ENERGY SPECTRUM OF ELECTRONS EMITTED DUE TO IONIZATION OF ATOMS BY α-PARTICLES PASSING THROUGH A SUBSTANCE

L.P. SIDORENKO,[1] V.T. KUPRYASHKIN,[1] A.I. FEOKTISTOV,[1]
YE. P. ROVENS'KYKH[2]

[1]**Institute for Nuclear Research, Nat. Acad. of Sci. of Ukraine**
(47, Nauky Ave., Kyiv 03680, Ukraine; e-mail: `kupryashkinvt@yahoo.com`*)*

[2]**Taras Shevchenko National University of Kyiv**
(11-a, Academician Glushkov Ave., Kyiv 03187, Ukraine; e-mail: `Junni@ukr.net`*)*

PACS 0.5; 0.7; 10; 11

The energy spectrum of electrons generated due to the ionization of atoms of a target by α-particles is studied, by using the (αe)-coincidence technique by applying the retarding voltage U in the electron registration channel. A ^{238}Pu alpha-source and targets representing films of different thicknesses with spray-coated aluminum were used. The obtained distribution $N_c(eU)$ is compared with the theoretical one calculated under the assumption that it is caused by the transition of an electron from the bound atomic state to the continuum due to a sudden perturbation of the atom by the α-particle charge. It is shown that the observed distribution of fast electrons generated due to the passage of the α-particle through a substance can be described in the approximation of a quantum-mechanical transition of the system (atom) from the initial neutral state to the final ionized one accompanied by the ejection of the electron from the bound state to the continuum due to a sudden perturbation of the atom by the charge of an α-particle passing near it (shake-off effect).

1. Introduction

The atomic ionization accompanying the passage of charged particles through a substance is usually considered as the kinetic electron emission (KEE), where an electron acquires a kinetic energy directly from the incident particle [1]. In that case, the main attention was paid to the energy loss by a charged particle rather than to the process of transition of a bound electron beyond the atomic limits [2, 3]. In contrast, the present work is concentrated on the consideration of the atomic ionization due to the transition of an electron located close to the target surface from the bound state to the continuum. Passing near the electron, a particle with charge Z_pe creates a perturbation $\frac{Z_pe^2}{r}$ at the time moment of the closest approach at a distance r. In the case of high velocities V_p, this perturbation acts during a very short time interval $\tau_p \sim \frac{r}{V_p}$ which is much smaller than the time $2\pi\omega_{fi}^{-1}$ of transition from state i to state f.

Such a perturbation appears sudden for a bound electron, which results in its ejection to the continuum with the kinetic energy $E = \frac{Ze^2}{r} - E_B$, where E_B stands for the electron binding energy in the atom with regard for the work function. In contrast to the shake-off effect, where the perturbation of an electron is caused by the interaction with a suddenly arising immobile charge, the perturbation is created in the case under consideration by a moving α-particle. Due to a high velocity of the α-particle, the interaction time is short, that is why we will consider firstly the perturbation as if the shake-off arises due to a suddenly appearing immobile charge.

2. Energy Distribution of Ionization Electrons during a Shake-Off

The basic formulas that describe transitions under the action of a sudden perturbation are given in the book by Landau and Lifshitz [4]. The most important point in this description is the condition that a perturbation must be so fast that the wave function of the initial state of the quantum-mechanical system $\psi_i^{(0)}(q)$ "had no time" to change during the action of the perturbation. This time must be short as compared with the time interval

