Radiation and Safety
Unit1:Basics of Atomic and Nuclear Physics

Dr Priya Hasan[1*]
Maulana Azad National Urdu University, Hyderabad 32

September 18, 2018

Abstract

Basics of Atomic and Nuclear Physics: Basic concept of atomic structure; X rays characteristic and production; concept of bremsstrahlung and auger electron, The composition of nucleus and its properties, mass number, isotopes of element, spin, binding energy, stable and unstable isotopes, law of radioactive decay, Mean life and half life, basic concept of alpha, beta and gamma decay, concept of cross-section and kinematics of nuclear reactions, types of nuclear reaction, Fusion, fission.

1 Plank Hypothesis

According to the Planck hypothesis, all electromagnetic radiation is quantized and occurs in finite "bundles" of energy which we call photons. The quantum of energy for a photon is the product of h and the frequency.

$$E = h\nu$$

2 de Broglie hypothesis: wave-particle duality

Max Planck proposed that light is emitted in discrete quanta of energy. Extending Planck's investigation in several ways, including its connection with the photoelectric effect, Albert Einstein proposed that light is also propagated and absorbed in quanta. Light quanta are now called photons. These quanta would have an energy given by the PlanckEinstein relation:

$$E = h\nu$$

h is Plancks constant

All matter can exhibit wave-like behaviour. For example a beam of electrons can be diffracted just like a beam of light or a water wave. Matter waves are a central part of the theory of quantum mechanics, being an example of waveparticle duality. The concept that matter behaves like a wave is referred to as the de Broglie hypothesis. Matter waves are often referred to as de Broglie waves.

De Broglie, proposed that just as light has both wave-like and particle-like properties, electrons also have wave-like properties. The wavelength, λ associated with an electron and its momentum, p is given by:

$$\lambda = \frac{h}{p}$$

$$p = \frac{E}{c} = \frac{h}{\lambda}$$

where ν and λ denote the frequency and wavelength of the light, c the speed of light, and$h$ Plancks constant.

Matter waves were first experimentally confirmed to occur in the Davisson-Germer experiment for electrons, and the de Broglie hypothesis has been confirmed for other elementary particles. Furthermore, neutral atoms and even molecules have been shown to be wave-like.

*e-mail:priya.hasan@gmail.com, priyashasan@yahoo.com

3 Uncertainty principle and its implication

The position and momentum of a particle cannot be simultaneously measured with arbitrarily high precision. There is a minimum for the product of the uncertainties of these two measurements. There is likewise a minimum for the product of the uncertainties of the energy and time.

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

This is not a statement about the inaccuracy of measurement instruments, nor a reflection on the quality of experimental methods; it arises from the wave properties inherent in the quantum mechanical description of nature. Even with perfect instruments and technique, the uncertainty is inherent in the nature of things.

4 Bohr Theory

In 1913, the Danish physicist Niels Bohr explained the spectrum of atomic hydrogen by an extension of Rutherford's description of the atom. In that model, the negatively charged electrons revolve about the positively charged atomic nucleus because of the attractive electrostatic force according to Coulomb's law.

But the electron can be taken not only as a particle, but also as a de Broglie wave (wave of matter) which interferes with itself. The orbit is only stable, if it meets the condition for a standing wave: The circumference must be an integer multiple of the wavelength. The consequence is that only special values of radius and energy are allowed.

