50 Years in Physics

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Abstract

I am a Doctor of Sciences in Physics. I belong to the school of physicists established by Alexander Prokhorov–Nobel Prize Laureate in Physics. I am a Laser Physicist by education, having published over 150 papers. I graduated from Moscow Institute of Physics and Technology with High Honors in 1970. I am eternally grateful to Academician A. M. Prokhorov and Prof. A. A. Manenkov, whose influence on my scientific life has been decisive.

19 years ago, I developed an interest in Cosmology. I have been elaborating a model I dubbed World-Universe Model (WUM) and published a series of papers in the Journal of High Energy Physics, Gravitation and Cosmology WUM is a natural continuation of Classical Physics, and it can already serve as a basis for a New Cosmology proposed by Paul Dirac in 1937.

In my view, there is a principal difference between Physics and Mathematics. I am convinced that Physics cannot exist without Mathematics, but Mathematics must not replace Physics. I absolutely agree with John von Neumann who said: "*The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct, which, with addition of certain verbal interpretations describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work".*

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In 1964, I enrolled in Moscow Institute of Physics and Technology (MIPT). During the final exam on General Physics, I have prepared a report on "Why is the sky blue?" theme, based on "Light Scattering" by Leonid Mandelstam. That report has started my life-long interest in Optics.

In 1967 I have started working at Lebedev Physical Institute in the Oscillations Laboratory headed by Alexander Prokhorov. In 1970 I've graduated MIPT with M.Sc. and defended a thesis on "*Nonlinear Scattering of Light in Inhomogeneous Media*" subject. In 1974 I have obtained my PhD. Topic of the thesis: "*Investigation of Light Scattering and Laser-Induced Damage in Crystals and Glasses*".

I have been fascinated with new and original ideas in Physics. For instance, Light Scattering in the Sky based on **Fluctuations** in the atmosphere (proposed by L. Mandelstam) went against the prevailing idea of Light Scattering on **Molecules** in the atmosphere (by the great physicist Lord Rayleigh). It is worth noting that eventually Lord Rayleigh accepted the idea of L. Mandelstam!

Below, I would like to share with you some **Original Ideas**, which I proposed and developed in 50 years of my scientific life.

1. Interaction of High-Power Laser Radiation with Crystals and Glasses

Nonlinear Light Scattering

My investigations of a Laser-Induced Damage (LID) in transparent dielectrics showed that there is a correlation between Light Scattering (LS) in materials and their LID threshold: the higher the intensity of LS, the lower the LID threshold. It follows that different kinds of inclusions and defects inside of materials are responsible for LS and LID. Then, LS can be used as a Measure of optical purity of transparent dielectrics. Moreover, at laser radiation intensities I close to LID threshold I_1: $I \lesssim I_1$ the nonlinear dependence of LS intensity from I was observed [1]. To explain this new effect, I developed a theory of nonlinear LS in inhomogeneous media considering various mechanisms of the nonlinearity of the refractive index: optical Kerr effect, heating, and electrostriction. Analytical

expressions for LS intensity and spectrum were obtained. The observed experimental results were in good agreement with the developed theory [2], [3].

Thermal Instability as a Principal Concept in Laser-Induced Damage

The concept of thermal instability in LID associated with absorbing inclusions has been proposed in our work [4]. It has been shown that the heating of inclusions produced by laser radiation has a character of thermal explosion at intensities higher than some critical value. Local temperature in the inclusion region turns out to be very high ($\sim 10^4 K$), giving rise to thermal radiation with a maximum intensity in the UV spectral region. This radiation being absorbed by the ambient matrix leads to its photoionization. As a result, absorption spreads to the inclusion vicinity, which was primarily transparent. A detailed analysis of these processes [5] indicates that laser heating of the inclusions and accompanying photoionization encourage thermal instability in the matrix, resulting in the catastrophic macrodamage. The critical intensity that gives rise to this instability corresponds to $\boldsymbol{I_1}$. The observed experimental results were in good agreement with the developed theory [4], [5].

