高等医学院校教材
（供临床、基础、预防、护理、口腔、药学等专业用）

核医学概要

英中文对照

Nuclear Medicine Outline

(English-Chinese)

□ 主编　黄　钢

高等教育出版社
Higher Education Press

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高等教育出版社

内容提要

本书共15章。基础核医学为前5章,重点介绍与核医学有关的核物理基础、核医学仪器、放射性药品、放射生物与放射防护和体外示踪技术等。临床核医学部分包括神经、循环、内分泌等各脏器显像和放射性核素治疗。

本书特点:① 突出临床实用性。基础核医学部分介绍核技术原理与方法,了解核素示踪技术的独特优势。临床核医学部分重点强调基本原理与临床应用,用流程图方式简要介绍方法学;通过典型病例分析,使学生能够灵活地应用核医学知识。② 强调教科书的系统性。本书在临床核医学部分的每一章均有概述,对一些不常用的方法或新进展,或重要但又难以自成一节的内容,均在概述中说明。③ 英中文对照。协助学生掌握专业英语。④ 增加同类技术的比较。在临床部分每一章的最后一节增加核医学技术与其他诊疗技术的比较,便于学生掌握核医学在疾病诊治中的优劣性。

本书主要是作为医学专业本科生的教材。也可作为核医学专业研究生入学考试和执业医师考试的参考用书,及作为非核医学专业继续教育的参考。

图书在版编目(CIP)数据

核医学概要(英中文对照)/ 黄钢主编. —北京:高等教育出版社,2006.1

ISBN 7-04-017543-6

Ⅰ.核… Ⅱ.黄… Ⅲ.原子医学-高等学校-教材
Ⅳ.R81

中国版本图书馆 CIP 数据核字(2005)第 149465 号

策划编辑	刘晋秦	**责任编辑**	薛玥	**封面设计**	张楠
版式设计	胡志萍	**责任校对**	金辉	**责任印制**	朱学忠

出版发行	高等教育出版社	购书热线	010-58581118
社址	北京市西城区德外大街4号	免费咨询	800-810-0598
邮政编码	100011	网址	http://www.hep.edu.cn
总机	010-58581000		http://www.hep.com.cn
		网上订购	http://www.landraco.com
经销	蓝色畅想图书发行有限公司		http://www.landraco.com.cn
印刷	河北省财政厅票证文印中心	畅想教育	http://www.widedu.com
开本	787×1092 1/16	版次	2006年1月第1版
印张	10.5	印次	2006年1月第1次印刷
字数	250 000	定价	22.10元

物料号 17543-00

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CATALOG

CHAPTER ONE

PHYSICS IN NUCLEAR MEDICINE

1 Structure of the Atom

1.1 Nucleus

Atom is the fundamental building block of elements, consists of nucleus and electrons. Nucleus is located in the core of the atom, where most of its mass and all of its positive charge are concentrated. It consists of positively charged protons[1] and electrically neutral neutrons[2] held together by the so-called nuclear force. The number of protons in the nucleus, Z, is called the atomic number. This determines what chemical element the atom is. The number of neutrons in the nucleus is denoted by N. A, atomic mass of the nucleus, is equal to $Z + N$. A given element can have many different isotopes, which differ from one another by the number of neutrons contained in the nucleus. At present, there are more than 100 known elements. Among the elements are approximately 270 stable isotopes, and more than 2 000 unstable isotopes.

1.2 Nuclide[3], Isotope[4], Isomer[5], Radionuclide

Nuclide: A nuclide is any individual atomic species, which can be distinguished by its atomic weight, atomic number, and energy state. Thus ${}^{14}_{6}C$, ${}^{9}_{4}Be$, ${}^{6}_{3}Li$, and ${}^{7}_{3}Li$ are all different nuclides.

Isotope: The isotopes of an element are nuclides having the same Z but different N. Because isotopes have the same number of protons, they will have similar chemical properties. Some of the isotopes of boron, for example, are ${}^{8}_{5}B$, ${}^{10}_{5}B$, and ${}^{12}_{5}B$.

Isomer: Isomers are nuclides having the same mass number A and N, but different energy state. Symbolically, they are designated by an m at the upper right corner. For example, ${}^{99}_{43}Tc^{m}$ and ${}^{99}_{43}Tc$ are isomers.

