MINISTRY OF SCIENCE AND HIGHER EDUCATION
OF THE RUSSIAN FEDERATION

NATIONAL RESEARCH NUCLEAR UNIVERSITY
"MEPHI"

Problem book for the course Nuclear Physics

Educational edition

Moscow 2020

УДК 539.1(075.8)
ББК 22.383 Я7
С23

Problem book for the course Nuclear Physics. Educational edition. // I.I. Astapov, N.S. Barbashina, A.N. Dmitrieva, E.A. Zadeba, S.S. Khokhlov, I.I. Yashin. M.: NRNU MEPHI, 2020. 64 p.p.

The book contains problems on the main topics of the course of nuclear physics, to be considered with first-year master's students at seminars, as well as intended for independent work of students (as a homework assignment). The book is compiled in accordance with the requirements of the Educational Standard of NRNU MEPhI: 03.04.02 "Physics", 14.04.01 "Nuclear power engineering and thermal physics", 14.04.02 "Nuclear physics and technologies", 22.04.01 "Materials science and technology", 11.04.04 "Electronics and nanoelectronics".

В сборнике собраны задания по основным темам курса ядерной физики, рассматриваемые со студентами первого курса магистратуры на семинарах, а также предназначенные для самостоятельной работы студентов (в качестве домашнего задания). Сборник составлен в соответствии с образовательными стандартами НИЯУ МИФИ: 03.04.02 "Физика", 14.04.01 "Ядерная энергетика и теплофизика", 14.04.02 "Ядерные физика и технологии", 22.04.01 "Материаловедение и технологии материалов", 11.04.04 "Электроника и наноэлектроника".

Reviewer: Dr. Phys. - Math. Sciences, Professor V.V. Borog

ISBN 978-5-7262-2697-2

Content

Recommendations to students

Due to the large amount of material and the limited number of classes in the course “Nuclear physics”, the student’s work on problems should be largely independent. You can use any literature and internet resources. It is strongly recommended to contact your teacher for guidance.

Before doing your homework you should first read the recommended literature and, if necessary, make a brief summary of the main concepts, terms and information that have to be remembered and are fundamental to this topic and for the understanding of subsequent sections of the course.

Problem solving should not be delayed until the last night before class. The solution of problems and used formulae should be accompanied by explanations. It is necessary to specify in the explanations the basic laws and formulae on which the solution of this problem is based. We recommend that you solve the problem firstly in a general form, i.e. only in a literal notation, explaining the letter designations in formulae scripting. The resulting solution in a general form should be checked for the correct dimension. In the numerical answer you should also specify the dimension of the calculated value.

The necessary reference materials are provided in the Appendix at the end of the book.

Recommended references

1. Introductory nuclear physics, 2nd edition. Samuel S. M. Wong. Wiley-VCH Verlag GmbH and Co. KGaA. 2004.
2. Modern nuclear chemistry. W.D. Loveland, D.J. Morrissey, G.T. Seaborg John Wiley and Sons, Inc., Hoboken, New Jersey. 2006.
3. Handbook of nuclear chemistry. Editors: A. Vértes, S. Nagy, Z. Klencsár R.G. Lovas, F. Rösch. Springer. 2011.
4. C. Bromberg, A. Das, T. Ferber. Introduction to nuclear and particle physics: solutions manual for second edition. New Jersey: World scientific, 2006.

List of recommended internet resources

1. www.library.mephi.ru
2. http://elibrary.ru/
3. http://www.sciencedirect.com/science/journals/
4. http://www.nature.com/
5. http://link.springer.com/
6. http://pdg.lbl.gov/
7. http://pdg.lbl.gov/2009/AtomicNuclearProperties/
8. http://periodictable.com/index.html
9. https://www.nndc.bnl.gov/chart/
10. https://www-nds.iaea.org/
11. https://www.nist.gov/pml/productsservices/physical-reference-data

1. Kinematics

The relative speed of a particle is

$$\beta = \frac{v}{c}, \tag{1.1}$$

where v is the particle velocity, c is the speed of light in a vacuum.

The momentum of a relativistic particle is

$$\vec{p} = m\vec{v} = \frac{m_0 \vec{v}}{\sqrt{1-\beta^2}}, \tag{1.2}$$

where m is the relativistic mass of a particle, m_0 is the rest mass of the particle:

$$m = \frac{m_0}{\sqrt{1-\beta^2}}. \tag{1.3}$$

The total energy of a relativistic particle is

$$E = \frac{m_0 c^2}{\sqrt{1-\beta^2}} = T + m_0 c^2. \tag{1.4}$$

The kinetic energy of a relativistic particle is

$$T = E - m_0 c^2. \tag{1.5}$$

The relationship between momentum and energy is

$$E^2 = (pc)^2 + (m_0 c^2)^2, \tag{1.6}$$

$$pc = \sqrt{T(T + 2m_0 c^2)}, \tag{1.7}$$

$$\beta = \frac{pc}{E} = \frac{pc}{\sqrt{(pc)^2 + (m_0 c^2)^2}} = \frac{\sqrt{T(T + 2m_0 c^2)}}{T + m_0 c^2}. \tag{1.8}$$

The de Broglie wavelength of a particle with momentum p is

$$\lambda = \frac{h}{p} = \frac{hc}{pc}, \quad \lambdabar = \frac{\hbar c}{pc}, \tag{1.9}$$

$\hbar c$ is the conversion constant.

The lifetime of an unstable particle in the laboratory coordinate system is

$$\tau = \frac{\tau_0}{\sqrt{1-\beta^2}}, \tag{1.10}$$

where τ_0 is the proper life time of the particle.

1.1. How to convert J to eV? How to convert eV to J? How to convert J to erg?

1.2. Knowing the mass of neutron, proton and electron in g (see Appendix), calculate their rest masses in MeV/c^2.

1.3. Using formulae above, derive the specific one for the calculation of kinetic energy in the non-relativistic case $T = mv^2/2$ (case $T \ll m_0c^2$).

1.4. Prove that the massive particle ($m_0 \neq 0$) always moves with a velocity $\beta < 1$, but γ-quanta (in vacuum) with $\beta = 1$.

1.5. The proton velocity is $V_p = 2.9 \cdot 10^8$ m/s. Find the total E and kinetic T energies of the proton and its momentum p (in eV and eV/c).

1.6. The kinetic energy of an electron is $T = 3$ MeV. Find its velocity V_e.

1.7. Calculate the kinetic energies of particles born in the decay of a resting π^+-meson: $\pi^+ \to \mu^+ + \nu_\mu$.

1.8. Calculate the kinetic energies of particles born in the decay of a resting π^0-meson: $\pi^0 \to e^+ + e^-$.

1.9. Calculate the kinetic energies of particles born in the decay of a resting K^--meson: $K^- \to e^- + \tilde{\nu}_e$.

1.10. Calculate the kinetic energies of particles born in the decay of a resting K^--meson: $K^- \to \pi^- + \pi^0$.

1.11. A π_0-meson has kinetic energy equal to the rest energy, it decays into two γ-quanta whose energies are equal. What is the angle between γ-quanta tracks?

1.12. How many times will the life time of the π-meson increase, if its kinetic energy is $T_\pi = 10 m_\pi c^2$?

1.13. Calculate the value of the conversion constant $\hbar c$ in MeV·fm.

1.14. A proton, an electron and a photon have the same wavelength $\lambdabar = 100$ fm. What time t do they need to pass $L = 10$ m distance?

1.15. A free electron moves with kinetic energy 1 GeV. Estimate the de Broglie wavelength $\lambdabar$.

1.16. A free electron moves with kinetic energy $T_e = 10$ keV, 1 MeV, 1 GeV. Estimate the de Broglie wavelength.

1.17. Estimate the total E and kinetic T energies of the proton if its de Broglie wavelength is $\lambdabar = 10^{-2}$ fm.

1.18. Find the electron velocity for several values of kinetic energy: $T = 5$ keV, 50 keV, 0.25 MeV, 3 MeV. How many percent will these energies differ from the calculations with the formula for the non-relativistic case?

1.19. Calculate the velocity of a proton that has kinetic energy equal to: a) 0.01 of its mass, b) 0.1, c) 1, d) 10. Compare the result with the values obtained by using non-relativistic formulae.

1.20. Using relativistic and classical formulae, calculate the energy that must be given to a proton to accelerate it to speed: a) 0.01 of the light velocity, b) 0.1, c) 0.5, d) 0.9. Ignore energy losses.

1.21. The maximum possible energy of particles in cosmic rays is estimated at $5 \cdot 10^{19}$ eV, this is due to the so-called relic cutoff of the spectrum in the region of extremely high energies (the Greisen-Zatsepin-Kuzmin limit). Convert this energy to J and determine the speed at which a bullet (weighing 3.4 g) with the same energy or a ping-pong ball (weighing 2.5 g) moves.

1.22. A scheme of an experiment for the determination of the momentum of positrons emitted by a monochromatic source is presented in Fig. 1.1. The positrons released from the collimator enter the magnetic field (directed perpendicular to the direction of the particle track), moving, as a result, in a semicirclular path, at the end of which the particles fall into a detector located at a distance of 20 cm from the collimator exit. Determine the momentum and kinetic energy of positrons if the field at which the greatest intensity of the detector response is observed is 0.044 T.

1.23. Using the dimensionality method, obtain a formula for the cyclic frequency w of the stretched string oscillations that depends on the tension force F, the mass of the string m, and the length of the string l. Compare with the exact answer.

1.24. Using the dimensionality method, obtain a formula for the free path length L of a particle with radius r in a medium with a concentration of the same particles n.

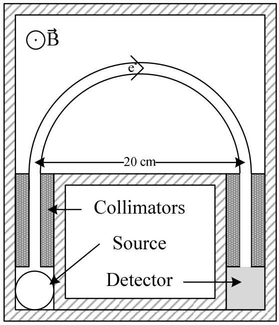


Fig. 1.1. A scheme of the experiment for the determination of the momentum of positrons

1.25. Using the dimensionality method, obtain a formula for the cyclic frequency w of a drop falling from a tap that depends on the surface tension σ [N/m], the density of the liquid ρ and the tap radius (the average radius of the drop) r.

1.26. Nanosatellite 1 moves at a speed of $v_1 = c - 1$ m/s, nanosatellite 2 moves in the same direction with a speed $v_2 = c - 2$ m/s. Find the speed of satellite 1 relative to satellite 2.

1.27. A proton with energy $E_1 = 10^{17}$ eV hits the resting nucleus ^{14}N. Find the total energy of the particles and the energy of each particle in the center of mass system.

1.28. Determine reaction thresholds (the first particle is moving, the second is at rest):

a) $\gamma + e^- \to e^- + e^- + e^+$;

b) $\gamma + X \to e^- + e^+ + X$ (X is the nucleus);

c) $p + p \to p + p + p + \tilde{p}$;

d) $e^- + p \to n + \nu_e$;

e) $^4\mathrm{He} + {}^3\mathrm{H} \to {}^6\mathrm{Li} + n$;

f) $^4\mathrm{He} + {}^7\mathrm{Li} \to {}^{10}\mathrm{B} + n$;

j) $^4\mathrm{He} + {}^{222}\mathrm{Rn} \to {}^{226}\mathrm{Ra}$.

2. Properties of Nuclei

The binding energy of a nucleus is given by

$$W = Z \cdot m_{^1_1\mathrm{H}} c^2 + (A - Z) \cdot m_n c^2 - M(A, Z)c^2, \qquad (2.1)$$

where $m_{^1_1\mathrm{H}}$ is the mass of a hydrogen atom, m_n is the neutron mass, $M(A, Z)$ is the mass of an atom with an ordinal number Z and a mass number A.