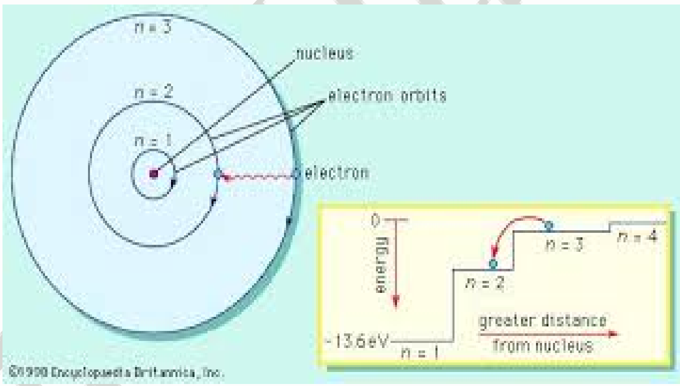

Figure 1: Bohr Theory

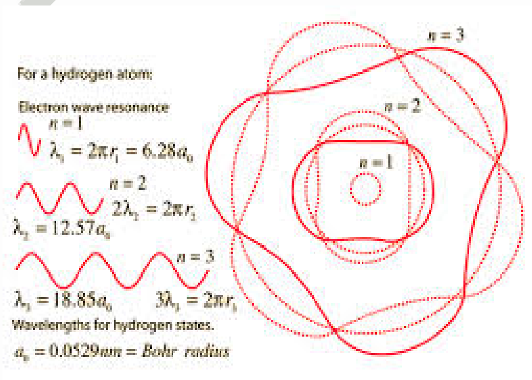

Figure 2: Bohr Orbits

In an hydrogen atom, the centripetal force is being supplied by the coulomb force between it and the proton in the hydrogen nucleus.

$$F_{centripetal} = F_{electrostatic}$$

$$\frac{mv_n^2}{r_n} = \frac{kZe(e)}{r_n^2}$$

$$mv_n^2 = \frac{kZe(e)}{r_n}$$

Z represents the atomic number (the number of protons), that electrons and protons have the same magnitude charge,±e, and that a negative $F_{electrostatic}$ merely means that the electrostatic force is attractive. Also note that the values of v_n of r_n are unknowns in this equation.

Bohr second hypothesis was that the electron's angular momentum was quantized.

$$2\pi r_n = n\lambda, \lambda = \frac{2\pi r_n}{n}$$

$$\lambda = \frac{h}{mv_n} = \frac{2\pi r_n}{n}, mv_n r_n = \frac{nh}{2\pi}$$

$$v_n = \frac{nh}{2\pi m r_n}$$

Upon solving the angular momentum equation for v_n substituting it into the centripetal force equation yields the following expression for r_n.

$$mv_n^2 = m(\frac{nh}{2\pi m r_n})^2 = \frac{kZe(e)}{r_n}$$

$$r_n = \frac{n^2 h^2}{4\pi^2 kmZe^2}$$

$$r_n = n^2 \frac{h^2}{4\pi^2 kmZe^2}$$

For ground state Hydrogen electron, n=1, Z=1

$$r_n = \frac{h^2}{4\pi^2 kme^2}$$

r_1= 0.53 X 10^{-10} m.

Bohr's third hypothesis in his model was that an electron only loses or releases energy (and therefore a photon) when it goes through de-excitation or drops from a higher energy state to a lower energy state.

$$E_1 - E_2 = h\nu$$

$$\frac{1}{2}mv_n^2 = \frac{1}{2}m(\frac{nh}{2\pi m r_n})^2 = k\frac{Ze^2}{2r_n}$$

$$KE = k\frac{Ze^2}{2r_n}$$

$$E_n = KE + PE$$

$$= -k\frac{Ze^2}{r_n} + k\frac{Ze^2}{2r_n}$$

$$= -k\frac{Ze^2}{2r_n}$$

Hence, the total energy is negative. This means that the electron is trapped in an energy well about the nucleus; that is, it would take the addition of energy to ionize or free the electron.

Substituting in the value for r_1 into this total energy expression yields a ground state energy of 2.18 x 10^{-18} Joules or -13.6 eV for a hydrogen atom. Using the fact that $r_n = n^2 r_1$,

$$E_n = km\frac{Z^2 e^4}{h^2 n^2} = h\nu$$

5 Spectral Lines

For spectral lines,

$$\nu = \frac{E_1}{h}(1/n_2^2 - 1/n_1^2)$$

And with λ,

$$1/\lambda = \frac{E_1}{ch}(1/n_2^2 - 1/n_1^2)$$

The Rydberg constant is defined as:

$$R_H = \frac{kme^4}{h^3}$$

The emission spectrum of atomic hydrogen is divided into a number of spectral series, with wavelengths given by the Rydberg formula. These observed spectral lines are due to the electron making transitions between two energy levels in an atom. Spectral emission occurs when an electron transitions, or jumps, from a higher energy state to a lower energy state. The energy of an emitted photon corresponds to the energy difference between the two states. Because the energy of each state is fixed, the energy difference between them is fixed, and the transition will always produce a photon with the same energy.

The spectral lines are grouped into series according to n_1 values. Lyman series with n_1=1, Balmer series with n_1=2, Paschen series with n_1=3, Brackett series with n_1=4, Pfund series with n_1=5...

