Mastering Physics

MODULE 8

NSW

From the Universe To the Atom

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Words to Watch

account, account for State reasons for, report on, give an account of, narrate a series of events or transactions.

analyse Interpret data to reach conclusions.

annotate Add brief notes to a diagram or graph.

apply Put to use in a particular situation.

assess Make a judgement about the value of something.

calculate Find a numerical answer.

clarify Make clear or plain.

classify Arrange into classes, groups or categories.

comment Give a judgement based on a given statement or result of a calculation.

compare Estimate, measure or note how things are similar or different.

construct Represent or develop in graphical form.

contrast Show how things are different or opposite.

create Originate or bring into existence.

deduce Reach a conclusion from given information.

define Give the precise meaning of a word, phrase or physical quantity.

demonstrate Show by example.

derive Manipulate a mathematical relationship(s) to give a new equation or relationship.

describe Give a detailed account.

design Produce a plan, simulation or model.

determine Find the only possible answer.

discuss Talk or write about a topic, taking into account different issues or ideas.

distinguish Give differences between two or more different items.

draw Represent by means of pencil lines.

estimate Find an approximate value for an unknown quantity.

evaluate Assess the implications and limitations.

examine Inquire into.

explain Make something clear or easy to understand.

extract Choose relevant and/or appropriate details.

extrapolate Infer from what is known.

hypothesise Suggest an explanation for a group of facts or phenomena.

identify Recognise and name.

interpret Draw meaning from.

investigate Plan, inquire into and draw conclusions about.

justify Support an argument or conclusion.

label Add labels to a diagram.

list Give a sequence of names or other brief answers.

measure Find a value for a quantity.

outline Give a brief account or summary.

plan Use strategies to develop a series of steps or processes.

predict Give an expected result.

propose Put forward a plan or suggestion for consideration or action.

recall Present remembered ideas, facts or experiences.

relate Tell or report about happenings, events or circumstances.

represent Use words, images or symbols to convey meaning.

select Choose in preference to another or others.

sequence Arrange in order.

show Give the steps in a calculation or derivation.

sketch Make a quick, rough drawing of something.

solve Work out the answer to a problem.

state Give a specific name, value or other brief answer.

suggest Put forward an idea for consideration.

summarise Give a brief statement of the main points.

synthesise Combine various elements to make a whole.

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Origins Of the Elements

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8.1 The Big Bang Theory

Investigate the processes that led to the transformation of radiation into matter that followed the Big Bang.

The Big Bang theory

- **The Big Bang theory** was first proposed by Father Georges Lemaître, a Roman Catholic priest in 1927.
- The Big Bang theory proposes that the Universe began with an 'event' that produced an enormous amount of energy.
- The Big Bang event occurred about 14 billion years ago.
- The Big Bang event occurred in a position called a single position, and is also known as the singularity.
- The energy produced expanded outwards in all directions and cooled to form matter.
- The Big Bang event also signifies the beginning of time.
- *Note:* It is technically incorrect to talk about a Big Bang **explosion** because an explosion requires the existence of matter to explode – there was no matter in existence at time zero.

Father Georges Lemaître

The basic ideas in the development of the Universe from the Big Bang

- The Universe was initially compressed into zero volume and has been expanding since the 'Big Bang'.
- The Big Bang produced an enormous amount of energy.
- The temperature of the Big Bang is estimated at 10^{32} K.
- Matter as we know it cannot exist at this temperature. Only pure energy existed.
- The Universe started at intense heat and is cooling.
- As the Universe cooled, the energy started changing into matter.
- The first matter to form were the fundamental particles – leptons, neutrinos and quarks, and zero mass particles gluons and photons at time 10^{-43} s after the Big Bang.
- The energy condensed to simple particles first, then to more complex particles as its temperature fell.
- The first more complex particles were protons and neutrons at time 10^{-35} s after the Big Bang.
- As matter particles formed, the gravitational force came into existence.
- Gravity collected the newly forming particles together to form larger particles.
- These larger particles gravitated together (accreted) to form gas clouds (nebulae).
- The matter in nebulae accreted to eventually form stars.
- Millions of stars forming with large gas clouds created galaxies.