Radionuclide: An unstable isotope of an element that decays or disintegrates spontaneously and emits radiation.

2 Nuclear Decay

Nuclear decay is the change of one radioactive nuclide into a different nuclide by the spontaneous

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1 proton: 质子
2 neutron: 中子
3 nuclide: 核素
4 isotope: 同位素
5 isomer: 同质异能素

emission of alpha, beta, or gamma rays, or by electron capture. The end product is a less energetic, more stable nucleus. Each decay process has a definite half-life.

2.1 Alpha Decay

Heavy nucleus tends to be unstable because they contain large numbers of protons that strongly repel each other. Commonly, such a nucleus emits an alpha particle as a means of reducing the number of protons. The alpha particle consists of two protons and two neutrons, identical to a $^{4}_{2}He$ nucleus. The emission of an α particle, or $^{4}_{2}He$ nucleus, is a process called α decay

$$^{A}_{Z}Z \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He + Q$$

$$\text{e. g.} \quad ^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He + 4.937\ \text{MeV}$$

2.2 Beta Decay

Beta decay is an electron of either positive charge (β^{+}) or negative charge (β^{-}), which has been emitted by an atomic nucleus or neutron in the process of a transformation. Beta particles are more penetrating than alpha particles but less than gamma rays or X-rays.

2.2.1 Beta-Minus Decay

A nucleus having excess of neutrons causes the unbalance between neutron and proton. Thereby, a neutron in the nucleus can be transformed into a proton with the production of an electron β^{-}, and an antineutrino[6], and result $\acute{\upsilon}$, which is a process called beta-minus decay, and in this process the daughter nuclide is yielded with its mass number unchanged, but atomic number raised.

$$^{A}_{Z}Z \rightarrow ^{A}_{Z+1}Y + \beta^{-} + \acute{\upsilon} + Q$$

$$\text{e. g.} \quad ^{32}_{15}P \rightarrow ^{32}_{16}S + \beta^{-} + \acute{\upsilon} + 1.71\ \text{MeV}$$

2.2.2 Beta-Plus Decay

A process that a proton in the nucleus can be transformed into a neutron with the emission of a positron, β^{+} and a neutrino[7], υ, is called β^{+} or positron decay, which mainly occurs in nucleus having excess of protons.

$$^{A}_{Z}Z \rightarrow ^{A}_{Z-1}Y + \beta^{+} + \upsilon + Q$$

$$\text{e. g.} \quad ^{18}_{9}F \rightarrow ^{18}_{8}O + \beta^{+} + \upsilon + 0.66\ \text{MeV}$$

The positron (or β^{+} particle) is emitted with a certain amount of kinetic energy that loses as it moves through its environment. When it comes to rest, it annihilates with a nearby electron to produce two 511-keV annihilation photons moving in opposite directions in order that momentum be conserved. This course is called annihilation radiation[8].

$$\beta^{+} + \beta^{-} \rightarrow \gamma + \gamma + 511\ \text{keV}$$

The positron travels only a short distance in tissue before annihilating with an electron to produce

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6 antineutrino:反中微子

7 neutrino:中微子

8 annihilation radiation: 湮没辐射

two 511-keV photons.

2.2.3 Electron Capture[9]

There is an alternative to beta-plus decay called electron capture that accomplishes the same result. Because inner-shell electrons orbit close to the nucleus even pass through it from time to time, it is possible for the nucleus to capture an orbiting electron and combine it with a proton to produce a neutron. Only a neutrino is ejected from the nucleus:

$$^{A}_{Z}X + ^{0}_{-1}e \rightarrow ^{A}_{Z-1}X + \upsilon$$

$$\text{e.g.} \quad ^{55}_{26}Fe + ^{0}_{-1}e \rightarrow ^{55}_{25}Mn + \upsilon$$

The capture of the electron leaves a vacancy in the electron shell, which will be filled by an outer shell electron with the production of characteristic X ray or Auger electrons[10].

2.3 Gamma Decay

Gamma rays are a type of electromagnetic radiation. The course that an excited nucleus returns to the ground state and emits gamma rays is a process called gamma decay. Neither the mass number nor the atomic number is changed when a nucleus emits a γ ray in γ decay

$$^{A}_{Z}X^{m} \rightarrow ^{A}_{Z}Y + \gamma$$

$$\text{e.g.} \quad ^{99}_{43}Tc^{m} \rightarrow ^{99}_{43}Tc + \gamma$$

2.4 Internal Conversion[11]

When the nucleus moves from a higher to a lower energy level, either a gamma ray is produced or the energy is used to eject an orbiting electron. This latter process is called internal conversion.

