum and the energy required both become infinite.

Mass energy equivalence

$E = mc^2$. Mass and energy are two measures of one quantity, related by a very large constant.

One gram of any substance is equivalent to $1.0 \times 10^{-3} \times (3.00 \times 10^8)^2 = 9.0 \times 10^{13}$ J. This is not a statement that mass can be converted into energy by any process you like. It says that a system holding more energy has more mass, and that nuclear processes release enough energy for the mass change to be measurable.

> Name the frame. Half the marks in a relativity question are for saying who is measuring what.

6. Practice under time

6.1 The twelve-minute drill

Twelve minutes, weekly. This module rewards explanation, so at least three of these are to be answered out loud rather than written.

STEP	MINUTES	WHAT YOU DO
1	2	List four properties of a star you can read from its spectrum, and how each one is read.
2	2	State three results the wave model explains and three it cannot.
3	2	Explain out loud why intensity does not change the maximum kinetic energy.
4	2	Calculate the threshold wavelength for a work function of 2.30 eV.
5	2	State both postulates of special relativity from memory.
6	2	Explain the Michelson Morley result in thirty seconds, out loud.

> If step 3 takes more than one attempt, that is the drill you need most, and it is worth marks in every paper.

6.2 Fill this in from memory, then check it

This table is the module. If you can complete it cold, the explanation questions will look easy.

RESULT	WHICH MODEL EXPLAINS IT	WHY THE OTHER CANNOT
Two slit fringes		
Polarisation		
Threshold frequency		
Instant emission at low intensity		
Black body curve		
Diffraction		
Line spectra		

Your module 7 progress, dated

Come back every few weeks and date it.

Improvement is invisible from the inside, which is why students who are getting better so often believe they are not.

DATE	WHAT I SAT	MARK AND THE ONE THING TO FIX

DATE	WHAT I SAT	MARK AND THE ONE THING TO FIX

Fill one row every time you sit a set. A tracker with three rows in it is worth more than a perfect one you never started, because the pattern you are looking for only shows up across attempts, not inside one.

About this resource

MA99 EDUCATION

Scope

NSW Physics, Year 12. Written to the NSW Physics Stage 6 Syllabus (2017), Module 7, for students sitting the HSC in 2027. A new Physics syllabus is first examined in HSC 2028. Many worked contexts use the Wyndarra site and its instruments, an invented facility, and every number was recomputed from its inputs before printing.

Permitted use

Print it, annotate it and keep it on any device you own, for your own study.

Not permitted

Sharing, posting, selling or redistributing it, in whole or in part. Each copy is licensed to one student.

Copyright MA99 Education.
ma99education.com.au