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REGULAR ARTICLE

Radiation-Induced Processes in Commercially Available Samples of Activated Carbon Under the Influence of Gamma- and Beta-Radioactivity

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Commercially available adsorbents, based on activated carbon, are often used to purify water solutions from organic pollutants, dyes, heavy metal ions, and radionuclides. Therefore, the investigations of radiation-induced processes in carbon adsorbents are relevant. This work investigates the effect of gamma- and beta-radiation on activated carbon's structure and adsorption properties. The commercially available activated carbon samples were irradiated by a linear accelerator, Halsyon Varian, and a 90Sr-90Y source, Sirius, in the air atmosphere and acidic and neutral water solutions. The adsorption characteristics of irradiated and non-irradiated carbon toward Na-EDTA molecules were studied. The Raman spectrometry was used to control the radiation-induced change in the carbon structure. The Raman spectra were fitted using fityk-1.3.1-setup.exe software. The maximum adsorption of Na-EDTA molecules by non-irradiated AC reaches 800 mg/g. Irradiation with beta- and gamma radioactivity in the air atmosphere does not affect the adsorption capacity of activated carbon, which is also capable of adsorbing the Na-EDTA complex with strontium ions. During irradiation of AC in the presence of water molecules on the surface, the –C–O–C– groups, aromatic rings, and carboxylic acid dimers form on the surface of AC, which lead to maxima of about 810 cm^{-1}, 990–1100 cm^{-1}, and 910–960 cm^{-1} on the Raman spectrum of AC. Fitting spectrum using program fityk-1.3.1-setup.exe shows that these transformations of the activated carbon surface involve mainly sp^3-hybridized atoms. Irradiation of activated carbon in this way negatively affects the adsorption capacity. However, this effect requires further research.

Keywords: Activated carbon, Gamma- and beta-irradiation, Raman spectroscopy, Na-EDTA.

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1. INTRODUCTION

At present, porous carbon material (PCM) is widely used as an adsorbent in various industries, as well as in medicine, analytical chemistry, etc. Carbon sorbents purify water from organic pollutants, heavy metal ions, and radionuclides. For example, a publication [1] describes an effective adsorbent for Pb^{2+} and Cu^{2+} based on activated carbon nanofibers. The synthesis of activated carbon nano-fiber (ACF) was performed from corn cobs by pyrolysis in the presence of H_3PO_4. The surface area of the synthesized material is (S_{BET} = 1824 m^2/g). The authors propose to use the synthesized material as an adsorbent to capture lead and copper ions. The authors reported that the maximum adsorption values for Pb^{2+} are 210.6 $mg \cdot g^{-1}$, and Cu^{2+} are 212.9 $mg \cdot g^{-1}$ from aqueous solutions. The use of activated carbon and carbon-based adsorbents for the adsorption of tri- and hexavalent chromium is described in another publication [2].

However, carbon materials are used not only for the adsorption of various contaminants but also as electrode materials for electrochemical capacitors [3-6]. The publication [3] is devoted to enhanced electro-adsorption of uranium ions onto carbon-composite electrodes. Carbon quantum dots synthesized from the starting substance – glucose – are used to colorimetrically determine ultra-low concentrations of heavy metal ions, such as Ca^{2+}, Fe^{2+}, Fe^{3+}, and silver (Ag^+) ions [6]. In publication [6], it was shown that in the concentration range of 0.06-1.23 μM, these sensors give a linear relationship with an increase in the concentration of metal ions, which is very valuable for analysis. These sensors are relevant to ecology and medicine. Quantum-sized graphite-based carbon composite materials are also used for photooxidation of nitrogen oxides [7]. 3-D-oriented graphene is recommended for CO_2 capture in the fight against global warming [8]. Porous carbon is widely used in medical practice as an enterosorbent. That is, without a doubt, the adsorption capacity of activated carbon is one of its most essential characteristics. At the same time, in the publication [9], the evolution of an adsorbent (poly-amide-oxime PAO) after the adsorption of radioactive uranium is described. It has been shown that the radiation

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of a radionuclide in an adsorbed state on the surface or the adsorbent's pores affects the adsorbent's properties and can destroy it over time. According to the authors, the conformation of polyamide oxime is destroyed by uranyl and sodium ions. In general, the authors of the publication [9] noted that the main result of their work is the establishment of the research of new radiation- and chemically-resistant adsorbents for uranium adsorption, which is useful.

