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Physics for radiological workers

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Summary
The graduate of the undergraduate course "Imaging Methods and Applications of Ionizing Radiation" can work as a Radiological assistant (e.g. at the hospitals), a Radiological technologist (e.g. at the nuclear power stations) or a Radiological specialist (e.g. for the municipal authorities). The profile of the graduate will be elaborated on the basis of analytical-synthetic modelling. Analytical-synthetic model of the profile enables to find out the role of physics for radiological workers in the framework of the relevant undergraduate course. It will be presented by means of several illustrations of partial topics of physics for radiological workers

Keywords: analytical-synthetic modelling – udergraduate course of physics – the graduate – core curriculum – ilustration of partial topics

INTRODUCTION

A graduate of the undergraduate course "Imaging Methods and Applications of Ionizing Radiation" can work as a Radiological assistant, a Radiological technologist or a Radiological specialist. The profile of the graduate will be elaborated on the basis of analytical-synthetic modelling. The analytical-synthetic model of the profile enables to find out the role of physics for radiological workers in the framework of the relevant undergraduate course.

The essence of analytical-synthetic modelling will be explained in Chapter 1. The lay out of *physics for radiological workers* will be described by means of a concrete model of the graduate´s profile. It will be further developed in Chapter 2. Further chapters will present a number of illustrations of partial topics of physics for radiological workers.

ANALYTICAL-SYNTHETIC MODELLING OF THE COGNITIVE STRUCTURE OF INVESTIGATED PROBLEM

In Czech education in physics a new theory – ("Didactic Communication of Physics") was developed by Brockmeyer (1982). Within the framework of this theory it is necessary to express and suitably communicate knowledge of physics. For this purpose new methods were devised which reflected the cognitive structure of concepts and knowledge in physics.

These methods emanate from the analytical-synthetic structure and from hierarchically arranged levels of conceptual knowledge systems. These methods utilize models and net graphs (see Volumes 1989, 1990, Záškodný 2001a).

The general model of the cognitive structure of the problem being investigated(see Fig. 1) consists of the analytical-synthetic modelling of the concrete problem (see Van Deursen and Záškodný 2001, Záškodný 2001b). It can be shown that this analytical-synthetic modelling is acceptable not only for education in physics but also for research into problems concerning other scientific branches.

In addition, such analytical-synthetic modelling can be connected with the interactive modelling of the structure of the problem being investigated. The whole procedure can be presented by means of two steps:

a) The Creation of a model of analytical-synthetic (cognitive) structure of the investigated problem (see Fig. 1)
b) The creation of a model of the interactive structure of the investigated problem on the basis of the existing model of the analytical-synthetic structure