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Sample Questions

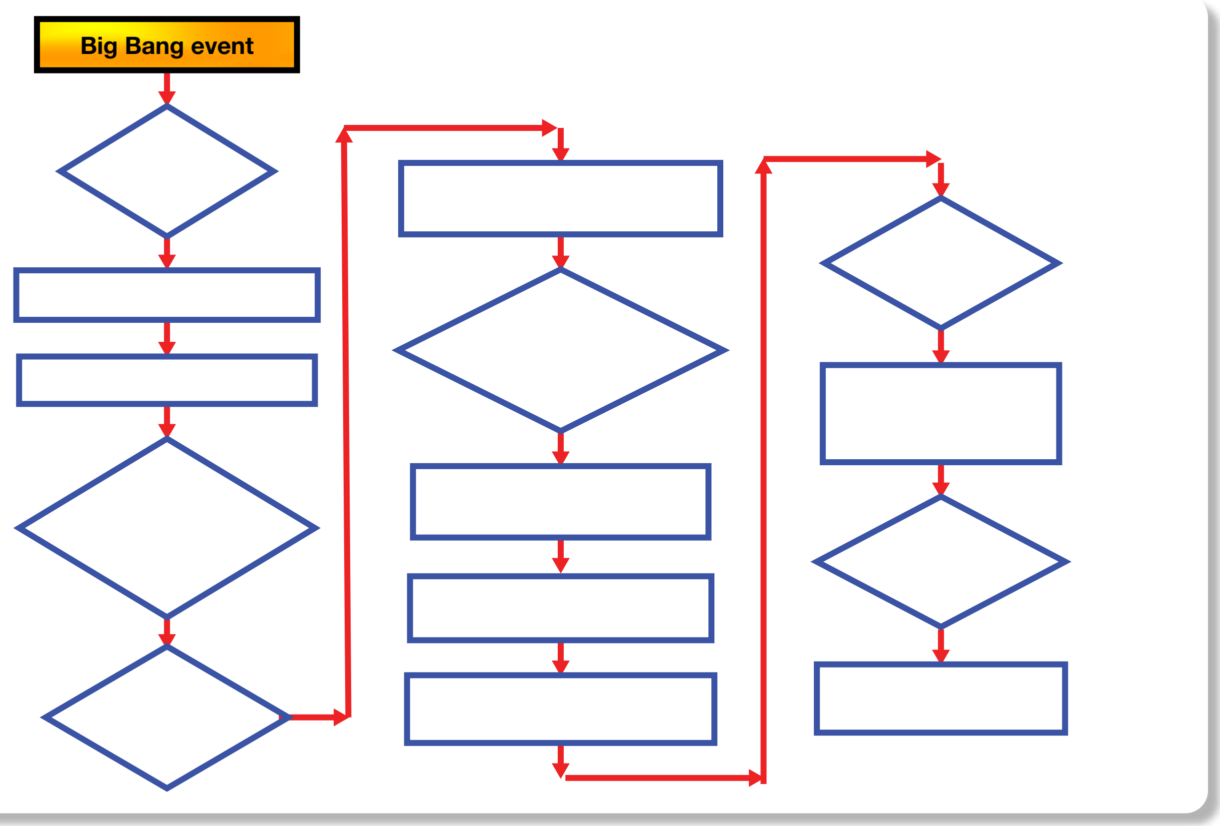
1. State the main ideas in the Big Bang theory.

2. Match the sentence halves below to get a brief summary of the evolution of the Universe.

(a)	The Big Bang produced	A	estimated to have been about 10^{32} K.
(b)	The Universe started at intense heat	B	energy started changing into matter.
(c)	The Universe was initially compressed into	C	temperature. Only pure energy existed.
(d)	The temperature of the Big Bang is	D	and has been cooling ever since.
(e)	Matter as we know it cannot exist at this	E	forces slowly formed gas clouds.
(f)	As the Universe cooled, the	F	more complex particles as it expanded and its temperature fell.
(g)	The Universe started as energy, condensing to simple particles first, then to	G	an enormous amount of energy.
(h)	Accretion of newly formed matter particles by gravitational	H	of stars and eventually galaxies.
(i)	Further accretion of matter within gas clouds saw the beginning	I	zero volume and has been expanding since the 'Big Bang'.

