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INVESTIGATION OF RADIATION EFFECTS CAUSED BY THE INTERACTION OF β^--RADIATION WITH POLYVINYL CHLORIDE

B. B. Kolupaev

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The dissipation of the energy of β^--radiation in polyvinyl chloride has been analyzed. The change in the properties of polyvinyl chloride under the action of β^--particles with an energy of 2.32 MeV has been characterized using the potentials of intermolecular and intramolecular interactions and the Bohr potential. The interrelation between certain micro- and macroproperties of polyvinyl chloride was determined and methods of their control with the use of β^--radiation were developed.

Introduction. Charged particles passing through a polymer exchange their energy and momentum with the energy and momentum of the polymer structural elements [1]. As a result, various defects are formed in the polymer, its equilibrium energy state is disturbed, and the macroproperties of the composite material are changed. Unfortunately, there is no a universal method for determining the number and spatial distribution of defects arising in a polymer under β^--irradiation [2]. This is especially true for flexible adhesive linear polymers, a typical representative of which is polyvinyl chloride (PVC).

Since the study of the interaction of β^--radiation with polymers is of great theoretical and practical interest, we considered the dissipation of the energy of β^--particles by the structural elements of PVC, the destruction of PVC, and the local heat release as a result of this destruction. The results obtained by us make it possible to control the macroproperties of composite materials based on flexible adhesive linear polymers with the use of β^--radiation.

Model. We have developed a model of a flexible adhesive linear polymer, taking into account the known fact that amorphous polymers consist of only fluctuating structural elements and microblocks (however, their structure can be discrete) [3]. In this case, different structural elements of these polymers have two lifetimes: in the vibrational or translational regimes they have a "settled" lifetime τ_{1i}, and concrete elements, representing composite structures that can break down or change substantially under the action of heat, β^--radiation, or other external actions have a lifetime τ_{2i}. The structural-kinetic parameter of a system (the mobility of the highest-order subsystems) is determined to a large measure by the lifetime of the structural elements forming its subsystems or by the lifetime of the lowest-order subsystems. Therefore, supermolecular structures will be defined and polymer structures will be classified using double averaging: averaging over space and time, which entirely corresponds to the ergodic principle of statistical thermodynamics [4]. Using the statistical approach (representing the polymer as a set of subsystems, beginning with parts of a macromolecule or even side groups of links and ending with large microblocks or supernets connecting the system as a whole), we will consider the relaxation spectrum of PVC in the same way as this was done for an individual macromolecule in [5]. It will be assumed that the total lifetimes $\tau_i = \tau_{1i} + \tau_{2i}$ of individual structural elements of PVC are determined by the Boltzmann relation [6], the probability that the main chain of PVC is broken under β^--irirradiation is independent of the position of the site of breaking in the polymer molecule, the mean molecular mass is fairly large, the total number of the main-chain breaks is much smaller than the total number of the monomer links, the cross links are formed in a random way under β^--irradiation, and their number is proportional to the radiation dose. In this case, the energy balance equation for interacting particles will take the form [7]

Rovno State Humanities University, 31 Ostafov Str., Rovno, 33000, Ukraine; email: Boris_Kolupaev@ukr.net.
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$$\frac{\partial E_\alpha}{\partial \tau} = \sum_{\nu=1}^{N} \sigma_{\alpha\nu} j_{\nu\alpha} - q_\alpha + q'_\alpha + q''_\alpha . \qquad (1)$$

On the basis of the above-described model of a flexible adhesive linear polymer, we will investigate the dissipation of the energy of β^--radiation in PVC as well as the necessary and sufficient conditions for its destruction, cross-linking, and local heating by high-energy β^--particles. For this purpose the potential of intramolecular interaction $U_1(r)$ in PVC will be represented in the form of the Lennard–Jones relation [8] and the potential of intermolecular interaction $U_2(r)$ will be represented in the form of the Morse relation [9]. The use of these relations is warranted by the fact that the potentials determined by them are minimum at a distance between the atoms $r = a$, behave, respectively, as the Thomas–Fermi [10] and Born–Mayer [11] potentials at a distance between the atoms smaller than r, which agrees satisfactorily with the experimental values of these potentials [12], and tend to zero at larger r.

