STUDY OF THE e_0-ELECTRON YIELD FROM THE SURFACE OF ^{64}Cu RADIOACTIVE SOURCES OF VARIOUS THICKNESSES AT THEIR POSITRON DECAY

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The (eγ)-coincidence method was used to study the yield of e_0-electrons from the surface of ^{64}Cu radioactive sources of various thicknesses. The values of 0.120(7), 0.076(4), 0.044(4), 0.034(10), and 0.034(2) for the e_0-electron yield per a single event of β^+-decay were obtained for the source thicknesses of 1.1, 2.0, 4.8, 11.0, and 14.5 μg/cm^2, respectively. These values are several times lower than the known e_0-electron yield at β^--decay under the same experimental conditions.

1. Introduction

A "zero-energy peak" is always observed in the low-energy part of the electron spectrum when solid-phase radioactive sources decay [1]. Its energy distribution is peaked at about 0.5 eV, with the halfwidth equal approximately 1 eV. As the energy grows, the intensity of emitted nearzero-energy electrons (e_0-electrons) falls quickly down, and it can be neglected at the energies more than about 20 eV. We believe that the occurrence of the zero-energy peak is caused by the quantum-mechanical transition of electrons from the surface into vacuum under the action of an electric charge that suddenly arises near the surface [2]. The phenomenon itself is similar to the shake off of shell electrons of an atom when the latter undergoes β^--decay [3].

The reasons for the electric charge to appear near the surface are different for different types of radioactive decay. For example, at the internal conversion of γ-rays or at the electron capture, the near-surface charge results from the cascade of Auger-transitions while filling the vacancies at deep atomic shells. It causes a high degree of atomic ionization. Under β^--decay, the charge is considerably smaller. It arises owing to the change of the nucleus charge and to atomic self-ionization by shake off as well as a result of direct collisions of the β^--particle with electrons of the atomic shell [4].

The increase of the distance between the location where the charge emerges and the surface is accompanied by the rapid decrease of e_0-electron emission; therefore, such a notion as a near-surface layer can be introduced. We suppose that such a layer contains approximately 5 atomic ones. If the decay happens in the bulk of the source (behind the near-surface layer), the emission of e_0-electrons is possible only due to the appearance of a charge in the near-surface layer induced by the external ionization of the atom caused by the passage of charged particles through this layer. The charge can also arise in the near-surface layer if solid targets are bombarded by charged particles, which also leads to the emission of e_0-electrons. Ionization of atoms in the near-surface layer by x- and γ-rays is very low and can be neglected. The yield of e_0-electrons, Y_{e_0}, is the mean number of e_0-electrons emitted by the source, provided that the charge emerges with an equal probability at various places of the near-surface layer.

This work aimed at studying the dependence of the yield of near-zero-energy electrons on the source thickness at the positron decay of ^{64}Cu. Similar researches have not been carried out for the positron decay earlier.

2. Preparation Radioactive Sources

Radioactive sources of ^{64}Cu of various thicknesses were prepared by irradiating copper specimens of various thicknesses deposited onto aluminum substrates with neutrons in a reactor. Along with copper specimens, a reference one — a weighted piece of zirconium foil — was irradiated. The weights of ^{64}Cu specimens under investigation were determined on the basis of the reference specimen weight by comparing the activities of ^{64}Cu and ^{95}Zr, provided that the cross-sections of (n,γ)-reactions for ^{63}Cu and ^{94}Zr are known; the thicknesses of ^{64}Cu sources were found knowing the weight of the latter and the area of the spot deposited. Thus, every ^{64}Cu source was a radioactive spot 14 mm in diameter, deposited onto an aluminum foil 25 mm in diameter and 6 μm in thickness. In the researches, we used the sources with the following thicknesses: 1.1, 2.0, 4.8, 11.0, and 14.5 μg/cm^2. The activities of those ^{64}Cu specimens at the end of their irradiation were 1.3, 2.3, 5.6, 13, and 17 MBq, respectively.