3. The flow diagram below shows a diagrammatic version of the Big Bang event and what followed it to form our Universe. Complete the diagram by placing in the diamond shapes statements that identify products of processes (blue), and in the rectangles put processes (black). Choose from the following statements.

Statements – random order		
Matter lumps in gas clouds become very dense	Expansion of energy	Stars form
Formation of hydrogen and helium atoms	Lumps form within gas clouds	Galaxies form
Expansion of the Universe continues	Hydrogen fusion commences	Gas clouds form
Gravitational forces attract atoms together	Universe starts cooling	Energy produced
Stars grouped by gravitational forces	Temperature within lumps rises	



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Evidence for the Big Bang theory

The spectrum shift of light from distant galaxies – Doppler effect

- This shows that the Universe is expanding, no matter in what direction we look.
- Galaxies further away from us are moving faster.

The helium-hydrogen ratio

- The Universe is composed of about 25% helium and 75% hydrogen.
- Calculations show that if the Universe began with a big bang, then hydrogen and helium would have formed in those proportions.

Cosmic background radiation

- If the Universe started with a highly energetic event, then the remnants of the energy formed should exist as a 'background radiation' of wavelength about 1 mm throughout all space.
- Two engineers, Arnold Penzias and Robert Wilson working on a new telescope at the Bell Laboratories accidentally discovered the predicted background radiation in 1964.
- In the 1980s and 1990s, following the launch of the **Co**smic **B**ackground **E**xplorer (COBE) satellite, the range of wavelengths of energy in this radiation was examined and mapped.

Not enough hot stars

- All stars (except dwarfs) fuse hydrogen to form helium.
- If the 25% helium in the Universe had been formed in this way, then most stars would be much hotter than they are because of the amount of nuclear fusion of hydrogen required.
- Calculations show that very hot stars have a very short life span and only occur in larger numbers at the edge of the Universe.
- These facts favour a big bang expansion rather than fusion inside stars.

The existence of radio galaxies

- Radio galaxies are so called because they emit radio frequency electromagnetic radiation because of the presence of the hot blue stars.
- These confirm the presence of very hot blue stars at large distances.

The presence of radio galaxies and blue stars in deep space

- If the Universe started with a Big Bang we should be able to see signs of this – light from young stars a long way away.
- Distant galaxies contain many younger, very hot, short lived blue stars.
- Light from these young stars proves their formation billions of years ago (it has taken that long for the light to reach us), thrown outwards at a huge velocity.
- This supports the idea of a Big Bang event.

Connection between particle physics and cosmology

- Particle accelerators are producing conditions and particles that could be similar to those formed shortly after the Big Bang.
- Astronomers are hypothesising the nature of the young Universe from time zero forwards, and particle physicists are working backwards from now.
- They are both arriving at the same conclusions about an initial Big Bang event.

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Sample Questions

1. (a) What is the Doppler effect?
   (b) Explain the term ‘red shift’.
   (c) What two things does the red shift tell us about the Universe?
   (d) How does this provide us with evidence for a Big Bang event?
   (e) When would a blue shift occur?

2. (a) What is the measured ratio of hydrogen to helium in the Universe?
   (b) Why is this ratio evidence for a Big Bang event?
   (c) What percentage of the Universe is calculated to be composed of hydrogen and helium?

