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Article

Spectroscopic analysis of α-particle emission from ^{241}Am and ^{226}Ra sources

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Abstract. This paper investigates the energy spectra of α-particles emitted by radioactive sources ^{241}Am and ^{226}Ra using a multichannel analyzer. Calibration of the detection system was performed with the primary peak of 241Am at 5486 keV, yielding a sensitivity of S = 0.4631 mV/keV. The energy dependence on channel number was established, ensuring accurate energy characterization of the measured spectra. The effect of air pressure on α-particle spectra was analyzed by varying the pressure from vacuum to 500 hPa and 1000 hPa. Results demonstrated a systematic shift of the main peak position towards lower channels due to energy losses in the air, accompanied by peak broadening. For ^{241}Am, the primary peak shifted from approximately channel 2500 in vacuum to channels 2200 and 2000 at 500 hPa and 1000 hPa, respectively. The peak broadening increased linearly with energy loss, described by the relationship $q = 0.073 \cdot \Delta E + 24.2$ keV, where the constant 24.2 keV represents the intrinsic resolution of the detector. Comparative analysis of ^{241}Am and ^{226}Ra spectra revealed the simpler structure of ^{241}Am, characterized by a single primary peak, versus the more complex, multi-component spectrum of ^{226}Ra, which reflects contributions from daughter nuclides. Despite this complexity, the detector successfully captured the overall profile of ^{226}Ra. These findings confirm the high precision of the detection system in measuring α-particle spectra under varying experimental conditions and highlight its potential for further studies of α-radiation interactions and the development of advanced detector technologies.
Keywords: α-particle spectroscopy, radioactive sources, energy loss in the air, detector calibration, peak broadening.

1. Introduction

α-particle emission and its interactions with matter play a pivotal role in understanding nuclear decay processes and the fundamental principles of radiation detection. α-particles, which are helium nuclei emitted during the decay of certain radionuclides, exhibit strong interactions with matter due to their positive charge [1]. As a result, their range in materials is limited to a few centimeters in air or micrometers in condensed matter. The theoretical framework for α-particle interactions, including energy loss mechanisms, is well-documented in nuclear physics [2], [3].

One of the key characteristics of α-particles is their energy loss as they traverse matter [4]. This loss is primarily governed by interactions with electrons in the material, leading to a decrease in particle energy that is approximately proportional to the particle's path length or the electron density of the medium. Such proportionality is particularly valid for α-particles with initial energies exceeding 2.8 MeV [5]. However, additional factors, such as the physical configuration of the radioactive source and the presence of encapsulating materials, can significantly influence the energy spectrum observed by a detector.

The decay chain of ^{226}Ra provides a unique opportunity to examine these effects [6]. Radium-226 is typically in radioactive equilibrium with its decay products up to ^{210}Po, which has a half-life of 22.3 years [7]. However, depending on the age of the source, equilibrium may not extend to later decay products, such as ^{210}Po. In such cases, the fraction of ^{210}Po present in the source may be reduced, leading to the absence or attenuation of its characteristic peak in the observed spectrum. By analyzing the relative intensities of peaks associated with ^{210}Po and neighboring nuclides, it is

possible to estimate the production date of the radioactive source. For ^{226}Ra, several α-particle emissions are expected to appear in the spectrum, including peaks at 4784 keV (^{226}Ra), 5304 keV (^{210}Po), 5489 keV (^{222}Rn), 6002 keV (^{218}Po), and 7687 keV (^{214}Po) [7]. These peaks represent the contributions of different decay products within the radium series.

Similarly, ^{241}Am, which decays exclusively to stable ^{237}Np, emits α-particles with a predominant energy of 5486 keV in 85% of its decays (Figure 1) [8]. This emission serves as a calibration point for the energy scale and provides a benchmark for comparison with the more complex spectrum of ^{226}Ra.

