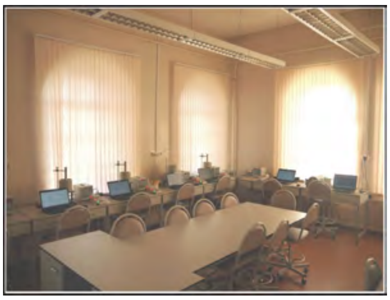
KAZAN FEDERAL UNIVERSITY
INSTITUTE OF PHYSICS

RECORDING BETA SPECTRUM WITH A SCINTILLATION COUNTER

PASSING OF β-RADIATION THROUGH MATTER



Kazan
2013

UDK 539.164
BBK 22.38

Approved by
the Editorial Board of Kazan Federal University
the Methodical Commission of the Institute of Physics
Protocol №6 from 5 November 2013

the Solid State Physics Department meeting
Protocol №2 from 16 October 2013

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Voronina E.V., *Recording beta spectrum with a scintillation counter. Passing of beta radiation through matter.* An educational guide to a general laboratory practicum on nuclear physics / Voronina E.V., Maslennikova A.E., Dulov E.N. // Kazan: Kazan Federal University publishing house, 2013. – 9 p.: 7 ill.

Destination:

The methodical guide is intended for students of the Institute of Physics and Institute of Geology Petroleum Technologies, as a support to the general physical practicum to the courses «Physics of particles and atomic nuclei», «Nuclear physics» and «Physics».

Introduction

Beta decay is a type of radioactive decay in which nucleons in atomic nucleus spontaneously changes their type. The decay occurs when it is energetically allowed and it can be accompanied by electron emission (β^--decay, a neutron in an atomic nucleus transforms into a proton), positron emission (β^+-decay, a proton in an atomic nucleus transforms into a neutron). Beta decay also may occur without emission of any charged particle. It is K-capture, when a proton in an atomic nucleus captures electron from atomic shell and transforms into a neutron. K-capture occurs mainly in heavy nuclei where the nuclear radii are larger (the larger radii, the more probable K-capture), and the electronic orbits are more compact. Usually, the electrons are captured from innermost (the "K") shell since such K-electrons are closest to the nucleus.

Beta-decay is a process which allows atom to obtain the optimal ratio of protons and neutrons.

The lifetimes of β-unstable nuclei vary between a few milliseconds and 10^{16} years. They strongly depend on released energy and on the nuclear properties of the mother and daughter nuclei.

Beta-decay is mediated by *weak force*, existence of which was supposed to explain relatively large times and small probabilities of the corresponding reactions.

Examples of the beta-decays:

β^--decay: $\quad {}^3_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + e^- + \tilde{\nu}_e$,

β^+-decay: $\quad {}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + e^+ + \nu_e$,

K-capture: $\quad {}^{57}_{28}\mathrm{Co} + e^- \rightarrow {}^{57}_{27}\mathrm{Fe} + \nu_e$,

where e^- (e^+) is an electron (positron), and ν_e ($\tilde{\nu}_e$) is a neutrino (antineutrino).

Graphical decay scheme of beta radioactive nucleus comprising all types of decay is shown in Fig. 1. It is interesting to notice that ^{40}K is a beta-radioactive isotope in natural mixture of potassium isotopes with 0.012% abundance.

Beta decays are always accompanied by a neutrino or antineutrino radiation.

In the beta decay a mother nucleus transforms into a daughter nucleus with the same number of nucleons or the same mass number. Such nuclei reveal some similarities due to the charge symmetry of the *strong force* and they are named *isobars*. Due to the same daughter nuclei, electron capture reactions compete with β^+-decay.