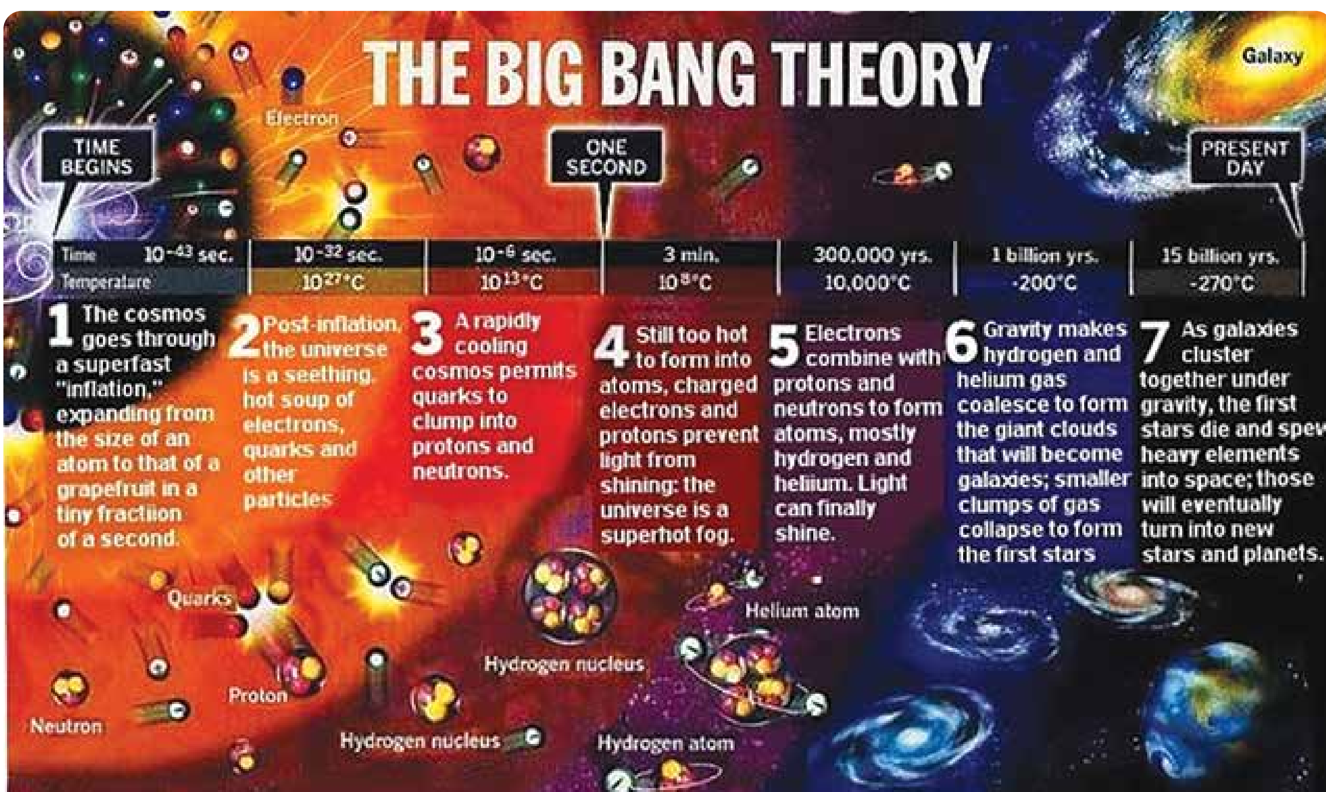
3. (a) Explain how the small number of hot stars in the known Universe provides evidence for a Big Bang event.
   (b) Where are most of these hot stars found?

4. (a) The discovery of radio galaxies at great distances from us provides evidence for a Big Bang event. Explain how.
   (b) Are there really many radio galaxies and hot blue stars at great distances from us? Explain your answer.

5. (a) Explain how the work of particle physicists is, in a way, working in the opposite direction to the events that are proposed to have occurred after the Big Bang.
   (b) How does this provide evidence for a Big Bang?

6. (a) What is the cosmic background Radiation?
   (b) How is this thought to provide evidence for a Big Bang?

7. (a) Explain how distant, very hot blue stars provide evidence for the Big Bang event.
   (b) Are astronomers actually seeing these stars? Explain your answer.



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8.2 Ideas Leading To the Big Bang Theory

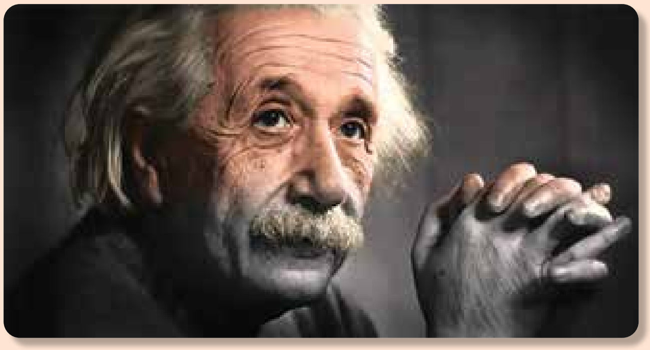
Investigate the evidence that led to the discovery of the expansion of the Universe by Hubble.