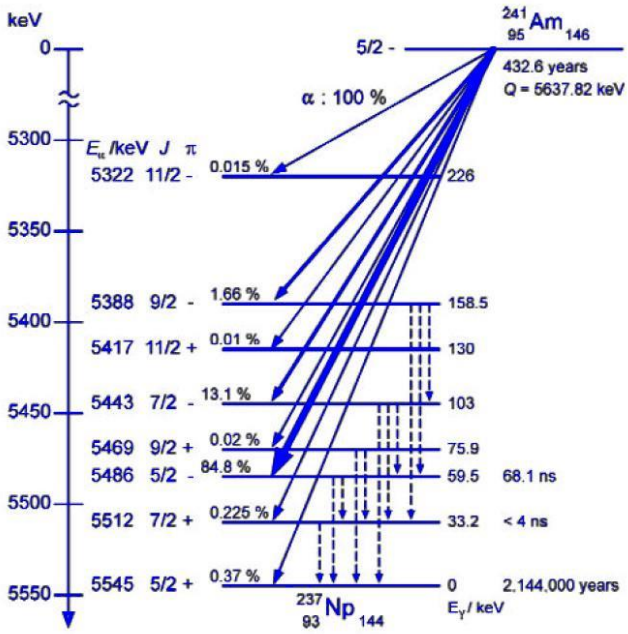

Figure 1 – ^{241}Am decay diagram [8]

While numerous studies have investigated α-particle spectra and energy loss mechanisms, certain limitations persist. Earlier research [9], [10] often focused on idealized scenarios where α-emitting radionuclides were assumed to reside in infinitely thin layers or sources with uniform radionuclide distributions. These assumptions oversimplify the actual conditions of encapsulated sources, where the presence of non-uniform material layers and varying source thicknesses significantly affect energy loss and spectral broadening.

Moreover, many studies [11], [12] did not adequately address the combined effects of encapsulation and radionuclide distribution depth. The encapsulation layers were often treated as uniform barriers, overlooking the variability in material composition and thickness. This oversight can lead to inaccuracies in interpreting spectral features, particularly in determining mean energy losses and the associated peak shifts.

Additionally, past research [13] has frequently neglected the implications of radioactive disequilibrium within decay chains, particularly for long-lived nuclides. The absence or attenuation of certain decay products due to source age or manufacturing variations was not systematically incorporated into spectral analyses. As a result, the potential to estimate source production dates based on peak intensity ratios remains underexplored.

In this regard, this work aims to address these limitations by systematically investigating the effects of encapsulation layers and radionuclide distribution depth on α-particle spectra. The main aspects are developing a comprehensive understanding of peak broadening and energy loss mechanisms due to encapsulation and material composition; and establishing a methodology to analyze the spectral contributions of decay products in radioactive equilibrium. Also, estimating the production date of radioactive sources by comparing peak intensity ratios, particularly for ^{226}Ra. The findings of this study hold significant value for nuclear physics, radiation safety, and material

characterization. By addressing the gaps in prior research and providing a detailed analysis of spectral features, this work contributes to enhancing the accuracy of α-particle detection systems and advancing the field of α spectroscopy.

2. Methods

In the present paper, α-particle emissions from ^{226}Ra and ^{241}Am sources were investigated, considering the effects of source encapsulation and radionuclide distribution within the material. Encapsulation layers, commonly used to isolate radioactive sources, introduce notable changes to the observed spectra. All α-particles emitted from the ^{226}Ra source must pass through the encapsulating layer before reaching the detector [14]. This interaction results in energy loss proportional to the thickness of the covering, which in turn causes peak broadening in the detected energy spectrum. Since all particles encounter the same layer, the mean energy loss can be considered uniform.

However, encapsulation is not the sole factor influencing the observed spectra. The radionuclides within the ^{226}Ra source are distributed over a finite thickness of the source material rather than being confined to a thin surface layer. Consequently, α-particles emitted from varying depths encounter different material thicknesses, resulting in additional energy loss and contributing further to the broadening of the detected peaks. The combined effects of encapsulation and radionuclide distribution require careful consideration to accurately interpret the observed spectral features.

