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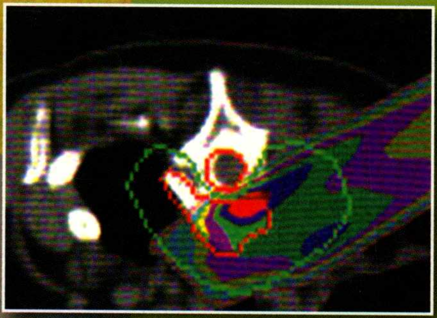
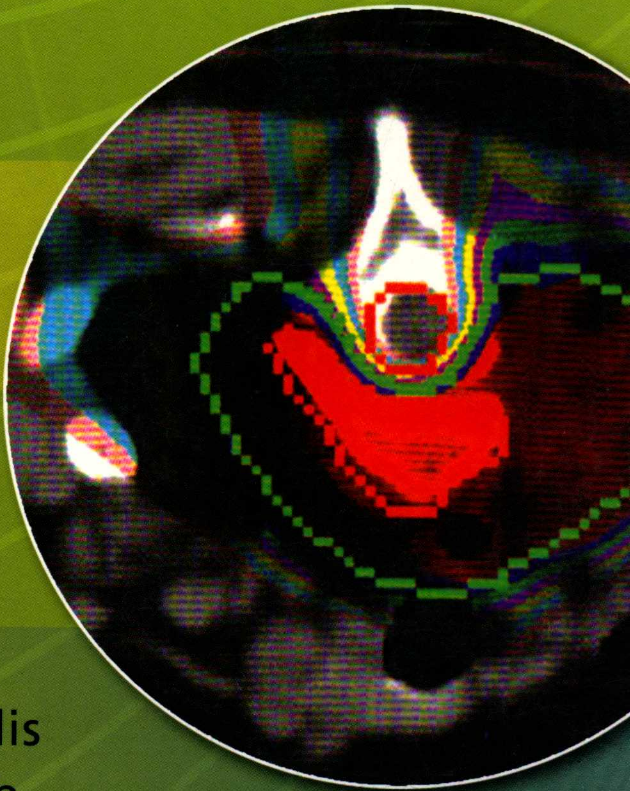
Khan's Lectures

Handbook of the Physics of Radiation Therapy





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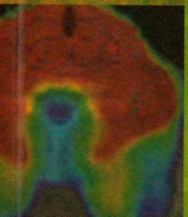

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KHAN'S LECTURES

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PREFACE

The objective of the Lectures is to provide a digest of the material contained in *The Physics of Radiation Therapy, Fourth Edition* ("the Textbook"). Key points of individual chapters are presented with a discussion that is condensed and often bulleted. For further details, the Textbook may be consulted. A problem set in the form of multiple choice questions is provided at the end of each chapter, with an answer key at the end of the book.

Like the Textbook, the lecture book is written for the radiotherapy team: radiation oncologists, medical physicists, dosimetrists, and therapists. The information presented is concise and to the point and may be used by those who need a quick review. As a companion book to the main Textbook, the *Khan's Lectures* will be most useful for those preparing for their board exams, whether for initial certification or renewal of certification. Teachers may use the material for their lecture presentations or writing exam questions for their classes.

As the author of *Khan's Lectures,* I was assisted by my former residents and contributors Drs. John Gibbons, Dimitris Mihailidis, and Hassaan Alkhatib. I greatly appreciate their providing editorial comments on the lectures and participation in writing the review questions.

I acknowledge Jonathan Pine, the Senior Executive Editor, Emilie Moyer, the Senior Product Manager, and other editorial staff of Lippincott Williams & Wilkins for their valuable contributions in making this publication possible.

Finally, I greatly appreciate my wife Kathy for her love and companionship she has given me for the last 45 years.

