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HSC LIVE

Physics

Module 7 & 8

TRIAL PREPARATION LECTURES

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Physics - Modules 7 and 8

For each question, there is space for you to take notes on relevant points related to each question.

Question 1

James Maxwell presented a paper outlining the nature of light.

a) Describe the four pieces of evidence that Maxwell used in his work.

b) How did he use these to unify electricity and magnetism?

c) How was he able to predict the velocity of light?

d) What was important about Maxwell's theory of light in relation to other forms of electromagnetic waves?

Question 2

a) Describe two historical methods used to determine the speed of light.

b) Describe two contemporary methods used to determine the speed of light.

c) How is the speed of light currently defined?

Question 3

The $hydrogen_{beta}$ line in the spectrum of hydrogen occurs at a wavelength of 4.86×10^{-7} m. The light from a star in our galaxy was analysed and that particular line actually appeared at 4.83×10^{-7} m.

a) Provide a reason why the $hydrogen_{beta}$ line in the star's spectrum is not where it should be.

b) Assuming Earth is stationary; determine the speed of the other star relative to Earth.

How can the light from a star give us information about its: -

c) Rotational velocity

d) Composition

e) Density

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Question 4

Isaac Newton was able to provide a theory for the propagation of light.

a) Outline the main feature of Newton's model.

b) Explain how this model could explain
   i) Rectilinear propagation
   ii) Reflection
   iii) Refraction

c) Explain how Newton's model was discredited.

Christiann Huygens was able to provide a theory for the propagation of light.

a) Outline the main feature of Huygens' model.

b) Explain how this model could explain
   i) Rectilinear propagation
   ii) Reflection
   iii) Refraction

c) Describe the experimental evidence that provided proof for Huygens' model.

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Question 5

Slits 0.100 mm apart are illuminated by light of wavelength 540 nm. An interference pattern is produced on a screen 130 cm away.

a) What is the distance between the bright fringes?

b) What is the angle made between the central bright fringe, the double slits and the 5th bright fringe to the right of the central maximum?

c) A diffraction grating with 800 lines per millimetre is illuminated by light of 633 nm. How many maxima will be visible on a screen? Explain your answer.

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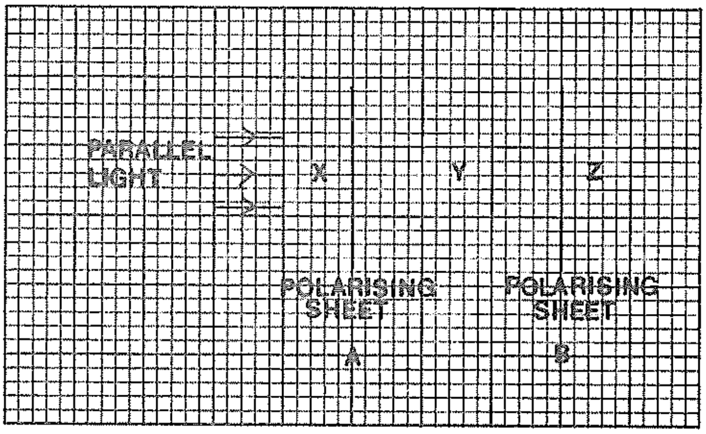
Question 6

Consider the following arrangement used in an experiment to investigate polarized light.



A parallel beam of light passes through two polarizing sheets, A and B. The intensity of the light at positions X, Y and Z is measured.
The light at X is unpolarized and has an intensity of I_o.

The light at Y is polarized and has an intensity $\frac{1}{2}I_o$.

The light at Z is polarized and has an intensity $\frac{1}{8}I_o$.

(i) On the basis of the wave model of light, explain the terms *unpolarized* and *polarized.*

(ii) Explain why the intensity of the light at position Y is less than that at position X.

(iii) What is the angle between the polarizing directions of sheets A and B? Show your working.