The specific binding energy is

$$\varepsilon = W/A. \qquad (2.2)$$

The separation energy of a neutron is

$$\varepsilon_n = m_n c^2 + M(A - 1, Z)c^2 - M(A, Z)c^2. \qquad (2.3)$$

The separation energy of a proton is

$$\varepsilon_p = m_{^1_1\mathrm{H}} c^2 + M(A - 1, Z - 1)c^2 - M(A, Z)c^2. \qquad (2.4)$$

The separation energy of an α-particle is

$$\varepsilon_\alpha = m_{^4_2\mathrm{He}} c^2 + M(A - 4, Z - 2)c^2 - M(A, Z)c^2. \qquad (2.5)$$

The mass defect is

$$\Delta(A, Z) = M(A, Z)c^2 - A \cdot m_{\mathrm{a.m.u.}} c^2, \qquad (2.6)$$

where $m_{\text{a.m.u.}}$ is the atomic mass unit.

The radius of the nucleus (in the approximation of a spherical nucleus of uniform density) is

$$R \approx r_0 \cdot A^{1/3}, \tag{2.7}$$

where $r_0 \approx 1.4$ fm.

2.1. Estimate the density of matter in the nucleus.

2.2. Estimate the volume density of electric charge in the nucleus.

2.3. Evaluate the concentration of nucleons in the nucleus.

2.4. Estimate the average distance between nucleons in the nucleus.

2.5. Based on the definition of the atomic mass unit, find the value $m_{\text{a.m.u.}}c^2$ in MeV.

2.6. Derive the formula for the calculation of the energy that is necessary – E (or that will be released – Q) to divide the nucleus (A, Z) into two fragments (a, z) and $(A - a, Z - z)$, if the mass excesses of original and daughter nuclei are given.

2.7. Find the binding energy and binding energy per nucleon for the following nuclei: ^{4}He, ^{5}He, ^{9}B, ^{12}C, ^{27}Al, ^{56}Fe, ^{107}Ag, ^{236}U.

2.8. Calculate the binding energy of a neutron ε_n in the nuclei: ^{4}He, ^{5}He, ^{9}B, ^{12}C, ^{27}Al, ^{56}Fe, ^{107}Ag, ^{236}U.

2.9. Calculate the binding energy of a proton ε_p in the nuclei: ^{4}He, ^{5}He, ^{9}B, ^{12}C, ^{27}Al, ^{56}Fe, ^{107}Ag, ^{236}U.

2.10. Calculate the binding energy of an α-particle ε_α in the nuclei: ^{12}C, ^{27}Al, ^{56}Fe, ^{107}Ag, ^{236}U, ^{210}Po, ^{226}Ra.

2.11. Calculate the energy that will be released in the decay of ^{236}U to ^{143}Ba, ^{90}Kr and 3 neutrons. Estimate the amount of heat that will be released in the decay of 1 kg of uranium. Determine the amount of anthracite (specific heat of combustion is 34 MJ/kg) that must be burned to obtain the same amount of heat.

2.12. Calculate the energy required to split the nucleus ^{16}O into two identical fragments.

2.13. Calculate the energy required to split the nucleus ^{8}Be into two identical fragments.

2.14. Calculate the energy required to split the nucleus ^{12}C into three α-particles.

2.15. Calculate the excitation energy that the ^{235}U nucleus will get after the absorption of a neutron with negligible kinetic energy. Calculate the excitation energy that the ^{6}Li nucleus will get after the absorption of a thermal neutron with negligible kinetic energy.

2.16. What is the size of objects that Rutherford could study if he scattered α-particles with energy $T = 5$ MeV on them?

2.17. During the scattering of electrons with $T_e = 750$ MeV on ^{40}Ca nuclei, in the diffraction pattern minima are observed at the angles $\theta_{\min} = 18$, 31 and 48°. Determine the radius of the ^{40}Ca nucleus.

2.18. By the difference in the binding energies of the mirror ^{3}H and ^{3}He nuclei estimate the distance between the protons in the ^{3}He nucleus.

2.19. Using the table with binding energies, calculate the energy released in each proton-proton cycle reaction:

1) $p + p \to {}^2\text{H} + e^+ + \nu_e$;

2) ${}^2\text{H} + p \to {}^3\text{He}$;

3) ${}^3\text{He} + {}^3\text{He} \to {}^4\text{He} + 2p$.

3. Models of nuclei

The binding energy of a nucleus is given by the formula of Weizsacker

$$W(A,Z) = \alpha A - \beta A^{2/3} - \gamma \frac{Z(Z-1)}{A^{1/3}} - \\ - \delta \frac{(A-2Z)^2}{A} + \zeta A^{-3/4}. \quad (3.1)$$

Parameter values: $\alpha = 15.6$ MeV, $\beta = 17.2$ MeV, $\gamma = 0.72$ MeV, $\delta = 23.6$ MeV,

$$\zeta = \begin{cases} +34 \text{ MeV} & \text{– } Z \text{ even - } N \text{ even,} \\ 0 & \text{– } A \text{ odd,} \\ -34 \text{ MeV} & \text{– } Z \text{ odd - } N \text{ odd.} \end{cases}$$

The intrinsic quadrupole moment of a uniformly charged ellipsoid is

$$Q = \frac{2}{5} Z(b^2 - a^2), \quad (3.2)$$

where a and b are the long and short ellipsoid semiaxes;

$$Q \approx \frac{4}{5} Z \bar{R}^2 \beta, \quad (3.3)$$

where $\bar{R}$ is the average nucleus radius, β is the nucleus deformation parameter.

$$\bar{R} = \frac{b+a}{2}, \;\; \beta = \frac{b-a}{\frac{1}{2}(b+a)} = \frac{1}{2} \frac{b^2 - a^2}{\bar{R}^2}.$$

The relation between experimental $\langle Q \rangle$ and intrinsic Q quadrupole moment of a nucleus is given by

$$\langle Q \rangle = \frac{J(2J-1)}{(J+1)\cdot(2J+3)}\,Q. \qquad (3.4)$$

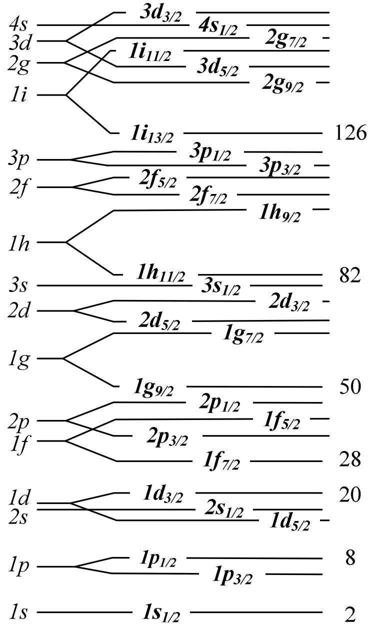


Fig. 3.1. Schematic representation of single-particle levels in a spherically symmetric potential

The shell model of the nucleus is given in Fig. 3.1. The rules for spins J and parities P in the ground state of the nucleus are

$$\begin{array}{ll} Z \text{ is even and } N \text{ is even} & J^P = 0^+; \\ A \text{ is odd} & J = j,\ P = (-1)^l; \\ Z \text{ is odd and } N \text{ is odd} & \begin{array}{l} |j_p - j_n| \le J \le j_p + j_n, \\ P = (-1)^{l_p + l_n}, \end{array} \end{array} \qquad (3.5)$$

where j, l, j_p, l_p, j_n, l_n refer to the total and orbital angular momentum of the odd nucleon (neutron, proton).

The magnetic moment of the nucleus (maximal projection) is

$$\mu = gJ\mu_N, \tag{3.6}$$

where g is the gyromagnetic factor, J is the nuclear spin, μ_N is the nuclear magneton.

The gyromagnetic factor of a nucleon in the state j, l is given by

$$g = g_l \pm \frac{g_s - g_l}{2l+1}, \tag{3.7}$$

where the plus sign is for $j = l + 1/2$; the minus sign is for $j = l - 1/2$; g_s, g_l are spin and orbital gyromagnetic factors. For the proton $g_s = 2 \cdot 2.793$, $g_l = 1$. For the neutron $g_s = 2 \cdot (-1.913)$, $g_l = 0$.

3.1. Find the relation between A and Z for β-stable nuclei.

3.2. Using the formula derived in 3.1, predict the character of the activity of the following β-active nuclei: ^{107}Cd, ^{133}Xe, ^{141}Ce, ^{163}Er.

3.3. Find the Z_{opt} for the nuclei with $A = 20$, 21, 116, 117, 123, 124, 128 and 129, at which the mass of the nucleus will be minimal.

3.4. Plot the dependence $Mc^2(Z)$ for the nuclei with $A = 116$ and 117 in the region $[Z_{\text{opt}} - 5; Z_{\text{opt}} + 5]$.

3.5. Using the Weizsäcker formula, calculate the energy released in the fission of ^{238}U into two equal fragments.

3.6. Find the critical value of Z^2/A at which the fission of the nucleus into two equal fragments will be possible. In the third term in equation (3.1) approximate $Z(Z-1) \approx Z^2$.

3.7. Find the critical value of Z^2/A at which the nucleus becomes unstable. In the third term in equation (3.1) approximate $Z(Z-1) \approx Z^2$.

3.8. Compare the binding energy and the binding energy per nucleon calculated by using the liquid drop model for ^{4}He, ^{12}C, ^{27}Al, ^{56}Fe, ^{107}Ag, ^{236}U with tabular values (cf. the answer for 2.7).

3.9. Derive a formula for calculating the energy of the Coulomb repulsion of protons $W(Z,R)$, where Z is the nucleus charge, R is the nucleus radius. Consider the distribution of charge in the volume of the nucleus as uniform and the nucleus itself spherical.

3.10. Assuming that the difference in the binding energies of mirror nuclei is determined only by the difference in the Coulomb repulsion energies in these nuclei (cf. the answer for 3.9), calculate the radii of mirror nuclei ^{23}Na, ^{23}Mg.

3.11. Calculate the spin, parity and magnetic moment of the following nuclei: ^{3}H, ^{7}Li, ^{13}C, ^{25}Mg. Compare the results with tabular values.

3.12. Calculate the spin, parity and magnetic moment of the nuclei: ^{29}Si, ^{39}K, ^{45}Sc, ^{63}Cu. Compare the results with tabular values.

3.13. Estimate the possible values of the spins and parity of nuclei: ^{2}D, ^{6}Li, ^{10}B, ^{14}N, ^{22}Na, ^{26}Al. Compare the results with tabular values.

3.14. Derive the formula 3.2 for the calculation of the electric quadrupole moment of a uniformly charged ellipsoid.

3.15. Observed electrical quadrupole moments of nuclei ^{36}Cl and ^{55}Mn are -0.018 and +0.33 b. What forms do these nuclei have? What are the intrinsic electric quadrupole moments of these nuclei?

3.16. Observed electrical quadrupole moments of nuclei ^{39}K and ^{63}Cu are +0.0585 and -0.211 b. What are the deformation parameters of these nuclei?

3.17. In the Fermi-gas model, it is assumed that the density of the state of nucleons is $dN/dp = 2 \cdot 4\pi p^2 V/(2\pi\hbar)^3$, where p is the momentum of nucleon, $V = 4\pi r_0^3 A/3$ is the volume of nucleus. Calculate the maximum possible momentum.

3.18. Calculate the maximum kinetic energy of nucleons and estimate the depth of the potential well for nucleons in the nucleus in the frame of the Fermi gas model.

3.19. Calculate the average kinetic energy of nucleons in the nucleus in the frame of the Fermi gas model .

4. Interaction of charged particles with matter

The Rutherford formula describes the macroscopic differential cross section of scattering

$$d\Sigma = \frac{dN}{N} = an\left(\frac{Zze^2}{4\pi\varepsilon_0 4T}\right)^2 \frac{d\Omega}{\sin^4(\theta/2)}, \qquad (4.1)$$

where a is the thickness of the target, n is the concentration of the target nuclei, θ is the scattering angle (deviation of the particle from the initial direction), N is the total number of incident particles, dN is the number of particles scattered at an angle θ in the element of the solid angle $d\Omega$, T is the kinetic energy of the incident particles, Z and z are the charge of the target nuclei and incident particles (in units of electron charge), respectively, and $\varepsilon_0 = 8.85 \cdot 10^{-12}$ C^2/(N·m^2) is the electric constant.

