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INSTITUTE OF PHYSICS

NEUTRON ACTIVATION ANALYSIS

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Destination:

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

Introduction

The purpose of this laboratory work is introduction to and main regularities of nuclear reactions taking place by formation of a compound nucleus. The practical part of the work includes mastering of equipment and a technique of the isotope analysis by method of neutron activation given on an example of natural metallic silver activation. An analysis of the isotope products of nuclear reactions based on their half-life decay time is offered given by activation of the sample containing stable nuclides with known characteristics.

Neutron properties

Neutron is an electrically neutral elementary particle, one of constituents of atomic nuclei, nearly 2000 times heavier than an electron. Free neutron life-time is about 15 minutes. The free neutron decays according to the β^--decay scheme:

$$n \rightarrow p + e^- + \bar{\nu}, \qquad (1)$$

where n denotes neutron, p denotes proton, e^- denotes electron, and $\bar{\nu}$ denotes antineutrino. This example of reaction clearly demonstrates necessity of a neutrino hypothesis, a lack of which violates the conservation law of the momentum as long as a neutron spin is equal 1/2, the same for a proton and an electron. The antineutrino is required to balance the total spin in Equation (1).

A neutron has nearly the same magnetic moment as a proton

$$\mu_n = -(1.91315 \pm 0.00007)\mu_N, \qquad (2)$$

where μ_N – nuclear magneton, and the "minus" sign denotes opposite direction of the magnetic moment vector with respect to the spin.

The property of a neutron to have a magnetic moment testifies, at first, existence of its internal structure, and, second, such distribution of a charge inside a neutron that the negative charge is concentrated on the periphery. Nowadays, in experiments on collisions of electrons on neutrons, it is established that the neutron size is about 1 Fm (10^{-15} m), and a neutron consists of three charged quarks, one *u*-quark and two *d*-quarks (quarks are sub-elementary particles of different kinds).

De-Broglie wavelength of slowed-down neutrons can be comparable with interatomic distances. The wave properties of a neutron allow to study structures of a matter in the range of 10^{-5} – 10^{5} Å. Various physical methods of materials investigations are based on the neutrons scattering.

Basic properties of neutrons applied in the neutron scattering techniques are as follows:

1. The energy of the slowed-down neutrons is comparable with the energy of nuclear and molecular movements, and it lies in the range from meV to eV.
2. Neutrons are neutral (chargeless) particles, they interact with atomic nuclei, but not with distributed electronic shells. Cross-sections of the neutrons scattering can be very different even for neighboring nuclei which allows to distinguish light nuclei against heavier once. Hence, isotopic replacements allow to clarify abundances of different elements in compounds. This feature is an essential advantage against (or complementarily to) a method of X-ray scattering in which the radiation dissipates and scatters on electronic shells of atoms.
3. Existence of the magnetic moment at neutrons allows to study microscopic magnetic structures and magnetic fluctuations which determine macroscopic parameters of magnetic substances.
4. Neutron radiation deeply penetrates into substances that allows to investigate macroscopic properties like microcracks, fabrication faults, etc. Similar studies can not be carried out by means of optical methods, X-ray scattering or electron microscopy.

The scattering of neutron radiation by nuclei of atoms has an advantage that there is no need to consider a nuclear form factor, as it is necessary for X-rays to take into account a shape of an electronic cloud of an atom. Besides, a dispersive ability of an atom against neutrons does not decrease with increasing the angle of scattering, which is commonly observed for the X-ray scattering. Neutron diffraction scattering has sharp peaks even at large angles of scattering.

Nuclear reactions induced by neutrons

A compound nucleus, which forms as a result of neutrons capture by atomic nuclei, can decay following the main channels:

1. The radiation capture. The most widespread channel. After transition of a compound nucleus to the ground state it can be β-radioactive because it receives an excess neutron. Goes on all nuclei. Cross-section: for thermal neutrons varies in a wide range from 0.1 to 10^3 and occasionally reaches 10^4 barn (1 barn is numerically equal to 10^{-28} $m^2 = 10^{-24}$ cm^2 = 100 Fm^2 – the approximate cross section of a heavy atomic nucleus); for fast neutrons – from 0.1 to several barn.
2. The alpha-particle emission. Reactions on nuclei of Boron-10 and Lithium-7 are used for registration of neutrons. The cross-section of these reactions is about one thousand barn.
3. The proton emission. This reaction can be used for registration of neutrons. Reaction with tritium has cross-section of about 5000 barn.
4. Emission of two and more nucleons. A threshold reaction, the threshold is near 10 MeV. The cross-section – fractions of barn.
5. The nuclear fission. The energy introduced into a nucleus by a neutron, even the slowest, in certain cases exceeds the threshold energy of fission, and the fission reaction happens instantly. This happens, for example, with uranium-235 nuclei. For the majority of nuclei this channel is threshold. As an example, for uranium-238 the energy of a neutron has to exceed 1.8 MeV. The cross-section is small, except for some nuclei.
6. Elastic scattering.
7. Inelastic scattering. The threshold reaction, used for moderation of neutrons.