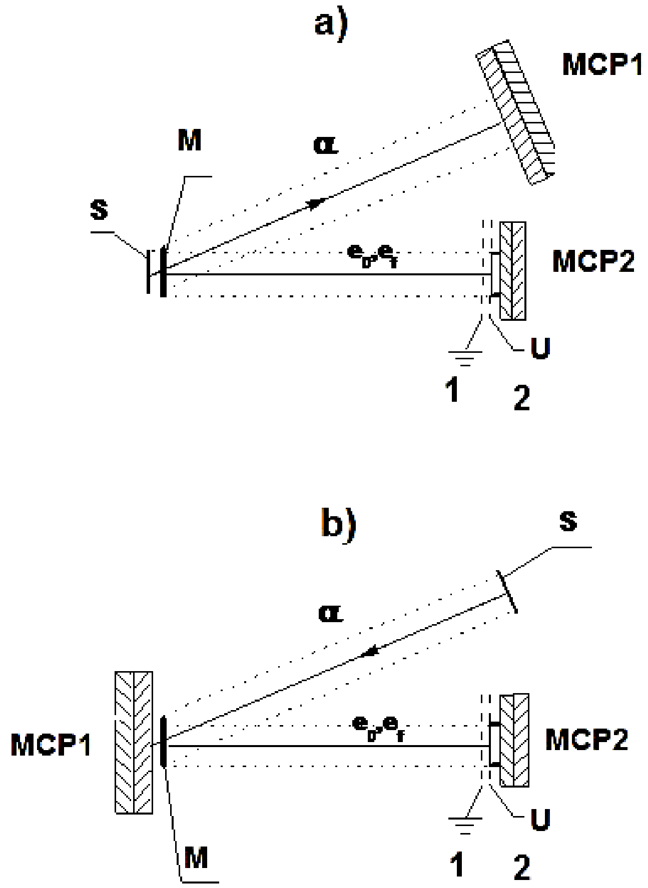

Fig. 1. Experimental set-up in the transmission (*a*) and reflection (*b*) geometries. S – ^{238}Pu source, M — target, MCP$_1$ – alpha-detector, MCP$_2$ – electron detector. Outer grid (*1*) is grounded, inner grid (*2*) is subjected to the retarding potential U

$2\pi\omega_{fi}^{-1}$ of the transition from state i to state f, and the $\psi_i^{(0)}(q)$ function must remain the same as before the perturbation. Using these ideas and taking the level density obtained from the examination of the phase volume for electrons able to pass to vacuum into account, we can write the following formula for the energy distribution of ionization electrons after their ejection to vacuum [5]:

$$\frac{dN}{dE} = \frac{a\sqrt{E}}{(E+E_B)^2}, \tag{1}$$

where $a = \frac{\sqrt{2}m^{\frac{3}{2}}V}{\pi^2\hbar^3}$, m is the atomic mass, and V is the volume occupied by one electron in the final state. The integral electron spectrum will have the form

$$\int\limits_0^{eU} \frac{dN}{dE}dE = a\left[\frac{1}{\sqrt{E_B}}\,\mathrm{arctg}\sqrt{\frac{E}{E_B}} - \frac{\sqrt{E}}{E+E_B}\right] =$$

$$= aF(E), F(0) = 0. \tag{2}$$

In order to compare the experimental values with the results of theoretical calculations, formula (2) must be converted to the form that makes such a comparison possible. Formula (2) allows one to determine the number of fast ionization electrons e_f^i registered in the energy interval between 0 and $E = eU$ under the corresponding application of the retarding potential U to the grid, whereas the experimental curve shows the number of electrons left after the application of this potential. That is, the integration limits from 0 to $E = eU$ in (2) must be replaced by those from $E = eU$ to $E_{\max}$. Thus, formula (2) can be presented as

$$\int\limits_{eU}^{E_{\max}} \frac{dN}{dE}dE = a[F(E_{\max}) - F(eU)]. \tag{3}$$

The agreement between the experimental and theoretical distributions (1)–(3) can testify to the validity of the assumptions about the sudden perturbation of an electron for the description of the atomic ionization. Such a comparison earlier performed in [5] for the explanation of the appearance of near-zero energy electrons due to the shake-off effect has demonstrated a good agreement.