It is worth noting our work went against the prevailing linear theory of laser-induced thermal destruction of transparent dielectrics containing absorbing inclusions. That theory explained the role of foreign inclusions in LID of transparent materials, but it could not explain a catastrophic behavior of a process of macrodamage development inside of transparent dielectrics under laser irradiation.

The obtained scientific results were used in the development of the High-Power Laser Optics made of extremely pure Fused Silica and became a chapter in Cycle of Research on "*Laser-Induced Damage to Glasses*" that won the prestigious Komsomol award in 1979.

2. Interaction of High-Power Laser Radiation with Optical Polymers

Accumulation Effect in Laser-Induced Damage

At the laser radiation intensity below the critical value for the thermal instability, catastrophic macrodamage does not appear after a single shot, but irreversible changes may occur in both the inclusion itself and the ambient matrix. Various kinds of defects, e. g. color centers and radicals, can be produced under laser irradiation, which might absorb the radiation of successive laser pulses. In other words, the effective area and absorption coefficient of both the inclusion and ambient matrix increase from pulse to pulse. This accumulation of irreversible changes may produce thermal instability and catastrophic damage at some critical pulse $\boldsymbol{N}$ that depends on the laser radiation intensity $\boldsymbol{I_N}$ below single-shot LID threshold $\boldsymbol{I_1}$. The above consideration indicates that the thermal instability is the key process in both the single-shot and multi-shot LID, and that multi-shot damage characteristics can be determined by laser-induced defect generation mechanism.

In 1976, a novel method to study multi-shot LID in Optical Materials at $\boldsymbol{I < I_1}$ was proposed. The method was based on the observation of nonlinear light scattering from a region of interaction of laser radiation and optical materials. Utilizing this method, we discovered the accumulation of irreversible changes in the bulk of sapphire crystals and a number of glasses upon their exposure to a series of consecutive laser shots of Ruby laser with $\boldsymbol{I < I_1}$. The accumulation process results in the appearance of visible damage after the last shot [6].

The accumulation effect in LID of polymer materials has been revealed and studied in our works (see, for example [7-16]). This effect is the most pronounced one in standard transparent polymers. It can be observed at $\boldsymbol{I \lesssim 0.01\, I_1}$. This fact was the main obstacle for applications of polymer materials in Laser Optics. The purposeful experiments carried out with different optical polymers allowed us to

reveal their LID mechanism and propose efficient methods to increase a multi-shot damage threshold I_N up to I_1. We achieved this result by physical modification of polymer matrix with Low-Molecular Additives (LMAs), which significantly change viscoelastic properties of polymer matrix and provide efficient vibrational cross-relaxation from macromolecules to LMAs.

Role of Viscoelastic Properties of Polymers in Laser-Induced Damage

It is well known that polymers possess a thermal expansion coefficient that is much larger than the coefficient of crystals and glasses. At the same time, a tensile strength of polymers is much smaller than tensile strength of crystals and glasses. Our theoretical analysis of combined equations of thermal conductivity and elasticity for an absorbing inclusion in polymer matrix shows that the tensile strength of the matrix due to thermoelastic stresses can be achieved at the inclusion heating about 100 °C . It means that I_1 of transparent polymers should be much smaller than I_1 of crystals and glasses that is observed in experiments. On the other hand, LID mechanism of polymers should depend on their viscoelastic properties. The influence of thermoelastic stresses can be taken down by changing viscoelastic properties of the matrix towards reducing brittleness and increasing plasticity, which can be attained by introducing plasticizers in polymers. Using this approach, we were able to increase I_N of transparent polymers in our experiments [7], [8], [9].

Decisive Role of Vibrational Cross-Relaxation

A very promising method of defect formation inhibition is physical modification of a material by introducing special additives which reduce the lifetime of energy states of macromolecules from which the defects (e. g. radicals in polymers) are developed. I proposed this method in 1982 [10], and it has been realized for optical polymers and turned out to be exclusively effective and resulted in a more than 100-fold increase of I_N [11- 16]. This result is intriguing since radicals in polymers are developing from vibrational states of macromolecules, which should have long enough relaxation time that the transfer of vibrational energy from the macromolecule to LMA could be efficient. This idea went against the commonly accepted opinion that the relaxation of vibrational excited states in Solid States has a very high rate and consequently very short relaxation time.

