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RADIATIONAL SYNERGETICS: CONCEPTS AND EFFECTS

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Синергетикани радиациявий физикада замонавий трансдисциплинар фан сифатида қўллаш тартиби муҳокама қилинади. Синергетиканинг асосий тушунчалари кристалларнинг миқдори ва уларнинг сиртларида радиациявий жараёнларнинг бир қатори таърифлашда жуда яхши қўлланилиши кўрсатилган. Ёндашувнинг самарадорлиги молекуляр ионлар билан бомбардимон пайтида қаттиқ моддаларнинг сочилиш жараёнларининг таърифи ва «Фобос-Грунт» космик қурилмасининг радиациявий фалокатининг тавсифи билан намоён бўлади.

Обсуждается применение синергетики как современной трансдисциплинарной науки в радиационной физике. Показано, что базовые концепции синергетики хорошо приложимы к описанию ряда радиационных процессов как в объёме кристаллов, так и на поверхностях. Эффективность подхода продемонстрирована на примере описания процессов распыления твёрдых тел при бомбардировке молекулярными ионами и объяснения радиационной аварии космического аппарата «Фобос-Грунт».

The application of synergetics as a modern transdisciplinary science in radiation physics is discussed. It is shown that the basic concepts of synergetics are very well applicable to the description of the number of radiation processes both in the volume of crystals and on their surfaces. The effectiveness of the approach is demonstrated by the example of the description of the sputtering processes of solids under bombardment by molecular ions and of the explanation of the radiation accident of the «Phobos-Grunt» spacecraft.

I. INTRODUCTION

In the last decade, synergetics broadens its area of applications, including interaction of radiation with matter. At the present, we can already introduce non-contradictory notions, which work well for radiational synergetic effects both in bulk and on surface. Based on the fundamentals of synergetics [1-5] we can define three necessary properties of the macrosystem under the search: the large number of subsystems, N>>1; the subsystems interact with each other non-linearily (e.g autocatalytically); the openness of nonequilibrium systems, which is conditioned by radiation.

These systems exhibit the following effects: self-organization of matter in space and time; violation of chiralic symmetry at bifurcation points, caused by radiation; an enhancement of macroscopic fluctuations; the existence of prediction limit, the value of which is defined by radiational interaction; realization of continuous and discrete changes of properties.

On the basis of those concepts, we explained and predicted a number of radiation effects.

In bulk:

1) development of the theory of radiation-stimulated autocatalytic reactions and on this basis explanation, in particular, of the radiation accident of the spacecraft "Phobos-Grunt";

2) creation of a new scheme of radiation resistance of materials and instruments for terrestrial and cosmic exposure; 3) the theory of trophic defect chains.

On surface:

1) development of new unified approaches to the problem of ion sputtering, which revealed the conditions for the manifestation of various regimes (atomic, cluster) and their mechanisms (elastic displacement, thermal peak, shock wave, ionization);

(2) the special role of fractality of surfaces in the degradation properties of instrument structures (including solar cells of the third generation), technology and other aspects of radiation technology has been revealed.

For a brief illustration of the features and capabilities of radiation synergetics, we will demonstrate below the solution of only two specific problems based on it.

II. SYNERGETIC THEORY OF SPUTTERING IN THE BOMBARDMENT OF SOLIDS BY POLYATOMIC ION BEAMS.

The promising possibility of using synergetics in ion sputtering problems is connected with the fact that the synergetic approach is capable of analyzing deterministic and probabilistic processes in a unified framework [1-6]. In the case of sputtering under molecular ions, such a unified approach is especially relevant, since in this effect, as shown by experiment [7], different mechanisms simultaneously appear: elastic displacement, electronic excitation, thermal peak and shock waves.