The interaction between the atoms of the principal-valence chain of PVC will be defined as [13]

$$U_1 = 4D\left[\left(\frac{a}{r}\right)^{12} - \left(\frac{a}{r}\right)^{6}\right]. \qquad (2)$$

Using relation (2), we will determine the force confining atoms in a certain position relative to each other:

$$|F_1(r)| = -\frac{dU_1(r)}{dr} = 24D\left(2\frac{a^{12}}{r^{13}} - \frac{a^6}{r^7}\right). \qquad (3)$$

Using the extremum condition $\left(\frac{dF_1(r)}{dr} = 0\right)$, we will determine $F_{\max}$:

$$F_{\max} = \frac{24D}{b^7 a}\left(\frac{2}{b^6} - 1\right), \qquad (4)$$

where $b = 1.245$ in the case where the distance between the atoms $r_{\max} = 1.245a = ba$.

Since $2/b^a < 1$, this is an attracting force and

$$F_{\mathrm{br}} = \frac{24D}{b^7 a}\left(1 - \frac{2}{b^6}\right). \qquad (5)$$

It was established [2] that the interaction of β^--radiation with the substance increases when the electron shells of atoms overlap, with the result that there arise repulsive forces [1] and Coulomb forces [11]. This makes it possible to define the process in the form of the Bohr atomic potential [1]

$$U_2(r) = \frac{Ze^2}{r}\exp\left(-\frac{r}{a}\right). \qquad (6)$$

Accordingly, the force of interaction of a β^--particle with an atom of the principal-valence chain of PVC will be determined as

$$|F_2(r)| = -\frac{dU_2(r)}{dr}. \qquad (7)$$

Then, the condition for the possible destruction of the polymer matrix under β^--irradiation can be represented in the form

$$|F_2(r)| \geq |F_{\mathrm{br}}|. \qquad (8)$$

Consequently, the main contribution to the destruction of PVC is made by the β^--particles that will pass at a definite distance r_* from a PVC atom. The value of r_* will be determined from condition (8) in the first approximation:

$$r_* \le \left(\frac{Ca}{D}\right)^{1/2}, \tag{9}$$

where $C = Ze^2b^7/24\left(1 - \frac{2}{b^6}\right)$ is a constant for a given atom.

Macromolecules of PVC can be cross-linked under the action of high-energy β^--particles [2]. It is significant that chemical-bond forces arise when the distance between the atoms of macromolecules is of the order of several angstroms [9]; these forces are of importance in the defect formation [8]. According to the above-indicated assumption, the potential energy of interaction between the atoms of the side groups of the neighboring molecules can be approximated by the Morse potential [9]

$$U_3\,(r) = U_{\max}\left\{\exp\left[-\,2\gamma\,(a - r_0) - 2\exp\left[-\,\gamma\,(a - r_0)\right]\right]\right\}. \tag{10}$$

Considering the atoms of the side groups of the PVC macromolecules as isotropic oscillators, we will estimate the frequency ω of their vibrations in the region $0 \le a \le r_1$ corresponding to the ultimate strength of the model selected, i.e., to the maximum force

$$\left| F_3\,(r) = -\frac{dU_3\,(a)}{da} \right| .$$

As a result, we obtain that

$$\omega = \left(\frac{2K_1\,(a)}{m_i}\right)^{1/2}, \tag{11}$$

where $K_1(a) = \left(\frac{d^2U_3(a)}{da^2}\right)_{a=r}$ decreases monotonically from infinity to zero, taking, at $r > r_0$, imaginary values. Differentiating (10) with respect to a two times and assuming that $a - r_0 = \xi$, we obtain

$$K_1\,(a) = 2U_{\mathrm{m}}\,\gamma^2\,[2\exp\,(2\gamma\xi) - \exp\,(-\,\gamma\xi)]\,. \tag{12}$$