Nineteen percents of ^{64}Cu decay ($T_{1/2} = 12.7$ h) by the β^+-decay mode with the following annihilation of positrons and emission of two γ-quanta, with the energy of 511 keV each; 41% by the electron capture; and 40% by the β^--decay. Owing to the presence of impurities in the Al foil, the sources, after the irradiation of the specimens in the reactor, also contained ^{24}Na ($T_{1/2} = 15$ h) and ^{72}Ga ($T_{1/2} = 14.1$ h), the activities of which at the end of irradiation were usually 300 and 150 kBq, respectively. The isotope ^{56}Mn ($T_{1/2} = 2.6$ h) was also present in the sources, but it had practically decayed before the measurements started. Moreover, it turned out that aluminum substrates involved copper in small amounts; therefore, the substrates also revealed the ^{64}Cu activity. To exclude the influence of the latter on the results of measurements where the ^{64}Cu sources were used, an aluminum substrate of the same dimensions but without deposited copper was irradiated simultaneously with the copper specimens. All numerical data quoted in this article were calculated by subtracting the ^{64}Cu activity of the substrate.

The number of atomic layers, k, in ^{64}Cu sources was estimated as follows. Consider that every atom in the crystalline lattice is located at the center of a cube. The thickness of the atomic layer is equal to the edge length of this cube filled with one atom. Then, the number of atomic layers can be evaluated as

$$k = m\sqrt[3]{N_\mathrm{A}/\rho^2 A}. \qquad (1)$$

Here, m is the source's mass measured in g/cm^2 units, ρ its density in g/cm^3, A the atomic weight, and N_A the Avogadro constant. In our case, the thicknesses of the deposited sources were equal to 5.4, 9.9, 24, 54 or 71 atomic layers, or, approximately, to 1, 2, 5, 11 or 14 near-surface layers, respectively.

3. Experimental Part

The experimental conditions were as follows. A radioactive source and a chevron of two microchannel plates (MCPs) were placed into a vacuum chamber at a distance of 5 cm from each other. A Ge(Li)-detector was positioned outside the chamber at a distance of 6 cm from the source. Simple γ-spectra and the spectra of coincidence between γ-rays and electrons were registered; electrons were registered by means of MCPs. Figure 1 demonstrates a γ-spectrum and a spectrum of (e$_0\gamma$)-coincidence. In the coincidence spectrum, e$_0$-electrons created at the β^+-decay of ^{64}Cu are represented by the 511-keV peak of positron annihilation, while the peaks at 834 and 1369 keV correspond to e$_0$-electrons formed at the β^--decay of ^{72}Ga and ^{24}Na in the Al substrate of the source. The intensity of e$_0$-electrons, $N_{e_0\gamma}$, was calculated as the difference between the (eγ)-coincidence spectra measured at either the zero voltage across the source, when the MCPs register both e$_0$- and fast electrons, or a braking voltage of +160 V, when only fast electrons (mainly β-particles) reach the MCPs. The MCP surface was biased to a voltage of +120 V for the more complete collection of e$_0$-electrons.

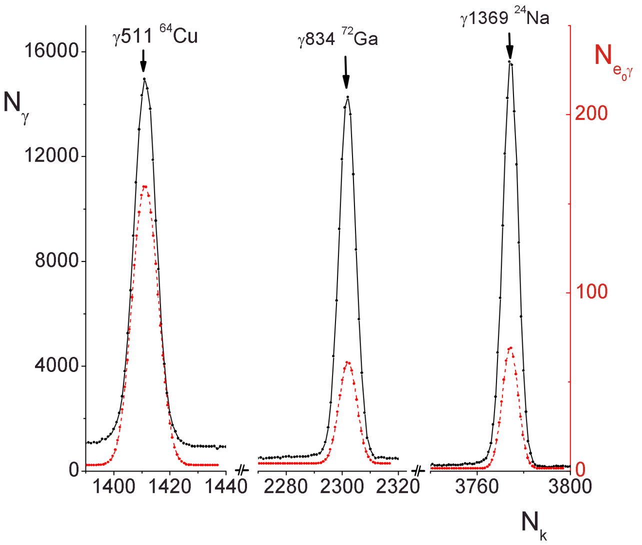

Fig. 1. Fragments of γ-ray and (e$_0\gamma$)-coincidence spectra measured for a ^{64}Cu source 1.1 μg/cm^2 in thickness. Solid curves are the fragments of γ-ray spectra, measured during 1 h; dashed curves are the fragments of (e$_0\gamma$)-coincidence spectra, measured during 2 h

The probability of e$_0$-electron registration, R_0, was determined by the formula

$$R_0 = \frac{N_{e_0\gamma}}{N_\gamma}, \qquad (2)$$

where $N_{e_0\gamma}$ and N_γ are the numbers of (e$_0\gamma$)-coincidences and γ-quanta, respectively, registered