Several scientific publications are devoted to studying the radiation resistance of adsorbents [10-12]. However, we could not find any articles dedicated to the radiation resistance of carbon adsorbents. The authors investigated the influence of gamma- and beta-radioactivity on the structure and adsorptional properties of TiO_2-based adsorbents. While in the scientific work [12], the task was not directly set to determine the radiation resistance of adsorbents. However, high doses of radioactivity that strontium-yttrium sources can create during the age-dating procedure assess the relevance of radiation stability of adsorbents that can be used to separate radionuclides. The publication [13] describes increased epoxy resin's radiation resistance after adding graphene oxide to its structure. The authors synthesized oxidized graphene using the Hammers method. Comparing the structure, the number of free radicals, and the mechanical properties of the samples before and after irradiation, the authors concluded that the addition of oxidized graphene as a filler increases the radiation resistance of epoxy resin.

In this work, we set ourselves the goal of studying the effect of gamma- and beta-radiation on the adsorption properties of activated carbon. To achieve this goal, we have defined the following tasks: (1) perform the adsorption characteristics of non-irradiated carbon toward Na-EDTA molecules; (2) irradiate samples of activated carbon by an external dose of beta- and gamma-irradiation. Experimentally simulate the internal irradiation of activated carbon by radionuclides ^{90}Sr and ^{90}Y using an aqueous solution and the "Sirius" facility. (3) Perform Raman spectroscopy of irradiated and non-irradiated samples and the samples of AC after Sr-EDTA adsorption.

It should be noted that Raman spectroscopy has now become accepted as one of the most potent techniques for characterizing structure-property relations in carbon materials, including 0D fullerenes, 1D CNTs and CFs, 2D graphene and its derivatives, 3D graphite, and diamond. Through the combination of Raman band position, FWHM, and intensity/area in the spectra, their structures can be analyzed in terms of orientation, the number of layers/walls, chirality, stacking order, defects, and functionalization [14]. Therefore, radiation-induced changes in the investigated samples were recorded using Raman spectroscopy.

2. MATERIALS AND METHODS

Commercially available activated carbon, which is used as an enterosorbent RP UA/12759/01/01, was investigated in this study. In addition, chemicals such as Na-EDTA, $MgSO_4$, Eriochrom Black T, HNO_3, and NH_4OH (Merck) analytical grades were used in the work. Two different types of equipment (Halcyon Varian linear accelerator and Sirius facility) were used to study the radiation resistance of activated carbon samples, which are described below.

2.1 Irradiation of Carbon Samples on the Halcyon Varian Linear Accelerator

In the first series of studies, the linear electron accelerator, the Halcyon Varian, was used to irradiate samples. In this accelerator, electrons are accelerated to an energy of 6 MeV, generating bremsstrahlung gamma-rays, which also have a maximal energy of 6 MeV. An IBA Dose1 equipment and an FC-65P (Farmer Type) camera were used to measure the dose received by the samples, and a Luft OPUS 20 equipment was used to measure temperature and pressure, the data from which were later used to make corrections to Dose1. The irradiation field was 10 × 10 cm, the SSD was 100 cm, and the dosimeter camera was fixed on the table next to the irradiated carbon samples. The geometry of the experiment is shown in Figure 1s. Usually, one carbon sample was not irradiated – it was a control sample.

2.2 Irradiation of Carbon Samples Using the "Sirius" Facility

The "Sirius" facility was used to investigate the radiation resistance of carbon-based materials in the second series of studies. The Sirius facility is a permanently installed ^{90}Sr-^{90}Y β- source. It consists of the radioactive isotope ^{90}Sr and its daughter isotope ^{90}Y, which is in secular equilibrium with strontium. This source was manufactured in 1980. It consists of 16 cassettes of ^{90}Sr; the initial activity on the surface at manufacture was $5.55 \cdot 10^9$ Bq. The activity at the time of manufacture was $1.6 \cdot 5.55\ 10^{10}$ Bq. In other words, more than six curies 6 Ci. After 1.5 half-lives (present time), the flux density of electrons at a distance of 20 cm from the surface of the source is 1.108 el/cm^2 per second, corresponding to 4 Røentgen per minute. The energy distribution of beta and bremsstrahlung radiation is described in detail in [15].

The samples were irradiated with electrons from a strontium-yttrium source at a distance of 20 cm; the radiation dose was from 10 Gy to 230.4 Gy.

In the experimental simulation of internal irradiation, a strontium-yttrium source of beta particles was also used. The radiation dose was (80.6 Gy). The experiment was carried out so that there was a small layer of water or a 0.1 M aqueous solution of HNO_3 acid between the surface of the adsorbent and the flow of ionizing radiation.

The choice of such exposure conditions made it possible to predict the features of the effect of radiation of adsorbed ^{90}Sr from an aqueous solution with neutral or acidic pH. After all, it is known that ^{90}Sr possesses significant activity and decays into radioactive pure beta-emitter ^{90}Y. In addition, adsorption is usually carried out from aqueous solutions; that is, water molecules or an aqueous acid solution can produce free radicals that also influence the surface of the adsorbent simultaneously with irradiation.