The following equipment was used in this experiment to investigate the α-energy of the ^{226}Ra isotope using a multichannel analyzer (MCA). A container for nuclear physics experiments, an α- and photo detector, a preamplifier for the α detector, a MCA from Gulmay Company, special software, a 220V two-stage diaphragm pump, a DVR 2 pro vacuum gauge with a measurement range of 1 to 1000 hPa, two NBR vacuum tubes 6/14 mm in size and 1 m long each, a Y-tube connector with an inner diameter of 8-9 mm, a 20 mm wide socket, an ^{241}Am radioactive source with an activity of 3.7 kBq, a ^{226}Ra radioactive source with a maximum activity of 4 kBq, and a 750 mm long shielded BNC cable. The schematic connection block is shown in Figure 2.

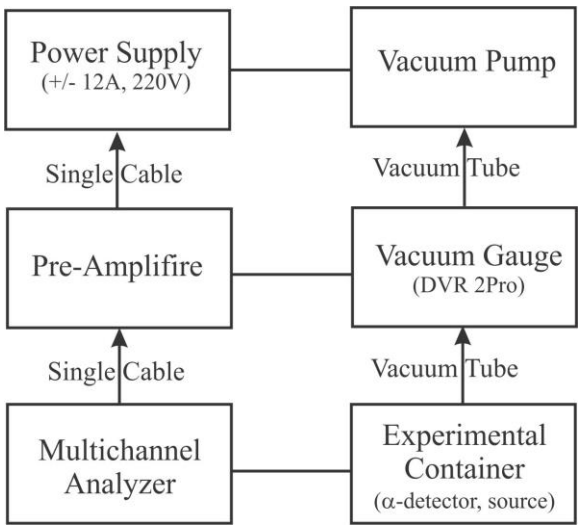

Figure 2 – Equipment wiring diagram

The black shield was mounted on the detector, after which the detector itself was attached to the flange cover. The uncovered ^{241}Am source was placed into the black shield of the detector as far as it would go, ensuring a minimum distance between the source and the sensitive area of the detector. The retractable rod was retracted and secured with a milled screw, ensuring a stable position of the source relative to the detector. The flanged cover with the detector mounted was mounted on the experimental container, ensuring a tight connection. The counting rate selected 50 – 60 per second.

A diaphragm pump created a vacuum in the experimental container, the level of which was monitored using a DVR 2 pro vacuum gauge. Vacuum tubing connected via a Y-connector and socket provided a reliable vacuum connection, minimizing air leaks. These measures contributed to the stable experimental conditions necessary to accurately measure the alpha spectra of the ^{226}Ra isotope using the multichannel analyzer.

The registration of the α-radiation spectrum from the uncovered ^{241}Am source with an energy of 5.486 MeV was used to calibrate the measuring equipment, which ensured high accuracy and reproducibility of the results. Calibration at this peak is an important step because it allows a correct interpretation of the data obtained during the experiment and ensures an adequate comparison of the measured values with theoretical expectations.

To further analyze α-particles of known energy, a portion of air was used as a deceleration medium. The effect of air on α-particles is to reduce the energy of the particles as they pass through this medium, resulting in a shift of the mean energy and a broadening of the peak in the energy spectrum. This phenomenon is the result of repeated collisions of particles with air molecules, during which they slow down and lose energy. The air from the vessel was brought to a pressure of 500 hPa followed by the collection of about 10000 pulses. The magnitude of the shift and broadening of the peak depends on various factors such as the density of the medium, the path length of the particles in the air, and the initial energy of the particles. To quantitatively analyze this process, the ratio of average energy loss to peak broadening was measured, and it was found that in the energy range above 2.8 MeV this ratio can be assumed to be linear. Then, with the air completely vented from the experimental vessel, the spectrum was recorded at ambient pressure (about 1000 hPa), with the source still directly in front of the detector and again collecting about 10 thousand pulses. This finding has important implications for the accurate estimation of particle energy loss in different environments and can be used to calibrate measurements in more complex environments.