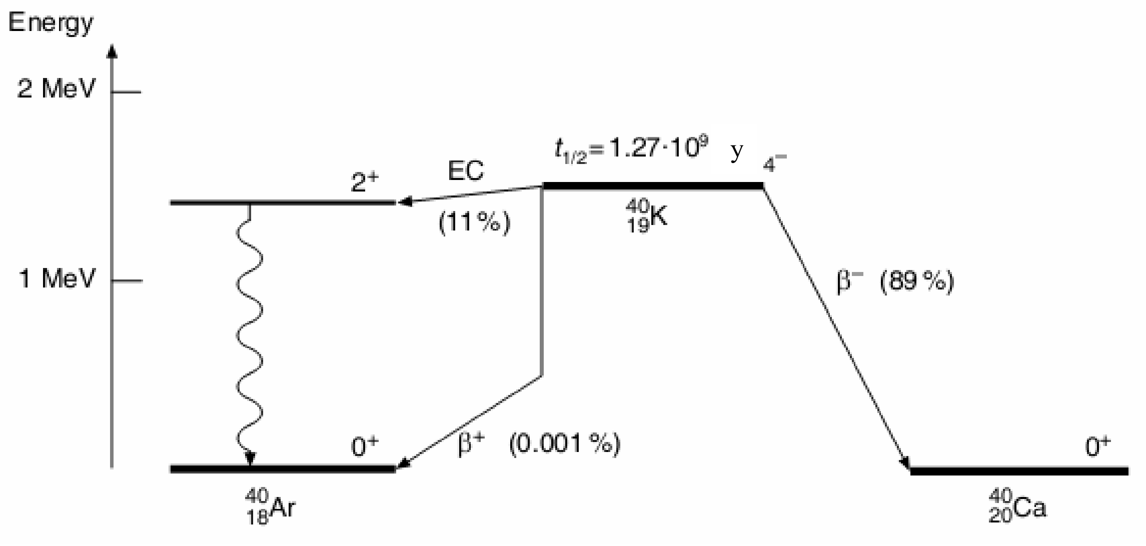

Figure 1. The β-decay of ^{40}K. The bent arrow in β^+-decay indicates that the production of a positron and the presence of surplus electron in ^{40}Ar requires energy of 1.022MeV ($2m_ec^2$), and the remainder is carried off as kinetic energy of the positron and neutrino. Half-life is measured in years. EC means electronic capture.

A simplest example demonstrating intraparticle origin of beta decay is the decay of a free neutron into a proton, an electron and an antineutrino:

$$n \rightarrow p + e^{-} + \tilde{\nu}_e .$$

The decay proceeds with 0.78 MeV energy release. Free neutron has an average lifetime ~887 s.

Neutrino (and antineutrino later) appears in 1930th as a hypothetic particle intended for theoretical explanation of some contradictions observed in experiments (W. Pauli hypothesis). One of these was the continuous spectrum of beta particles, which strongly differs the beta decay from two-particle processes like an alpha decay. Energy and momentum conservation laws combined with constant decay energy in a two-particle system must always lead to a constant energy of emitted particle. Moreover, the angular momentum conservation law is also broken without neutrino, as clearly seen from the free neutron decay where all particles have spin 1/2. The unique property of neutrino and antineutrino is extremely small probability of interaction with matter, which made the experimental discovery of neutrino possible only in 1950th. Mean free path of neutrinos in condensed matter is a value of the order of light years.

Theoretical explanation of beta decay was firstly proposed by E. Fermi in 1934. A key idea of the Fermi's theory was the analogy between beta particles in beta decay and photons emitted by excited atom. According to the idea, beta particles like photons do not exist in nucleons before decay, but are born in the decay moment. By addition of the hypothetic Pauli's neutrino Fermi has obtained elegant theory, which generally explains behaviors of beta-radioactive nuclei. At the same time, a new type of interaction was introduced in the theory – weak forces – as a scale value for interaction energy.