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Question 7

Applying the law of conservation of energy, explain why $E_k = hf - \Phi$

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Question 8

Explain how the analysis of quantitative observations contributed to the development of the concept that certain matter and energy are quantised.

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Question 9

A student states that “The maximum kinetic energy that a proton can have is 4.7×10^8 eV because it can’t travel faster than the speed of light.”

SLAC (Stanford Linear Accelerator Centre) literature states “particle accelerators can produce protons with kinetic energies greater than 3×10^{10} eV”.

Making use of appropriate calculations, analyse and assess these two statements.

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Question 10

Provide a timeline that describes transformations of energy into matter during the first million years after the big bang.

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Question 11

a) What is the Hertzsprung-Russell diagram?

b) What are the different ways in which the axes of the HR diagram can be labelled?

c) Draw a HR diagram that shows a typical set of stars in differing stages of evolution. On your diagram, label the following groups of stars: - Main Sequence, red giants, red supergiants, white dwarfs.

d) Explain the positioning of each of the groups above on the HR diagram.

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“Top Ten” Physics Experiments

Cathode Ray tubes

Balmer – Hydrogen Spectrum

Thomson – Electrons

Millikan – Charge on Electron

Rutherford – Nucleus

Bohr – Electron shells

De Broglie – Electrons as waves

Schrödinger – Shapes of orbitals (and cat!)

Chadwick - Neutrons

Question 12

An experiment was conducted to model Millikan's oil-drop experiment. In the experiment, different numbers of dominoes were placed inside seven identical boxes. The boxes were then sealed and weighed. The table below shows the mass of each sealed box and some preliminary analysis.

Box number	*Mass of box (including dominoes)* (g)	*Difference in mass between this box and the next box* (g)
1	15.45	17.2
2	32.65	25.8
3	58.45	4.3
4	62.75	8.6
5	71.35	12.9
6	84.25	43
7	127.25	

Analyse this experiment to assess its effectiveness in modelling Millikan's oil-drop experiment.

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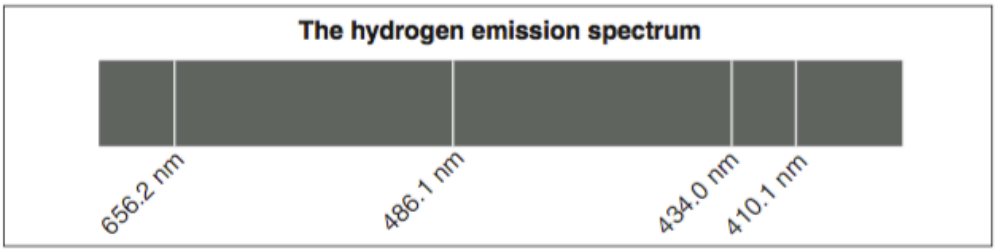
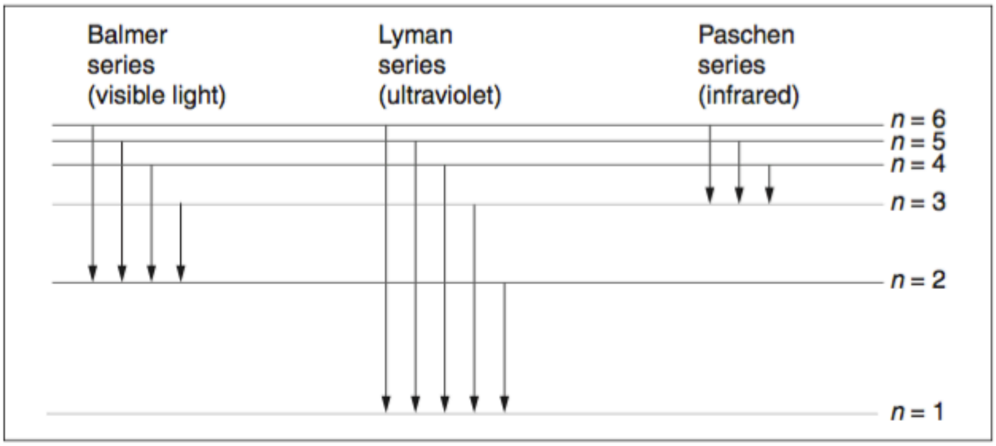
Question 13

The diagrams show features of the hydrogen emission spectrum.