Ionization losses of heavy particles in MeV/(g/cm^2) are described by the formula

$$-\frac{dE}{dx} = \frac{4\pi N_A r_e^2 m_e c^2 z^2 Z}{A\beta^2} \times \\ \times \left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right], \quad (4.2)$$

where N_A is the Avogadro constant, r_e is the classical electron radius, z the particle charge (in units e), Z is the charge of the nuclei of matter (in units e), A is the atomic number of matter, $\beta = v/c$, v is the velocity of the incoming particle, $\gamma = 1/\sqrt{1-\beta^2}$, I is the average ionization potential (tab. P. 1.8), $T_{\max}$ is the maximum energy that can be transferred to a free electron in a single collision, δ is the a term that takes into account the density effect.

$$T_{\max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}, \quad (4.3)$$

where M is the mass of the incoming particle.

For the nonrelativistic case ($2\gamma m_e/M \ll 1$) $T_{\max} \approx 2m_e c^2\beta^2\gamma^2$, the second and third terms in square brackets in the formula (4.2) can be neglected and then the calculation is carried out according to the following formula:

$$-\frac{dE}{dx} = \frac{Kz^2 Z}{A\beta^2}\ln\frac{2m_e c^2\beta^2}{I}, \quad (4.4)$$

where $K/A = 4\pi N_A r_e^2 m_e c^2/A = 0.307075$ MeV/(g/cm^2) for $A = 1$ g/mol.

Empirical dependences of the path of monoenergetic α-particles and protons R' (cm) in the air on the kinetic energy T (MeV):

$$\begin{aligned} R'_\alpha(T) &= 0.318 \cdot T^{3/2} && \text{for } 4 < T < 8 \text{ MeV}, \\ R'_p(T) &= R'_\alpha(4T) - 0.2 && \text{for } T > 0.5 \text{ MeV}. \end{aligned} \tag{4.5}$$

The average path of α-particles R (mg/cm^2) in a medium with mass number A:

$$R_\alpha(T) = 0.56 A^{1/3} R'_\alpha(T). \tag{4.6}$$

Empirical dependences of the path of monoenergetic electrons R (g/cm^2) in aluminium (and in almost any substance, if the electron energy losses are mainly due to ionization) on the kinetic energy T (MeV) are described by

$$R(T) = \begin{cases} 0.407 \cdot T^{1.38}, & 0.15 < T < 0.8 \text{ MeV}; \\ 0.542 \cdot T - 0.133, & 0.8 < T < 3 \text{ MeV}. \end{cases} \tag{4.7}$$

The electron path R (g/cm^2) in a substance with a charge Z and a mass number A is related to the path in aluminium as follows:

$$R(A, Z) = R_{\text{Al}} \frac{Z_{\text{Al}}/A_{\text{Al}}}{Z/A}. \tag{4.8}$$

Radiation losses of electron energy at $T \gg mc^2$ (MeV/(g/cm^2)):

$$-\frac{dE}{dx} = 4\alpha r_e^2 \frac{N_A}{A} T \left(Z(Z+1) \ln \frac{183}{Z^{\frac{1}{3}}} \right), \tag{4.9}$$

where α is the fine structure constant. Or

$$-\frac{dE}{dx} = \frac{T}{l_{\text{rad}}}, \tag{4.10}$$

where l_{rad} is the radiation length (g/cm^2):

$$\frac{1}{l_{\text{rad}}} = 4\alpha r_e^2 \frac{N_A}{A}\left(Z(Z+1)\ln\frac{183}{Z^{\frac{1}{3}}}\right). \qquad (4.11)$$

Approximate ratio between radiation and ionization losses of electrons (T – in MeV):

$$\frac{(dE/dx)_{\text{rad}}}{(dE/dx)_{\text{ion}}} \approx \frac{TZ}{1600 m_e c^2} \approx \frac{TZ}{800}. \qquad (4.12)$$

The change in the energy of charged particles after passing the x layer due to radiation losses at high energies ($T \gg T_{\text{crit}}$, T_{crit} is the energy at which the ionization and radiation losses are equal):

$$T = T_0 \cdot e^{-x/l_{\text{rad}}}, \qquad (4.13)$$

T_0 is the primary particle energy.

For a matter with a thickness less than the maximum path, the density attenuation of the β-particles beam J approximately follows the exponential law:

$$J = J_0 \cdot e^{-\mu_e d}, \qquad (4.14)$$

where μ_e is the electron absorption coefficient (in cm^{-1}), d is the thickness of the target (in cm).

The dependence of μ_e on the maximum energy of β-particles $T_{\beta\ \max}$ is approximated by the formula (0.5 MeV $< T_{\beta\ \max} <$ 7 MeV, ρ – in g/cm^3):

$$\mu_e = \rho \cdot 22 \cdot T_{\beta\ \max}^{-4/3}. \qquad (4.15)$$

4.1. A light particle with a charge of q_1 is scattered on a heavy stationary nucleus with a charge of q_2. Represent approximate trajectories of a particle in the case: a) $q_1 q_2 > 0$; b) $q_1 q_2 < 0$.

4.2. What is the minimum distance $r_{\min}$ that can be reached between α-particle and the fixed nucleus of a gold atom at the central collision, if the velocity of the particle at a great distance from the nucleus is $v = 2.5 \cdot 10^7$ m/s?

4.3. A beam of α-particles from the source is scattered on the gold foil $^{197}_{79}$Au (an experiment similar to Rutherford's). The kinetic energy of α-particles is $T_\alpha = 5.3$ MeV, the flux of α-particles is $J = 2.5 \cdot 10^5$ particles/s, the thickness of the foil is $a = 5.0$ microns, the distance from the intersection of the foil beam to the detector is $l = 25$ cm. Scattered particles are detected by the detector with a sensitive area $S = 0.5$ cm^2. Determine the number of the detector hits during $\Delta t = 2$ min, if the detector is installed at an angle θ 15, 45, 75, 105, 135, 165° to the direction of the incident beam.

4.4. How will the count of α-particles (see the problem 4.3) change when: a) the speed of incoming particles is increased 2 times; b) the gold foil is replaced with aluminium?

4.5. Find the probability P that α-particle in the experiment described in the problem 4.3 will be scattered in the following intervals of the Zenith angle: $5 \leq \theta \leq 45$, $45 \leq \theta \leq 90$, $90 \leq \theta \leq 135$, $\theta \geq 135$.

4.6. An α-particle with kinetic energy $T_\alpha = 25$ MeV moved near a resting free electron having an impact parameter $b = 20$ pm. Find the kinetic energy T_e of the recoil electron.

4.7. Represent the approximate graph for a dependence of ionization losses on kinetic energy T for proton, α-particle and muon.

4.8. Represent the approximate graph for a dependence of specific ionization losses on relative velocity β for proton, α-particle and muon.

4.9. Estimate the minimum energy required for a proton to pass a 10 cm thick lead plate.

4.10. Estimate the minimum energy required for a muon to pass through the atmosphere for the vertical and horizontal directions.

4.11. Calculate the value of the coefficient K/A in the formula (4.4) (in MeV/(g/cm^2)) for $A = 1$ g/mol.

4.12. Calculate the specific ionization energy losses of an α-particle in aluminium ^{27}Al if its kinetic energy is 160 MeV.

4.13. Calculate the specific ionization losses of a muon (in MeV/(g/cm^2) and in MeV/cm) with a kinetic energy of 10 MeV in lead ^{207}Pb and in nitrogen ^{14}N (under normal conditions).

4.14. How many times will the specific ionization losses of a proton in lead ^{207}Pb differ from those in iron ^{56}Fe if the kinetic energy of the proton is 80 MeV?

4.15. How many times will the specific ionization losses of α-particle and deuteron differ in copper ^{65}Cu if their kinetic energy is 100 MeV?

4.16. Estimate the minimum thickness of the aluminium foil that completely absorbs the flux of α-particles with kinetic energy of 7.5 MeV.

4.17. Find the energy loss ratio of α-particles on the first and last centimeter of the path in the air if their kinetic energy is 6.5 MeV.

4.18. Find the kinetic energy of electrons if their path in copper ^{64}Cu is 0.13 cm.

4.19. Determine the average number of ion pairs on the first 4 cm of the path of protons with an energy of 3 MeV through the air. The formation of one pair of ions in the air takes 35 eV.

4.20. Estimate the critical energy of electrons in nitrogen (at n.c.), aluminium, copper and lead.

4.21. Calculate the value of the radiation length for electrons (in g/cm^2 and in cm) in nitrogen ^{14}N (at n.c.), aluminium ^{27}Al, copper ^{65}Cu and lead ^{207}Pb.

4.22. Calculate the radiation losses of electrons with energy 70 MeV passing through a copper target ^{65}Cu and compare them with losses on ionization. What will total losses be equal to?

4.23. At what energy of electrons will their ionization losses in aluminium make 30 % from radiation ones? What will total losses be equal to?

4.24. Electrons and protons with kinetic energy $T = 100$ MeV fall on an iron plate (^{56}Fe) of 1 mm thick. Estimate their energy at the exit of the plate.

4.25. Determine the energy T_0 of electrons at the entrance to the lead plate with a thickness of $x = 1$ mm, if at its exit the electron energy is $T = 350$ MeV.

4.26. Estimate the thickness of the carbon absorber ^{12}C needed to reduce the electron energy from 1300 to 1084 MeV.

4.27. Estimate the radiation length of some element, if after passing the plate with a thickness of 1.8 mm the electron energy decreased by 20 %. Consider the losses as mainly radiation ones.

4.28. The beta-active product of strontium emits electrons with a maximum energy of 1.1 MeV. Find the minimum thickness of the product in mass (in g/cm^2), at which a further increase in its thickness will not lead to an increase in the intensity of the emitted electron flux.

4.29. The maximum electron path from some radioactive element in aluminium is 0.53 cm. How thick should the aluminium plate be to weaken the electron flux by 5 times?

4.30. The semi-attenuation layer of the electron flux from some product was 118.5 mg/cm^2. Estimate the mass coefficient μ_e/ρ of electron flux attenuation and the maximum particle path.

5. Interaction of γ-quanta with matter

The law of attenuation of a narrow monoenergetic collimated beam of γ-quanta by a layer of a homogeneous substance with a thickness of x is given by

$$I(x) = I_0 \cdot e^{-\mu x}, \tag{5.1}$$

where μ (cm^{-1}) is the linear attenuation coefficient of γ-radiation in matter ($\mu = \tau + \mu_{\text{scattering}}$, τ is the linear absorption coefficient).

$$\mu = \mu_{\text{Ph}} + \mu_{\text{C}} + \mu_{\text{P}}, \tag{5.2}$$

where μ_{Ph}, μ_{C} and μ_{P} are the macroscopic cross sections of the photoeffect, Compton scattering and electron-positron pair production, respectively.

The connection with the microscopic cross sections σ (in b/atom) is given by

$$\begin{aligned} \mu_{\mathrm{Ph}} &= n_{\mathrm{nuclei}} \sigma_{\mathrm{Ph}}, \\ \mu_{\mathrm{C}} &= n_{\mathrm{nuclei}} \sigma_{\mathrm{C}}, \\ \mu_{\mathrm{P}} &= n_{\mathrm{nuclei}} \sigma_{\mathrm{P}}, \end{aligned} \tag{5.3}$$

where $n_{\mathrm{nuclei}} = \rho N_A / M$ is the density of nuclei with density ρ and molar mass M.

5.1. A narrow beam of γ-quanta with an energy of 800 keV hits a 0.3 cm thick lead plate. Calculate how much the γ-quanta flux will be weakened after the plate.

5.2. Find the thickness of an aluminium plate that weaken the γ-quanta flux with an energy of 300 keV by a factor of three.

5.3. The source of γ-quanta with an energy of 150 keV is in an iron container. The thickness of the container walls is 30 mm. Estimate the fraction of γ-quanta (in %) that will be absorbed in the container walls. How thick should the walls of an aluminium container be in order to perform the same absorption?