Let us consider the bombardment of the surface of a solid by a molecular ion A_n, where n is the number of atoms in the irradiating particle [8]. When the ion A_n enters the near-surface region, the ion abruptly ("instantaneously") stops; such a stop can be considered as an "instantaneous" transfer of momentum q_i to each of the atoms in the ion, which can be modeled by a set of Einstein oscillators. According to the idea of the shake-up effect [9], the probability of disruption of j atoms out of n is defined as:

$$W(n,j)=\left\{\left|\int \psi_{ex}\left[\exp\left(i\frac{M\ \vec{v}_p\vec{r}}{\hbar}\right)\right]\psi_0 d^3r\right|^2\right\}^j . \qquad (1)$$

Here $M\vec{v}_p$ is the momentum of one atom in the ion A_n, ψ_0 and ψ_{ex} are the wave functions in the ground and excited states of the atom as a whole belonging to the A_n ion. Each of the detached j atoms is the origin of the cascade, the remaining part of the n-j A_n atoms is braked collectively and is the cause of the shock waves and the thermopeak. However, part of the j atoms of the cascade as a result of the stochastization process can lead to non-deterministic effects.

Let us consider the collision sequence of one of the j atoms. The whole process of successive collisions can be either stable or unstable, depending on whether the divergence of the scattering angle $\Delta\varphi$ decreases or increases for two close trajectories that differ from each other by $\Delta\varphi_0$ during the first scattering, which is a purely synergistic effect. After γ-scattering we have [6]:

$$\Delta\varphi_n=\Delta\varphi_0\left(\rho/R\right)^{\gamma}\equiv\Delta\varphi_0 K^{\gamma}, \qquad (2)$$

where ρ is the mean free path between scattering events, R is the doubled radius of the "scattering sphere". The splitting function of correlations by analogy with the classical Sinai billiard [6] has the form:

$$K^{-\gamma} = \exp\left(-\gamma \ln K\right) \approx \exp\left(-t / \tau_{cor}\right). \tag{3}$$

Here $\tau_{cor} = 1/\sigma N v \ln\left(\rho / R\right)$ is the correlation time, σ is the cross section for scattering by an angle φ, and N is the density of the scattering centers. Note that N is the density of atoms in a dense cascade. For simplicity, we consider the limiting case of sputtering by a completely disintegrated molecular ion, the probability of which is determined from (1) if we set $j = n$. Then we have $\tau_{cor} \sim \sqrt{E_{A(n)}}/\sqrt{n}$, i.e. the onset of chaotization is directly proportional to kinetic energy $E_{A(n)}$ of the ion and inversely proportional to the number of atoms n in the A_n ion. It is obvious that the number of atoms that have time to fly off along the surface by the elastic scattering mechanism $Y_{el} \sim \tau_{\text{cor}}$.

Atoms, sputtered by the elastic scattering mechanism carry away the energy $E_{kin}(j)$ proportional to $j\tau_{cor}$. The rest of the energy $\Delta E = E_{A(n)} - E_{kin}(j)$ will be wasted on the collective processes. To evaluate their role, we use the notions of statistical and completely statistical regimes of sputtering introduced in our work [10]. We proceed from the notion of a statistical ensemble occurring after the expiration of the time τ_{cor}, and describe it in the framework of the Fermi approach [11]. On this basis, a very important parameter in the theory of multiple production of particles, so-called statistical weight of production of n particles (atoms), is calculated

$$S_n = \left(\frac{\Omega}{8\pi\hbar^3}\right)^n \frac{dQ}{dE} \tag{4}$$

with the help of which the coefficient of sputtering in multiple (collective) processes is defined [10]:

$$Y_{st} = \sum_n n S_n \Big/ \sum_n S_n \tag{5}$$

that leads to

$$Y_{stat} \le \frac{1}{3} + \frac{\Delta E}{E_d} \ln \frac{\left(2\pi M \Delta E\right)^{1/2} \Omega^{1/3}}{2\pi\hbar}. \tag{6}$$

Here E_d is the displacement energy of the target atom, Ω is the region of the solid, where the energy of the A_n ion is released in the near-surface region. It is seen from (6) that Y_{stat} depends nonlinearly on $\Delta E = E_{A(n)} - E_{kin}(j)$. Thus, the quantity calculated from (6) determines the total yield of atoms through all nonlinear (collective) mechanisms: shock waves and a thermopeak.