Faiz M. Khan

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CHAPTER

1

STRUCTURE OF MATTER

LECTURE

1A

REFERENCE

Khan FM. *The Physics of Radiation Therapy,* 4th edition, 2009. Chapter 1 "Structure of Matter"

The Atom

TOPIC OUTLINE

The following topics will be discussed in this lecture:

- Atomic structure
- Specification of atoms
- Classification of atoms
- Nuclear stability
- Mass and energy equivalence
- Atomic energy levels
- Nuclear energy levels

ATOMIC STRUCTURE

Figure 1A.1 illustrates the structure of an atom.

An atom consists of a central nucleus packed with neutrons and protons and a surrounding cloud of electrons. The electrons revolve around the nucleus in various orbits. The radius of the atom as a whole is approximately 10^{-10} m. The radius of the nucleus is much smaller—on the order of 10^{-15} m. The subatomic particles are characterized by different masses and electrical charges.

- Protons have a unit positive charge.
- Neutrons have no charge.
- Electrons have a unit negative charge.
- A unit charge is equal to 1.60×10^{-19} coulombs.
- Number of protons in the nucleus equals the number of electrons revolving around the nucleus. So the atom is electrically neutral.
- If an electron is stripped from the atom by an ionizing event, the residual atom is called a positive ion (an atom with a net positive charge).
- If an extra electron is acquired by an atom, the atom is called a negative ion.

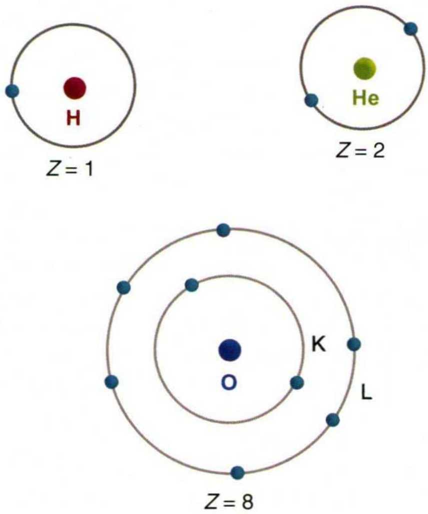

Figure 1A.1. Electron orbits for hydrogen, helium, and oxygen.

SPECIFICATION OF ATOMS

Each element is characterized by its basic constituent—the atom. An atom of an element is specified by

$$^{A}_{Z}X$$

where X is the chemical symbol for the element, A the mass number (the number of protons + neutrons in the nucleus), and Z the atomic number (the number of protons in the nucleus). The number of neutrons in the nucleus is given by $A - Z$.

CLASSIFICATION OF ATOMS

Atoms or elements are classified into isotopes, isotones, isobars, and isomers.

- *Isotopes*: Atoms that have the same number of protons but different number of neutrons (same Z but different A). EXAMPLE: $^{12}_{6}$C, $^{13}_{6}$C, $^{14}_{6}$C.
- *Isotones*: Atoms that have the same number of neutrons but different number of protons [same $(A - Z)$ but different A and Z]. EXAMPLE: $^{37}_{17}$Cl, $^{39}_{19}$K, $^{40}_{20}$Ca.
- *Isobars*: Atoms that have the same number of nucleons (protons + neutrons) but different number of protons and neutrons (same A, different Z). EXAMPLE: $^{17}_{7}$N, $^{17}_{8}$O, $^{17}_{9}$F.
- *Isomers*: Atoms that have the same number of protons and neutrons (same A and Z) but different nuclear energy states. EXAMPLE: $^{99m}_{43}$Tc (m stands for metastable state) and $^{99}_{43}$Tc.

NUCLEAR STABILITY

Certain combinations of neutrons and protons result in stable (nonradioactive) nuclides. Stability depends on neutron-to-proton (n/p) ratio, but not linearly. Figure 1A.2 shows a plot of the ratio of neutrons to protons in stable nuclei.