5.4. By how many millimeters should the thickness of the iron plate be increased to decrease the flux of γ-quanta with an energy of 500 keV by 25 %?

5.5. How thick should the glass window of a γ-quanta detector be to absorb less than 5 % γ-quanta with an energy of 200 keV in it?

5.6. Find the half-attenuation length for γ-quanta with an energy of 600 keV in air, glass, iron and lead.

5.7. The half attenuation length for γ-quanta in aluminium is 46.7 mm. Find the energy of the γ-quanta.

5.8. How many layers of half attenuation should be put on the path of a γ-quanta beam to reduce its intensity by 100 times?

5.9. What is the average free path length for γ-quanta with an energy of 1.5 MeV in air, water, iron and lead?

5.10. The average free path length for γ-quanta in aluminium is 104.6 mm. Find the length of the half attenuation. What is the energy of γ-quanta?

5.11. Determine the cross section in b/atom for γ-quanta with an energy of 2 MeV in iron ^{56}Fe and in lead ^{206}Pb.

5.12. Calculate the linear and mass attenuation coefficients for γ-quanta with an energy of 14 MeV in lead ^{206}Pb knowing the interaction cross section in b/atom.

5.13. Calculate the linear and mass coefficients for γ-quanta with an energy of 13 MeV in aluminium ^{27}Al knowing the interaction cross section in b/atom.

5.14. Calculate the probability of the Compton effect for γ-quanta with an energy of 11 MeV in an iron plate with a thickness of 15 mm.

5.15. How thick should a lead plate be so that the probability of the photoelectric effect for γ-quanta with an energy of 3 MeV will be equal to 0.7 %?

6. Radioactivity

The basic law of radioactive decay of nuclei is

$$N = N_0 e^{-\lambda t} = N_0 2^{-t/T_{1/2}}, \tag{6.1}$$

where N is the number of radioactive nuclei at time t, N_0 is the initial number of radioactive nuclei, λ is the decay constant (probability of nuclear decay per unit time), $T_{1/2}$ is the half-life (the time during which the initial number of radioactive nuclei will decrease by half):

$$T_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2. \tag{6.2}$$

The average life time is

$$\tau = 1/\lambda. \tag{6.3}$$

The activity A (average number of nuclei decaying per unit time, Bq) is

$$A(t) = -\frac{dN}{dt} = \lambda N(t) = A_0 e^{-\lambda t}. \tag{6.4}$$

where $A_0 = \lambda N_0$.

The specific activity is

$$a = \frac{A}{m}, \tag{6.5}$$

where m is the mass of a radioactive sample.

The volumetric activity is

$$a_V = \frac{A}{V}, \tag{6.6}$$

where V is the volume of a radioactive sample.

The energy released in the process of

$$\begin{array}{ll} \beta^-\text{-decay:} & Q_{\beta^-} = M(A,Z)c^2 - M(A,Z+1)c^2; \\ \beta^+\text{-decay:} & \begin{aligned} Q_{\beta^+} = M(A,Z)c^2 - \\ - M(A,Z-1)c^2 - 2m_e c^2; \end{aligned} \\ \text{K-capture:} & Q_{\text{K}} = M(A,Z)c^2 - M(A,Z-1)c^2. \end{array} \quad (6.7)$$

6.1. Calculate the decay constant λ and the average lifetime τ for ^{22}Na.

6.2. What part of ^{37}Ar nuclei will decay in 1 year? What part will remain in 180 h?

6.3. The activity of some radioactive element decreased by 1.5 times in 51.1 days. Find its half-life $T_{1/2}$, decay constant λ and average lifetime τ.

6.4. The kinetic energy of a muon is $T_\mu = 4$ GeV. What is the average distance $\langle L \rangle$ that a muon with such an energy will pass before decay?

6.5. Determine the age of an ancient wooden object, if it is known that its specific activity $^{14}_{6}$C decreased by 35 % relative to the specific activity of the same object in newly felled trees.

6.6. Estimate the limit from below on the proton lifetime if there was no proton decay registered in a water detector with a mass of $m = 10000$ t for $t = 3$ years.

6.7. The mass of the freshly prepared radioactive substance of ^{59}Fe is 2 g. Determine: initial activity; activity after 70 days.

6.8. The measurement of the decay rate has been started 9 min after receiving of the ^{11}C substance and has been carried out for 12 min. The detector has registered 22547 pulses during this time. Determine the activity of the ^{11}C substance at the initial time.

6.9. The freshly prepared substance contains 1 μg of active ^{23}Mg and 20 mg of inactive ^{24}Mg. Determine the specific activity of the substance a.

6.10. The freshly prepared ^{24}Na substance weighing m_0 was dissolved in 7.5 l of a solvent. After $t = 11$ h the volumetric specific activity of the substance a_V was $3.1 \cdot 10^8$ Bq/cm^3. Find the initial weight of the substance m_0.

6.11. Measurements of the activity of a substance containing one radioactive element produced the following dependence on time $A(t)$:

t, hr	3	6	9	12
$A(t)$, Bq	$4.66 \cdot 10^{15}$	$2.09 \cdot 10^{15}$	$9.41 \cdot 10^{14}$	$4.23 \cdot 10^{14}$

Determine the half-life of the element $T_{1/2}$ and its initial number of nuclei N_0.

6.12. The radioactive element ^{24}Na is produced at a constant rate of $q = 10^7$ nuclei per second. Find the dependence of the number of ^{24}Na nuclei on the time $N(t)$ ($N(0) = 0$). Plot the dependence $N(t)$ (qualitatively). Determine the activity of the substance after 1, 3, 6, 90 h.

6.13. There is a decay along the following radioactive chain:

$$^{200}_{82}\text{Pb} \xrightarrow[K]{} {}^{200}_{81}\text{Tl} \xrightarrow[\beta+]{} {}^{200}_{80}\text{Hg}.$$

At the initial moment, the substance weighing 2 g contained only $^{200}_{82}$Pb nuclei. Find the time period $t_{\max}$ at which the number of nuclei $^{200}_{81}$Tl will be the maximum, calculate this number.

6.14. The initial sample contained only ^{232}Th nuclei that have α decay. In 200 years each atom of ^{228}Ra will correspond to $2.43 \cdot 10^9$ atoms of ^{232}Th. Find the half-life of ^{232}Th if it is known that $T_{1/2}(^{232}\text{Th}) \gg T_{1/2}(^{228}\text{Ra})$, $T_{1/2}(^{228}\text{Ra}) = 5.75$ years.

6.15. Based on the laws of conservation of charge, lepton and baryon numbers, determine whether the following reactions are possible:

1) $^{200}\text{Tl} \to {}^{200}\text{Hg} + \mu^+ + \nu_e, \quad {}^{200}\text{Tl} \to {}^{200}\text{Hg} + e^+ + \nu_e;$

2) $\gamma + A \to e^+ + A + e^-, \quad \gamma \to e^+ + \mu^-;$

3) $\pi^+ \to e^+ + \nu_\mu, \quad \pi^+ \to \mu^+ + \nu_\mu;$

4) $\tilde{\nu}_\mu + p \to n + \mu^+, \;\; \nu_e + n \to p + \mu^-, \;\; \tilde{\nu}_\mu + n \to p + \mu^-;$

5) $p + p \to p + p + p + \tilde{p}, \quad p + p \to p + p + p + e^-;$

6) $\mu^+ \to e^+ + \tilde{\nu}_e + \tilde{\nu}_\mu, \quad \mu^- \to e^- + \tilde{\nu}_e + \nu_\mu.$

6.16. A nucleus of $^{232}_{90}\text{Th}$ emits an α-particle and goes to the ground (unexcited) state of $^{228}_{88}\text{Ra}$. Determine the kinetic energy of an α-particle and nuclei. What portion of the total energy is spent on the kinetic energy of the daughter nucleus? What is the recoil velocity of the daughter nucleus?

6.17. Resting nuclei of $^{192}_{84}\text{Po}$ decay (from the ground state) with the emission of three groups of α particles: with energy $T_1^\alpha = 6416$ keV (0.7 %), $T_2^\alpha = 6611$ keV (1.4 %), $T_3^\alpha = 7167$ keV (97.3 %). Find the energy of α-decays of these nuclei and the energy of γ - quanta emitted by the daughter nuclei.

6.18. Resting nuclei of $^{212}_{84}\text{Po}$ decay (from the ground state) with the emission of α-particles with an energy $T_\alpha = 8.78$ MeV. Almost all daughter nuclei are formed directly in the ground state. Find the amount of heat that 5 mg of the preparation will release in a time equal to $3T_{1/2}$.

6.19. Derive the formulae (6.7).

6.20. Determine, if these processes are possible: β^--decay, β^+-decay and K-capture for nuclei: 1) $^{64}_{29}\text{Cu}$, 2) $^{65}_{29}\text{Cu}$, 3) $^{66}_{29}\text{Cu}$.

6.21. A nucleus of ${}^{66}_{29}$Cu at rest has a β^--decay, the daughter nucleus is in the ground state. Determine the maximum kinetic energy of an electron and its velocity. What are the kinetic energy of the daughter nucleus and its speed?

6.22. A nucleus of ${}^{66}_{29}$Cu at rest has a β^--decay, the daughter nucleus is in the ground state. Determine kinetic energies of an electron and an antineutrino if the daughter nucleus has no recoil.

6.23. A nucleus of ${}^{64}_{29}$Cu at rest has a β^+-decay, the daughter nucleus is in the ground state. Determine the maximum kinetic energy of a positron and its velocity. What are the kinetic energy of the daughter nucleus and its speed in this case?

6.24. A nucleus of ${}^{64}_{29}$Cu at rest has a β^+-decay, the daughter nucleus is in the ground state. Determine kinetic energies of a positron and a neutrino if the daughter nucleus has no recoil.

6.25. A part weighing 1 kg contains 0.005 mass percent of the stable silver isotope ^{109}Ag. The part is placed in a neutron flux of $2 \cdot 10^{13}$ n/(cm^2·s). Find the activity of the radioactive isotope of silver ^{110}Ag 5 min after the start of irradiation, if the cross-section of the radiation capture of the silver isotope ^{109}Ag is 91 barn, and the half-life of the isotope ^{110}Ag is 25 s.

6.26. A steel sample weighing 2 kg contains 0.5 % of manganese ^{55}Mn, it was placed in a nuclear reactor with a thermal flux of $5 \cdot 10^{13}$ n/(cm^2·s). As a result of radiation capture of neutrons a radioactive isotope of manganese ^{56}Mn is formed. The sample was removed after 10 days of irradiation. What number of γ-quanta will it emit per second after one hour of the exposure? The neutron capture cross-section for ^{55}Mn is 13.4 barn. The β^--decay of ^{56}Mn is accompanied by the emission of the following γ-quanta: 0.85 MeV (in 99 % of decays), 1.81 MeV (26 %), 2.11 MeV (15 %).

Answers

1.2.

939.6 MeV, 938.3 MeV, 0.511 MeV.

1.5.

3.70 GeV, 2.76 GeV, 3.58 GeV/c.

1.6.

$V_e = 2.97 \cdot 10^8$ m/s.

1.7.

$T_{\mu^+} = 4.1$ MeV, $T_{\nu_\mu} = 29.6$ MeV.

1.8.

$T_{e^-} = T_{e^+} = 66.98$ MeV.

1.9.

$T_{e^-} = 246.3$ MeV, $T_{\tilde{\nu}_e} = 246.8$ MeV.

1.10.

$T_{\pi^-} = 108.54$ MeV, $T_{\pi^0} = 110.58$ MeV.

1.11.

60°.

1.12.

$\tau = 11\tau_0$.

1.13.

$\hbar c = 197.33 \text{ MeV} \cdot \text{fm} \approx 200 \text{ MeV} \cdot \text{fm}$.

1.14.

$t_p = 1.59 \cdot 10^{-5}$ s, $t_e = 3.45 \cdot 10^{-8}$ s, $t_\gamma = 3.33 \cdot 10^{-8}$ s.

1.15.

$ƛ = 0.2$ fm.

1.16.

1969 fm, 141 fm, 0.2 fm.