6 Nuclear Structure

Nuclei are at the center of atoms and are composed of protons and neutrons. The number of protons is the atomic number Z, and the mass number A is approximately the total number of nucleons, a collective name for protons and neutrons. Therefore A = N + Z where N is the number of neutrons. We know that nuclei are very small. The size of the nuclei, from scattering experiments is

$$R = r_0 A^{1/3}$$

r_0 = 1.12 fm A Fermi or femto-meter = 10^{13}cm. Nuclear density is more-or-less constant for any nuclei, = 1.72 1038 nucleons/cm3 = 0.172 nucleons/fm3

The empirical mass formula is mass of nucleus(Z, N) = $Zm_p + Nm_nB/c^2$

where the last term is the 'mass deficit' due to the binding energy B. roughly The binding energy per nucleon is almost constant 8.5 MeV/nucleon.

Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it. The difference is a measure of the nuclear binding energy which holds the nucleus together. This binding energy can be calculated from the Einstein relationship:

Nuclear binding energy = Δmc^2

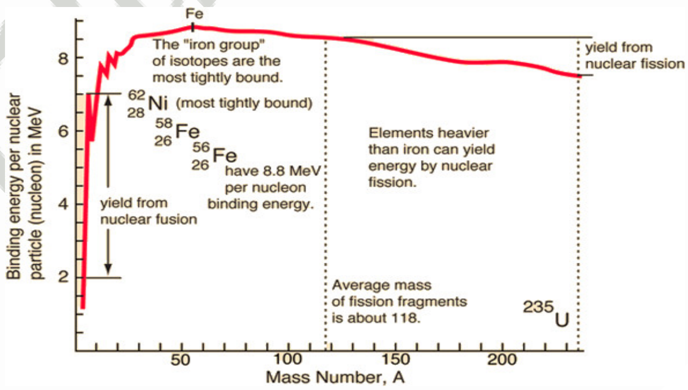

Figure 3: Binding energy curve

The binding energy curve 3 is obtained by dividing the total nuclear binding energy by the number of nucleons. The fact that there is a peak in the binding energy curve in the region of stability near iron means that either the breakup of heavier nuclei (fission) or the combining of lighter nuclei (fusion) will yield nuclei which are more tightly bound (less mass per nucleon).

The binding energies of nucleons are in the range of millions of electron volts compared to tens of eV for atomic electrons. Whereas an atomic transition might emit a photon in the range of a few electron volts, perhaps in the visible light region, nuclear transitions can emit gamma-rays with quantum energies in the MeV range.

There are two main types of nuclear reactions: fusion and fission. In fusion reactions, two light nuclei are combined to form a heavier, more stable nucleus. In fission reactions, a heavy nucleus is split into two nuclei with smaller mass numbers.

The buildup of heavier elements in the nuclear fusion processes in stars is limited to elements below iron, since the fusion of iron would subtract energy rather than provide it. Iron-56 is abundant in stellar processes, and with a binding energy per nucleon of 8.8 MeV, it is the third most tightly bound of the nuclides. Its average binding energy per nucleon is exceeded only by 58Fe and 62Ni, the nickel isotope being the most tightly bound of the nuclides.

Nuclear fission is a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay.

Nuclear fission of heavy elements was discovered on December 17, 1938 by German Otto Hahn and his assistant Fritz Strassmann, and explained theoretically in January 1939 by Lise Meitner and her nephew Otto Robert Frisch. For heavy nuclides, it is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). In order for fission to produce energy, the total binding energy of the resulting elements must be more negative (greater binding energy) than that of the starting element.

In nuclear physics, nuclear fusion is a reaction in which two or more atomic nuclei are combined to form one or more different atomic nuclei and subatomic particles (neutrons or protons). The difference in mass between the reactants and products is manifested as either the release or absorption of energy. This difference in mass arises due to the difference in atomic 'binding energy' between the atomic nuclei before and after the reaction. Fusion is the process that powers stars.

7 NMR and Precautions

Nuclear magnetic resonance (NMR) is a physical phenomenon in which nuclei in a strong static magnetic field are perturbed by a weak oscillating magnetic field (in the near field and therefore not involving electromagnetic waves[1]) and respond by producing an electromagnetic signal with a frequency characteristic of the magnetic field at the nucleus. This process occurs near resonance, when the oscillation frequency matches the intrinsic frequency of the nuclei.