After all irradiation methods, the adsorbent samples were transferred to an air-dry state and analyzed using

Raman spectroscopy. Raman spectroscopy of investigated samples was performed, i.e., samples that were irradiated with doses of 10 Gy, 80.6 Gy, and 230.4 Gy, as well as an unirradiated (control) sample (Table 1).

Table 1 – Conditions of irradiation of carbon samples for the study of their radiation resistance

№	Type of irradiation	Dose, Gy	Source of irradiation
1	–	0	–
2	gamma	10	Halcyon Varian: *irradiation in the air atmosphere*
3	beta	10	Sirius: *irradiation in the air atmosphere (*Dry irradiation)
4	gamma	230	Halcyon Varian: *irradiation in the air atmosphere*
5	beta	230.4	Sirius: *irradiation in the air atmosphere*
6	beta	80.6	Sirius: *irradiation in the air atmosphere*
7	beta	80.6	Sirius: *samples irradiation in the presence of molecules H_2O*
8	beta	80.6	Sirius: *samples irradiation in the presence of 0.1M HNO_3 water solution*

2.3 Raman Spectroscopy

Raman spectra are commonly used to estimate the state of carbon atoms in the compounds. In addition, Raman spectroscopy is used to evaluate interfacial properties, such as in composites [16]. Raman spectroscopy of irradiated and nonirradiated samples of activated carbon was performed at the Center for Collective Use of Scientific Equipment "Laboratory of Experimental and Applied Physics" of Uzhhorod National University. The technical characteristics of the Raman spectrometer XploRA PLUS are given in Table 2. Results of Raman spectrometry of investigated samples are shown in Fig. 2(a-c).

Table 2 – Characteristics of the Raman spectrometer XploRA PLUS

Parameters	Value
Acceleration of the spectrum mode	SWIFT with a motorized table
Confocal mapping	05 μmXY
Optical microscope	direct
Wavelengths of excitation lasers	532 nм
Sample Dimensions	(5÷10mm) × (5÷10mm) × (0.2÷2 mm)
Drift ACM through XY	2 nm/min

2.4 Methods of Adsorption Studies

The adsorption ability of activated carbon toward Na-EDTA molecules by irradiated and non-irradiated samples was used to determine the effect of irradiation on the adsorption properties of activated carbon.

It should be noted that the sodium salt of ethylenediamine-tetraacetic acid (Na-EDTA) is used in pharmacy, food industry, analytical chemistry, and for decontamination of radionuclides [17, 18]. That is, the study of the adsorption of this compound is relevant. The structural formula of this compound is shown in Fig. 1, which is built using MolView software.

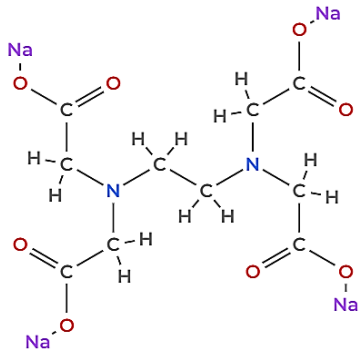


Fig. 1 – Structure formula of Na EDTA

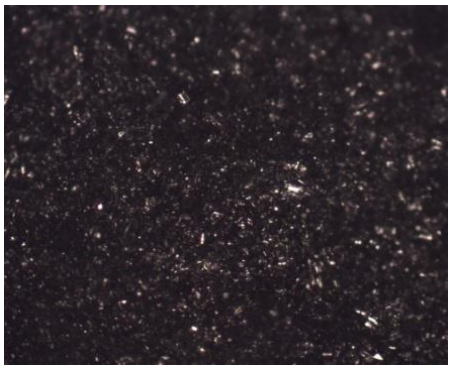
Table 3 – Property of NaEDTA according to the PubChem database

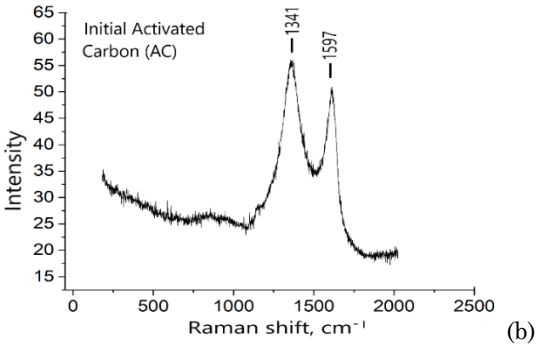
Property Name	Property Value	Reference
Molecular Weight	380.17 g/mol	Computed by PubChem 2.2 (PubChem rel.)
Hydrogen Bond Acceptor Count	10	Computed by Cactvs 3.4.8.18 (PubChem rel.)
Topological Polar Surface Area	167Å^2	Computed by Cactvs 3.4.8.18 (PubChem rel)
Covalently-Bonded Unit Count	5	Computed by PubChem

The adsorption of Na-EDTA was investigated under batch conditions. The weight of the adsorbent was 0.1 g. The volume of the solution was 5 ml. The residual concentration of Na-EDTA was determined by titration with a standard magnesium sulfate solution with Eriochrome Black T as an indicator (color transition from inky blue to pink). Adsorption kinetics, adsorption isotherm, and pH dependence of the adsorption process were measured. In addition, the adsorption isotherm of Na-EDTA molecules by irradiated carbon was constructed. Results are shown in Figure 3 (a-c).