Thus, at $\xi = 0$

$$K_1\,(a) = 2U_{\max}\,\gamma^2, \tag{13}$$

and at $\xi = \frac{1}{\gamma}\ln 2$, corresponding to $a = r_1$, $K_1(r_1)$ turns to zero and then takes negative values. Consequently, the frequencies of vibrations of the atoms of the side groups of PVC macromolecules range, depending on the intermacromolecular distance, from $\omega_{\max}$ to zero in accordance with relation (11). In this case, the value of the impact parameter of a β^--particle changes and the force of the interaction of this particle with an atom of the side group of a macromolecule changes sign [2]. At first a β^--particle and an electron cloud repel one another, and then they displace and attract due to the formation of an induced positive charge that is neutralized then. Consequently, a β^--particle behaves, when passing through the PVC, as a source of an electromagnetic field exciting the corresponding vibrations of the structural elements of the polymer matrix ($\omega = v/a$). In this case, PVC atoms can be ionized by the field components with a frequency $\omega \ge \omega_0$. Then, according to [2], the displacement of polymer atoms relative to the corresponding site (whether it is an actual equilibrium position or not) of the pseudoequilibrium state will also change with time. It is significant that, as the energy of a β^--particle decreases in the process of its passage through the substance, initially its interaction with the acoustic vibrations of the structural elements dominates and then the interaction with the optical vibrations becomes dominant [12]. The cross section of the interaction of β^--radiation with the PVC atoms will be determined as [2]

$$G = \int_0^a \mu\pi r dr = \pi a^2 \mu \, , \tag{14}$$

where the quantity μ [13] depends on the chemical structure of the polymer. Since the vibrational spectrum of the PVC polymer chain consists of three components [14], torsional, deformation, and stretching vibrations, the atoms execute harmonic vibrations with a frequency [15]

$$\omega = \left[\frac{3 m_i c^3}{Ze^2} \left(\frac{2D\gamma^2}{m_i} \right)^{1/2} \right]^{1/2} . \tag{15}$$

Since the energy of a β^--particle is transferred most effectively to the PVC atoms under resonance conditions, we obtain, using relations (13) and (14), that

$$a = \left(\frac{Ze^2}{2D\gamma^2} \right)^{1/3} , \tag{16}$$

and the absorption energy is correspondingly equal to

$$U(\omega) = \frac{2Ze^2\omega^2}{3c^3} va \, . \tag{17}$$

Rearranging equality (17) with the use of (15) and (16), we obtain

$$U(\omega) = CE(\omega)^{1/2} , \tag{18}$$

where $C = \dfrac{2(Ze^2)^{4/3}}{3c^3 m} \left(\dfrac{3}{2} m \right)^{-1/2} (2D\gamma^2)^{2/3}$ is a constant for a given PVC atom. This resonance energy absorption $U(\omega)$ can lead to the destruction of PVC microblocks.

The energy transferred by a β^--particle to the medium is equal to the total work done on individual atoms of the substance, which causes a heat release. Let us determine, using relation (1), the local heating of PVC under β^--irradiation. We will assume that the amount of heat Q_1 released for a unit time in separate parts of the PVC volume is equal to

$$Q_1 = \sum_{i=1}^{N} U_i(\omega_i) \, . \tag{19}$$

If the amount of heat removed every second is equal to

$$Q_2 = g(T - T_0) \, , \tag{20}$$

on condition that $Q_1 > Q_2$, the polymer matrix of a local volume of the system can experience a thermal destruction (q''_α). Consequently,

$$\sum_{i=1}^{N} U_i(\omega_i) = g(T - T_0) + q''_\alpha . \tag{21}$$

It was established that the microdefects formed under β^--irradiation cause a nonuniform absorption of β^--rays and are responsible for the differences between the heat-conductivity coefficients of microvolumes of the medium, i.e., they change the properties of the system [16]. In an PVC sample exposed to β^--irradiation, $T_{\max}$ arises at the boundary of formation of a new phase in the form of a boundary layer. In the process of irradiation of PVC by β^--particles, $T_{\max}$ as well as the amount of heat Q_1 released in the boundary layer increase. It will be assumed that, in this case, the amount of heat Q_2 removed from the source due to the heat conduction is equal to

$$Q_2 = -\operatorname{div}(\lambda_1 \operatorname{grad} T) . \tag{22}$$

Then, for the one-dimensional case, on condition that the system is in the quasi-equilibrium state, we obtain [17]

$$\sum_{i=1}^{N} U_i(\omega_i) = q''_\alpha + Q_1 - \operatorname{div}(\lambda_1 \operatorname{grad} T) . \tag{23}$$

In our experiment, the flux of β^--particles was perpendicular to the surface of a sample with an unbounded area ($d >> h$). Consequently, (23) can be rewritten as

$$\sum_{i=1}^{N} U_i(\omega_i) = -\lambda_1 \frac{d^2T}{dx^2} \tag{24}$$

or, on integration with account for the boundary conditions (at $x = h$ and $x = 0$, $T = T_0$, and at $x = l$, $T = T_{\max}$) and the heat-flow continuity, we obtain

$$T_{\max} - T_0 = \sum_{i=1}^{N} U_i(\omega_i) \frac{l^2}{2\lambda_1} . \tag{25}$$

Consequently, the local heating of a PVC sample is determined by the state of the interphase boundary and by the β^--radiation energy absorbed by the system.

