Національний Педагогічній Університет
імені М. П. Драгоманова

Міждисциплінарний науково-дослідний центр
складних систем

Dragomanov National Pedagogical University

Interdisciplinary research center
for complex systems

МІЖДИСЦИПЛІНАРНІ ДОСЛІДЖЕННЯ СКЛАДНИХ СИСТЕМ

INTERDISCIPLINARY STUDIES OF COMPLEX SYSTEMS

Номер 1 • Number 1

Київ • Kyiv
2012

УДК 001.5
ББК 72
М57

Свідоцтво про державну реєстрацію друкованого засобу масової інформації
серія КВ № 19094-7884Р від 29 травня 2012 року

Рекомендовано до друку Вченою радою Національного педагогічного університету
імені М. П. Драгоманова (протокол № 3 від 23 жовтня 2012 року)

М 57 Міждисциплінарні дослідження складних систем : [збірник наукових праць]. — Номер 1. — К. : Вид-во НПУ імені М. П. Драгоманова, 2012. — 120 с.

УДК 001.5
ББК 72

Interdisciplinary Studies of Complex Systems
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Від головного редактора

Міждисциплінарні дослідження стали характерною рисою сучасної науки. Синтез ідей і методів різних, інколи дуже віддалених, галузей виявляється плідним як у фундаментальній, так і в прикладній науці, приносить нове знання і породжує нові технології.

Національний педагогічний університет імені М. П. Драгоманова не є винятком, тому міждисциплінарні дослідження також відіграють у ньому значну роль. Одним із основних завдань педагогічного університету сьогодні є ознайомлення майбутніх учителів із сучасними науковими теоріями та відкриттями, що формують нову наукову парадигму та науковий світогляд загалом. Питання, які сучасне життя ставить перед наукою, вимагають кооперації вчених різних спеціалізацій. Дослідження складних систем, — незліченного класу об'єктів, що нас оточують, від атомів до Галактик — вимагають об'єднаних зусиль не тільки математиків, фізиків, біологів, але й психологів, соціологів, лінгвістів, і є нагальними завданнями сучасної науки.

Усвідомлюючи важливість міждисциплінарних досліджень, ми створили Міждисциплінарний науково-дослідний центр складних систем, який має на меті активізацію взаємодії вчених різних галузей, як нашого Університету, так і інших наукових та освітніх установ. Науковий журнал цього центру містить як суто наукові роботи з актуальних досліджень, так і науково-популярні матеріали, статті з історії та філософії науки. Журнал має стати важливим внеском у наукову та просвітницьку діяльність університету, а міжнародний статус цього видання та міжнародний склад редакційної колегії сприятиме популяризації наукових здобутків відомих закордонних та вітчизняних учених. Сподіваюся, що цей науковий часопис буде значним стимулюючим фактором у реалізації нашої мети і буде ще одним вагомим кроком кроком на шляху до дослідницького університету, яким ми його бачимо і яким він має бути.

Листопад, 2012 *Віктор Андрущенко*

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From Editor-in-Chief

Interdisciplinary studies become a characteristic feature of the modern science. A synthesis of ideas and methods for different, sometimes very distant, branches appears a fruitful approach to the fundamental science as well as to the applications. This synthesis brings in a new knowledge and induce new technologies.

In the our University, interdisciplinary studies also play a significant role. One of the main objectives of the Pedagogical University today is a acquaintance of the future teachers with modern scientific theories and discoveries which form a new scientific paradigm and the scientific world view on the whole. Problems stating by the modern life before the science demand a cooperation of scientists of different specialisations. Complex systems consist a numberless class of objects which are around us, from atoms, to Galaxies. Studies of complex systems need joint efforts of non only mathematicians, physicists, biologists but also psychologists, sociologists, linguists. These studies are the barest necessity of the modern science.

Taking into account the importance of interdisciplinary researches, we founded the Interdisciplinary Research Center for Complex Systems. The Center purposes an activization of interaction between scientists of different areas which work in the our University as well as in another scientific and education organizations. The journal of this Center consists of pure scientific articles and, on the other side, of materials in popular science, in history and philosophy of the science. The journal shall be an important contribution to the scientific and educational activities of the University. The international status of the journal as well as the international membership of the Editorial Board will be conducive to publications of the noted foreign and ukrainian scientists. I hope *Interdisciplinary Studies of Complex Systems* will be a significant challenging factor for the realization of the our aim and will be the next important step on the way to the Research University, such like we see it and such like it should be.

November, 2012 *Viktor Andruschenko*

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Від виконавчого редактора

Представлений журнал пов'язаний із Міждисциплінарним науково-дослідним центром складних систем (МНДЦСС), що було створено близько року тому при київському Національному педагогічному університеті імені М. П. Драгоманова з декількома взаємопов'язаними цілями. З одного боку, ми намагалися впровадити взаємодію між вченими з різних інститутів при університеті, яка б реалізовувала загальну тенденцію до міждисциплінарних досліджень. Ця тенденція стає дедалі вагомішою в сучасній науці. Теорія складних систем є яскравим прикладом науки, що виникла в результаті синтезу ідей, методів та завдань з різних галузей фізики, математики, біології, соціології тощо. Одним із шляхів реалізації міждисциплінарного підходу ми бачимо організацію дослідницьких проектів, які мають бути сконцентрованими на питаннях спільного інтересу експертів з різних галузей. Ми також сподіваємося, що цей центр може відігравати роль наукового форуму для вчених з університетів та дослідницьких інститутів України та зарубіжжя. Іншою формою реалізації наших цілей є впровадження та розвиток міждисциплінарних магістерських програм в університеті. Також ми розглядаємо семінари, симпозіуми та конференції з актуальних тем міждисциплінарних досліджень як важливу частину діяльності МНДЦСС.

Журнал «Міждисциплінарні дослідження складних систем» може розглядатися як практична форма взаємодії між вченими на міждисциплінарному ґрунті. Міркуючи про мету та тематику журналу, ми б хотіли бачити його іншою частиною згаданого вище наукового форуму, відкритим та цікавим як для експертів з різних галузей, так і для широкої аудиторії: від студентів до досвідчених дослідників. Саме тому в журналі до уваги читача будуть представлені наукові статті міждисциплінарного характеру, а також статті про історію та філософію науки, інформація про наукові події, простір для дискусії читачів про актуальні події наукового життя тощо. Ми сподіваємося, що вільний доступ до електронної версії журналу надасть можливість для активної взаємодії між читачами, авторами та редакційною колегією. Одним із конкретних завдань журналу є надання можливості вченим з різних дисциплін презентувати нові ідеї, гіпотези та піонерські дослідження. Такі публікації можуть бути гарним об'єктом для наукових дискусій, які можуть виявитися корисними для авторів та цікавими для читачів.

Листопад, 2012 *Юрій Кондратьєв*

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From Managing Editor

This journal is associated with the Interdisciplinary Research Center for Complex Systems (IRCCS) at the Dragomanov National Pedagogical University, Kyiv, Ukraine. IRCCS was organized about one year ago with several interconnected aims. On one side we try to organize an interaction of scientists from different departments of the university realizing a general tendency of the interdisciplinary studies. This tendency became more and more essential in the modern science. The theory of complex systems itself is a prominent example of a science which appeared as a result of the synergy of ideas, methods and problems from many areas: physics, mathematics, biology, sociology etc. As a particular way for the implementation of the interdisciplinary approach, we see the organization of research projects which shall be concentrated on topics of joint interests for experts from different areas. We also hope that this center may play a role of a scientific forum for scientists from universities and research institutes located in Ukraine and abroad. Another form of realization of our aims is a development and implementation of interdisciplinary research master programs at the university. Additionally, we include seminars, workshops, and conferences in actual topics of interdisciplinary researches as an important part of IRCCS activity.

The presented journal "Interdisciplinary Studies of Complex Systems" may be considered as a practical form of an interaction between scientists on an interdisciplinary ground. Thinking about aims and scopes, we would like to have this journal as another part of the scientific forum, open and interesting for experts from several areas and for a broad audience from students to senior researchers. It is why here will be presented research papers of interdisciplinary character and, at the same time, papers in the history and philosophy of science, informations about scientific events, a place for discussions of the readers on actual moments of the scientific life etc. We hope that an open access electronic version of the journal will give a possibility for an active direct communication between readers, authors and the Editorial Board. One of the particular aims of the journal is to give a possibility for scientists from different disciplines to present new ideas, conjectures and pioneering developments. Such publications may be a good point for scientific discussions that will be (at least to some extend) productive for the authors and interesting for the readers.

November, 2012 *Yuri Kondratiev*

Наукові публікації
Research Papers

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Stochastic modeling of complex systems

Y. Kondratiev[1]

The aim of this short note is to give a brief description (oriented on non-mathematical audience) concerning some directions under an active development in the theory of complexity which are closely related to the scientific activity of the Interdisciplinary Research Center for Complex Systems (IRCCS) at the Dragomanov National Pedagogical University. This review is based on the talk given at the First annual meeting of IRCCS in September 2012. We will try to present certain key ideas in the area without an attempt to give an overview complete at any extend. It is why the references are restricted to minima just to give, for the motivated reader, some sources of a more detailed explanation. This note may be considered as an introduction into the more mathematical description of the corresponding problems of stochastic dynamics for complex systems which is presented in the next article of the present journal issue.

In all sciences, stochastic effects can rarely be ignored when we model, analyze or quantify any type of dynamics. In addition, the study of large complex systems (i.e., systems with large or infinite number of degrees of freedom) can often only be done using stochastic methods. The stochastic paradigm, recognizing the significant meaning of uncertainty, plays a fundamental role in dynamics researches of such systems. A fundamental concept is such that the randomness is just a reflection of a high complexity (due to A. N. Kolmogorov). In many cases, we use a probabilistic characterization as a reduced description of observed events. In the modern science, the stochastic modeling and statistical approach to the study of complex systems became a widely used technical tool. Note that the probabilistic interpretations of the real world notions are not always easily accepted. It is enough to mention a sceptic comment by Albert Einstein w.r.t. the probabilistic interpretation of quantum mechanics: "I am convinced that He (God) does not play dice".

Stochastic methods play a key role in the study of complex systems. Representative examples of complexity in the real world are given by molecular motors, neuron networks, immune systems, social networks, financial markets, economics webs, communication networks, multi-particle systems in physics (gases, fluids, plasmas etc.).

Complex systems are those composed of many elements which mutual interaction gives rise to unexpected emergent phenomena. For example, the behavior of brain cannot be anticipated from the study of an isolated neuron. Similarly, superconductivity cannot be anticipated from the study of a single

[1] IRCCS, Dragomanov National Pedagogical University, Kyiv, Ukraine; Faculty of Mathematics, Bielefeld University, Germany

electron. Statistical mechanics, originally developed to study physical systems consisting of a large number of particles, provides tools and techniques that are well suited to study complex systems. The emergence of collective behavior is certainly not restricted to the physical sciences, but it is ubiquitous in nature, from biology, to social systems and economics. For this reason, the study of complex systems, being at the theoretical or empirical level, requires a truly interdisciplinary mindset. In particular, in applications to life sciences, the central problem is to develop an appropriate mathematical methods in the framework of statistical mechanics for complex systems. Such mechanics have to deal with heterogeneous ensembles of interacting agents and with the continual refreshment of that ensemble by novel and unpredictable types. A statistical approach to the stochastic dynamics of interacting particle systems makes the state evolution to be a main object of the study instead of the standard random path description for Markov processes [5]. The difference between both concepts became essential in the case of topologically complicated phase spaces as, e.g., configuration spaces in the continuum. In the most of known models of Markov dynamics in the continuum, we can not expect the existence of the process which starts from any initial configuration (i.e., microscopic state). On the other hand, such dynamics can exist for an initial distribution (i.e., macroscopic state) from the proper set of admissible states. This observation is an essence of the statistical approach.

Complex systems which appear in life sciences have several specific aspects. Description of these systems should take into account diversity and individuality of components, localized interactions among components, the outcomes of interactions used for replication or enhancement of components [6]. An essential typical property of biological systems (comparing with many situations in mathematical physics) is such that they are intrinsically out of the equilibrium.

In a more particular area of the spatial ecology, we have an active development of the concept of individual based models. In the mathematical terminology, each such model is a stochastic (Markov) process with events comprising birth, death and mobility for members of considered populations [3, 5].

Last years we observe an intensive and extensive development of a new area which may be called the physics of society. The complexity theory seeks to understand how the order and stability arise from the interactions of many agents. An appeared paradigm states that we can make predictions about a society even in the face of individual free will, and perhaps even illuminate the limits of that free will. As a typical aspect of the complexity theory, we stress that the physics of society is a science of humans' collective behavior. It is interesting to mention that the question about the roots of social events was already posed by Thomas Hobbes in his famous book "Leviaphan" (1651). Namely, he wrote: "We must ask not just how things happen in society, but also why". And here also the statistical point of view is a key concept. In fact, a shift from Newtonian determinism to statistical science makes a physics of society possible. Moreover, we shall accept that "the society itself is fundamentally a statistical phenomenon" [1].

The central technical problem is to develop an appropriate statistical mechanics that allows one to separate the knowable unknown from the truly un-

knowable. Such mechanics will have to deal with heterogeneous ensembles of interacting agents and with the continual refreshment of such ensembles by novel and unpredictable types. We would like to stress again that there is a principal difference between two possible points of view on the random evolution of complex systems. We put the macroscopic state evolution for the system as a fundamental notion in the statistical description of considered dynamics. In the terminology of probability theory, we are interesting in the Markov function dynamics instead of traditional study of Markov stochastic process starting from an individual points in the phase space (i.e., from microscopic states). Such random path description is more informative from the probabilistic point of view. But, as it was pointed out above, in the complex systems dynamics very often only statistical description is possible [5]. Actually, to understand clearly the appearance of statistical paradigm was a crucial step in the Boltzmann approach in the theory of classical gases.

The problem of relationships between various scales of description is one of the most important problems of the mathematical modeling of complex systems. The unity of knowledge (science) has been a widely discussed issue in the philosophy of science, as well as in specific scientific fields. A first step towards the unity of science is an establishment of relationships between different theories and models. Knowledge about the nature would be more reliable when relationships between different descriptions are more visible.

Perhaps, the most studied topics in physics are scaling phenomena. In this area we are based on the observation that the nature has a hierarchical structure with strongly separated levels. We believe in the following dogma: "Behavior at any level can be deduced entirely from the dynamics of the level below it, i.e. there are no new physical laws, only new phenomena, as one goes from atoms to fluids to galaxies" [2].

There exists a fundamental concept of three levels of the description for complex systems. In mathematical terms we are interesting in the links between the following levels:

– the micro-scale of stochastically interacting entities (cells, individuals, ...) described in terms of linear Markov semigroups (or corresponding processes);

– the meso-scale of statistical entities realized in terms of nonlinear semigroups (evolutional families) related to the solutions of nonlinear nonlocal kinetic equations. Such structures have an interpretation as nonlinear Markov processes;

– the macro-scale of densities of interacting entities formulated in terms of dynamical systems related to local nonlinear equations (e.g., reaction–diffusion type equations).

One of the basic problems in each concrete model of interacting particle systems is to derive rigorously the description of transition from one level to another one [4].

All the history of the science demonstrates the presence and nontrivial interaction of two tendencies which we can call analysis and synthesis. They always exist in the science but their roles are different for particular periods of time. We clearly see that the tendency of a deep specialization (which was a dominant of the development during main part of 20th century) changed in last

decades to an active motion in the direction of interdisciplinary researches. The theory of complex systems gives us a prominent example for this statement.

Mathematical methods play a crucial role in the successful realization of such motion. Note that a suspicious estimation of mathematical style of thinking was quite extended in the society. We remember that J. W. Goethe said: "Mathematicians are like Frenchmen: whatever you say to them they translate into their own language, and forthwith it is something entirely different". And it was not only an opinion of the great poet. Such giant of natural sciences as V. I. Vernadsky wrote in his monograph "La Biosphere" (1926) the following: "Considered in the abstract time and space of mathematics, Life is a fiction, a creation of our mind which is very different from reality". But later the quantum revolution in physics, an implementation of mathematical methods in biology, ecology and other life sciences, developments in informatic technologies and many other great scientific evens made the leading role of mathematics in the interdisciplinary researches obvious.

