THE INVESTIGATION OF e_0-ELECTRON YIELDS FROM THE SURFACE OF VARIOUS TARGETS UNDER BOMBARDMENT BY α-PARTICLES FROM ^{226}Ra DECAY

V.T. KUPRYASHKIN, L.P. SIDORENKO, O.I. FEOKTISTOV, I.P. SHAPOVALOVA

Institute for Nuclear Research, Nat. Acad. Sci. of Ukraine
(47, Nauky Prosp., Kyiv 03028, Ukraine)

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The dependences of the yields of near-zero-energy electrons (e_0-electrons) on the energy of α-particles are measured for targets with various Z irradiated by α-particles from the ^{226}Ra decay. The yields of e_0-electrons for various targets are found to change within the limits of 15%. The small growth of the yield of fast electrons e_f is observed when Z increases. The ratios of e_0-electron yields for various α-particle energies E_α in ^{226}Ra are well described by the dependence $Y_{e_0}(E_\alpha) \sim E_\alpha^{-1/2}$. The theoretical analysis of the experimentally obtained e_0-electron yields with the use of a quantum-mechanical treatment of the sudden atomic excitation by an α-particle allows us to evaluate the energy of the transition from a bound state to the continuum at the level approximately equal to 70 eV which is comparable with the known energies of low-energy Auger electrons in gold (69.8 eV) and aluminum (63.2 eV).

1. Introduction

We imply the near-zero-energy electrons (e_0-electrons) to be those low-energy electrons radiated by the surface of radioactive sources which make up the “zero-energy peak” in electron spectra [1]. The width of this peak has an order of 1 eV, and its maximum approximately corresponds to 0.5 eV. The intensity of e_0-electron radiation quickly decreases when the energy increases, and it can be neglected at an energy of about 20 eV [2].

As we assume, the radiation of e_0-electrons from the surface of a source arises due to the sudden appearance of an electric charge near the surface. This charge is a perturbation for the electrons in the conduction band and is the reason for their emission into vacuum. The deeper the charge appears, the weaker its perturbation for the near-surface electrons. The emission of e_0-electrons practically vanishes when such a charge appears at a distance of 5-6 atomic layers from the surface. We call these several layers located near the surface as a near-surface layer. The charge in the near-surface layer may appear not only due to a radioactive decay, but also due to the bombardment of a target by charged particles. Therefore, an analogous “zero-energy peak” is observed in the electron spectrum upon the bombardment of solid targets with charged particles [3]. The yield of e_0-electrons, Y_{e_0}, is proportional to the square of the charge which appears in the near-surface layer, and the angular distribution is very stretched forward due to the necessity for e_0-electrons to overcome the surface barrier at a sharp decrease in the intensity of e_0-electrons with increase in the energy [4,5]. The yield Y_{e_0} is the averaged number of emitted e_0-electrons for a uniform probability distribution of the sudden appearance of charges throughout the source.

In [4, 5], we studied the peculiarities of the e_0-electron creation at a β^--decay, electron capture, and γ-ray internal conversion. In the present work, we want to consider thoroughly the peculiarities of the e_0-electron creation during the transition of α-particles through the surface. The yield of e_0-electrons is the same for both the α-decay and the target bombardment by α-particles, since it is determined only by the amount of the charge which appears in the near-surface layer when an α-particle is passing through it. Therefore, there is no difference, in principle, from which direction an α-particle comes to the near-surface layer: it may come

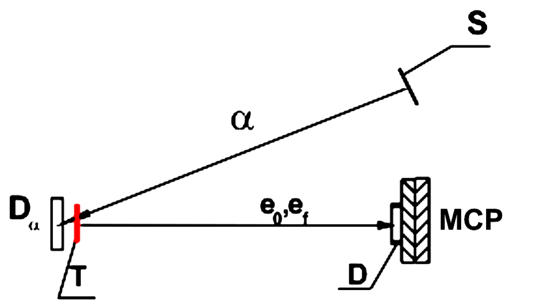

Fig. 1. Geometric arrangement of the setup: T — target, MCP — microchannel plates, S - ^{226}R source, D_α – α-detector, D — aperture

