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From The Inside Out: The Atomic Basis of Radiation

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This unit covers the atomic basis of radiology including the structure of the atom, the formation of x-rays, the effect of x-rays on living tissues and on film; as well as fluoroscopy.

It supplements Joyce Calarco's unit on the historical development of cathode ray tubes, as well as the unit by Marcella Flake and Carolyn Kinder which deals with the subject of radiology and safety on a middle school level.

My unit can be used most effectively by ninth-grade physical science, tenth-grade biology, high school physics, chemistry, laboratory technology, and human physiology classes.

Structure of the atom

The atom is the smallest unit of matter. It is like a miniature solar system with a nucleus in the center consisting of protons and neutrons. (The exception is the hydrogen atom which has only one proton and no neutron.)

The proton has a positive charge and the number of protons in the nucleus identifies the atom. For instance, hydrogen has one proton, carbon has six and tungsten has 74. The number of protons is called the atomic number and is represented by the symbol, Z.

Neutrons have approximately the same weight as protons, but they are electrically neutral. The combined number of protons and neutrons is called the atomic mass number (symbol is A). Atoms of the same element may have varying numbers of neutrons. These different forms of an element are called isotopes (see Joyce Bryant's unit).

Spinning around the central nucleus with the speed of light are the tiny electrons. They weigh only l/l800th as much as protons. There is always an equal number of protons and electrons, and since electrons have a negative charge, that means that atoms are electrically neutral.

The electrons move in definite orbits or shells around the nucleus. These shells are designated by letters starting with the K shell nearest the nucleus, followed by the L, M, N, 0, P and Q shells.

The maximum number of electrons that can occupy each electron shell can be figured by using the formula $2n^2$ where n = the shell number. For instance, the maximum number of electrons in the M shell (third shell from the nucleus) would be 18 (2×3^2).

What is important to know in radiology is that each shell has a characteristic binding energy; in fact, the shells are also called energy shells. This binding energy is a measure of the force of attraction that the nucleus exerts on the electrons; or to express it differently, how much energy it would take to remove an electron from that particular energy shell.

The electrons in the innermost K shell are bound much more tightly to the nucleus than the electrons in the outermost shells. For instance, in an atom of barium, the characteristic binding energy of the K shell is approximately 37 kilo-electron volts (keV), whereas the binding energy of the 0 shell (the fifth shell) is only 0.039 keV. (The electrons in the outermost shells are called free electrons, indicating that it takes very little energy to remove them.)

Heavier atoms such as tungsten have a much greater characteristic binding energy of their shells than do light atoms such as carbon. The binding energy of the K shell of tungsten is approximately 69 keV, whereas the K shell energy of carbon is only 0.28 keV. (See Table I, which compares the K shell energy of various atoms).

Electrons are able to jump from shell to shell. If they jump from a higher shell to a lower shell, they will give off energy equivalent to the difference in energies between the two shells. If this energy is high enough, it will be released in the form of an x-ray photon.

Problem: How much energy in keV would be given off if an L shell electron (4.9 keV) in an iodine atom dropped to the K shell (33.2 keV). Answer: 28.3 keV = EK EL.

One more fact should be emphasized about the atom. It consists mostly of empty space. If the nucleus of an atom were enlarged to the size of a grape seed, the radius of the atom would stretch the length of a football field, about 300 feet. Or, to put it another way, if the hydrogen nucleus were a ball three inches in diameter, then the electron would be a ball 1/4 inch in diameter spinning 1.5 miles away from the nucleus [2]. Another useful way to explain to your students the fact that atoms are mostly empty space is this quote from Christensen:.

If all the electrons in the atoms of the world could be removed and the nuclei packed together (a condition that exists in the white dwarf stars), the diameter of the earth would be reduced to about one-tenth mile [3].

Formation of x-rays

X-rays are produced in a cathode ray tube (Figure 1). These tubes produce a stream of electrons moving in a straight line from the cathode (-) to the anode (+). The electric potential between the two terminals is expressed in kilovolts (kV) and the higher it is, the greater the energy imparted to the electron stream. The number of electrons, or current, is measured in milliamperes (mA). The higher the amperage, the greater the flow of electrons.