Experimental. We investigated the C-65 PVC of molecular mass $1.4 \cdot 10^5$ obtained by slurry polymerization and purified from a solution [18]. Samples used in investigations were prepared in the T–p regime at $p = 10^7$ Pa and $T = 403$ K in the form of disks of thickness $(10–12) \cdot 10^{-6}$ m and diameter $7 \cdot 10^{-2}$ m. The thermophysical properties of the material were investigated using a λ-calorimeter [13], its IR spectrum was measured in the frequency range 400–4000 cm^{-1} on a Specord-75IR spectrometer connected to a personal computer [18]. The differential thermal analysis of the polymer and its thermogravimeter analysis were performed using a Paulic–Paulic–Erdei derivatograph [13]. The β^--radiation sources were ${}_{91}Pa^{234}$, ${}_{38}Sr^{90}$ [18], and a standard radioactive solution of K^{42} (technical instructions 1050) with a nominal specific activity of 10^5 decay·sec^{-1}·g^{-1}.

Results and Discussion. According to the above-described model, the transfer of the β^--radiation energy in the PVC will be represented as the energy exchange between the atoms of macromolecules, coupled by the principal-valence forces, and (or) the atomic groups that are not incorporated into the main chain as well as between the neighboring macromolecules. In this case, the linear dimensions of bonds are as follows: $1.54 \cdot 10^{-10}$ m for the C–C bond, $1.08 \cdot 10^{-10}$ m for the H–H bond and $1.74 \cdot 10^{-10}$ m for the H–Cl bond. The results of calculations of the main characteristics of the interaction of β^--radiation ($E_{\max} = 2.32$ MeV) with the PVC are presented in Table 1. The coefficient of overlapping (μ) was calculated on the basis of the representations of [19], according to which the volume of an atom represents a sphere with an intermolecular radius R. If this atom is chemically bonded to other atom, these

TABLE 1. Energy Losses and Other Characteristics of Interaction of β^--Radiation with PVC

Atom	$l_0 \cdot 10^{-10}$, m	$L \cdot 10^{-10}$, m	$A \cdot 10^{-2}$, $m^2 \cdot sec^{-1}$	$\varphi \cdot 10^{-2}$, m	Collisions		Bremsstrahlung radiation
					elastic	inelastic	
					$\Delta E \cdot 10^{-24}$, N·m	$\Delta E \cdot 10^{-22}$, N·m	$\Delta E \cdot 10^{-23}$, N·m
Gas							
H	2	12	0.4	6	$4.0 \cdot 10^{-2}$ $^{*}2.0 \cdot 10^{1}$	$3 \cdot 10^{-2}$	$8 \cdot 10^{-3}$
Cl	14	48	1.4	40	$8.0 \cdot 10^{-1}$ $^{*}8.0 \cdot 10^{2}$	$6 \cdot 10^{3}$	$7 \cdot 10^{2}$
C	4	12	4.0	20	$2.0 \cdot 10^{-1}$ $^{*}2.0 \cdot 10^{1}$	$1 \cdot 10^{2}$	$2.0 \cdot 10^{1}$
PVC							
H—H	3	10	0.5	7	3.0 $^{*}3.6 \cdot 10^{2}$	1	2
C—C	80	340	13.0	36	$2.4 \cdot 10^{2}$ $^{*}6.0 \cdot 10^{4}$	$5 \cdot 10^{2}$	$2 \cdot 10^{3}$
H—Cl	100	500	19.0	44	$8.0 \cdot 10^{2}$ $^{*}1.0 \cdot 10^{4}$	$4 \cdot 10^{3}$	$2 \cdot 10^{4}$

*Slow β^--particles.

neighboring atoms cut a part of the sphere (a spherical segment) from it because the sum of the intermolecular radii of bivalent-bound atoms is always larger than the length of the bond d_i. Then μ will be determined as

$$\mu = 1 - \frac{\Delta S}{S_\alpha + S_\beta},$$

where $S_\alpha = 4\pi R_\alpha^2$, $S_\beta = 4\pi R_\beta^2$, $\Delta S = 2\pi RH$, and $H = R - (R^2 + d^2 - R_i^2)/2d_i$.