In addition to analyzing the spectrum from the uncoated source, the energy spectrum of α-particles emitted from a ^{226}Ra source coated with a shielding was also recorded. In this stage, the speed was much higher and amounted to 200 – 250 pulses per second. The emission spectrum recorded using the same multichannel analyzer was evaluated to study the effect of the coating on the α-emission characteristics. The source coating has a significant effect on the energy and distribution of α-particles, as it can significantly alter both their initial energy and the path they take through the environment. Analysis of this spectrum allows a comparative study between the radiation from coated and uncoated sources, which in turn provides a better understanding of the effect of shielding materials on the radiation characteristics. This study has important implications for the development of more effective shielding techniques and for improving measurement accuracy in radiation experiments.

Thus, in this study, modern methods of recording and analyzing α-radiation spectra using a multichannel analyzer were used to obtain accurate data on radiation characteristics and to evaluate the influence of various factors, such as the deceleration medium and source coating, on the energy and distribution of α-particles.

3. Results and Discussion

When recording the α-particle spectrum, the MCR divided the input voltage range from 0 V to 4 V into 4000 equal intervals. Each interval corresponds to a specific channel, and the width of one channel is 1 mV. To adapt the measuring range, an offset function is used that shifts the entire 4-volt interval relative to a starting point specified as a percentage of the maximum voltage. For example, with an offset of 5%, the measurement interval starts at 0.2 V. In such a case, channel zero recorded pulses between 0.1995 V and 0.2005 V, and channel 3999 recorded pulses between 4.1935 V and 4.2005 V. This approach provides accurate registration of energy spectra and allows to adapt the sensitivity of the system to the given experimental conditions. All collected data are presented in Table 1.

Table 1 – Data for the ^{241}Am with x_1 position of the left side of the peak at half-max and the x_2 position of the right side of the peak at half-max

hPa, air	Peak, counts	FWHM	$\frac{\chi_1}{ch}$	$\frac{\chi_2}{ch}$	$\frac{(x_1+x_2)}{2}$
11	260	11	2335	2346	2340.5
50	266	25	2144	2169	2156.5
1000	366	39	1937	1976	1956.5

The graph on Figure 3 shows the spectra of α-particles registered at different pressures of the medium. Each curve of the spectrum corresponds to a certain pressure: vacuum, 500 hPa, and 1000 hPa. The horizontal axis of the graph denotes the number of the MCR channel, which is related to the energy of the registered particles. The vertical axis represents the number of registered impulses (number of events) for each channel.