The experimental setup

The main units of the experimental setup are shown in Figures 1 to 4. In the setup, the source of neutrons placed into the lead protection shell (Fig. 1), the cascade of Geiger counters with a large solid angle of collection, is protected by a lead jacket (Fig. 2), the high-voltage power unit (Fig. 4, “3”) for the Geiger counters (Fig. 4, “1”) and the universal counter device (Fig. 4, “2”) are used.

Figure 1. The neutrons source.

The properties of the sample

As a sample, the strip from natural metallic silver is used. It contains two stable isotopes (with the natural abundance) ${}_{47}Ag^{107}$ (51%) and ${}_{47}Ag^{109}$ (49%). An average effective cross-section σ of the thermal neutrons capture is: $\sigma \cong 30$ barn for ${}_{47}Ag^{107}$; $\sigma \cong 84$ barn for ${}_{47}Ag^{109}$. The sample is fixed on the aluminum holder, allowing to put it into one of canals of the neutron source.

Figure 2. The cascade of Geiger counters, protected by a lead jacket.

The neutron source

Pu-α-Be ampoule ”1” (see the scheme in Figure 3) of the neutron source is placed in a paraffin block “3” for moderation of neutrons. Canals “4” (experimental canals), which are rooms for the sample in the neutron moderator block. The canals are placed at a distance from the source “1” sufficient for complete thermalization of the fast neutrons, generated by the source, at insignificant weakening of the neutron flux density. Thus, in the canal, optimum conditions for activation of nuclei by slow neutrons are created. The layer of cadmium “5”, surrounding the paraffin block, is effective protection against thermal neutrons. The lead cover “2” build of thick lead bricks serves as a protection against γ-radiation.

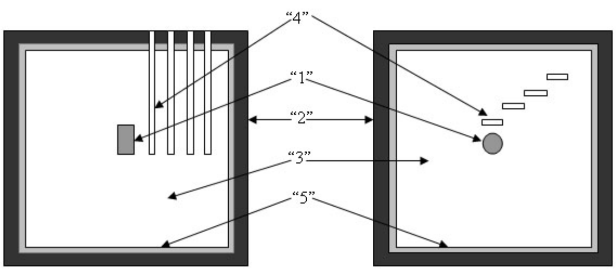

Figure 3. The internal arrangement of the neutron source (the side view – left, the top view – right).

For activation, the sample is located into the canal of the neutron source for not less, than 12-15 min – the time surpassing 5-6 times a half-life time for long-living nuclides. A numbered canal of the neutron source, chosen for activation of a sample, is specified by an advisor.

The order of implementation

The setup preparation

1. Before a run of the setup, please, check completeness of all units of the setup according to the previous section.
2. Turn on the power supply switch “Pwr” on the high-voltage power unit (Fig. 4, “3”, front panel, right-hand-side switch).
3. Turn on the high-voltage supply switch “Hi-V” on the high-voltage power unit (Fig. 4, “3”, front panel, left-hand-side switch).
4. Set up high-voltage level to (4.00±0.20)×100 V [means 400 V] for Geiger counters using helipot precision potentiometer labeled “Manual” on the front panel (Fig. 4, “3”)
5. Turn on the power network button on the *rear panel* of the counting device (Fig. 4, “2”).
6. Specify settings of the counting device:
   a) choose the pulses counting channel “B” (left bottom corner of the front panel, Fig. 4, “2”);
   b) by the button “RATE” choose 10 s (selection of the time window τ_p for measurements of the counting rate);
   c) buttons “N”, “R”, “f”, “Δt”, “t” – choose “N”.

Activation of the sample

After studying the description of the work and turning on of the devices, report on to an adviser readiness for the further work. Under supervision of the adviser make sample activation: for this purpose put down the holder with a sample into the experimental canal of the source of neutrons for the period of not less than 15 min.