Ideas leading to the Big Bang theory

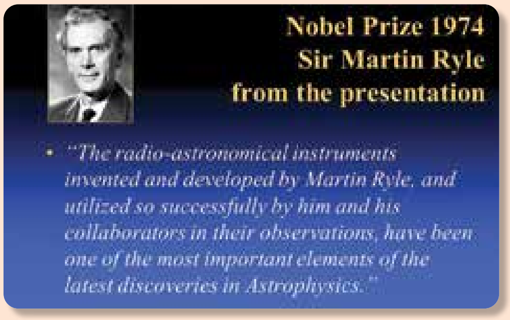
A timeline of thoughts and discovery

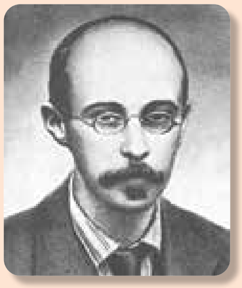
The information below identifies a few of the main scientists involved in the development of theories about the origins of the Universe.

1915 Albert Einstein
1912 Vestro Slipher
1922 Aleksandr Friedmann (1888-1925)
1927 Edwin Hubble
1927 Georges Lemâitre (1894-1966)
1948 George Gamow
1950+ Fred Hoyle
1955+ Martin Ryle
1964 Penzias and Wilson



Albert Einstein (1879-1955)





Aleksandr Friedmann

Slipher's spectroscope

Sample Questions

1. Research the main contribution of each of the scientists mentioned above and present a two page summary of your research data.

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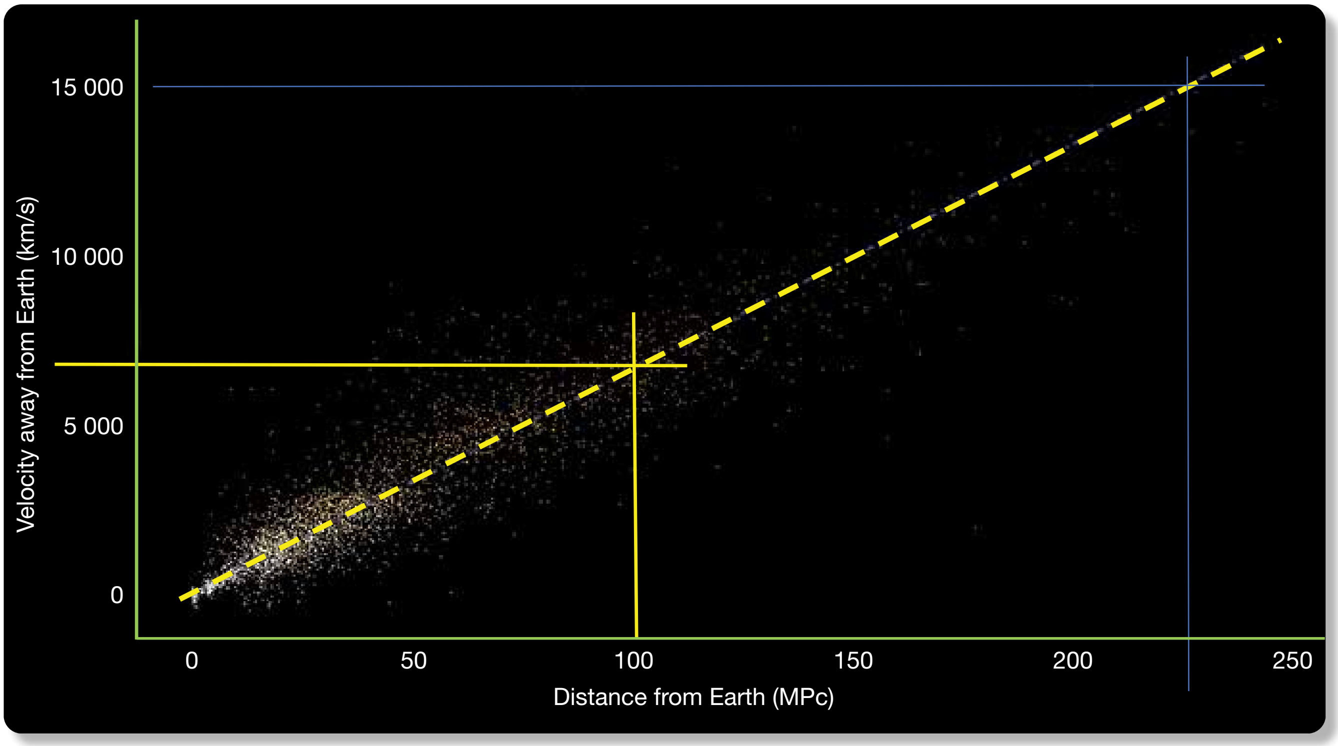
Analysing Hubble data

