STUDIES OF e_0-ELECTRON YIELD FROM THE SURFACE OF A TARGET BOMBARDED BY α-PARTICLES FROM THE U-120 CYCLOTRON

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The yields of near-zero-energy electrons (e_0-electrons) emitted from the surface of an Al target bombarded with cyclotron-generated α-particles with different energies have been determined. The spectra of α-particles and (e,α)-coincidences are measured to establish the dependence on the e_0-electron yield on the α-particle energy. The e_0-electron yield has been demonstrated to be reciprocal to the α-particle velocity, similarly to what was observed earlier for β-particles. Probable origins of such a dependence are discussed.

1. Introduction

At the radioactive decay or at the bombardment of a target with charged particles, the surface always emits electrons possessing a very low energy which are responsible for the appearance of a "zero-energy peak" in the electron spectrum [1]. We call such electrons as near-zero-energy ones and denote them as e_0-electrons, unlike other electrons in the spectrum, which we refer to as fast electrons and denote as e_f-electrons. The origin of

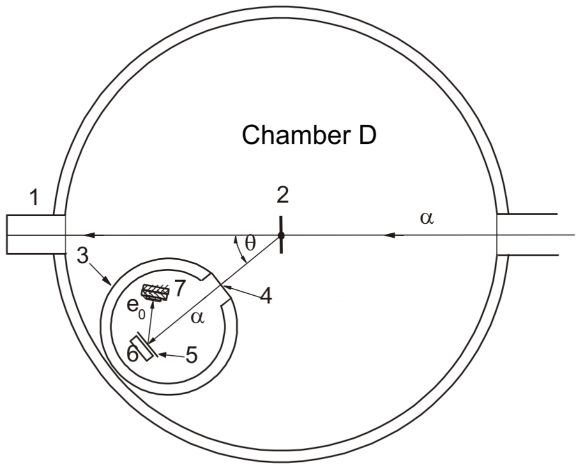

Fig. 1. Experimental setup: (*1*) Faraday cylinder, (*2*) scatterer, (*3*) measuring chamber, (*4*) input window of the measuring chamber, (*5*) target, (*6*) α-detector, (*7*) electron detector (MCP)

e_0-electron emergence is a sudden appearance of a charge ΔZe near the target surface, when a charged particle flies through it. In its turn, this charge is generated as a result of the atomic ionization by charged particles.

In work [2], we have established that the yield of e_0-electrons Y_{e_0} is proportional to $E_\alpha^{-1/2} \sim v_\alpha^{-1}$ for several groups of α-particles with different energies, which are emanated at the ^{226}Ra nucleus decay. By the e_0-electron yield, we mean the average number of emitted e_0-electrons per one incident α-particle. However, those groups of ^{226}Ra-emanated α-particles turned out close by energy, and, to check the energy dependence of e_0-electron yield in a wider energy range, we carried out the researches making use of an α-particle beam generated by a U-120 cyclotron at the Institute for Nuclear Research of the National Academy of Sciences of Ukraine.

2. Experimental Installation

The scheme of the installation used for studying the dependence of the yield of e_0-electrons emitted from the target surface on the energy of α-particles bombarding it is shown in Fig. 1. A beam of α-particles accelerated in the U-120 cyclotron to an energy of 27.2 MeV passed through an aperture in vacuum chamber D and became suppressed in Faraday cylinder *1*. The current of the latter was integrated and further used as an exposure measure at measurements. At the center of chamber D, there was mounted scatterer *2*. A beam of α-particles scattered by the scatterer at the angle $\theta = 40°$ from the primary-beam direction entered into measuring chamber *3,* totally located in chamber D. Chamber *3* prevented detectors from being bombarded by plenty of scattered α-particles and electrons. Nevertheless, the background signal in the measuring chamber given by scattered electrons remained so high that it was impossible to carry out measurements. Therefore, input window *4* in the measuring chamber was closed by an aluminum foil, the main purpose of which was to protect the internal volume of the chamber against a high-intensity flux of low-energy electrons which arises as the primary beam of α-particles passes through scatterer *2*.