Our calculations have shown that $\mu_H = 0.81$, $\mu_C = 0.86$, and $\mu_{Cl} = 0.87$. A cascade of collisions of β^--particles with PVC atoms was considered in accordance with [1, 2]. The distribution of the primary collisions along a track and the losses in the energy of the β^--particles due to the elastic collisions (fast and slow particles), the electron deceleration (excitation and ionization of the electron shells of the PVC atoms), and the bremsstrahlung radiation were determined in accordance with [20, 21].

As follows from the above-presented results, the losses and other characteristics of the interaction of β^--radiation with PVC depend on the type of bonds between the structural elements in the linear polymer system. For example, in the case where fast β^--particles are used (primary interaction acts), the losses caused by the inelastic interaction are larger by two orders of magnitude than the losses caused by the elastic collisions and by an order of magnitude than the losses caused by the bremsstrahlung radiation that is due to the H–H bonds. In the case where slow particles are used, the losses in the radiation of the H–H bonds due to the elastic collisions are larger by $\sim 10^2$ times than in the case of fast particles. Table 1 also presents the main characteristics of the interaction of β^--radiation with the structural elements of PVC. In this case, according to [6], the polymer is initially considered as a very compressed gas of isolated H, C, and Cl atoms. It is significant that an electron found in this isolated atom can escape it due to the energy transferred to it as a result of the collision with a β^--particle [2]. It follows from the results presented in Table 1 that, despite the differences between the PVC consisting of isolated atoms and the condensed PVC in interaction with β^--radiation, the total losses in the energy of this radiation are close and equal to $6.0 \cdot 10^{-19}$ N·m and $7.5 \cdot 10^{-19}$ N·m.

We now determine, using relation (9), the conditions necessary for the destruction of PVC under β^--irradiation. As follows from the calculation results, when $D_{\text{C–H}} = 8.34 \cdot 10^{-26}$ J, $D_{\text{C–Cl}} = 4.58 \cdot 10^{-26}$ J, $D_{\text{C–C}} = 12.01 \cdot 10^{-26}$ J, and $D_{\text{H–H}} \cong D_{\text{C–H}}$, for the PVC atoms the value of r_* falls within the range $0.4 \cdot 10^{-11}\ \text{m} \le r_* \le 2.4 \cdot 10^{-11}$ m. The energy of binding (D_i) of the elements of an atomic subsystem of PVC was determined by the IR-spectroscopy method [22]. It was established that the stretching vibrations of the C–Cl bonds with frequencies of 615 and 635 cm^{-1} are most intense at $r_* \le 2.4 \cdot 10^{-11}$ m, the stretching vibrations of the skeletal C–C bonds with a frequency of 764 cm^{-1} are very weak and these vibrations with frequencies of 764 and 837 are weak at $r_* \le 0.9 \cdot 10^{-11}$ m, and the deformation vibrations of C–H bonds with a frequency of 1255 cm^{-1} are intense at $r_* \le 0.4 \cdot 10^{-11}$m.

It follows from relation (15) that macromolecules of PVC can be cross-linked by β^--radiation in the case where ω falls within the range $0.5 \cdot 10^{19}\ \text{sec}^{-1} \le \omega \le 1.2 \cdot 10^{19}\ \text{sec}^{-1}$. This can take place in the case where the energy determined by (17) is equal to $0.5 \cdot 10^{-26}\ \text{J} \le U(\omega) \le 3.0 \cdot 10^{-26}$ J in the process of one interaction of a PVC atom with a β^--particle. The results obtained correspond to the statement that the main sources of such interactions are the radiation of atoms in the case of excitation of their outer-shell and inner-shell electrons [12], the nuclear processes, the radioactive decay, and the cosmic rays [2].