A further development of the quantum field theory and experimental particle physics has demanded some developments of the theory. Firstly, the original Fermi model supposed instantaneous transformation of a nucleon into three particles (so-called 4-point Fermi's interaction or four-fermion interaction). Secondly, Fermi's theory had some discrepancies with experiments in particle physics, especially in high energy scale. Because of these reasons, the conception about mediators for the weak forces has appeared in 1960th. Weak forces are mediated by field quanta like electromagnetic forces by photons. At the present time, beta decay is considered as a decay of single quarks (parts of nucleon) by means of weak forces via massive intermediate bosons (W^+,W^-,Z^0). The same as for electromagnetic forces, appearing probability for intermediate bosons combined with their masses allow unifying weak and electromagnetic interactions into the *electroweak interaction*.

Principles

The energy distribution of the emitted beta particles ranges from E_β=0 up to the decay energy E_0. As far as the electric field of the positively charged nucleus acts on beta particles, the beta spectra – the energy distributions – of positrons and electrons have different shapes (see Fig. 2).

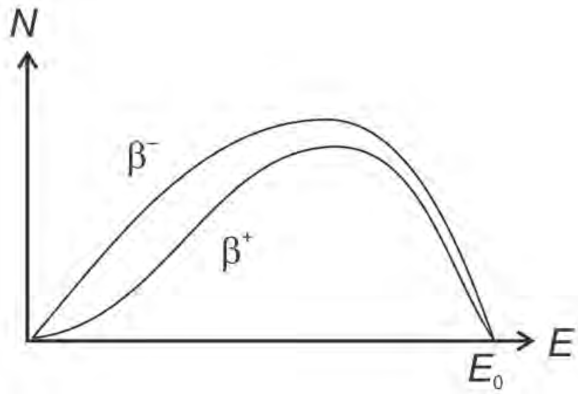

Figure 2. Beta spectra of electrons (β^-) and positrons (β^+).

In the experiment of present work, the beta spectrum of ^{90}Sr radioactive source is recorded by means of an energy calibrated scintillation counter: in the beta decay of ^{90}Sr the daughter nuclide ^{90}Y is produced, which is also β-instable (see Fig. 3). Therefore, the superposition of two β-spectra with different decay energies E_0 is measured.

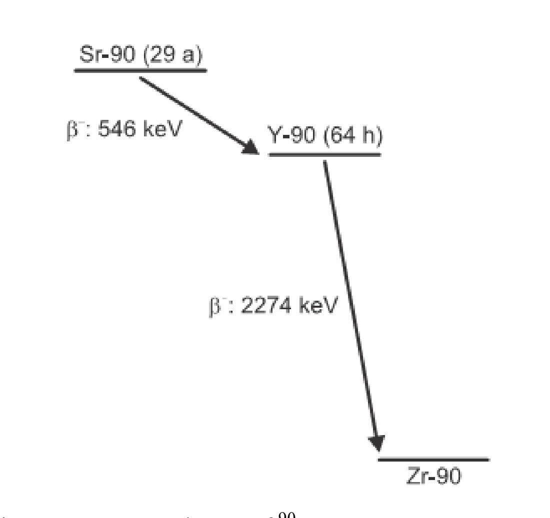

Figure 3. Decay scheme of ^{90}Sr.

Since the emitted β-particles loose energy in the jacket of the radioactive source and the aluminium shield of the scintillation counter, the maximum β-energy that can be measured is smaller than the decay energy E_0 (see Fig. 4).

The energy loss of the β-particles in aluminium is determined by placing aluminium absorbers of varying thickness x into the ray path between the radioactive source and the scintillation counter. The maximum energy E measured is plotted as a function depending on the thickness x of the absorber. From the slope of the function $E(x)$, the energy loss per path length, dE/dx, of the β-particles in aluminium is determined.

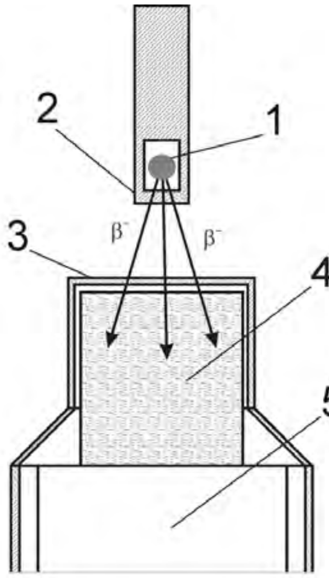

Figure 4. Schematic of the experiment. 1 – the radioactive source; 2 – jacket of the radioactive source; 3 – shield of the scintillation counter; 4 – scintillation crystal; 5 – photomultiplier.

