European Radiation Protection Course

Basics

Philippe Massiot and Christine Jimonet
Coordinators

instn

SEVENTH FRAMEWORK
PROGRAMME

edp sciences

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Preface: European Network on Education and Training in RAdiological Protection II-ENETRAP II

Radiation protection is a major challenge when using ionising radiation, both in nuclear and non-nuclear industries, as well as in other areas such as healthcare and research. Therefore, maintaining a high level of competence in radiation protection is crucial to ensure the protection of man and environment and to ensure the development of new technologies in a safe way.

Within the European 7FP project ENETRAP II, specific attention is given to the development of radiation protection training, with the view to maximising transfer of high-level knowledge and understanding. As in all 7FP projects in the area of education and training in nuclear fission, safety and radiation protection, emphasis is put on multi-disciplinary and transnational and inter-sectorial mobility. The ultimate goal is to contribute to a European system for continuous professional development, which relies on the principles of modularity of courses and common qualification criteria, a common mutual recognition system, and facilitating lecturer, learner and worker mobility across the EU.

This text book is developed in the frame of ENETRAP II and supports radiation protection training for Radiation Protection Experts (RPEs), and for any other person dealing with ionising radiation in their daily practice.

The topics treated are in line with the requirements for RPEs as stated in the new EURATOM Basic Safety Standards. They reflect the content of the generic modules of the European Reference Training Scheme for RPEs that forms an essential basis for the implementation of mutual recognition of RPEs through Europe.

This book contains the theoretical background of radiation protection principles and invites the learner to implement the acquired knowledge in daily work situations via exercises. In addition, QR code is added that guides the learner to supplementary on-line exercises. An e-book complements this text book and provides continuously updated exercises and simulations of practical situations for which the RPE must be able to advise on the radiation protection measures to be taken.

We wish you interesting reading.

Michèle Coeck
ENETRAP II Coordinator
On behalf of the ENETRAP II Consortium

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Foreword: Textbook, cyberbook and ECVET

The European ENETRAP II (European Network on Education and Training in Radiological Protection II) project was made up of several parts, one of which was focused on the development of a textbook. After an analysis of nearly 60 books on radiation protection, it was decided to write a textbook combining both theory and exercises where the reader becomes responsible for his own learning.
In this text book, you will find the first chapters of Module 1 of the training of Radiation Protection Expert (RPE) where the definition and missions are defined in the new European Directive. At the end of each chapter, exercises allow you to assess yourself.
In addition, the QR code sends you to a site where additional resources such as exercises and corrections enable you to develop the concepts outlined in the textbook.

Cyberbook QR code

This educational resource, sometimes called an e -book, aims to offer the reader additional resources. This site is based on Moodle (Learning Management System) LMS widely used by project partners.
During the project, we were asked to implement the ECVET (European Credit for Vocational Education and Training) approach. This approach aims to promote mobility within Europe through a process of recognition of acquired skills and mutual confidence.
Each competence is characterized by the following three descriptors: knowledge, skills and attitudes.
Thus, the RPE training is described in the e-book by about 80 skills and about 400 learning outcomes. Training is therefore driven by the expected skills and not by the content of training provided. So, the question becomes implicit "what is acquired and not what are the subjects taught".
We hope you enjoy reading this book that aims to be in some way a precursor of a series to come.

Paul Livolsi
Head of the WP7 and WP4 of ENETRAP II

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Jean-Christophe BODINEAU holds a BTS in Radiation Protection, he began his career at the CEA by monitoring the X-ray generators, particle accelerators and radiation sources used in research and industry. This experience has allowed him to teach the practice of radiation protection. He became an engineer in nuclear science and technology and he began to teach radioactivity, interaction and radiation detection at the INSTN. After obtaining a Master in Applied Physics, he became responsible for teaching in the institute. He specializes in teaching the detection of ionising radiation, a field in which he is recognized as a senior expert at the CEA. An important part of his activities for the training of doctors and nurses of the French nuclear power plants in the field of anthropogammametry.