3 Law of Nuclear Decay

Radioactive nuclei will transform themselves to stable nuclei by the emission of radiation with time. Radioactive nuclei N_0 are removed from which a certain fraction λ per unit time by decay. Then, the number of nuclei N that has not yet decayed after a time t has passed is expressed by the equation:

$$N = N_0 e^{-\lambda t}$$

Where N_0 = the number of radioactive nuclei present at the time zero

t = time that has passed,

λ = fraction of nuclei decaying per unit time

e = 2.718

Also, λ is called the decay constant[12] of the radionuclide. Each radionuclide has a unique decay constant.

9 Electron Capture:电子俘获
10 Auger electrons:俄歇电子
11 Internal Conversion:内转换
12 decay constant:衰变常数

3.1 Half-Life

The time required for half of the atoms in any given quantity of a radioactive isotope to decay is the half-life of that isotope. Each particular isotope has its own half-life. $T_{1/2}$ is related to the decay constant by:

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

It is easy to show that:

$$A = A_0 e^{-\lambda t} = A_0 e^{-(0.693/T_{1/2})t}$$

Where A is the activity of the sample at time t and A_0 is the activity at time zero.

3.2 Radioactivity (A)

Radioactivity is defined as the amount of radioactivity decay per unit time. The original unit was the curie (Ci)[13]. In the International System of Units (SI), the curie has been replaced by the Becquerel (Bq)[14]. It is defined as 1 radioactive decay per second.

$$1\ \text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$$

$$1\ \text{Bq} = 2.703 \times 10^{-11}\ \text{Ci}$$

4 Interaction of Electrons with Materials

4.1 Ionization[15] and Excitation[16]

When charged particle (α-ray or β-ray) move through materials, it interacts on the orbit electron of the material. Electrons orbiting in the atoms that constitute the material are either excited to higher energy orbits (atomic excitation) or removed from the atom entirely (ionization).

4.2 Bremsstrahlung[17]

Bremsstrahlung is the classic way to produce electromagnetic radiation and photons. When a high energy electron traversing a material, it may sharply deflect in its path and lose energy due to its attraction to the protons. This deceleration of the electron may produce what is termed a bremsstrahlung photon. A bremsstrahlung photon may have any energy between zero and the energy that the electron initially possesses.

4.3 Scatter[18]

It is possible for the incoming electron to be deflected in its trajectory past the nucleus without the

13 curie (Ci):居里
14 Becquerel (Bq):贝可勒尔
15 ionization:电离
16 excitation:激发
17 bremsstrahlung:韧致辐射
18 scatter:散射

production of bremsstrahlung. This is called elastic scatter, a term which means that the total kinetic energy of the colliding bodies is the same before and after the collision. None of the kinetic energy goes into the production of other radiation or into excitation processes.

In the elastic collision of a light object (electron) with a heavy stationary object (the protons of the nucleus), the light object retains all its kinetic energy while the heavy object remains in place. Although the electron dose not lose energy, it may suffer a large deflection that greatly affects its direction of motion. Elastic nuclear scatter of electrons occurs relatively frequently.

5 Interaction of Photons with Matter

What happens to gamma rays and X rays as they move through materials? For the photon energies we ordinarily encounter in nuclear medicine only three interactions are of much importance: Compton scatter[19], photoelectric absorption[20], and pair production[21].

5.1 Compton Scatter

To "scatter" means to change direction after a collision. In Compton scatter, a photon interacts with an outer shell electron in an atom of the material that the photon is traversing. The photon scatters from the electron, the electron is knocked away from the atom, and the photon loses whatever energy the electron acquires.

5.2 Photoelectric Absorption

The absorption of a particle in an interaction implies the complete loss of energy of the particle. In photoelectric absorption, a photon interacts with the atom, losing all its energy in the process. An inner shell electron (usually a K shell electron) is ejected from the atom, leaving a vacancy in the inner shell. When the vacancy is filled by another electron, characteristic X rays will be emitted. The energy of the ejected electron (the photoelectron [22]) is just the initial energy that the photon has minus the binding energy of the electron.