3. Experimental Technique

The energy spectrum of ionization electrons generated after the passage of an α-particle through a substance is investigated with the use of the (αe)-coincidence method by applying the retarding voltage in the electron registration channel. The coincidence counting rate N_c was measured as a function of the voltage across the grid that decelerated electrons. The electron energy spectrum was measured in two geometries presented in Fig. 1. In one of them (transmission experiment, Fig. 1,*a*), alpha-source S was located close to target M. In this case, α-particles pass through the target and are registered by a detector representing an assembly of two microchannel plates (MCP$_1$) in the form of a chevron 16×24 mm^2 in size. Electrons emitted from the target under its bombardment with α-particles were registered by another detector MCP$_2$ 10×20 mm^2 in size. The distance between target M and the MCP$_1$ detector amounts to 58 mm, while that between the MCP$_2$ detector and the target equals 38 mm. In the other measuring geometry (reflection experiment, Fig. 1,*b*), the alpha-particle detector MCP$_1$ was placed immediately behind the target, whereas source S itself was located in the place of the MCP$_1$ detector. It is worth noting that, both in the transmission and reflection experiments, electrons were ejected from the same surface of the target.

The alpha-source was presented by ^{238}Pu from the collection of standard spectrometric alpha-sources (OSAI) that represented a substrate made of stainless steel 24 mm in diameter with a radioactive 12-mm ^{238}Pu spot at the center [6]. The energy of α-particles amounted to 5.5 MeV. The target's base was formed by dacron films 180 μg/cm^2 and 1760 μg/cm^2 in thickness with evaporated transparent layers of aluminum. On the front surface of the MCP^2 electron detector, there were fixed two grids at a distance of 2 mm. To the inner grid, we supplied the retarding voltage U that changed in the course of measurements, while the outer grid was always grounded and served to keep a solid angle of the registration of electrons constant under a change of the retarding potential. The whole system was placed into a vacuum chamber at a pressure of 5×10^{-6} Torr.

Figure 2 presents fragments of the spectra obtained in one of the series of measurements in the transmission and reflection geometries at different retarding potentials U. For example, the spectra of time (αe)-coincidences measured in the transmission and reflection geometries at $U = 0$ V are given in Fig. 2,*a*. Each of them contains two peaks: the left one is caused by near-zero energy electrons e_0 and the right one — by fast electrons e_f. The generation of e_0 electrons results from the interaction of surface electrons with an immobile charge that suddenly appears near the surface when an α-particle passes through the latter (the effect of shake-off of e_0-electrons from the surface). Since the appearance of a charge in the surface layer in the transmission and reflection experiments does not depend on the direction of motion of the α-particle, the peak of near-zero energy electrons e_0 has approximately equal intensities in the both spectra. The maximum of its energy distribution is located close to 0.5 eV, the half-width amounts to 1 eV, and its intensity decreases so fast that it can be neglected at 20 eV. The angular distribution of e_0-electrons is sharply elongated forward and backward in the direction normal to the target surface. The ejection of e_0-electrons generated at the radioactive decay (as the shake-off effect) is considered in detail in [5, 7, 8].

The formation of the second peak is related to fast electrons e_f. As an α-particle passes through the target, it interacts with bound atomic electrons, which results in the atomic ionization and escape of fast electrons, whose angular distribution is directed forward, in the direction of motion of the α-particle [8]. In the opposite direction, one does not register fast electrons formed due to the ionization. But the ejection of an electron is followed by the formation of a vacancy in the atomic shell, whose occupation results in the escape of Auger electrons that are also fast, though the direction of their ejection does not depend on the direction of motion of the α-particle, i.e. their distribution is isotropic. These results were obtained in our experiments devoted to the study of the angular distribution of electrons ejected from the target surface bombarded by α-particles [8]. It is worth noting that the shake-off of e_0-electrons from the target surface takes place only after the formation of a charge close to the surface due to the ejection of Auger electrons.

Thus, the peaks of fast electrons e_f in the transmission and reflection experiments considerably differ in their nature. In the transmission experiments, the peak of fast electrons e_f includes the contributions of electrons appearing due to the atomic ionization, e^i_f, and Auger electrons, e_f^{Aug}, i.e. $e_f = e^i_f + e_f^{\mathrm{Aug}}$. In the reflection experiments, it is caused only by Auger electrons, $e_f = e_f^{\mathrm{Aug}}$. In order to determine the intensity of the peak of ionization electrons e^i_f, one should subtract the peak intensity of fast electrons in the reflection spectrum from that in the transmission spectrum.