Here I would like to give a reference to the talk of I. M. Gelfand at the conference "The Unity of Mathematics", Cambridge MA, USA, 2003. He was not only the great mathematician with highest level results in the pure mathematics, but also the Director of the Laboratory of Mathematical Biology at Moscow State University. In particular, I. M. Gelfand said: "An important side of mathematics is that it is an adequate language for different areas: physics, engineering, biology. Here, the most important word is adequate language. I can give you examples of adequate and non-adequate languages. For example, to use quantum mechanics in biology is not an adequate language, but to use mathematics in studying gene sequences is an adequate language... My search for an adequate language is based on my work in applied mathematics. Mathematical language helps to organize a lot of things".

One of the aims in general theory of complex systems is an elaboration of mathematical models for observed notions appearing in several particular areas of the science. There is a popular name "real world models" for the characterization of this direction. Interacting particle systems are used often as a technical tool for the construction and the study of these models. They are used as basic ingredients in developing concrete models in physics (gases, fluids, condensed matter), chemical kinetics, biology, ecology (individual based models), medicine (tumor growth models), sociology, economics (agent based models) etc.

Here we arrive in a very delicate area which may be called the art of modeling. It is clear, that a mathematical model which takes into account too much details of the considered notion may be, as a result, very far from a rigorous mathematical study. On the other side, mathematically convenient simplifications may lead to an empty set of possible applications. The necessary balance here was formulated by Albert Einstein: "Everything should be made as simple as possible, but not simpler". Another question is the following: what we may expect from a particular model? In fact, we must remember that, due to Mark Kac, "models are, for the most part, caricatures of reality, but if they are good, then, like good caricatures, they portray, though perhaps in distorted manner, some of the features of the real world". And a British mathematician George Box added: "All models are wrong; some models are useful". In any

case, models describe observed (or expected) notions rather than real systems. There is an additional notable moment. A "good model" may became a part of scientific reality itself with its own life and development. A prominent example here is the celebrated Ising model. An exiting attempt of the complexity science is to recognize such particular gold fishes in the flow of considered models and to analyze them with all respect and the careful attention they are deserved.

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Vol. 1, No. 1 (2012) 14–32

Statistical approach for stochastic evolutions of complex systems in the continuum

D. Finkelshtein,[1] *Y. Kondratiev,*[2] *O. Kutoviy*[3]

Abstract. We present a general background for the study of complex systems in the continuum and explain the mathematical tools to deal with stochastic evolutions in the continuum. The statistical description of Markov dynamics of complex systems in the continuum is described in details. The review of recent developments for birth-and-death evolutions is given.

1 Complex systems in the continuum

In recent decades, different brunches of natural and life sciences have been addressing to a unifying point of view on a number of phenomena occurring in systems composed of interacting subunits. This leads to formation of a interdisciplinary science which is referred to as the theory of complex systems. It provides reciprocation of concepts and tools involving wide spectrum of applications as well as various mathematical theories such that statistical mechanics, probability, nonlinear dynamics, chaos theory, numerical simulation and many others.

Nowadays complex systems theory is a quickly growing interdisciplinary area with a very broad spectrum of motivations and applications. For instance, having in mind biological applications, S. Levin [40] characterized complex adaptive systems by such properties as diversity and individuality of components, localized interactions among components, and the outcomes of interactions used for replication or enhancement of components. We will use a more general informal description of a complex system as a specific collection of interacting elements which has so-called collective behavior that means appearance of system properties which are not peculiar to inner nature of each element itself. The significant physical example of such properties is thermodynamical effects which were a background for creation by L. Boltzmann of statistical physics as a mathematical language for studying complex systems of molecules.

[1] Dragomanov National Pedagogical University; Institute of Mathematics of NAS of Ukraine, Kyiv, Ukraine. fdl@imath.kiev.ua

[2] IRCCS, Dragomanov National Pedagogical University, Kyiv, Ukraine; Fakultät für Mathematik, Universität Bielefeld, 33615 Bielefeld, Germany. kondrat@math.uni-bielefeld.de

[3] Fakultät für Mathematik, Universität Bielefeld, 33615 Bielefeld, Germany. kutoviy@math.uni-bielefeld.de

We assume that all elements of a complex system are identical by properties and possibilities. Thus, one can model these elements as points in a proper space whereas the complex system will be modeled as a discrete set in this space. Mathematically this means that for the study of complex systems the proper language and techniques are delivered by the interacting particle models which form a rich and powerful direction in modern stochastic and infinite dimensional analysis. Interacting particle systems have a wide use as models in condensed matter physics, chemical kinetics, population biology, ecology (individual based models), sociology and economics (agent based models). For instance a population in biology or ecology may be represented by a configuration of organisms located in a proper habitat.

In spite of completely different orders of numbers of elements in real physical, biological, social, and other systems (typical numbers start from 10^{23} for molecules and, say, 10^5 for plants) their complexities have analogous phenomena and need similar mathematical methods. One of them consists in mathematical approximation of a huge but finite real-world system by an infinite system realized in an infinite space. This approach was successfully approved to the thermodynamic limit for models of statistical physics and appeared quite useful for the ecological modeling in the infinite habitat to avoid boundary effects in a population evolution.

Therefore, our phase space for the mathematical description should consist of countable sets from an underlying space. This space itself may have discrete or continuous nature that leads to segregation of the world of complex systems on two big classes. Discrete models correspond to systems whose elements can occupy some prescribing countable set of positions, for example, vertices of the lattice $\mathbb{Z}^d$ or, more generally, of some graph embedded to $\mathbb{R}^d$. These models are widely studied and the corresponding theories were realized in numerous publications, see e.g. [41, 42] and the references therein. Continuous models, or models in the continuum, were studied not so intensively and broadly. We concentrate our attention exactly on continuous models of systems whose elements may occupy any points in Eucledian space $\mathbb{R}^d$. Having in mind that real elements have physical sizes we will consider only the so-called locally finite subsets of the underlying space $\mathbb{R}^d$, that means that in any bounded region we assume to have a finite number of the elements. Another our restriction will be prohibition of multiple elements in the same position of the space.

We will consider systems of elements of the same type only. The mathematical realization of considered approaches may be successfully extended to multi-type systems, meanwhile such systems will have more rich qualitative properties and will be an object of interest for applications. Some particular results can be found e.g. in [12, 13, 23].

2 Mathematical description of complex systems

We proceed to the mathematical realization of complex systems. Let $\mathcal{B}(\mathbb{R}^d)$ be the family of all Borel sets in $\mathbb{R}^d$, $d \geq 1$; $\mathcal{B}_{\mathrm{b}}(\mathbb{R}^d)$ denotes the system of all bounded sets from $\mathcal{B}(\mathbb{R}^d)$.

The configuration space over space $\mathbb{R}^d$ consists of all locally finite subsets (configurations) of $\mathbb{R}^d$. Namely,

$$\Gamma = \Gamma(\mathbb{R}^d) := \Big\{ \gamma \subset \mathbb{R}^d \;\Big|\; |\gamma_\Lambda| < \infty, \text{ for all } \Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d) \Big\}. \tag{1}$$

Here $|\cdot|$ means the cardinality of a set, and $\gamma_\Lambda := \gamma \cap \Lambda$. We may identify each $\gamma \in \Gamma$ with the non-negative Radon measure $\sum_{x\in\gamma} \delta_x \in \mathcal{M}(\mathbb{R}^d)$, where δ_x is the Dirac measure with unit mass at x, $\sum_{x\in\emptyset} \delta_x$ is, by definition, the zero measure, and $\mathcal{M}(\mathbb{R}^d)$ denotes the space of all non-negative Radon measures on $\mathcal{B}(\mathbb{R}^d)$. This identification allows to endow Γ with the topology induced by the vague topology on $\mathcal{M}(\mathbb{R}^d)$, i.e. the weakest topology on Γ with respect to which all mappings

$$\Gamma \ni \gamma \mapsto \sum_{x\in\gamma} f(x) \in \mathbb{R} \tag{2}$$

are continuous for any $f \in C_0(\mathbb{R}^d)$ that is the set of all continuous functions on $\mathbb{R}^d$ with compact supports. It is worth noting the vague topology may be metrizable in such a way that Γ becomes a Polish space (see e.g. [32] and references therein).

The corresponding (to the vague topology) Borel σ-algebra $\mathcal{B}(\Gamma)$ appears the smallest σ-algebra for which all mappings

$$\Gamma \ni \gamma \mapsto N_\Lambda(\gamma) := |\gamma_\Lambda| \in \mathbb{N}_0 := \mathbb{N} \cup \{0\} \tag{3}$$

are measurable for any $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$, see e.g. [1]. This σ-algebra may be generated by the sets

$$Q(\Lambda, n) := \big\{ \gamma \in \Gamma \;\big|\; N_\Lambda(\gamma) = |\gamma_\Lambda| = n \big\}, \qquad \Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d), n \in \mathbb{N}_0. \tag{4}$$

Clearly, for any $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$,

$$\Gamma = \bigsqcup_{n\in\mathbb{N}_0} Q(\Lambda, n). \tag{5}$$

Among all measurable functions $F : \Gamma \to \bar{\mathbb{R}} := \mathbb{R} \cup \{\infty\}$ we mark out the set $\mathcal{F}_0(\Gamma)$ consisting of such of them for which $|F(\gamma)| < \infty$ at least for all $|\gamma| < \infty$. The important subset of $\mathcal{F}_0(\Gamma)$ formed by cylindric functions on Γ. Any such a function is characterized by a set $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$ such that $F(\gamma) = F(\gamma_\Lambda)$ for all $\gamma \in \Gamma$. The class of cylindric functions we denote by $\mathcal{F}_{\rm cyl}(\Gamma) \subset \mathcal{F}_0(\Gamma)$.

Functions on Γ are usually called *observables*. This notion is borrowed from statistical physics and means that typically in course of empirical investigation we may estimate, check, see only some quantities of a whole system rather then look on the system itself.

Example 2.1. Let $\varphi : \mathbb{R}^d \to \mathbb{R}$ and consider the so-called *linear function* on Γ, cf. (2),

$$\langle \varphi, \gamma \rangle := \begin{cases} \sum\limits_{x\in\gamma} \varphi(x), & \text{if } \sum\limits_{x\in\gamma} |\varphi(x)| < \infty, \quad \gamma \in \Gamma, \\ +\infty, & \text{otherwise.} \end{cases} \tag{6}$$

Then, evidently, $\langle\varphi,\cdot\rangle \in \mathcal{F}_0(\Gamma)$. If, additionally, $\varphi \in C_0(\mathbb{R}^d)$ then $\langle\varphi,\cdot\rangle \in \mathcal{F}_{\mathrm{cyl}}(\Gamma)$. Not that for e.g. $\varphi(x) = \|x\|_{\mathbb{R}^d}$ (the Euclidean norm in $\mathbb{R}^d$) we have that $\langle\varphi,\gamma\rangle = \infty$ for any infinite $\gamma \in \Gamma$.

Example 2.2. Let $\phi : \mathbb{R}^d \setminus \{0\} \to \mathbb{R}$ and ϕ is an even function, namely, $\phi(-x) = \phi(x)$, $x \in \mathbb{R}^d$. Then one can consider the so-called *energy function*

$$E^\phi(\gamma) := \begin{cases} \sum\limits_{\{x,y\}\subset\gamma} \phi(x-y), & \text{if } \sum\limits_{\{x,y\}\subset\gamma} |\phi(x-y)| < \infty, \quad \gamma \in \Gamma, \\ +\infty, & \text{otherwise.} \end{cases} \tag{7}$$

Clearly, $E^\phi \in \mathcal{F}_0(\Gamma)$. However, even for ϕ with a compact support, E^ϕ will not be a cylindric function.

As we discussed before, any configuration γ represents some system of elements in a real-world application. Typically, investigators are not able to take into account exact positions of all elements due to huge number of them. For quantitative and qualitative analysis of a system researchers mostly need some its statistical characteristics such as density, correlations, spatial structures and so on. This leads to the so-called statistical description of complex systems when people study distributions of countable sets in an underlying space instead of sets themselves. Moreover, the main idea in Boltzmann's approach to thermodynamics based on giving up the description in terms of evolution for groups of molecules and using statistical interpretation of molecules motion laws. Therefore, the crucial role for studying of complex systems plays distributions (probability measures) on the space of configurations. In statistical physics these measures usually called *states* that accentuates their role for description of systems under consideration.

We denote the class of all probability measures on $\big(\Gamma, \mathcal{B}(\Gamma)\big)$ by $\mathcal{M}^1(\Gamma)$. Given a distribution $\mu \in \mathcal{M}^1(\Gamma)$ one can consider a collection of random variables $N_\Lambda(\cdot)$, $\Lambda \in \mathcal{B}_{\mathrm{b}}(\mathbb{R}^d)$ defined in (3). They describe random numbers of elements inside bounded regions. The natural assumption is that these random variables should have finite moments. Thus, we consider the class $\mathcal{M}^1_{\mathrm{fm}}(\Gamma)$ of all measures from $\mathcal{M}^1(\Gamma)$ such that

$$\int_\Gamma |\gamma_\Lambda|^n \, d\mu(\gamma) < \infty, \qquad \Lambda \in \mathcal{B}_{\mathrm{b}}(\mathbb{R}^d), n \in \mathbb{N}. \tag{8}$$

Example 2.3. Let σ be a Radon measure on $\big(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d)\big)$ which has not atoms. Then the *Poisson measure* π_σ with intensity measure σ is defined on $\mathcal{B}(\Gamma)$ by equality

$$\pi_\sigma\big(Q(\Lambda,n)\big) = \frac{\big(\sigma(\Lambda)\big)^n}{n!} \exp\big\{-\sigma(\Lambda)\big\}, \qquad \Lambda \in \mathcal{B}_{\mathrm{b}}(\mathbb{R}^d), n \in \mathbb{N}_0. \tag{9}$$

On the other words, the random variables N_Λ have Poissonian distribution with mean value $\sigma(\Lambda)$, $\Lambda \in \mathcal{B}_{\mathrm{b}}(\mathbb{R}^d)$. Note that by the Rényi theorem [30, 52] a measure π_σ will be Poissonian if (9) holds for $n = 0$ only. In the case then $d\sigma(x) = \rho(x)\,dx$ one can say about nonhomogeneous Poisson measure π_ρ with density (or intensity) ρ. This notion goes back to the famous Campbell formula [8, 9] which states that

$$\int_\Gamma \langle\varphi,\gamma\rangle \, d\pi_\rho(\gamma) = \int_{\mathbb{R}^d} \varphi(x)\rho(x)\,dx, \tag{10}$$

if only the right hand side of (10) is well-defined. The generalization of (10) is the Mecke identity [44]

$$\int_\Gamma \sum_{x\in\gamma} h(x,\gamma)\, d\pi_\sigma(\gamma) = \int_\Gamma \int_{\mathbb{R}^d} h(x,\gamma\cup x)\, d\sigma(x)\, d\pi_\sigma(\gamma), \tag{11}$$

which holds for all measurable nonnegative functions $h : \mathbb{R}^d \times \Gamma \to \mathbb{R}$. Here and in the sequel we will omit brackets for the one-point set $\{x\}$. In [44], it was shown that the Mecke identity is a characterization identity for the Poisson measure. In the case $\rho(x) = z > 0$, $x \in \mathbb{R}^d$ one can say about the homogeneous Poisson distribution (measure) π_z with constant intensity z. We will omit subindex for the case $z = 1$, namely, $\pi := \pi_1 = \pi_{dx}$. Note that the property (8) is followed from (11) easily.