Further, α-particles reached target *5* (an aluminum foil of 10 μm in thickness), passed through it, and were registered with the help of α-detector *6*. When an α-particle entered into the surface of target *5*, there were generated near-zero-energy, e_0, and fast, e_f, electrons. These electrons were registered by MCP detector *7* (a chevron composed of two microchannel plates (MCPs)) placed at a distance of 4 cm from target *5*. To eliminate the influence of electrons scattered by the internal surface of measuring chamber *3*, a cylindrical diaphragm was mounted on the surface of MCP detector.

3. Experimental Procedure

In order that the α-particles that bombard target *5* have various energies, either a thin carbon film or a titanic foil of 10 μm in thickness was placed as a scatterer at the center of chamber *D*, at the path of the primary α-particle beam. In the case of carbon target, four peaks with different energies were observed in the spectrum: one peak given by the elastic scattering and two peaks given by the inelastic scattering of α-particles by the carbon target, and one peak given by protons emanated in the (αp)-reaction. If a titanic target was installed, only the elastic scattering peak was observed. To broaden the energy spectrum of α-particles bombarding target *5*, aluminum absorbers of 10, 26, or 40 μm in thickness, which shifted the energy spectrum of α-particles by different values, were mounted on input window *4* of the measuring chamber.

Dependence of the registration probability R_{e_0} and the e_0-electron yield Y_{e_0} on the α-particle energy

E_α, MeV	v, 10^9 cm·s^{-1}	R_{e_0}, 10^{-2}	Y_{e_0}
4.7	1.51	–	7.0
5.4	1.62	–	6.6(1)
5.9	1.69	–	6.1(1)
7.6	1.92	2.38(10)	5.4(1)
9.6	2.16	2.10(16)	4.7(4)
11.3	2.34	2.10(22)	4.9(6)
12.2	2.43	1.73(16)	4.0(4)
16.1	2.80	1.79(18)	4.1(4)
17.1	2.89	1.58(8)	3.7(2)
18.2	2.97	1.46(8)	3.4(2)
20.9	3.18	1.54(10)	3.6(2)
21.7	3.25	1.42(6)	3.3(2)
22.6	3.31	1.33(6)	3.1(2)
24.3	3.43	1.22(13)	2.8(3)

The energy calibration of the α-spectrometer was carried out making use of α-lines in the spectrum of a ^{226}Ra radioactive source from the OSAI set and an elastic scattering line of cyclotron-generated α-particles by a thin carbon target. In so doing, the energy losses by α-particles in all foils and the scattering kinematics were taken into account. The calibration testified to a good linear dependence of the pulse amplitude at the output of the spectrometer path on the energy of α-particles penetrated through the input window of the α-spectrometer. The energy of α-particles bombarding target *5*, which e_0- and e_f-electrons were emitted from, were determined after the determination of the energy of α-particles entering into the detector and making allowance for the energy losses in the bulk of target *5*. All considered energies of bombarding α-particles are listed in the first column of the Table (see below).

The dependence of the e_0-electron yield on the energy of α-particles bombarding the target was studied by the (α,e)-coincidence method. The electronic circuitry was standard and identical to that used by us repeatedly for carrying out similar measurements [5, 6]. In this work, three spectra were measured: a simple α-spectrum and two (α, e)-coincidence spectra at different voltages of 0 and +24 V applied to target *5*; in the latter case, zero-energy electrons were not emitted from the target. In order to have a possibility to vary the voltage applied to the surface of target *5*, the latter was isolated from the α-detector. The voltage at the front surface of the MCP chevron was selected to be 0 V with the purpose to reduce the influence of electrons scattered by foil 4 and the internal surface of chamber *3*. The probability of e_0-electron registration was determined by the formula