from the source interior or fall on the target surface. Moreover, it makes no difference whether the source is thin or thick. Coming through the near-surface layer, an α-particle collides with a certain number of atoms and ionizes them. As a result, the charge ΔZe is created in the near-surface layer. The probability of its creation depends on the probability of atom ionization in the near-surface layer P by an α-particle in a single ionization event. After that, the e_0-electron yield Y_{e_0} is determined, first, by the probability of the e_0-electron creation W under the influence of the perturbation $\Delta Ze^2/r$, where r is the distance between the charge and a conduction electron on the surface, and, secondly, by the number of such electrons N_e capable to react to this perturbation and to come out in vacuum. Then the yield of e_0-electrons from the target under the influence of an α-particle may be represented as a product

$$Y_{e_0} \sim PWN_e.$$

In [4], we already considered the variables W and N_e. Now we dwell on the relation between P and W. It was noted in review [6] devoted to the emission of secondary electrons that the yield of secondary electrons emitted during the passage of a charged particle through the target is proportional to $E_\alpha^{-1/2}$. We observed the same dependence when α-particles with various energies pass through a TiO_2 film [7]. Such a dependence takes place due to that the ionization probability P of the atom in the near-surface layer of the target depends on the velocity of an α-particle at their collision. In this paper, we intend to study this dependence more thoroughly for a number of targets with various Z by using α-particles of different energies from the ^{226}Ra decay in the equilibrium with its daughter nuclei.

2. Experimental Setup

The electron emission from the target surface is investigated in coincidences with α-particles which give rise to this emission. The targets are various materials deposited on the disk made of an aluminum foil with a thickness of 10μm and ∅10 mm. To detect α-particles, we use a surface-barrier detector with n-type silicon having dimensions of ∅24×4 mm^2 and an active area of ∅12 mm. To detect electrons, we use the assembly of two microchannel plates (MCP) in the form of a chevron with dimensions of 3×2 cm, in front of which we arrange a brass aperture with ∅10 mm to cut down a part of the electron beam.

The simplified scheme of the setup is represented in Fig. 1. The α-detector is placed in the immediate vicinity of the target T (a gap between them is less than 1 mm). The ^{226}Ra source is placed on the other side of the target at a distance of 7.2 cm, a little above it. The MCP-detector is installed against the target at a distance of 5 cm. The side of the target with deposited material is turned to the MCP, while the substrate to the α-detector. The α-particles radiated by the source pierce the target, create the electric charge in the near-surface layer, and further get to the α-detector. The created charge gives rise to the emission of e_0-electrons detected by the MCP. In addition, fast electrons e_f, which are created during the knocking out of bound electrons of the target, get to the MCP. The pressure in a vacuum chamber is $2{\cdot}10^{-6}$ Torr.

We use ^{226}Ra as the α-source from a spectrometric collection OSAI with an active spot with ∅12 mm deposited on a stainless steel substrate with ∅24 mm and a thickness of 2 mm [8]. The spectrum of the source has four main α-lines with energies of 4708(95), 5414(100), 5926(100), and 7611(100) keV. Their intensities in percentages per one decay are represented in parentheses. In addition, there are two weak lines 4529(5) and 5321 keV. After the analysis of spectra, the former was summed with the 4708-ke V line and the latter with the 5414-keV line. The spectra were registered by a multichannel pulse analyzer ORTEC.

3. Experimental Procedure

To obtain the dependences of the e_0-electron yield Y_{e_0} on the energy of incident α-particles, we measured the simple α-spectrum and the spectrum of electron-α-particle coincidences. At first, the voltage supplied to the MCP front surface was +120 V, and that supplied to the source was zero. At this voltage on the source, the main part of e$_0$-electrons goes to the MCP. Then, a voltage of +160 V was supplied to the source. In this case, e$_0$-electrons did not fall onto the MCP, and only fast e_f-electrons were detected. For each α-line, we calculate the probabilities of detecting the coincidences of e_0- and e_f-electrons with a single α-particle [R_{e_0} and R_{e_f}, respectively] as

$$R_{e_0} = \frac{N_{(e_0+e_f)\alpha} - N_{e_f\alpha}}{N_\alpha} \quad \text{and} \quad R_{e_f} = \frac{N_{e_f\alpha}}{N_\alpha},$$

where $N_{(e_0+e_f)\alpha}$ and $N_{e_f\alpha}$ are the intensities of α-lines in the spectrum of coincidences at the voltages on the source equal to zero and +160 V, respectively, and N_α is its intensity in the simple spectrum. The intensities of the lines were calculated by means of the comparison with the 7611-keV line from the simple α-spectrum in a tabular form.