With reference to Bohr's postulates, explain how the line at 434.0 nm in the hydrogen emission spectrum is produced. Support your answer with calculations.

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Question 14

The following is a nuclear reaction that produces a neutron.

$$^{4}_{2}\alpha + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

The table shows the masses of the particles in the reaction.

Particle	*Mass (u)*
$^{4}_{2}\alpha$	4.0012
$^{9}_{4}Be$	9.0122
$^{12}_{6}C$	12.0000
$^{1}_{0}n$	1.0087

Using the data from the table, calculate the energy released in this reaction. State your answer in joules.

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Question 15

Using the standard model, analyse the roles of both forces and particles in the current understanding of the atom.

Sample Answers

Question 1

a) *Gauss's Law of electricity* The amount of electric flux through a Gaussian surface depends on the charge inside the Gaussian surface.

Gauss's Law of magnetism The net magnetic flux through a Gaussian surface is zero.

Faraday's Law of induction Showed the relationship between a changing magnetic field and the production of electric fields.

Ampere's Circuital Law The magnetic field around a conductor is related to the magnitude of the current flowing in the conductor.

b) Maxwell developed four equations based on the work of the physicists above that mathematically described their work. In his work he was able to show that the speed of light depended on the permittivity of free space and the permeability of free space (constants that are associated with electric and magnetic fields.

c) $$c^2 = \frac{1}{\upsilon_o \varepsilon_o} \quad \therefore c = \sqrt{\frac{1}{\upsilon_o \varepsilon_o}} = \sqrt{\frac{1}{4\pi \times 10^{-7} \times 8.854 \times 10^{-12}}} = 2.998 \times 10^{8} \text{ m s}^{-1}$$

d) Maxwell's equations did not limit the frequencies of the radiation to just those of the visible light spectrum. This implied that theoretically, EMW could exist beyond the frequencies of visible light, leading the way to subsequent discoveries of other types of EMW.

Question 2

a) Many to choose from - make sure that your answer has as much detail as you can put in. Below are some brief (not full) descriptions of some of the methods used. You should know at least two of them in significant detail, including reasons why they may not have been an accurate method and approximate value for speed of light obtained.

Galileo 1638 - uncovering lights to measure time interval for light to travel to a distant observer and back.

Romer - observations of Jupiter's moon Io moving into and out of eclipse. Time difference due to light crossing Earth's orbit meant observation of eclipses happening at different to predicted time allowed speed of light to be estimated.

Fizeau 1849 - toothed cog rotating rapidly, blocking path of light.

Focault 1862 - rotating mirror (also allowed speed of light in other substances to be measured).

b) Need to be able to give a detailed description of: -

Resonant Cavity method (knowing exact frequency of waves that set up a standing wave pattern in a box of very accurately measured length) - distance between nodes can be measured, hence wavelength known. Allows speed of light to be determined.

Interferometry Splitting a beam of known frequency into two perpendicular paths, then adjusting path lengths to determine path difference using interference of recombined beams allows wavelength to be accurately measured, allowing speed of light to be calculated.

c) The speed of light is defined in terms of the metre. A metre is defined to be the distance that light travels in $\frac{1}{299792458}$ s.

Hence, the speed of light is defined as $c = \frac{s}{t} = \frac{1\text{ m}}{\frac{1}{299792458}\text{ s}} = 299792458\text{ m s}^{-1}$

NESA rounds this to 3.00×10^8 m s^{-1} (3 sig figs) on the data sheet.