The cathode (negative side of the tube) consists of one or two filaments made of tungsten. An x-ray generator supplies electrical current which flows through the filaments heating them to extremely high temperatures. When they get hot enough, electrons fly off from the tungsten filament and are propelled through the vacuum of the tube towards the anode. The reason that tungsten is used in the wires is that it has an extremely high melting point (3380o) and doesn't vaporize easily. The electrons move with tremendous speeds once they leave the cathode; although the distance between the cathode and anode is only from one to three cm, they may accelerate to half the speed of light (186,000 miles/second) by the time they hit the anode target.

This target is made of a small square of tungsten embedded in a larger piece of copper. The projectile electrons strike the tungsten target giving off huge amounts of heat, but since the tungsten has such a high melting point, it is not altered and the heat is conducted away by the copper part of the anode.

The atomic basis for this heat production is interesting. The speeding electrons have different energies. Those with the lowest energies may strike outer orbital electrons of the tungsten target just hard enough to make them vibrate in place. This vibration causes corresponding low energy electromagnetic waves in the wave length of infrared to be given off. Infrared is, of course, heat. More than ninety-five percent of the energy given off in an x-ray tube is heat.

The remaining less than five % of the energy emitted when the electrons strike the target is in the form of x-rays. There are two ways in which these x-rays are produced: by Bremsstrahlung radiation and by Characteristic radiation.

Bremsstrahlung is a German word. Brems means “braking or slowing down” and strahlung is “radiation”. Bremsstrahlung, which produces 85% of the x-rays in a tube, is caused by the attraction of the projectile electron with its negative charge to the nucleus of the tungsten atom in the anode with its positive charge. This attraction causes the electron to change its path and, therefore, to slow down (Figure 2). Part of its kinetic energy is converted to a photon of x-ray energy. An electron may be involved in many of these interactions with a tungsten nucleus and each time, some of its kinetic energy is converted to x-rays until it finally stops moving. Tungsten is advantageous as the target material because heavier atoms (it has an atomic number of 74) produce more bremsstrahlung than lighter atoms. The reason why we can't use an even heavier atom such as gold ($Z = 79$) instead of tungsten is that gold melts at 1063°C (whereas tungsten melts at 3380°C).

Bremsstrahlung radiation accounts for about 85% of the total x-ray production of a tube, and characteristic radiation makes up the other 15%. Characteristic radiation occurs when a projectile electron actually knocks out an inner orbital electron of a tungsten atom in the anode target. To take its place, an electron from an outer shell drops down into the lower orbit and in so doing gives off a photon of x-ray energy equivalent to the difference between the electron binding energy of the two shells (Figure 3). For instance: if an electron in the K shell of the tungsten atom is knocked out (binding energy of the K shell is 69.5 keV) and an electron from the L shell (binding energy = 12.1 keV) drops down to take its place, then an x-ray photon of 57.4 keV will be emitted. All K shell x-rays of tungsten have an effective energy of from 57 to 69 keV. The same phenomenon is true for the other shells as well. Whenever an electron drops from a higher shell to a lower shell, a definite amount of energy is always given off. Since this kind of energy is based on the energy levels of the shells, it is called Characteristic energy. Characteristic energy, with its definite bands of emitted energy, stands in contrast to Bremsstrahlung radiation, where x-rays are produced with a continuous spectrum of energy.

One interesting note should be added about mammography (breast radiography). It is desirable to have low energy x-rays when this procedure is done. Since atoms with lower atomic numbers have lower shell energies than those with higher atomic numbers, a molybdenum target is used in the anode instead of tungsten. The K shell effective energies of the molybdenum atom are in the range of 17.9 to 19.5 keV.

The effect of x-rays on body tissues

X-rays are produced when the moving electrons strike the anode target and their kinetic energy is converted to electromagnetic energy with very short wave lengths. These x-rays show the same duality of their nature as other electromagnetic radiation such as visible light—they behave both as waves and as particles. However, the majority of the time they behave as particles (whose energy is expressed by keV).

X-ray radiation is dangerous because it is capable of ionizing the atoms in our body tissues. That is, the energy of x-rays is great enough to knock orbital electrons out of their shells, thus causing electrically imbalanced ions. This ionization disrupts molecules in our bodies. Dividing cells such as those in the body of an unborn baby are especially vulnerable to ionizing radiation.

There are two main ways in which x-rays affect our bodies: 1) by Compton scattering effect and 2) by the photoelectric effect. Each of these will be described in detail below.