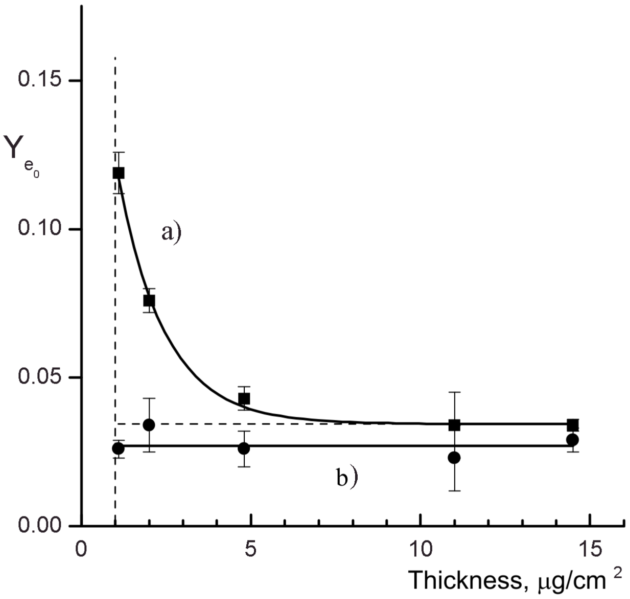

Fig. 2. Dependences of the e$_0$-electron yield Y_{e_0} on the ^{64}Cu (a) or ^{24}Na (b) source thickness. The vertical dashed line denotes the thickness of the near-surface layer in the source. The horizontal dashed line denotes the contribution to Y_{e_0} from the external ionization

during the same time interval. The yield of e$_0$-electrons per one positron decay was determined by the formula

$$Y_{e_0} = \frac{R_0}{\eta\varepsilon_0}, \tag{3}$$

where η is the fraction of collected e$_0$-electrons, and ε_0 the efficiency of the e$_0$-electron registration by MCPs. We found that $\eta\varepsilon_0 = 0.07$ under our conditions. For this purpose, we carried out, provided the same experimental conditions, the measurements of R_0 for a thin (about 1 μg/cm^2) ^{152}Eu source; its e$_0$-electron yield per one β^--decay, $Y_{\mathrm{e}_0} = 0.34$, had been determined earlier [5].

The Table quotes the values of the registration probability R_0 of e$_0$-electrons in coincidences with 511-keV γ-quanta per one event of β^--decay for various thicknesses of deposited copper, which were obtained in our work. The Table also quotes the values of the registration probability for ^{24}Na and ^{72}Ga in the aluminum substrate.

As one can see from the Table, the values of R_0 for ^{64}Cu varied by a factor of approximately 3.5, whereas they remained approximately constant for ^{24}Na and ^{72}Ga, because ^{24}Na and ^{72}Ga were located in the depth of the aluminum substrate, onto which ^{64}Cu was deposited.

4. Discussion of Results

The dependence of the e$_0$-electron yield Y_{e_0} on the ^{64}Cu source thickness is depicted in Fig. 2, curve a. For comparison, a similar dependence measured at the β^--decay of ^{24}Na is also shown (curve b). ^{24}Na is located in the bulk of the Al substrate, and, in this case, the emergence of e$_0$-electrons is related to the formation of a charge in the near-surface layer owing to the ionization of atoms in this layer by penetrating β^--particles. Therefore, the e$_0$-electron yield Y_{e_0} for ^{24}Na remains constant independent on the ^{64}Cu source thickness. In the figure, the latter dependence is shown by a solid straight line b.

For thick ^{64}Cu sources (11.0—14.5 μg/cm^2 or 54—72 atomic layers), the yield of e$_0$-electrons Y_{e_0} is also determined by the external ionization of atoms in the near-surface layer at penetrating β^--particles through it. This contribution to Y_{e_0} is denoted in the figure by a horizontal dashed line. However, as the thickness of the ^{64}Cu source decreases, the role of the near-surface layer activity grows, and, at the source thickness of about 1 μg/cm^2, its value becomes 3.5 times higher than the corresponding value for a thick source. If ^{64}Cu atoms decay in the near-surface layer, then, while calculating Y_{e_0}, one should take into account, in addition to the charge associated with external ionization, the charge induced by the atomic self-ionization at β^+-decay. The appearance of the latter charge is caused by the sudden change of the nucleus charge by $-1e$ and the internal ionization due to the shake off and direct collisions in the process of β^+-decay. The charge that arises in the near-surface layer at the internal ionization is larger than that appearing at the external one, which explains the observed dependence of the yield on the source thickness (see Fig. 2).