Question 3

a) The H_β line is appearing at a shorter wavelength (higher frequency) than it ordinarily would. This means that it has been blue-shifted (toward the blue end of the spectrum) and is most likely caused by the star moving toward Earth.

b) $v = f\lambda \quad \therefore f = \frac{v}{\lambda} = \frac{3.00 \times 10^8\text{ m s}^{-1}}{4.86 \times 10^{-7}\text{ m}} = 6.17 \times 10^{14}\text{ Hz}$

$f' = \frac{v}{\lambda} = \frac{3.00 \times 10^8\text{ m s}^{-1}}{4.83 \times 10^{-7}\text{ m}} = 6.21 \times 10^{14}\text{ Hz} \qquad f' = f\left(\frac{v_{wave} + v_{observer}}{v_{wave} - v_{source}}\right)$

$\therefore 6.21 \times 10^{14} = 6.17 \times 10^{14}\left(\frac{c + 0}{c - v_{source}}\right) \qquad \therefore \frac{6.21}{6.17} = \frac{c}{c - v}$

$\therefore v = c - \frac{6.17}{6.21}c = 1.93 \times 10^6\text{ m s}^{-1}$ toward Earth

c) As a star rotates, light being emitted from the edges of the star (as viewed from Earth) is either red-shifted (from the receding side) or blue-shifted (from the approaching side). This causes spectral lines in the spectrum to become broader. Analysis of the amount of broadening can provide the rotational speed of the star.

d) As light from the star passes through the atmosphere of the star, elements in the atmosphere absorb at their characteristic wavelengths. Analysis of the absorption spectrum received from the star will indicate the elements present in the atmosphere of the start, and hence the composition of the star. The intensity of absorption will be proportional to the amount of each element present and so the relative abundance of elements in the star can also be determined.

e) Lower density stars allow light to travel further before being absorbed by atoms/ions in the star. Hence, absorption spectral lines of less dense stars tend to be sharper than absorption lines in denser stars.

Question 4

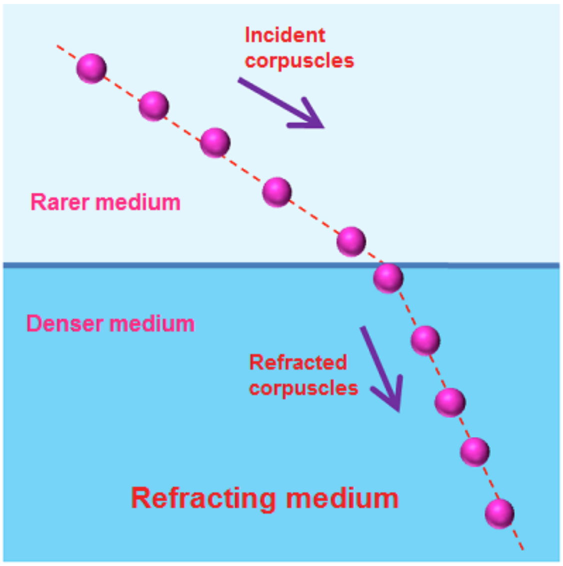
Newton

a) Newton thought that light consisted of small particles, or "corpuscles". These particles had mass and would obey the laws of Physics like billiard balls. However, they are so small that when two beams cross, they do not scatter each other as the chance of collisions is negligible.

b) *Rectilinear propagation* Being particles with mass and obeying laws of physics meant that the particles would continue in a straight line until acted on by a force. Newton saw that sharp shadows were made, confirming the light travelled in straight lines. However, he also realised that in a gravitational field, they should follow parabolic paths. He used this to explain diffraction, where light could bend around corners, by interactions of particles running into each other at the edges of objects.

Reflection The particles underwent elastic, frictionless collisions when they hit a smooth surface and so bounced off with an angle of incidence equal to the angle of reflection.

Refraction When passing from air into a denser substance, the gravitational attraction of the denser substance increased the component of the velocity of the particle toward the surface, and so would bend in a parabolic path as it entered the denser medium.