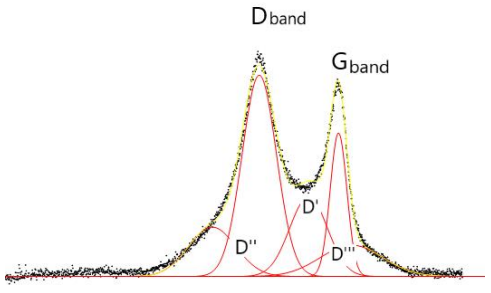
3. RESULTS AND DISCUSSION

The Raman spectra of the initial non-irradiated activated carbon are shown in Fig. 2 (a-c). The general pattern of the Raman spectrum confirms that the carbon sample was activated at a temperature not exceeding 726 °C and is an amorphous mixture of sp^3-sp^2 hybridized carbon atoms [14].


(a)



(b)



(c)

Fig. 2 – Raman photo (a) and spectrum (b) of non-irradiated carbon with highlighted carbon lines. The spectrum was deciphered using NIST DATABASE; (c) the Raman spectrum was fitted by Gaussian using fityk-1.3.1-setup.exe

Table 4 – Raman spectrum of non-irradiated carbon with highlighted carbon lines

Peak	Center, cm^{-1}	Spline type
1	**1597**	**Gaussian**
2	**1341**	
3	2236	
4	1158	
6	1483	

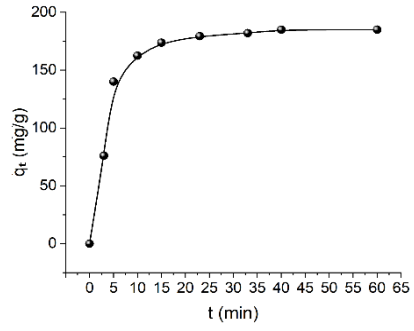
Two distinct lines are visualized on the spectrum: the sp^3-hybridized carbon atom (*D*-band) and the sp^2-hybridized carbon atom (*G*-band). *G*-band is a line of graphene [14, 19-23]. Graphene, which is considered the building unit of all graphite carbon allotropes, is a flat sheet formed by a network of sp^2-hybridized carbon atoms arranged in a honeycomb structure. *D′* and *D″* bands correspond to the vacancies in the sp^2-structure and defects in the sp^3-carbon structure [14].

Analysis of the figures and comparison of our experimental data with the data available in the literature indicate that the maxima of the sp^3-hybridized carbon are present in the vicinity of 1341 cm^{-1}. The maxima belonging to the oscillations of the sp^2-hybridized carbon should be at 1578 cm^{-1}. Still, because of the presence of sp^3 hybridized carbon in the sample, they are shifted to the 1586-1597 cm^{-1} region. Irradiation with high-energy electrons with a dose of 230.4 Gy (dry irradiation) slightly shifts the *G*-band's maximum to 1580-1583 cm^{-1}.

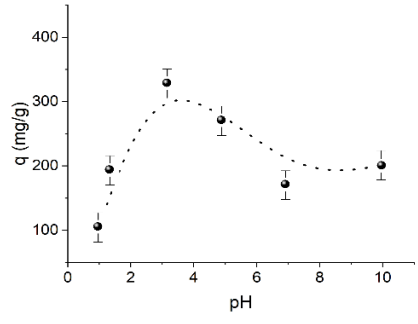
In our opinion, dry irradiation with electrons with a dose of 230.4 Gy does not affect the graphene line of the sp^2-hybridized carbon, but the degenerate lines of sp^3-hybridized carbon, which reduces the displacement of the graphene line due to the presence of sp^3-hybridized carbon atoms. However, this effect requires further research.