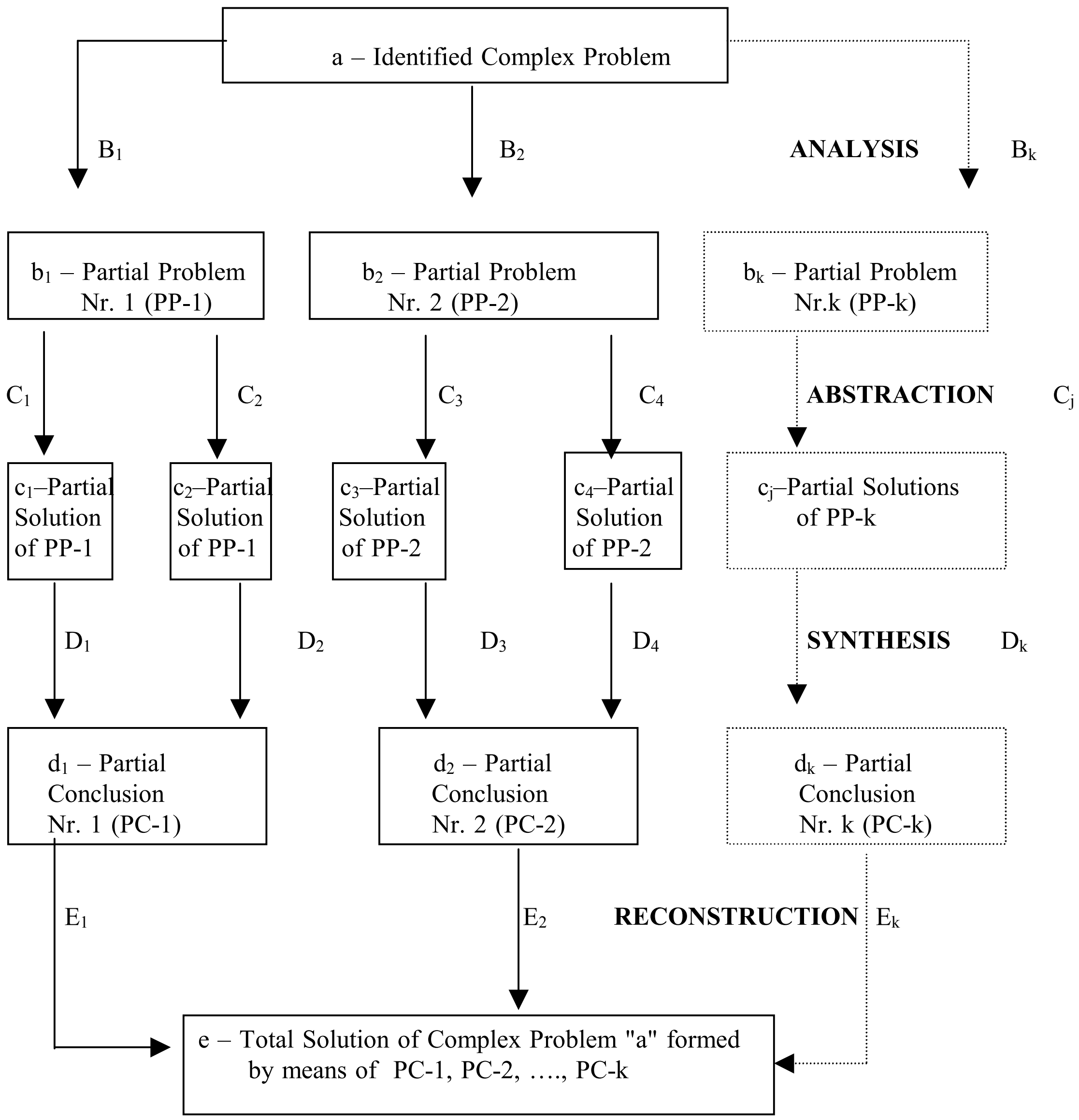


Fig. 1. **General model of analytical-synthetic (cognitive) structure**

a (Identified Complex Problem) – Investigated area of reality, investigated phenomenon

B_k (Analysis) – Analytical lay out within the framework of corresponding knowledge level

b_k (Partial Problems PP-k) – Result of analysis: essential attributes and features of investigated phenomenon

C_k (Abstraction) – Qualification of abstraction essences within the framework of corresponding knowledge level

c_k (Partial Solutions of PP-k) – Result of abstraction: partial concepts, partial knowledge, various relationship etc.

D_k (Synthesis) – Synthetic finding of dependences among the results of abstraction within the framework of corresponding knowledge level

d_k (Partial Conclusions PC-k) – Result of synthesis: principle, law, dependence, continuity etc.

E_k (Intellectual Reconstruction) – Intellectual reconstruction of investigated phenomenon / investigated area of reality

e (Total Solution of Complex Problem "a") – Result of intellectual reconstruction: analytical-synthetic structure of conceptual knowledge systém