The graph show information about our Universe as collected by the Hubble telescope.



As shown by Hubble, the further away a galaxy is from us, the faster it is moving. This idea is defined mathematically by the equation known as **Hubble's law**.

$$v = H_o D$$

Where v = velocity of a particular galaxy (km s^{-1})
H_o = Hubble constant (about 67 km s^{-1} Mpc^{-1})
D = the distance the particular galaxy is from us (Mpc)

Sample Questions

1. How does the information in the graph support Hubble's equation?

2. (a) What is a Mpc?
(b) How big is a Mpc?
(c) Why do we use a unit like the Mpc?

3. (a) What is a light year?
(b) How far, in km, is a light year?
(c) How far, in km, is a Mpc?
(d) How far in light years, is a Mpc?

4. (a) Use the graph and the equation to find a value for the Hubble constant based on this data.
(b) Compare your answer with the theoretical value for the Hubble constant.

5. (a) A galaxy is 100 Mpc from us. How far is this in light years?
(b) Approximately how fast is this galaxy receding from us?
(c) How long does it take light from this galaxy to reach us?

6. (a) Use the data in the graph for a galaxy at a distance of 100 Mpc to find the age of the Universe (note – you must change velocity to m s^{-1} and Mpc to metres to do this).
(b) Compare this with the currently accepted value.

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8.3 The Mass-Energy Relationship

Analyse and apply Einstein's description of the equivalence of energy and mass and relate this to the nuclear reactions that occur in stars.

The mass-energy relationship

Equivalence of energy and mass

- Special relativity led to the idea that mass and energy are equivalent.
- The rest energy of the mass (when it is not moving) is, given by: **Rest energy = m_oc^2**
- We observe rest energy only when the mass to energy conversion is made, and this occurs on Earth only when nuclear reactions take place.
- During nuclear reactions some of the mass of the reacting nuclides is converted to pure energy. That is the source of our nuclear energy.
- The energy released results from the conversion of the strong nuclear force (which appears as mass in an intact nucleus), into energy as some of the nucleons are separated from others.

Mass defect

- The **mass converted to energy** is known as the **mass defect** of the reaction.
- In a nuclear reaction it is the difference between the sum of the masses of the reactants and the sum of the masses of the products.

Mass defect (*m*) = sum of masses of reactants – sum of masses of products

- The energy involved in the reaction can be calculated from Einstein's mass/energy equivalence equation:

$$E = mc^2 \text{ (joules)}$$

Where E = energy released (J)
m = mass defect (kg)
c = velocity of light (3×10^8 m s^{-1})

- If the mass defect is calculated in atomic mass units (amu), then the energy released is given in **MeV** (mega electron volts).

$$E = \text{mass defect} \times 931.5 \text{ (MeV)}$$

Where E = energy in MeV
m = mass defect in amu (u)

Note: 1 amu = 1.661×10^{-27} kg
1 MeV = $10^6 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-13}$ J

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Sample *Questions*

1. (a) What is meant by 'rest mass'?
   (b) Why is 'rest mass' needed?
   (c) What is rest energy?

2. A neutron has a mass of 1.66×10^{-27} kg. Calculate its energy equivalence.

3. Imagine an experiment in which various masses were converted to energy and the results graphed. Describe the gradient of the graph.

4. If an object is moving, what is its total energy?

5. Would more or less energy be released from 1 kg of plutonium (mass number 239) than 1 kg of uranium (mass number 238)? Explain your answer.