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1 Radioactivity and nuclear physics

Hugues Bruchet, Marc Ammerich, Cécile Etard, Hervé Viguier, Abdel-Mjid Nourreddine

Introduction

Radioactivity is the property, exhibited by some nuclei, of transforming into one or more new nuclei, while emitting – in that transformation – a helium nucleus (i.e. an alpha particle), an electron (beta particle), or electromagnetic radiation (gamma radiation).

Radioactivity is a natural phenomenon, which was discovered, at the close of the 19th century, by French physicist Henri Becquerel. Investigating the phenomenon of phosphorescence, he sought to find out whether the radiation emitted by phosphorescent uranium salts was to be identified with the X-rays discovered by German physicist Wilhelm Roentgen, the preceding year. He showed that a photographic plate could become clouded through the agency of such salts, without first exposing these to any light. He came to the conclusion, therefore, that uranium spontaneously emits radiation that has the ability to cloud a photographic plate, quite apart from any phosphorescence process.

To refer to this phenomenon, Pierre and Marie Curie coined the term "radioactivity." In the months that followed the discovery Henri Becquerel had made, Marie Curie showed that, in like manner to uranium, thorium is naturally radioactive. Subsequently, working with several tonnes of uranium oxide ore, the Curies were able to isolate first polonium, then radium – a chemical element that is 2.5 million times more highly radioactive than uranium.

Radioactivity is an integral part of atomic physics, this being the science concerned with the study of the phenomena inherent in the atomic nucleus, and its constituents. Consequently, the present chapter begins with a review, describing the basic constituents of matter, and setting out the nomenclature in use. Thereafter, the phenomenon of radioactive decay, and the associated processes are described, and detailed. Finally, definitions are given for the fundamental physical quantities and properties involved, in particular the activity of a radioactive source, its half-life, and the concept of a radioactive decay series, to round out the chapter.

1.1. General considerations

1.1.1. The structure of matter

In nature, matter – whether it be air, water, stars, living organisms… – consists of molecules, which in turn are combinations of atoms. As early as classical Antiquity, Greek philosophers averred that matter is made up of minute "building blocks," combining with one another. The present-day word "atom" indeed has come down from that time, being derived from the Greek *atomos,* meaning "that which cannot be cut, indivisible."

> Things retain their substance unimpaired, till a powerful enough
> force be found to come upon them, in proportion to their structure.
> Nothing whatever, therefore, recedes into nothingness, but all things,
> being rent asunder, turn back into the elements of matter. …
> Nothing at all, then, is seen to pass away utterly,
> since Nature recruits one thing from another.
>
> Lucretius (99–55 BCE), *De rerum natura (On the Nature of Things),* Bk. 1, 246–263

In an atom, two components may be distinguished: the nucleus, at the center, and the electron cloud.

- the central nucleus consists of an assembly of two kinds of particle: **protons**, and **neutrons**, also known, collectively, as nucleons;
- the electron cloud consists of an ensemble of **electrons**, orbiting the nucleus at high speed. Mathematical formulae are the only means allowing the regions to be determined, where electrons are most likely to be found, in the cloud they form around the nucleus. Such regions are known as "electron shells;" despite the uncertainty inherent in any electron's position, the localization of these regions is nonetheless fairly precise, and this so-called "shell" model – while altogether inaccurate by present standards – does make it possible to account, fairly simply, for the physical phenomena that arise.

The atom's electron cloud is spherical, with a diameter of the order of 10^{-10} meter. The nucleus is smaller still, since it fills a sphere some 10^{-14} meter in diameter, on average – in other words, it is 10 000 times smaller than the sphere containing the atom as a whole. The huge gap extending between the nucleus and the electrons is empty: taking an atom's nucleus to be as a football placed in the middle of a sports ground, then the electrons would be seen as tiny marbles around the stands.