Precautions for work with NMR include the following:

1. Post clearly visible warning signs in areas with strong magnetic fields.

2. Measure stray fields with a gaussmeter, and restrict public access to areas of 5-gauss or higher.

3. The strong magnetic field can suddenly pull nearby unrestrained magnetic objects into the magnet with considerable force. Keep all tools, equipment and personal items containing ferromagnetic material (e.g., steel, iron) at least 2 metres away from the magnet.

4. Though not a safety issue, advise users that the magnetic field can erase magnetic media such as tapes and floppy disks, disable credit and automated teller machine (ATM) cards, and damage analog watches.

5. Avoid skin contact with cryogenic (liquid) helium and nitrogen; wear a protective face mask and loose-fitting thermal gloves during dewar servicing and when handling frozen samples.

6. Ensure that ventilation is sufficient to remove the helium or nitrogen gas exhausted by the instrument.

7. Avoid positioning your head over the helium and nitrogen exit tubes.

8. NMR tubes are thin-walled; handle them carefully and reserve them for NMR use only.

In the event of exposure to cryogen liquid or gas, the following first aid procedures are recommended:

Immediately remove the victim from the cryogen hazard (or vice versa). Remove clothing that may interfere with the circulation of blood to the frozen tissues, but do so slowly, to prevent additional damage to skin. Do not rub or massage the affected region. Immerse the affected area in a warm water bath, ¡ 40C (¡ 105 F) or exposure to warm air of the same temperature range. Eyes exposed to cryogen liquids or gases should be flushed them with warm water, ¡ 40C, for at least 15 minutes. The victim should seek immediate medical attention.

8 Radioactive decay

Radioactive decay is the spontaneous breakdown of an atomic nucleus resulting in the release of energy and matter from the nucleus. Remember that a radioisotope has unstable nuclei that does not have enough binding energy to hold the nucleus together. Radioisotopes would like to be stable isotopes so they are constantly changing to try and stabilize. In the process, they will release energy and matter from their nucleus and often transform into a new element. This process, called transmutation, is the change of one element into another as a result of changes within the nucleus. The radioactive decay and transmutation process will continue until a new element is formed that has a stable nucleus and is not radioactive.

All nuclei with 84 or more protons are radioactive and elements with less than 84 protons have both stable and unstable isotopes. All of these elements can go through nuclear changes and turn into different elements.

In natural radioactive decay, three common emissions occur. When these emissions were originally observed, scientists were unable to identify them as some already known particles and so named them alpha particles (α),beta particles, (β) , and gamma rays (γ). Some later time, alpha particles were identified as helium-4 nuclei, beta particles were identified as electrons, and gamma rays as a form of electromagnetic radiation like x-rays except much higher in energy and even more dangerous to living systems.

The nuclear disintegration process that emits alpha particles is called alpha decay. An example of a nucleus that undergoes alpha decay is uranium-238. The alpha decay of Uranium 238 is

$$U_{92}^{238} == He_2^4 + Th_{90}^{234}$$

A beta particle is simply a high energy electron that is emitted from the nucleus. Thorium 234 is a nucleus that undergoes beta decay. Here is the nuclear equation for this beta decay.

$$Th_{90}^{234} == e_1^0 + Pa_{91}^{234}$$

Gamma ray production accompanies nuclear reactions of all types. In the alpha decay of UU -238, two gamma rays of different energies are emitted in addition to the alpha particle.

$$U_{92}^{238} == He_2^4 + Th_{90}^{234} + 2\gamma_0^0$$

9 Radioactive Half-Life

The radioactive half-life for a given radioisotope is the time for half the radioactive nuclei in any sample to undergo radioactive decay. After two half-lives, there will be one fourth the original sample, after three half-lives one eight the original sample, and so on.

If dN is the number of nuceli that disintegrates in time dt from a sample of N_0 nuclei,

$$dN/dt \propto N$$

$$dN/dt = \lambda N$$

$$N_t = Ne^{-\lambda t}$$

N_t = mass of radioactive material at time interval (t) N_0 = mass of the original amount of radioactive material λ = decay constant

$$t_{1/2} = 0.693/\lambda$$