The proposed method based on vibrational cross-relaxation is very efficient not only for LID of optical polymers. We found significant (more than 10-fold) increase of polymers' resistance to the high-power UV and gamma-radiation [17] and lasing and bleachable dyes impregnated into laser-resistant polymer matrix [18], [19]. In our opinion, this method can be used for increasing thermostability, photostability, gamma-stability, and laser-stability of different materials used in various applications. Based on the conducted research the following results were obtained:

- New class of physically modified optical polymers for laser applications was created [20];
- Efficient plastic-host dye lasers are used for medical applications [21];
- Polymer laser optical elements were developed for various applications [22];
- Doctor of Sciences dissertation "*Interaction of High-Power Laser Radiation with Optical Polymers*" was defended at the Institute of General Physics headed by A. Prokhorov in 1987.

3. Solid State Physics

Diffusion of Point defects Participating in Solid-Phase Chemical Reactions

A problem of trap diffusion , that is a diffusion of first component in solid states participating in solid-phase chemical reaction with motionless second component, is solved in our work [23]. Time

dependences of the reaction front displacement X_f and its steepness $(dC/dX)_f$ are determined analytically for $N_0 \ll C_0$ and numerically for all relations of N_0 and C_0 (N_0 and C_0 are the equilibrium concentration of the first component and the initial concentration of the second component, respectively). It was shown that the displacement of the chemical reaction front obeys the diffusion law having a coefficient of the reaction-front displacement D_f equals to: $D_f = 2\frac{N_0}{C_0}D$. This coefficient in its essence is considerably different from the diffusion coefficient of the first component D by the fact that D_f depends on the ratio of N_0 and C_0 concentrations. In literature, this fact has not been given proper consideration, and D_f parameter has been identified with D. Dependence of X_f vs. C_0 and time t is confirmed for oxygen annealing of corundum crystals doped with titanium by measurements for the $Ti^{3+} \rightarrow Ti^{4+}$ transition-front displacement as a function of initial concentration of Ti^{3+}, partial oxygen pressure, and temperature [23].

Analogous experiments were performed with optical polymers impregnated with bleachable dye for Nd-laser: we observed a front of the discolored dye as a result of dye molecules reaction with radicals caused by oxygen penetrating into the polymer matrix from the environment. Based on the obtained results we conclude that, for high stability of dyes in polymers during long-term use and storage, the polymer synthesis must be performed under conditions that exclude radical products [19].

Nonlinear Diffusion of Low-Molecular Additives in Polymers

Low-Molecular Additives (LMAs) introduced into polymers can evaporate from the polymer matrix during long-term operation and storage. Then, to create polymer materials that are efficient in high-power lasers for a long time, it was necessary to find out what requirements should be met by LMAs that prevent evaporation. Previously, it was believed that LMAs introduced into a polymer should have the lowest possible diffusion coefficient. This conclusion was based on solving the diffusion equation provided that the diffusion coefficient of LMA: $D_0 = const$ and that the evaporation coefficient of LMA from the polymer surface is quite large, such that the Bio parameter: $Bi > 100$. It was shown that the relative change in the sample mass $p(t)$ due to evaporation of LMA depends on D_0 and changes over time as $p(t) \sim \sqrt{t}$.

However, in practice, both of these conditions are usually not met: D_0 depends on concentration of LMA in the polymer and the Bio parameter: $Bi < 100$. For an adequate description of the evaporation of LMA from the polymer, it is necessary to solve the nonlinear diffusion equation considering the finiteness of Bi . The theoretical analysis of this equation showed that at the initial stage $p(t)$ is determined by an evaporation coefficient from a polymer surface and $p(t) \sim t$ [24]. These results are principally different from the commonly accepted results described above.

Study of the characteristics of the nonlinear diffusion of LMAs in polymers was carried out by using samples of PMMA with 20% ethanol, which is a readily-evaporated plasticizer. Experiments have shown that the evaporation of ethanol at the initial stage is well described by our formula. The calculated value of $Bi = 33.6$ confirms our nonlinear approach to this physical phenomenon. Thus, LMA introduced into the polymer for ensuring high-power laser resistance for a long time, must have the lowest possible evaporation coefficient from the polymer surface [24].