For the conditions under consideration, the probability to detect the coincidence R_{e_0} is related to the e$_0$-electron yield Y_{e_0} through the relation $R_{e_0} \approx Y_{e_0}\varepsilon_0\Omega$, where ε_0 is the registration efficiency of e$_0$-electrons, and W is a part of those electrons which fall onto the MCP relative to all the electrons radiated by the target. Therefore, hereinafter, we consider the value of R_{e_0} as the e$_0$-electron yield expressed in some arbitrary units.

The simple spectrum of α-particles and the spectra of their coincidences with e_0- and e_f-electrons during the bombardment of an Au-target by α-particles from the ^{226}Ra source are shown in Fig. 2. In addition, the spectra of (eα)-coincidences measured at a zero voltage on MCP and voltages equal to 0 and +24 V on the source are given in the same figure. The values of R_{e_0} and R_{e_f} are calculated by the above-presented formulas. The similar measurements were carried out for the Al, Ge, Cu, Ru, Er, Hf, and Au targets deposited on the aluminum substrate and for Al, Cu, Au targets deposited on the thin Dacron films. The point is that the Al substrate with a thickness of 10 μm decelerates α-particles in such a way that the lines of the α-spectrum considerably widen at lower energies, which results in the measurement accuracy decrease. The Dacron substrates are one order thinner to eliminate this defect. But Dacron films can acquire an electric charge, which can introduce a distortion in the electron spectrum. However, it was found no essential difference between the results of measurements for various targets during the analysis of spectra, thus our fears about a possible charge of Dacron substrates turned out to be groundless. On the whole, 12 similar measurements were carried out, and the following results were obtained.

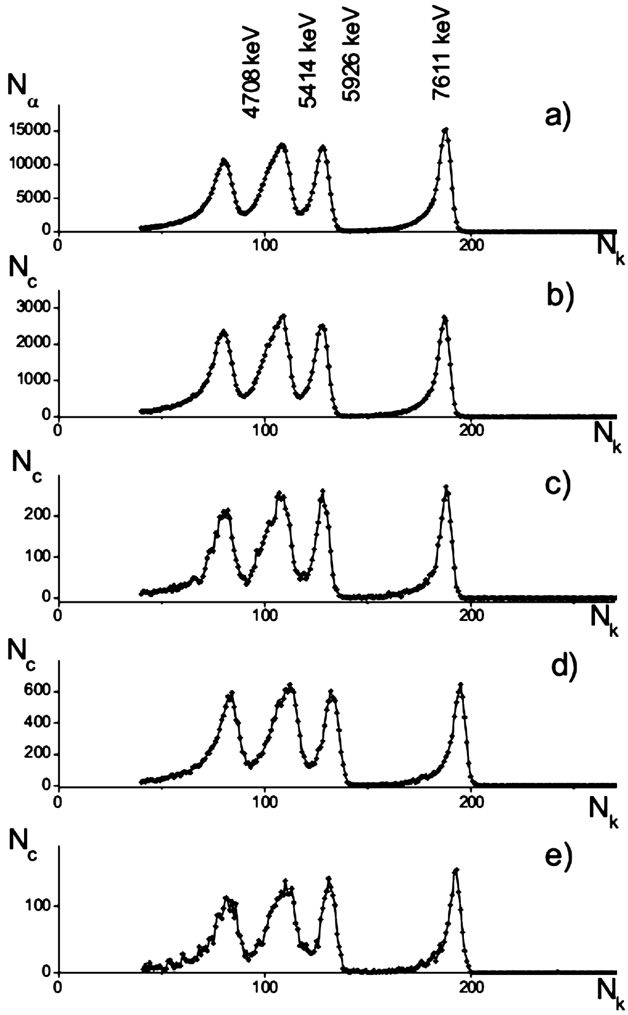

Fig. 2. Simple α-spectrum and the α-spectra for coincidences with electrons emitted by the target surface: *a*) — simple α-spectrum. Exposure time is 1 h; *b*) — α-spectrum for coincidences with electrons, the voltages supplied to the MCP surface and the source are +120 V and 0, respectively, ((α, e$_0$ + e$_f$)-coincidences). Exposure time is 1 h; *c*) — the same as in Fig. 2*b*, but the voltage on the source is +160 V ((α, e$_f$)-coincidences). Exposure time is 2 h; *d*) — α-spectrum for coincidences with electrons at a zero voltage supplied to the MCP surface and source ((α, e$_0$+e$_f$)-coincidences). Exposure time is 2 h; *e*) — the same as in Fig. 2,*d*, but the voltage on the source is +24 V ((α, e_f)-coincidences). Exposure time is 6 h