In the course of our work, we measured more than 60 time coincidence spectra in the energy range from 5 to 800 eV with different steps. Figure 2,*b–f* shows examples of the time spectra of (αe)-coincidences measured at different values of the retarding potential $U = 24$, 50, 100, 200, and 800 V. One can see from the figure that, in the case of application of the retarding potential, the zero-energy peak disappears, and the intensity of the peak of fast electrons falls with increase in the retarding potential. In these cases, the peak intensities were determined using the same procedure as that described for Fig. 2,*a*, i.e. by means of subtracting the peak intensity in the reflection spectrum from that in the transmission one.

4. Experimental Results

Figure 3 demonstrates the counting rates of coincidences of α-particles with electrons N_c as functions of the energy (that is determined by the retarding potential U across the second grid) obtained for the target with the base thickness equal to 1760 μg/cm^2. They were obtained in the transmission (upper curve *a*) and reflection (lower curve *b*) experiments. The experimental points are connected by lines for easier observation. The points between the curves (also connected by lines) represent their difference in the transmission and reflection experiments (curve *c*). Curve *d* shows the theoretical distribution calculated according to formula (3) that corre-

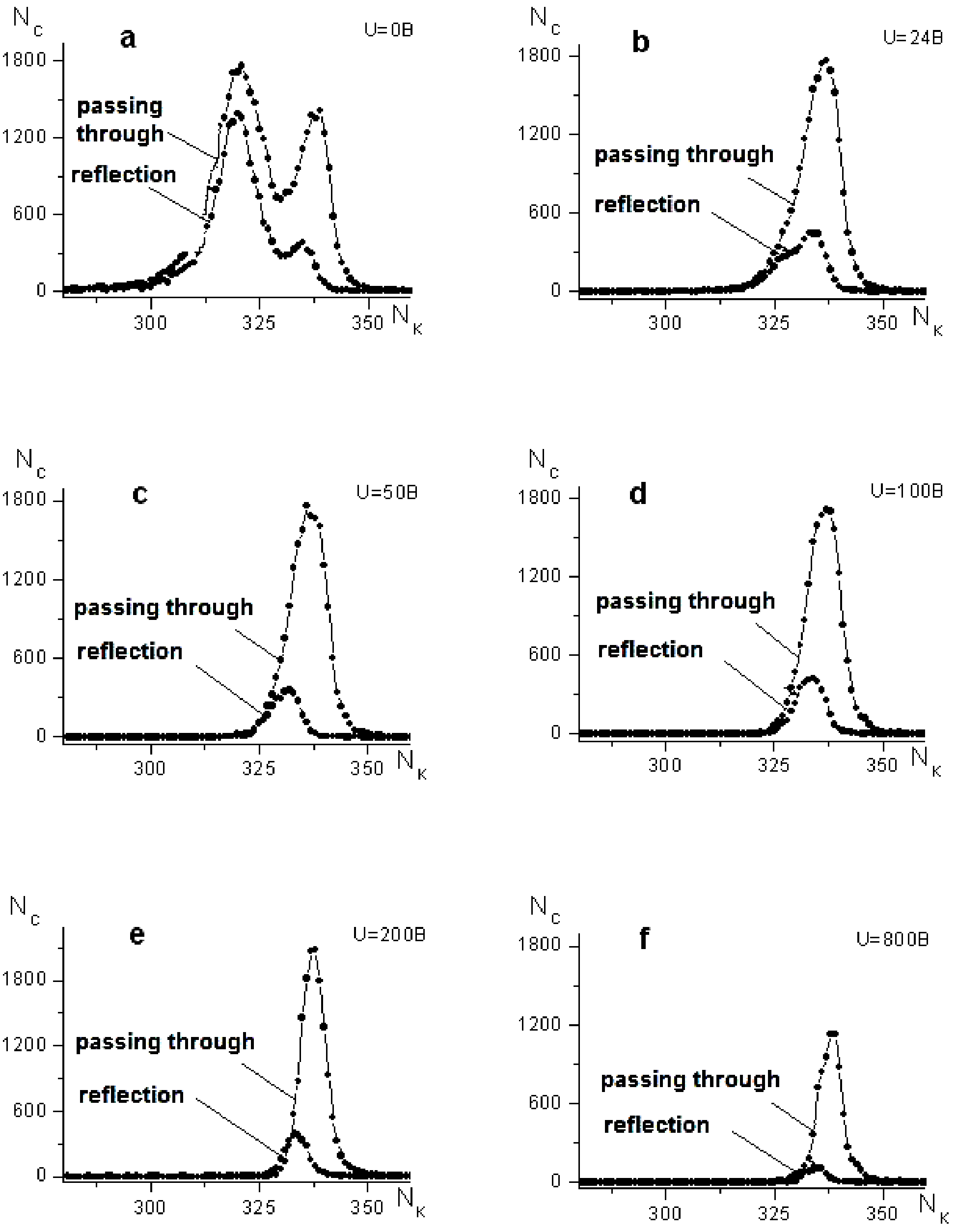

Fig. 2. Regions of the (αe)-coincidence spectra measured in the transmission and reflection geometries at the retarding potentials $U = 0$, 24, 50, 100, 200, and 800 V

sponds to the integral spectrum of (αe)-coincidences for fast ionization electrons under the shake-off effect.

The measurements were performed in the energy range from 5 to 800 eV. Ionization electrons with energies lower than 5 eV were not considered in order to avoid their mixing with near-zero energy electrons. The 800-eV retarding energy includes the energy region of escorting electrons that arise as α-particles of ^{238}Pu with an energy of 5.5 MeV move through a substance. However, in the transmission geometry, the angle between the MCP$_1$ detector that registers α-particles and the MCP$_2$ electron detector exceeds 30°. It is known that the intensity of escorting electrons abruptly decreases with increase of this angle. Therefore, in our experiment, escorting electrons must not noticeably influence the observed dependences.