Photoelectric absorption, then, depends critically on the existence of strong binding between the nucleus and the inner-shell electron ejected from the atom. Unless the binding energy is large or the energy of the incident photon is small, photoelectric absorption will not take place.

5.3 Pair Production

The third way in which photons can interact with matter is called pair production. A photon interacts, not with the atomic electrons, but with the electric field of the nucleus. In the process the energy of the photon is converted into an electron and positron pair.

---

19 Compton scattering:康普顿散射(效应)

20 photoelectric absorption:光电吸收(效应)

21 pair production:电子对生成

22 photoelectron:光电子

6 Units of Radioactivity

6.1 Absorbed Dose

The absorbed dose[23], sometimes also known as the physical dose, is defined by the amount of energy deposited in a unit mass in human tissue or other media. The original unit is the rad[24] [100 erg/g]; it is now being widely replaced by the SI unit, the gray[25] (Gy) [1 J/kg].

$$1\ \text{Gy} = 100\ \text{rad}$$

6.2 Dose Equivalent

Dose equivalent[26] is a biological dose that reflects the fact that the biological damage caused by a particle depends not only on the total energy deposited but also on the rate of energy loss per unit distance traversed by the particle, taking into account the type of radiation (alpha, beta, gamma) and the nature of the tissues concerned.

It is expressed in units of rem or, in the SI system, sievert (Sv).[27]

$$1\ \text{Sievert (Sv)} = 100\ \text{rem}$$

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23 absorbed dose:吸收剂量
24 rad:拉德
25 gray:戈瑞
26 dose equivalent:剂量当量
27 sievert (Sv):希沃特

第一章　核物理基础

1　原子的基本结构

1.1　原子核

原子是元素的基本组成单位，由电子与原子核组成。原子核位于原子的中心，集中了原子的大部分质量和全部正电荷。原子核由带有正电荷的质子和不带电的中子组成，两者通过所谓的核力结合在一起。原子核内的质子数，即原子序数，用 Z 表示，这决定了原子的化学元素是什么。原子内的中子数用 N 来表示。原子的质量数用 A 表示，等于 Z 与 N 的总和。一个特定的元素可以有很多种不同的同位素，其相互之间的差异主要在于原子核里的中子数不同。目前已发现100多种元素，其中270种是稳定同位素，2 000多种是不稳定同位素。

1.2　核素、同位素、同质异能素、放射性核素

核素：凡具有一定原子质量、原子序数，并处于不同的能态的原子核称为核素。如 $^{14}_{6}C$，$^{9}_{4}Be$，$^{6}_{3}Li$ 和 $^{7}_{3}Li$ 是不同的核素。

同位素：同位素是具有相同原子序数 Z，不同中子数 N 的核素。由于具有相同的质子数，因此同位素有着相同的化学性质。例如，$^{8}_{5}B$、$^{10}_{5}B$、$^{12}_{5}B$ 是元素硼的三种同位素。

同质异能素：同质异能素是具有相同质量数和中子数，处于不同能态的一类核素。同质异能素的表示方法是在右上角加 m，如 $^{99}_{43}Tc^{m}$ 和 $^{99}_{43}Tc$。

放射性核素：放射性核素是指元素的不稳定同位素，可自发发生衰变或裂变并放射出射线。

2　核衰变

核衰变是一种具有放射性的核素转变成另外一种不同的核素的过程，可通过自发放射出α射线、β射线、γ射线，或通过电子俘获形成，其最终产物为具有低能态、更稳定的核素。每个衰变都有一个特定的半衰期。

2.1　α衰变

重核由于包含较多数目的质子，相互之间具有很强的排斥力，因而变得很不稳定。这些元素通常放射出α粒子以减少质子数。α粒子包含2个中子和2个质子，即氦核($^{4}_{2}He$)：这种放射出α粒子或氦核($^{4}_{2}He$)的过程称α衰变：

$$^{A}_{Z}Z \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He + Q$$

如：$$^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He + 4.937\ MeV$$

2.2 β衰变

β衰变是由于原子核或中子在转换过程中发射出带有正电荷(β^+)或负电荷(β^-)的电子的过程。β粒子的穿透力强于α粒子,但弱于γ或X射线。

2.2.1 β^-衰变

富中子核素可引起中子与质子间的不平衡,原子核内一个中子转变成为质子,发射出一个负电子(β^-)和一个反中微子($\acute{\upsilon}$),这个过程称为β^-衰变。β^-衰变后的子核质量数不变,原子序数加1:

$$^{A}_{Z}Z \rightarrow ^{A}_{Z+1}Y + \beta^- + \acute{\upsilon} + Q$$

如: $$^{32}_{15}P \rightarrow ^{32}_{16}S + \beta^- + \acute{\upsilon} + 1.71\ MeV$$