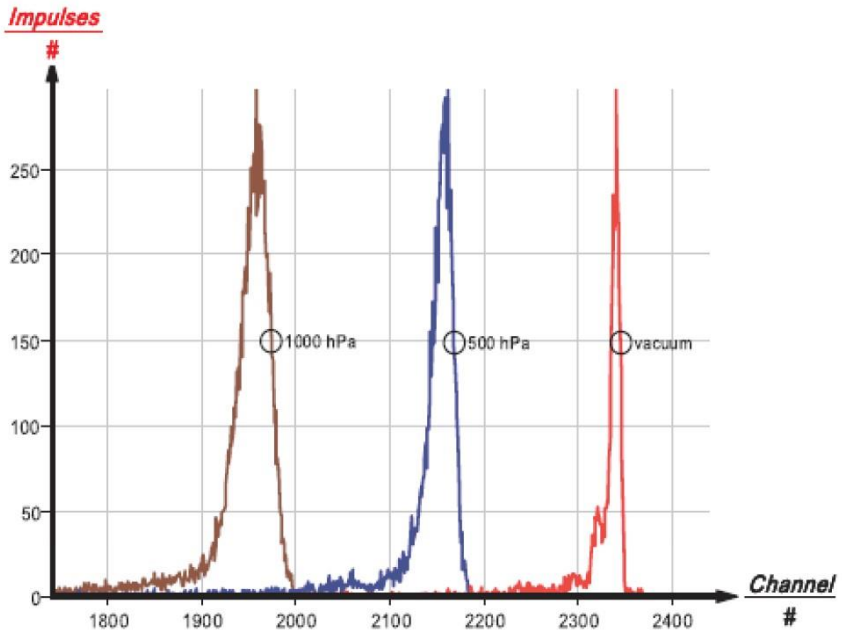

Figure 3 – Test results of ^{241}Am

Spectrum in vacuum (red curve): It is in the channel region around 2400, which corresponds to the maximum energy of the α-particles, since there is no significant deceleration in vacuum. The peak is narrow, indicating minimal broadening and high precision in recording the particle energy. Spectrum at 500 hPa (blue curve): There is a shift of the peak to lower channel numbers, around 2200, indicating a loss of α-particle energy as it passes through the pressurized medium. The broadening of the peak becomes prominent, which is due to the scattering of particles on air molecules. Spectrum at 1000 hPa (brown curve): The peak is significantly shifted to the low channel number region, around 2000, indicating an even greater particle energy loss in the denser medium. The broadening of the peak increases, which is explained by the intensification of scattering processes.

To accurately determine the energy of the α-particles detected by the multichannel analyzer, a calibration relation based on the main peak energy of 5486 keV for the ^{241}Am α-emitter was used. The sensitivity of the detector system calculated from this energy was S=0.4631mV/keV. As a calibration factor, this value allows us to determine the energy E corresponding to the channel number n, by the Equation (1):

$$E = \frac{(n+2)}{S} \quad (1)$$

The introduced coefficient correctly relates the channel numbers of the spectrum to the particle energies, providing a high estimation accuracy. Figure 4 shows the graphical dependence of the peak

width of α-particles on the average energy loss ΔE, corresponding to the data given in Table 2. The peak broadening is directly related to the energy loss of particles as they pass through the medium, which is confirmed by the experimental results.

Table 2 – A linear relationship between the average energy loss

Peak ch.	Δ ch.	ΔE, keV	σ/ch.	σ, keV
2340.5	0	0	11	23.8
2156.5	-184	397.3	25	54.0
1956.5	-384	829.2	39	84.2

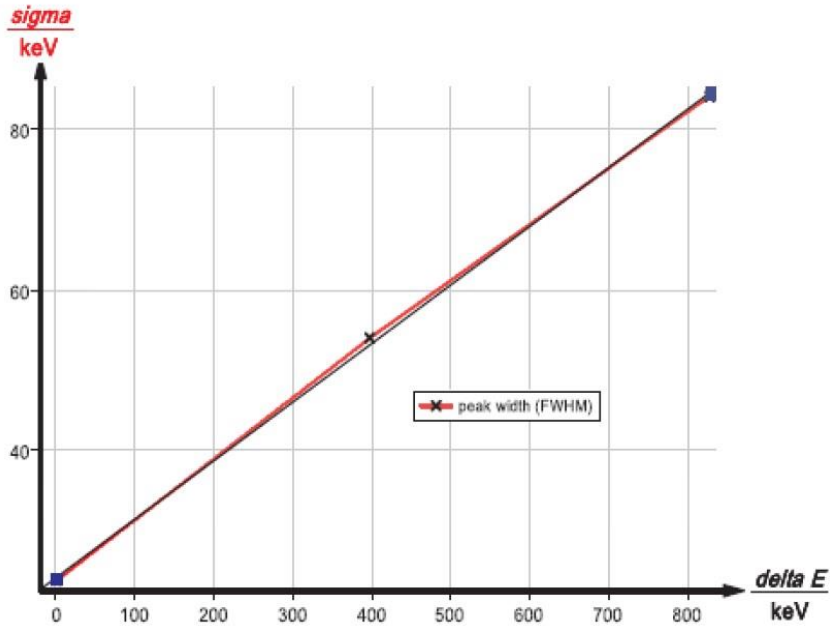

Figure 4 – Peak width as it relates to energy loss

Value of ΔE and peak width, especially in the energy range above 2.8 MeV. These data were obtained by measurements under different pressures (vacuum, 500 hPa, 1000 hPa). The experimental results confirm that an increase in the average energy loss leads to an increase in the peak width due to the growing contribution of scattering and braking processes.