The number of coincidences N_c for each point of the difference spectrum is proportional to the total number of fast electrons N_d formed due to the atomic ionization in the energy range from $E = eU$ to the maximum energy $E_{\max}$ and can be presented in the form

$$N_d = A[F(E_{\max}) - F(eU)]. \quad (4)$$

The coefficient A in this formula was determined by the fitting of the theoretical curve (d) to the experimental curve (c) with the help of the least-squares technique. The maximum energy of ionization electrons in the case of the interaction of ^{238}Pu α-particles with the aluminum film is unknown. However, at high energies, $F(E_{\max})$ changes very slowly. If we assume that $E_B = 70$ eV, which is close to the electron binding energy at the L_2- or L_3-subshells of an aluminum atom, then $E_{\max} \to \infty$ and $F(E_{\max}) \to 0.188$. If the energy $E_{\max}$ would be equal to 5.5 MeV, which corresponds to the transfer of the whole kinetic energy of the α-particle to the atomic electron, then $F(E_{\max}) = 0.187$. But it is impossible. Applying the least-square fit, we chose the value of the binding energy $E_B = 70$ eV and $F(E_{\max}) = 0.170$, which corresponds to the maximum energy of ionization electrons $E_{\max} = 104$ eV.

As one can see from Fig. 3, the theoretical curve is in good agreement with the experimental one. The studied dependence can be considered at the narrower region of the applied retarding voltages, for example up to 400 V instead of 800 V. In this case, the experimental and theoretical values for the points at 200, 300, and 400 V will get closer (by approximately 1related to a decrease of the possible influence of escorting electrons mentioned above. One should take into account that the divergences between the experimental and theoretical curves can remain due to neglecting the coincidences of α-particles with X-ray radiation independent of the retarding voltage. However, the effectiveness of the registration of X-rays by the microchannel plates is very low and cannot considerably affect the electron energy distribution.