Example 2.4. Let ϕ be as in Example 2.2 and suppose that the energy given by (7) is *stable*: there exists $B \geq 0$ such that, for any $|\gamma| < \infty$, $E^\phi(\gamma) \geq -B|\gamma|$. An example of such ϕ my be given by the expansion

$$\phi(x) = \phi^+(x) + \phi^p(x), \quad x \in \mathbb{R}^d, \tag{12}$$

where $\phi^+ \geq 0$ whereas ϕ^p is a positive defined function on $\mathbb{R}^d$ (the Fourier transform of a measure on $\mathbb{R}^d$), see e.g. [24, 53]. Fix any $z > 0$ and define the *Gibbs measure* $\mu \in \mathcal{M}^1(\Gamma)$ with potential ϕ and activity parameter z as a measure which satisfies the following generalization of the Mecke identity:

$$\int_\Gamma \sum_{x\in\gamma} h(x,\gamma)\, d\mu(\gamma) = \int_\Gamma \int_{\mathbb{R}^d} h(x,\gamma\cup x) \exp\{-E^\phi(x,\gamma)\}\, z dx\, d\mu(\gamma), \tag{13}$$

where

$$E^\phi(x,\gamma) := \langle \phi(x-\cdot),\gamma\rangle = \sum_{y\in\gamma} \phi(x-y), \quad \gamma \in \Gamma, x \in \mathbb{R}^d \setminus \gamma. \tag{14}$$

The identity (13) is called the Georgii–Nguyen–Zessin identity, see [28, 46]. If potential ϕ is additionally satisfied the so-called integrability condition

$$\beta := \int_{\mathbb{R}^d} \left| e^{-\phi(x)} - 1 \right| dx < \infty, \tag{15}$$

then it can checked that the condition (8) for the Gibbs measure holds. Note that under conditions $z\beta \leq (2e)^{-1}$ there exists a unique measure on $\big(\Gamma, \mathcal{B}(\Gamma)\big)$ which satisfies (13). Heuristically, the measure μ may be given by the formula

$$d\mu(\gamma) = \frac{1}{Z} e^{-E^\phi(\gamma)}\, d\pi_z(\gamma), \tag{16}$$

where Z is a normalizing factor. To give rigorous meaning for (16) it is possible to use the so-called DLR-approach (named after R. L. Dobrushin, O. Lanford, D. Ruelle), see e.g. [2] and references therein. As was shown in [46], this approach gives the equivalent definition of the Gibbs measures which satisfies (13).

Note that (16) could have a rigorous sense if we restrict our attention on the space of configuration which belong to a bounded domain $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$. The space of such (finite) configurations will be denoted by $\Gamma(\Lambda)$. The σ-algebra $\mathcal{B}(\Gamma_\Lambda)$ may be generated by family of mappings $\Gamma(\Lambda) \ni \gamma \mapsto N_{\Lambda'}(\gamma) \in \mathbb{N}_0$, $\Lambda' \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$, $\Lambda' \subset \Lambda$. A measure $\mu \in \mathcal{M}^1_{\rm fm}(\Gamma)$ is called locally absolutely continuous with respect to the Poisson measure π if for any $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$ the projection of μ onto $\Gamma(\Lambda)$ is absolutely continuous with respect to (w.r.t.) the projection of π onto $\Gamma(\Lambda)$. More precisely, if we consider the projection mapping $p_\Lambda : \Gamma \to \Gamma(\Lambda)$, $p_\Lambda(\gamma) := \gamma_\Lambda$ then $\mu^\Lambda := \mu \circ p_\Lambda^{-1}$ is absolutely continuous w.r.t. $\pi_\Lambda := \pi \circ p_\Lambda^{-1}$.

Remark 2.1. Having in mind (16), it is possible to derive from (13) that the Gibbs measure from Example 2.4 is locally absolutely continuous w.r.t. the Poisson measure, see e.g. [14] for the more general case.

By e.g. [31], for any $\mu \in \mathcal{M}^1_{\rm fm}(\Gamma)$ which is locally absolutely continuous w.r.t the Poisson measure there exists the family of (symmetric) *correlation functions* $k_\mu^{(n)} : (\mathbb{R}^d)^n \to \mathbb{R}_+ := [0, \infty)$ which defined as follows. For any symmetric function $f^{(n)} : (\mathbb{R}^d)^n \to \mathbb{R}$ with a finite support the following equality holds

$$\int_\Gamma \sum_{\{x_1,\dots,x_n\}\subset\gamma} f^{(n)}(x_1,\dots,x_n)\, d\mu(\gamma) = \frac{1}{n!}\int_{(\mathbb{R}^d)^n} f^{(n)}(x_1,\dots,x_n) k_\mu^{(n)}(x_1,\dots,x_n)\, dx_1 \dots dx_n \quad (17)$$

for $n \in \mathbb{N}$, and $k_\mu^{(0)} := 1$.

The meaning of the notion of correlation functions is the following: the correlation function $k_\mu^{(n)}(x_1,\dots,x_n)$ describes the nonnormalized density of probability to have points of our systems in the positions $x_1,\dots,x_n$. More precisely,

Proposition 2.1. *Let $\mu \in \mathcal{M}^1_{\rm fm}(\Gamma)$ be locally absolutely continuous w.r.t. the Poisson measure, and let $k_\mu^{(n)}$, $n \in \mathbb{N}$ be the corresponding correlation functions. Denote by $B_r(x)$ a ball in $\mathbb{R}^d$ with center at an $x \in \mathbb{R}^d$ and a radius $r > 0$. Then, for any $n \in \mathbb{N}$ and for a.a. $x_1,\dots,x_n \in \mathbb{R}^d$,*

$$k_\mu^{(n)}(x_1,\dots,x_n) = \lim_{r\to 0} \frac{\mu\big(\{\gamma \in \Gamma \mid |\gamma \cap B_r(x_1)| = \dots = |\gamma \cap B_r(x_n)| = 1\}\big)}{\big(B_r(0)\big)^n}. \quad (18)$$

Correlation functions describe properties of a probability measure much more precisely than measure's moments (8). For instance, one can obtain measures of sets $Q(\Lambda, n)$, defined in (4), in terms of correlation functions or, in the other words, one can fully describe the distribution of random variables $N_\Lambda(\cdot)$ defined in (3). Namely,

Proposition 2.2. *For any $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$, $n \in \mathbb{N}_0$,*

$$\mu\big(Q(\Lambda, n)\big) = \frac{1}{n!}\sum_{m=0}^\infty \frac{(-1)^m}{m!}\int_{\Lambda^{n+m}} k_\mu^{(n+m)}(x_1,\dots,x_{n+m})\, dx_1 \dots dx_{n+m}. \quad (19)$$

Remark 2.2. Iterating the Mecke identity (11), it can be easily shown that

$$k_{\pi_\rho}^{(n)}(x_1,\dots,x_n)=\prod_{i=1}^{n}\rho(x_i), \tag{20}$$

in particular,

$$k_{\pi_z}^{(n)}(x_1,\dots,x_n)\equiv z^n. \tag{21}$$

Substituting the right hand side (r.h.s.) of (20) to (19) one can obtain (9).

Remark 2.3. Note that if potential ϕ from Example 2.4 satisfies to (12), (15) then, by [54], there exists $C=C(z,\phi)>0$ such that for μ defined by (13)

$$k_{\mu}^{(n)}(x_1,\dots,x_n)\le C^n,\qquad x_1,\dots,x_n\in\mathbb{R}^d. \tag{22}$$

The inequality (22) is referred to as the Ruelle bound.

We dealt with symmetric function of n variables from $\mathbb{R}^d$, hence, they can be considered as functions on n-point subsets from $\mathbb{R}^d$. We proceed now to the exact constructions.

The space of n-point configurations in $Y\in\mathcal{B}(\mathbb{R}^d)$ is defined by

$$\Gamma^{(n)}(Y):=\big\{\eta\subset Y\;\big|\;|\eta|=n\big\},\qquad n\in\mathbb{N}.$$

We put $\Gamma^{(0)}(Y):=\{\emptyset\}$. As a set, $\Gamma^{(n)}(Y)$ may be identified with the symmetrization of

$$\widetilde{Y^n}=\big\{(x_1,\dots,x_n)\in Y^n\;\big|\;x_k\ne x_l \text{ if } k\ne l\big\}.$$

Hence, one can introduce the corresponding Borel σ-algebra, which we denote by $\mathcal{B}\big(\Gamma^{(n)}(Y)\big)$. The space of finite configurations in $Y\in\mathcal{B}(\mathbb{R}^d)$ is defined as

$$\Gamma_0(Y):=\bigsqcup_{n\in\mathbb{N}_0}\Gamma^{(n)}(Y). \tag{23}$$

This space is equipped with the topology of the disjoint union. Let $\mathcal{B}\big(\Gamma_0(Y)\big)$ denote the corresponding Borel σ-algebra. In the case of $Y=\mathbb{R}^d$ we will omit the index Y in the previously defined notations. Namely,

$$\Gamma_0:=\Gamma_0(\mathbb{R}^d),\qquad \Gamma^{(n)}:=\Gamma^{(n)}(\mathbb{R}^d),\quad n\in\mathbb{N}_0. \tag{24}$$

The restriction of the Lebesgue product measure $(dx)^n$ to $\big(\Gamma^{(n)},\mathcal{B}(\Gamma^{(n)})\big)$ we denote by $m^{(n)}$. We set $m^{(0)}:=\delta_{\{\emptyset\}}$. The Lebesgue–Poisson measure λ on Γ_0 is defined by

$$\lambda:=\sum_{n=0}^{\infty}\frac{1}{n!}m^{(n)}. \tag{25}$$

For any $\Lambda\in\mathcal{B}_{\rm b}(\mathbb{R}^d)$ the restriction of λ to $\Gamma_0(\Lambda)=\Gamma(\Lambda)$ will be also denoted by λ.

Remark 2.4. The space $\big(\Gamma,\mathcal{B}(\Gamma)\big)$ is the projective limit of the family of measurable spaces $\big\{\big(\Gamma(\Lambda),\mathcal{B}(\Gamma(\Lambda))\big)\big\}_{\Lambda\in\mathcal{B}_{\rm b}(\mathbb{R}^d)}$. The Poisson measure π on $\big(\Gamma,\mathcal{B}(\Gamma)\big)$ from Example 2.3 may be defined as the projective limit of the family of measures $\{\pi^\Lambda\}_{\Lambda\in\mathcal{B}_{\rm b}(\mathbb{R}^d)}$, where $\pi^\Lambda:=e^{-m(\Lambda)}\lambda$ is the probability measure on $\big(\Gamma(\Lambda),\mathcal{B}(\Gamma(\Lambda))\big)$ and $m(\Lambda)$ is the Lebesgue measure of $\Lambda\in\mathcal{B}_{\rm b}(\mathbb{R}^d)$ (see e.g. [1] for details).

Functions on Γ_0 will be called *quasi-observables*. Any $\mathcal{B}(\Gamma_0)$-measurable function G on Γ_0, in fact, is defined by a sequence of functions $\{G^{(n)}\}_{n\in\mathbb{N}_0}$ where $G^{(n)}$ is a $\mathcal{B}(\Gamma^{(n)})$-measurable function on $\Gamma^{(n)}$. We preserve the same notation for the function $G^{(n)}$ considered as a symmetric function on $(\mathbb{R}^d)^n$. Note that $G^{(0)} \in \mathbb{R}$.

A set $M \in \mathcal{B}(\Gamma_0)$ is called bounded if there exists $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$ and $N \in \mathbb{N}$ such that

$$M \subset \bigsqcup_{n=0}^{N} \Gamma^{(n)}(\Lambda). \tag{26}$$

The set of bounded measurable functions on Γ_0 with bounded support we denote by $B_{\rm bs}(\Gamma_0)$, i.e., $G \in B_{\rm bs}(\Gamma_0)$ iff $G \restriction_{\Gamma_0\setminus M} = 0$ for some bounded $M \in \mathcal{B}(\Gamma_0)$. For any $G \in B_{\rm bs}(\Gamma_0)$ the functions $G^{(n)}$ have finite supports in $(\mathbb{R}^d)^n$ and may be substituted into (17). But, additionally, the sequence of $G^{(n)}$ vanishes for big n. Therefore, one can summarize equalities (17) by $n \in \mathbb{N}_0$. This leads to the following definition.

Let $G \in B_{\rm bs}(\Gamma_0)$, then we define the function $KG : \Gamma \to \mathbb{R}$ such that:

$$(KG)(\gamma) := \sum_{\eta\Subset\gamma} G(\eta) \tag{27}$$

$$= G^{(0)} + \sum_{n=1}^{\infty} \sum_{\{x_1,\dots,x_n\}\subset\gamma} G^{(n)}(x_1,\dots,x_n), \quad \gamma \in \Gamma, \tag{28}$$

see e.g. [31, 38, 39]. The summation in (27) is taken over all finite subconfigurations $\eta \in \Gamma_0$ of the (infinite) configuration $\gamma \in \Gamma$; we denote this by the symbol, $\eta \Subset \gamma$. The mapping K is linear, positivity preserving, and invertible, with

$$(K^{-1}F)(\eta) := \sum_{\xi\subset\eta} (-1)^{|\eta\setminus\xi|} F(\xi), \quad \eta \in \Gamma_0. \tag{29}$$

By [31], for any $G \in B_{\rm bs}(\Gamma_0)$, $KG \in \mathcal{F}_{\rm cyl}(\Gamma)$, moreover, there exists $C = C(G) > 0$, $\Lambda = \Lambda(G) \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$, and $N = N(G) \in \mathbb{N}$ such that

$$|KG(\gamma)| \le C\big(1 + |\gamma_\Lambda|\big)^N, \quad \gamma \in \Gamma. \tag{30}$$

The expression (27) can be extended to the class of all nonnegative measurable $G : \Gamma_0 \to \mathbb{R}_+$, in this case, evidently, $KG \in \mathcal{F}_0(\Gamma)$. Stress that the left hand side (l.h.s.) of (29) has a meaning for any $F \in \mathcal{F}_0(\Gamma)$, moreover, in this case $(KK^{-1}F)(\gamma) = F(\gamma)$ for any $\gamma \in \Gamma_0$.

For G as above we may summarize (17) by n and rewrite the result in a compact form:

$$\int_\Gamma (KG)(\gamma) d\mu(\gamma) = \int_{\Gamma_0} G(\eta) k_\mu(\eta) d\lambda(\eta). \tag{31}$$

As was shown in [31], the equality (27) may be extended on all functions G such that the l.h.s. of (31) is finite. In this case (27) holds for μ-a.a. $\gamma \in \Gamma$ and (31) holds too.

Remark 2.5. The equality (31) may be considered as definition of the correlation functional k_μ. In fact, the definition of correlation functions in statistical physics, given by N. N. Bogolyubov in [5], based on a similar relation. More precisely, consider for a $\mathcal{B}(\mathbb{R}^d)$-measurable function f the so-called coherent state, given as a function on Γ_0 by

$$e_\lambda(f,\eta) := \prod_{x\in\eta} f(x),\ \eta\in\Gamma_0\backslash\{\emptyset\}, \qquad e_\lambda(f,\emptyset) := 1.$$

Then for any $f\in C_0(\mathbb{R}^d)$ we have the point-wise equality

$$\big(Ke_\lambda(f)\big)(\gamma) = \prod_{x\in\gamma}\big(1+f(x)\big), \quad \eta\in\Gamma_0. \tag{32}$$

As a result, the correlation functions of different orders may be considered as kernels of a Taylor-type expansion

$$\begin{aligned}\int_\Gamma \prod_{x\in\gamma}\big(1+f(x)\big)\,d\mu(\gamma) &= 1+\sum_{n=1}^\infty \frac{1}{n!}\int_{(\mathbb{R}^d)^n}\prod_{i=1}^n f(x_i)k_\mu^{(n)}(x_1,\dots,x_n)\,dx_1\dots dx_n\\ &= \int_{\Gamma_0} e_\lambda(f,\eta)k_\mu(\eta)\,d\lambda(\eta).\end{aligned} \tag{33}$$

Remark 2.6. By (23)–(25), we have that for any $f\in L^1(\mathbb{R}^d,dx)$

$$\int_{\Gamma_0} e_\lambda(f,\eta)d\lambda(\eta) = \exp\Big\{\int_{\mathbb{R}^d} f(x)dx\Big\}. \tag{34}$$

As a result, taking into account (20), we obtain from (33) the expression for the Laplace transform of the Poisson measure

$$\begin{aligned}\int_\Gamma e^{-\langle\varphi,\gamma\rangle}\,d\pi_\rho(\gamma) &= \int_{\Gamma_0} e_\lambda\big(e^{-\varphi(x)}-1,\eta\big)e_\lambda(\rho,\eta)\,d\lambda(\eta)\\ &= \exp\Big\{-\int_{\mathbb{R}^d}\big(1-e^{-\varphi(x)}\big)\rho(x)dx\Big\}, \qquad \varphi\in C_0(\mathbb{R}^d).\end{aligned} \tag{35}$$

Remark 2.7. Of course, to obtain convergence of the expansion (33) for, say, $f\in L^1(\mathbb{R}^d,dx)$ we need some bounds for the correlation functions $k_\mu^{(n)}$. For example, if the generalized Ruelle bound holds, that is, cf. (22),

$$k_\mu^{(n)}(x_1,\dots,x_n)\le AC^n(n!)^{1-\delta}, \quad x_1,\dots,x_n\in\mathbb{R}^d \tag{36}$$

for some $A,C>0$, $\delta\in(0,1]$ independent on n, then the l.h.s. of (33) may be estimated by the expression

$$1+A\sum_{n=1}^\infty \frac{\big(C\|f\|_{L^1(\mathbb{R}^d)}\big)^n}{(n!)^\delta} < \infty.$$

For a given system of functions $k^{(n)}$ on $(\mathbb{R}^d)^n$ the question about existence and uniqueness of a probability measure μ on Γ which has correlation functions $k_\mu^{(n)} = k^{(n)}$ is an analog of the moment problem in classical analysis. One of the group of results in this area was obtained by A. Lenard.