Thus, the above dependences and graphical data confirm the high calibration accuracy and efficiency of the method for analyzing the spectra of α-particles, which is important for further studies of the interaction of high-energy particles with various media.

To describe the dependence of the peak width σ on the average energy loss ΔE, the line of best fit was calculated and expressed by the Equation (2):

$$q = 0.073 \cdot \Delta E + 24.2\ keV \quad (2)$$

Where 24.2 keV is due to the energy resolution limit of the detector. This value characterizes the contribution of hardware resolution to the measurements and confirms the accuracy of the data obtained. The equation shows a linear dependence of the peak width on the average energy loss, which corresponds to the expected influence of scattering and inhibition of α-particles during their interaction with the medium.

Figure 5 shows the α-radiation spectrum of source ^{226}Ra, supplemented by the results obtained for source ^{241}Am. The spectrum of the ^{226}Ra source shows a clear structure, where four main lines corresponding to the α-decay of isotopes belonging to the radionuclide series can be distinguished. Despite the overlap of the lines, the whole profile is seen as a single composite line, which is due to the limitations of the detector resolution. The results of analyzing the spectrum of the ^{226}Ra source are presented in Table 3. The table contains data on peak positions (channel numbers), their widths σ, calculated energies E, and relative intensities. Comparison with the results for ^{241}Am allows us to

evaluate the calibration accuracy of the detector setup and to confirm its suitability for recording α-radiation spectra with high resolution.

Table 3 – Collected data of two sources ^{241}Am and ^{226}Ra

n/ch.	E, keV	Literature value, keV	Energy loss ΔE, keV	Peak displacement, channels
2897	6688	7687	999	463
2027	4809	6002	1193	552
1744	41988	5489	1291	598
1407	3470	4784	1314	608

Thus, the analysis of the spectra ^{226}Ra and ^{241}Am spectra demonstrated the agreement of experimental data with theoretical models, which confirms the high accuracy and reliability of the applied technique of α-particle registration. The Figure 5 shows a comparison of the energy spectra of α-particles recorded for two radioactive sources, ^{241}Am and ^{226}Ra, under different pressure conditions. The spectra show significant changes in the shape, position, and width of the peaks depending on the pressure of the medium and the type of radioactive emitter.