For the 7611-keV line, the dependence of R_{e_0} on the atomic number Z for various target materials was obtained using the measurements of the probabilities of detecting the coincidences of e$_0$-electrons with α-particles. This dependence is presented in Fig. 3. The

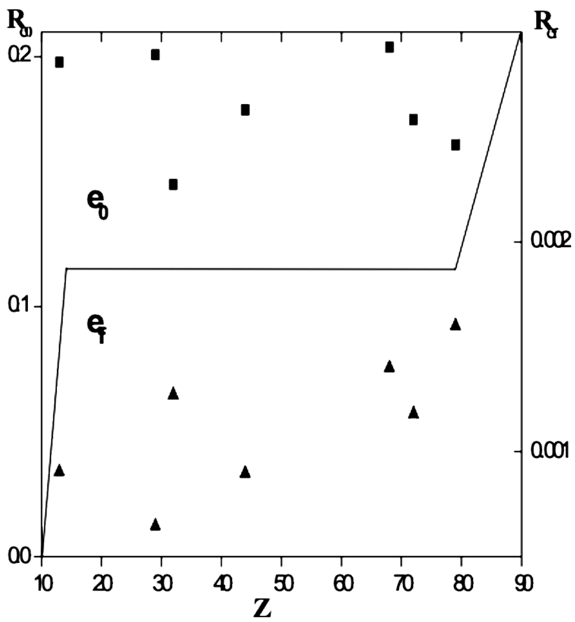

Fig. 3. Dependence of the probability to detect e$_0$- and e$_f$-electrons on Z of the target material for α7611 keV: ■ — $R_{e0}(Z)$ (the voltage on the MCP surface is +120 V); ▲ — $R_{ef}(Z)$ (the voltage on the MCP surface is 0)

graphic presentation of the statistical error is less than the dot size, but the observed scattering is much larger and equals ± 15%. It is possible that the scattering is caused by the uncontrolled surface states of various targets, though all the measurements were carried out in the same geometry, by the same program, and at the same gas pressure in a chamber. The presented dependence is obtained during the measurements at a voltage of +120 V supplied to the MCP surface and voltages of 0 and +160 V supplied to the source. The same dependence, but with a higher dispersion of dots, is obtained at a zero voltage supplied to the MCP and that of 0 and +24 V supplied to the source. However, in this case, the count rate of coincidences and the values of R_{e_0} are less by a factor of 10, but the e_f-electron spectrum is less distorted in comparison with that in the first regime.

For the 7611-keV line, the dependences of R_{e_f} on the atomic number Z for various target materials were obtained using the measurements with α-particles. In this case, the voltages supplied to the MCP surface and the ^{226}Ra source were 0 and +24 V, respectively. As for the R_{e_0} dependence, the observed dispersion of R_{e_f} is much larger than the statistical one which is a little larger than the dot size (see Fig. 3). The observed dispersion of data may be used as an argument in favor of the periodic dependences of $R_{e_0}$and R_{e_f} on Z of the target material, since the value of R_{e_f} is independent of the target surface state for fast electrons. The small increase in the yield Y_{e_f} of fast e_f-electrons with the target atomic number probably takes place. We recall that, for the geometry of the experimental setup (Fig. 1), fast electrons have an isotropic angular distribution [5], and they are, most likely, the Auger electrons created due to the filling of vacancies in the atom shells after the ionization event induced by an α-particle. They have the energy of δ-2φ, where δ is the binding energy of the electron knocked out, and φ is the electron work function. These electrons knocked out from the atoms have mainly a low energy (it is less than 5 eV) and cannot leave the target [9].

The ratios of the yields Y_{e_0} for all four lines of the α-spectrum of ^{226}Ra are defined by the ratio of the logarithms ln($1 - R_{e_0}$) averaged over the all results of measurements. We obtained the following ratios (the energies of α-particles are given in the parentheses):

$$Y_{e_0}(4708\text{ keV}) : Y_{e_0}(5414\text{ keV}) :$$

$$: Y_{e_0}(5926\text{ keV}) : Y_{e_0}(7611\text{ keV}) =$$

$$= (1.29 \pm 0.02) : (1.21 \pm 0.01) : (1.13 \pm 0.02) : 1.$$

These are derived in the case where a voltage of +120 V is supplied to the MCP, and the voltages supplied to the source are 0 and +160 V. When the zero voltage is supplied to the MCP, and the voltage supplied to the source is 0 and +24 V, these ratios remain practically the same:

$$(1.28 \pm 0.02) : (1.20 \pm 0.01) : (1.15 \pm 0.01) : 1.$$

The errors of the ratios are those of the dispersion calculated by using all of 12 measurements carried out. The obtained ratios are well agree with the dependence $Ye0(E_\alpha) \sim E_\alpha^{-1/2}$ which gives, for our values of energy,

$$1.27 : 1.19 : 1.13 : 1.$$

Thus, the probability of ionization is inversely proportional to the velocity of the passage of an α-particle near the atom, i.e. inversely proportional to the time of its perturbation.