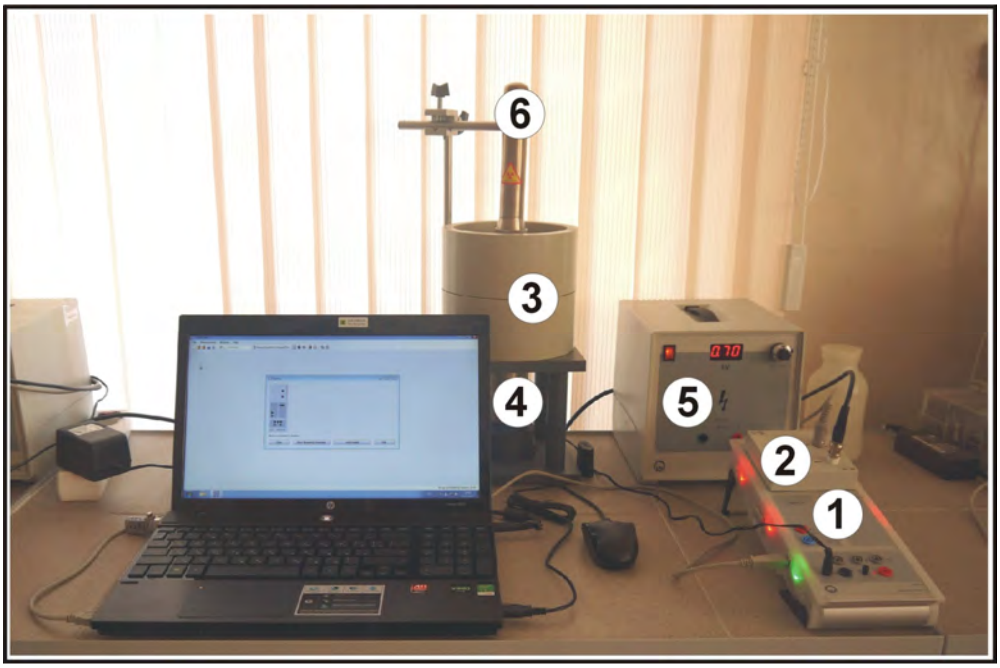

Figure 5. The experimental setup. 1 – the CassyLab2 data acquisition unit; 2 – the multichannel analyzer module; 3 – the scintillator screening (Pb, ~1 cm); 4 – the scintillation detector; 5 – the high-voltage scintillator power supply; 6 – the holder for the beta radioactive source.

Setup

Experimental setup is shown in Fig. 5. Universal CassyLab2 data acquisition unit **1** with the module **2** of multichannel analyzer MCA and appropriate software is used. A sample is set around scintillation detector **4** or placed in source holder **6**. Scintillation detector is connected to the input of CassyLab2 data acquisition unit **1** (Fig. 5). Detector voltage is adjusted by high voltage power supply **5**. A notebook with specified software installed is used to display and process the data.
Take care while working with the scintillation counter and the radiation source.

Carrying out the experiment

Before operations make sure that all units of the setup are available and connected according to the scheme above.

Preparation
- Switch on the notebook, the power supply of the CassyLab2 unit, and the high-voltage power supply.
- Run the CassyLab2 by clicking the icon on the desktop.
- In the window "Cassy" select "measurements channel" by the upper square selection of the left column (multichannel analyser). Measurements scale will appear and the window Voltage U_a too.
- In the window "Cassy" click on "Show Measuring Parameters". In the tab "Settings" on the right the "Measuring Parameters" window will pop-up. Set the measurements time 10 min, with the measurement increments – 1sec.
- Adjust voltage on the high-voltage power supply – 500 V.