Proposition 2.3 ([39], [37]). *Let $k : \Gamma_0 \to \mathbb{R}$.*

1. *Suppose that k is a positive definite function, that means that for any $G \in B_{\rm bs}(\Gamma_0)$ such that $(KG)(\gamma) \geq 0$ for all $\gamma \in \Gamma$ the following inequality holds*

$$\int_{\Gamma_0} G(\eta)k(\eta)\, d\lambda(\eta) \geq 0. \tag{37}$$

Suppose also that $k(\emptyset) = 1$. Then there exists at least one measure $\mu \in \mathcal{M}^1_{\rm fm}(\Gamma)$ such that $k = k_\mu$.

2. *For any $n \in \mathbb{N}$, $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$, we set*

$$s^\Lambda_n := \frac{1}{n!} \int_{\Lambda^n} k^{(n)}(x_1, \dots, x_n)\, dx_1 \dots dx_n.$$

Suppose that for all $m \in \mathbb{N}$, $\Lambda \in \mathcal{B}_{\rm b}(\mathbb{R}^d)$

$$\sum_{n\in\mathbb{N}} \left(s^\Lambda_{n+m}\right)^{-\frac{1}{n}} = \infty. \tag{38}$$

Then there exists at most one measure $\mu \in \mathcal{M}^1_{\rm fm}(\Gamma)$ such that $k = k_\mu$.

Remark 2.8. 1. In [37, 39], the wider space of multiple configurations was considered. The adaptation for the space Γ was realized in [36].

2. It is worth noting also that the growth of correlation functions $k^{(n)}$ up to $(n!)^2$ is admissible to have (38).

3. Another conditions for existence and uniqueness for the moment problem on Γ were srudied in [31].

3 Statistical descriptions of Markov evolutions

Spatial Markov processes in $\mathbb{R}^d$ may be described as stochastic evolutions of configurations $\gamma \subset \mathbb{R}^d$. In course of such evolutions points of configurations may disappear (die), move (continuously or with jumps from one position to another), or new particles may appear in a configuration (that is birth). The rates of these random events may depend on whole configuration that reflect an interaction between elements of the our system.

The construction of a spatial Markov process in the continuum is highly difficult question which is not solved in a full generality at present, see e.g. a review [49] and more detail references about birth-and-death processes in [18] and in the next Section. Meanwhile, for the discrete systems the corresponding processes are constructed under quite general assumptions, see e.g. [41]. One of the main difficulties for continuous systems includes the necessity to control number of elements in a bounded region. Note that the construction of spatial processes on bounded sets from $\mathbb{R}^d$ are typically well solved, see e.g. [25].

The existing Markov process $\Gamma \ni \gamma \mapsto X^\gamma_t \in \Gamma$, $t > 0$ provides solution to the backward Kolmogorov equation for bounded continuous functions:

$$\frac{\partial}{\partial t} F_t = LF_t, \tag{39}$$

where L is the Markov generator of the process X_t. The question about existence and properties of solutions to (39) in proper spaces itself is also highly nontrivial problem of infinite-dimensional analysis. The Markov generator L should satisfies the following two (informal) properties: 1) to be conservative, that is $L1 = 0$, 2) maximum principle, namely, if there exists $\gamma_0 \in \Gamma$ such that $F(\gamma) \le F(\gamma_0)$ for all $\gamma \in \Gamma$, then $(LF)(\gamma_0) \le 0$. These properties might yield that the semigroup, related to (39) (provided it exists), will preserves constants and positive functions, correspondingly.

To consider an example of such L let us consider a general Markov evolution with appearing and disappearing of groups of points (giving up the case of continuous moving of particles). Namely, let $F \in \mathcal{F}_{\rm cyl}(\Gamma)$ and set

$$(LF)(\gamma) = \sum_{\eta \Subset \gamma} \int_{\Gamma_0} c(\eta, \xi, \gamma \setminus \eta) \big[F((\gamma \setminus \eta) \cup \xi) - F(\gamma)\big] \, d\lambda(\xi). \tag{40}$$

Heuristically, it means that any finite group η of points from the existing configuration γ may disappear and simultaneously a new group ξ of points may appear somewhere in the space $\mathbb{R}^d$. The rate of this random event is equal to $c(\eta, \xi, \gamma \setminus \eta) \ge 0$. We need some minimal conditions on the rate c to guarantee that at least

$$LF \in \mathcal{F}_0(\Gamma) \qquad \text{for all } F \in \mathcal{F}_{\rm cyl}(\Gamma). \tag{41}$$

The term in the sum in (40) with $\eta = \emptyset$ corresponds to a pure birth of a finite group ξ of points whereas the part of integral corresponding to $\xi = \emptyset$ (recall that $\lambda(\{\emptyset\}) = 1$) is related to pure death of a finite sub-configuration $\eta \subset \gamma$. The parts with $|\eta| = |\xi| \neq 0$ corresponds to jumps of one group of points into another positions in $\mathbb{R}^d$. The rest parts present splitting and merging effects. In the next section we consider the more traditional case of the one-point birth-and-death parts only, i.e. the cases $|\eta| = 0$, $|\xi| = 1$ and $|\eta| = 1$, $|\xi| = 0$, correspondingly.

As we noted before, for most cases appearing in applications, the existence problem for a corresponding Markov process with a generator L is still open. On the other hand, the evolution of a state in the course of a stochastic dynamics is an important question in its own right. A mathematical formulation of this question may be realized through the forward Kolmogorov equation for probability measures (states) on the configuration space Γ. Namely, we consider the pairing between functions and measures on Γ given by

$$\langle F, \mu \rangle := \int_\Gamma F(\gamma) \, d\mu(\gamma). \tag{42}$$

Then we consider the initial value problem

$$\frac{d}{dt}\langle F, \mu_t \rangle = \langle LF, \mu_t \rangle, \quad t > 0, \quad \mu_t\big|_{t=0} = \mu_0, \tag{43}$$

where F is an arbitrary function from a proper set, e.g. $F \in K\big(B_{\rm bs}(\Gamma_0)\big) \subset \mathcal{F}_{\rm cyl}(\Gamma)$. In fact, the solution to (43) describes the time evolution of distributions instead of the evolution of initial points in the Markov process. We rewrite (43) in the following heuristic form

$$\frac{\partial}{\partial t}\mu_t = L^* \mu_t, \tag{44}$$

where L^* is the (informally) adjoint operator of L with respect to the pairing (42).

In the physical literature, (44) is referred to the *Fokker–Planck equation*. The Markovian property of L yields that (44) might have a solution in the class of probability measures. However, the mere existence of the corresponding Markov process will not give us much information about properties of the solution to (44), in particular, about its moments or correlation functions. To do this, we suppose now that a solution $\mu_t \in \mathcal{M}^1_{\mathrm{fm}}(\Gamma)$ to (43) exists and remains locally absolutely continuous with respect to the Poisson measure π for all $t > 0$ provided μ_0 has such a property. Then one can consider the correlation functionals $k_t := k_{\mu_t}$, $t \geq 0$.

Recall that we suppose (41). Then, one can calculate $K^{-1}LF$ using (29), and, by (31), we may rewrite (43) in the following way

$$\frac{d}{dt}\langle\!\langle K^{-1}F, k_t\rangle\!\rangle = \langle\!\langle K^{-1}LF, k_t\rangle\!\rangle, \quad t > 0, \quad k_t\big|_{t=0} = k_0, \tag{45}$$

for all $F \in K\big(B_{\mathrm{bs}}(\Gamma_0)\big) \subset \mathcal{F}_{\mathrm{cyl}}(\Gamma)$. Here the pairing between functions on Γ_0 is given by

$$\langle\!\langle G,\, k\rangle\!\rangle := \int_{\Gamma_0} G(\eta)k(\eta)\, d\lambda(\eta). \tag{46}$$

Let us recall that then, by (25),

$$\langle\!\langle G, k\rangle\!\rangle = \sum_{n=0}^{\infty} \frac{1}{n!} \int_{(\mathbb{R}^d)^n} G^{(n)}(x_1, \dots, x_n)k^{(n)}(x_1, \dots, x_n)\, dx_1 \dots dx_n, \tag{47}$$

Next, if we substitute $F = KG$, $G \in B_{\mathrm{bs}}(\Gamma_0)$ in (45), we derive

$$\frac{d}{dt}\langle\!\langle G, k_t\rangle\!\rangle = \langle\!\langle \widehat{L}G, k_t\rangle\!\rangle, \quad t > 0, \quad k_t\big|_{t=0} = k_0, \tag{48}$$

for all $G \in B_{\mathrm{bs}}(\Gamma_0)$. Here the operator

$$(\widehat{L}G)(\eta) := (K^{-1}LKG)(\eta), \quad \eta \in \Gamma_0 \tag{49}$$

is defined point-wise for all $G \in B_{\mathrm{bs}}(\Gamma_0)$ under conditions (41). As a result, we are interested in a weak solution to the equation

$$\frac{\partial}{\partial t}k_t = \widehat{L}^* k_t, \quad t > 0, \quad k_t\big|_{t=0} = k_0, \tag{50}$$

where $\widehat{L}^*$ is dual operator to $\widehat{L}$ with respect to the duality (46), namely,

$$\int_{\Gamma_0} (\widehat{L}G)(\eta)k(\eta)\, d\lambda(\eta) = \int_{\Gamma_0} G(\eta)(\widehat{L}^* k)(\eta)\, d\lambda(\eta). \tag{51}$$

The procedure of deriving the operator $\widehat{L}$ for a given L is fully combinatorial meanwhile to obtain the expression for the operator $\widehat{L}^*$ we need an analog of integration by parts formula. For a difference operator L considered in (40) this discrete integration by parts rule is presented in the following well-known lemma (see e.g. [35]):

Lemma 3.1. *For any measurable function* $H : \Gamma_0 \times \Gamma_0 \times \Gamma_0 \to \mathbb{R}$

$$\int_{\Gamma_0} \sum_{\xi \subset \eta} H(\xi, \eta \setminus \xi, \eta)\, d\lambda(\eta) = \int_{\Gamma_0} \int_{\Gamma_0} H(\xi, \eta, \eta \cup \xi)\, d\lambda(\xi)\, d\lambda(\eta) \tag{52}$$

if both sides of the equality make sense.

We recall that any function function on Γ_0 may be identified with an infinite vector of symmetric functions of the growing number of variables. In this approach, the operator $\widehat{L}^*$ in (50) will be realized as an infinite matrix $\big(\widehat{L}^*_{n,m}\big)_{n,m\in\mathbb{N}_0}$, where $\widehat{L}^*_{n,m}$ is a mapping from the space of symmetric functions of n variables into the space of symmetric functions of m variables. As a result, instead of equation (43) for infinite-dimensional objects we obtain an infinite system of equations for functions $k_t^{(n)}$ each of them is a function of a finite number of variables, namely

$$\begin{aligned} &\frac{\partial}{\partial t} k_t^{(n)}(x_1, \dots, x_n) = \big(\widehat{L}^*_{n,m} k_t^{(n)}\big)(x_1, \dots, x_n), \quad t > 0, \quad n \in \mathbb{N}_0, \\ &k_t^{(n)}(x_1, \dots, x_n)\big|_{t=0} = k_0^{(n)}(x_1, \dots, x_n). \end{aligned} \tag{53}$$

Of course, in general, for a fixed n, any equation from (53) itself is not closed and includes functions $k_t^{(m)}$ of other orders $m \neq n$, nevertheless, the system (53) is a closed linear system. The chain evolution equations for $k_t^{(n)}$ consists the so-called *hierarchy* which is an analog of the BBGKY hierarchy for Hamiltonian systems, see e.g. [11].

One of the main aims of our considerations is to study the classical solution to (50) in a proper functional space. The choice of such a space might be based on estimates (22), or more generally, (36). However, even the correlation functions (21) of the Poisson measures shows that it is rather natural to study the solutions to the equation (50) in weighted L^∞-type space of functions with the Ruelle-type bounds. The integrable correlation functions are not natural for the dynamics on the spaces of locally finite configurations. For example, it is well-known that the Poisson measure π_ρ with integrable density $\rho(x)$ is concentrated on the space Γ_0 of finite configurations (since in this case on can consider $\mathbb{R}^d$ instead of Λ in (9)). Therefore, typically, the case of integrable correlation functions yields that effectively our stochastic dynamics evolves through finite configurations only. Note that the case of an integrable first order correlation function is referred to *zero density* case in statistical physics.

We restrict our attention to the so-called *sub-Poissonian* correlation functions. Namely, for a given $C > 0$ we consider the following Banach space

$$\mathcal{K}_C := \big\{ k : \Gamma_0 \to \mathbb{R} \;\big|\; k \cdot C^{-|\cdot|} \in L^\infty(\Gamma_0, d\lambda) \big\} \tag{54}$$

with the norm

$$\|k\|_{\mathcal{K}_C} := \|C^{-|\cdot|} k(\cdot)\|_{L^\infty(\Gamma_0, \lambda)}. \tag{55}$$

It is clear that $k \in \mathcal{K}_C$ implies, cf. (22),

$$\big|k(\eta)\big| \leq \|k\|_{\mathcal{K}_C}\, C^{|\eta|} \qquad \text{for } \lambda\text{-a.a. } \eta \in \Gamma_0. \tag{56}$$

One can distinguish at least two possibilities for a study of the initial value problem (50). We may try to solve this equation in one space $\mathcal{K}_C$. The well-posedness of the initial value problem in this case is equivalent with an existence

of the strongly continuous semigroup (C_0-semigroup in the sequel) in the space $\mathcal{K}_C$ with a generator $\widehat{L}^*$. However, the space $\mathcal{K}_C$ is isometrically isomorphic to the space $L^\infty(\Gamma_0, C^{|\cdot|}d\lambda)$ whereas, by the H. Lotz theorem [43], [3], in the L^∞ space any C_0-semigroup is uniformly continuous, that is it has a bounded generator. Typically, for the difference operator L given in (40), any operator $\widehat{L}^*_{n,m}$, cf. (53), might be bounded as an operator between two spaces of bounded symmetric functions of n and m variables whereas the whole operator $\widehat{L}^*$ is unbounded in $\mathcal{K}_C$.

To avoid this difficulties we use a trick which goes back to R. Phillips [50]. The main idea is to consider the semigroup in L^∞ space not itself but as a dual semigroup T^*_t to a C_0-semigroup T_t with a generator A in the pre-dual L^1 space. In this case T^*_t appears strongly continuous semigroup not on the whole L^∞ but on the closure of the domain of A^* only.

In our case this leads to the following scheme. We consider the pre-dual Banach space to $\mathcal{K}_C$, namely, for $C > 0$,

$$\mathcal{L}_C := L^1\big(\Gamma_0, C^{|\cdot|}d\lambda\big). \tag{57}$$

The norm in $\mathcal{L}_C$ is given by

$$\|G\|_C := \int_{\Gamma_0} \big|G(\eta)\big|C^{|\eta|}\, d\lambda(\eta) = \sum_{n=0}^{\infty} \frac{C^n}{n!} \int_{(\mathbb{R}^d)^n} \big|G^{(n)}(x_1, \dots, x_n)\big|\, dx_1 \dots dx_n. \tag{58}$$

Consider the initial value problem, cf. (48), (50),

$$\frac{\partial}{\partial t} G_t = \widehat{L} G_t, \quad t > 0, \quad G_t\big|_{t=0} = G_0 \in \mathcal{L}_C. \tag{59}$$

Whereas (59) is well-posed in $\mathcal{L}_C$ there exists a C_0-semigroup $\widehat{T}(t)$ in $\mathcal{L}_C$. Then using Philips' result we obtain that the restriction of the dual semigroup $\widehat{T}^*(t)$ onto $\overline{\mathrm{Dom}(\widehat{L}^*)}$ will be C_0-semigroup with generator which is a part of $\widehat{L}^*$. This provides a solution to (50) which continuously depends on an initial data from $\overline{\mathrm{Dom}(\widehat{L}^*)}$. And after we would like to find a more useful universal subspace of $\mathcal{K}_C$ which is not depend on the operator $\widehat{L}^*$. As a result, we obtain the classical solution to (50) for $t > 0$ in a class of sub-Poissonian functions which satisfy the Ruelle-type bound (56). Of course, after this we need to verify existence and uniqueness of measures whose correlation functions are solutions to (50), cf. Proposition 2.3 above. This usually can be done using proper approximation schemes.