It is very interesting, however, to find out the relative proportion of each of the nonlinear mechanisms. To do this, we consider another special case, when no atom is splitted off from the molecular ion (i.e., $j = 0$). Let's carry out the following argument: according to the experimental data [7], in emitted atoms there is a pronounced lateral part, the origin of which is hypothetically attributed to shock waves. Then we calculate the statistical weight of the distribution of the produced atoms only for particles moving perpendicular to the direction of motion of the irradiating molecular ion. In this case, we arrive at a two-dimensional (in the sense of geometry) situation, when the atoms are

scattered in the direction perpendicular to the axis of the cylindrical track, and a statistical equilibrium is established between them. Again, we use the formula (4), but we adapt it for the two-dimensional (in the geometric sense) case corresponding to the distribution of states in the Poincaré section and get $S_n^{(2)}$. If we denote the statistical weight for the three-dimensional (in the sense of geometry) case of the distribution of the produced particles through $S_n^{(3)}$ and calculate it by the formula (4), then for the relative fraction of atoms emitted by the shock wave mechanism, we obtain:

$$\zeta = \frac{n^{(2)}}{n^{(3)}} \approx \frac{S_n^{(2)}}{S_n^{(3)}} \approx \left(\frac{2\hbar}{\Omega^{1/3}}\right)^{\overline{n}} \frac{1}{(2\pi)^{\overline{n}/2}} \frac{\Gamma(3\overline{n}/2)}{\Gamma(\overline{n})} \frac{1}{[2M(\Delta E - \overline{n}E_d)]^{\overline{n}/2}}. \quad (7)$$

Here M is the mass of the emitted atom, $\Gamma(\cdots)$ is the gamma function, $\overline{n}$ is the arithmetic mean for the values of n corresponding to the extrema $S_n^{(2)}$ and $S_n^{(3)}$. It can be seen that the fraction of the mechanism of shock waves falls with the increase of the volume of energy release, the mass of emitted atoms, the energy of the bombarding ion, and increases with increasing displacement energy.

Accordingly, the fraction of emitted atoms by the mechanism of the thermopeak can be determined as $1-\zeta$. Note that this value, with the generally accepted heuristic description of the thermopeak [12], will be determined as follows:

$$Y_{spike} = 1 - \zeta \sim \exp\left[-\frac{const}{\breve{\Delta}E}\right]. \quad (8)$$

Here $\breve{\Delta}E$ is the remainder of the energy $E_{A(n)}$, minus the energy carried away in the elastic processes and in shock wave processes. The expression for const has a standard form for the thermopeak mechanism [12]. We note that the separation into statistical and completely statistical regimes introduced by us to describe radiation-stimulated atomic and electron emission [10] has long been observed in nuclear physics [13, 14].

It is important to specify the condition for the presence of shock wave in the sputtering fractions: $\tau_{лат}$, $\langle T_{\tilde{n}} \rangle$. The time $\tau_{лат}$ is easily estimated in the framework of known theories (see [15]). As for time $T_{\tilde{n}}$ (the lifetime of a state involving $\tilde{n}$ excited atoms from the motion of the material in the form of shock waves), an analog of this problem was studied by Smoluchowski (see [14]) in the theory of solutions and concerned fluctuations in the density of colloidal solutions. With appropriate modifications, this approach can also be used for fluctuations in momentum space.

Considering the decay of such a fluctuation simulates the process of stochastization in momentum space, when the initial state is the arrangement of momenta in the Poincaré section, and the final state is the distribution of $\tilde{n}$ states over the entire volume of the momentum space. Modifying Smoluchowski's approach (see [14]), we obtain: $T_{\tilde{n}} = (\tilde{\omega}/\tilde{\sigma}\tilde{n})/\dot{p}$, where $\tilde{\omega}$ and $\tilde{\sigma}$ is the volume and surface of the fluctuation region in the momentum space corresponding to the excitation after the molecular ion is decelerated, $\tilde{n}$ is the number of states in the momentum space corresponding to the participation of atoms in the shock waves. Note that we are talking about a part of the entire momentum space, accessible from the condition of constancy of the total excitation energy.

All this, in general, seems to us to give a scheme for describing the phenomenon of sputtering by molecular ions. We believe that in the existing works on sputtering by polyatomic ions, different fractions in the emitted atoms are actually observed [7, 16]. At the same time, we also note a series of experimental studies (see, for example, Refs. [17]), where the authors prefer only the mechanism of the thermal peak.