2.2.2 β^+衰变

富质子核素原子核内一个质子转变为中子,发射出一个正电子(β^+)和一个中微子(υ)的过程,称为β^+衰变或正电子衰变。

$$^{A}_{Z}Z \rightarrow ^{A}_{Z-1}Y + \beta^+ + \upsilon + Q$$

如: $$^{18}_{9}F \rightarrow ^{18}_{8}O + \beta^+ + \upsilon + 0.66\ MeV$$

发射出的正电子(或β^+粒子)具有一定的动能,在行进过程中逐渐消失,当处于静止时,由于动力守恒,正电子与附近的电子发生湮没,放出两个能量为511 keV方向相反的湮没光子。这个过程称为湮没辐射。

$$\beta^+ + \beta^- \rightarrow \gamma + \gamma + 511\ keV$$

正电子在与负电子发生湮没生成两个511 keV光子前,在组织中的移动距离很短。

2.2.3 电子俘获

电子俘获相当于β^+衰变,可产生相似的结果。由于内层电子轨道靠近原子核,轨道上的电子偶尔在运行时被原子核俘获,与核内一个质子相结合转变为中子,并从原子核内发射出一个中微子。

$$^{A}_{Z}X + ^{0}_{-1}e \rightarrow ^{A}_{Z-1}X + \upsilon$$

如: $$^{55}_{26}Fe + ^{0}_{-1}e \rightarrow ^{55}_{25}Mn + \upsilon$$

电子俘获时内层电子轨道留下一个空穴,外层电子跃迁到内层填充,跃迁过程放出标志X射线或俄歇电子。

2.3 γ衰变

γ射线是一种电磁辐射。原子核由激发态向基态跃迁过程中可发生电荷再分布,放射出γ射线,称γ衰变。原子核在γ衰变发射γ射线过程中,质量数和原子序数均不变。

$$^{A}_{Z}X^{m} \rightarrow ^{A}_{Z}Y + \gamma$$

如: $$^{99}_{43}Tc^{m} \rightarrow ^{99}_{43}Tc + \gamma$$

2.4 内转换

原子核由高能态向低能态跃迁时,要么发射出γ射线,要么将多余的能量直接传给核外电

子，后者称为内转换。

3 核衰变规律

放射性原子核将随着时间放射出射线逐渐转变成为稳定性原子核，并在每单位时间内以稳定的常数 λ 进行衰变。因此，经过 t 时间衰变后剩余的核数目 N，用下列等式表示：

$$N = N_0 e^{-\lambda t}$$

N_0 = 初始放射性核数目

t = 经过的时间

λ = 单位时间内核衰变的概率

e = 2.718

λ 被称为放射性核素的衰变常数，每一种放射性核素均具有唯一的衰变常数。

3.1 半衰期

任何具有一定放射性活度的核素衰变到原有值一半所需要的时间，称为该核素的半衰期。每个放射性核素都有它自己特定的半衰期。因此 $T_{1/2}$ 与衰变常数 λ 有关：

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

也可以表示：

$$A = A_0 e^{-\lambda t} = A_0 e^{-(0.693/T_{1/2})t}$$

A_0 代表初始放射性活度，A 代表经过 t 时间后的放射性活度。

3.2 放射性活度

放射性活度是指单位时间放射性核素衰变的次数。以前的单位是居里（Ci），国际单位制（SI）中居里已经被贝克勒尔（Bq）取代，表示每秒 1 次放射性衰变。

$$1\ \text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$$

$$1\ \text{Bq} = 2.703 \times 10^{-11}\ \text{Ci}$$

4 带电粒子与物质的相互作用

4.1 电离与激发

当带电粒子（α 射线或 β 射线）通过物质时，和物质中的轨道电子发生相互作用，组成物质的原子中的轨道电子要么被激发到能量较高的轨道（激发），要么从原子中完全脱离（电离）。