Using relation (28), we will determine the local heating of PVC as a result of the absorption of β^--rays with an energy of 2.32 MeV. The calculations carried out for one interaction have shown that the value of $T_{\max} - T_0$ is close to zero. However, when the condition $T_{\max} > T_0$ is fulfilled, the energy of the vibrational motion of the structure-forming elements of PVC begins to increase. This, according to relations (8) and (16), decreases the force that is necessary for structural changes in the macromolecules (destruction, cross-linking, and other defects). It is seen that at the point of the PVC polymer matrix, corresponding to a definite boundary temperature $T > T_{\max}$, there arise local changes that extend then over the whole volume of the system. Actually, it was established that the chain depolymerization accompanied by the successive separation of monomer links from the end of a macromolecule or from the sites of weak bonds is most typical for polymers of the vinyl series [14]. Our experimental investigations have shown [18] that, in the adiabatic regime, the samples investigated were heated as a result of the absorption of β^--radiation. It is significant that, as the time of β^--irradiation of PVC increases, the number of free radicals formed increases and the secondary reactions influence the further destruction of the material. It seems likely that the structural defects formed absorb the β^--radiation energy more intensely because the linearity of the dependence $Q_1 = f(t)\big|_E$ breaks down at $t \ge 3 \cdot 10^3$ sec [18].

Conclusions. Our investigations have shown that the interaction of β^--radiation (E = 2.32 MeV) with PVC can be defined using the Lennard–Jones and Morse potentials of inter- and intramolecular interaction as well as the Bohr potential. In this case, when fast or slow β^--particles are used, the losses caused by the ionization and excitation of Cl, C, and H atoms dominate. The conditions necessary and sufficient for the destruction and cross-linking of PVC macromolecules under β^--irradiation have been determined on the basis of consideration of the resonance effects arising in the PVC + β^- system. The local heating of PVC in the process of β^--irradiation is due to the interphase boundary arising as a result of the formation of defects in the system and depends on the energy of the β^--rays absorbed by the polymer. The data obtained can be used for the development of polymer materials, the structure and properties of which can be modified by β^--radiation.

NOTATION

A, diffusion coefficient, $\text{m}^2 \cdot \text{sec}^{-1}$; a, distance between the atoms at the equilibrium state, m; b, C, constants; c, velocity of light, $\text{m} \cdot \text{sec}^{-1}$; D, dissociation energy of a bond, J; d, diameter of a sample, m; d_i, length of a bond, m; E_α, energy of an α particle in the intrinsic coordinate system relative to the zero level, J; $E(\omega)$, energy of a β^--particle, J; ΔE, losses in the energy of β^--radiation as a result of its interaction with PVC, N·m; e, electron charge, C; F, force, N; $F(r)$, force of the interatomic interaction, N; G, cross section of the interaction of β^--radiation with the PVC atoms, m^2; g, coefficient of energy losses due to the heat removal, $\text{J} \cdot \text{k}^{-1}$; H, height of a segment, m; h, thickness of a sample, m; j, specific energy flux of carriers, $\text{J}/(\text{m}^2 \cdot \text{sec})$; K, quasi-elastic force coefficient, $\text{N} \cdot \text{m}^{-1}$; L, length of a polygonal line, m; l, mean free path, m; m, mass of a corresponding atom, kg; N, number of particles of a body emitting carriers reaching the α particle; p, pressure, Pa; Q, amount of heat, J; q, energy of carriers emitting by the α particle in a unit time, J; q', energy obtained by a particle in a unit time from a β^--source, J; q'', energy obtained by a particle in a unit time due to the action of internal sources; R, intermolecular radius, m; r, distance, m; r_0, distance between the centers of the interacting particles at any instant of time and at the state of equilibrium; r_*, distance from a β^--particle to a PVC atom; S, area of a segment, m^2; T and T_0, temperature of the heated regions and the thermostat (PVC sample) respectively, K; T, temperature, K; $U_1(r)$, Lennard–Jones potential; $U_2(r)$, Morse potential; $U_3(r)$, energy of interaction of side-group atoms, J; U_m, dissociation energy of a bond; $U(\omega)$, absorbed energy, J; v, velocity of travel of a β^--particle having an energy $E(\omega)$, $m \cdot sec^{-1}$; Z, atomic number; γ, constant equal to the amplitude of vibrations of interacting atoms; λ, heat-conductivity coefficient of the boundary layer, $J \cdot m^{-1} \cdot sec^{-1} \cdot K^{-1}$; μ, coefficient of overlapping; ξ, displacement of an atom from the equilibrium position, m; σ, cross section of the interaction of β^--radiation with the PVC atoms, m^2; τ, lifetime, sec; φ, average square distance, m; ω, frequency, sec^{-1}; ω_0, average frequency of vibrations of the majority of electrons in an atom, sec^{-1}. Subscripts: 0, initial value; 1, 2, ..., serial number; i, α, ν, indices characterizing a particle; max, maximum; br, break.