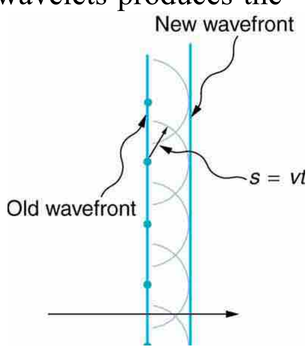


c) Foucault was able to measure the speed of light in water and was able to show that it was actually lower than for the speed of light in air. Hence, Newton was incorrect in saying that the speed of light was greater in denser media.

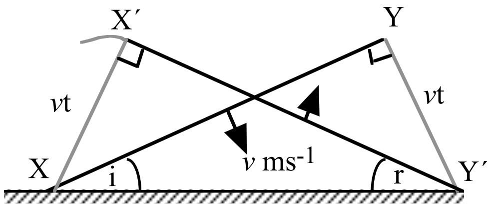
Huygens

a) Huygens proposed that every point on a wavefront acted as a source of secondary semicircular wavelets that propagate at the speed of the wave from that point, in the direction of wave travel. The envelope (common tangent) to the wavelets produces the next wavefront.

b) *Rectilinear Propagation* Each point produces a semi-circular wavefront. The envelope of these will be vt from the old wavefront. Since the new wavefront is always vt from the old wavefront, it is parallel to the old wavefront. The only way that this can happen is if the wave is travelling in a straight line (i.e. rectilinear propagation is occurring).



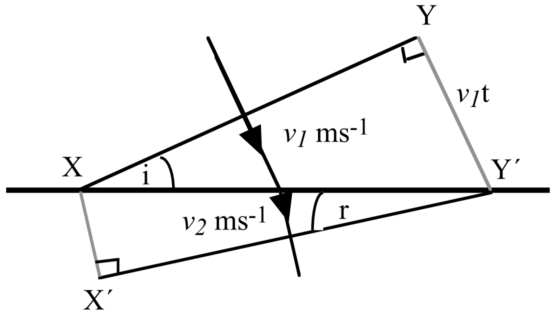
Reflection Consider the wavefront XY as it approaches a boundary. The wave is travelling at v m s^{-1}.



It takes t seconds for the wavelet produced at Y to travel to Y′, a distance of vt. At the same time, the wavelet produced at X has travelled a distance vt to X′. The envelope from Y′ is a tangent to the wavelet at X′. The triangles XYY′ and XX′Y′ are similar. (right angle, common side XY′, another side length vt.) Hence, angle i = angle r (law of reflection).

Refraction Consider a wave striking a boundary between two media at an angle i.

$V_1 > V_2$.



In the time it takes the wavelet produced at Y to travel v_1t to Y′, the wavelet produced at X travels v_2t to X′.

This causes a change in direction of the wave as it passes from medium 1 into medium 2.

$$\sin i = \frac{v_1 t}{XY'} \quad \text{and} \quad \sin r = \frac{v_2 t}{XY'}$$

$$\frac{\sin i}{\sin r} = \frac{\frac{v_1 t}{XY'}}{\frac{v_2 t}{XY'}} \qquad \therefore \frac{\sin i}{\sin r} = \frac{v_1}{v_2} \quad \text{(Snell's Law)}$$

c) Experimental evidence that proved that light existed as waves involved interference effects, such as Fresnel showing Poisson's spot or the double slit interference experiments conducted by Young.