The transmission and reflection measurements of such a kind were also carried out for the target with a base thickness of 180 μg/cm^2. But the statistical accuracy of these measurements was twice worse than that in the case of a thick target, while the step of variation of eU was smaller. However, the obtained results demonstrate that the integral electron spectra are similar to each other and well agree. This fact can be explained by that the ionization of atoms located deep in the target affects weakly the form of the low-energy spectral region, whereas the energy distribution of electrons ejected from the target is mainly determined by the ionization of atoms close to the surface.

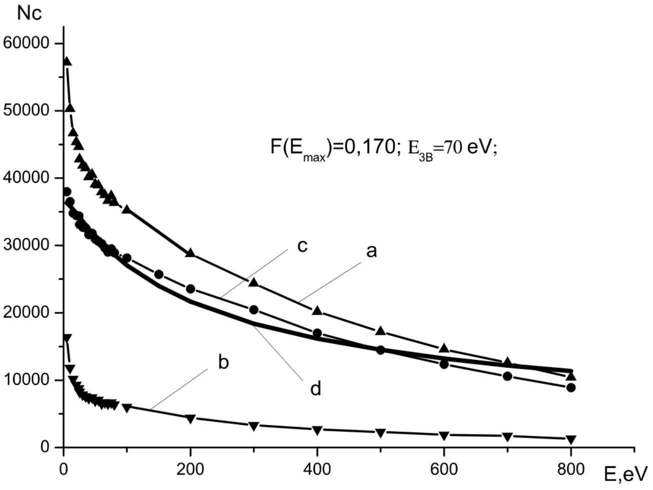

Fig. 3. The (αe)-coincidence counting rate depending on the retarding potential at different geometries of the experiment: *a*) transmission geometry; *b*) reflection geometry; *c*) integral energy spectrum of ionization electrons; *d*) integral spectrum calculated by formula (3)

5. Conclusions

Thus, the observed distribution of fast electrons generated during the passage of an α-particle through a substance can be described in the approximation of the quantum-mechanical transition of the system (atom) from the initial neutral state to the final ionized one accompanied by the ejection of the electron from the bound state to the continuum due to a sudden perturbation of the atom by the charge of the passing α-particle (shake-off effect).

However, in contrast to the common shake-off taking place under the action of a suddenly appearing immobile charge [4], the probability of ionization due to the passage of a charged particle through the target must be described by the formula $W_{\exp} \sim (Z_p e^2)^2/V_p$. That is, the probability of ionization is proportional to the squared charge of the particle and inversely proportional to its velocity. Such a dependence was observed in our experiments for β-particles, protons, and α-particles [9,10], as well as for heavy ions [11]. The formula is valid for charged particles of different sorts and velocities. For example, as was established in our work [12], the atomic ionization for α-particles at the radioactive decay of ^{232}U exceeded that for β-particles approximately by a factor of 40, because $V_\alpha \approx 0.1 V_e$ and $Z_\alpha^2 = 4 Z_e^2$.

We have established [9] that, as the velocity of β-particles ($V_\beta \sim 2.7 \times 10^{10}$ cm·c^{-1}) approaches the velocity of light ($c = 3 \times 10^{10}$ cm^{-1}), the character of the dependence does not change, while the ionization probability approaches its minimal value. *Vice versa*, with decrease in the velocity of a charged particle, its meeting with the atomic electrons gets longer, which results in an increase of the shake-off probability. In order to describe the atomic ionization by a charged projectile, the formula for the shake-off probability given in [4] must be supplemented with the multiplier $\frac{c}{V_p}$, and the following inequality must be satisfied: $\frac{r}{c} < \frac{r}{V_p} < 2\pi\omega_{fi}^{-1}$. Then the formula for the probability of the escape of an electron in the energy range from 0 to $E_{\max}$ in the case of the passage of a charged particle through the atom with regard for the velocity of its motion can be presented as

$$W = \mathrm{const}\frac{c}{V_p}\left(\frac{Z_p e^2}{r}\right)^2 \left|\int \psi_i^{(0)}\psi_f^* dq\right|^2 aF(E_{\max}). \qquad (5)$$