The atom's mass is not distributed evenly across the atom. Protons and neutrons have about the same mass ($1.67 \cdot 10^{-27}$ kg), however they are some 2000 times heavier than an electron: the nucleus thus contains virtually all of the atom's mass. The nucleus has a density of some 10^{13} g·cm^{-3}.

In order to estimate an atom's mass, since nucleons all have about the same mass, it is thus sufficient to know that atom's **number of nucleons – noted *A* – also known as its mass number**.

Every one of these particles – i.e. the erstwhile so-called "fundamental" particles – is bound to the atom by a **binding force**; the binding energy, for a particle, being the energy that must be provided to extract it from the atom.

Of the three particles that stand as constituents of the atom, the neutron is the only one that bears no electric charge – hence its name. A proton bears a positive charge, of $+1.6{\cdot}10^{-19}$ C, while an electron bears a negative charge, of $-1.6{\cdot}10^{-19}$ C. This quantity, noted *e,* is known as the "elementary charge."

Since matter is electrically neutral, an atom thus holds as many protons as it does electrons.

Further information

In 1911, New Zealand-born British physicist Ernest Rutherford was investigating the structure of matter. He was seeking, in particular, to ascertain more precisely the positions of atoms, relative to one another, in matter. He developed a novel model – the so-called Rutherford theory of the atomic nucleus – soon complemented by the model devised by Danish physicist Niels Bohr, in 1913. In this model, atoms consist of a nucleus, of vanishingly small size, compared to the atom as a whole, which nucleus nevertheless holds nearly all of the atom's mass. This nucleus is surrounded by an electron cloud. Electrons travel along stationary orbits, orbiting the nucleus somewhat in the manner of planets around the Sun, as shown in Figure 1.1. Hence the term "planetary model," which is often used to refer to the Bohr model. That model's specific feature was that it allowed for the application of the energy-quantum theory. Electrons may "jump" from one orbit to another, by gaining, or losing a quantum (i.e. a definite, discrete amount) of energy. With the advent of modern quantum theory, this model is now known to be inaccurate.

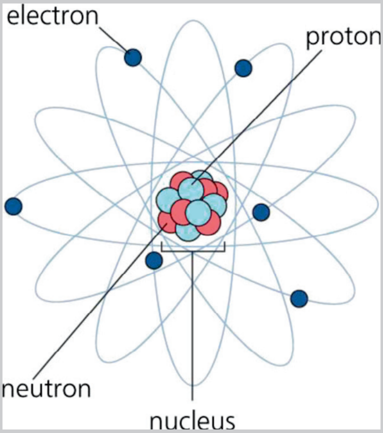

Figure 1.1. Representation of the atom according to the Niels Bohr model.

In 1927, the model put forward by Erwin Schrödinger provided further support for the presence of the nucleus, and its composition, while disallowing the notion of "paths" followed by electrons. It is only possible to determine the region in space where electrons are most frequently to be found: in other words, it is possible to determine the probability of an electron's presence, within a region extending around the nucleus. The radius of the atom now becomes the radius of the region of highest probability for the presence of electrons, around the nucleus. This model is still current, and is shown in Figure 1.2. In this representation, the three electrons of a lithium atom are most probably to be found within the darker regions.

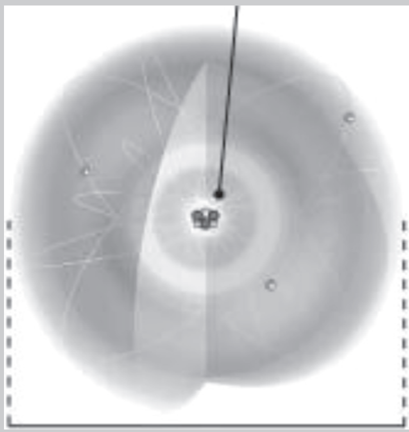

Figure 1.2. Representation of the atom according to the quantum model. http://www.cea.fr/Fr/jeunes/livret/Atome/img/Nuage_atome_01.jpg

1.1.2. Definitions. Nomenclature

A **chemical element** (or, more simply, an **element**) is the ensemble of all atoms having nuclei that contain the same number of protons. This number is known as the element's **atomic number**. Atoms of a given element thus all feature – when in the electrically neutral state – the same number of orbiting electrons.