6. Is it possible for the rest mass of a particle to be zero? Explain.

7. Is it possible for the mass of a particle to be less than its rest mass? Explain.

8. Explain the relationship between the mass/energy equivalence and the energy released during a nuclear reaction.

9. Which choice best describes the 'equivalence between mass and energy'?
   (A) Mass and energy are interchangeable.
   (B) Mass is simply another form of energy.
   (C) Mass and energy can have the same units.
   (D) Mass and energy are equivalent quantities.

10. Einstein derived the equation $E = mc^2$ to show the relationship between mass and energy. What observation do we make in support of this idea?
    (A) The mass of moving particles decreases as their speed increases.
    (B) An object which is stationary has zero energy.
    (C) The mass defect during a nuclear reaction provides the nuclear energy.
    (D) The masses of particles in accelerators increases.

11. An oxygen atom has a mass of 15.999 amu. What is its rest energy?
    (A) 2.39×10^{-9} J
    (B) 2.39×10^{-11} J
    (C) 7.97×10^{-18} J
    (D) 2.66×10^{-26} J

12. The rest energy of a particle is 2.6×10^{-12} joules. What is the mass of the particle?
    (A) 1.5×10^{15} kg
    (B) 8.7×10^{-14} kg
    (C) 8.6×10^{-20} kg
    (D) 2.9×10^{-29} kg

13. What mass needs to be converted into energy to produce 6.3×10^{-16} joules?
    (A) 56.7 kg
    (B) 1.9×10^{-7} kg
    (C) 7.0×10^{-33} kg
    (D) 2.1×10^{-24} kg

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14. How much energy would be released if 1 kg of lead (mass number = 207) was converted into pure energy during a nuclear reaction?
   (A) 3.0×10^8 J
   (B) 9.0×10^{16} J
   (C) 6.2×10^{12} J
   (D) 1.9×10^{19} J

15. What is the rest mass of an object?
   (A) The total mass of the object when its velocity is considered.
   (B) The mass of the object in an inertial frame of reference.
   (C) The increase in mass of an object as its speed increases.
   (D) The mass of an object when it is stationary.

16. Calculate the energy released in the following reaction in joules and MeV. Use data from the table to make your calculation.

$${}^{235}_{92}U + {}^{0}_{1}n \xrightarrow{\text{yields}} {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{0}_{1}n$$

17. Calculate the energy released in the following reaction in joules and MeV. Use data from the table to make your calculation.

$${}^{3}_{1}H + {}^{2}_{1}H \xrightarrow{\text{yields}} {}^{4}_{2}He + {}^{1}_{0}n$$

18. Calculate the energy released in the following reaction in joules and MeV. Use data from the table to make your calculation.

$${}^{238}_{92}U \xrightarrow{\text{yields}} {}^{4}_{2}He + {}^{234}_{90}Th$$

19. (a) Calculate the mass defect for the radioactive decay of tritium, ${}^{3}_{1}H$, to helium, ${}^{3}_{2}He$ and a beta particle, ${}^{0}_{-1}e$.
   (b) Explain this answer (you may need to do some research).
   (c) Calculate the energy (in joules and MeV) involved in the reaction.

Particle	Mass (amu)
${}^{141}_{56}Ba$	140.9144110
${}^{0}_{-1}e$	0.0005488
${}^{2}_{1}H$	2.014102
${}^{3}_{1}H$	3.016048
${}^{3}_{2}He$	3.016029
${}^{4}_{2}He$	4.002603
${}^{92}_{36}Kr$	91.926156
${}^{1}_{0}n$	1.008665
${}^{234}_{90}Th$	234.04360
${}^{235}_{92}U$	235.04393
${}^{238}_{92}U$	238.050788