3.1 Results of Adsorption Investigations

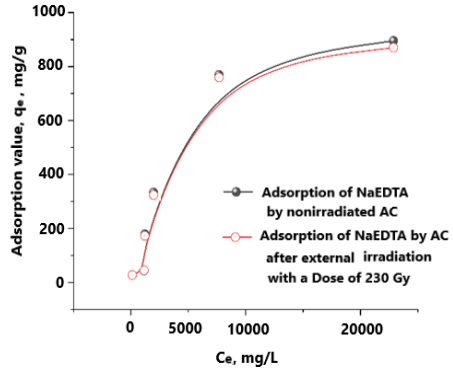
Kinetics of adsorption of Na-EDTA molecules by activated carbon, dependence of adsorption on the solution's acidity, and isotherms of adsorption of Na-EDTA molecules by the investigated samples are shown in Figures 3 (a-c). With the help of these measurements, the time (duration of interaction) at which equilibrium was established was determined.



(a)



(b)



(c)

Fig. 3 – **(a)** Kinetics of adsorption of Na-EDTA by activated carbon; (**b**) dependence of adsorption of Na-EDTA molecules on the solution's acidity; **(c)** adsorption isotherms of Na-EDTA by non-irradiated AC, and AC irradiated in the air atmosphere

These figures indicate that the adsorption equilibrium of Na-EDTA molecules by activated carbon is established rapidly in the first 10-15 minutes of interaction. The duration of the interaction, which was 30 minutes, with periodic stirring, was chosen for the adsorption isotherm measurements. The adsorption isotherm was measured for samples of unirradiated carbon and irradiated with a dose of dry (air atmosphere) irradiation of 230.4 Gy. The results are shown in Fig. 3 (c). The dry irradiation of activated carbon by high-energy electrons with a dose of 230.4 Gy did not influence its adsorption activity toward Na-EDTA molecules, as seen in Figure 3(c) (red line).

One of the possible mechanisms of adsorption of Na-EDTA molecules is the formation of hydrogen bonds with the surface of the adsorbent. According to publication [24], hydrogen bonds are formed between the oxygen molecules of sodium EDTA and the – OH groups of the adsorbent surface. In addition, hydrogen bonds can be formed between – OH groups of the surface and nitrogen atoms. At the same time, there is still an electrostatic attraction between the O-oxygen of the surface of activated carbon and the nitrogen atoms N^+ of the Na-EDTA molecule, which carries a partially positive charge.

We believe $EDTA^{4+}$ molecules do not "lie" on the surface entirely but interact with the surface of activated carbon to form only one or two hydrogen bonds. More precisely, Na-EDTA is completely attached by all free oxygen atoms only at a low concentration of adsorbate in solution, about 0.01-0.02 mol/L. If the molecule were attached to the surface by all oxygen atoms capable of entering into hydrogen bonds, then the surface area of the adsorbent (with such significant adsorption) would have to be more than 2000 m^2/g. However, the surface area of these samples, measured by low-temperature nitrogen adsorption-desorption, is about 200 m^2/g, or 117 m^2/g. Another circumstantial evidence of the correctness of our assumption is that activated carbon adsorbs a complex of strontium ions with Na-EDTA. It is known that complexes of Na-EDTA with ions of heavy metals and radionuclides are formed. This ability is the basis for the widespread use of Na-EDTA in analytical chemistry in the complexometric determination of cations with various indicators [17, 18, 25, 26].

As mentioned earlier, the ability of sodium edetate to form complexes with radionuclides determines the use of this compound for decontaminating radionuclide-contaminated surfaces [17]. When decontaminating strontium ions or ^{90}Sr occurs by a solution of Na-EDTA, a complex of corresponding compounds is also formed. The ability of sodium edetate to be an acceptor of hydrogen bonds (and, accordingly, the ability of activated carbon to be a donor of hydrogen bonds) determines the adsorption of the ^{90}Sr-EDTA complex, for example, at the final stage of decontamination of surfaces.

The Raman spectrum of the sample after adsorption of strontium (Sr^{2+}) ion complex with Na-EDTA is shown in Figures 4 (a-c).

According to Figures 4 (a and c), changes in the Raman spectrum of Activated carbon after Sr-EDTA complex adsorption occur mainly with the involvement of line *D″*. Fitting the Raman spectrum by Gaussian shows clear maximums near 1031 cm^{-1} and 800-835 cm^{-1} on the spectrum of investigated samples.

