The Open University of Sri Lanka
B.Sc. Degree Programme – Level 5 - 2009/2010
Department of Physics
PHU 3143 / PHE 5143: Atomic and Nuclear Physics

MODEL ANSWERS – Home Assignment

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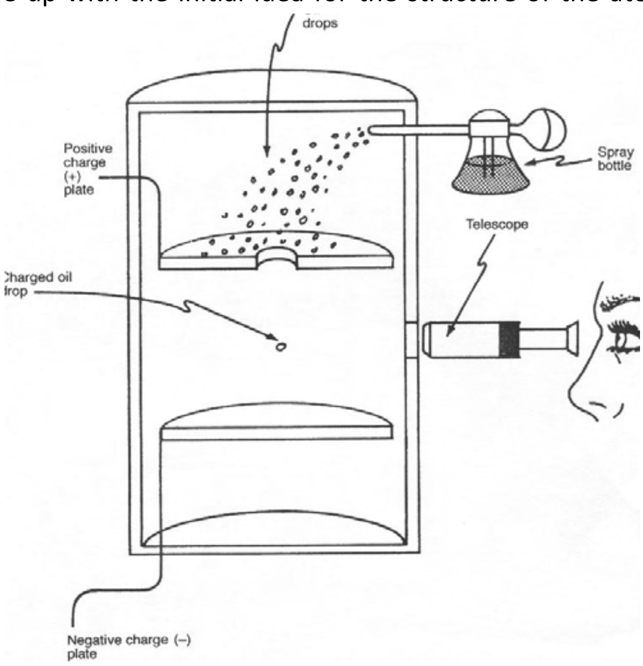
1. (a) Thomson thought rays emitted from various elements in a cathode ray tube were inseparable from a unique latent charge. He built a cathode ray tube with a metal cylinder on the end. This cylinder had two slits in it, leading to electrometers, which could measure small electric charges. He found that by applying a magnetic field across the tube, there was no activity recorded by the electrometers and so the charge had been bent away by the magnet. This proved that the rays are indeed charged particles.

   In the next stage, he constructed a slightly different cathode ray tube, with a fluorescent coating at one end and a near perfect vacuum. Halfway down the tube were two electric plates, producing a positive anode and a negative cathode, which he hoped would deflect the rays. As he expected, the rays were deflected by the electric field, proving beyond doubt that the rays were made up of charged particles carrying a negative charge. This result was a major discovery in itself, but Thomson resolved to understand more about the nature of these particles.

   Further Thomson tried to find the bending effects of electric field of **varying strengths** on the particles from **various elements (**as cathode). He found out that the mass to charge ratio was so high that the particles either carried a huge charge, or were a thousand time smaller than a hydrogen ion. He decided upon the latter and came up with the idea that the "electrons are a fundamental constituents of matter".

   Based on his results, Thomson came up with the initial idea for the structure of the atom, postulating that it consisted of these negatively charged particles swimming in a sea of positive charge.



   (b) Millikan's oil-drop experiment was the first direct measurement of the electric charge of a single electron. It was performed originally in 1909 by the American physicist Robert A. Millikan. Using a perfume atomizer, he sprayed tiny drops of oil into a transparent chamber. At the top and bottom were metal plates hooked to a battery, making one positive and the other negative. Since each droplet picked up a slight charge of static electricity as it traveled through the air, the speed of its motion could be controlled by altering the voltage on the plates. When the space between the metal plates is ionized (by radiation), electrons from the air attach themselves to oil droplets, causing them to acquire a negative charge.

Millikan observed one drop after another, varying the voltage and noting the effect. After many repetitions he concluded that charge could only assume certain fixed values. The smallest of these portions was none other than the charge of a single electron.

Importance of Millikan's Oil Drop experiment: It establishes,
(i) discreteness of charge and
(ii) electron as a fundamental unit of charge (negative)

Refer OUSL Basic Electromagnetism book for more details.

(c) When the water drop remains balanced,

$$Ee = mg \qquad \text{(Symbols have their usual meaning)}$$

$$Ee = \frac{4}{3}\pi a^3 \rho g$$

Where, 'a' is radius of the drop and 'ρ' is density of water.

$$\therefore e = \frac{4\pi a^3 \rho g}{3E}$$

$$= \frac{4\pi a^3 \rho g d}{3V} \qquad \left(E = \frac{V}{d}\right)$$

$$= \frac{4 \times \pi \times \left(7.47 \times 10^{-7}\right)^3 \times 1000 \times 9.8 \times 2.1 \times 10^{-2}}{3 \times 2250}$$

$$= \underline{\underline{1.5970 \times 10^{-19} C}}$$

This corresponds to one electron.