Another possibility for a study of the initial value problem (50) is to consider this evolutional equation in a proper scale of spaces $\{\mathcal{K}_C\}_{C_* \le C \le C^*}$. In this case we will have typically that the solution is local in time only. Namely, there exists $T > 0$ such that for any $t \in [0, T)$ there exists a unique solution to (50) and $k_t \in \mathcal{K}_{C_t}$ for some $C_t \in [C_*, C^*]$. We realize this approach using the so-called Ovsyannikov method [21, 48]. This method provides less restrictions on systems parameters, however, the price for this is a finite time interval. And, of course, the question about possibility to recover measures via solutions to (50) should be also solved separately in this case.

4 Birth-and-death evolutions in the continuum

One of the most important classes of Markov evolution in the continuum is given by the birth-and-death Markov processes in the space Γ of all configurations from $\mathbb{R}^d$. These are processes in which an infinite number of individuals exist at each instant, and the rates at which new individuals appear and some old ones disappear depend on the instantaneous configuration of existing individuals [29]. The corresponding Markov generators have a natural heuristic representation in terms of birth and death intensities. The birth intensity $b(x,\gamma) \geq 0$ characterizes the appearance of a new point at $x \in \mathbb{R}^d$ in the presence of a given configuration $\gamma \in \Gamma$. The death intensity $d(x,\gamma) \geq 0$ characterizes the probability of the event that the point x of the configuration γ disappears, depending on the location of the remaining points of the configuration, $\gamma \setminus x$. Heuristically, the corresponding Markov generator is described by the following expression, cf. (40),

$$(LF)(\gamma) := \sum_{x\in\gamma} d(x,\gamma\setminus x)\,[F(\gamma\setminus x) - F(\gamma)] + \int_{\mathbb{R}^d} b(x,\gamma)\,[F(\gamma\cup x) - F(\gamma)]\,dx, \quad (60)$$

for proper functions $F : \Gamma \to \mathbb{R}$.

The study of spatial birth-and-death processes was initiated by C. Preston [51]. This paper dealt with a solution of the backward Kolmogorov equation (39) under the restriction that only a finite number of individuals are alive at each moment of time. Under certain conditions, corresponding processes exist and are temporally ergodic, that is, there exists a unique stationary distribution. Note that a more general setting for birth-and-death processes only requires that the number of points in any compact set remains finite at all times. A further progress in the study of these processes was achieved by R. Holley and D. Stroock in [29]. They described in detail an analytic framework for birth-and-death dynamics. In particular, they analyzed the case of a birth-and-death process in a bounded region.

Stochastic equations for spatial birth-and-death processes were formulated in [26], through a spatial version of the time-change approach. Further, in [27], these processes were represented as solutions to a system of stochastic equations, and conditions for the existence and uniqueness of solutions to these equations, as well as for the corresponding martingale problems, were given. Unfortunately, quite restrictive assumptions on the birth and death rates in [27] do not allow an application of these results to several particular models that are interesting for applications (see e.g. [6, 7, 10, 19, 45, 47]).

A growing interest to the study of spatial birth-and-death processes, which we have recently observed, is stimulated by (among others) an important role which these processes play in several applications. For example, in spatial plant ecology, a general approach to the so-called individual based models was developed in a series of works, see e.g. [6, 7, 10, 45] and the references therein. These models are described as birth-and-death Markov processes in the configuration space Γ with specific rates b and d which reflect biological notions such as competition, establishment, fecundity etc. Other examples of birth-

and-death processes may be found in mathematical physics. In particular, the Glauber-type stochastic dynamics in Γ is properly associated with the grand canonical Gibbs measures for classical gases. This gives a possibility to study these Gibbs measures as equilibrium states for specific birth-and-death Markov evolutions [4]. Starting with a Dirichlet form for a given Gibbs measure, one can consider an equilibrium stochastic dynamics [34]. However, these dynamics give the time evolution of initial distributions from a quite narrow class. Namely, the class of admissible initial distributions is essentially reduced to the states which are absolutely continuous with respect to the invariant measure. In [18], we construct non-equilibrium stochastic dynamics which may have a much wider class of initial states.

This approach was successfully applied before to the construction and analysis of state evolutions for different versions of the Glauber dynamics [17, 20, 33] and for some spatial ecology models [16]. Each of the considered models required its own specific version of the construction of a semigroup, which takes into account particular properties of corresponding birth and death rates.

In [18], we realized a general approach considered in Section 2 to the construction of the state evolution corresponding to the birth-and-death Markov generators. We presented there conditions on the birth and death intensities which are sufficient for the existence of corresponding evolutions as strongly continuous semigroups in proper Banach spaces of correlation functions satisfying the Ruelle-type bounds. Also, in papers [15, 21, 22], we considered weaker assumptions on these intensities which provide the corresponding evolutions for finite time intervals in scales of Banach spaces as above.

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Interdisciplinary Studies of Complex Systems
Vol. 1, No. 1 (2012) 33–54

Control of multiscale systems with constraints
1. Basic principles of the concept of evolution of systems with varying constraints

S. Adamenko,[1] *V. Bolotov,*[2] *V. Novikov*[3]

Abstract. Physical fundamentals of the self-organizing theory for the system with varying constraints are considered. A variation principle, specifically the principle of dynamic harmonization as a generalization of the Gauss-Hertz principle for the systems with varying internal structure is formulated. In compliance with this principle the system evolves through dynamics of the processes leading to harmonization of the internal multiscale structure of the system and its connections with external actions as a result of minimizing the dynamic harmonization function. Main principles of the 'shell' model of self-organization under the action of the dominating entropic disturbance are formulated.

1 Introduction

People for many centuries have been concerned with the problems of predictability and predeterminacy of events or, in other more general terms, with the problems of irreversible evolution and invention of methods to influence evolution in a desirable way. Revolutionary steps in understanding the processes of evolution and self-organization of the systems of various types were made in the second half of the previous century. I. Prigogine and his school greatly contributed in resolving these problems. The interest to these problems has quickened in the recent times.

For a long time science has mainly focused on analysis of the Nature phenomena, however now is the time when the problems of synthesis and control become especially urgent. Solution of the mankind energy problems is related to solution of the problem on actual control for the nuclear structure synthesis. However, despite of successes gained in the evolution theory, still there is a lack of clear understanding of general laws of control for synthesis of new structures and evolution trends, neither there are considerable advances in synthesizing nuclear structures. Problems of controlling evolution trends have not yet been solved and it is still impossible to reliably predict consequences of technogeous interventions in the Nature evolution.

[1] Electrodynamics Laboratory *Proton-21*
[2] V. Karazin National University of Kharkov
[3] The Institute of Electrophysics and Radiation Technologies of the National Academy of Sciences of Ukraine

At the same time ongoing successful synthesis of new biological structures and development of technologies for creation of the gene-modified objects without clear understanding of their remote consequences for the biological evolution enhances the potential environmental threats.

I. Prigogine's works made it clear that in certain conditions under rapid growth of electromagnetic pollutions our influence on the evolution may be only inconsiderable, thus generating concerns with unpredictability of electromagnetic smog as an unconscious stimulus for the biological evolution with unpredictable consequences. There is a long-felt need to address the problem of controlling self-organization in various systems consisting of various elements.

One of the most general definitions of the system as a set of interrelated components proposed by L. Bertalanffy in the general systems theory already contains a notion of interplay between the elements, i.e. connections. Constraints or conditions disallowing the systems elements to occupy arbitrary positions or have arbitrary velocities or other characteristics are called constraints. These are the constraints that ensure the system's wholeness, structure and stability. Evolution of the system presents, in its turn, evolution of the systems' inner structure, i.e. evolution of the system's constraints.

Unfortunately, the current self-organization theory does not use either generalized structure parameters or bonding energy and mass defects as basic variables. To our opinion, this factor is the limitation of the available dynamic systems evolution theory, which does not allow its effective application for governing the synthesis processes. Understanding of self-organization in any system as a purposeful process of varying structure and bonding energy as well as formulation of a general variation principle governing the open systems evolution serve the grounds for the theory we are developing.

Recognizing specifics in governing evolution of various systems we see common ways for solution of these problems in various spheres of knowledge from cosmology to nuclear physics and from biology to sociology.

We are offering for your attention a series of works, which state the general concept of evolution of complex systems with varying constraints and show some applications of this concept for creating new methods of governing synthesis of new structures in these systems.

The works [1–2] report the prehistory of creating the concept of collective controlled synthesis of new nuclear structures with definite energy directiveness and provide its fundamental principles based on the use of the following:

- Notions of binding energy and mass defect;
- Notions of mass forces and accelerations;
- Relations of the sign of mass defect and accelerations;
- Collective processes for effective initiation and control of the synthesis of systems with the required mass defect;
- Variation principle of the complex systems evolution—the principle of dynamic harmonization.

A notion of dissipative structures introduced by Prigogine (see, for example [3]) proved very useful in many spheres of science and engineering. Essential aspects of the dynamic systems control theory are developed in the framework of the theory of chaos, fractal physics and synergetics with their successful application in many spheres of science and technology. Nuclear physics is prac-

tically the only science where the notions of the theory of dissipative structures, dynamic chaos and self-organization are not yet effectively applicable, while solution of the problems on nucleosynthesis control is vital for obtaining answers to the following questions:

- How to solve the problem of the world's growing energy needs in the most harmonious and environmentally friendly way?
- What key phenomena and effects can serve as a basis for creating new efficient energy technologies and governing the potential energy opportunities in the surrounding Nature?

On the other hand, development of the theory of complex systems self-organization is hindered by the fact that such physical values as bonding energy and mass defect defining energy potential in any physical processes and being widely used in the nuclear physics are not yet employed in the theory of evolution.

We will try to include these new aspects into the complex systems self-organization theory in these series of works. We will provide in this work physical substantiation of the concept basic principles while theoretical development of these concepts will be reported in the next two works.

2 Main notions of the concept: bonding energy, structure, mass defect, scaling, fractal dimension and clusters

All primary energy sources in Nature have common basis, namely the processes of the system bonding energy variation. This is related both to the most common energy sources based on transformation of the bonding energy at the atomic and molecular levels, for example in organic fuel combustion, and in nuclear processes generated by the variation of the bonding energy of nucleons in the atom nuclei during nuclear reactions.

Under the bonding energy B of a system consisting of i components (particles) one understands the difference between the apparent energy of a system of bodies or particles W and the total energy of the same bodies or particles in the state of equilibrium in the absence of any interaction $\sum\limits_i W_i$:

$$B = \sum_i W_i - W, \tag{1}$$

where W_i — apparent energy of i component in the unbound rest state. Mass defect of the system Δm is the difference between the sum of the system elements masses m_i and total mass of the system m

$$\Delta m = \sum_i m_i - m. \tag{2}$$

Mass defect of the system is characterized by its stability. In addition to mass, the system inertia in response to the forces acting on the system is its another most significant characteristic. Mass of the system depends on its structure and relations within it, and determines inertia of the system at

rest. Inertia in contrast to the mass depends on the coordinate system (see, for example [4]).

With all versatility of particles and systems motions, the latter may be classified. Nature abounds with periodic regular phenomena ranging from pendulum motion to atomic oscillations. Most of the real phenomena are non-linear and instead of periodicity produce aperiodic and chaotic motions while the generated geometric structures are not continuous. With all variety of nonlinear evolution there are general properties uniting many of them, which are self-similarity and invariance in relation to the scale variations (scaling). Scaling manifests itself in many non-linear physical processes, especially when studying critical phenomena characterizing behavior of the substances in the vicinity of the phase transition points.

Proceeding from the general definition of the system it follows at once that the system has at least two spatial scales—internal microscopic scale L, determining its specific dimensions as an integral object, and minimal spatial scale l_1, related to specific dimensions of minimal system elements (monomers) being the parts of the system. In this case monomers are considered as objects without internal structure. Thus, the most important characteristics of the system for general analysis of self-organization are as follows:

- Space limitation and, thus, its space scale;
- Internal structure of its relations and complexity, that may be appropriately characterized by any of the fractal dimensions;
- Space and mass characteristics of the structural elements of the system (monomers).

Clusters of various scales are a general model of such systems [5]. One may say that the systems evolves through formation of mesoscopic structures, which are clusters with scales l_i satisfying the inequality $l_1 \ll l_i \ll L$.

Growth of the structure from a A set of monomers naturally divides the system into two parts—the structured one consisting of A_{cog} monomers and the structureless one consisting of the remaining $A_g = A - A_{cog}$ monomers. A proportion of all monomers in composition of the structured part is called 'order parameter' $\eta \approx A_{cog}/(A_{cog} + A_g)$.

Thus, the system evolution results in formation of the cluster consisting of monomers. This cluster is composed of elements, which in their turn are fractal clusters of a smaller scale l_i from A_i monomers. Multiscale systems possessing scale invariance in the sphere of $l_1 \ll l_i \ll L$ scales are the most important for implementing control processes.

In the general case, constraints in the system and their complexity may be characterized by a fractural dimensions, for example, connectedness dimension D_c, determined by the structure of constraints or mass fractal dimension of the system D_f, determined by distribution of the substance in the system [6]. Dependence of the angle-averaged correlation function on a distance from its geometrical center is one of the exponential functions typical for the fractal. In this case average density of particles in the cluster $\rho(r)$ with moving away from the center within the cluster varies according to the law complying with the law of space correlations decay:

$$\rho(r) = \rho_m (l_m/r)^{3-D_f}, \tag{3}$$

ρ_m—density of monomers from which the fractal structure is composed.

From these general correlations of the fractal geometry a simple correlation between the mass number of the fractal cluster A (i.e., the number of monomers of which the cluster consists), the cluster overall dimension R_A and the monomers characteristic dimension l_m follows:

$$A \propto (R_A/l_m)^{D_f}, \text{ or } R_A = l_m A^{1/D_f}. \tag{4}$$

From the correlation (3) it also follows a dependence of the fractal dimension of the cluster with the mass number A and its average density ρ on the mass number A_m and density ρ_m of the structureless units—monomers of which the cluster is composed:

$$D_f = 3\frac{\ln(A/A_m)}{\ln(A/A_m) + \ln(\rho_m/\rho)}, \quad \rho = \rho_m \left(\frac{A_m}{A}\right)^{\frac{3-D_f}{D_f}} \tag{5}$$

The fractal dimension characterizes properties of the system's scale invariance related to the system's coherence parameter. Let us estimate correlation between the coherence parameter and the fractal dimension.

The coherent part of the system in the sufficiently general case may be considered as a fractal cluster. Since the potential energy of the substance is mainly proportional to the density, then it obeys the exponential law (3), true for the cluster substance. That is, the cluster potential energy is the function with the similarity coefficient $k_{sc} = D_f - 3$: $U(r) \propto \rho(r) \propto r^{k_{sc}}$, i.e. $U(\alpha r) = \alpha^{k_{sc}} U(r)$. From the virial theorem for the systems with potential energy possessing similarity a correlation between the mean values of the kinetic $\overline{W_{kin}}$ and potential energies $\overline{U}$ satisfies the equality $\dfrac{\overline{W_{kin}}}{\overline{U}} = \dfrac{k_{sc}}{2}$. If it is remembered that the coherent part possesses mainly the potential energy, while all kinetic energy is concentrated in the non-regular and non-coherent component, then one may obtain the estimate of the order parameter $\eta \approx \bar{U} \,/\, (\overline{W_{kin}} + \bar{U}) = 1 \,/\, \left(1 + \dfrac{k_{sc}}{2}\right)$. Whence it follows:

$$\eta \approx (3 - D_f)/(D_f - 1), \quad 0 \leqslant \eta \leqslant 1. \tag{6}$$

Each stage of the scales hierarchy ranging from the largest to the smallest scale may have its own order parameters. If the order parameters at different scales proved to be connected, then one may state that a whole multi-scale macroscopic object appeared.

3 Bonding energy in a system of particles with internal cluster structure

Let us consider a simple but at the same time important example of the classical multi-scale systems—a system of many correlating particles capable to transform the cluster structure inside the system. The simplest general model of such systems may be represented by a drop of liquid composed of A molecules able for form clusters of several molecules.