The term $\frac{c}{V_p}(\frac{Z_p e^2}{r})^2$ determines the probability of a perturbation of the atom. It depends on the charge Z_p of the particle (electron, α-particle, multiply charged ion, and so on) and its velocity V_p. The formulas for the shake-off probability usually do not contain this multiplier, because it is considered that the excitation has already occurred [4]. The value of a const factor in formula (5) is determined by the probability of the atomic ionization in the case where the particle moves at the velocity of light. The factor $|\int \psi_i^{(0)}\psi_f^* dq|^2$ determines the probability of transition of the system (atom) from the initial unexcited state to the final state accompanied by the appearance of a vacancy in the place of the ejected electron, whereas the factor $aF(E_{\max})$ determines the probability for the ejected electron to find its place in the continuum depending on its energy in the range from 0 to $E_{\max}$.

1. D. Hasselkamp, Springer Tracts Modern Phys. **123**, 1 (1992).
2. N. Bohr, *The Penetration of Atomic Particles through Matter* (Munksgaard, Kobenhaven, 1948).
3. E.I. Sternglass, Phys. Rev. **108**, 251 (1957).
4. L.D. Landau and E.M. Lifschitz, *Quantum Mechanics* (Pergamon Press, Oxford, 1977) .
5. O.I. Feoktistov, Ukr. Fiz. Zh. **55**, 165 (2010).
6. Yu.I. Bregadze, E.K. Stepanov, V.P. Yarina, *Applied Metrology of Ionizing Radiations* (Energoatomizdat, Moscow, 1990) (in Russian).
7. V.T. Kupryashkin, L.P. Sidorenko, A.I. Feoktistov, and I.P. Shapovalova, Izv. RAN. Ser. Fiz. **67**, 1446 (2003).
8. V.T. Kupryashkin, L.P. Sidorenko, A.I. Feoktistov, and I.P. Shapovalova, Izv. RAN. Ser. Fiz. **68**, 1208 (2004).
9. A.O. Valchuk, V.T. Kupryashkin, L.P. Sidorenko, A.I. Feoktistov, and I.P. Shapovalova, Ukr. Fiz. Zh. **51**, 126 (2006).
10. A.O. Valchuk, V.T. Kupryashkin, L.P. Sidorenko, A.I. Feoktistov, A.E. Borzakovsky, and V.I. Kuts, Ukr. Fiz. Zh. **53**, 853 (2008).
11. V.P. Kovalev, *Secondary Electrons* (Energoatomizdat, Moscow, 1987) (in Russian).
12. V.T. Kupryashkin, L.P. Sidorenko, and A.I. Feoktistov, Izv. RAN. Ser. Fiz. **63**, 153 (1999).

Received 12.10.09
Translated from Ukrainian by H.G. Kalyuzhna

ЕНЕРГЕТИЧНИЙ СПЕКТР ЕЛЕКТРОНІВ, ЩО ВИНИКАЄ ВНАСЛІДОК ІОНІЗАЦІЇ АТОМІВ ПРИ ПРОХОДЖЕННІ α-ЧАСТИНОК ЧЕРЕЗ РЕЧОВИНУ

Л.П. Сидоренко, В.Т. Купряшкін, А.І. Феоктістов, Є.П. Ровенських

Резюме

Методом (αe)-збігів, при подачі гальмівної напруги U у каналі реєстрації електронів проведено дослідження енергетичного спектра електронів, що утворюються при іонізації атомів мішені α-частинками. У роботі використано джерело α-частинок ^{238}Pu і мішені у вигляді плівок різної товщини з напиленим на них алюмінієм. Отриманий розподіл N_c(eU) порівнювали з теоретичним, який випливає з розрахунків у припущенні опису його як переходу електрона із зв'язаного стану атома в область неперервного спектра при раптовому збуренні атома зарядом α-частинки. Показано, що спостережуваний розподіл швидких електронів, що утворюються при проходженні α-частинки через речовину, можна описати в наближенні квантово-механічного переходу системи (атома) з початкового нейтрального стану в кінцевий іонізований стан з викиданням електрона із зв'язаного стану в неперервний спектр при раптовому збуренні атома зарядом пролітаючої повз нього α-частинки (ефект струсу).