$$R_{e_0} = \frac{N_{\alpha e} - N_{\alpha e_f}}{N_\alpha}, \tag{1}$$

where $N_{\alpha e}$ is the area under the α-line in the (α, e)-coincidence spectrum at the zero target voltage, $N_{\alpha e_f}$ the corresponding area at the target voltage of +24 V, and N_α the area under the α-line in the simple α-spectrum (all quantities are related to the identical measurement exposure). The difference $\left(N_{\alpha e} - N_{\alpha e_f}\right) = N_{e_0}$ determines the area under the e_0-electron line. The e_0-electron yield was determined by the formula

$$Y_{e_0} = \frac{R_{e_0}}{\varepsilon_0 \Omega}, \tag{2}$$

where the value $\varepsilon_0\Omega = 0.0044$ was found in measurements with the ^{226}Ra source [5], where we obtained the yield of 7 electrons per one registered α-particle with an energy of 4.6 MeV.

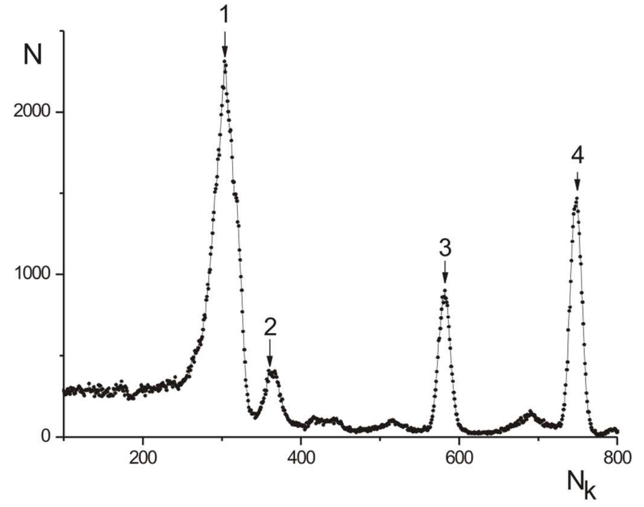

Fig. 2. Simple spectrum of α-particles scattered by a carbon target: (*1*) peak of protons generated in the C(α, p)-reaction (E_1 = 9.7 MeV); (*2,3*) peaks of inelastic α-scattering by the carbon target (E_2 = 11.3 MeV, E_3 = 17.1 MeV); (*4*) peak of elastic α-scattering by the carbon target (E_4 = 21.7 MeV). The thickness of an Al absorber is 26 μm

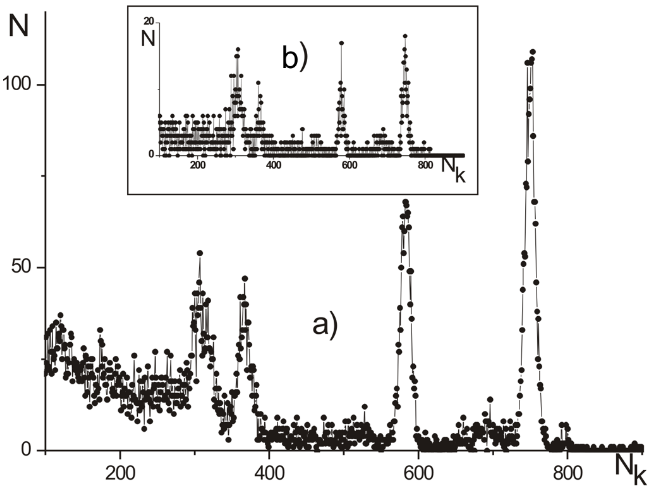

Fig. 3. Spectrum of α-particles scattered by the carbon target in their coincidences with electrons: (*a*) $e_0 + e_f, \alpha$ -coincidence spectrum at the zero voltage at the MCP surface; (*b*) e_f, α -coincidence spectrum at a voltage of +24 V at the MCP surface

In Fig. 2, a simple spectrum for α-particles, which were scattered by the carbon target and which passed through 26-μm aluminum absorber *4*, is shown as an example. Four peaks are observed in the spectrum: peak *1* is associated with protons generated in the ^{12}C(α, p) reaction, peaks *2* and *3* with the inelastic and peak *4*