In work [6], we demonstrated that, in the case of thick sources, when the activity of the near-surface layer can be neglected, the yields Y_{e_0} at β^-- and β^+-decays are approximately identical. Whence, it follows that β^-- and β^+-particles, penetrating the near-surface layer,

Values of R_0 for sources of various thicknesses

Source thickness, μg/cm^2	^{64}Cu	^{24}Na	^{72}Ga
1.1	0.0083(5)	0.0018(2)	0.0018(2)
2.0	0.0053(3)	0.0024(6)	0.0025(13)
4.8	0.0031(3)	0.0018(4)	0.0020(3)
11	0.0024(8)	0.0016(8)	0.0016(8)
14.5	0.0024(1)	0.0020(3)	0.0017(5)

Footnote: To determine the yield of e$_0$-electrons, Y_{e_0}, the value of R_0 should be divided by $\eta\varepsilon_0 = 0.07$

induce the identical ionization which does not depend on the charge sign. The e_0-electron yield Y_{e_0} for thick ^{64}Cu sources can be calculated using the relation $R_0/\eta\varepsilon_0 = 0.034$. Excluding this component, we obtain the e_0-electron yield Y_{e_0} for a thin source ^{64}Cu which is related only to the atomic self-ionization at β^+-decay, $Y^+_{e_0} = 0.084$. But this value is several times smaller than, e.g., a similar value $Y^-_{e_0} = 0.31$ obtained for the β^--decay of ^{152}Eu after subtracting the component that arises owing to the external ionization.

In work [7], we demonstrated that the yield of e_0-electrons is proportional to the squared charge that stimulates their emission. In this case, the ratio of the e_0-electron yields at β^-- or β^+-decays from a thin source, when the activities are located in the near-surface layer, can be written down as

$$\frac{Y^-_{e_0}}{Y^+_{e_0}} = \left(\frac{+1+\Delta Z^-}{-1+\Delta Z^+}\right)^2, \qquad (4)$$

where ±1 is the self-ionization charge caused by a change of the nucleus charge at β^+- or β^--decay, and ΔZ^- and ΔZ^+ are the charges under the atomic self-ionization that arise at shake off and direct collisions (all the charges are measured in the electron charge units). Since the average energies of ^{64}Cu β^-- and β^+-decays are close (221 and 278 keV, respectively), the values of ΔZ^- and ΔZ^+ are approximately equal. In work [2], we showed that the influence of direct collisions on the atomic self-ionization manifests itself appreciably only at energies lower than 200 keV; therefore, in our case, their influence on the self-ionization can be neglected. We did not study the β^--decay of ^{64}Cu; therefore, in order to estimate the value of ΔZ, we can use the value of $Y^-_{e_0}$ for ^{152}Eu, the average energy of β-decay for which, $\bar{E}_{\beta^-} = 319$ keV, is close to $\bar{E}_{\beta^+}$ for ^{64}Cu.

Substituting the numerical values for the quantities $Y^-_{e_0}$ and $Y^+_{e_0}$ into formula (4), we obtain $\Delta Z = 0.3$. This value agrees with the values for the atomic self-ionization at shake off calculated by us elsewhere. We reject another root of Eq. (4), $\Delta Z = 3.2$, because it is too large and do not agree with experimental data.

Thus, the results of this work demonstrate that the e_0-electron yield at β^+-decay is several times smaller than that at β^--decay for equal decay energies, if the activities are located in the near-surface layer. It is explained by the fact that the charge created in the near-surface layer at β^+-decay is smaller than that created at β^--decay, because the β-particle escaping from the nucleus in the former case changes its sign from +1 to −1.

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ДОСЛІДЖЕННЯ ВИХОДУ e_0-ЕЛЕКТРОНІВ З ПОВЕРХНІ РАДІОАКТИВНИХ ДЖЕРЕЛ ^{64}Cu РІЗНОЇ ТОВЩИНИ ПРИ ПОЗИТРОННОМУ РОЗПАДІ

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Резюме

Методом ($e\gamma$)-збігів проведено вивчення виходу e_0-електронів з поверхні радіоактивних джерел ^{64}Cu різної товщини (1,1; 2,0; 4,8; 11,0; 14,5 мкг/см^2). Отримано значення виходів e_0-електронів на один акт β^+-розпаду, а саме: 0,120(7); 0,076(4); 0,044(4); 0,034(10); 0,034(2) відповідно. Ці значення в декілька разів менші, ніж відомі значення виходів e_0-електронів для β^--розпаду, отримані у тих же експериментальних умовах.