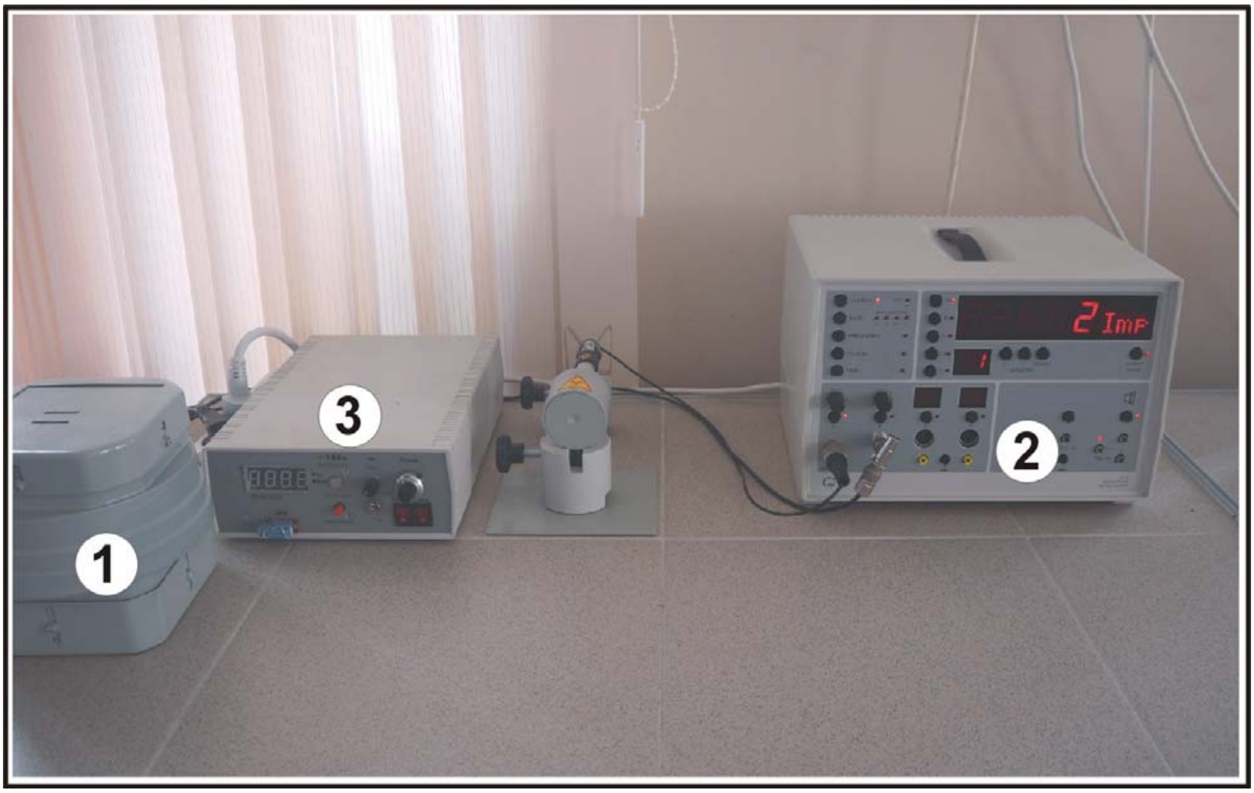

Figure 4. The experimental setup. 1 – a cascade of Geiger counters; 2 – the universal counter device; 3 – the high-voltage source for the Geiger counters.

During the activation make measurement of the background counting rate. For this purpose start automatic measurement by pressing the “START” button on the front panel of the counting device (Fig. 4, “2”). The device does the measurement automatically, the “STOP” button won't be pressed yet. Save up in the memory of the counting device not less than 20 values of the background counting rate measurements (the digital display in the center of the front panel counts number of measurements) and press the “STOP” button. Buttons “<” and “>” above the “MEMORY” label are used *to list consecutively and write down* the measured values of the background counting rate into a personal notebook (paper-made or electronic, whatever). Calculate an average value of the background counting rate $\mathbf{n_f}$ according to the obtained data.

Clear memory of the counting device (press “CLEAR” button above the “MEMORY” label) bringing it into initial condition.