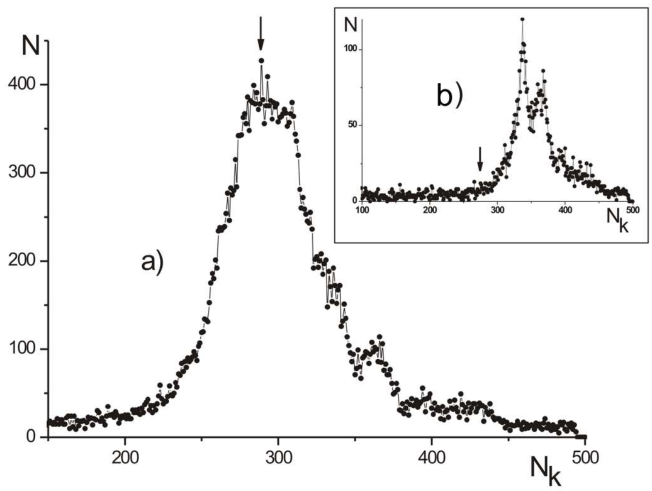

Fig. 4. Time spectra of α-particle coincidences with electrons at a voltage of 0 (*a*) and +24 V (*b*)

with the elastic scattering of α-particles. In Fig. 3, two spectra are presented: (*a*) the $e_0 + e_f$, α)-coincidence spectrum at a zero voltage at the MCP surface and (inset *b*) the (e_f, α)-coincidence spectrum if the MCP surface voltage is +24 V. Three series of similar measurements were executed in total. The exposure of coincidence spectrum measurements was 4 times as long as that for the measurement of the simple α-spectrum.

While analyzing the results of measurements, we also used the time-coincidence spectra, which are exposed in Fig. 4. Provided a zero voltage at the target surface, the time-coincidence spectrum demonstrates a wide peak with a maximum in the vicinity of the 300-th channel, which corresponds to coincidences between α-particle and e_0-electrons. The corresponding time spectrum obtained at a target voltage of +24 V is depicted in the inset. One can see from the figure that the peak associated with e_0-electrons disappeared, and only weak peaks associated with fast e_f-electrons and shifted by approximately 50 channels with respect to the e_0-electron peak survived.

The results of measurements are presented in the Table; the first column contains the considered energies of α-particles, the second one their corresponding velocities, the third one the probabilities of e_0-electron registration, and the fourth one the e_0-electron yield per one registered α-particle. The four first values of Y_{e_0} – for α-particles with energies of 4.7, 5.4, 5.9, and 7.6 MeV – were obtained from the results of measurements which had been carried out earlier making use of the ^{226}Ra source [2]. In order to connect the results of measurements carried out with the help of either a cyclotron beam or a radioactive ^{226}Ra source, the latter was mounted in chamber D at the place of scatterer *2*; afterwards, the measurements of the α-line with an energy of 7.6 MeV were carried out, and the values of the R_{e_0} and Y_{e_0} quantities were determined. The values for R_{e_0} and Y_{e_0}, which are quoted in the Table for $E_\alpha =$ 9.6 MeV, were obtained from proton measurements and recalculated for the case of α-particles.

The errors for the cited R_{e_0}-values – as such, the doubled statistical errors 2σ were admitted – are enclosed in parentheses. The obtained dependence of the e_0-electron yield of the α-particle energy is demonstrated in Fig. 5. The solid curve was drawn making use of the least squares method and corresponds to the dependence $Y_{e_0} \sim E^{-1/2}$. Hence, the yield of e_0-electrons emitted from the target surface at the bombardment of the latter by α-particles is reciprocal to their velocities in the wide energy range from 4.7 to 24.3 MeV.