We will denote these clusters A_m, where m—the number of molecules in the cluster. These clusters in their turn may create the dendrite structure with the fractal dimension D_f. It means that the drop itself is a multi-scale macroscopic object composed of the coherent part formed by the dendrite of monomers A_m, comprising ηA molecules, and structureless liquid part of $(1-\eta)A$ molecules.

Correlation of the liquid molecules may be approximately described by the Lennard-Jones potential

$$U(r) = \varepsilon_0 \left((r_{\min}/r)^{12} - 2(r_{\min}/r)^6 \right), \tag{7}$$

which corresponds to the molecules attraction at sufficiently large distances $r \gg r_{\min}$ and their sharp repulsion at smaller distances $r \ll r_{\min}$. Such correlation pattern provides integrity to the system of molecules with typical distances between them $r_{\min}$ and positive energy of bonds between the molecules of the order ε_0.

Full volumetric bonding energy B_v of the liquid drop is determined by the integral $B_v = \int U(r-r')\,\rho(r)\rho(r')\,d^3r d^3r'$ and because of sharp repulsion at smaller distances it proves proportional not to the square but to the first order of the molecules quantity in the drop A. Corrections grow along with density because the system of particles is not ideal [7] and it may be written as:

$$B_v \approx g_0 A + a_0 \rho^{2/3} A, \quad g_0 \approx \varepsilon_0. \tag{8}$$

According to the principles of a simple and effective classical Ya. Frenkel theory of the liquid drop [8] in addition to the indicated positive contribution to the bonding energy there is a negative contribution from the surface energy of the interface boundary B_{surf}, which is proportional to the boundary square S_{drop}:

$$B_{surf} = -\sigma S_{drop}, \quad S_{drop} = 4\pi R_A^2 (A/A_m)^{2/D_f - 2/3}, \quad R_A = l_m \left(\frac{A}{A_m} \right)^{1/3}. \tag{9}$$

The system of particles in addition to the potential energy has a kinetic energy of the chaotic motion B_{kin} with temperature T, reducing the bonding energy of the cluster $B_{kin} = -\dfrac{3}{2} T \left(\dfrac{A}{A_m} \right)$. Using for estimation a general polytropic process $\dfrac{T}{\rho^{\gamma-1}} = const$ with an indicator γ:

$$B_{kin} = -a_T \left(\frac{\rho}{\rho_m} \right)^{\gamma-1} A \tag{10}$$

If a part of the system is ionized and has the charge Z, then instead of one component of the system with the density ρ, there appear three ones—neutral with density ρ_0, a positively charged component with density ρ_Z and electron component with density ρ_{el}: $\rho_0 = \dfrac{A-Z}{A}\rho$, $\rho_Z = \dfrac{Z}{A}\rho$.

Contributions to the volumetric part of the bonding energy and to the kinetic energy of the neutral and charged component take the form:

$$\begin{aligned}
B_v &\approx g_0 A + a_0 \rho_0^{2/3} (A - Z) + a_0 \rho_Z^{2/3} Z \\
&= g_0 A + a_0 \rho_m^{2/3} \left(\left(1 - \frac{Z}{A} \right)^{5/3} + \left(\frac{Z}{A} \right)^{5/3} \right) \left(\frac{A_m}{A} \right)^{\frac{2}{3} \frac{(3 - D_f)}{D_f}} A, \\
B_{kin} &= -a_T \left(\frac{\rho}{\rho_m} \right)^{\gamma - 1}, \\
A &= -a_T \left(\frac{\rho_0}{\rho_m} \right)^{\gamma - 1} (A - Z) - a_T \left(\frac{\rho_Z}{\rho_m} \right)^{\gamma - 1}, \\
Z &= -a_T \rho_m^{\gamma - 1} \left(\left(1 - \frac{Z}{A} \right)^{\gamma} + \left(\frac{Z}{A} \right)^{\gamma} \right) \left(\frac{A_m}{A} \right)^{(\gamma - 1) \frac{3 - D_f}{D_f}} A.
\end{aligned} \tag{11}$$

Moreover, new contributions appear in the bonding energy—bonding energy resulted from the Coulomb repulsion of the like-charged particles B_q and bonding energy of electrons B_{el} (calculated in approximation of the degenerate electron Fermi—liquid with regard of quasi-neutrality):

$$B_q = -\frac{3}{5} \frac{e^2 Z (Z - 1)}{R_A (A/A_m)^{1/D_f - 1/3}}, \qquad B_{el} = -\frac{3}{4} a_\varepsilon \left(\frac{\rho}{\rho_m} \right)^{4/3} \left(\frac{Z}{A} \right)^{4/3} \tag{12}$$

By introducing a variable $y = \dfrac{1}{2} - \dfrac{Z}{A}$, one may take advantage of a convenient approximation:

$$\begin{aligned}
\left(1 - \frac{Z}{A} \right)^{\gamma} + \left(\frac{Z}{A} \right)^{\gamma} = \left(\frac{1}{2} + y \right)^{\gamma} + \left(\frac{1}{2} - y \right)^{\gamma} &\underset{y \ll 1}{\approx} 2^{1 - \gamma} + \gamma (\gamma - 1) y^2 \\
&= 2^{1 - \gamma} + \frac{\gamma (\gamma - 1)}{4} \left(1 - 2 \frac{Z}{A} \right)^2
\end{aligned}$$

and present the full bonding energy as:

$$B_{drop} = \left(c_0 - c_3 \left(1 - \frac{2Z}{A} \right)^2 \right) A - c_1 A^{2/3} - c_2 \frac{Z^2}{A^{1/3}} - c_{el} \left(\frac{Z}{A} \right)^{4/3}, \tag{13}$$

$$\begin{aligned}
c_0 &= g_0 + a_0 \rho_m^{2/3} \frac{1}{2^{2/3}} \left(\frac{A_m}{A} \right)^{\frac{2}{3} \frac{(3 - D_f)}{D_f}}, \qquad c_1 = 4 \pi \sigma l_m^2 \left(\frac{A}{A_m} \right)^{\frac{2}{D_f}}, \\
c_2 &= \frac{3}{5} \frac{e^2 Z^2}{l_m} \left(\frac{A_m}{A} \right)^{\frac{1}{D_f}}, \qquad c_3 = -\frac{5}{2^{1/3} 9} a_0 \rho_m^{2/3} \left(\frac{A_m}{A} \right)^{\frac{2}{3} \frac{(3 - D_f)}{D_f}}, \\
c_T &= \rho_m \left(\frac{A_m}{A} \right)^{\frac{3 - D_f}{D_f}} T, \qquad c_{el} = \frac{3}{4} a_\varepsilon \left(\rho_m^{4/3} \left(\frac{A_m}{A} \right)^{\frac{4}{3} \frac{3 - D_f}{D_f}} \right).
\end{aligned}$$

Expression for the bonding energy of the drop with the cluster structure (13) allows from the equilibrium condition $\frac{\partial}{\partial Z} B_{drop} = 0$ determining the charge of the quasi-stationary cluster with a maximal bonding energy. This algebraic equation has an exact solution, which may be approximately presented in a simple form:

$$\frac{Z}{A} \approx \frac{1}{2 + \frac{c_2}{2c_3} A^{2/3}}.$$

Evolution of the cluster presents transitions between quasi-stationary states that may be described by the equations of the variation principle of the dynamic harmonization obtained in the end of the work.

4 Mass defect, production of entropy and entropic forces

One of the main problems of the evolution of systems with varying constraints is the problem on the general laws governing variations of the fractal dimension, the order parameter and the system's inner structure over time.

Variation of the fractal dimension D_f is accompanied, according to (13), with variation of the bonding energy and mass defect $\delta m_i \left(D_f\right) = B_i \left(D_f\right) / c^2$. Variation of the mass defect is related to the mass force and corresponding acceleration:

$$F_m = -\frac{\Delta \delta m}{\tau} u_i, \qquad a_m = -\frac{1}{m} \frac{d\delta m}{dt} u_i \approx \bar{\sigma}_s u_i. \tag{14}$$

In the last correlation it is considered that relation of the mass defect to the total mass presents the value approximately equal to the order parameter, while

$$-\frac{1}{m} \frac{d\delta m}{dt} \approx \frac{\delta m}{m} \frac{d}{dt} \left(-\ln \eta\right) \approx \bar{\sigma}_s, \tag{15}$$

where $\bar{\sigma}_s$—average production of the entropy in the system.

Processes of the entropy production and the entropy flows are caused by the entropy forces. Apparently, existence of the entropy flows is conditioned by the entropy gradients and we may determine these forces as follows:

$$F_S = w\left(\eta\right) \nabla S. \tag{16}$$

Coefficient w, depending on the current order parameter η, represents the energy density of the processes related to the entropy flows. In case of the local equilibrium, $w \underset{\eta \to 0}{\longrightarrow} T$ and (16) is in agreement with the expression for the mass entropy forces following from the main correlations of the locally equilibrium thermodynamics.

It is noteworthy that the entropic forces introduced in the work [9], essentially differ from the multi-scale structure-forming entropic forces (16). In (16) the entropy gradient creates the force acting through the forces of the system equally on all its particles, which is the mass force by definition.

Behaviour of the system near the phase transition presents a simple example demonstrating the appearance of the mass force. If to place a new phase nucleus into the supercooled liquid, this will generate the explosive transition to the nucleus phase accompanied by the mass entropy forces. In this case, in contrast to the intermolecular forces, this force is not directly connected with direct correlation between particles, but has a collective nature: as a result of dynamics the systems evolves through temperature-related 'trials and errors' tending to transfer from the less probable state to the more probable one.

Since the dissipative factors may be neglected in the processes of multiscale self-organization under study while energy variations in the system are mainly related to the evolution of the bonding energy in the system under the action of the structure-forming entropic forces, then the arising structures may be called entropic (informational) in contrast to the Prigogine's dissipative structures. It is notable that thereby the system creates a memory on the action of mass entropic forces and even after termination of this action they leave traces as the formed entropic structures whose further dynamics may be determined by the Prigogine's irreversible thermodynamics.

5 Mass forces and flow in the phase space

Approximation of the local equilibrium is based on the assumption that the distribution functions in the variable point of the space in physically infinitesimal volumes have an equilibrium form corresponding to the assumption on the detailed balance with the flow in the phase space equal to 0. In this case the distribution function parameters (temperature, density, the Fermi energy) may depend on the point, while their evolution fully determines the evolution of the disequilibrium states. However, with sufficiently powerful forces and drains corresponding to the flows that exceed the dissipative flows in the system an essentially different physical situation may develop.

The idea about the system's elements—particles as material points causes a number of problems. For example, the electromagnetic field energy is infinite for charged point particles.

Consistent use of the system particles presentation through their distribution in the coordinate space and other kinematic variables (velocities and accelerations) remove these problems [10–12], while the main equations for the system in the collective states are not only dynamic equations of the motion of correlating particles but also kinetic equations for distribution functions of the system's elements. In the next article we will obtain and analyze the kinetic equations as generalization of the Vlasov's kinetic equation for the open systems with varying constraints while here we only give quality observations.

The kinetic equation for the system of particles in absence of external forces may be written as the continuity equation in the phase space

$$\frac{\partial f}{\partial t} + div_r(\vec{j}) = I_{st}, \quad I_{st} = -div_p(\vec{j}), \quad j_i = D_{ij}\frac{\partial f}{\partial p_j} + F_i f, \tag{17}$$

since for the collision integral I_{st} we use representation as the flow divergence in the phase space j_i and the distribution function dynamics is represented by the dynamics of the effective incompressible liquid. The flow is written through the

diffusion coefficient D_{ij} and friction force F in the phase space, which is true for the kinetic equations, which in various forms consider collective correlation of the particles through natural oscillations of the medium (equations of Vlasov, Landau or Lennard-Balesku).

Let us assume that evolution is a number of bifurcations between a sequence of quasi-stationary states, which, thus, may be considered as the ones determined by a system of equations:

$$div_r(\vec{j}) = 0, \quad div_p(\vec{j}) = 0. \tag{18}$$

The first equation is apparently satisfied in spatially homogeneous systems and the stationary distribution functions for them should satisfy the equation:

$$div_p(\vec{j}) = 0 \ \text{ or } \left|\vec{j}\right| = P, \ P = const. \tag{19}$$

Solution of this equation with permanent flow P (see [13–14]), different from zero, corresponds to the action of the mass forces on the system.

Genuinely, the system by definition is called 'mass' if it acts not only on the particles on the boundary of the system, but also on all particles inside the system. If in this case the mass force exceeds the dissipative forces in the system, then dissipation inside the system may be neglected, while all points inside the systems may be considered as approximately equivalent. The mass forces exceeding the dissipative ones will be called the general dominating disturbance for this system. Therefore, the system under the action of the general dominating disturbance may be well simulated by the spatially homogeneous non-equilibrium system with flows in the phase space constant in each point of the space.

Vlasov analyzed in [10–12] and in [15–16] important examples of physical mechanisms fostering formation of structures in plasma due to renormalization of particles correlation through natural collective oscillations of the medium.

The renormalization of particles correlation is determined by their distribution function. It is generally regarded that the only stationary solution of the kinetic equations in the spatially homogeneous system is the equilibrium distribution function $f_T(p) \propto \exp\left(-p^2/(2mT)\right)$, corresponding to $P = 0$ and representing the trivial solution (17). It appears to be that the stationary states of the spatially homogeneous systems in case of permanent, not equal to zero, flows in the phase space have a power form or power asymptotics (see [13–14]).

As it will be shown in the next work, it is convenient to represent the power solutions in the form of the solution of the generalized Vlasov's equation:

$$f_q(\varepsilon) = A \ exp_q(-\varepsilon/T), \quad exp_q(x) = (1 + (q-1)x)^{1/(q-1)}. \tag{20}$$

Here for notation of solutions we use the quasi-power generalizations of the exponential functions introduced by C. Tsallis for his open systems thermodynamics [17]. The distribution functions (20) describe the collective state resulted from the action of the mass force while the parameter $q \approx 1 + \alpha P$ is determined by the value of the corresponding flow P. Average energy on the particle in the non-equilibrium state (18) is equal to

$$T\left(1 + (1-q)\ S_q\right), \tag{21}$$

where $S_q = -\ln_q \eta$—the entropy of the state (18), written with the use of the expression for the generalized algorithm $\ln_q(x) = \dfrac{x^{1-q}-1}{1-q}$ [17]. Solutions of the (20) type in absence of the flow (i.e. with $P = 0$ and $q = 1$) form the homogeneous equilibrium state.

In the general case the system has two components:

- A structureless one with thermal motion and, evidently, distribution approaching equilibrium;
- A coherent one related to the appearance of the long-range orders and with (18) type distribution.

Since proportion of the number of particles in the components is regulated by the order parameter, then it is possible to use further and with good accuracy the model representation for the distribution function as follows:

$$f(p,T,q) = (1-\eta)\, f_T(p) + \eta f_q(p) \tag{22}$$

It is noteworthy that existence of the two components of the distribution function with different average energy leads to the appearance of a new branch of the medium natural oscillations with linear dispersion [18] and to renormalization of the Coulomb interaction in compliance with the theory [19], owing to the interaction through the exchange of these quantums of the medium natural oscillations. Renormalization depends on the order parameter and q, i.e. finally on the mass forces and flows in the system.

6 Shell model of self-organization of a system with constraints

Gravitational forces are the most well known examples of the mass forces because being in the cosmic scale the main factor of evolution, they lead, as the experiments show, to formation of the specific structures in the evolving Universe—the 'pancakes' that further evolve into a cluster of galaxies. Increase of the system coherence and decrease of characteristic dimensions towards coherence due to the action of the mass forces are, to our opinion, one of the key elements for initiation of self-organization in any complex systems.

In the general case, a system, isotropic at the initial moment and with distribution of particles in the space with a typical scale l_0 evolves into a deformed state with the large number of external spatial scales. Let us in the simplest case consider evolution anisotropy by introducing two scales as macroscopic geometric characteristics of the system instead of only one—its radius:

- $l_\perp < l_0$ in one direction;
- $l_s > l_0$ in orthogonal directions.

A smaller scale may be called the scale of the space coherence of the system, which characterizes the 'pancake' thickness, while the larger scale—the characteristic scale of interaction, which characterizes the maximal size of correlations in the system.