When high-energy x-ray photons strike our bodies, much of their energy is scattered in a phenomenon called the Compton effect. X-ray scattering is not desirable because a) it causes fogging of the x-ray film and b) it presents a health hazard to medical staff who are in the same room with the patient during fluoroscopic examinations. The Compton effect occurs in the following way: an x-ray photon strikes an outer orbital electron in one of the atoms of the body. Some of its energy ejects this electron from its shell and thus ionizes the atom. However, the x-ray photon retains most of its former energy and may either go on to ionize other atoms or, if its energy is high enough, it may exit from the patient's body. That is why the Compton effect causes such a health threat to other people in the room. That is also why it causes film fogging. The deflected photon strikes the film at an angle that gives no useful information about the body, but does cause unnecessary exposure of the film.

The photoelectric effect is extremely important in the exposure of x-ray film because it provides the needed contrast on the film between bone and soft tissues. It occurs most frequently when lower energy x-ray photons interact with heavy atoms. The process is very similar to that of characteristic radiation in the x-ray tube.

An x-ray photon traveling through the body strikes an inner orbit electron. The x-ray transfers all its energy to this electron, which is then ejected from its shell as a photoelectron. As in characteristic radiation, another electron in a higher energy level shell drops down to take its place and in doing so, gives off an x-ray photon with an energy equivalent to the difference of the energies between the two shells. Thus, two types of energy are given off in the photoelectric effect: the photoelectron and an x-ray photon. Both these types have rather low energies (they are called soft radiation) and are completely absorbed by the tissues they interact with. However, they are capable of further ionization before they are absorbed and therefore are dangerous to the patient.

As previously stated, the photoelectric effect occurs much more readily in atoms with high atomic numbers than in lighter ones. Since the radiation from the photoelectric effect is absorbed by the tissue it affects, that means that more x-ray energy is absorbed by bone than by soft tissues. (Bone is made of calcium with a higher atomic number than the atoms in soft tissues). In other words, if a patient was having his leg x-rayed, his femur would absorb so much of the radiation that very little would get through to the film below and it would remain clear when developed. On the other hand, the soft tissues would permit most of the x-rays to pass through to the film below, thus darkening it in these areas (Figure 4).

In order to see internal organs by means of radiography, contrast agents with high atomic numbers such as barium and iodine compounds are used. Because of the photoelectric effect, these heavy compounds (ZBa= 56, ZI-53) absorb most of the radiation, producing ideal contrast on the film.

The effect of x-rays on the film

A pattern of x-rays corresponding to their differential absorption by the tissues leaves the body and strikes the film.

X-ray film is made of a flexible base coated on both sides with a gelatine emulsion containing crystals of silver halide, (90-99% silver bromide and 1-10% silver iodide). When energy of the proper wave length strikes these silver halide atoms, a chemical reaction occurs to form a latent image on the film. This latent image is invisible until the radiographic technician puts the film in a solution called developer. At this point, the silver halide crystals exposed to energy change to black metallic silver (Figure 5).

The problem with x-rays is that they have so much energy that most of them pass right through the film without affecting it. It has been estimated that only 1 to 2% of x-ray photons actually interact with the film—a very low number. To rectify this situation, devices have been developed called fluorescent intensifying screens. Two of these screens are sandwiched into a lightproof cassette on each side of the central film. When the x-ray photons leave the body, they strike the nearest intensifying screen. This is coated with a material called a phosphor that converts the x-ray energy to visible light energy by the process of fluorescence. The phosphor used until recently was calcium tungstate (CaWO4), which fluoresced in the blue-violet range. Film is particularly sensitive to light with these wavelengths and, thus, a better image is produced than if a phosphor fluorescing in a different wave length had been used. (The reason why red light can safely be used in the darkroom is that film is not sensitive to this wave length).

At present, rare earth phosphors are used much more commonly in intensifying screens than calcium tungstate, because their efficiency in converting x-rays to visible light is much higher.

Intensifying screens have allowed a large reduction in the amount of exposure needed to expose film. In fact, patients need only from 1/50 to l/100th as much radiation now. This, of course, makes radiography much safer.

Fluoroscopy

Thomas Edison invented fluoroscopy in 1896. In contrast to conventional radiography, fluoroscopy allows the direct and dynamic visualization of moving body parts on a fluorescent screen (instead of film).

