RADIATION MEDICINE

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PREFACE

THIS book is intended for medical students in higher educational institutions and for physicians who are interested in the increasing applications of radioactivity to medicine and biology. The methods of diagnosis and therapy utilizing radioactive substances have achieved a considerable level of success, and it is expected that they will be used more extensively in our country before long.

It must, however, be remembered that if protective safeguards are not observed, there is a danger that radiation sickness will occur if the constant level of radiation due to radioactive isotopes in the neighbourhood, or to γ- and β-rays is above 50 r.

The main safeguard against radiation damage must be based on a precise and up-to-date knowledge of the nature of the radiations and of existing methods of dosage control. The relevant data is presented in the first chapter of this guide.

The therapy of radiation sickness is based on a study of pathogenesis; modern views on the subject are presented in the sections on the "Pathological Physiology of Radiation Sickness" and on "Management and Treatment of Radiation Sickness".

We have made use of investigations on the pathology of radiation sickness. Where necessary we have referred to foreign publications describing the radiation after-effects in Japan, and we have also reported a clinical study of accidents occurring in the atomic industry of the U.S.A.

Considerations of length have compelled us to omit treatment of subjects which are normally presented in courses on normal and pathological physiology, internal diseases, and in other disciplines.

We hope that the present work will help students and physicians to master the principles of the pathology and management of radiation sickness, and that it will serve to introduce the study of atomic energy into medical practice on a large scale. Our effort represents one branch of the resolute political endeavour of our government to utilize what is one of the greatest achievements of modern science for peaceful purposes.

The second edition of *Radiation Medicine* gives a fuller treatment, and has been carefully revised. It includes the following new sections:

1. General biological effects of radiation (Prof. N. N. Demin and Corresponding Member AMN S.S.S.R. Prof. A. V. Lebedinskii);
2. Infection and immunity in irradiated organisms (Prof. N. N. Klemparskaya and Candidate of Medical Sciences R. V. Petrov);
3. Chemical protection of organisms against the action of ionizing radiation (Candidate of Medical Sciences E. F. Romantsev);
4. Atomic explosions (Candidate of Technical Sciences Yu. M. Shtukkenberg).

The chapters "Clinical Aspects of Radiation Sickness" (Corresponding Member AMN S.S.S.R. Prof. N. A. Kurhsakov and Prof. I. S. Glazunov) and "Delayed After-Effects of Damage due to Ionizing Radiations" (Prof. D. I. Zakutinskii) have been thoroughly revised and expanded.

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CHAPTER 1

THE PHYSICS AND DOSE MEASUREMENT OF PENETRATING RADIATIONS

YU. M. SHTUKKENBERG

Structure of the atom

Nuclear structure and transformations

All substances are made up of very small particles called molecules, which are capable of an independent existence and possess the chemical properties of the parent substance. The molecules of elements consist of one kind of atom, while those of complex substances are made up of different kinds of atoms. In the natural condition, only the inert gases consist of atoms which are not combined to form molecules.

Both the size and the mass of atoms and molecules are extremely small. Their diameter is a few hundred millionths of a centimeter. One one-hundred-millionth of a centimeter (10^{-8} cm) is called the Ångstrom and is indicated by Å. The lightest atom is that of hydrogen which has a diameter of $0{\cdot}53 \times 10^{-8}$ cm and a mass of $1{\cdot}67 \times 10^{-24}$ g. The number of atoms in one gram of hydrogen is given by the immense figure of $6{\cdot}02 \times 10^{23}$, which may be appreciated by considering the following example. Suppose that $6{\cdot}02 \times 10^{23}$ water molecules were labelled in some way and then evenly distributed among all the water molecules on earth, then one glass of water collected from anywhere on the globe would contain 500 labelled molecules.

The following example will illustrate the magnitude of the atomic mass: The ratio of the mass of a hydrogen atom to that of a small drop is the same as the ratio of the mass of a man to the mass of the earth.

For long it was thought that atoms and molecules were indivisible, and it was not until near the end of the last century, after radioactivity had been discovered, that methods were developed which enabled the structure of atoms, molecules, and atomic nuclei to be unravelled.

We must note that long ago Russian scientists proposed that atoms and molecules were not the ultimate elementary particles of matter, but had a complex structure. M. V. Lomonosov not only pointed out the necessity for studying the internal structure of atoms, but with a stroke of genius foresaw the value of such a study for the subsequent advancement of science. He wrote: "Physicists and especially chemists who are not aware of the internal structure of invisible particles must remain in darkness".