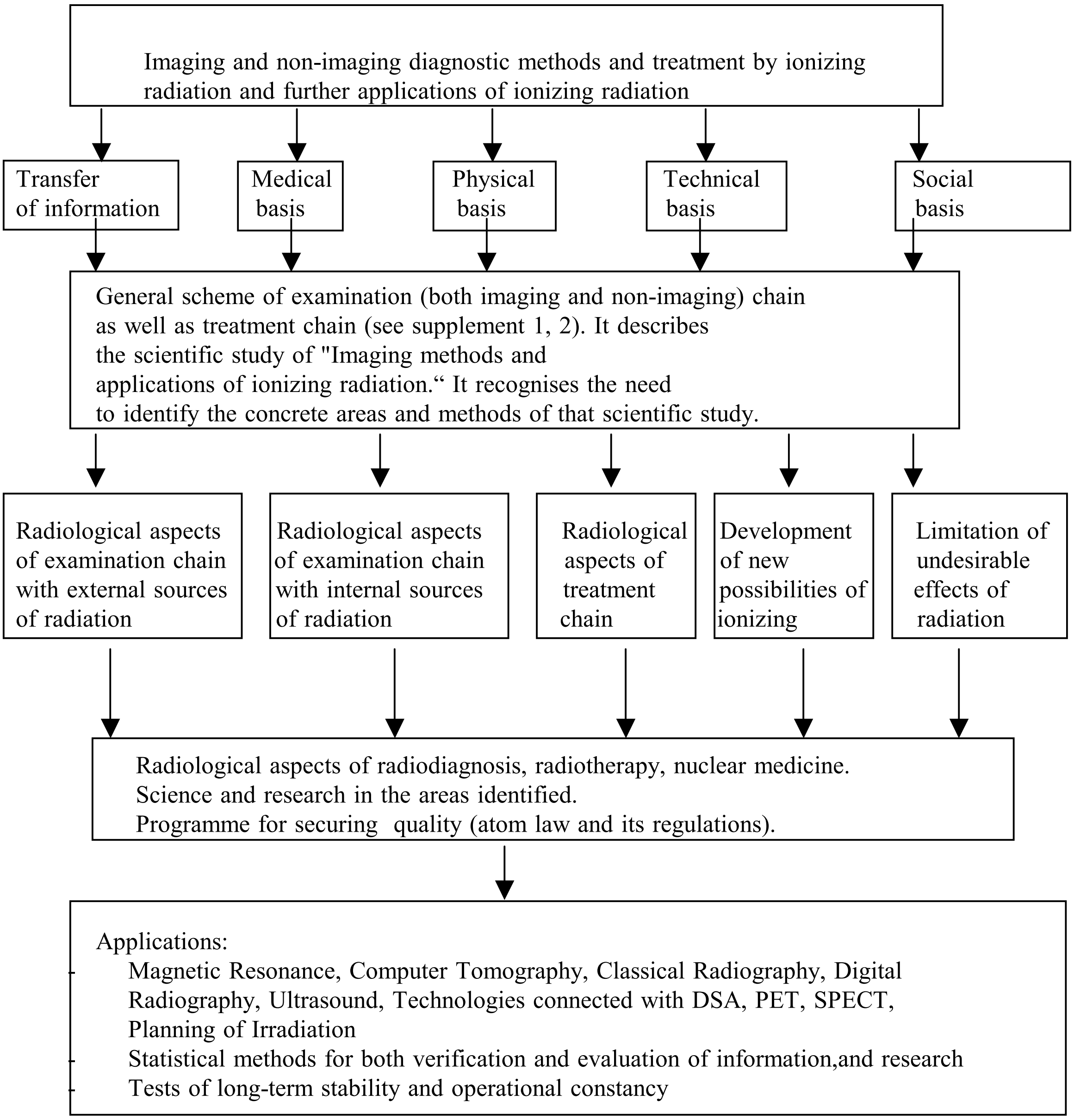
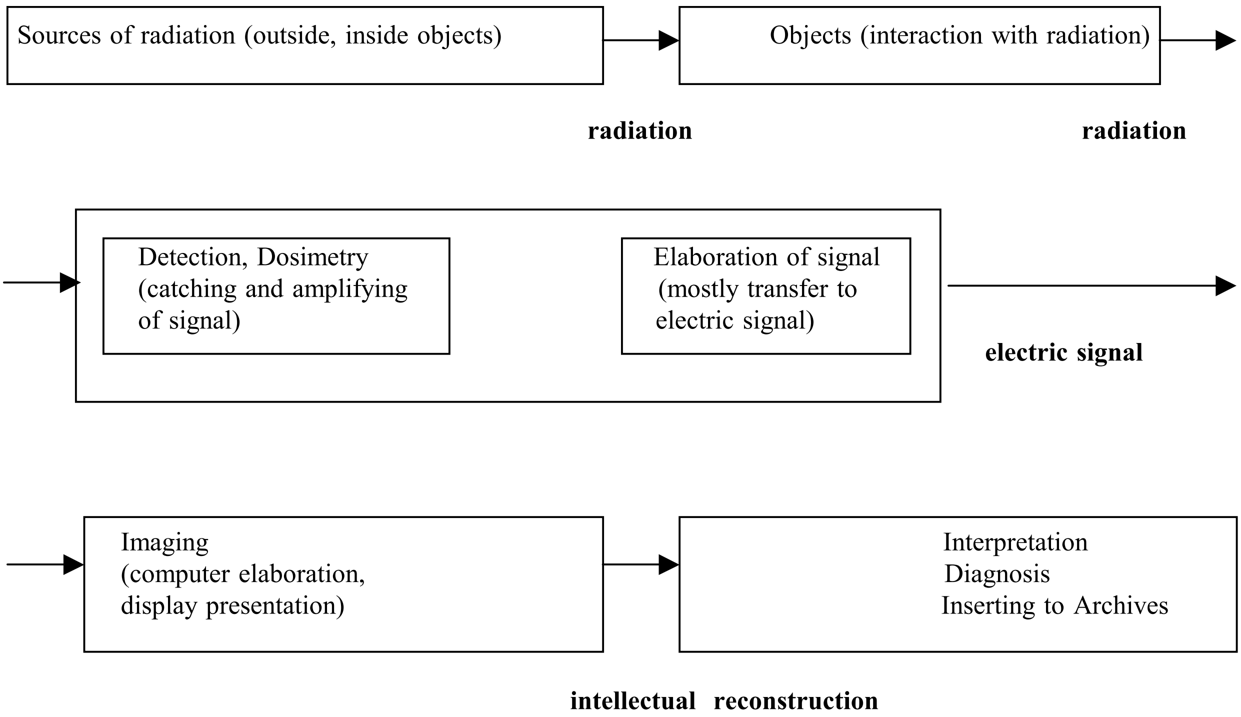
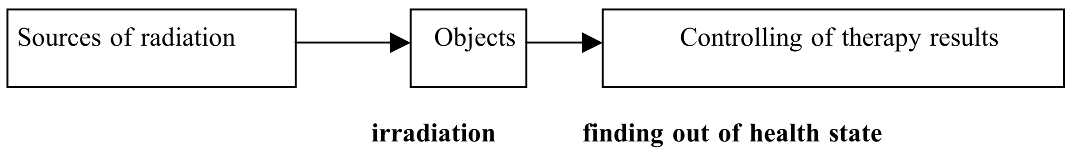