From the figure we can see that:

- Stable nuclei in the low atomic number range ($Z \leq 20$) have an almost equal number of neutrons and protons.
- As Z increases more than 20, the neutron-to-proton ratio for stable nuclei becomes greater than 1.
- In general, if the nucleus is packed with more protons than neutrons, it tends to be unstable.

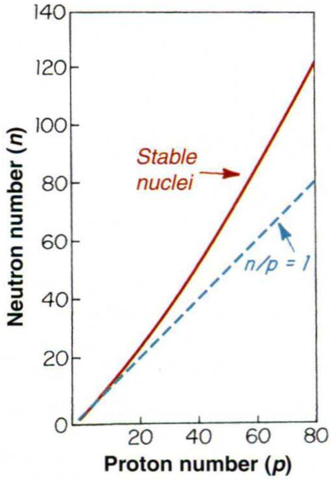

Figure 1A.2. A plot of neutrons versus protons in stable nuclei.

MASS AND ENERGY EQUIVALENCE

Masses of atoms and atomic particles are conveniently expressed in terms of atomic mass units (amu). An amu is defined as 1/12 of the mass of a $^{12}_{6}$C atom. Thus the $^{12}_{6}$C atom is arbitrarily assigned a mass of 12 amu. In basic units of mass

$$1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

The masses of subatomic particles in units of amu are as below:

- *Electron*: 0.000548
- *Proton*: 1.00727
- *Neutron*: 1.00866

Thus, neutron is slightly heavier than a proton, and electron is much lighter (~1/1,840 the mass of a proton).

Mass and energy are interconvertible. Einstein's famous equation, $E = mc^2$, where E is the energy, m the mass, and c the velocity of light, describes the relationship between matter and energy. Using this formula, one obtains

$$1 \text{ amu} = 931.5 \text{ MeV}$$

Because the rest mass of an electron is 0.000548 amu, its equivalent energy at rest (E_0) is

$$E_0 = 0.511 \text{ MeV}$$

MASS, VELOCITY, AND ENERGY OF A PARTICLE

- The mass of a particle depends on its velocity.
- If m is the mass of a particle moving with velocity v and m_0 is its mass at rest, then

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

- The kinetic energy (E_k) is given by

$$E_k = mc^2 - m_0c^2 = m_0c^2\left[\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1\right]$$

DISTRIBUTION OF ORBITAL ELECTRONS

Electrons are restricted to discrete energy levels or shells. The innermost orbit or shell is the K shell. The next shells are L, M, N, and O.

- The maximum number of electrons that an orbit or shell can hold is given by 2 n^2, where n is the number of shell. EXAMPLE: The maximum number of electrons is 2 in the K shell, 8 in the L shell, 18 in the M shell, 32 in the N shell, and so on.
- A shell need not be completely filled before the electrons begin to fill the next shell.
- The maximum number of electrons that the outermost shell can hold is eight. Additional electrons begin to fill the next level to create a new outermost shell before more electrons are added to the lower shell. EXAMPLE: An atom of calcium has 20 electrons, with 2 in the K shell, 8 in the L shell, 8 in the M shell, and the remaining 2 in the N shell.
- Electrons in the outermost orbit are called the valence electrons. The chemical properties of an atom depend on the number of electrons in the outermost orbit.

ATOMIC ENERGY LEVELS

Electron orbits represent discrete energy states or energy levels. The energy in this case is the potential energy of the electrons. With opposite sign, it is also called the binding energy (Figure 1A.3).