The fluoroscopy x-ray tube generates a very low current (0.5 to 5.0 mA) and thus produces fewer x-rays. These pass through the patient's body and strike the fluorescent screen which is coated with a phosphor, zinc cadmium sulfide. This phosphor converts the x-ray energy into a yellowish-green light, an area of the spectrum that the human eye is especially sensitive to.

The light glowing from the fluorescent screen is incredibly dim—in fact, it is only 1/10,000th that of the light used to look at radiographs. How can the image be seen in such dim light: The answer lies in the functioning of the rods and cones of the eye. We use our cones in bright light to see a range of colors. At night, our cones are no longer effective and we depend on the rods instead, because they are able to perceive extremely dim light. However, the eye must become adapted to the dark first before the rods are maximally effective.

Twenty five years ago, radiologists would wear red glass goggles for 20 minutes or so before a fluoroscopic examination. They were causing their eyes to become adapted to the dark. Now, because of new advances in fluoroscopy, we no longer see doctors running around in their red goggles. New image intensifiers have been invented, which means that the image is bright enough to be viewed by the cones as well as the rods.

Another important advance is the television screen. This allows the doctor to view the moving image in another room from the patient, thus eliminating the unnecessary radiation danger caused when high energy scattered radiation due to the Compton effect leaves the patient's body.

Conclusion

This unit serves as an introductory source of information about the atomic basis of radiation. This information is constantly being reviewed and explored. Faster means of imaging, decreasing uses of radiation and, yes, in the future no radiation may make it possible to see from the inside out.

TABLE 1 CHARACTERISTICS OF SOME RADIOLOGICALLY IMPORTANT ATOMS

Element	Chemical Symbol	Atomic Number (Z)	K-electron Binding Energy
Carbon	C	6	0.284
Oxygen	0	8	0.532
Aluminum	Al	13	1.560
Calcium	Ca	20	4.038
Copper	Cu	29	8.979
Silver	Ag	47	25.68

Barium	Ba	56	37.44
Tungsten	W	74	69.53
Lead	Pb	82	88.00
Iodine	I	53	33.17

*Bushong, Stewart—Radiologic Science for Technologists, C.V. Mosby Co., St. Louis, 1980, 2nd edition, p. 42.

Figure 1 X-Ray Tube Model

(figure available in print form)

Two circuits in the X-ray tube:

1. Low voltage heating circuit through cathode itself.

2. High voltage circuit between cathode and anode to drive electrons.

Selman, Joseph: Fundamentals of X-Ray and Radium Physics. Springfield: Charles Thomas Publishing Co., 1980, p. 159.

Figure 2 Production of Bremsstrahlung (Brems Radiation)

(figure available in print form)

E1 = electron approaching nucleus

hv = energy from kinetic energy of electrode

E2 - electron moving away from nucleus

Radiated Brems photon energy: hv = E1 Ð E2

Selman, Joseph: Fundamentals of X-Ray and Radium Physics. Springfield: Charles Thomas Publishing Co., 1980, p. 159.

Figure 3 Characteristic Radiation

(figure available in print form)

Selman, Joseph Fundamentals of X-Ray and Radium PHysics, the Charles C. Thomas Pub. Springfield, ILL 1980 6th edition. p. 163.

Figure 4 Formation of the radiologic image

(figure available in print form)

The x-ray beam, on passing through the body, undergoes absorption and scattering which depend on the KV and on the atomic number and density of any particular tissue. The beam emerging on the opposite side of the body contains information in terms of the number of photons per unit cross-sectional area of the beam; this comprises the remnant radiation or radiologic image. The resulting image on the film—the radiologic image—consists of the various densities corresponding to the radiologic image.

Ibid. Selman, p. 309.

Figure 5 Radiographic Chemistry

(figure available in print form)

Basic theory of photographic chemistry

A. Radiant energy in form of light or x-rays converts silver bromide crystal containing (silver sulfide) into a latent image center.

B. Developer reacts with altered crystal and reduces it to metallic silver, which constitutes the manifest image.

Selman, Joseph, M.D. *Fundamentals of X-Ray and Radium PHysics* , Charles Thomas Pub., Springfield, Ill. 1980, 6th ed., p. 307.

Notes

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3. Ibid.

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