Fig. 2. **Analytical-synthetic model of the graduate´s profile**

Supplemet 1 to Fig. 2**. General Scheme of Examination Chain**



Supplement 2 to Fig. 2. - **General Scheme of Therapeutic (Treatment) Chain**



Substantial Parts of Analytical - Synthetic Model

- Transfer of information (see supplement 1, 2)
- Medical Basis (Anatomy, Physiology, General and Special Pathology etc.)
- Physical Basis (General Physics Basis-e.g. Standard Model of Fundamental Particles and Interactions, Radiological Physics-Sources, Interaction, Detection and Dosimetry, Elaboration of Signals)
- Technical Basis (Informatics, Electronics, Application of Nuclear and Atomic Physics, Optical Electronics)
- Social Basis (Necessary Knowledge from Social Sciences, Psychology, Ethics, Philosophy etc.)

LAY OUT OF PHYSICS FOR RADIOLOGICAL WORKERS

The lay out of *Physics for Radiological Workers* will be described by means of the concrete analytical-synthetic model of the graduate´s profile (see Fig. 2). Now, the lay out of physics for radiological workers can be expressed (via both Fig. 2 and Legend to Fig. 2) in the form of the core curriculum (see Záškodný 1991, Graham 1999):

1. Introduction to physics for radiological workers (structure of general physics, structure of radiological physics basis, comparison between graduate´s profile and

physical basis, physical quantities, SI base units, derived SI units)
2. Requisite basis of classical and relativistic mechanics (kinematics, dynamics, mass-energy equivalence)
3. Requisite basis of theory of electromagnetic field (electrical charge, microcharge and macrocharge, Maxwell´s equations, lay out of theory of electromagnetic field, electromagnetic induction, motion of electron in homogenous electric and magnetic field, electrostatics, direct current-steady theory, current in gas-ionization effects of radiation)
4. Requisite basis of oscillation and undulation (kinematics and dynamics of oscillation, alternating current with lower frequency-electromagnetic oscillator, quasi-steady theory, kinematics and dynamics of undulation, alternating current with higher frequency-electromagnetic undulation, non-steady theory)
5. Requisite basis of light and radiation (optics in the best sense of the term - theory of radiation, optics in a narrow sense – theory of light, spectrum of electromagnetic radiation, X-radiation and gamma-radiation, basis of quantum optics, wave-particle duality)
6. Requisite basis of quantum mechanics and nuclear physics (cycle of cognition in classical and quantum mechanics, principle of correspondence, principle of complementarity, Heisenberg´s uncertainty principle, physical quantity and mathematical operators, Schrödinger´s equation, principle of identity – fermions and bosons, Pauli´s exclusion principle, structure of atom, parameters of nucleus, parameters of nucleon, quantum mechanics of electron, quantum mechanics of nucleus, radioactivity, decay exponential law, absorption exponential law)
7. Sources of ionizing radiation (standard model of fundamental particles and interactions, natural radioactive radiation, artificial radioactive radiation, X-ray tube, X-ray spectrum, radionuclides, accelerators)
8. Interactions of ionizing radiation with matter (attenuation and absorption, photoelectric absorption, Rayleigh scattering , Compton scattering, pair production, bremsstrahlung and characteristic radiation)
9. Detection of ionizing radiation (mechanisms od detection, ionization chamber – graphic expression of function stress-dependent, Wilson chamber, bubble chamber, scintillation detector, semiconductor detector, some other types of detectors)
10. Radiation dosimetry (units of exposure and dose, quality factor and dose equivalent, absolute measurement of absorbed dose, proportional counter, Geiger-Muller counter, anticoincidence counter, Tcherenkov counter, crystal counter, spark counter, some other types of dosimeters)

ILLUSTRATION OF PARTIAL TOPICS OF PHYSICS FOR RADIOLOGICAL WORKERS

(cf. Graham 1999, Záškodný 2002)

MATERIAL AND FIELD FORM OF MATTER, FERMIONS AND BOSONS

Modern physics regards the material particles (these particles travel with a velocity, v, which is less than velocity, c, of light and velocity, v, can be equal to 0) and the field particles (these particles always travel with velocity c and they cannot exist in a stationary state) as being two manifestations of the same phenomenon – matter. The material form of matter and the field form of matter exist simultaneously and can be converted into each other.

Einstein showed that the mass, m, of material particle and its energy, E, (excluding potential energy) are related by the formula $E = mc^2$. Planck showed that the energy of the most typical field particle, photon as quantum of electromagnetic radiation, is given by the formula $\varepsilon = h\nu$ (Greek letter ν marks the frequency of relevant electromagnetic radiation).

The material particles (e.g. proton, neutron, electron, atom, molecule etc.) can often be connected with construction elements of the world and can be considered as the constituents of matter The material particles as the constituents of matter are the fermions. The spin as intrinsic angular momentum of fermions is equal to an odd multiple of $h / 4\pi$ (the constant, h, is Planck´s constant). The fermions obey the Pauli´s exclusion principle – individual quantum state can be occupied to an extreme degree by only one fermion.

Some material particles and all field particles are connected with force fields which hold the construction elements of the world together and can be considered as the force carriers. The particles as the force carriers are the bosons. The spin as intrinsic angular momentum of bosons is equal to an even multiple of $h / 4\pi$. The bosons do not obey the Pauli´s exclusion principle.

As can be seen from the above discussion, the material form and the field form can be considered as two manifestations of the same thing and may be changed from one form to the other in appropriate circumstances, as the following examples show:

- the force fields which hold the atomic nucleus together are obtained because part of the mass of nuclear particles (protons and neutrons above all) is converted into particles as the force carriers. Because of this the mass of nucleus is less than the sum of the masses of the individual nuclear particles
- if a gamma radiation has an energy ε greater than 1,02 MeV and passes close to the nucleus of an atom, the group of gamma photons may spontaneously disappear and create the pair particle-antiparticle, i.e. an electron and a positron. This process is known as pair production. The positron created via pair production will interact with an electron and their mass will be converted into two photons of radiation, each photon having an energy of 0,51 MeV. This process is known as annihilation of matter, the radiation created via annihilation of matter is referred to as annihilation radiation.