Question 5

a) $d = 1.00 \times 10^{-4}$ m, $L = 1.30$ m, $\lambda = 540 \times 10^{-9}$ m, $X = ?$

$$m\lambda = d\frac{X}{L} \quad \therefore X = \frac{m\lambda L}{d} = \frac{1 \times 540 \times 10^{-9}\text{ m} \times 1.30\text{ m}}{1.00 \times 10^{-4}\text{ m}} = 7.02 \times 10^{-3}\text{ m} \quad (7.02\text{ mm})$$

b) $m\lambda = d\sin\theta \quad \therefore \sin\theta = \frac{m\lambda}{d} = \frac{5 \times 540 \times 10^{-9}\ \text{m}}{1.00 \times 10^{-4}\ \text{m}} = 0.0270 \quad \therefore \theta = 1.55°$

c) Maxima that are diffracted by more than 90° will not be visible. Hence, will find what order maximum will produce diffraction of 90°.

$$m\lambda = d\sin\theta \quad \therefore m = \frac{d\sin\theta}{\lambda} = \frac{\frac{1.00 \times 10^{-3}\ \text{m}}{800} \times \sin 90°}{633 \times 10^{-9}\ \text{m}} = 1.97$$

Hence, only the central maximum (m = 0) and the first order maxima (m = ±1) will be visible. Just missed on seeing the second order maxima. A total of 3 maxima are visible.

Question 6

(i) Unpolarised light has the electric fields of the light vibrating in all possible planes.

Polarised light means that the all the electric fields of the light are vibrating in the same plane.

(ii) When the unpolarised light passes through the polarising sheet only the component of the electric fields that are parallel to the characteristic direction of the sheet will be transmitted, while the component perpendicular to the characteristic direction will not be transmitted. Hence, the intensity at Y will be half the intensity at X.

(iii) $I = I_o \cos^2\theta \qquad \text{(Malus' Law)}$

Now $I_Y = \tfrac{1}{2} I_o$, and $I_Z = \tfrac{1}{8} I_o$

$\tfrac{1}{8} I_o = \tfrac{1}{2} I_o \cos^2\theta$

$\cos^2\theta = \tfrac{1}{4} \quad \text{so } \theta = 60°$

I.e. the angle between sheets A and B is 60°

Question 7

The law of conservation of energy states that energy cannot be created or destroyed. It is transferred or transformed. The initial energy of a photon of light is hf. If this photon hits a metal surface, the energy is passed onto an electron, which can be released from the metal surface. For the electron to be released, it will possess kinetic energy (E_k) and some energy to remove the electron from the metal surface (the work function of Φ). Therefore, $hf = E_k + \Phi$ which is $E_k = hf - \Phi$.

Question 8

Experiments such as the ones testing the photoelectric effect and Millikan's measurement of the fundamental unit of charge have demonstrated that certain quantities measured in physics are quantised. That is, they only appear as exact multiples of some fundamental value, or quantum.

Millikan found that the value of the charge on an oil drop was an integer multiple of 1.6×10^{-19} C, and so he concluded that this was the charge on a single electron. In this situation, quantisation was expected since the electron had been determined to be a particle. However, this result provided critical experimental evidence. This, combined with the Thomson experiment, which determined the charge to mass ratio, allowed for the mass of an electron to be determined. Thus the quantum of mass of an electron was shown through quantitative observations.

The discovery of quantisation of light, and hence energy in the form of electromagnetic radiation, as shown in the photoelectric effect experiments, was much more surprising. The understanding that light was a wave was well supported by experimental evidence, and so it was not expected that the energy would be divided into discrete packets. However, when experiments showed that there was a minimum frequency of light that would produce a photocurrent and that the amount or intensity of light did not affect the ability of electrons to be removed from a metal surface, it was explained by one electron receiving one photon or quantum of energy specific to the frequency of that light ($E = hf$). If a photon did not have enough energy, an electron could not be removed. This could only be adequately explained by a quantum model. In this case, experimental evidence generated a change in physicists' concept of energy, requiring a broader understanding of quantisation in physical processes.

Answers could include:

- spectroscopy and the existence of fixed energy levels in the atom
- cathode ray experiments showing the particle nature of the electron
- radioactivity experiments
- scintillation experiments
- blackbody radiation experiments.