The energy scale is arbitrarily set as zero at the position of the valence electrons when the atom is in the unexcited state (when all the valence electrons occupy the outermost orbit energy level). Below that position, the potential energy is given a negative sign and the binding energy is given a positive sign. Thus, the following can be noticed:

- The potential energy increases (becomes less negative) as we go from the lower to the higher energy orbits.
- Correspondingly, the binding energy decreases as we go from lower to higher energy orbits (reverse the energy sign in Figure 1A.3).
- The binding energy of electrons is the amount of energy required to remove an electron from its orbit. Electrons close to the nucleus have a higher

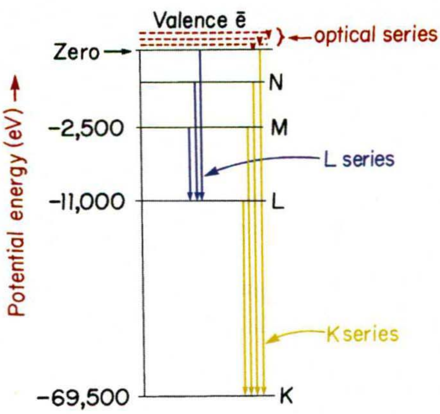

Figure 1A.3. A simplified energy-level diagram of the tungsten atom (not to scale). Only a few possible transitions are shown for illustration. Zero of the energy scale is arbitrarily set at the position of the valence electrons when the atom is in the unexcited state.

binding energy (are more tightly bound) compared to the outer orbit electrons. EXAMPLE: In a tungsten atom ($Z = 74$), the binding energies of K, L, and M shells are respectively 69.5, 11.0, and 2.5 keV.

- An electron can be ejected from its orbit if it receives energy greater than its binding energy. The vacancy thus created in the shell is filled by an outer shell electron, thereby creating another vacancy that is then filled by an outer orbit electron. These electronic transitions in which electrons cascade from outer to inner orbits give rise to characteristic x-rays (of energy equal to the energy difference between the shells involved).
- If an electron in the outermost orbit (a valence electron) is given energy of a few electron volts, it may be moved out to one of the optical orbits. But the electron cannot remain in any of the optical orbits for long and falls back to the outermost orbit of the atom (the unexcited state of the atom). In so doing energy is radiated as optical radiation.

NUCLEAR ENERGY LEVELS

The nucleus also has a shell structure. Nuclear particles (or nucleons) are arranged in shells that represent discrete energy states of the nucleus analogous to the atomic energy levels.

- A nucleus can be excited to a higher energy state if energy is imparted to it (e.g., by bombarding it with particles and having a particle overcome the nuclear barrier and penetrate it).
- When an excited nucleus returns to a lower energy state, it gives off energy equal to the energy difference of the two states.

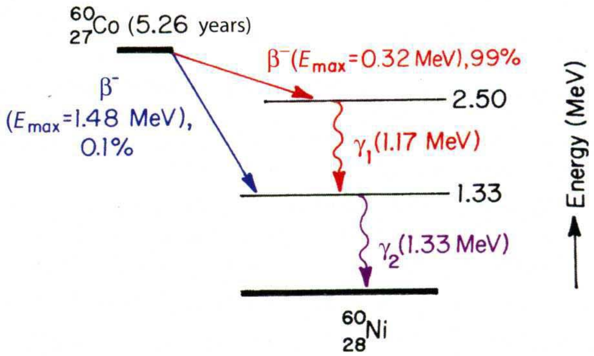

Figure 1A.4. Energy-level diagram for the decay of $^{60}_{27}Co$ nucleus.

- The excess energy may be radiated in one or more steps. The nucleus may descend to intermediate states before it settles down to stable or ground state.

Figure 1A.4 shows a decay scheme of a ^{60}Co nucleus that has been made radioactive in a reactor by bombarding stable ^{59}Co atoms with neutrons.

- The decay scheme shows that a ^{60}Co nucleus has two possible energy states to decay to before settling down to the stable or ground state. The predominant mode of decay is through two steps, giving rise to two γ-rays of 1.17 and 1.33 MeV.