In 1886 A. M. Butlerov wrote: "Atoms are not indivisible by nature, but cannot be divided by available means; they are preserved only in those chemical processes which are known at the present day, but will be divided by new processes which will be discovered in the future".

It is now known that such processes have in fact been discovered, and by modern methods we are able to change the nuclei of atoms, and to transform the elements.

Of what do atoms consist? A number of experiments have shown that they have a complex structure, of which negatively charged particles or electrons form part, as is demonstrated by the following facts. Electrification of bodies by friction is brought about by electrons passing form one body on to the other; the passage of an electrical current through a conductor is also due to the passage of electrons; when bodies are heated to a sufficiently high temperature, they give off electrons; the same thing happens when bodies are illuminated by ultra-violet light or by X-rays.

From a large number of other more complicated experiments it has been found that negatively charged particles or electrons are part of the constitution of all atoms. Measurements have shown that the charge on an electron is $4 \cdot 8 \times 10^{-10}$ absolute units, and the mass is $0 \cdot 91 \times 10^{-27}$ g, i.e. 1840 times less than that of a hydrogen atom.

If negatively charged particles form a part of the atomic structure and the atoms themselves are neutral, it follows that positive particles must also be present. In 1911, Rutherford bombarded very thin pieces of metal with charged particles (alpha-particles), and was then able to determine the distribution of charge within the atom. These experiments showed that the positively charged part of the atom occupies a very small volume and yet constitutes almost the whole of the atomic mass. This part of the atom is called the nucleus, and it has a diameter tens of thousands times smaller than that of the atom. Thus the diameter of an atom is 10^{-8} cm, whereas the diameter of the nucleus is 10^{-12}–10^{-13} cm. Rutherford's experiments were the basis of the nuclear or planetary model of the atom, according to which the nucleus lies at the centre, and round it electrons revolve in closed orbits which lie in separate layers or sheaths round it.

We will not consider the problem of the structure of the sheaths of electrons, but will turn our attention to the structure of the nucleus, and nuclear transformations. The nucleus is that part of the atom which determines all its properties. Actually it is possible to act on the atom and to remove from it either some or all of the electrons (so as to ionize the atom partially or completely). However if such a nucleus falls into an atmosphere of electrons, it combines with the appropriate number in such a way that the original atomic structure is restored. It has been shown experimentally that the charge on the nucleus of any atom is always equal to an integral number of electronic charges. Thus, the charge on the hydrogen nucleus has the same value as that on the electron; the charge on the helium nucleus is twice the charge on one electron, while the nucleus of the lithium atom is three times this fixed elementary amount, and so forth. This result can be understood when it is realized that the atom is neutral, and that only a whole number of electrons can be included in it.

Because the charge on the electron is very small, and is the smallest naturally occurring quantity of charge, it is adopted as a unit in atomic physics, and all quantities of charge are measured in terms of the number of electronic charges which they comprise.

In the same way, in physics and chemistry we do not deal with the actual weight of atoms, but only with their relative weights. The weight of the lightest, the hydrogen atom is the unit, though at the present time, for practical reasons the unit of atomic weight is taken as 1/16 of the mass of the isotope of oxygen O_8^{16}. The atomic weight of all the atoms can be represented by amounts which differ from whole numbers only in the third decimal place. The atomic weights reduced to the nearest whole number are called the *mass numbers* and are represented by the letter A. Thus in the hydrogen atom the nucleus has a charge of unity, and a mass number also of unity; in the helium atom the charge on the nucleus is 2, and the mass number is 4, etc. The whole number representing the charge on the nucleus is called the atomic number, and is represented by the letter Z. It can be seen therefore that the value of Z is also equal to the number of electrons in the atom; it is also equal to the number of the element in D. I. Mendeleev's Periodic Table.

Thus, all the nuclei can be described in terms of two quantities: the atomic number Z, which is the relative charge on the nucleus, and the mass number A, which is the relative mass or weight of the nucleus.

By methods which enable the mass of the nucleus to be determined with a high degree of accuracy, it has been shown that most elements consist of atoms all of which possess the same atomic number but which differ in their mass numbers. For instance, hydrogen consists of two different kinds of atoms having mass numbers of 1 and 2. Again, oxygen is a mixture of three different kinds of atoms, having mass numbers of 16, 17 and 18.