2. (a) He discovered the presence of a small, dense, positively charged nucleus by the alpha particle experiment on Thomson's model. Found that the volume of atoms consists mostly of empty spaces and proposed a new model, known as Rutherford's atomic model.

(b) Rutherford carried out the alpha particle scattering experiment on a gold foil, where he directed alpha particles at thin gold foil, and observed the scattering of the alpha particles.

Refer OUSL Atomic Physics book for description of his experiment and the theory.

(c) Contrary to the predictions of Thomson's atomic model, the alpha particles passed through the gold foil most of the time without change in direction; but approximately 1 out of 10,000 times, it bounced back or was greatly deflected.

Refer OUSL Atomic Physics book for description of the results.

(d) Major conclusions were: (i) most part of the atom consists of empty spaces and (ii) atoms must have a very tiny, dense, positively charged concentration (called nucleus) that bounces back the alpha particles without being knocked off the position.

3. (a) Bohr's postulates:

- Electrons orbit the nucleus. They are held in orbit by an electrostatic force.
- Electrons can only be in certain, permitted orbits and an electron does not emit radiation when it is in one of these orbits.
- An electron only emits radiation when it jumps from a higher energy state to a lower state.
- The radii of the allowed orbits are also quantized - each energy state has a specific radius proportional to h/2π. Angular momentum of electron will be mvr = nh/2π, n is principle quantum number and n = 1, 2, 3, … etc..

Refer the OUSL Atomic Physics course material for details.

(b) The equation for the radii of the n^{th} Bohr orbit is $r_n = \dfrac{\varepsilon_o n^2 h^2}{\pi m Z e^2}$

where, ε_o - permittivity of free space
n - n^{th} Bohr orbit
h - Planck's constant
m - mass of the electron
Z - atomic number
e - electronic charge

Refer the OUSL Atomic Physics course material for derivation details.

(c) We know that the Bohr radius is, $r_n = \dfrac{\varepsilon_o n^2 h^2}{\pi m Z e^2}$ ----------- (1)

Angular momentum of the electron in the Bohr orbit is given by,

$$mvr_n = \frac{nh}{2\pi} \quad \text{----------- (2)}$$

∴ The tangential speed (v) of the electron in the Bohr orbit is,

$$v = \frac{nh}{2\pi\, mr_n} \quad \text{----------- (3)}$$

By substituting the equation (1) in (3), we get

$$v = \frac{Ze^2}{2\varepsilon_0 nh}$$

And, we know that the angular speed is,

$$\omega = \frac{v}{r_n} = \frac{Ze^2}{2\varepsilon_0 nh}\frac{\pi m Z e^2}{\varepsilon_o n^2 h^2}$$

$$= \frac{\pi m Z^2 e^4}{2\varepsilon_o^2 n^3 h^3}$$

(d) The energy required to remove an electron from a particular orbit to infinity is called the binding energy of electron in that orbit.

This could be given by, $E_n = \frac{me^4Z^2}{8\varepsilon_o{}^2n^2h^2}\left(\frac{1}{n^2} - \frac{1}{\infty}\right)$

$= \frac{me^4Z^2}{8\varepsilon_o{}^2n^2h^2}\left(\frac{1}{n^2}\right)$

Therefore, the binding energy of the electron,

when n = 1,	B.E. = 21.8×10^{-19} J	(or)	13.6 eV
when n = 2,	B.E. = 5.44×10^{-19} J	(or)	3.4 eV
when n = 3,	B.E. = 2.42×10^{-19} J	(or)	1.5 eV

4. (a) Generally β radiations are nothing but electrons. By applying suitable electric or magnetic field these particles can be turned to particular direction and observed. γ radiations are charge-less radiations and hence travel straight in a electric or magnetic field region. Compare to γ radiations, the penetration power of β radiations are very much less.

Using the ionization property β radiations, a *Geiger Muller Counter* or a *Cloud Chamber* could be used to detect them. Refer any standard text book on Nuclear Physics for properties of two radiations and for working principles of the above detectors.