The phase volume of the system $\Omega_{ph} = \Omega_p \Omega_r$ is the product of the volumes. Here $\Omega_r$is the volume in the coordination space, while Ω_p- in the pulse space. The phase volume of the system may be estimated by the distribution

function, hence the quasi-stationary distribution function of the system $\dfrac{\partial f}{\partial t} \approx 0$ is followed by the stationary condition of the phase volume $\dfrac{\partial \Omega_{ph}}{\partial t} \approx 0$ under meeting the condition of the flow constancy (19). If the flow equals zero, the state of the system is in equilibrium, while Ω_{ph} is constant.

Methods of the regularization on the basis of the fractional operators developed in the work [20] may provide qualitative description of the properties of the quasi-stationary states with the non-zero constant flow in the phase space. Stationary condition of the phase volume regarding regularization takes the form:

$$D^{1-\nu}\Omega_{ph}(t) = 0, \quad (D^{\alpha} f)(x) = -\frac{1}{\Gamma(1-\alpha)} \frac{d}{dx} \int_{x}^{\tau} \frac{f(t)}{(t-x)^{\alpha}} dt \tag{23}$$

and has a solution

$$\Omega_{ph}(t) = \Omega_{ph0} \frac{\tau^{\nu}}{(\tau - t)^{\nu}}, \tag{24}$$

where Ω_{ph0} is the value of the phase volume at the initial moment of time. The derivative index ν in this correlation is proportional to the mass force or flow in the phase space and transforms into an equilibrium expression at $\nu = 0$. The above obtained expression for the phase volume of the system under the action of the mass forces shows the appearance of the mode with aggravation and reduction of the coherence scale $l_{\perp}$ and leads to an increase of the typical interaction scale l_s in compliance with the correlation:

$$l_s = l_0 \sqrt{\frac{\Omega_{p0}}{\Omega_{ps}}} \sqrt{\frac{l_0}{l_{\perp}}} = l_0 \frac{1}{(1 - t/\tau)^{\nu/2}} \sqrt{\frac{l_0}{l_{\perp}}}. \tag{25}$$

For the typical interaction scale in the correlation (25) the phase volume of the systems is not preserved while an additional rheonomous multiplier appears and explosively changes the localization of the states due to the entropy production.

To our opinion, initiation of the evolution not only in the cosmological domain but also in the general case is related to the following: increase of the system coherence is accompanied by the renormalization of the fundamental interactions in the system and corresponding changes in its structure through the increase of the typical space scales of interaction in the directions orthogonal to the direction of the coherence. An effective reduction of the dimensionality of many particles in the direction of the coherence growth of the system and 'flattening' of its collective state take place.

There appears a new class of phenomena related to the quantum nonlocality while appearance of the coherent states and processes governed by the external sources of energy and information act as a prerequisite.

In the course of interaction the quantum systems acquire classical features, which correspond to the information available in the external sources affecting the quantum system while nonlocality appears as a result of entanglement of the quantum states in the irreversible processes under interaction with the medium. One may say that the evolution of the open nonlocal quantum

system generates internal information-intensive structures capable to exchange information with external sources. In this situation the system loses many of its specific quantum features and becomes to a certain degree classical. The theory of such macroscopic quantum objects and quasi-stationary states will be reported in the next articles on the basis of the modified Vlasov's equation.

Self-consistent full ionization of substance is the physical basis of the modes with aggregation. Ionization is known to lead to a density increase when electron shells of atoms reduce their radius in the process of ionization. Increase of the substance density may induce further ionization of the substance, which does not take place under the normal conditions because density increase resulted from ionization is not enough for further ionization, thus providing stability of the surrounding substance preventing its spontaneous collapse.

However, it is possible to create collapse of the electronic system by using renormalization of the electromagnetic interaction in the medium thanks to its polarization, which fits perfectly into the formalism of the dielectric permeability $\varepsilon\left(\omega, \vec{k}\right)$ and exchange of quanta of the medium natural oscillations.

Fractal properties of the medium related with its scale invariance, resonance properties and space limitation of the particles subsystems are the most essential factors, which permit controlling properties of the dielectric permeability (and thus, correlation of ions and nuclei). That is, the initial Coulomb interaction of nuclei with the Fourier-transform of the potential written in the form $U(\omega, k) = \dfrac{4\pi Z^2 e^2}{k^2}$ essentially changes as a result of interaction through collective plasma oscillations and is determined by the dielectric permeability $\varepsilon\left(\omega, \vec{k}\right)$ of the medium: $U(\omega, k) = \dfrac{4\pi Z^2 e^2}{\varepsilon\left(\omega, \vec{k}\right) k^2}$.

We will show that presence of the fractal structure in the system leads to the renormalization of the vacuum interaction and further spontaneous growth of fractal structures in its volume.

Fractals with the Cantor set structure (see [21]), which are built by a similitude of the bounded interval with eliminated central part whose size equals to ξ^{th} fraction of the whole interval $0 < \xi < 0.5$ are convenient for simulation and theoretical studies.

Let us consider a thin fractal layer of the length$L$, which the Cantor set with the preset parameter ξ and, thus, with fractal dimension $D_f = \dfrac{\ln 2}{|\ln \xi|}$. Distribution of the potential and charge in such fractal thin layer is considered homogeneous through all its thickness. Distribution of the charge density in the perpendicular direction x (along surface of the layer where the charge density distribution is the Cantor function $\Delta_\xi(x)$) is described by the Poisson equation:

$$\frac{d^2 U}{dx^2} = -4\pi e \Delta_\xi(x). \tag{26}$$

The Fourier component of the potential in this layer is ($k_\perp$- the wave number along layer):

$$U_k = \frac{4\pi e}{k^2} \gamma_\xi(k_\perp L), \quad \gamma_\xi(k_\perp L) = \prod_{n=0}^{\infty} \cos\left[\frac{(1-\xi)\xi^n}{2} k_\perp L\right]. \tag{27}$$

Expression for the Fourier transform (25) coincides with the general expression through the dielectric permeability at $\varepsilon(k_\perp) = \dfrac{1}{\gamma_\xi(k_\perp L)}$.

Fig. 1 shows the Fourier component of the Coulomb potential in the medium with the fractal structures.

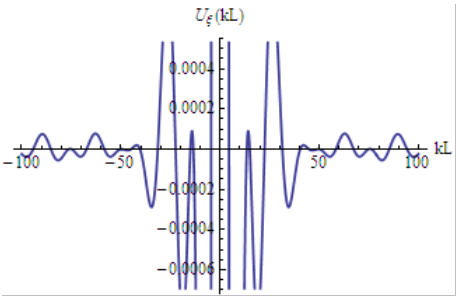

Fig. 1: Graph of the Fourier transformation of the potential in the fractal layer $\gamma_\xi(k)$, $\xi = 0.3$

The medium fractality leads to the appearance of the large number of the wave vector domains where the dielectric permeability is negative and interaction of the similar charges has a nature of attraction.

The inverse Fourier transformation—the component U_k leads to the dependence of the potential on the coordinate for the fractal layer as the fractal function where the measure of non-zero values equals zero. That is, the volume of domains with zero values of the potential fills practically all space, while the volume of domains with the non-zero values of the potential tends to zero.

A set of points, on which the values of potential are concentrated, forms the Cantor set while the potential may be represented as follows:

$$U(r) = \sum_{i \in \Delta_\xi(r)} \frac{\exp(-\kappa_r r_i)}{r_i}, \quad \kappa_r = \frac{2\pi}{\delta_{sh}}, \tag{28}$$

where $\Delta_\xi(r)$—the Cantor set on which the values of the potential are concentrated, k_r—the wave number of the wave along direction r, where the shell is limited and coherent, δ_{sh}—thickness of the shell.

Since almost everywhere (except a set of points of the zero measure) the Coulomb interaction proved suppressed and nothing prevents the particles to contact, then the fractal structure initiates its explosive growth.

A system of particles aggregated as a result of the pair contacts represents a set of clusters of various sizes. Size distribution of the clusters, i.e. concentration of the clusters of $k$size (clusters composed of $k$nucleons) as a function of time is described by a system of reactions:

$$A_{k0} + A_{k0} \to A_{2k0}, \quad A_{k0} + A_{2k0} \to A_{3k0} \ldots$$

In this case the equation for concentrations C_k of clusters of k nucleons may be described as the Smolukhovsky's coagulation equation [22], where competition of two processes is considered: (1) adhesion of the cluster components, i.e. increase of the cluster size, and (2) collapse of the cluster components, i.e. growth of the number of clusters smaller by weight. For probability K_{ij} of the

adhesion of clusters of the sizes i and j one may assume approximation under which this probability is proportional to the product of the areas of the initial clusters surface—$K_{ij} \propto (ij)^{2/3}$.

The Smolukhovsky's equation may be integrated analytically in this approximation of the permeability of the Coulomb nuclei barriers due to the increase of correlation in the system, and it appears that the average size of the cluster may become infinite for the finite time—the time of phase transition in gel.

Solution of the problem on determination of the most general laws of the structure growth is the most important element of the self organization theory, which is reported below.

7 Variational principle for evolution of complex systems—a principle of dynamic harmonization in the non-covariant Gaussian form

Variational principles are the most concentrated expression of the laws on dynamics of the particles system, therefore, it is desirable to formulate the laws of the complex systems evolution in terms of the variational principles.

The variational principles of mechanics are its fundamental principles expressed in the form of variational correlations from which differential equations of motion logically follow.

According to the variational principles, actual motions of the system under the action of the preset forces are compared with the kinetically possible motions prompted by the constraints applied on the system and satisfying certain conditions. The variational principles differ by their form, variational ranges as well as by generality, however each principle incorporates everything in this sphere of science and unites all its principles in one formulation in the frames of its applicability.

In [2] the variational principle of evolution of the systems with constraints was formulated, which is the principle of dynamic harmonization. The system self-organization results from variation of the structure of constraints between the elements of the system in response to the system acceleration, and is aimed at:

- either counteraction to the forced acceleration because of the steady state due to the system energy inertia;
- or facilitation of the forced motion acceleration towards steady state at the account of the system inertia decrease.

Changes in the system structure lead either to binding of free energy of the external accelerating mass force in the structure or to a release of the previously conserved free energy in various forms into the environment.

Below we will explain this principle and its analytical formulations.

The variational principles may have various forms for the dynamics of the mechanical systems different in quality.

The systems with constraints may be open (exchanging energy and/or mass with the environment) and closed or conservative (not changing its energy and mass). Evolution of the system is always connected with structural variations, therefore with variations in the bonding energy of the evolving system and with mass defect, so in evolution processes we deal only with open systems. As to the constraints in the systems, they have more detailed classification in mechanics. Let a system be characterized with the coordinates x^i and velocities $u^i = dx^i/dt$, $i = 1, ..., n$. The constraints existing in the system in the general case are characterized by a set m of functions:

$$\varphi_j \left(x^1....x^n, u^1....u^n, t\right) = 0, \ j = 1, ..., m \tag{29}$$

As is know, the constraints are called:

- scleronomic, if functions φ_j are not time-dependent;
- rheonomic , if functions φ_j are time-dependent;
- holonomic, if functions φ_j are not velocity-dependent;
- non-holonomic, if functions φ_j are dependent not only on the coordinates but also on the velocities.

It is clear that constraints in the evolving system of general position will vary with time, i.e. rhenonomic, but may also be holonomic and non-holonomic.

Let us change the analysis of the variation principles describing development of system particles with time.

The variation principles differ from one another by forms and varying patterns as well as by the generality degree.

The most general differential principles characterizing the motion properties of open systems with constant and variable constraints for any given point in time are the Gauss and Hertz variation principles, while the most general integral principle characterizing the motion properties at any finite time intervals, is the least action principle in the Hamilton–Ostrogradsky form [23].

For constructing the variation principle for the self-organizing open systems we start from the most general variation principle of dynamics, which is also true even for systems with non-stationary non-holonomic constraints—the Gaussian principle.

Gauss introduced the general principle of mechanics as the mechanical analog of the least square method underlain all statistical studies and it is called *the principle of least constraint*. According to the Gauss principle, positions occupied by the points of the system at the moment $t + \tau$ in true motion are distinguished among all positions allowed by the constraints by the fact that the constraint measure in them $Z_G = \sum\limits_{i=1}^{N} m_i s_i^2$ has a minimal value (here s_i—length of the vector between the points representing true or any other position of the point). The Gauss principle has the following peculiarities:

- addition of inertia mass forces to the external forces acting on the system;
- varying of accelerations under preset coordinates and velocities (the Gauss variation).

The inertia mass force proves inseparable from the corresponding acceleration, which shows its key role in self-organization processes. For the closed

systems (the systems in which Hamiltonian is explicitly time-nondependent) the Gauss principle is reduced to the principle of the Hamiltonian least action.

However, even in the general variation principle of mechanics the nonstationary constraints in the system are assumed to be fully prescribed prior to the dynamic process initiation, hence this principle in its initial form cannot be the basis for the self-organization theory. Dirac [24] was the first to consider the dynamic systems with the variable structure where not only trajectories of particles but also constraints were viewed as variable parameters.

For self-organizing systems with the particle dynamics occurred in the configuration space it is necessary to take into account a possibility for the system of particles to evolve through varying the constraint fields and generation of system's most steady and optimal structures.

Moreover, since variation of the system's inner structure is connected with variation of its mass (with mass defect of the system), such processes are most effective in the course of the system evolution and may serve as a source of energy for the evolution itself. *Therefore, it is evident that control of the system with the help of the laws of evolution of its constraints (variational principles for the systems with varying constraints) is the only effective way for desirable transformations in the system at the account of its internal energy resources instead of direct 'forcing' the system by external energy only.*

It follows from the above that the use of the general dominating disturbance specially selected for the given system is the tool for initiation of the self-organization processes (dynamic harmonization) of the structure of constraints in the system.

In order to write analytically the principle of dynamic harmonization let us calculate a shift of the particle $s_i$as a result accelerations variation. Considering time variation τ small with the accuracy to the second order it appears that:

$$s_i\left(t+\tau\right)=\frac{1}{2}\delta a_i\left(t\right)\tau^2,\quad \text{where } \delta a_i=w_i-\frac{F_i\left(t\right)+F_m}{m_i\left(D_f\right)}. \tag{30}$$

By inserting the shift of particles from (30) into the constraint function we receive: $\sum\limits_{i=1}^{N} m_i s_i^2 = \sum\limits_{i=1}^{N}\left(\frac{\tau^2}{2}\left(m_i w_i - F_i + \left(m_i a_m\right) u_i\left(t\right)\right)\right)^2 \Big/ m_i$. From here it follows that in view of the value $\tau^4/\left(4m_i\right) > 0$ the dynamic harmonization function may be represented as follows:

$$Z_{dh}=\sum_{i=1}^{N}\left(m_i\left(D_f\right)w_i-\left(F_i+F_m\right)\right)^2,\quad m_i\left(D_f\right)=\left(A_i m_p-\delta m_i\left(D_f\right)\right) \tag{31}$$

Finally, the principle of the dynamic harmonization may be formulated as follows: the system varies its trajectory and structure under the action of external forces so that to be in the harmony with the environment and external actions as a result of minimization of the generalized constraint function Z_{dh} regarding all constraints in the system. In other words, the system tends to make trajectories of its forced motion under the action of mass forces maximally approaching the trajectory of its own natural undisturbed motion.

In (31) summation is performed both by collective variables and by all particles. Since the structure variation is inseparably connected with the variation

of entropy and information, the dynamic harmonization principle simultaneously describes purposeful exchange of information and entropy by the system with the environment.

At the first glance, a property of the quadratic function minimality (31) is explicit and produces nothing new but the Newton equation $m_i w_i = F_i + F_m$. However, this is not true. From (31) *for variable determining the state of the system and its internal structure, after accelerations variation a_i regarding constraints at the fixed positions and velocities of all particles follow differential equations, which do not coincide with the Newton equations for dynamic of particles under the action of forces when constraints are in place.*

In order to obtain a specific form of the dynamic harmonization equations and effectively apply it, it is necessary to use an expression for constraints in the system. It turns out that all open systems with varying constraints have significant similarities, and can suggest a general model for the evolution of such systems based on the principle of dynamic harmonization.

8 Dynamic harmonization equation

In accordance with the dynamic harmonization principle the evolution equations are determined by a minimum of the dynamic harmonization function Z_{dh} under variation.