Energy calibration
- Ask adviser to mount the known source (for example, ^{60}Co) to record the calibration gamma-spectrum.
- In the tab "Measurement" press → "Start/stop Measurement". This operation will initiate measurement of the spectrum. Note that the same action is caused by pressing the <F9> key.
- Tune up high voltage so that the spectrum is not cut off on the right-hand side. At this stage there is no need to record the spectrum during all 10 min.
- Repeat the item 6.
- Click by the right button to get "Menu of Actions" with the spectrum. Select "Fit Function" → "Gaussian of equal Width". Then, hold the left button to mark the line of the spectrum.
- Read a result of the processing in the line at the bottom of the window CassyLab2 (line center - μ, line width – σ).
- In the tab "Settings" perform the energy calibration of abscissa. Select in the Settings tree the item "Cassys" → "Input A_1" → "Channel n_A".
- In the Group Box named "Energy Calibration" set the check mark in the line "Global for all channels" and type two calibration points in the corresponding windows. Enter for the first point: channel – "0", energy – "0". Enter for the second point channel – "μ". The energy should be chosen from the drop-down menu window corresponding to the line of the calibration source.
- Select in the Settings tree the item Cassys → Display → Standard → $N_A(n_A)$, after that rename *Ox* axis: E_A instead of n_A. The spectrum should be redrawn in energy scale.
- It is recommended to determine the background without radioactive source.

Recording beta spectra with different absorbers thickness
- Ask adviser to mount the ^{90}Sr source once more, and to see if there is enough space for the absorbers.
- One after the other record the spectra without absorber, put an aluminium plate as an absorber over the scintillator counter and repeat the spectrum measurements for at least two values of the aluminium absorber

thickness, for example, 0.5 mm and 1 mm.

• In the measured spectra determine E_m (E_m – the point corresponding the spectrum and *Ox* axis to coincide (see Fig. 6).

• Plot E_m versus the absorber thickness. Select in the tree "Settings" the item Cassys → Display, the button "New".

• In the field "Name" type "Energy loss" and press the button "Add new Curve".

• Specify in the drop-down window the label for the *x*-axis: *d*. Specify the label for the *y*-axis: E_m. In the column "Style" set the check mark at "Values".

• In the plot, select "Fit Function"→ "Best fit Straight Line" clicking with the button of the mice.

• Estimate the aluminium absorber thickness required for the total absorption of electrons from ^{90}Sr.