(b) Decay of ${}^{42}_{19}K$

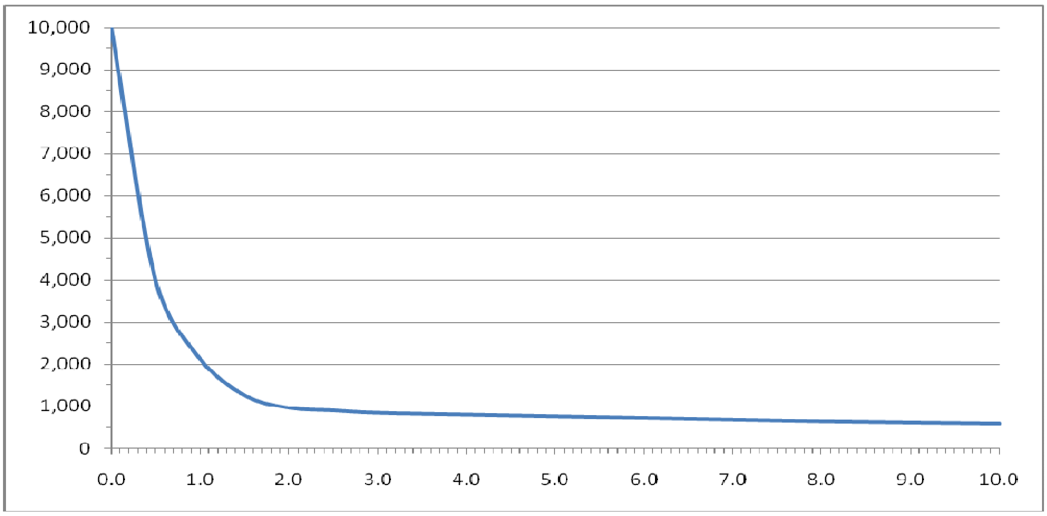
$${}^{42}_{19}K \longrightarrow {}^{42}_{20}Ca + \beta^- + \tilde{\gamma}_e$$

Decay of ${}^{44}_{19}K$

$${}^{44}_{19}K \longrightarrow {}^{44}_{20}Ca + \beta^- + \tilde{\gamma}_e$$

Both are stable atoms (isotopes).

(c)



Using the equations for number of radio active atoms remain after a given time (for both isotopes), and interpreting the values from the graph,

(i) the half-life of ${}^{42}_{19}K$ which is the longer lived isotope.
12.04h

(ii) the half-life of ${}^{44}_{19}K$ which is the shorter lived isotope.
20.63 min

(iii) the initial count rates due to ${}^{42}_{19}K$ and ${}^{44}_{19}K$.
966, 9034

(iv) The ratio of the amounts of ${}^{42}_{19}K$ and ${}^{44}_{19}K$ present in the source at the start of the measurements.
3.74

5. (a) Refer the OUSL Nuclear Physics course material for details and examples.

(b) The power generation rate is = 1×10^9 Js^{-1}

Energy released per fission is = $175 \times 1.602 \times 10^{-13}$ J

Therefore, no. of atoms undergo fission per second = $\frac{1\times10^9}{175\times1.602\times10^{-13}}$

= 3.567×10^{19} atoms

No. of atoms undergo fission during one year period

= $60 \times 60 \times 24 \times 365 \times 3.567 \times 10^{19}$

= 1.125×10^{27} atoms

Weight of these U^{235} atoms (in kg) is = $\frac{1.125\times10^{27}\times235}{6.022\times10^{26}}$

= 439 kg

(c) (i) Refer the OUSL Atomic Physics course material for Q values of each reaction in proton-proton cycle.

(ii) Refer the OUSL Atomic Physics course material for Q values of each reaction in the carbon-nitrogen cycle.

6. (a) There are 4 fundamental forces that have been identified. In our present Universe they have rather different nature and properties.

Properties of the Fundamental Forces:

1. The *strong interaction force* is very strong, but very short-ranged. It acts only over ranges of order 10^{-15} meters and is responsible for holding the protons and neutrons of atoms together. It is mediated by the exchange of gluons between quarks making up protons and neutrons. The strong nuclear force is 100 times stronger than the electromagnetic force. When nuclei are smashed in nuclear reactions, energy from the strong force is released. Described by the theory of physics called quantum chromodynamics, the strong force loses all its strength on distances much wider than the atomic nucleus. It is basically attractive, but can be effectively repulsive in some circumstances.
2. The *electromagnetic force* causes electric and magnetic effects such as the repulsion between like **electrical charges** or the interaction of **bar magnets**. It is long-ranged, but much weaker than the strong force. It is responsible for all atomic / particle reactions and the most recognizable physical properties around us. The electromagnetic force is mediated by photons, which make up all electromagnetic radiation, from cosmic rays to visible light to extremely low frequency radio waves. Both heat and light are made up of photons. It can be attractive or repulsive, and acts only between pieces of matter carrying electrical charge.
3. The *weak force* is responsible for radioactive decay and neutrino interactions. It mediates beta decay, what happens when a neutron breaks down into a proton and an electron or positron and so on. It is mediated by W and Z bosons. The weak nuclear force is about a hundred billion times weaker than the electromagnetic. It has a very short range (10^{-18} m) and, as its name indicates, it is very weak.
4. The *gravitational force* is the weakest of all forces, but very long ranged and the most pervasive in the universe because it is generated by all bodies with mass. Gravitational force is 10^{36} times weaker than the electromagnetic force. The particles thought to mediate gravity, the *gravitons*, have not yet been detected. It is always attractive, and acts between any two pieces of matter in the Universe since mass is its source.

(b) Conservation laws in particle interactions:

Conservation laws are empirical laws that we use to justify consistent patterns in physical processes. Typically these laws are needed to explain why some otherwise possible process does not occur. Conservation laws are a set of rules that forbid all such non-occurring decays. Though the rules are simple, they can be extremely powerful and govern a huge variety of processes.

There are many well established conservation laws that govern all particle interactions. Key laws are, conservation of:

- Energy
- Momentum
- Angular momentum (including particle spin or intrinsic angular momentum)
- Charge number
- Baryon number (= Quark number / 3)

- Lepton number
- Parity

All these conservation laws are consequences of the Standard Model of particle interactions. The first four are classical conservation laws, which still apply to the particle interactions. **Strong overall conservation laws** are the conservation of **baryon number** and the conservation of **lepton number**.

Specific quantum numbers have been assigned to the different fundamental particles, and other conservation laws are associated with those quantum numbers. The observation of a process that violates one of these rules would be evidence for additional laws of nature beyond the Standard Model.

(c) (i)

(i)	n^0	$\longrightarrow$	p^+	+	e^-	+	$\tilde{\gamma}_e$	
Charge (Q):	0	$\longrightarrow$	1	+	(-1)	+	0	Conserved
Baryon No. (B):	1	$\longrightarrow$	1	+	0	+	0	Conserved
Lepton No. (L):	0	$\longrightarrow$	0	+	1	+	(-1)	Conserved

Therefore, this reaction is ***Not forbidden***.

(ii)	p^+	$\longrightarrow$	e^+	+	γ	
Charge (Q):	1	$\longrightarrow$	1	+	0	Conserved
Baryon No. (B):	1	$\longrightarrow$	0	+	0	Not Conserved
Lepton No. (L):	0	$\longrightarrow$	1	+	0	Not Conserved

Therefore, this reaction is ***forbidden.***

(iii)	π^-	$\longrightarrow$	μ^-	+	$\tilde{\gamma}_e$	
Charge (Q):	-1	$\longrightarrow$	-1	+	0	Conserved
Lepton No. (L):	0	$\longrightarrow$	1	+	(-1)	Conserved

Therefore, this reaction is ***Not forbidden***.

(iv)	π^-	$\longrightarrow$	μ^-	+	$\tilde{\gamma}_\mu$	
Charge (Q):	-1	$\longrightarrow$	-1	+	0	Conserved
Lepton No. (L):	0	$\longrightarrow$	1	+	(-1)	Conserved

Therefore, this reaction is ***Not forbidden***.

(v)	p^+	+	π^-	$\longrightarrow$	Λ^0	+	K^0	
Charge (Q):	1	+	(-1)	$\longrightarrow$	0	+	0	Conserved
Baryon No. (B):	1	+	0	$\longrightarrow$	1	+	0	Conserved

Therefore, this reaction is ***Not forbidden***.

(vi)	p^+	+	p^+	$\longrightarrow$	$2n^0$	+	$2e^+$	
Charge (Q):	1	+	1	$\longrightarrow$	0	+	2	Conserved
Baryon No. (B):	1	+	1	$\longrightarrow$	2	+	0	Conserved
Lepton No. (L):	0	+	0	$\longrightarrow$	0	+	(-2)	Not Conserved

Therefore, this reaction is ***forbidden***.

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