Atoms from one and the same chemical element exhibit identical chemical properties; since they feature the same number of electrons. Indeed, an atom's chemical properties are largely related to the electronic bonds it is able to set up with electrons in neighboring atoms. The differences arising between atoms of one and the same chemical element solely concern the number of neutrons they hold.

Thus, every chemical element has its own name, and is assigned its own symbol, consisting of one or two letters (H for hydrogen, Fe for iron …), together with its atomic number – noted Z – corresponding to the number of protons in the nucleus. Any atom, taken at random from the vast number of atoms, whether presently in existence, or liable to be generated, belongs to a particular "family" of atoms, referred to as a chemical element.

A total of 118 chemical elements have been identified, to date, of which 112 have been given a name, and 89 occur naturally. The elements are often set out in table form, known as the "periodic table" – first devised by Dmitri Mendeleev – an example of which is shown as Annex 1.

To provide a complete description of an atom, the following notation is used:

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

– X stands for the element's chemical symbol;

– *A, Z* indicate, respectively, the number of nucleons, and the number of protons.

A is known as the mass number, *Z* as the atomic number (also referred to as the charge number). Setting *N* to stand for the number of neutrons, the relation between these three numbers is:

$$A = N + Z$$

Example:

$^{208}_{82}\mathrm{Pb}$

Pb stands for the chemical element lead [Latin *plumbum*]; the atom's mass number is 208, its atomic number is 82; its number of neutrons therefore stands equal to 126.

Hereafter, the *Z* value will no longer be indicated, since this number is implicitly specified, once the chemical symbol is given. The following notation is therefore used:

$^{A}\mathrm{X}$

Examples: $^{12}\mathrm{C}$, $^{32}\mathrm{P}$, $^{56}\mathrm{Fe}$, $^{60}\mathrm{Co}$, $^{131}\mathrm{I}$, $^{222}\mathrm{Rn}$, $^{238}\mathrm{U}$, …

1.1.3. Isotopes and isobars

Atoms that are different, while belonging to one and the same chemical element, are known as **isotopes** of that element. Every isotope of a given element thus features the same number of protons (i.e. an identical atomic number *Z*). For any element, all isotopes exhibit identical chemical properties: this being the common character, serving to define the chemical element. However, isotopes do vary in terms of the number of neutrons they hold, and thus have different mass numbers A.

Example: the isotopes of the element hydrogen: $^{1}\mathrm{H}$, $^{2}\mathrm{H}$, $^{3}\mathrm{H}$.

Isobars are atoms that have the same mass number *A,* but different atomic numbers.

Examples of isobars: $^{14}\mathrm{C}$, $^{14}\mathrm{N}$, $^{14}\mathrm{O}$.

Such atoms will not exhibit any common chemical property.

1.2. Nuclear stability and instability

Nuclei may be grouped into two classes: stable nuclei, involving infinite (or near-infinite) lifetimes; and unstable nuclei, featuring lifetimes ranging from one nanosecond to billions of years.

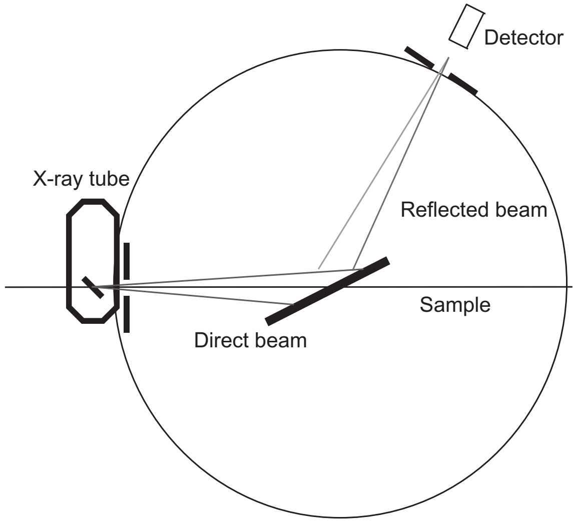

Figure 6.18. Operating principles of a diffractometer.