Question 9

The student is not considering the relativistic increase in mass of the proton caused by it being accelerated to nearly the speed of light. Without mass dilation, the kinetic energy of a proton travelling at the speed of light would be:

$$KE = \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 1.673 \times 10^{-27}\,\text{kg} \times (3.00 \times 10^{8}\,\text{ms}^{-1})^2 = 7.54 \times 10^{-11}\,\text{J} = 4.7 \times 10^{8}\,\text{eV},$$

which agrees with the student's statement.

However, with mass dilation considered, it would be possible to exceed this kinetic energy. For example, a proton travelling at 99% of the speed of light would have a mass of

$$m_v = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1.673 \times 10^{-27}\,\text{kg}}{\sqrt{1-0.99^2}} = 1.186 \times 10^{-26}\,\text{kg}$$

and a kinetic energy of

$$KE = \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 1.186 \times 10^{-26}\,\text{kg} \times (0.99 \times 3.00 \times 10^{8}\,\text{ms}^{-1})^2 = 5.23 \times 10^{-10}\,\text{J} = 3.27 \times 10^{9}\,\text{eV}.$$

Hence, the protons at SLAC must have been travelling even faster than 99%c. The SLAC literature is quite correct, taking into consideration mass dilation, which the student did not consider, but should have!.

Question 10

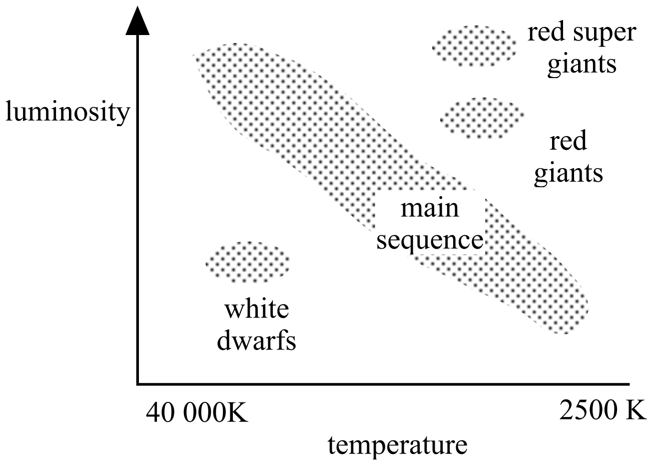
Age of Universe	Temperature (K)	What's Happening?
0	?	• ?
10^{-43} s	10^{32}	• Beginning of space and time • Universe smaller than a proton • Energy only present
10^{-34} s	10^{27}	• Universe size of pea (Huge inflation in size) • Much of the energy had been converted to fundamental particles such as quarks and electrons ($E=mc^2$)
10^{-15} s	10^{15}	• Four fundamental forces of the universe (gravitational, electromagnetic, SNF, WNF) become decoupled from the Grand Unified Theory (GUT) force. • Matter in universe composed of quark gas or plasma.
10^{-6} s	10^{13}	• Temperature low enough for quarks and antiquarks to combine to form protons and antiprotons. • Slightly highly proportion of protons over antiprotons creates a universe with matter instead of antimatter. Matter/antimatter annihilation releases much energy into expanding universe. (1 000 000 001 protons to 1 000 000 000 antiprotons)
10^{-4} s		• neutrons formed by beta(+) decay of protons • Universe consists of protons, neutrons, electrons, neutrinos and a lot of energy, that can't travel very far without hitting matter.
10^{-2} s		• Universe now size of solar system
1 s	10^{10}	• Universe 1 - 10 light years across (expands faster than the speed of light during the "superinflationary stage" • Density 10 kg cm^{-3} • 82% protons. 18%neutrons (ratio slowly increased as universe ages)
3 s	5.9×10^9	• electron - positron annihilation occurs, leaving slight excess of electrons
3.2 min	3×10^9	• Fusion between protons and neutrons begins, forming nuclei of deuterium, tritium, helium and lithium
13 min		• Fusion stops • Universe is dark, as matter density is too high for radiation to travel far. and no stars exist yet
380 000 years	3000 K	• electrons captured by atoms, allowing radiation to pass through, universe becomes transparent.