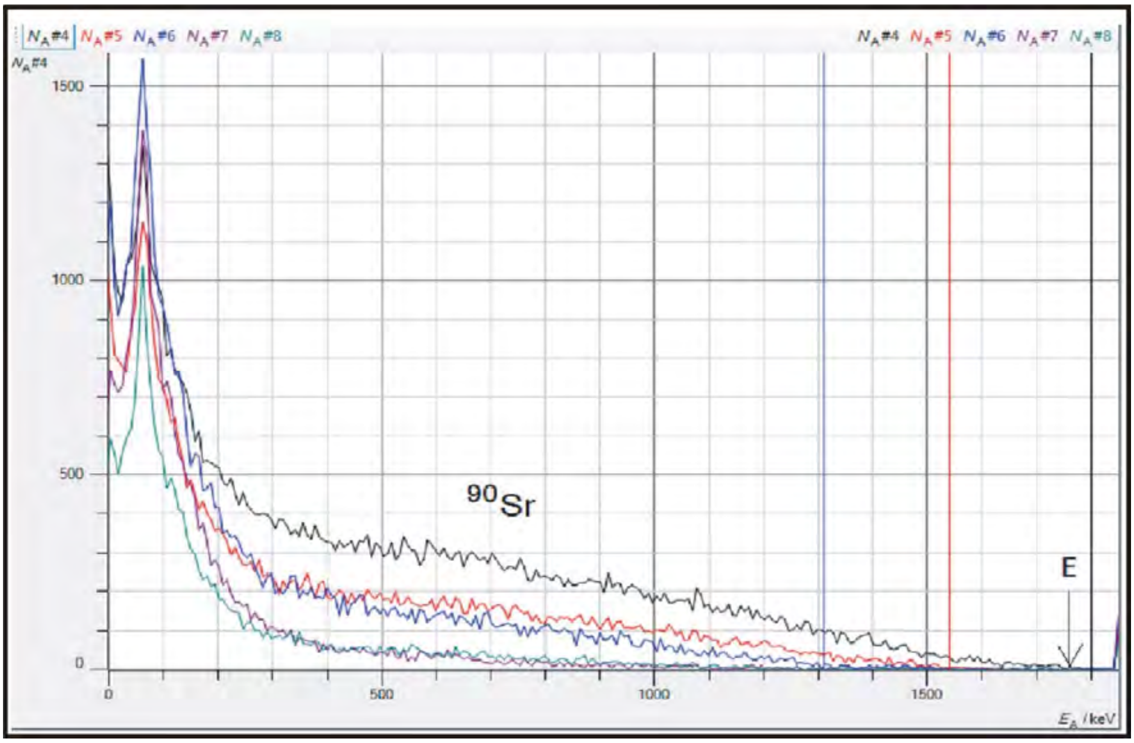

Figure 6. Beta spectrum of ^{90}Sr without absorber (black line) and with an aluminium absorber (colored lines) of different thickness.

An example of measurements

Table 1. Maximum β energy *E* as a function of the absorber thickness *d*.

d / mm	*E* / keV
0.0	1840
0.5	1540
1.0	1310
1.5	1160
2.0	870
2.5	620
3.0	490

Evaluation and results

Shape of the beta spectrum

Figure 6 shows the β spectrum of ^{90}Sr measured with the scintillation counter. The superposition of two distributions can be identified, each of which has the shape shown in Fig. 2. The first distribution is due to the transition from ^{90}Y to ^{90}Zr ($E_0 = 2274$ keV) and the second one – to the transition from ^{90}Sr to ^{90}Y ($E_0 = 546$ keV).

Determining the energy loss per path length

In Fig. 7, the dependence of the maximum β energy E on the thickness d of the aluminium absorber is shown graphically. The slope of the straight line drawn in the plot corresponds to the energy loss per path length of the β-particles in aluminium:

$$\frac{dE}{dx} = 452 \frac{\text{keV}}{\text{mm}}.$$

Value quoted in the literature:

$$\frac{dE}{dx} = 410 \frac{\text{keV}}{\text{mm}} \text{ at } E_\beta = 2000 \text{keV}.$$

The measured value is higher than that quoted in the literature for pure aluminium because commercial aluminium contains a large amount of admixtures of substances with higher ordinal number.

Determining the decay energy:

The aluminium screening of the scintillation counter (d_0 = 0.4 mm) causes a further energy loss of the β particles:

$$\Delta E = \frac{dE}{dx} d_0 = 180 \text{keV}.$$

The maximum energy of the β particle escaping from the ^{90}Sr radioactive source thus is

E_β = 1840 keV + 180 keV = 2020 keV.

The decay energy E_0 for the transition from ^{90}Y to ^{90}Zr is E_0 = 2274 keV, that is, by 254 keV, above the value determined in the experiment. This difference is due to the energy loss of the β particles in the jacket of the radioactive source (gold-palladium foil, d = 0.15 mm).

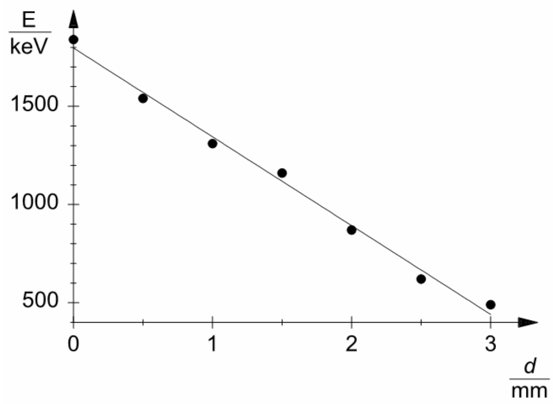

Figure 7. Maximum β energy E as a function of the absorber thickness d.