MAIN SUBATOMIC PARTICLES

Most of the phenomena, important for radiological workers, can be explained using a relatively simple planetary model of the atom. In this model the solid electrons orbit a solid nucleus.

Some phenomena (for example: origin of both characteristic and bremsstrahlung X-radiation) must be explained using the quantum physics model (explanation of origin of X-radiation: application of the Schrödinger equation for free or bound electron). In this model the electrons are regarded as probability clouds – they occur in different points of the nucleus neighbourhood with different probability (the probability clouds of electrons coincide themselves – respective electrons aren´t distinguished).

If the atom isn´t absorbing or emitting the photons of electromagnetic radiation, the bound electron is in the stationary state, it doesn´t move, it occurs in the neighbourhood of the nucleus as a probability cloud. The motion of the bound electron is connected with the change of shape of the probability cloud – in this case the atom radiates or absorbs the radiation.

The electron as a reflection of such a quantum model is neither particle nor wave, it is a manifestation of particle-wave duality, it is a new physical quality which is not possible to understand by means of methods of classical physics. Newton´s classical mechanics must be substituted by quantum mechanics, classical physical quantities must be substituted by mathematical operators, solution of Lagrange´s or Hamilton´s equations must be substituted by the solution of the steady or non-steady Schrödinger equation.

The planetary model of the atom was first described by Rutherford. It describes an atom consisting of a small positively charged central nucleus (proved via experimental work connected with the scattering of alpha-particles by atoms) around which negatively charged electrons move in defined orbitals (from the point of view of the quantum model such an image isn´t correct, the electrons don´t move, they only occur in the neighbourhood of the nucleus as probability clouds). This model can be used to illustrate the carbon atom C with atomic number $Z = 6$ and nucleon number $N = 12$. The nucleus of this atom consists of 12 fundamental particles, 6 protons and 6 neutrons. The electrons are arranged in orbitals or shells called K, L, M, … starting the orbital closest to the nucleus. The electron envelope of this atom consists of K-shell containing 2 electrons and L-shell with remaining 4 electrons.

On the basis of experimental works it was recently verified whether protons and neutrons can be broken into smaller pieces. These experiments use high-energy electrons to bombard the protons and neutrons and measure the angle of deflection of falling electrons. The results have shown that there are small solid structures within the protons and neutrons. These may be the basic building elements of universe; they are known as quarks and 18 different types of quark were identified (6 quarks called up quark, down quark, charm quark, strange quark, top quark, bottom quark; each quark carries one of 3 types of "colour charge" - 6 multiplied by 3 is equal to 18).

WAVE-PARTICLE DUALITY

Modern physics identifies material particles (their particle properties expressed via mass, m, and momentum, p, are self-evident) and field particles (their wave properties expressed via wavelengths, λ, and frequency, ν, are self-evident also) as being two manifestations of the same phenomenon - matter. Similarly, modern physics blurs the distinction which exists in classical physics between a particle and a wave.

Especially modern physics of the microworld (quantum physics above all) presents the material form of matter as well as the field form of matter as an absolutely perfect connection of particle and wave properties. This unity of particle and wave properties has been given the name "wave-particle duality".

Wave-particle duality, should be proved. It will be necessary to show that the field particles (e.g. photons which are associated with electromagnetic undulation; electromagnetic waves travel with a velocity, c, of light. In this case $c = \nu\lambda$, where ν is the frequency of the radiation and λ is its wavelength) have got the particle properties, i.e. they have got mass, m, as well as momentum, p. Similarly, it will be necessary to show that the material particles (e.g. electrons, their rest mass, m_0, is known $m_0 = 5{,}1.10^{-4}$ GeV / c^2; electrons travel with a velocity, v, less than velocity of light and this velocity determines their momentum, p. In this case $p = mv$, where m is the relativistic mass of the electron) have got wave properties, i.e. they have got wavelength, λ, as well as frequency, ν.