After activation of the sample take out the holder with the sample from the experimental canal and place it into *closest to yourself* canal in the lead container of the counter setup (Fig. 2). Start the measurement by pressing “START” button on the front panel of the counting device (Fig. 4, “2”) *just after* the sample installation into the counters block (Fig. 4, “1”). Make this part of the work *for the minimum time* because of fast decay of radioactivity of the sample (tens of seconds). It is worth being trained before activation of the sample.

Make consecutive measurements of the counting rate until it approaches the average value of the background counting rate measured before *without* the activated sample in the counters unit. Use buttons “<” and “>” above the “MEMORY’ label consecutively to *retrieve and write down* the measured values of the counting rates of the activated sample to the notebook.

Switching off of the setup

1. Switch off the “High-V” button on the high-voltage power unit (Fig. 4, “3”).
2. Switch off the «Pwr» button on the high-voltage power unit (Fig. 4, “3”).

3. Switch off the «Pwr» button on the *rear panel* of the counting device (Fig. 4, “2”).
4. Take out the sample from the measuring unit (Fig. 4, “1”).

Processing of the measurements results

1. Put the measurement results into a table:

t_i, sec	10 20 … 100 …
n_i, imp	
$N_i = (n - n_f)/\tau_p$	
ln$N$	

Find values $N(t_i) = (n_i - n_f)/\tau_p$, ($\tau_p$=10 sec, trace back above) and **ln$N(t_i)$**, put them into the table and draw curve of the dependence **ln$N(t_i)$**.

2. Further processing of the results is carried out in the assumption that decay half-life times of the generated nuclides are significantly different. It suggests that on the curve ln$N$(t) there is a range (at rather large values of t), caused by only activity of a long-living nuclide (labeled by 2) and, therefore, it is possible to approximate this range by the linear dependence, $\ln N_2 = \ln N_{20} - \lambda_2 t$ (the range BC in the sketch in Fig. 5). Here, N_2 is the current activity of the long-living nuclide; N_{20} is the initial activity of the long-living nuclide at the initial time-point of starting the measurements, $t = 0$; λ_2 is a particular decay constant for the long-living nuclide.

The best values of N_{20} and λ_2 can be received applying a method of the least squares, however, initial N_{20} and λ_2 values can be estimated approximately at rather small statistical dispersion of results. Thus, it is possible to draw through the received points a straight line (given in RED color) which crosses the ln$N$ axis and gives the $\ln N_{20}$ estimation. The line inclination tangent provides a value of λ_2 (see Fig. 5).

For calculation of the $\ln N_{10}$ and λ_1 values, describing a short-living nuclide (labeled by 1), it is necessary to:

a) extrapolate the straight line BC to $t = 0$;

b) find according to this drawing the $\mathbf{N_2(t_i)}$ values (the values of the current activity of the long-living nuclide measured at the time moment t_i when the counting rate was recorded, and the measurement point was put in the graph, Fig. 5, in the range of times AB);

c) calculate values of the current activity of the short-living nuclide at the same time poits t_i using the formula $\mathbf{N_1(t_i) = N(t_i) - N_2(t_i)}$ (see in Fig. 5, in the same colors). Then, draw a graph $\mathbf{\ln N_1(t_i)}$;

d) approximate the obtained dependence by the straight line $\mathbf{\ln N_1 = \ln N_{10} - \lambda_1 \cdot t}$ similar to the case of the long-living nuclide. Here, $\mathbf{N_1}$ is the current activity of the short-living nuclide, $\mathbf{N_{10}}$ – the initial activity of the short-living nuclide at the time point $t = 0$, λ_1 is a decay constant for the short-living nuclide.