Theory of Free Volume in Polymers

The free volume concept in condensed media proves to be very useful for a theoretical description of many processes occurring in liquids and polymers: LMA diffusion, thermal conductivity, thermal expansion that is mostly due to higher free volume. Williams, Landell, and Ferri developed the theory

of polymer viscoelastic properties on the basis of the Doolittle empirical equation, involving viscosity $\eta(T)$ and specific free volume $f(T)$ through the following ratio: $\eta(T) = aexp[b/f(T)]$, where a and b are constants. Assuming that $b = 1$ and a free volume depends linearly on T: $f(T) \sim T$, they obtained a free volume at glass transition temperature T_g: $f(T_g) = 0.025$. It worth noting that the experimentally observed dependence is $f(T) \sim T^{3/2}$ and $f(T_g) = 0.1 - 0.15$, if calculated using the data on compressibility [25]. All of this suggests that the polymer free volume theory is far from complete and requires new concepts to be developed.

Usually, all theories of condensed media are based on structural elements, which behave like oscillators with small value of damping factor when affected by periodic force. It is a good approach to the medium, like crystal. We propose to consider the medium, like polymer, that consists of structural elements, which behave like oscillator with very high value of damping factor. We named them "relaxators". Their motion is aperiodic (nonoscillatory) with the minimal relaxation time. Then, we consider fluctuations of relaxators in the medium. According to the fluctuation-dissipation theorem, involving the fluctuation of physical quantities and the dissipative properties of the system externally affected, we find the mean-square value of the fluctuation deviation of the relaxator from the equilibrium [25]: $X^2 = k_B T/K$, where k_B is Boltzmann constant and K is the elasticity coefficient. The mean-square value of the fluctuation volume of relaxator v_f is proportional to: $v_f \sim X \times Y \times Z \sim T^{3/2}$ and the free volume of polymer V_f equals to: $N_f = Nv_f$, where N is the number of relaxators. It follows that $V_f \sim T^{3/2}$ is in agreement with experimental results. The calculated value of $f(T_g) = 0.124$ is in good agreement with the experimentally measured values using the data on compressibility [25].

Theory of Relaxation Spectra

Relaxation spectroscopy refers to the response of a material to any external periodic force field (electric, magnetic, mechanical, etc.) and the observation of the absorption of the energy of the field, depending on its frequency, which is the relaxation spectrum. The absorption bands in the relaxation spectrum are due to the resonant interaction of the force field with the structural elements of the material and characterize their molecular mobility at a fixed temperature. Using the principle of temperature-time equivalence, the temperature dependences of the absorption of field energy at fixed frequencies are usually studied, since this method is more easily realized experimentally.

Before my work, the relaxation spectra were described on the basis of the following concept of the thermal motion of structural elements. The motion occurs through the transition of elements from one equilibrium position to an adjacent one. The rate of such a transition depends on the height of the potential barrier U separating two neighboring equilibria, the volume of the element v_c and temperature T. Each element is characterized by the relaxation time, which, according to Frenkel and Eyring, has the following temperature dependence [26]: $\tau = Bexp(U/k_B T)$, where B is the preexponential coefficient associated with the activation entropy. However, attempts to apply this dependence in the analysis of relaxation spectra in a number of cases lead to the values of the parameters U and B, which have no physical meaning. Thus, in PMMA for the α-process, values $U = 228kcal/mol$ and $B = 10^{-130}s$ are obtained and a strong dependence of U from T is observed.

In contrast with the "Energetical" approach considered above, in which τ is determined by U, we developed a "Spatial" approach, in which τ is determined by a specific available fluctuation volume f_d. In our work [25], we developed a model of a condensed medium, consisting of structural elements – relaxators. The thermal movement of relaxators occurs as follows: due to thermal fluctuations, the

elements are removed from the equilibrium positions and return to them after relaxation time $\tau = \tau_0 \exp(f_d^{-1})$, where τ_0 is the minimum relaxation time. The value of f_d is based on the fluctuation-dissipation theorem [25]. The calculated theoretical results for β-process in PMMA are in good agreement with the experimentally found values [26].