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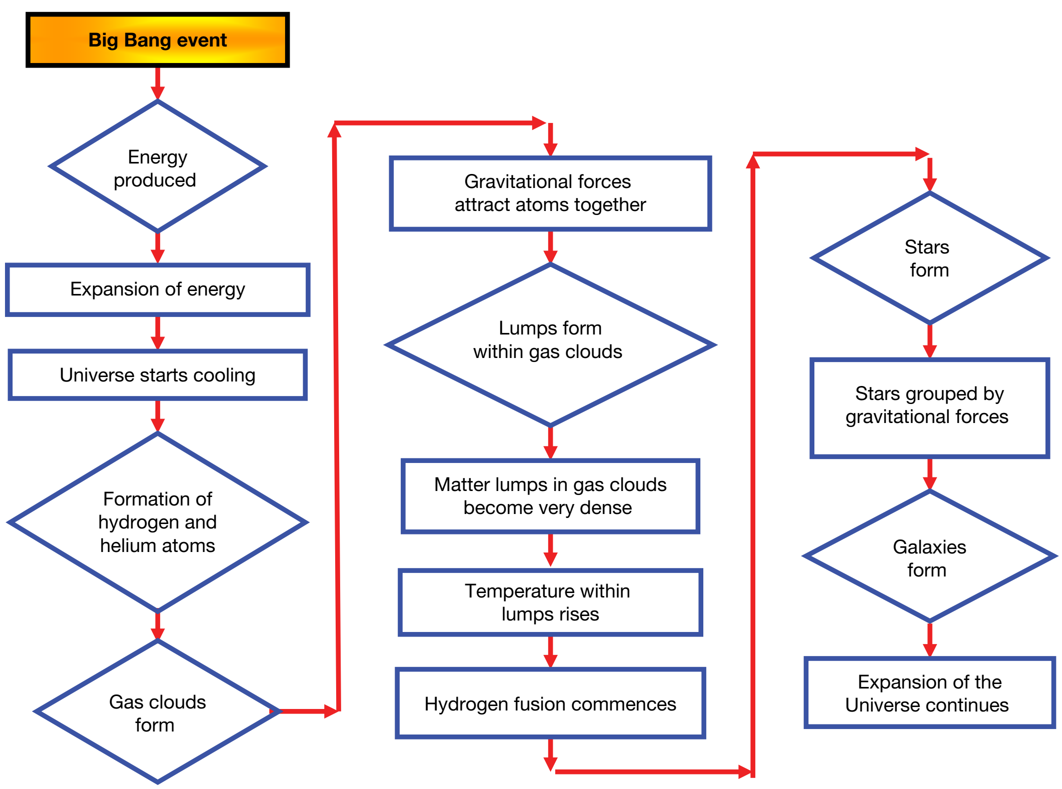
8.1 The Big Bang Theory

The Big Bang theory

1. The Big Bang theory proposes that the Universe began with an 'event' that produced an enormous amount of energy in a single position, known as the singularity, and that all matter has condensed from this energy as it expanded outwards and cooled.
2. (a) The Big Bang produced an enormous amount of energy. (G)
   (b) The Universe started at intense heat and has been cooling ever since. (D)
   (c) The Universe was initially compressed into zero volume and has been expanding since the 'Big Bang'. (I)
   (d) The temperature of the Big Bang is estimated to have been about 10^{32} K. (A)
   (e) Matter as we know it cannot exist at this temperature. Only pure energy existed. (C)
   (f) As the Universe cooled, the energy started changing into matter. (B)
   (g) The Universe started as energy, condensing to simple particles first, then to more complex particles as it expanded and its temperature fell. (F)
   (h) Accretion of newly formed matter particles by gravitational forces slowly formed gas clouds. (E)
   (i) Further accretion of matter within gas clouds saw the beginning of stars and eventually galaxies. (H)
3.



Evidence for the Big Bang theory

1. (a) The Doppler effect refers to the change in the wavelength (and frequency) of sound or electromagnetic radiation when its source is in relative motion to the observer.
   (b) The red shift describes the displacement of the spectral lines in the light emitted by galaxies towards the red end of the spectrum when compared to the spectrum produced by a similar, stationary emitter.
   (c) Nearly all galaxies are moving away from us, no matter in which direction we look.
   The further away from us galaxies are, the faster they are moving away, and that this is a mathematically direct relationship.
   (d) This was the first concrete evidence for the expansion of the Universe in that it reflects the situation that would occur in real life with an object exploding and the pieces moving outwards in all directions.
   (e) A blue shift will be produced by any galaxies that are moving towards us, resulting in us seeing light of shorter wavelength than that emitted.
2. (a) Three to one (75% to 25%).
   (b) Calculations have shown that if the Universe began with a Big Bang event, then after the energy condensed into matter, hydrogen and helium would have formed in these proportions.

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