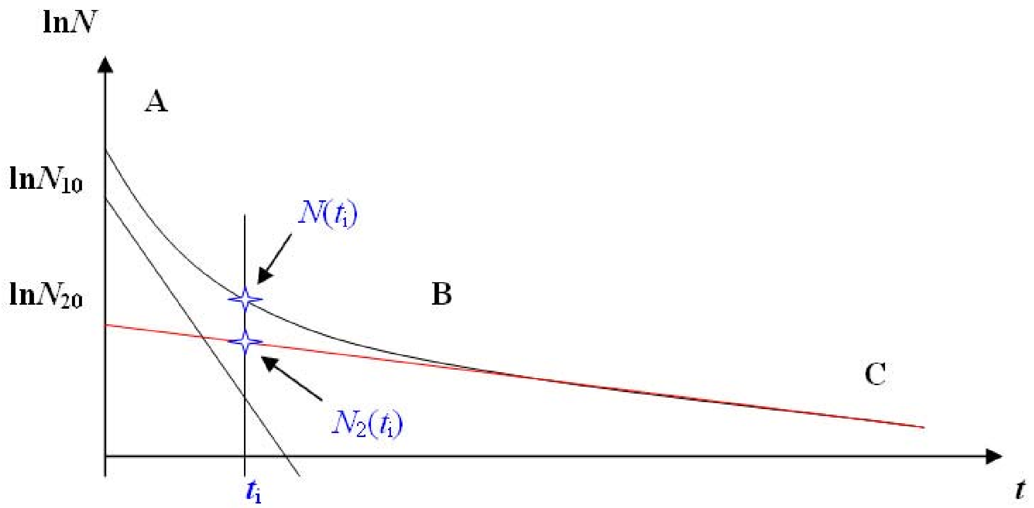

Figure 5. Dependence of the counting rate on time

3. As far as a decay half-life time T is a time during which the number of radioactive nuclei decreases twice, then, generally:

$$\frac{N(T)}{N_0} = e^{-\lambda T} = 1/2,$$

from which

$$T = \frac{\ln 2}{\lambda}.$$

Calculate values of half-life times for the short-living (label 1) and the long-living (label 2) isotopes making use of the formulas:

$$T_1 = \frac{\ln 2}{\lambda_1}; \quad T_2 = \frac{\ln 2}{\lambda_2}.$$

Analysis of the results

1. Using the obtained T_1 и T_2 values, estimate, what nuclides can be formed from the stable nuclides of silver. What could be possible reasons of instability of these nuclides and a type of decay.
2. Using tables of the properties of radioactive nuclides, available in the laboratory, check validity or falsity of the preliminary assumptions.

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 are general regularities of neutrons interaction with matter?
2. Which neutrons do have better ability to interact with nuclei, fast or slow?
3. Estimate the de-Broglie wavelength of a thermal neutron. Compare the obtained value with nuclei sizes.
4. Explain the origin of resonances in cross-section dependence on energy of a neutron.
5. What does mean negative sign of magnetic moment of neutron?
6. How is large a neutron mass in comparison with the proton mass?
7. Supposing point-like neutron, estimate cross section of the neutron interaction with nuclei.
8. What is a type of radioactivity induced by neutrons that observed in the present work?
9. What is a reaction channel that realized in the present work?

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РЕЦЕНЗИЯ

на учебно-методическое пособие

Пятаева А.В., Дулова Е.Н., Бикчантаева М.М., Хрипунова Д.М.,

Тагирова Л.Р.

«Neutron activation analysis»

Рецензируемое учебно-методическое пособие «Neutron activation analysis» 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 сведения о свойствах нейтрона и рассматриваются физические основы взаимодействия нейтронов с веществом. 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 метода нейтронного активационного анализа 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 взаимодействии нейтронов с веществом.

Рецензируемое пособие актуально и представляет несомненный интерес для преподавателей и студентов, сталкивающихся с темой ядерных реакций в учебной работе.

Считаю, что учебно-методическое пособие Пятаева А.В., Дулова Е.Н., Бикчантаева М.М., Хрипунова Д.М., Тагирова Л.Р. «Neutron activation analysis» 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 Манапова Р.А.

ВЫПИСКА ИЗ ПРОТОКОЛА № 9
от 18 декабря 2013
заседания Учебно-методической комиссии Института физики КФУ

ПРИСУТСТВОВАЛИ: проф. Таюрский Д.А. (председатель комиссии), доц. Шерстюков О.Н. (зам. председателя комиссии), Хуснутдинов Н.Р., Ильясов К.А., Воронина Е.В., Тюрин В.А., Корчагин П.А., Дуглав А.В., Мокшин А.В., Гарнаева Г.И., Шиманская Н.Н., Соколова М.Г.

СЛУШАЛИ: рекомендацию в печать методического пособия «Neutron activation analysis» (авторы: Пятаев А.В., Дулов Е.Н., Бикчантаев М.М., Хрипунов Д.М., Тагиров Л.Р.)

ПОСТАНОВИЛИ: на основании положительной рецензии к.ф.-м.н., старшего научного сотрудника КИББ КНЦ РАН Манапова Р.А. рекомендовать вышеуказанное методическое пособие к опубликованию в электронном виде на сайте Института физики.

Председатель Учебно-методической комиссии
Института физики, профессор Таюрский Д.А.