The chemical properties of all atoms are determined by the number of electrons and by the structure of the electron sheaths. Because the number of electrons in the atom is equal to the atomic number, all atoms having a particular atomic number will have identical chemical properties. *Atoms which have the same atomic number but different mass numbers are called isotopes.*

Therefore hydrogen consists of two isotopes, and oxygen of three. Many elements consist of a large number of isotopes, and tin, for example, contains 10.

The discovery of radioactivity

Two major discoveries were made at the end of the last century, X-rays in 1895, and radioactivity, by Becquerel, in 1896. He studied the fluorescence of various substances under the influence of visible light, and among them were minerals containing uranium salts. When fluorescent substances are illuminated by visible light, they themselves become luminous and so can darken a photographic plate. However, Becquerel accidentally laid on a photographic plate a piece of mineral which had not been previously illuminated, but which contained uranium salts. It was then found the plate received the imprint of the portions of the mineral which contained the uranium salts. Subsequent experiments showed that uranium spontaneously and without any previous treatment produces invisible rays which cause a photographic plate to darken. The phenomenon represents spontaneous radiation and has been called *radioactivity*, while the radiation itself is called *radioactive radiation.*

M. and Mme. Curie became interested in this phenomenon, and by further work discovered two new radioactive elements which were present in the form of impurities in the uranium salts. One was called radium, and the other polonium. Both gave a far more intense radiation than uranium, and it caused the photographic plate to darken, and a screen of zinc sulphide to scintillate. Shortly afterwards the harmful biological effect of these radiations was discovered. Becquerel suffered an erythema from a preparation kept in the side pocket of his coat, and Pierre Curie deliberately exposed his hand to radium radiation, and an ulcer developed which was slow to heal. Thus the first radiation damage occurred in 1897–1898, and was described by Pierre Curie.

It was natural that the first problem which he investigated was whether all radioactive substances emit the same radiations, and what was their nature.

The answer was quickly found, by loading the uranium into a lead box bearing an aperture, which was then placed between two charged plates. In the electrical field, the radiation emerging from the aperture separated into three parts: One was deviated towards the negative plate, the other to the positive, and the third suffered no deviation (Fig. 1). It was clear that the radiation was of three kinds. The rays which were deviated to the negative plate were called alpha-rays (α-rays), those deviated towards the positive plate were called beta-rays (β-rays), and the undeflected bundle were known as gamma-rays (γ-rays). The radiations are invisible, though their deviation may be observed by means of either a photographic plate or a fluorescent screen.

Later work showed that the three kinds of radiation possess very different penetrating powers. If the aperture in the lead box is closed by a piece of writing paper, the α-radiation is completely

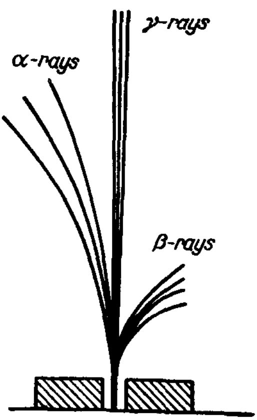

FIG. 1. Division of radiation from a radioactive source produced by an electrical field.

absorbed by the paper, whereas the β- and the γ-radiations pass freely through it. If the aperture is closed by a piece of aluminium 4 mm thick, or by a one-millimetre thickness of lead sheet, then the β-rays are also completely absorbed, and only the γ-rays pass through. It was also shown that pure radioactive isotopes do not emit all three kinds of radiation, but that some of them produce almost exclusively α-rays (e.g. polonium, radium and uranium), while others emit β-rays only, or a mixture of β- and γ-rays.

We must now enquire into the nature of these radiations. If a zinc sulphide screen is irradiated with α-rays from polonium, then in a dark room separate flashes of light can be seen on the screen.

The light flashes are called scintillations. The fact that α-radiation causes separate flashes of light to appear indicates that the beam must consist of a stream of particles, which have been called α-particles.