The following ratios are obtained from the measurements of the probability of the registration of (αe_f)-coincidences per one registered α-particle:

$$Y_{e_f}(4708\text{ keV}) : Y_{e_f}(5414\text{ keV}) :$$

$: Y_{e_f}(5926 \text{ keV}) : Y_{e_f}(7611 \text{ keV}) =$

$= (1.19 \pm 0.01) : (1.14 \pm 0.03) : (1.11 \pm 0.04) : 1.$

These ratios are slightly different from those for the yields of e_0-electrons. We did not seek for the reasons for the weakening of the dependence, though the dependences $Y_{e_f}(E_\alpha)$ and $Y_{e_0}(E_\alpha)$ should not be identical, because e_f-electrons are created not only in the near-surface layer, but also in the deeper layers of the target, provided that Auger electrons can leave it.

4. Discussion

In monograph [10], the excitation of an atom with a heavy charged particle passing near it is considered. Since the electrons of the atom are subjected to a perturbation $V(t)$ induced by the charge of such a particle, only in the region of their maximum approach D, the probability of the electron transition from the state m to the state n during the perturbation action time t is defined by the formula

$$\mathrm{W}_{nm} = \frac{1}{\hbar^2}\left|\int\limits_0^\tau \langle n|V(t)|m\rangle e^{i\omega_{nm}t}dt\right|^2.$$

The effective time of the collision is $t = D/v$, where v is the particle velocity, and w_{nm} is the transition frequency. In the approximation of a sudden change of the interaction for a low energy of the electron excitation $w_{nm}D/v \leq 1$ during the time of the effective collision, we can assume that $e^{i\omega_{nm}t} \sim 1$. This allows us to calculate the probability of the atom excitation per unit time, when N charged particles pass through a unit area [10]. We do not write the final formula for the probability of the atom excitation and give only its part concerning the dependence of this probability on the velocity of an α-particle. In the notations used, it has the form

$$P_{nm} = A\frac{\ln(\mathrm{v}/a\omega_{nm})}{\mathrm{v}^2},$$

where a is the atom radius. The factor A includes all other coefficients of the formula from [10], including the squared charge of an incident particle Z^2. The formula is valid provided $a\omega_{nm}v^{-1} \leq 1$. Upon α-decays, the velocities of α-particles have an order of 10^9 cm/s, whereas the atom size is 10^{-8} cm. Then, for α-particles emitted upon the radioactive decay, the effective time