Waves as particles

Classical physics was very successful in explaining the wave phenomena associated with electromagnetic radiation, e.g. diffraction and interference. However phenomena like the Compton scattering and photoelectric phenomenon cannot be explained using wave theory. These effects are explained by considering that sometimes electromagnetic radiation behaves as "packets" of energy which have obtained a mass, m, and a momentum, p. Such a quantum of energy (the quantum will have an energy, ε, given by $\varepsilon = h\nu$) is called a photon. So called "old quantum theory" (created by M. Planck) has been able to discover the mass, m, and the momentum, p, of a photon.

Using Einstein´s equation $E = mc^2$ and Planck´s equation $\varepsilon = h\nu$ it is possible to get the formula for the mass of photon $m = h\nu / c^2$.

Using classical relation $p = mc$ and Planck´s equation it is possible to get the formula for the momentum of photon $p = h\nu / c$.

Thus, the electromagnetic wave may also behave like a particle, possessing mass, energy and momentum.

Particles as waves

Perhaps the most dramatic example of particles behaving like waves is in the operation of the electron microscope. Here high-energy electrons are passed through or are scattered by a sample. A very highly magnified image of the sample is obtained so that individual large molecules may be seen in materials. The reason for the high degree of magnification is the very small wavelength of the electrons.

By analogy with the formulae for a photon (installing $c = \nu\lambda$) and using classical relation $p = mv$ de Broglie has got the formula for the wavenlenght of electron $\lambda = h / mv$.

By analogy with the formulae for a photon (installing $p = mc$) de Broglie has obtained the formula for the frequency of electron $\nu = mc^2 / h$.

The velocity, v_{dB}, of an enlargement of de Broglie´s wave is given by $v_{dB} = \nu\lambda$. Installing above derived the formulae it is possible to get $v_{dB} = c^2 / v$, where v is velocity of electron as particle. The velocity of enlargement of de Broglie´s wave is more than the velocity of light – from this reason it is evident that de Broglie´s wave is connected with the probable wave. Because of this, the image of an electron connected (in the stationary state) with the constant shape of the probable cloud is entirely qualified.

For example, the de Broglie´s wavelength associated with an electron moving with half the velocity of light is about 4.10^{-12} m. This size is less than the diameter of the hydrogen atom (100.10^{12} m).

STANDARD MODEL OF FUNDAMENTAL PARTICLES AND INTERACTIONS

Standard model of fundamental particles and interactions was created by the Fundamental Particles and Interactions Chart Committee, an outgrowth of the Conference on Teaching of Modern Physics (U.S.A., 1998). This project received support from the Particle Data Group of Lawrence Berkeley Laboratory and from the Stanford Linear Accelerator Center.

Standard model consists of 6 parts:

Part 1 – Structure within the Atom
Part 2 – Fermions as Matter Constituents
Part 3 – Bosons as Force Carriers
Part 4 – Properties of the Interactions
Part 5 – Neutron β Decay
Part 6 – Annihilation of Matter (electron-antielectron, quark-antiquark)

SELF – TEST

a. Explain the meaning of the following:
(i) a nuclide
(ii) a radionuclide
(iii) an isotope
(iv) an isobar
(v) atomic number
(vi) nucleon (atomic mass) number

b. With the aid of previous item, describe the $^{14}_{7}N$ atom

c. What is meant by the terms excitation and ionization when used to describe changes in electron energy within an atom?

d. Give four equations which link the photon energy, mass, momentum and wavelength of electromagnetic radiation

e. What is the wavelength of radiation which has a photon energy of 50 keV? (1 eV = $1{,}6.10^{-19}$ V, h = $6{,}6.10^{-34}$ J s)

f. What is the photon energy of radiation which has a wavelength of 0,0124 nm?

g. Define the terms:
(i) rest mass
(ii) relativistic mass
(iii) mass-energy equivalence

h. Discuss the concept of wave-particle duality

i. Identify a situation where a wave behaves as a particle and a situation where a particle behaves as a wave.

j. Discuss the image of an electron in a stationary state and in motion

k. Discuss the relation of the de Broglie wave to the probable cloud

l. Define the terms:
(i) a fermion
(ii) a boson
(iii) a matter constituent
(iv) a force carrier
(v) annihilation of matter
(vi) type of interaction
(vii) neutron β decay

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