Thus, α-radiation consists of rapidly moving α-particles. Measurement of the mass of an α-particle has shown that it has a value of 4, i.e. it is four times greater than the mass of the hydrogen atom. The charge of the α-particle has also been measured in the following very simple way. A screen of zinc sulphide is attached to an insulator, and is irradiated with α-particles, all of which are completely absorbed by the screen, and because they are positively charged, the screen also acquires a charge of the same sign. As each particle falls onto the screen, a light flash occurs, so that the number of flashes is equal to the number of incident particles. By measuring the charge on the screen after irradiation, and knowing the number of α-particles incident upon it, the charge of a single particle may be calculated. It is clear that the charge on one α-particle must be equal to the charge on the screen divided by the number of particles. It was found that the charge on one particle had the value 2. It is natural to enquire whether α-particles may be identical with some other previously known particle. In D. I. Mendeleev's Periodic Table, the second position is occupied by helium, whose atomic number is 2 and whose mass number 4, i.e. the charge and mass are the same as those of an α-particle. On this evidence it was concluded that α-particles are helium nuclei.

Rutherford proved the hypothesis experimentally as follows. A closed glass tube having a very thin window was irradiated with α-particles. Within the tube atoms of helium were formed. Because the only possible substance from which the helium atoms could be formed was the stream of α-particles, it followed that the α-particles themselves must consist of helium nuclei. It is clear that as the

α-particles entered the tube they each collected two electrons and became transformed into helium atoms.

Attention was then turned to the nature of α-particles. Similar studies showed that they were electrons, i.e. particles having a negative charge of 1 and a mass 1840 times less than that of the hydrogen atom.

Like X-rays, γ-rays are not deviated either by an electric or by a magnetic field; they are of the same nature as X-rays and visible light rays, i.e. they are a form of electromagnetic radiation. Experiments to determine the velocity of X-rays and γ-rays which have been carried out in the last few years have shown that both are transmitted with the same velocity as visible light, i.e. at 300,000 km/sec, or 3×10^{10} cm/sec.

A number of investigations carried out by Stoletov (1888), Lebedev (1900) and Einstein (1905) led to an understanding of the nature of all kinds of electromagnetic radiations and showed that they consist of a stream of corpuscles or atoms of radiant energy which possess no charge, but which have a definite energy and mass and travel with the stupendous velocity of propagation of 300,000 km/sec. These atoms of radiant energy have been called *photons* or *quanta*. All kinds of radiant energy (infra-red, visible light, ultra-violet radiation, X-rays, and γ-rays) differ from each other only in the energy and mass of the photons. Infra-red radiation consists of very low energy photons. γ-rays consist of a stream of high energy photons which are called gamma-quanta. It is interesting to note that when photons of different energy fall on a photographic plate, processes occur which cause it to darken. Indeed, a photographic film is darkened most by infra-red and by visible radiation, but also by ultra-violet light and γ-rays.

If a stream of photons impinges on a highly organized material, then the latter will undergo processes which will depend on the nature of the radiant energy. Thus, the human organism perceives infra-red radiation as a sensation of warmth, and visible light as a visual impression. γ-Radiation and X-rays cannot be directly perceived, but they lead to a number of very complex biochemical and biological processes.

Thus the nature of α-, β-, and γ-radiations has been determined. α-Radiation consists of a stream of helium nuclei, β-radiation is a stream of electrons, and γ-radiation, a stream of γ-quanta.

Natural nuclear transformation

When considerable quantities of the pure radioactive isotopes of uranium, radium and polonium had been obtained, they were submitted to violent physical processes in order to attempt to influence the nature and intensity of their radiation. However, neither immense pressures, very high temperatures, magnetic fields nor electric fields which had a strong influence on the electron shells round the atoms had any effect on the nature of the radiation of these isotopes. It was therefore thought that their radiations must be due to nuclear transformations, and this conclusion was confirmed experimentally.

It was noticed that when the element radium was placed in a hermetically sealed vessel, it formed in it two gaseous substances of which one was helium, and the other a new radioactive substance called *radium emanation* or *radon* (Rn). Evidently radium nuclei gave out α-particles, and themselves became transformed into the nuclei of a new element—radon. To confirm this conclusion the atomic weight and the atomic number of radon had to be determined. Because in all naturally occurring processes the laws of the preservation of mass and charge are always observed, when an α-particle is lost from the nucleus, a new nucleus must be formed which will have two units less of charge and four units less of mass than the radium nucleus. Because the nucleus has an atomic number of 88 and a mass number of 226, when an α-particle is lost the new nucleus ought to be formed having an atomic number of $88-2=86$, and a mass number of $226-4=222$. This transformation of the radium nucleus may be written in short as follows:

$$Ra_{88}^{226} \rightarrow He_2^4 + Rn_{86}^{222}.$$

(The atomic numbers are represented below the symbol representing the element, and the mass number above.) The atomic weight