Report

Process the spectra by CassyLab2 software. Analyze the spectra obtained.
Save the results as graphs making screenshots or by exporting windows as images by means of the CassyLab2 software. Save the graphs in an external storage and use in the documentation of your work.
Represent the results in print including all estimations and graphs.

Safety notes

The following safety rules must nevertheless be kept to:

- **Prevent access to the preparations by unauthorized persons.**
- **Before using the preparations make sure that they are intact.**
- **For the purpose of shielding, keep the preparations in their safety vessel.**
- **To ensure minimum exposure time and minimum activity, take the preparations out of the safety vessel only as long as is necessary for carrying out the experiment.**
- **To ensure maximum distance, hold the preparations only at the upper end of the metal holder and keep them away from your body as far as possible.**

Self-test problems

1. What is the energy range of beta particles?
2. Explain the term “K-capture”.
3. Show typical spectrum of beta particles from radioactive source. How does look corresponding neutrino spectrum? How does look the neutrino spectrum in K-capture?
4. Estimate in percents the recoil energy of a daughter nucleus in beta decay.
5. How do beta particles change their energy when passing through matter?
6. How large is the mean free path length of neutrino in solids?
7. What conservation law is sometimes broken in beta decay?
8. Are the beta spectroscopy with scintillation counter is applicable to radionuclides identification? What disadvantages has beta spectroscopy in comparison with alpha spectroscopy?
9. How large are the maximum path length of beta particles in aluminium?

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РЕЦЕНЗИЯ
на учебно-методическое пособие

Ворониной Е.В., Масленниковой А.Е., Дулова Е.Н., Бикчантаева М.М.

«Recording beta spectrum with a scintillation counter. Passing of beta-radiation through matter»

Рецензируемое учебно-методическое пособие «Recording beta-spectrum with a scintillation counter. Passing of β-radiation through matter» разработано авторами в рамках общефизического лабораторного практикума к лекционным курсам «Ядерная физика», «Физика ядра и частиц» и «Атомная и ядерная физика», и предназначено для англоязычных студентов, проходящих ядерно-физический практикум на материально-технической базе лаборатории ядерной физики кафедры ФТТ Института физики КФУ.

Пособие начинается с обзорной вводной части, в которой даются физические основы бета-распада. Затем следует часть с описанием экспериментальной лабораторной установки, в которой показаны основные узлы и их назначение. Далее приводится описание порядка выполнения работы, даются рекомендации по анализу и представлению экспериментальных результатов.

В пособии последовательно изложен материал, необходимый для понимания и применения регистрации бета-спектров в решении практических задач. Подробно рассматриваются многие явления и эффекты, необходимые как для работы с оборудованием, так и для анализа результатов.

Практическая часть задания даёт наглядное представление о физических процессах, происходящих при регистрации бета-частиц сцинтилляционным детектором, содержит все необходимые элементы для получения навыков работы на экспериментальных установках, в том числе на современном спектроскопическом оборудовании.

Рецензируемое пособие актуально и представляет несомненный интерес для преподавателей и студентов, сталкивающихся со спектроскопией ионизирующих излучений в учебной работе.

Считаю, что учебно-методическое пособие Ворониной Е.В., Масленниковой А.Е., Дулова Е.Н., Бикчантаева М.М. «Recording beta spectrum with a scintillation counter. Passing of β-radiation through matter» может быть рекомендовано в качестве пособия для англоязычных студентов.

С.н.с. КИББ КазНЦ РАН,
к.ф.-м.н. Манапов Р.А.

ОТДЕЛ КАДРОВ

Подпись

Заверяю