LECTURE

1B

REFERENCE

Khan FM. *The Physics of Radiation Therapy*, 4th edition, 2009. Chapter 1 "Structure of Matter"

Forces of Nature and Fundamental Particles

TOPIC OUTLINE

The following topics will be discussed in this lecture:

- Mass defect
- Forces of nature
- Nuclear potential barrier
- Fundamental particles
- Electromagnetic radiation

MASS DEFECT

Mass of an atom is less than the sum of the masses of its constituent particles. The reason for this is that when the nucleus is formed, a certain amount of mass is converted into energy that acts as a "glue" to keep the nuclear particles (nucleons) together. This mass difference is called the mass defect. The energy equivalence of the mass defect is called the binding energy of the nucleus. EXAMPLE: Mass of a deuterium ($^{2}_{1}H$) atom is 2.014102 amu. It is less than the sum of the masses of its individual constituent particles (ie, mass of 1 neutron + 1 proton + 1 electron = 2.016368 amu). The difference 0.002266 amu is the mass defect. When multiplied by 931 MeV/amu, it gives the nuclear binding energy of 2.11 MeV.

FORCES OF NATURE

At the very start of our universe, there was probably one force that governed it. The single force then broke down into four forces at the end of 10^{-10} seconds. Since then, the universe has managed itself with these four forces.

The four forces of nature today, in order of their strengths, are the following:

- *Strong nuclear force*: It is a short-range force that comes into play when the distance between particles becomes smaller than the nuclear diameter (~10^{-15} m).
- *Electromagnetic force*: It is called so because electricity and magnetism are fundamentally the same by nature. This force causes oppositely charged particles to attract each other and similarly charged particles to repel each other.
- *Weak nuclear force*: It is a weak nuclear force, as its name suggests. It comes into play in certain types of radioactive emissions such as β-particle decay.

- *Gravitational force*: It is the weakest of all the natural forces. It does not play any part at the nuclear or atomic level. However, gravity has played a huge part in the creation and evolution of our universe.

NUCLEAR POTENTIAL BARRIER

As a result of mass defect that provides the nuclear binding energy, a potential barrier exists against any nucleon to escape or enter the nucleus (Figure 1B.1).

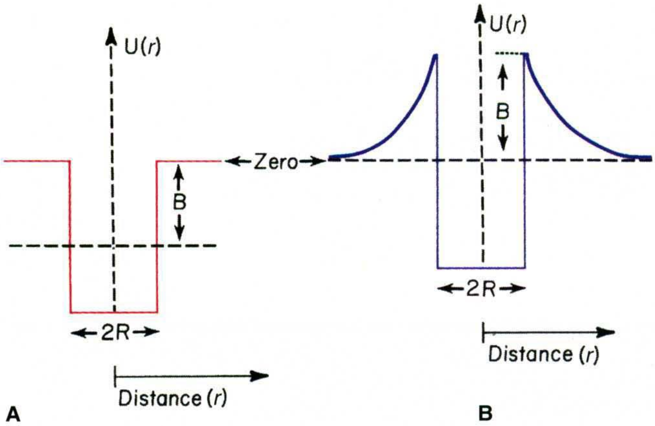

Figure 1B.1. Energy-level diagram of a particle in a nucleus. **A:** Particle with no charge. **B:** Particle with positive charge. $U(r)$ is the potential energy as a function of distance r from the center of the nucleus, B is the barrier height, and R the nuclear radius.

- A positively charged external particle, such as an α-particle approaching a nucleus, will experience repulsion because of the coulomb force of repulsion between the positively charged particle and the positively charged nucleus. However, if the particle is able to overcome the Coulomb force and get close enough to the nucleus so as to be within the range of the strong nuclear force, the repulsive forces would be overcome and the particle would be able to enter the nucleus.
- A particle with no charge such as a neutron has an easier time approaching a nucleus (no repulsive Coulomb force), but still experiences a nuclear barrier before it can enter the nucleus.
- Because particles have a dual nature, that is, they are particles of matter (have mass) but are also associated with waves (de Broglie waves), they can penetrate the nucleus with energies much lower than the height of the potential barrier.
- Particles within the nucleus are in continual motion but are constrained from escaping the nucleus by the nuclear barrier.
- In a stable nucleus, no particle attains enough energy to escape; however, in a radioactive or excited nucleus, a particle may attain enough energy (through random interactions with other nucleons) to escape the nucleus. The probability of this process occurring is pure chance. But in an aggregate of large number of excited nuclei such as in a chunk of a radioactive material, a certain percentage will disintegrate predictably in a given time (exponential radioactive decay).