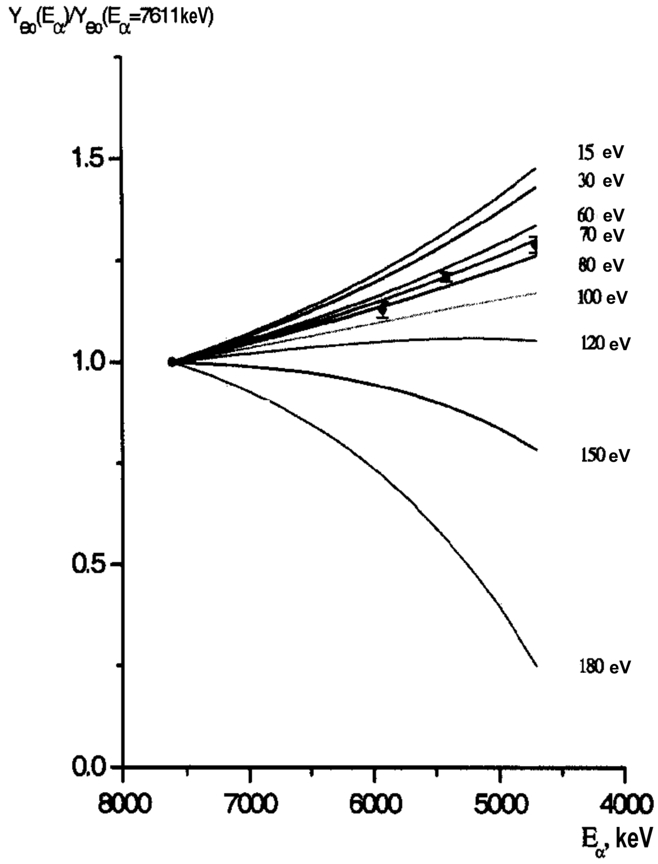

Fig. 4. Dependences of the ratios of the e_0-electron yields from the target surface $Y_{e_0}(E_\alpha)/Y_{e_0}$ (E_α = 7611 keV) on the energy of α-particles at various energies of electron excitation in a target atom. Dots represent the ratios for the energy of ^{226}Ra α-particles. The transition energies $h\omega$ (in eV) are designated near each curve

of collision $t \sim 10^{-17}$ s, that allows us to consider the collision in the approximation of a sudden change of the interaction at low transition energies.

Since the e_0-electron yields Y_{e_0} for α-particles are proportional to the probabilities of the excitation of an atom P_{nm} (and its subsequent ionization), they are supposed to have the same dependence on the velocity of α-particles. The calculated dependence of the ratio of the yields Y_{e_0} on the energy of α-particles is represented in Fig. 4 in the units of the yield Y_{e_0} for E_α = 7611 keV (from ^{226}Ra) for various transition energies $h\omega_{nm}$, the first Bohr orbit $a = 5.29 \cdot 10^{-9}$ cm being taken as the atom radius. Having compared the experimental ratios of the yields Y_{e_0} with those calculated, we obtain the evaluation of the transition energy of an electron upon its perturbation by an α-particle: $h\omega_{nm} \approx 70$ eV. The Auger electrons which come out in vacuum after filling this vacancy are supposed to have the energy which is lesser by the work function, i.e. it is approximately equal to 65 eV. The Auger structure is observed experimentally for Au and Al at energies of 69.8 eV N_7VV and 63.2 eV, respectively [11]. Therefore, the theoretical analysis and the comparison with experimental data allow us to evaluate the transition energy upon the excitation of the atomic electrons by α-particles.

We have considered the electron excitation in atoms by α-particles. There is no basic difference whether the excitation or the electron escape from the atom is considered. In the latter case, the final state n has to be considered as one of the states of the continuous spectrum [12]. Such an electron has the energy less than 5 eV on the average and cannot leave the target [9], but it comes out from the atom (and, possibly, from the near-surface layer) and gets lost, leaving the vacancy in the atom. The filling of this vacancy through the Auger process results in the appearance of the +2e charge in the conduction band, while such a charge is only + 1e after the atom excitation. Therefore, in the first case, the total electric charge (that gives rise to the e_0-electron emission) created in the near-surface layer is twice larger.

Thus, the e_0-electron emission induced by the bombardment of the target with α-particles is defined by two sudden sequential perturbations: the first one is the electron excitation in the atom caused by the transiting α-particle, which results in the creation of the electric charge in the near-surface layer, and the second is the perturbation of the conduction electrons in the near-surface layer which is induced by the appearance of this charge.

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ДОСЛІДЖЕННЯ ВИХОДУ e_0-ЕЛЕКТРОНІВ З ПОВЕРХНІ РІЗНИХ МІШЕНЕЙ ПРИ БОМБАРДУВАННІ ЇХ α-ЧАСТИНКАМИ З РОЗПАДУ ^{226}Ra

В.Т. Купряшкін, Л.П. Сидоренко, О.І. Феоктістов, І.П. Шаповалова

Р е з ю м е

Виміряно виходи електронів близьконульової енергії — e_0-електронів — в залежності від енергії α-частинок для ряду мішеней з різними Z при їхньому опроміненні α-частинками з розпаду ядер ^{226}Ra. Для різних мішеней вихід e_0-електронів змінюється в межах 15 %. Спостерігається невеликий ріст виходу швидких електронів e_f зі збільшенням Z. Відношення виходів e_0-електронів для α-частинок різної енергії E_α з ^{226}Ra добре описуються залежністю $Y_{e_0}(E_\alpha) \sim E_\alpha^{-1/2}$. Аналіз отриманих експериментальних значень виходів e_0-електронів на основі квантово-механічних уявлень про раптове збудження атома α-частинкою, що пролітає, дозволяє оцінити енергію переходу електрона зі зв'язаного стану у неперервний спектр — близько 70 еВ, що узгоджується з відомими енергіями низькоенергетичних оже-електронів у золоті (69,8 еВ) і в алюмінії (63.2 еВ).