1.17.

20 GeV, 19 GeV.

1.18.

$V_{\rm rel}$ is the electron velocity by relativistic formulae, $V_{\rm cl}$ – by non-relativistic formulae:

a) $V_{\rm rel} = 4.16 \cdot 10^7$ m/s, $V_{\rm cl} = 4.19 \cdot 10^7$ m/s, 0.7 %,

b) $V_{\rm rel} = 1.24 \cdot 10^8$ m/s, $V_{\rm cl} = 1.33 \cdot 10^8$ m/s, 7.2 %,

c) $V_{\rm rel} = 2.22 \cdot 10^8$ m/s, $V_{\rm cl} = 2.97 \cdot 10^8$ m/s, 33.5 %,

d) $V_{\rm rel} = 2.97 \cdot 10^8$ m/s, $V_{\rm cl} = 10.3 \cdot 10^8$ m/s ($> c$), 246 %.

1.19.

$V_{\rm rel}$ is the proton velocity by relativistic formulae, $V_{\rm cl}$ – by non-relativistic formulae:

a) $V_{\rm rel} = 4.21 \cdot 10^7$ m/s, $V_{\rm cl} = 4.24 \cdot 10^7$ m/s,
$V_{\rm cl}/V_{\rm rel} = 1.007$,

b) $V_{\rm rel} = 1.25 \cdot 10^8$ m/s, $V_{\rm cl} = 1.34 \cdot 10^8$ m/s,
$V_{\rm cl}/V_{\rm rel} = 1.07$,

c) $V_{\text{rel}} = 2.60 \cdot 10^8$ m/s, $V_{\text{cl}} = 4.24 \cdot 10^8$ m/s ($> c$),
$V_{\text{cl}}/V_{\text{rel}} = 1.6$,

d) $V_{\text{rel}} = 2.99 \cdot 10^8$ m/s, $V_{\text{cl}} = 13.4 \cdot 10^8$ m/s ($> c$),
$V_{\text{cl}}/V_{\text{rel}} = 4.5$.

1.20.

W_{rel} – by relativistic formulae, W_{cl} – by non-relativistic formulae:

a) $W_{\text{rel}} = 4.69 \cdot 10^{-2}$ MeV, $W_{\text{cl}} = 4.69 \cdot 10^{-2}$ MeV,
$W_{\text{rel}}/W_{\text{cl}} = 1.00007$,

b) $W_{\text{rel}} = 4.73$ MeV, $W_{\text{cl}} = 4.69$ MeV, $W_{\text{rel}}/W_{\text{cl}} = 1.008$,

c) $W_{\text{rel}} = 145$ MeV, $W_{\text{cl}} = 117$ MeV, $W_{\text{rel}}/W_{\text{cl}} = 1.24$,

d) $W_{\text{rel}} = 1214$ MeV, $W_{\text{cl}} = 380$ MeV, $W_{\text{rel}}/W_{\text{cl}} = 3.2$.

1.21.

68.6 m/s, 80 m/s.

1.22.

$pc = 1.32$ MeV, $T = 0.9$ MeV.

1.23.

The dimensionality method: $w = \sqrt{F/ml}$; the exact answer: $w = \sqrt{2F/ml}$.

1.24.

$L = 1/(nr^2)$.

1.25.

$w = \sqrt{\sigma/\rho r^3}$, matches the exact formula.

1.26.

$v_{12} = (v_1 - v_2)/(1 - v_1 v_2/c^2) = c/3$.

1.27.

$E^* = \sqrt{(m_p c^2)^2 + (m_N c^2)^2 + 2E_p m_N c^2} = 53$ TeV.
$E^*_{p,N} = (E^{*2} + (m_{p,N}c^2)^2 - (m_{N,p}c^2)^2)/2E^* = 26.5$ TeV.

1.28.

$E_{\text{thres}} = (M^2 - m_1^2 - m_2^2)c^2/2m_2$.

2.1.

$\approx 1.45 \cdot 10^{14}$ g/cm^3.

2.2.

$\approx 7 \cdot 10^{18}$ C/cm^3.

2.3.

$\approx 9 \cdot 10^{37}$ 1/cm^3.

2.4.

≈ 2 fm.

2.5.

$m_{\text{a.e.m.}}c^2 = \frac{1}{12} M_{{}^{12}_{6}\mathbf{C}} c^2 = 931.5$ MeV.

2.6.

$E = \Delta(A - a, Z - z) + \Delta(a, z) - \Delta(A, Z)$, $Q = -E$.

2.7.

W is the binding energy in MeV, ε is the binding energy per nucleon in MeV/nucleon.

Element	^{4}He	^{5}He	^{9}B	^{12}C
W	28.3	27.6	56.3	92.16
ε	7.07	5.51	6.26	7.68

Element	^{27}Al	^{56}Fe	^{107}Ag	^{236}U
W	224.95	492.26	915.27	1790.4
ε	8.33	8.79	8.55	7.59

2.8.

Element	^{4}He	^{5}He	^{9}B	^{12}C	^{27}Al	^{56}Fe	^{107}Ag	^{236}U
ε_n, MeV	20.6	-0.74	18.6	18.7	13.1	11.2	9.5	6.5

2.9.

Element	^{4}He	^{5}He	^{9}B	^{12}C	^{27}Al	^{56}Fe	^{107}Ag	^{236}U
ε_p, MeV	19.8	20.7	-0.19	16	8.3	10.2	5.8	7.1

2.10.

Element	^{12}C	^{27}Al	^{56}Fe	^{107}Ag	^{236}U	^{210}Po	^{226}Ra
ε_α, MeV	7.4	10.1	7.6	2.8	-4.6	-5.4	-4.9

2.11.

$Q = 167.13$ MeV, $W = 4.26 \cdot 10^{26}$ MeV $= 68.3 \cdot 10^{6}$ MJ, $m = 2 \cdot 10^{6}$ kg.

2.12.

14.6 MeV.

2.13.

-0.09 MeV.

2.14.

7.27 MeV.

2.15.

6.5 MeV, 7.3 MeV.

2.16.

$\lambda = 6.5$ fm.

2.17.

$\sin(\theta_{\min}) = m2\pi ƛ \cdot 0.61/R$, $m = 1,2,3$, $R = 3.3 - 4.1$ fm.

2.18.

1.9 fm.

2.19.

1. $Q_1 = 0.42$ MeV. 2. $Q_2 = 5.49$ MeV. 3. $Q_3 = 12.86$ MeV. $Q_{\text{tot}} = 24.68$ MeV.

3.1.

$Z_{\text{opt}} \approx A/(0.015A^{2/3} + 1.973)$.

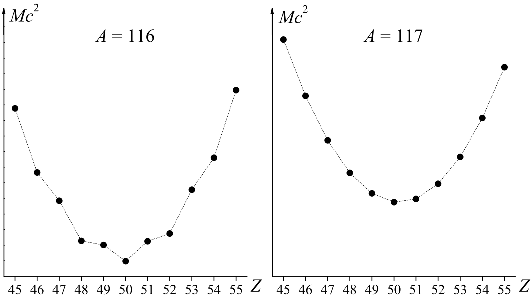
3.2.

β^+, β^-, β^-, β^+.

3.3.

10, 10, 50, 50, 52, 53, 54, 55.

3.4.



3.5.

≈ 194 MeV.

3.6.

≈ 17.

3.7.

≈ 49.

3.8.

Element	^{4}He	^{12}C	^{27}Al	^{56}Fe	^{107}Ag	^{236}U
W	30.2	92.9	228.1	494.4	916.4	1779.5
ε	7.54	7.74	8.45	8.83	8.56	7.54

3.9.

$$W = \frac{3}{5} \cdot \frac{Z^2 e^2}{4\pi\varepsilon_0 R}, \text{ J.}$$

3.10.

$W(^{23}\text{Na}) = 186.56$ MeV, $W(^{23}\text{Mg}) = 181.73$ MeV. $R = 4.1$ fm.

3.11.

Element	^{3}H	^{7}Li	^{13}C	^{25}Mg
J^P	$1/2^+$	$3/2^-$	$1/2^-$	$5/2^+$
μ/μ_N	2.793	3.793	0.638	-1.913

3.12.

Element	^{29}Si	^{39}K	^{45}Sc	^{63}Cu
J^P	$1/2^+$	$3/2^+$	$7/2^-$	$3/2^-$
μ/μ_N	-1.913	0.1242	5.793	3.793

3.13.

Element	^{2}D, ^{14}N	^{6}Li, ^{10}B	^{22}Na, ^{26}Al
J	$0 \le J \le 1$	$0 \le J \le 3$	$0 \le J \le 5$
P	+1	+1	+1

3.15.

Ellipsoid flattened along the axis of symmetry Z, ellipsoid stretched along the axis of symmetry Z. -0.063 b and 0.92 b.

3.16.

0.09 and -0.15.

3.17.

$(pc)_{\max} = (\hbar c)/r_0 \cdot (9\pi/8)^{1/3} = 214$ MeV.

3.18.

$T_{\max} = (pc)^2_{\max}/2m_N c^2 = 32$ MeV, $U = T_{\max} + \varepsilon = 40$ MeV ($\varepsilon = 8$ MeV – average binding energy per nucleon).

3.19.

$\langle T \rangle = 3T_{\max}/5 = 19$ MeV.

4.2.

$r_{\min} = 1.7 \cdot 10^{-14}$ m.

4.3.

2810, 38, 6, 2, 1.1, 0.8.

4.4.

a) will decrease 16 times; b) will decrease 36 times.

4.5.

0.22, $2.1 \cdot 10^{-3}$, $3.5 \cdot 10^{-4}$, $7.3 \cdot 10^{-5}$.

4.6.

$$T_e = \frac{m_\alpha Z^2 e^4}{(4\pi\varepsilon_0)^2 m_e b^2 T_\alpha} = 6 \text{ eV}.$$

4.9.

~ 226 MeV.

4.10.

~ 2 GeV, ~ 72 GeV.

4.11.

0.307075 MeV/(g/cm^2).

4.12.

45.6 MeV/(g/cm^2).

4.13.

3.9 MeV/(g/cm^2) and 44.2 MeV/cm; 7.1 MeV/(g/cm^2) and 0.009 MeV/cm.

4.14.

$$\frac{(dE/dx)^{\mathrm{Pb}}_{\mathrm{ion}}}{(dE/dx)^{\mathrm{Fe}}_{\mathrm{ion}}} = 0.7.$$

4.15.

$$\frac{(dE/dx)^{\alpha}_{\mathrm{ion}}}{(dE/dx)^{{}^2_1\mathrm{H}}_{\mathrm{ion}}} = 6.8.$$

4.16.

40.6 micron.

4.17.

$$\frac{\Delta T_{\mathrm{after}}}{\Delta T_{\mathrm{before}}} = 2.5.$$

4.18.

2.3 MeV.

4.19.

18300.

4.20.

114 MeV, 62 MeV, 28 MeV, 10 MeV.

4.21.

39.3 g/cm^2 and 314 m, 24.4 g/cm^2 and 9 cm, 13.1 g/cm^2 and 1.5 cm, 5.8 g/cm^2 and 5.2 mm.

4.22.

5.35 MeV/(g/cm^2), radiation losses are 2.5 times higher, 7.5 MeV/(g/cm^2).

4.23.

205 MeV, 10.9 MeV/(g/cm^2).

4.24.

$T_e \approx 93$ MeV, $T_p \approx 96$ MeV.

4.25.

425 MeV.

4.26.

3.5 cm.

4.27.

0.8 cm.

4.28.

0.46 g/cm^2.

4.29.

1.1 mm.

4.30.

$\mu_e/\rho = 5.85$ (g/cm^2)$^{-1}$, 1.33 g/cm^2.

5.1.

1.35 times.

5.2.

3.9 cm.

5.3.

84.5 %, 24.4 cm.

5.4.

12.7 mm.

5.5.

< 7.4 mm.

5.6.

66.6 m, 3.5 cm, 1.2 cm, 5 mm.

5.7.

1.25 MeV.

5.8.

7.