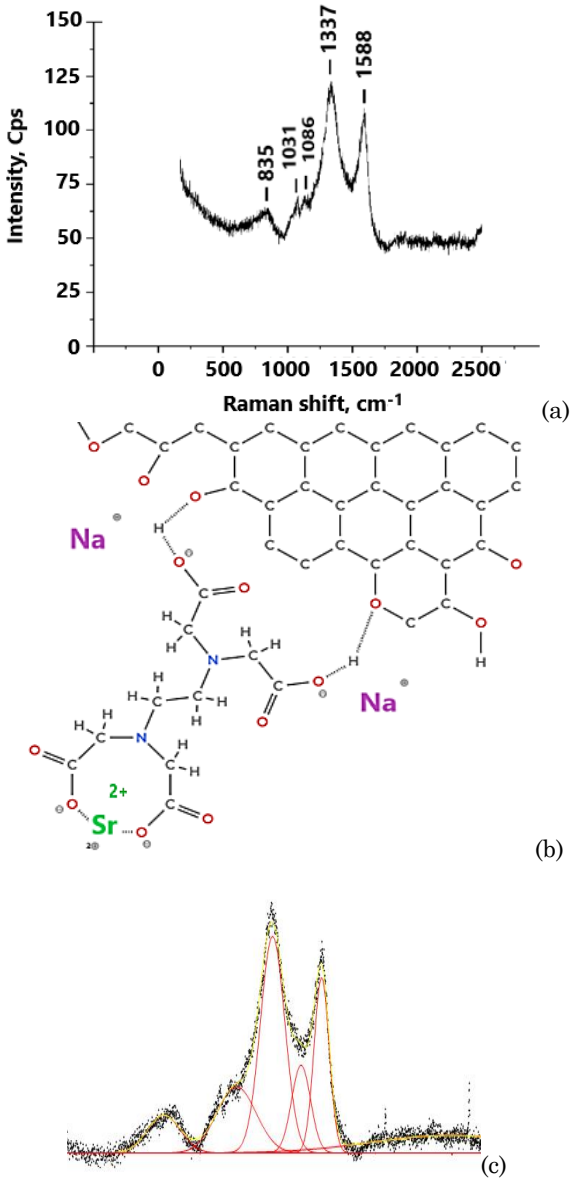


Fig. 4 – **(a)** The Raman spectrum of the AC sample after adsorption of strontium Sr^{2+}-EDTA; **(b)** Schematic representation of the mechanism of adsorption of Sr-EDTA by AC; **(c)** Fitting the corresponding Raman spectrum by Gaussian using fityk-1.3.1-setup.exe

Table 5 – Peak centers in the Raman spectrum of the activated carbon sample after adsorption of Sr-EDTA

Peak	Center, cm^{-1}	Spline type
1	**1588**	**Gaussian**
2	**1337**	
3	1031*	
4	1086*	
6	1483	
7	835*	

It is well known that oscillation near 810 cm^{-1} can belong to –C–O–C– groups. This line is absent in the Raman spectrum of activated carbon (Fig. 2 (b and c)). According to [18, 27-29], these maximums near 1031 cm^{-1} and 800-835 cm^{-1} belong to the molecule of ethylene diamine tetraacetic acid [28]. According to the database

EDTA magnesium disodium (14402-88-1) Raman spectrum (chemicalbook.com), the Na-EDTA lines on the Raman spectrum lie between 600 and 1600 cm^{-1}. The peaks of the D-band were shifted to position 1337 cm^{-1} after the adsorption of complex Sr^{2+} with Na-EDTA. In our opinion, the adsorption of the complex mostly takes place in sp^3-hybridized carbon.

The main conclusion from this investigation is as follows: the adsorption capacity of activated carbon irradiated in the atmosphere of the air toward Na-EDTA molecules does not change.

3.2 Results of Experimental Simulation of Internal Irradiation of Activated Carbon

Raman spectra of activated carbon samples irradiated with solvent molecules on the adsorbent surface are shown in Figures 5, 6 (a and b).

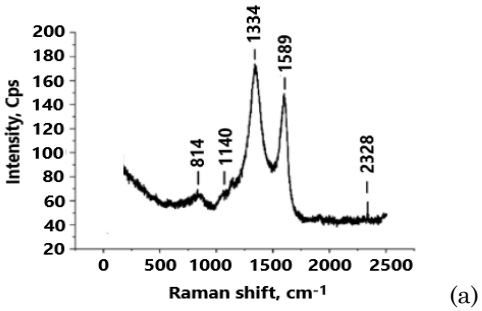


Fig. 5 – **(a)** Raman spectrum of AC treated by 0,1M HNO_3 and irradiated with a Dose of 80.6 Gy of β-irradiation; **(b)** Fitted Raman spectrum of AC treated by 0.1M HNO_3 and irradiated with a Dose of 80.6 Gy of β-irradiation

Table 6 – Peak's centers in the Raman spectrum of the AC treated by 0.1M HNO_3 and irradiated with a Dose of 80.6 Gy of β-irradiation

Peak	Center, cm^{-1}	Spline type
1	1589.57	Gaussian
2	1334.59	
3	1483.06	
4	2010	
5	2328.51	
6	1140	
7	814.77	

As can be seen from the above figures, the presence of water during irradiation significantly affects the pattern of the Raman spectrum of the AC. It can be assumed that radiolysis of water occurs under the influence of beta-radioactivity, and free radicals attack the surface of the AC simultaneously with beta- and bremsstrahlung gamma-radiation. At the same time, the formation of –C–O–C– bonds and, possibly, dimers of carboxylic acids occurs [22]. This is evidenced by the maxima on the Raman spectra of 876 cm^{-1} and 1016 cm^{-1}, which are not found on the spectrum of the original unirradiated sample.