III. SYNERGETIC ANALYSIS OF THE RADIATION ACCIDENT OF THE PHOBOS-GRUNT SPACECRAFT

One of the most important examples of synergistic radiation phenomena in the volume of solids is undoubtedly the crash of the Russian spacecraft "Phobos-Grunt" (KAFG) [18] in near-earth orbit (~ 250–300 km). The main results of observations are as follows: after 1.7 turns in the orbit, the connection with the Earth was interrupted, and then it suddenly resumed and continued until it was finally interrupted. Preliminary analysis [18] led to the conclusion that the integrated microcircuit WS512K32V20G24M, damaged by heavy fast ions, was installed on the ship. At the same time, the ultrashort time of obtaining the "lethal dose" brought the effect of small doses out of the explanations, and the quasiperiodical switching-off of electronic equipment raised the question of the very possibility of the radiation nature of this effect.

In the framework of solving this problem, we theoretically constructed [19, 20] a possible scheme of radiation-physical processes, which allows us to understand the reason of what happened at KAFG. The proposed scheme was based on the ideas of synergetics, since it was clarified that during the proton irradiation with an energy of 10–800 MeV and at the standard impurity composition of the integrated circuit, the above mentioned principles 1) and 3) are fully realized. Particularly, it was significant the idea of implementing the following autocatalytic reactions:

$$A + 2V \underset{k_2}{\overset{k_1}{\rightleftarrows}} 3V\,, \qquad A \underset{k_2}{\overset{k_1}{\rightleftarrows}} V\,, \tag{9}$$

where A is an isolated defect, V is a bound defect. Based on the master equation, the following characteristics of the processes in the instrument were calculated: the stationary probability of generating X defects (for example, vacancies), their concentrations, realizing the extremality of this probability, their fluctuations, etc. On this basis, the possibility of catastrophic intermittent transitions from normal to abnormal regimes was shown [19, 20]. The attention was focused on the role of a catalyst in autocatalytic reactions of this type (for example, impurities of the nitrogen N realizing the Jahn-Teller effect in Si), and it was revealed an intermittency regime (from the theory of dynamic chaos) by analyzing the Lamerey diagrams, which led to the conclusion on turbulent behavior in the concentration of defects.

Thus, it became clear that the periodic on-off of the device is the intermittency mode in the defective system (Fig. 1). Note that this example itself served as an impetus to constructing [19, 20] a new theory of radiation failure of devices, applicable both under terrestrial and cosmic radiation conditions.

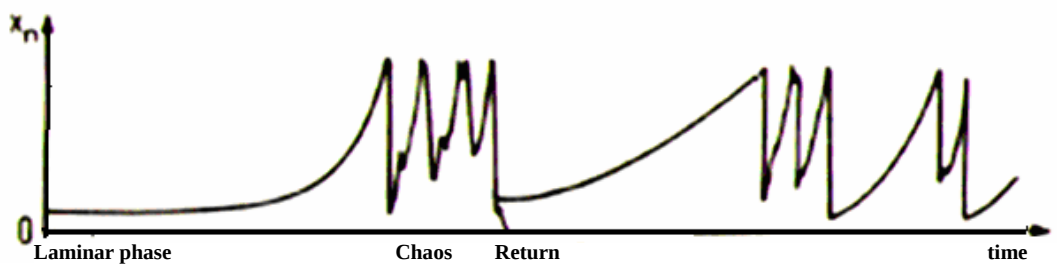


Fig. 1. Kinetics of defects accumulation in the intermitten regime, showing the coexistence of laminar and chaotic phases

IV. CONCLUSION

The results obtained by the present time show that the basic concepts of synergetics are well applicable to the description of a number of radiation processes both in the volume of crystals and on the surface. These results allow us to explain a number of paradoxical phenomena and predict new effects, which makes possible to reveal the role of radiation as a controlling parameter in self-organization of different types. The synergistic effects in Uzbekistan are also being successfully studied on the basis of kinetic equations [22, 23]. All this allows us to conclude that the intense use of synergetics approaches as a modern interdisciplinary science in solving fundamental and applied problems of radiation physics of solids is of a great promise.

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