5.9.

149.5 m, 17.4 cm, 2.6 cm, 1.7 cm.

5.10.

72.5 mm, 3 MeV.

5.11.

3.96 b/atom, 15.75 b/atom.

5.12.

0.63 cm^{-1}, 0.0556 $(\mathrm{g/cm}^2)^{-1}$.

5.13.

0.06 cm^{-1}, 0.0223 $(\mathrm{g/cm}^2)^{-1}$.

5.14.

13 %.

5.15.

2.5 mm.

6.1.

$\lambda = 8.45 \cdot 10^{-9}$ s^{-1}, $\tau = 3.75$ years.

6.2.

99.9 %, 86.2 %.

6.3.

$T_{1/2} = 87.4$ days, $\lambda = 9.2 \cdot 10^{-8}$ s^{-1}, $\tau = 126.1$ days.

6.4.

$\langle L \rangle = 25.6$ km.

6.5.

~ 3500 years.

6.6.

$T_{1/2} > N_0 \cdot t = 10^{34}$ years, where $N_0 = 10 \cdot N_A m/M(H_2O)$ is the number of protons in the water of a detector.

6.7.

$A_0 = 3.68 \cdot 10^{15}$ Bq, $A = 1.24 \cdot 10^{15}$ Bq.

6.8.

$A_0 = 51.9$ Bq.

6.9.

$a = 8.03 \cdot 10^{16}$ Bq/g.

6.10.

$m_0 = 12$ μg.

6.11.

$T_{1/2} = 2.6$ h, $N_0 = 1.4 \cdot 10^{20}$.

6.12.

$N(t) = \frac{q}{\lambda}(1 - e^{-\lambda t})$; $4.5 \cdot 10^5$ Bq, $1.3 \cdot 10^6$ Bq, $2.4 \cdot 10^6$ Bq, $9.8 \cdot 10^6$ Bq.

6.13.

34.1 h, $2.43 \cdot 10^{21}$.

6.14.

$1.4 \cdot 10^{10}$ years.

6.15.

1) no, yes;

2) yes, no;

3) no, yes;

4) yes, no, no;

5) yes, no;

6) no, yes.

6.16.

$T_\alpha = 4$ MeV, $T_{\text{Nucleus}} = 70$ keV, 1.7 %, 244 km/s.

6.17.

$Q_1 = 6553$ keV, $Q_2 = 6752$ keV, $Q_3 = 7320$ keV, $E_1^\gamma = 767$ keV, $E_2^\gamma = 568$ keV.

6.18.

$W = 17.8$ MJ.

6.20.

1) yes, yes, yes;

2) no, no, no;

3) yes, no, no.

6.21.

$T_e^{\max} = 2.64$ MeV, $v_e^{\max} = 2.96 \cdot 10^8$ m/s, $T_{\text{Nucleus}} = 79$ eV, $v_{\text{Nucleus}} = 15.2$ km/s.

6.22.

$T_e = 1.11$ MeV, $T_\nu = 1.53$ MeV.

6.23.

$T_e^{\max} = 0.65$ MeV, $v_e^{\max} = 2.69 \cdot 10^8$ m/s, $T_{\text{Nucleus}} = 9$ eV, $v_{\text{Nucleus}} = 5.3$ km/s.

6.24.

$T_e = 0.18$ MeV, $T_\nu = 0.47$ MeV.

6.25.

$A = 5 \cdot 10^{11}$ Bq.

6.26.

An activity of the source after an hour of the exposure is $A = 5.72 \cdot 10^{13}$ decays/s, an average energy of γ-quanta for a single decay is $W_{\text{decay}} = 1.63$ MeV/decay, source of γ-quanta $W = 9.32 \cdot 10^{13}$ MeV/c.

Appendix 1

Table A.1.1. Physical constants

Constant	Symbol	Value
Speed of light in vacuum	c	299 792 458 m/s
Planck's constant	h $\hbar \equiv h/2\pi$	$6.626\ 070\ 040 \cdot 10^{-34}$ J·s= $= 1.054571800 \cdot 10^{-34}$ J·s= $= 6.582119514 \cdot 10^{-22}$ MeV·s
Electron charge	e	$1.602\ 176\ 6208 \cdot 10^{-19}$ C
Conversion constant	$\hbar c$	197.326 9788 MeV·fm
Rest mass of electron	m_e	$0.510\ 998\ 9461$ MeV$/c^2$ = $= 9.10938356 \cdot 10^{-31}$ kg
Rest mass of proton	m_p	$938.272\ 0813$ MeV$/c^2$ = $= 1.672621898 \cdot 10^{-27}$ kg
Rest mass of neutron	m_n	$939.565\ 379$ MeV$/c^2$ = $= 1.674927351 \cdot 10^{-27}$ kg
Atomic mass unit	$m_{\text{a.m.u.}}$	$931.494\ 0954$ MeV$/c^2$ = $= 1.660539040 \cdot 10^{-27}$ kg
Vacuum permittivity	ε_0	$8.854\ 187\ 817 \cdot 10^{-12}$ $C^2/(N \cdot m^2)$
Vacuum permeability	μ_0	$4\pi \cdot 10^{-7}$ N/A^2
Fine-structure constant	$\alpha =$ $= e^2/4\pi\varepsilon_0\hbar c$	1/137.035 999 139
Classical electron radius	$r_e =$ $= e^2/4\pi\varepsilon_0 m_e c^2$	$2.817\ 940\ 3227 \cdot 10^{-15}$ m
Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\ 381\ 8012 \cdot 10^{-11}$ MeV/T
Nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\ 451\ 2550 \cdot 10^{-14}$ MeV/T
Gravitational constant	G_N	$6.674\ 08 \cdot 10^{-11}$ $m^3 \cdot kg^{-1} \cdot s^{-2}$
Standard gravitational acceleration	g_N	9.806 65 m/s^2
Gas constant	R	8.31441 J/(mol·K)
Avogadro constant	N_A	$6.022\ 140\ 857 \cdot 10^{23}$ mol^{-1}

Table A.1.2. Density of substances (under normal conditions: atmospheric pressure 760 mm Hg. art., $T = 0$ °C).

Material	Aggregate state	Density, g/cm^3
Aluminium	Solid	2.7
Gold		19.3
Copper		8.9
Window glass		2.5
Lead		11.3
Silver		10.5
Steel, Iron		7.8
Carbon		2.3
Zinc		7.1
Clean water	Liquid	1.0
Nitrogen	Gas	$1.2505 \cdot 10^{-3}$
Dry air		$1.2928 \cdot 10^{-3}$

Table A.1.3. Decimal prefixes to names of units

Prefix	Name	Order	Prefix	Name	Order
f	femto	10^{-15}	h	hecto	10^{2}
p	pico	10^{-12}	k	kilo	10^{3}
n	nano	10^{-9}	M	mega	10^{6}
μ	micro	10^{-6}	G	giga	10^{9}
m	milli	10^{-3}	T	tera	10^{12}
c	centi	10^{-2}	P	peta	10^{15}
d	deci	10^{-1}	E	exa	10^{18}

Table A.1.4. Properties of some particles

Particle	Charge (in e)	Rest energy	Spin	Average life time τ
p	$+1$	938.272 MeV	1/2	$> 2.1 \cdot 10^{29}$ years
n	0	939.565 MeV	1/2	880.1 s
$e^{\pm}$	± 1	0.511 MeV	1/2	$> 6.6 \cdot 10^{28}$ years
$\mu^{\pm}$	± 1	105.658 MeV	1/2	$2.2 \cdot 10^{-6}$ s
$\tau^{\pm}$	± 1	1776.86 MeV	1/2	$2.9 \cdot 10^{-13}$ s
ν_e, $\tilde{\nu}_e$	0	< 3 eV	1/2	–
ν_μ, $\tilde{\nu}_\mu$	0	< 0.19 MeV	1/2	–
ν_τ, $\tilde{\nu}_\tau$	0	< 18.2 MeV	1/2	–
$\pi^{\pm}$	± 1	139.57 MeV	0	$2.6 \cdot 10^{-8}$ s
π^0	0	134.98 MeV	0	$8.5 \cdot 10^{-17}$ s
$K^{\pm}$	± 1	493.677 MeV	0	$1.24 \cdot 10^{-8}$ s

Table A.1.5. Periodic table of elements

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9
1 H hydrogen 1.008								
3 Li lithium 6.94	4 Be beryllium 9.012							
11 Na sodium 22.9898	12 Mg magnesium 24.305							
19 K potassium 39.098	20 Ca calcium 40.078	21 Sc scandium 44.956	22 Ti titanium 47.867	23 V vanadium 50.942	24 Cr chromium 51.996	25 Mn manganese 54.938	26 Fe iron 55.845	27 Co cobalt 58.933
37 Rb rubidium 85.468	38 Sr strontium 87.62	39 Y yttrium 88.906	40 Zr zirconium 91.224	41 Nb niobium 92.906	42 Mo molybdenum 95.95	43 Tc technetium (97.907)	44 Ru ruthenium 101.07	45 Rh rhodium 102.906
55 Cs caesium 132.906	56 Ba barium 137.327	57-71 LANTHA- NIDES	72 Hf hafnium 178.49	73 Ta tantalum 180.948	74 W tungsten 183.84	75 Re rhenium 186.207	76 Os osmium 190.23	77 Ir iridium 192.217
87 Fr francium (223.02)	88 Ra radium (226.03)	89-103 ACTI- NIDES	104 Rf rutherford. (267.12)	105 Db dubnium (268.13)	106 Sg seaborgium (269.13)	107 Bh bohrium (270.13)	108 Hs hassium (269.13)	109 Mt meitnerium (278.16)

Lanthanide series	57 La lanthanum 138.905	58 Ce cerium 140.116	59 Pr praseodym. 140.908	60 Nd neodymium 144.242	61 Pm promethium (144.913)	62 Sm samarium 150.36	63 Eu europium 151.964
Actinide series	89 Ac actinium (227.028)	90 Th thorium 232.038	91 Pa protactinium 231.036	92 U uranium 238.029	93 Np neptunium (237.048)	94 Pu plutonium (244.064)	95 Am americium (243.061)

10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
								2 He helium 4.0026
			5 B boron 10.81	6 C carbon 12.0107	7 N nitrogen 14.007	8 0 oxygen 15.999	9 F fluorine 18.998	10 Ne neon 20.1797
			13 Al aluminium 26.982	14 Si silicon 28.085	15 P phosphorus 30.974	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.948
28 Ni nickel 58.693	29 Cu copper 63.546	30 Zn zinc 65.38	31 Ga gallium 69.723	32 Ge germanium 72.630	33 As arsenic 74.922	34 Se selenium 78.971	35 Br bromine 79.904	36 Kr krypton 83.798
46 Pd palladium 106.42	47 Ag silver 107.868	48 Cd cadmium 112.414	49 In indium 114.818	50 Sn tin 118.710	51 Sb antimony 121.760	52 Te tellurium 127.60	53 1 iodine 126.904	54 Xe xenon 131.293
78 Pt platinum 195.084	79 Au gold 196.967	80 Hg mercury 200.592	81 TI thallium 204.38	82 Pb lead 207.2	83 Bi bismuth 208.98	84 Po polonium (208.98)	85 At astatine (209.987)	86 Rn radon (222.018)
110 Ds darmstadt. (281.17)	ill Rg roentgen. (282.17)	112 Cn copernic. (285.18)	113 Nh (nihon.) (286.18)	114 FI flerov. (289.19)	115 Me (moscovium) (289.19)	116 Lv livermor. (294.21)	117 Ts (tennessine) (294.21)	118 Og (oganesson) (294.21)

64 Gd gadolinum 157.25	65 Tb terbium 158.925	66 Dy dysprosium 162.500	67 Ho holmium 164.930	68 Er erbium 167.259	69 Tm thulium 168.934	70 Yb ytterbium 173.054	71 Lu lutetium 174.967

96 Cm curium (247.070)	97 Bk berkelium (247.070)	98 Cf californium (251.080)	99 Es einsteinium (252.083)	100 Fm fermium (257.095)	101 Md mendelevium (258.098)	102 No nobelium (259.101)	103 Lr lawrencium (262.110)