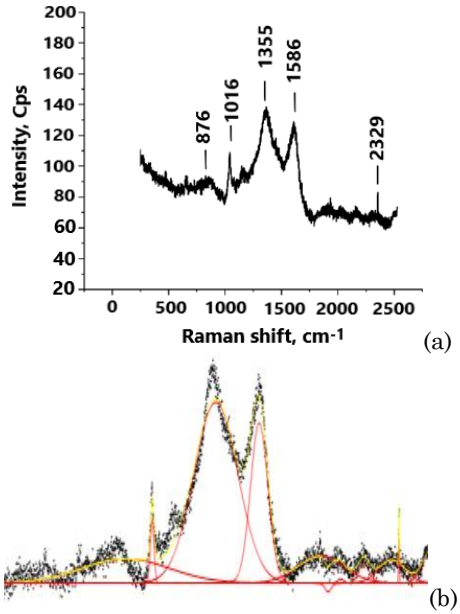


Fig. 6 – **(a)** Raman spectrum of AC treated by distilled H_2O and irradiated with a Dose of 80.6 Gy of β-irradiation; **(b).** Fitted Raman spectrum of AC treated by distilled H_2O and irradiated with a Dose of 80.6 Gy of β-irradiation

Table 7 – Peak's centers in the Raman spectrum of the AC treated by H_2O and irradiated with a Dose of 80.6 Gy of β-irradiation

Peak	Center, cm^{-1}	Spline type
1	**1586**	Gaussian
2	**1355.35**	
3	1951	
4	2506	
5	2329.51	
6	1016	
7	**876**	

A comparison of Figures 5 and 6 shows that an aqueous acid solution causes less surface modification than distilled water. This is an interesting result that requires further research. Also, a detailed spectra analysis using the fityk-1.3.1-setup.exe program indicates that sp^3-hybridized carbon atoms interact with radicals under the influence of ionizing radiation. Therefore, the main changes in the Raman spectra are observed near 800-1500 cm^{-1}. Perhaps this is an indirect confirmation of the radiation resistance of graphene clusters. In the publication [13], the authors explain the increased radiation resistance of epoxy resins doped with oxidized graphene by the influence of oxidized graphene. More precisely, sp^2-hybridized carbon atoms. The radiation resistance of graphene clusters is explained by the authors [13] as follows. This is because the π electrons formed by the six-membered ring honeycomb structure of oxidized graphene can produce a π-π free-radical accumula-

tion effect, thus reducing the free radicals produced during irradiation. At the same time, the mechanism of ionizing radiation on various polymers is the formation of free radicals that damage chemical bonds in polymers.

Irradiation of activated carbon in this way negatively affects the adsorption capacity. The results of test studies of the adsorption of Na-EDTA molecules by non-irradiated AC samples, irradiated samples in the air atmosphere, and irradiated in the presence of H_2O and 0.1M molecules of HNO_3 solution are given in Table 8.

Table 8 – Results of test studies of adsorption of Na-EDTA molecules by non-irradiated AC samples, irradiated samples in the air atmosphere, and the presence of H_2O and 0.1M HNO_3 molecules. The initial concentration of Na-EDTA was 0.01M, and the adsorbent dosage was 100 mg; pH = 7.

Adsorbent/ conditions	AC Non irradiated	AC Irradiation in the air atmosphere	AC irradiation in the presence of molecules H_2O	AC Irradiation in the presence of 0.1 M HNO_3 water solution
*Q, mg/g	179	173	29.5	39.1

*Adsorption value of Na-EDTA (pH=7)

The effects of irradiation mainly affect sp^3-hybridized carbon atoms. Adsorption of Na-EDTA molecules also occurs due to these atoms. This can explain the negative impact of irradiation in the presence of H_2O molecules on the adsorption properties of activated carbon.

From the obtained results, it can also be concluded that the study of radiation resistance under conditions of exposure in the air atmosphere does not give a complete pattern of the change in the properties of the adsorbent under the influence of radioactivity. During the adsorption of radionuclides from aqueous solutions, ionizing radiation interacts with the surface of the adsorbent in the presence of water molecules. Therefore, the adsorption capacity may decrease due to the influence of a combination of these two factors: radiation and water molecules. It would be noted that irradiation causes the radiolysis of water molecules (eq. 1) according to [4]:

$$H_2O \xrightarrow{\text{irradiation}} = e^-_{aq},\ HO\cdot \text{ (hydroxyl radicals)},\ H\cdot,\ HO_2\cdot,\ H_3O^+,\ OH^-,\ H_2O_2,\ H_2 \quad (1)$$

The free radicals formed during the radiolysis of water are very reactive. They attack the –OH groups of the activated carbon surface, which can be adsorption centers. One of the options for reducing the adsorption capacity of activated carbon irradiated in this way is to reduce the number of surface–OH groups capable of forming hydrogen bonds with adsorbate molecules.