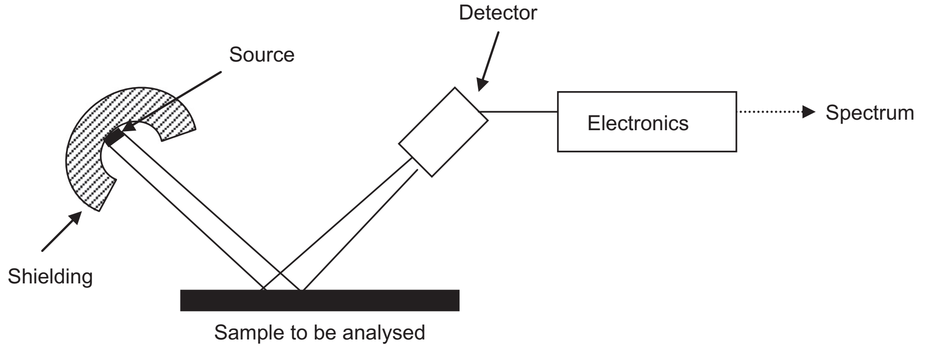

Figure 6.19. Operating principles of an X-ray fluorescence analyser.

This analytical technique is based on the excitation of the atoms in the analysed sample and the analysis of their characteristic X-ray lines. This X-ray fluorescence results from the photoelectric effect on the target atoms and it is therefore necessary that the sources used emit low-energy X or γ radiation (iron-55: 6 keV, cadmium-109: 22 keV, cobalt-57: 15 keV). The energies of the detected X-ray lines thus indicate which elements are present in the analysed sample, while the peak heights show the amount present (Figure 6.19).

This technique, which allows both qualitative and quantitative measures, is especially used in the chemical industry and in metallurgy to measure tinning or galvanizing, to analyse alloys and to sort scrap metal.

Further information: lead paint detectors

In order to prevent lead poisoning when using paint, specific detectors are used to detect the presence of this heavy metal. The measurements must be carried out in buildings when a case of lead poisoning is reported or prior to the sale of an old property, located in a risk area. They must be performed with a portable X-ray fluorescence device such as the one presented in Figure 6.20.

Figure 6.20. Example of lead paint detector (Photo: Fondis).

Such detectors operate on the same principles as the X-ray fluorescence analysers described above. They contain cadmium-109 or cobalt-57 sources, that have an activity of the order of 400 MBq. They enable the measurement of low levels of lead, below the legal threshold set at 1 $mg.cm^{-2}$.

These measurements can be performed by a wide variety of professionals: control agencies, architects, notaries and real estate agents.

6.3.2.3. Electron capture detectors

Electron capture detectors are used widely in gas chromatography to determine the impurity levels of solutions. The maximum activity of the β radiation emitting sources used is of the order of 500 MBq for nickel-63 and 7.4 TBq for tritium.

The gas coming from the chromatograph passes through an ionisation chamber containing a source of nickel-63 (or tritium), beta radiation emitter which ionises the medium. When a component containing impurities passes through the chamber, it combines with the free electrons present and the ionisation current drops. The concentration of the analysed component will be proportional to the decrease in ionisation current (Figure 6.21).

6.3.2.4. Thickness gauges

Thickness measurements can be performed with gauges containing sealed radioactive sources. Depending on the applications, two different techniques can be used:

- β or γ transmission,
- β or γ backscatter.