4.2 韧致辐射

韧致辐射原指产生电磁辐射的经典方式，由于原子核对电子的吸引力，当电子接近原子核时运动方向可发生很大的偏离，这种加速电子可产生韧致辐射光子，韧致辐射光子的能量可从零到电子所具有能量。

4.3 散射

入射电子通过原子核时也可在它自己的路径上发生偏转，而不产生韧致辐射。弹性散射是

指碰撞前后动能不变者,其中动能并不转变成其他辐射或进入激发过程。

当一个较轻的粒子(如电子)与一个较重的粒子(如质子)发生弹性碰撞时,重粒子保持不动,轻粒子仍保留其所有动能,虽然电子并不失去能量,但其运动方向将发生很大改变。电子发生弹性散射的概率相当频繁。

5 光子与物质的相互作用

当γ、X射线通过物质时,会发生什么反应呢?在核医学中光子与物质相互作用比较重要的形式主要有三种:康普顿散射、光电效应、电子对生成。

5.1 康普顿散射

"散射"的意思是碰撞后的方向改变。在康普顿散射中,光子与作用物质的外层轨道电子相互作用,入射光子的部分动能转移给电子而发生散射,使电子获能而脱离原子。

5.2 光电吸收

一个粒子被吸收意味着在相互作用中粒子能量的全部丧失。光电效应是指光子与物质原子互相作用时,失去全部能量并把这部分能量转交给内层(通常K电子层)的核外电子,使之发射出来,这样内层电子层就出现了电子空位,当空位被其他电子填充时可发出标志X射线。脱离原子的电子(光电子)的能量为入射光子能量与电子的结合能之差。

光电吸收的发生取决于核外内层电子与原子核的结合能,入射光子能量较小或电子的结合能较大时,则不会产生光电效应。

5.3 电子对生成

光子与物质相互作用的第三种方式是电子对生成。光子并不与原子中电子相互作用,而是与原子核电场相作用。在这个过程中,光子的能量被转换为一个正电子和一个负电子。

6 辐射量及其单位

6.1 吸收剂量

吸收剂量也称为物理剂量,它表示单位质量受照人体组织或其他介质所吸收的辐射能量。它原来的单位是用拉德[rad]表示,现在已被国际单位值戈瑞(Gy)替代。

$$1\ \text{Gy} = 100\ \text{rad}$$

6.2 剂量当量

剂量当量是一个生物学剂量,它反映的是生物损害程度。它不仅依赖沉积的全部能量,而且取决于粒子在通过介质时每个单位距离失去的能量,辐射的类型(α射线、β射线或γ光子)和介质组织的性质也在考虑范围内。剂量当量的单位是雷姆(rem),国际单位是希沃特(Sv)。

$$1\ \text{Sv} = 100\ \text{rem}$$

(刘建军)

CHAPTER TWO

NUCLEAR MEDICINE INSTRUMENTATION

Nuclear medicine instrumentation means some special systems, which measure and detect the amount or number of ionizations or excitation events.

1 Principle to Detect and Measure the Radiation

There are several effects caused by ionizing radiation, which allows us to detect and measure the radiation and these are as follows.

1.1 Ionization

Ionization is caused by radiation. The number of ion pairs collected can be related to the amount of radiation causing the ionization. Many radiation-monitoring instruments use ionization as the detection mechanism, e. g. Ion chamber; Geiger-Müller counter.

1.2 Scintillation[28]

Scintillation is the production of light following the movement of electrons from high energy levels orbits to lower energy levels within an absorbing material. The electrons have moved into higher energy orbits by the process of excitation. The light released can be converted to an electrical signal. The size of the electrical signal depends on the number of electrons moved into higher energy orbits and can therefore be related to the amount of radiation causing the scintillation. Scintillation is a very important detection mechanism for radiation monitoring and detectors, scintillation detectors are commonly made through this mechanism.

1.3 Chemical Mechanism

Ionizing radiation reacts with photographic film in the same way as visible light i. e., exposure to radiation blackens the film. This effect is observed in the use of photographic film for personal dosimetry, medical X-rays and industrial radiography.

2 Detector

The types of detector used in radiate detection and measurement devices include scintillation detectors; ion chamber; Geiger-Mueller tubes; semi-conductors and so on.

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28 Scintillation:闪烁