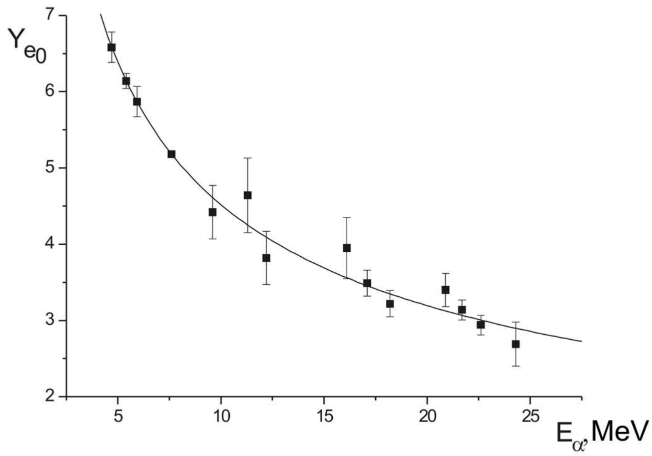

Fig. 5. Dependence of the e_0-electron yield Y_{e_0} on the α-particle energy E_α. The solid curve is drawn according to the $\chi^2_{\min}$-criterion for the dependence $Y_{e_0} \sim v^{-1}$

4. Discussion of Measurement Results

If a target is bombarded with charged particles, the emission of e_0-electrons from the target surface passes two stages in its development. A charged particle, when flying with a high velocity by an atom and being at a distance of their closest approach r_p, creates a sudden perturbation $Z_p e^2/r_p$; as a result, an atomic electron, having overcome its binding energy in the atom, transits into the continuous-spectrum range, so that the atom becomes ionized to the charge +1. Auger processes give rise to a quick occupation of the vacancy, which was formed at ionization, and the atomic charge becomes equal to ΔZe. If the atom is located near the surface, this charge exerts a sudden perturbation $\Delta Ze^2/r$ on those electrons, which are on the target surface (r being a distance between the charge and an electron on the surface); this perturbation stimulates the emission of e_0-electrons (the effect of "electron shaking" from the target surface).

The yield of e_0-electrons per one particle incident onto the target is proportional to the product of probabilities

$$Y_{e_0} \sim PW, \tag{3}$$

where P is the probability of the atom ionization in a single event of the collision with an α-particle in the near-surface layer, and W is the probability of the e_0-electron emergence. The probability of the ionization P is proportional to the squared perturbation of an atomic shell, when a charged particle flies by it, $\left(\Delta Z_p e^2/r_p\right)^2$, and the probability W to the squared perturbation $\left(\Delta Ze^2/r\right)^2$.

From the experimental data obtained in this work for α-particles and the results of our earlier works [2, 7] dealing with β- and α-particles, as well as from generalizations made in work [8] for heavy ions, it follows that the probability of the atomic ionization P not only depends on the square of the bombarding particle charge but is reciprocal to the velocity v_p. Since the yield of e_0-electrons is proportional to the probability of the ionization P, we can write down

$$Y_{e_0} = A\frac{\left(Z_p e^2\right)^2}{v_p}. \tag{4}$$

The coefficient A is identical for different particles bombarding the target, if measurements are carried out in the same experiment. For instance, in the ^{232}U-decay chain, the yield of e_0-electrons at α-decay is (40 ± 4) times larger than that obtained at the β^--decay of ^{212}Pb [6]. The same value is obtained, if one takes into account that the square of the charge ratio $(Z_a/Z_\beta)^2 = 4$ and the velocity ratio is $1.62 \times 10^9/1.65 \times 10^{10}$. For example, in this work, the ratio of the Y_{e_0}-yields produced by protons and α-particles of the same energy passing through the target should be equal to 8. Really, since the velocity of protons is twice as large as that of α-particles with the same energy, while the charge is half as large, a correction $Z_\alpha e^2/v_p = 8$ is to be introduced. Then, we obtain a value of 4.7(4) for α-particles, which agrees well with our other experimental data for α-particles. In work [8], having analyzed the yield of low-energy electrons produced by heavy ions passing through the target, the same dependence (4) was obtained. In work [8], similarly to our recalculations from the proton to the α-particle case, the yield of e_0-electrons produced by heavy ions was recalculated, making use of formula (4), to the yield produced by α-particles; in addition, experimental values for α-particles were obtained. Hence, the yield is described by formula (4) in every case, irrespective of the kind of charged particles, which allows recalculations of the e_0-electron yields from one kinds of particles bombarding the target to another to be carried out. This means that the mechanism of ionization by charged particles is the same as the mechanism of ΔZe-charge emergence after the ionization.