REFERENCES

1. N. Bohr, *Passage of Atomic Particles through Matter* [Russian translation], IL, Moscow (1950).
2. G. F. Drukarev, *The Theory of Collisions of Electrons with Atoms and Molecules* [in Russian], Nauka, Moscow (1978).
3. S. Ya. Frenkel', I. M. Tsygel'nyi, and B. S. Kolupaev, *Molecular Cybernetics* [in Russian], Svit, L'vov (1990).
4. S. Ya. Frenkel', *Introduction to the Statistical Theory of Polymerization* [in Russian], Nauka, Moscow–Leningrad (1965).
5. G. K. El'yashevich and S. Ya. Frenkel', Influence of specific polymer–solvent interactions on the phase transitions in polymer solutions, *Vysokomol. Soedin.*, **11** A, 323–328 (1969).
6. S. Ya. Frenkel', *Kinetic Theory of Fluids* [in Russian], Nauka, Leningrad (1975).
7. A. L. Fradkov, On application of cybernetic methods in physics, *Usp. Fiz. Nauk*, **175**, No. 2, 113–139 (2005).
8. *Encyclopedia of Polymers* [in Russian], Vol. 1, Sovetskaya Entsiklopedia, Moscow (1972).
9. A. A. Berlin and V. E. Basin, *Principles of the Adhesion of Polymers* [in Russian], Khimiya, Moscow (1969).
10. V. Bush and S. Caldwell, Thomas–Fermi equation solution by the differential analyzer, *Phys. Rev.*, **38**, No. 6, 1898–1902 (1981).
11. A. F. Akkerman and V. A. Botvin, *On the Interatomic Interaction Potentials Used in the Simulation of a Radiative Damage*, Preprint No. 29-76 of the Institute of High-Energy Physics, Alma-Ata (1976).
12. S. A. Pozdnev, Resonances in electron scattering by molecules, *Zh. Éksp. Teor. Fiz.*, **126**, Issue 5(11), 1051–1072 (2004).
13. B. S. Kolupaev and Yu. S. Lipatov, Investigation of the dependence of the thermal-energy transfer in linear polymers and compositions based on them depending on their microscopic properties, *Vysokomol. Soedin.*, **28** A, No. 8, 1706–1712 (1986).
14. E. N. Zil'berman (Ed.), *Preparation and Properties of Polyvinyl Chloride* [in Russian], Khimiya, Moscow (1968).
15. V. A. Kondrat'ev, *Structure of Atoms and Molecules* [in Russian], GIFML, Moscow (1959).
16. A. A. Koptelov, Calorimetric method of studying the radiative-chemical processes in condensed media, *Prib. Tekh. Éksp.*, No. 3, 157–160 (2003).
17. L. N. Novichenok and Z. P. Shul'man, *Thermophysical Properties of Polymers* [in Russian], Nauka i Tekhnika, Minsk (1971).
18. A. M. Rogalya, B. B. Kolupaev, and V. V. Shilov, Investigation of the absorption of β-emission by heterogeneous systems based on flexible-chain polymers, *Fiz. Kondens. Vysokomol. Sist.*, No. 10, 98–101 (2004).
19. G. L. Slonimskii, A. A. Askadskii, and A. I. Kitaigorodskii, On the packing of macromolecules in polymers, *Vysokomol. Soedin.*, **12**, No. 2, 494–512 (1970).
20. M. Dole (Ed.), *The Radiation Chemistry of Macromolecules* [Russian translation], Atomizdat, Moscow (1978).
21. N. F. Nelipa, *Introduction to the Theory of Multiple Scattering of Particles* [in Russian], Atomizdat, Moscow (1960).
22. Yu. Ya. Gotlib and V. G. Boitsov, *Molecular Spectroscopy* [in Russian], Izd. AN SSSR, Moscow (1963).