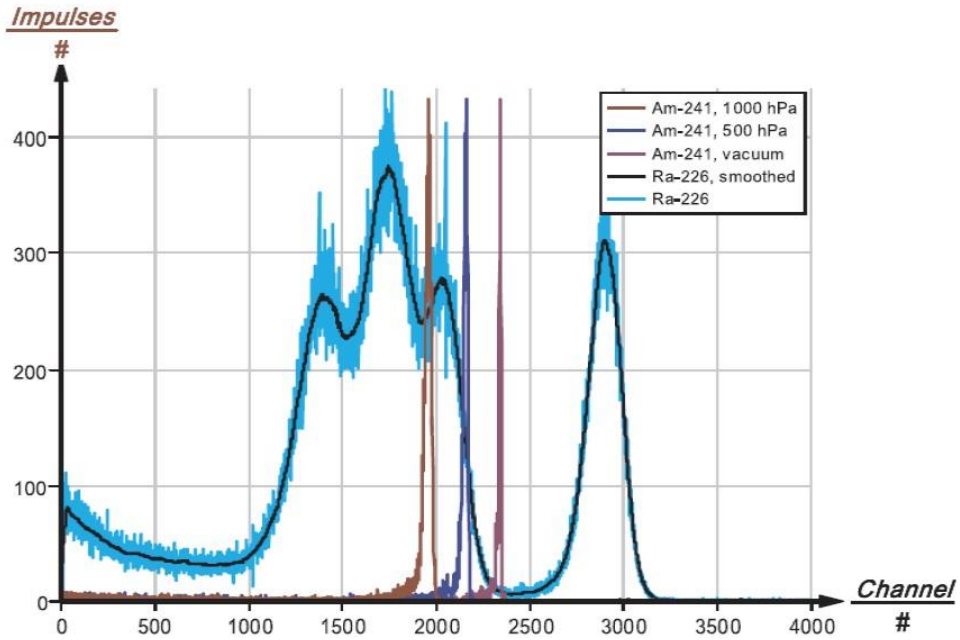

Figure 5 – ^{241}Am peak positions as a reference for the ^{226}Ra spectrum

The detailed review of spectra of ^{241}Am (curves for vacuum, 500 hPa and 1000 hPa) presents the following: at the vacuum (purple curve) the peak is at the maximum channel (around 2500), corresponding to an α-particle energy of 5486 keV recorded without deceleration in air. The shape of the peak is narrow, indicating that the influence of scattering processes is minimal. At a pressure of 500 hPa (blue curve) the peak shifts to the region of lower channel numbers (about 2200), which is due to the loss of particle energy by interaction with air molecules. The broadening of the peak increases, indicating the contribution of scattering and inhomogeneities in the medium. At a pressure of 1000 hPa (brown curve) the peak shifts even further (towards the 2000 channel) with a marked increase in width. This is due to the significant inhibition of particles in the denser medium, which increases both the average energy loss and its fluctuations.

For the source ^{226}Ra, the α-particles have a more complex spectrum including several components corresponding to different decay energies of the daughter nuclides in the radionuclide series. The spectrum includes four main lines, but due to the limited resolution of the detector the whole profile can be observed as a single composite line. The black smoothed curve is used to emphasize the general trend and shows the average energy distribution of the α-particles.

The ^{226}Ra spectrum generally occupies a lower channel region than the ^{241}Am spectrum, which is due to differences in the energies of the emitted α-particles. The broadening of the ^{226}Ra spectrum is also higher due to the contribution of daughter decay products.

This effect can be attributed to several factors. An increase in pressure leads to an increase in the number of collisions of α-particles with air molecules, which causes their inhibition. This is manifested by a shift of the peak to the region of smaller channel numbers. Also, the increasing number of collisions leads to fluctuations in energy loss, which causes the broadening of the spectrum. This dependence is linear in the energy range above 2.8 MeV, as shown earlier. These results confirm the sensitivity of the α-particle registration method to changes in experimental conditions (pressure, type of source) and demonstrate the ability of the detector system to distinguish spectra with high accuracy.

4. Conclusions

The energy spectra of α-particles emitted by ^{241}Am and ^{226}Ra radioactive sources were studied using a MCA. The measurements and analysis made it possible to characterize the influence of external conditions, such as the pressure of the medium, on the spectrum parameters and to determine the accuracy and resolution of the detector system. The main calibration source was ^{241}Am, with a main peak at an energy of 5486 keV. Based on this peak, the sensitivity of the detector system was calculated to be S = 0.4631mV/keV. The obtained value was used to convert the channel numbers into energy values, which provided an accurate relationship between the measured parameters and the energy of the α-particles. Under vacuum conditions, the spectra are characterized by narrow peaks, minimal energy loss, and an exact position corresponding to the energy of the α-particles.

At pressures of 500 hPa and 1000 hPa, the α-particles lose energy by interaction with air molecules, resulting in a shift of the peaks to a region of lower channel numbers. For example, the main peak of ^{241}Am, located near the 2500th channel in vacuum, shifted to the 2200 and 2000 channels at 500 and 1000 hPa, respectively. The ^{226}Ra spectrum shows a more complex structure including several components corresponding to different α-decay energies of the daughter nuclides. Despite this, the limited resolution of the detector smooths the individual lines into a composite spectrum. The ^{241}Am spectrum is characterized by a single main peak, which makes it convenient for calibration.

It was found that the minimum peak width (24.2 keV) is due to the hardware resolution of the system, which confirms its suitability for high-precision measurements of α-particle spectra.

Thus, the investigations have shown that the technique used allows us to accurately record the energy spectra of α-particles, to analyze the influence of experimental conditions on the spectrum parameters, and to identify the main lines for various radioactive sources. The results can be used for further studies of α-radiation, including the study of the interaction of high-energy particles with various media, as well as for the development and testing of new detector systems.

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