Among the key conditions, which are necessary for the consideration of the atomic ionization as a sudden perturbation of an electron by the charge of a particle flying beside to be valid, is a requirement that the time of the particle flight near the electron τ should be shorter than the period ω_{nm}^{-1} of the electron transition from the bound state into the continuous spectrum range, i.e. $\frac{r_{\max}}{v_p} \leq \frac{\hbar}{E_b}$. Taking into account that the transition energy (the binding energy E_b) was chosen to be 70 eV [9], and the radius of the closest approach of the particle and the electron, at which the potential energy transferred by the particle to the electron still remains higher than the binding energy, is $r_{\max} = Z_p e^2/E_b$, it turns out that, for example, for α-particles with the energy $E_\alpha = 4.7$ MeV ($v_\alpha = 1.5 \times 10^9$ cm/s), this inequality is satisfied, because $r_{\max} = 4.1 \times 10^{-9}$ cm and $\tau = 2.7 \times 10^{-18}$ s, which is less than $\omega_{nm}^{-1} = 9.4 \times 10^{-18}$ s.

For β-particles, the condition of perturbation suddenness is all the more satisfied, because, in this case, $r_{\max} = 2.1 \times 10^{-9}$ cm, which is 2 times smaller owing to the charge magnitude $Z_\beta = 1$, and the velocity of a 1- MeV electron is an order of magnitude higher than the velocity of an α-particle with an energy of 4.7 MeV.

At e_0-electron shaking, the suddenly emerged charge is at rest, so that no issues arise concerning the dependence of the effect on the velocity. At the atomic ionization, the sudden perturbation emerges at the moment, when the charged particle is flying by the electron, so that the probability of the ionization $P \sim v_p^{-1}$ and, hence, is proportional to the time of the interaction, which is as if it were composed of several interaction time intervals, and every of those intervals increases the probability of the transition. Our measurements of the Y_{e_0}-dependence on the α-particle velocity [7] gave the value of e_0-electron yield $Y_{e_0} = 5.5(12) \times 10^{-2}$ s for $v_\beta = 2.7 \times 10^{10}$ cm/s, which, despite that the particle velocity is close to that of light, is not left out of the general dependence $Y_{e_0}\left(v_\beta^{-1}\right)$. This means that the perturbation transfer speed to the electron in the atom and the escape velocity of the electron from the atom may be close to the speed of light.

In the course of measurements dealing with the electron emission from the surface, Y_{e_0}-yields can be easily separated from the contributions of other processes and, therefore, can be used for the observation of ionization in solids.

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ВИХІД e_0-ЕЛЕКТРОНІВ З ПОВЕРХНІ МІШЕНІ ПРИ БОМБАРДУВАННІ α-ЧАСТИНКАМИ РІЗНИХ ЕНЕРГІЙ НА ЦИКЛОТРОНІ У-120

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Р е з ю м е

Визначено виходи електронів близьконульової енергії e_0, які випромінюються з поверхні алюмінієвої мішені при її бомбардуванні α-частинками різної енергії з циклотрона У-120. Вимірювали α-спектри і спектри (e, α)-збігів, з яких отримували залежність виходу e_0-електронів від енергії α-частинок. Показано, що вихід e_0-електронів обернено пропорційний швидкості α-частинок, аналогічно тому, як це раніше ми спостерігали для β-частинок. Можливі причини такої залежності обговорюються.