Question 11

a) The HR diagram is a graph of a star's luminosity (on the vertical axis) against its temperature (or colour, or spectral type) on the horizontal axis.

b) The axes are not linear. The vertical axis has equal spacings corresponding by an increase in luminosity of a factor of 10. The horizontal axis starts at the right hand side, at about 2500 K, and extends to the left, at about 40 000K. Each equal spacing on the horizontal axes represents an approximate doubling of temperature.

c)



d) For main sequence stars, the more massive the star, the more energy it produces, and so the hotter it is, and so the more luminous. Hence, for the main sequence, small, cool stars are at the lower right, while large, hot stars are at the upper left.

However, a group of stars was discovered that were red in colour, indicating a relatively low surface temperature. However, these stars were very luminous, indicating they were giving out a lot of energy. The only way this could happen was if the stars were very big. These are the red giants and supergiants.

Another group of stars were white, indicating high surface temperatures, but they were not very luminous. Hence, they must be quite small. These are called white dwarfs.

Question 12

In this experiment, the smallest difference between two boxes is 4.3 g (between box 3 and box 4) and all other differences are multiples of 4.3. These characteristics indicate the quantised nature of the results and that the experiment was done accurately. While it cannot be certain that the smallest difference is the mass of one domino, further tests could improve the probability that this is true. If we assume that the difference is due to one domino, then the mass of a single domino would be 4.3 g, the fundamental quantity of the mass of a domino.

This method of analysis is similar to that used in Millikan's oil-drop experiment, in which he sought to determine the charge of an electron. He tested many charged oil drops and found that the value of the charge on an oil drop was always an integer multiple of a certain base value: 1.6×10^{-19} C. Thus, the domino experiment is very effective in demonstrating the analysis of Millikan's oil-drop experiment even though the method and components are completely different. It allows us to think about the assumptions and the problems Millikan must have had, such as whether only one electron was being measured.

Question 13

Bohr's postulates state that an electron orbits in fixed energy levels. Only when an electron jumps from a higher energy level to a lower energy level, it emits an exact amount of energy in the form of a photon. The specific wavelength of the photon can be determined according to the Rydberg equation. The blue light is part of the visible Balmer series and therefore $n_f = 2$.

The wavelength in this case is 434.0 nm. According to the equation, this corresponds to a jump from the 5th energy level to the 2nd energy level.

For Balmer series $n_f = 2$

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n_i^{\,2}}\right)$$

$$n_i^{\,2} = \frac{1}{\left(\frac{1}{4} - \frac{1}{1.097\times10^7 \times 434\times10^9}\right)}$$

$$n_i = 5$$

Answers could include:

Taking clues from the diagram of the Balmer series, student could put $n_f = 2$ and $n_f = 5$ into the equation to obtain $\lambda = 434.0$ nm.

Question 14

Initial mass $= 4.0012 + 9.0122 = 13.0134u$

Final mass $= 12.000 + 1.0087 = 13.0087u$

Mass difference $= 13.0087 - 13.0134 = -0.0047u$

Mass in kg $= 0.0047 \times 1.661 \times 10^{-27} = 7.8067 \times 10^{-30}$ kg

$$E = mc^2 = 7.8067\times10^{-30} \times \left(3.00\times10^8\right)^2 = 7.0 \times 10^{-13} \text{ J}$$

Question 15

In the standard model, fundamental particles – quarks and leptons – interact through four fundamental forces. The constituents of protons and neutrons are three quarks. The strong force holds nucleons together in the nucleus, overcoming the electrostatic repulsion between protons. An electron is a lepton, which has no constituents. The force of gravity attracts protons and neutrons within the nucleus but this force is negligible.

The electrostatic force results in a mutual repulsion of protons and an attraction for the electrons toward the nucleus. Electrons orbit the nucleus. The strong nuclear force counteracts the electrostatic force, but only within a limited range of subatomic distances. The weak force is involved in the process of radioactive decay.