The obtained scientific results were used in the development of the Polymer Passive Q-switch for the Laser Range Finder that was working for 11 years in the temperature range: ± 50 ℃ and stored for 13 years in the range: ± 65 ℃.

4. Hypersphere World-Universe Model

Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.

Albert Einstein

Essence of World-Universe Model (WUM)

The main ideas of WUM, which is an alternative to the prevailing Big Bang model, are as follows [27-31]:

- The Finite World is a 3D Hypersphere of the 4D Nucleus of the World, which is 4D ball expanding in the fourth spatial dimension. All points of the Hypersphere are equivalent; there are no preferred centers or boundaries of the World;
- The Universe is responsible for the creation of Dark Matter (DM) in the 4D Nucleus of the World. Dark Matter Particles (DMPs) carry new DM into the World. Luminous Matter is a byproduct of DMPs self-annihilation. DM plays a central role in creation and evolution of all Macroobjects;
- WUM introduces Dark Epoch (spanning from the Beginning of the World for 0.45 billion years) and Luminous Epoch (ever since, 13.77 billion years). Transition from Dark Epoch to Luminous Epoch is due to Rotational Fission of Overspinning DM Supercluster's Cores and self-annihilation of DMPs;
- The Medium of the World, consisting of protons, electrons, photons, neutrinos, and DMPs, is an active agent in all physical phenomena in the World. Time, Space and Gravitation are closely connected with the Impedance, Gravitomagnetic parameter, and Energy density of the Medium, respectively. It follows that neither Time, Space nor Gravitation could be discussed in absence of the Medium. WUM confirms the Supremacy of Matter postulated by Albert Einstein: "*When forced to summarize the theory of relativity in one sentence: time and space and gravitation have no separate existence from matter*";
- Macroobjects of the World possess the following properties: their Cores are made up of DMPs; they contain other particles, including DMPs and Ordinary Particles, in shells surrounding the Cores. Macroobjects' cores are essentially Dark Matter Reactors fueled by DMPs. All chemical elements, compositions, substances, rocks, etc. are produced by Macroobjects themselves as the result of DMPs self-annihilation;
- WUM is the only cosmological model in existence that is consistent with the Fundamental Law of Conservation of Angular Momentum;
- WUM revealed the Inter-Connectivity of all Primary Cosmological Parameters;
- Fermi Bubbles are DMPs' clouds containing uniformly distributed Dark Matter Objects, in which DMPs self-annihilate and radiate X-rays and gamma rays;

- WUM is based on two parameters only: dimensionless Rydberg constant α (later named Fine-structure constant) and time-varying Quantity Q that is, in fact, the Dirac Large Number and a measure of the Worlds' curvature in the fourth spatial dimension and the Age of the World.

Predictions of WUM

In 2013, WUM revealed a self-consistent set of time-varying values of Primary Cosmological Parameters of the World: Gravitation parameter, Hubble's parameter, Age of the World, Temperature of Microwave Background Radiation, and concentration of Intergalactic plasma. Based on the inter-connectivity of these parameters, WUM solved the Missing Baryon problem and predicted the values of the following Cosmological parameters: gravitation G, concentration of Intergalactic plasma, and the minimum energy of photons [27], which were experimentally confirmed in 2015 – 2018. "*The Discovery of a Supermassive Compact Object at the Centre of Our Galaxy*" (Nobel Prize in Physics 2020) made by R. Genzel and A. Ghez confirms one of the most important predictions of WUM in 2013: "*Macroobjects of the World have cores made up of the discussed DM particles. Other particles, including DM and baryonic matter, form shells surrounding the cores*" [27].

WUM does not attempt to explain all available cosmological data, as that is an impossible feat for any one manuscript. Nor does WUM pretend to have built an all-encompassing theory that can be accepted as is. The Model needs significant further elaboration, but in its present shape, it can already serve as a basis for a new Physics proposed by Paul Dirac in 1937. The Model should be developed into a well-elaborated theory by entire physical community.

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