Table A.1.6. Some quantum numbers

Group		Particle (antiparticle)	Charge, in units e	Spin	Isospin	Lepton number			Baryon number B	Strangeness
						L_e	L_μ	L_τ		
Photons		γ	0	1	–	0	0	0	0	0
Leptons		$e^-(e^+)$	-1(+1)	1/2	–	+1(-1)	0	0	0	0
		$\nu_e(\tilde{\nu}_e)$	0	1/2	–	+1(-1)	0	0	0	0
		$\mu^-(\mu^+)$	-1(+1)	1/2	–	0	+1(-1)	0	0	0
		$\nu_\mu(\tilde{\nu}_\mu)$	0	1/2	–	0	+1(-1)	0	0	0
		$\tau^-(\tau^+)$	-1(+1)	1/2	–	0	0	+1(-1)	0	0
		$\nu_\tau(\tilde{\nu}_\tau)$	0	1/2	–	0	0	+1(-1)	0	0
Hadrons	Mesons	π^0	0	0	1	0	0	0	0	0
		$\pi^+(\pi^-)$	+1(-1)	0	1	0	0	0	0	0
		$K^0(\tilde{K}^0)$	0	0	1/2	0	0	0	0	+1(-1)
		$K^+(K^-)$	+1(-1)	0	1/2	0	0	0	0	+1(-1)
		η^0	0	0	0	0	0	0	0	0
	Baryons	$p(\tilde{p})$	+1(-1)	1/2	1/2	0	0	0	+1(-1)	0
		$n(\tilde{n})$	0	1/2	1/2	0	0	0	+1(-1)	0
		$\Lambda^0(\tilde{\Lambda}^0)$	0	1/2	0	0	0	0	+1(-1)	-1(+1)
		$\Sigma^0(\tilde{\Sigma}^0)$	0	1/2	1	0	0	0	+1(-1)	-1(+1)
		$\Sigma^+(\tilde{\Sigma}^+)$	+1(-1)	1/2	1	0	0	0	+1(-1)	-1(+1)
		$\Sigma^-(\tilde{\Sigma}^-)$	-1(+1)	1/2	1	0	0	0	+1(-1)	-1(+1)

Table A.1.7. The table of the nuclide properties

Z	Nuclide	J^P	$\frac{M(A,Z)}{m_{\text{a.m.u.}}}$	Decay	$T_{1/2}$	$\frac{\mu}{\mu_N}$
0	n	$1/2^+$	1.008665	β^-	613.9 s	-1.913
1	${}^{1}_{1}\text{H}$	$1/2^+$	1.007825			+2.793
	${}^{2}_{1}\text{H}$	1^+	2.014102			+0.857
	${}^{3}_{1}\text{H}$	$1/2^+$	3.016049	β^-	12.32 years	+2.979
	${}^{4}_{1}\text{H}$	2^-	4.026432	n	$9.9 \cdot 10^{-23}$ s	
2	${}^{3}_{2}\text{He}$	$1/2^+$	3.016029			-2.128
	${}^{4}_{2}\text{He}$	0^+	4.002603			
	${}^{5}_{2}\text{He}$	$3/2^-$	5.012057	n	$7.04 \cdot 10^{-22}$ s	
3	${}^{6}_{3}\text{Li}$	1^+	6.015123			+0.822
	${}^{7}_{3}\text{Li}$	$3/2^-$	7.016004			+3.256
4	${}^{8}_{4}\text{Be}$	0^+	8.005305	2α	$8.2 \cdot 10^{-17}$ s	
	${}^{10}_{4}\text{Be}$	0^+	10.013535	β^-	$1.5 \cdot 10^{6}$ years	
5	${}^{8}_{5}\text{B}$	2^+	8.024607	β^+	0.77 s	1.036
	${}^{9}_{5}\text{B}$	$3/2^-$	9.013330	p	$8.4 \cdot 10^{-19}$ s	
	${}^{10}_{5}\text{B}$	3^+	10.012937			+1.801
	${}^{11}_{5}\text{B}$	$3/2^-$	11.009305			+2.689
6	${}^{11}_{6}\text{C}$	$3/2^-$	11.011433	β^+	20.3 min	-0.964
	${}^{12}_{6}\text{C}$	0^+	12.000000			
	${}^{13}_{6}\text{C}$	$1/2^-$	13.003355			+0.702
	${}^{14}_{6}\text{C}$	0^+	14.003242	β^-	5700 years	
7	${}^{13}_{7}\text{N}$	$1/2^-$	13.005739	β^+	9.97 min	0.322
	${}^{14}_{7}\text{N}$	1^+	14.003074			+0.404
	${}^{15}_{7}\text{N}$	$1/2^-$	15.000109			-0.283
8	${}^{15}_{8}\text{O}$	$1/2^-$	15.003066	β^+	2.04 min	0.719
	${}^{16}_{8}\text{O}$	0^+	15.994915			
	${}^{17}_{8}\text{O}$	$5/2^+$	16.999132			-1.894
10	${}^{19}_{10}\text{Ne}$	$1/2^+$	19.001880	β^+	17.2 s	

Z	Nuc-lide	J^P	$\frac{M(A,Z)}{m_{\text{a.m.u.}}}$	De-cay	$T_{1/2}$	$\frac{\mu}{\mu_{\text{N}}}$
11	$^{22}_{11}$Na	3^+	21.994437	β^+	2.6 years	+1.746
	$^{23}_{11}$Na	$3/2^+$	22.989769			+2.218
	$^{24}_{11}$Na	4^+	23.990963	β^-	15 h	+1.690
12	$^{22}_{12}$Mg	0^+	21.999571	β^+	3.9 s	
	$^{23}_{12}$Mg	$3/2^+$	22.994124	K	11.3 s	
	$^{24}_{12}$Mg	0^+	23.985042			
	$^{25}_{12}$Mg	$5/2^+$	24.985837			-0.855
	$^{26}_{12}$Mg	0^+	25.982593			
	$^{27}_{12}$Mg	$1/2^+$	26.984341	β^-	9.5 min	-0.041
13	$^{26}_{13}$Al	5^+	25.986892	K	$7.2 \cdot 10^5$ years	+2.804
	$^{27}_{13}$Al	$5/2^+$	26.981538			+3.642
	$^{28}_{13}$Al	3^+	27.981910	β^-	2.2 min	
14	$^{27}_{14}$Si	$5/2^+$	26.986705	K	4.2 s	0.865
	$^{28}_{14}$Si	0^+	27.976927			
	$^{29}_{14}$Si	$1/2^+$	28.976495			-0.555
	$^{31}_{14}$Si	$3/2^+$	30.975363	β^-	2.6 h	
15	$^{32}_{15}$P	1^+	31.973908	β^-	14.3 days	-0.252
16	$^{33}_{16}$S	$3/2^+$	32.971459			+0.644
	$^{35}_{16}$S	$3/2^+$	34.969032	β^-	87.4 days	+1.00
17	$^{35}_{17}$Cl	$3/2^+$	34.968853			+0.822
	$^{36}_{17}$Cl	2^+	35.968307	β^-, β^+	$3 \cdot 10^5$ years	+1.285
18	$^{36}_{18}$Ar	0^+	35.967545			
	$^{37}_{18}$Ar	$3/2^+$	36.966776	K	35 days	+1.145
	$^{40}_{18}$Ar	0^+	39.962383			
19	$^{39}_{19}$K	$3/2^+$	38.963706			+0.391
20	$^{40}_{20}$Ca	0^+	39.962591			
21	$^{45}_{21}$Sc	$7/2^-$	44.955908			+4.756
24	$^{52}_{24}$Cr	0^+	51.940505			

Z	Nuc-lide	J^P	$\frac{M(A,Z)}{m_{\text{a.m.u.}}}$	De-cay	$T_{1/2}$	$\frac{\mu}{\mu_N}$
25	$^{55}_{25}$Mn	$5/2^-$	54.938043			3.453
	$^{56}_{25}$Mn	3^+	55.938903	β^-	2.6 h	+3.227
26	$^{55}_{26}$Fe	$3/2^-$	54.938291	K	2.7 years	
	$^{56}_{26}$Fe	0^+	55.934936			
	$^{59}_{26}$Fe	$3/2^-$	58.934874	β^-	44.5 days	-0.336
27	$^{60}_{27}$Co	5^+	59.933816	β^-	5.3 years	+3.799
28	$^{64}_{28}$Ni	0^+	63.927966			
	$^{65}_{28}$Ni	$5/2^-$	64.930085	β^-	2.5 h	
	$^{66}_{28}$Ni	0^+	65.929139	β^-	54.6 h	
29	$^{63}_{29}$Cu	$3/2^-$	62.929597			+2.223
	$^{64}_{29}$Cu	1^+	63.929765	K, $\beta^\pm$	12.7 h	-0.217
	$^{65}_{29}$Cu	$3/2^-$	64.927790			+2.382
	$^{66}_{29}$Cu	1^+	65.928869	β^-	5.1 min	-0.282
30	$^{64}_{30}$Zn	0^+	63.929142			
	$^{65}_{30}$Zn	$5/2^-$	64.929241	K	243.9 days	
	$^{66}_{30}$Zn	0^+	65.926034			
36	$^{90}_{36}$Kr	0^+	89.919528	β^-	32.3 s	
45	$^{103}_{45}$Rh	$1/2^-$	102.905494			-0.088
46	$^{106}_{46}$Pd	0^+	105.903480			
47	$^{106}_{47}$Ag	1^+	105.906664	K, β^-	24 min	+2.85
	$^{107}_{47}$Ag	$1/2^-$	106.905092			-0.114
56	$^{143}_{56}$Ba	$5/2^-$	142.920625	β^-	14.5 s	+0.443
59	$^{141}_{59}$Pr	$5/2^+$	140.907658			+4.275
77	$^{194}_{77}$Ir	1^-	193.965076	β^-	19.3 h	+0.39
78	$^{197}_{78}$Pt	$1/2^-$	196.967343	β^-	19.9 h	0.51
79	$^{197}_{79}$Au	$3/2^+$	196.966570			
	$^{198}_{79}$Au	2^-	197.968244	β^-	2.7 days	+0.593
80	$^{200}_{80}$Hg	0^+	199.968327			
81	$^{200}_{81}$Tl	2^-	199.970964	K	26.1 h	0.04

Z	Nuclide	J^P	$\frac{M(A,Z)}{m_{\text{a.m.u.}}}$	Decay	$T_{1/2}$	$\frac{\mu}{\mu_N}$
82	$^{188}_{82}$Pb	0^+	187.980875	K, α	25.1 s	
	$^{200}_{82}$Pb	0^+	199.971818	K	21.5 h	
	$^{206}_{82}$Pb	0^+	205.974465			
	$^{207}_{82}$Pb	$1/2^-$	206.975897			
	$^{208}_{82}$Pb	0^+	207.976652			
84	$^{210}_{84}$Po	0^+	209.982874	α	138.4 days	
86	$^{222}_{86}$Rn	0^+	222.017576	α	3.8 days	
88	$^{226}_{88}$Ra	0^+	226.025408	α	$1.6 \cdot 10^3$ years	
	$^{228}_{88}$Ra	0^+	228.031069	β^-	5.75 years	
90	$^{232}_{90}$Th	0^+	232.038054	α	$1.4 \cdot 10^{10}$ years	
	$^{233}_{90}$Th	$1/2^+$	233.041580	β^-	21.8 min	
91	$^{235}_{91}$Pa	$3/2^-$	235.045399	β^-	24.4 min	
92	$^{235}_{92}$U	$7/2^-$	235.043928	α	$7 \cdot 10^8$ years	-0.38
	$^{236}_{92}$U	0^+	236.045566	α	$2.3 \cdot 10^7$ years	
	$^{238}_{92}$U	0^+	238.050787	α	$4.5 \cdot 10^9$ years	
	$^{239}_{92}$U	$5/2^+$	239.054292	β^-	23.45 min	
94	$^{238}_{94}$Pu	0^+	238.049558	α	87.7 years	
	$^{239}_{94}$Pu	$1/2^+$	239.052162	α	$2.4 \cdot 10^4$ years	+0.203