FUNDAMENTAL PARTICLES

FUNDAMENTAL PARTICLES OF MATTER (FERMIONS)

Figure 1B.2 is a chart of fundamental particles according to the Standard Model. There are two kinds of fundamental particles of matter: quarks and leptons. There are six types of each of these, as listed below:

- *Quarks*: Up, down, charm, strange, top, and bottom;
- *Leptons*: Electron, electron neutrino, muon, muon neutrino, tau, and tau neutrino.
    - ➤ Besides the above 12 basic particles of matter, there are 12 corresponding basic particles of antimatter—with the same mass but opposite charge.
    - ➤ Quarks are the building blocks of heavier particles (hadrons) such as neutrons, protons, and mesons. EXAMPLE: It takes three quarks to make a proton (up, up, and down) and three quarks to make a neutron (up, down, and down).

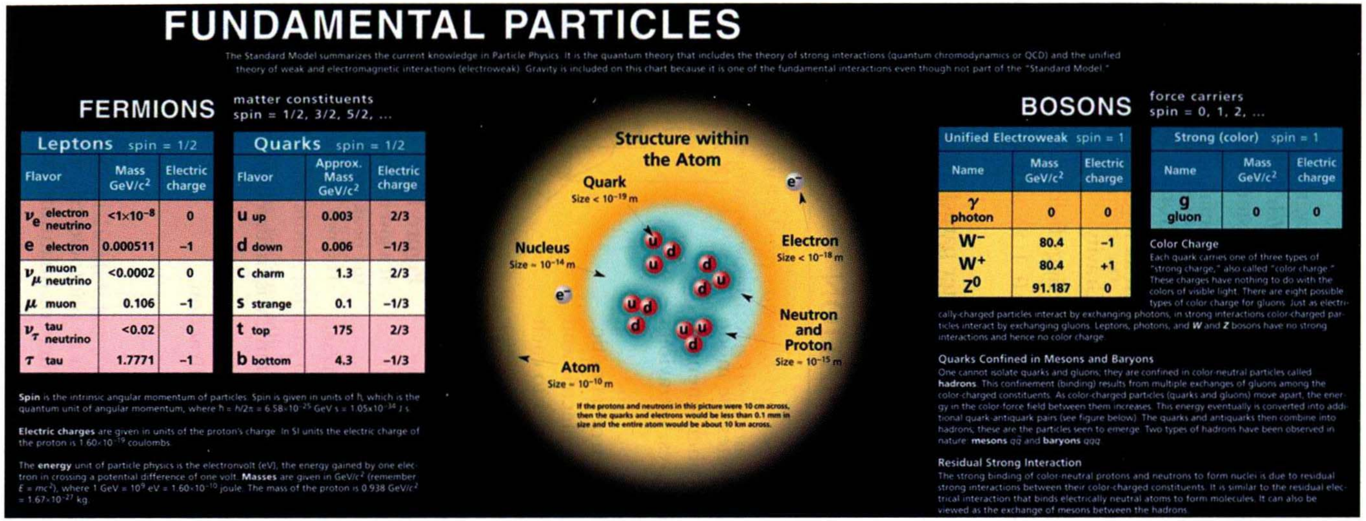

Figure 1B.2. A chart of fundamental particles and interactions. (Reproduced with permission from Contemporary Physics Education Project [CPEP], Lawrence Berkeley National Laboratory: Berkeley, CA. http://CPEPweb.org.)