4. CONCLUSIONS

The adsorption capacity of activated carbon toward Na-EDTA molecules was investigated. It was shown that commercial activated carbon intensively absorbs Na-EDTA molecules. The maximum adsorption reaches 800 mg/g. Irradiation with beta- and gamma radioactivity in the air atmosphere does not affect the adsorption capacity of activated carbon, which is also capable of adsorbing the Na-EDTA complex with strontium ions. Dry irradiation by the high-energy electrons with a dose of 230.4 Gy does not affect the graphene line of the sp^2-hybridized carbon.

The surface of the adsorbent changes in the presence of water molecules or an aqueous acid solution in contact with the surface of the adsorbent during irradiation.

During irradiation of AC in the presence of water molecules on the surface, the –C–O–C– groups, aromatic rings, and carboxylic acid dimers form, which lead to the occurrence of maxima of about 810 cm^{-1}, 990-1100 cm^{-1}, and 910-960 cm^{-1} on the Raman spectrum of AC. From the obtained results, it can also be concluded that the study of the material's radiation resistance under conditions of exposure in the air atmosphere does not give a complete pattern of the change in the properties of the adsorbent under the influence of radioactivity. During the adsorption of radionuclides from aqueous solutions, ionizing radiation interacts with the surface of the adsorbent in the presence of water molecules. Therefore, the adsorption capacity may decrease due to the influence of a combination of these two factors: radiation and water molecules.

Fitting shows that these transformations of the activated carbon surface involve mainly sp^3-hybridized atoms. Therefore, our results do not contradict the results of the papers [13], which state that the graphene component of carbon is radiation-resistant. In all our studies, the graphene component remained almost unchanged. However, this effect requires further research.

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Радіаційно-індуковані процеси у зразках комерційного активованого вугілля під впливом гамма- та бета-радіоактивності

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Комерційні зразки активованого карбону пропонують для очищення водних розчинів від органічних забрудників, барвників, йонів важких металів і радіонуклідів. Тому дослідження радіаційно-індукованих процесів у зразках комерційного активованого вугілля під впливом гамма- та бета-радіоактивності є актуальними.

Метою даної роботи є дослідження радіаційно-індукованих процесів в комерційно доступному активованому вугіллі за допомогою раманівської спектрометрії та вивчення впливу радіації на адсорбційні властивості активованого вугілля. Досліджувані зразки активованого вугілля були опромінені лінійним прискорювачем Halcyon Varian і джерелом ^{90}Sr-^{90}Y Sirius в атмосфері повітря, а також при наявності розчинів, що контактують з поверхнею адсорбенту. Було вивчено спектр комбінаційного розсіювання світла та адсорбційні характеристики опроміненого та неопроміненого вуглецю щодо молекул Na-EDTA. Раманівську спектроскопію опромінених та неопромінених зразків активованого вуглецю виконано в Центрі колективного користування науковим обладнанням «Лабораторія експериментальної та прикладної фізики» Ужгородського національного університету. Раманівські спектри розшифровували за допомогою програмного застосунку fityk-1.3.1-setup.exe. Показано, що опромінення зразків активованого карбону бета- і гамма-радіоактивністю в атмосфері повітря не впливає на адсорбційну здатність активованого вугілля. Максимальна адсорбція молекул Na-EDTA неопромінюваним активованим вугіллям досягає 800 мг/г. При опроміненні активованого вугілля в присутності молекул води на поверхні АС утворюються групи –C–O–C–, ароматичні кільця і димери карбонових кислот, які зумовлюють утворення максимумів близько 810 см$^{-1}$, 990-1100 см$^{-1}$ і 910-960 см$^{-1}$ в раманівському спектрі зразків активованого вугілля. Апроксимація спектра за допомогою програми fityk-1.3.1-setup.exe показує, що в цих перетвореннях поверхні активованого вугілля беруть участь в основному sp3-гібридизовані атоми. Опромінення активованого вугілля таким способом навіть при дозі близько 80 Грей негативно позначається на адсорбційної здатності, значно зменшуючи її. Однак цей ефект потребує подальших досліджень.

Ключові слова: Активоване вугілля, Гамма- та бета-опромінення, Раманівська спектроскопія, Na-EDTA.