Table A.1.8. The average ionization potential I

Z	Element	I, eV
7	N	82
13	Al	166
26	Fe	286

Z	Element	I, eV
29	Cu	322
79	Au	790
82	Pb	823

Table A.1.9. Massive coefficients of attenuation μ/ρ and absorption τ/ρ of γ-quanta for air, water and glass

E_γ, MeV	Air		Water		Glass	
	μ/ρ, cm^2/g	τ/ρ, cm^2/g	μ/ρ, cm^2/g	τ/ρ, cm^2/g	μ/ρ, cm^2/g	τ/ρ, cm^2/g
0.10	0.15410	0.02325	0.1707	0.02546	0.1657	0.03209
0.15	0.13560	0.02496	0.1505	0.02764	0.1389	0.02727
0.20	0.12330	0.02672	0.1370	0.02967	0.1246	0.02757
0.30	0.10670	0.02872	0.1186	0.03192	0.1069	0.02885
0.40	0.09549	0.02949	0.1061	0.03279	0.0954	0.02946
0.50	0.08712	0.02966	0.09687	0.03299	0.08696	0.02957
0.60	0.08055	0.02953	0.08956	0.03284	0.08035	0.02941
0.80	0.07074	0.02882	0.07865	0.03206	0.07052	0.02868
1.00	0.06358	0.02789	0.07072	0.03103	0.06337	0.02774
1.25	0.05687	0.02666	0.06323	0.02965	0.05667	0.0265
1.50	0.05175	0.02547	0.05754	0.02833	0.05160	0.02533
2.00	0.04447	0.02345	0.04942	0.02608	0.04447	0.02337
3.00	0.03581	0.02057	0.03969	0.02281	0.03611	0.02069
4.00	0.03079	0.01870	0.03403	0.02066	0.03140	0.01904
5.00	0.02751	0.01740	0.03031	0.01915	0.02838	0.01795
6.00	0.02522	0.01647	0.02770	0.01806	0.02632	0.01721
8.00	0.02225	0.01525	0.02429	0.01658	0.02373	0.01629
10.0	0.02045	0.01450	0.02219	0.01566	0.02223	0.01579
15.0	0.01810	0.01353	0.01941	0.01441	0.02045	0.01522
20.0	0.01705	0.01311	0.01813	0.01382	0.01982	0.01503

Table A.1.10. Massive coefficients of attenuation μ/ρ and absorption τ/ρ of γ-quanta for aluminium, iron and lead

E_γ, MeV	Aluminium		Iron		Lead	
	μ/ρ, cm^2/g	τ/ρ, cm^2/g	μ/ρ, cm^2/g	τ/ρ, cm^2/g	μ/ρ, cm^2/g	τ/ρ, cm^2/g
0.10	0.1704	0.03794	0.3717	0.21770	5.549	1.976
0.15	0.1378	0.02827	0.1964	0.07961	2.014	1.056
0.20	0.1223	0.02745	0.1460	0.04825	0.9985	0.587
0.30	0.1042	0.02816	0.1099	0.03361	0.4031	0.2455
0.40	0.09276	0.02862	0.0940	0.03039	0.2323	0.1370
0.50	0.08445	0.02868	0.08414	0.02914	0.1614	0.09128
0.60	0.07802	0.02851	0.07704	0.02836	0.1248	0.06819
0.80	0.06841	0.02778	0.06699	0.02714	0.0887	0.04644
1.00	0.06146	0.02686	0.05995	0.02603	0.07102	0.03654
1.25	0.05496	0.02565	0.05350	0.02472	0.05876	0.02988
1.50	0.05006	0.02451	0.04883	0.02360	0.05222	0.02640
2.00	0.04324	0.02266	0.04265	0.02199	0.04606	0.02360
3.00	0.03541	0.02024	0.03621	0.02042	0.04234	0.02322
4.00	0.03106	0.01882	0.03312	0.01990	0.04197	0.02449
5.00	0.02836	0.01795	0.03146	0.01983	0.04272	0.02600
6.00	0.02655	0.01739	0.03057	0.01997	0.04391	0.02744
8.00	0.02437	0.01678	0.02991	0.02050	0.04675	0.02989
10.0	0.02318	0.01650	0.02994	0.02108	0.04972	0.03181
15.0	0.02195	0.01631	0.03092	0.02221	0.05658	0.03478
20.0	0.02168	0.01633	0.03224	0.02292	0.06206	0.03595

Appendix 2

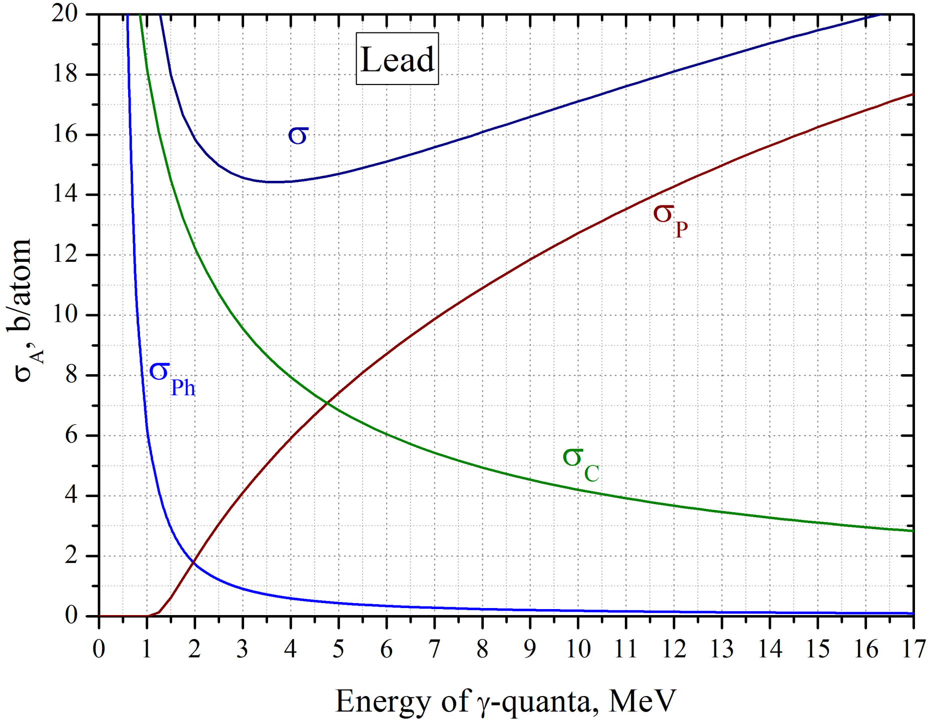


Fig. A.2.1. Cross-section of interaction of γ-quanta in lead

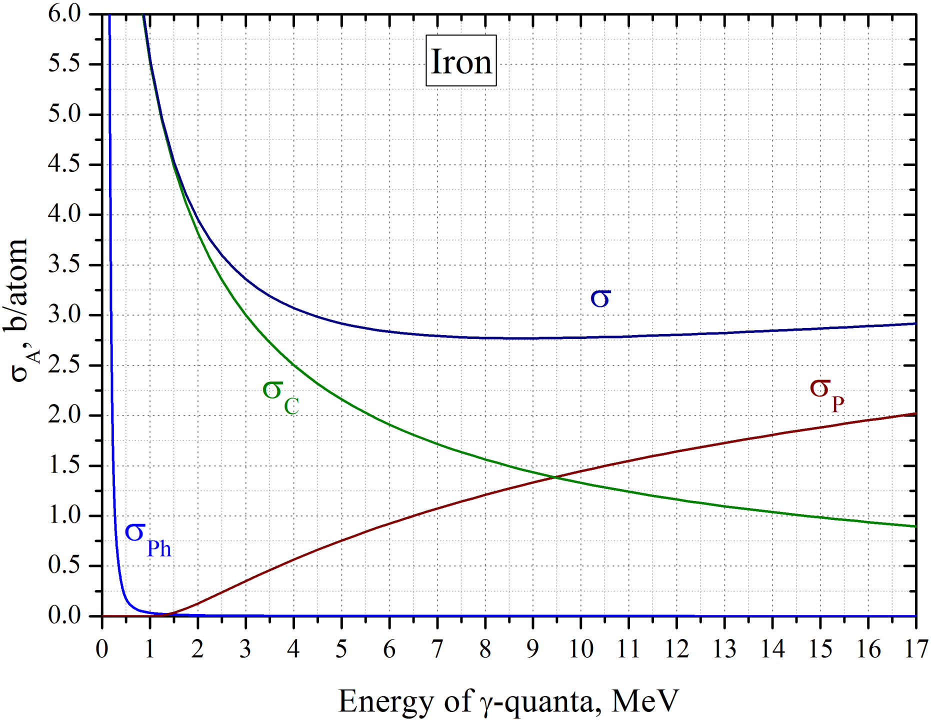


Fig. A.2.2. Cross-section of interaction of γ-quanta in iron

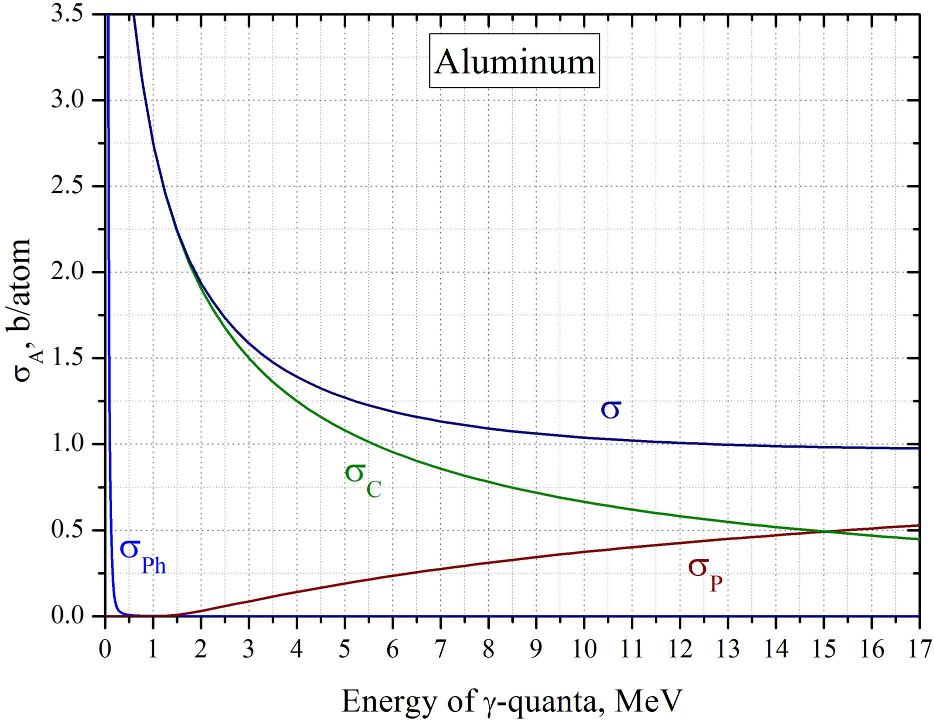


Fig. A.2.3. Cross-section of interaction of γ-quanta in aluminium

Ivan Ivanovich Astapov
Natalia Sergeevna Barbashina
Anna Nikolaevna Dmitrieva
Egor Alexandrovich Zadeba
Semyon Sergeevich Khokhlov
Igor Ivanovich Yashin

Problem book for the course Nuclear Physics

Учебное пособие

Корректор Е.Е. Шумакова

Подписано в печать 17.09.2020. Формат 60×84 1/16.
Печ. л. 4,0. Уч.-изд. л. 4,0. Тираж 200 экз.
Изд. № 013-1. Заказ №   .

Национальный исследовательский ядерный
университет “МИФИ”.

Типография НИЯУ МИФИ.

115409, Москва, Каширское ш., д. 31.