Let us consider an example of the liquid drop with radius R, which depends on the structure internal system using the equation of constraints $R = g(D_f)$, and write the dynamic harmonization function for it:

$$Z_{dh} = \frac{1}{2}(m\, w_R - F_R)^2, \quad m = m_0 - B_A(D_f)/c^2. \tag{32}$$

For applying the principle let us consider that force F_R may be expressed through the bonding energy gradient $B_A(D_f)$:

$$F_R(D_f) = \frac{\partial B_A(D_f)}{\partial R}. \tag{33}$$

Not counting the constraints, the conditions of the constraint quadratic function lead to general Newton equations. However, owing to the constraint $R = g(D_f)$ acceleration w_R cannot vary independently and is expressed through acceleration of the fractal dimension under preset values of the coordinates and velocities (the Gaussian variation of accelerations). The Gaussian variations are the variations of the second order tangent plane of the tangency at a fixed plane of the first order of tangency. Variations of the accelerations of all orders, i.e. vectors in the respective different planes are independent, therefore the Gaussian variations lead to the following: the correlations for the variations of accelerations are similar to correlations for the variation of the respective coordinates, and the first derivatives are absent in the following correlations for accelerations:

$$w_R = \frac{d^2}{dt^2}R = g_R \ddot{D}_f, \quad g_R = \frac{\partial^2 g}{\partial^2 D_f}. \tag{34}$$

Inserting the obtained expression for acceleration into Z_{dh}, we obtain the dynamic harmonization function as dependent on acceleration of the fractal dimension:

$$Z_{dh}\left(\ddot{D}_f\right) = \frac{1}{2}\left(g_R\ddot{D}_f - \frac{F_R\left(D_f\right)}{m}\right)^2. \tag{35}$$

Condition for minimum of the dynamic harmonization function in relation to accelerations of the fractal dimension, $\dfrac{\partial Z_{dh}\left(\ddot{D}_f\right)}{\partial \ddot{D}_f} = 0$, leads to the differential equation determining evolution of the dynamic system with varying constraints:

$$m_{str}R_0\ddot{D}_f - F_R\left(D_f\right) = 0, \quad m_{str} = mg_R. \tag{36}$$

In the simplest case when considering evolution of the system with slowly varying forces the equation may be once integrated and presented as the Lagrange equation with the corresponding Lagrangian function:

$$L_{stri} = m_{str}\left(D_f\right)R_0\frac{\dot{D}_f^2}{2} + B_A\left(D_f\right), \tag{37}$$

where the system structural inertia appears $m_{str}\left(D_f\right)$. Analysis of the specific models of the system of particles regarding correlations of (25) type for space scales and bonding conditions (for example, nuclear structure models) shows an explosive growth of structural inertia with the order parameter growth, which may be approximated by the dependence $m_{str}\left(D_f\right) = \dfrac{m_{0str}}{\left(1-\eta\left(D_f\right)\right)^{\gamma}}$. Such dependence provides hysteresis phenomenon under structure formation. Under the action of the forces with positive acceleration, structures form from the state with initial value of the order parameter while the order parameter grows and achieves corresponding maximal value. Acceleration reverses its sign while the action of the mass forces is coming to an end and these forces tend to zero, and the order parameter somewhat decreases in compliance with the harmonization equations (the Lagrangian equation with the Lagrangian function L_{stri}). However, since the structural inertia has already grown, the order parameter does not reduce down to its initial value and the 'residual' order parameter appears as an element of the system memory.

Structural inertia (mass) appears in the phenomena accompanied by the symmetry disturbance. This fact is well known in the theory of elementary particles. Spontaneous disturbance of the symmetry in the calibration theories may lead to the appearance of the finite mass in massless calibration particles.

After completion of the action of external entropy force, which disturbed a symmetry of the system, the long-range order, characterized by the parameter η, may appear in the system. It is the structural inertance, characterized by the order parameters at each hierarchy level that accounts for inertance of the self-organization processes. In the general case the structural inertia (mass) m_{str}, connected with the appearance of the fractal clusters is expressed through the fractal dimension or the order parameter.

Conclusion

Consistent theoretical development of the basic principles of the concept on self-organizing synthesis of new structures in the dynamic systems opens new potentials for creation of the theory on self-organization of the complex systems and for the development of fundamentally new technologies.

This work proposes generalization of the Gaussian variation principle, which is a mathematical formulation of the dynamic harmonization principle for the open systems with varying constraints. The proposed variation principle allows obtaining equations that describe the self-organization process and expose the nature of the constraints fields and their collective states.

It makes intuitive sense that self-organization of the system is inseparably connected with evolution of its structure and leads to the changes in its mass, stability and bonding energy. However, the available self-organization theories (for example, the Prigogine non-equilibrium thermodynamics) where the system self-organization is determined by the gradients of the thermodynamic parameters inside the system, while the distribution functions are locally equilibrium, are not applicable for the open systems with varying constraints. At the same time the theory on the basis of the variational principle of dynamic harmonization may claim to become the general theory on self-organization of the open systems with varying constraints .

Formalism of the variation principle of dynamic harmonization presented in the work suggests a general platform for solution of the problems of self-organization and control for evolution of various complex systems from the general positions of the theory of thermodynamic systems with varying constraints.

Since entropic forces have a considerable contribution to the proposed theory of self-organizing synthesis it is necessary to mention Kozyrev's works (see, for example [25]), where time plays a key role. Kozyrev also considered the open systems with not only degradation processes (law of the energy degradation), but also the processes of the structure synthesis and, thus the entropy reduction. He stated that the time density value, introduced in his theory, depends in a given point of the space on the processes occurring in the vicinity of this point. In the processes, where the entropy grows, the time density increases, therefore such processes are time-emitting. Hence, time density increases when a substance loses its organization. Kozyrev noted that even this circumstance suggests a conclusion that time contains organization or negative entropy that may be transmitted to another object in the vicinity of such processes. In other words, time affects the substance. It is especially interesting that Kozyrev could observe evolution in stars and stars motion from the laboratory on the Earth using his time theory in the real time mode. Using our theory on self-organization of systems with varying constraints it is possible to disclose the essence of time density variation according to Kozyrev.

In the next works we will show that this is connected with metrics change and appearance of the local space-time curvature determining in the simplest cases the value of the natural and laboratory time relations.

Herz paid attention to the fact that varying accelerations according to Gauss with minimality of the constraint function corresponds to the variations

in motion on condition of the trajectory curvature minimality, hence real motion always chooses the straightest path coordinated with constraints. This principle is represented by Herz also in the form of the functional minimum denoting the length of the system path from n particles with weights m_i.

It will be shown that the principle of dynamic harmonization regarding the Hertz ideas can be transformed to the functional minimum representing not the length of the path in the three-dimensional space but the length of world lines of particles in space-time stated and formulated as follows: *The system with constraints evolves in space-time by geodetic lines with the space-time curvature tensor corresponding to the evolution of the internal system constraints, being harmonized in response to the action of mass forces*

The works of this series will show that the idea of a liquid drop with a fractal structure can be naturally applied to a drop of nuclear liquid and a range of possible values of the nuclei binding energies is much broader than it is accepted in nuclear physics. The appearance of the internal structure of nuclei in the nucleon scale, which is reflected by introduction of a new nuclear option—their fractal dimension, opens up great prospects for synthesis of new nuclear structures based on self-organization of nuclear matter obeying the dynamic harmonization principle.

The concept of self-organizing synthesis allows obtaining theoretical and experimental results that may be applied in many fields of science and technology.

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Interdisciplinary Studies of Complex Systems
Vol. 1, No. 1 (2012) 55–77

Control of multiscale systems with constraints
2. Fractal nuclear isomers and clusters

S. Adamenko,[1] *V. Bolotov,*[2] *V. Novikov*[3]

Abstract. We consider the influence of the Fermi statistics of nucleons on the binding energy of a new type of nuclear structures such as fractal nuclear clusters (fractal isomers of nuclei). It is shown that the fractal nuclear isomers possess a wide spectrum of binding energies that exceed, in many cases, the values known at the present time. The transition of the nuclear matter in the form of ordinary nuclei (drops of the nuclear fluid) in the state with the fractal structure or in the form of bubble nuclei opens new sources of energy and has huge perspectives. This transition is based on a new state of matter – collective coherently correlated state. It manifests itself, first of all, in the property of nonlocality of nuclear multiparticle processes. We develop a phenomenological theory of the binding energy of nuclear fractal structures and modify the Bethe–Weizsäcker formula for nuclear clusters with the mass number A, charge Z, and fractal dimension D_f. The consideration of fractal nuclear isomers allows one to interpret the experimental results on a new level of the comprehension of processes of the nuclear dynamics. The possibility to determine the fractal dimension of nuclear systems with the help of the method of nuclear dipole resonance for fractal isomers is discussed. The basic relations for fractal electroneutral structures such as the electron—nucleus plasma of fractal isomers are presented.

1 Introduction

During many decades, the development of the fundamental and applied nuclear physics is referred to the priority trends of science and technology in many countries. The special interest in the development of nuclear physics is mainly related to the hope for that the nuclear power industry could become the most powerful source of energy.

All primary sources of energy in the Nature have the single base, namely the processes with a change of the binding energy of systems. This concerns the most spread sources of energy based on the transformation of the binding energy on the atomic and molecular levels, e.g., at the combustion of organic fuel, and the nuclear processes generated by a change of the binding energy of nucleons in the nuclei of atoms [1] at the running of nuclear reactions.

[1] Electrodynamics Laboratory *Proton-21*
[2] V. Karazin National University of Kharkov
[3] The Institute of Electrophysics and Radiation Technologies of the National Academy of Sciences of Ukraine

The most powerful sources of energy are those which use the binding energy of many-nucleon nuclear systems, because the density of this energy has a value (by modern representations) of the order of several MeV per nucleon, as distinct from the chemical energy, whose value is several eV per atom or molecule.

The significance of the quantities directly related to the binding energy (mass defect, packing coefficient [2]) for the comprehension of the nature of nuclear phenomena and processes becomes clear very rapidly. When nuclear physics originated, the structure of nuclei and the interactions between nucleons composing a nucleus were known only in the very general features. At that time, some attempts to clarify the structure of a nucleus were based on the analysis of available data on the masses of nuclei (and, hence, their mass defects).

In [3], Weizsäcker obtained a rather awkward phenomenological formula for the masses of nuclei on the basis of experimental data on mass defects and the binding energy of nuclei in the Thomas–Fermi approximation of self-consistent field with regard for the finite size of a nucleus (finite value of the surface energy). The formula includes the sum of contributions of the bulk energy, surface energy, and Coulomb energy and well represents the general dependence of the binding energy of nuclei on the parameters of a nucleus (the number of protons Z and the number of neutrons $N = A - Z$ in a nucleus). In work [4], Bethe modified the formula for the binding energy (in MeV) to the commonly accepted form, where the meaning of terms is quite transparent (especially from the viewpoint of collective representations):

$$B(A,Z) = \left(c_0 - c_3\left(1 - \frac{2Z}{A}\right)^2\right)A - c_1 A^{2/3} - c_2\frac{Z^2}{A^{1/3}} + \frac{c_p}{A^{1/2}}\begin{cases}1, & Z = 2l,\ N = 2k\\ 0, & A = 2k+1\\ -1, & Z = 2l+1,\ N = 2k+1\end{cases}; \qquad (1)$$

$$c_0 = 15.75,\ c_1 = 17.8,\ c_2 = 0.71,\ c_3 = 23.7, c_p \approx 12.0.$$

The first term gives the bulk contribution of the strong interaction jointly with the so-called symmetry energy related to the Pauli principle. The second term is the contribution of the surface of a nucleus to the binding energy. The third term corresponds to the Coulomb energy of a charged drop. The last term is the "pairing" energy related to the quantum corrections and the shell effects in the structure of a nucleus. By the order of magnitude, the "pairing" energy is equal to the energy of separation of a neutron from a nucleus $S_n = B(A,Z,D_f) - B(A-1,Z,D_f)$. The coefficients in (1) are usually chosen from the condition of the best fitting of experimental data.

For the first time, the representations about a nucleus as a system revealing the collective behavior and properties arose in connection with the attempt to describe the processes of fission of nuclei. Moreover, the term "fission" appeared in work [5] due to the analogy with the biological process of fission of cells. The description of properties of a nucleus involved the Frenkel model ideas of a charged liquid drop [6] which were developed in the theory of a liquid nuclear drop by Bohr and Wheeler [7, 8] and well agreed with the Bethe–Weizsäcker theory.

Formula (1) was further modified, and its coefficients were corrected on the basis of permanently renewed experimental data [9]. The development of the ideas of nuclei and the nuclear matter within the theory of Fermi-fluid allowed one to calculate the coefficients in the Bethe–Weizsäcker formula and, proceeding from the general representations about the structure of a nucleus, to theoretically determine the binding energy of nuclei with a sufficient accuracy [10, 11].

The phenomenological theory of the binding energy of nuclei on the basis of the drop model leads to a nonmonotonous of the specific binding energy per nucleon on the ratio of the numbers of protons and neutrons (see (1)) and to the existence of the maximum of the specific binding energy per nucleon in the region of nuclei with mass numbers close to those of the stable isotopes of iron and nickel.

As a result, it is traditionally considered that only two types of nuclear processes (reactions) with a positive energy yield (i.e., processes causing the growth of the binding energy of a system):

- reactions of fusion, at which nuclei lighter than iron form heavier nuclei;
- reactions of fission of nuclei heavier than iron into lighter ones.

In any case, according to these ideas accepted also at the present time, the elements in a neighborhood of the *local* maximum of the specific binding energy (elements of the "iron" peak) cannot be used as an efficient source of energy.

However, it becomes more and more clearly now that the ideas of a spatial structure of the dense matter in nuclei should be reconsidered, and the analysis of the variety of possible nuclear structures is required again.

The steady ideas of structures of the nuclear matter do not already correspond to the level of our knowledge and experimental results [12]: "What we have learned over the last decade of research on exotic nuclei forces us to revise some of our basic truths. These were deduced from intensive studies of stable nuclei, but it has become clear that stable isotopes do not exhibit all features... *Nuclear radii don't go as* $A^{1/3}$. For all stable isotopes the density in the atomic nucleus as well as the diffuseness of the surface are nearly constant. Explorations into the far-unstable regions of the nuclear chart have convincingly shown that the diffuseness, and thus the radii of the atomic nuclei, vary strongly... *Many more bound nuclei exist than anticipated.* The neutron drip line is much further out than anticipated twenty years ago. The importance of nucleon correlations and clustering that create more binding for the nuclear system has been underestimated."

The indicated circumstances make it necessary to construct the new more general relations for the calculation of the binding energy of developed nuclear structures. All previous studies and attempts to generalize the Weizsäcker formula (see, e.g., [9, 10]) were based on the application of the theory of analytic functions and the geometry of regular formations. Here, we first make attempt to estimate the coefficients of the Weizsäcker formula with the use of general notions of the fractal geometry. We will demonstrate that the nuclei with more complicated structure than that a drop of the nuclear fluid (in the general case, the nuclei representing fractal nuclear structures) have properties qualitatively different from those of ordinary nuclei. The binding energy of such fractal nu-

clei increases significantly, and the dependence of the binding energy on the nucleus mass changes qualitatively. In particular, there appears the possibility for the existence of stable superheavy nuclei with specific binding energy exceeding the relevant values characteristic of nuclei of the "iron" peak from the Periodic Mendeleev table, which open new perspectives in the development of the nuclear power industry.

2 Geometrical properties of fractal structures

Among the commonly accepted postulates, the assertions concerning the structure of nuclei and their stability give rise now to the strongest doubts. According to the hydrodynamical model (where a nucleus is represented by a homogeneous spherical drop of the nuclear Fermi-fluid [8] with the mean density of nucleons $\rho \approx 0.17$ nucleon/(fm)3), the number of nucleons in a nucleus, A, and the external radius of a nucleus, R_A, are connected with each other by the relations

$$R_A\,(A,\rho) = r_0 A^{1/3}, \quad r_0 = \left(\frac{3}{4\pi\rho}\right)^{1/3}. \tag{2}$$

However, as was indicated above, the contemporary studies of the structure of nuclei show that such ideas of the structure of a nucleus must be reconsidered and reanalyzed from the viewpoint of the extension of the set of elements of the "nuclear Lego constructor." For example, it was assumed in [13] that the superheavy nuclei are clusters of α-particles, the possibility of the existence of bubble and quasibubble nuclei was comprehensively studied in [14], and the results of numerical studies of the stability of nuclear structures at low densities indicate the possibility of the existence of nuclear structures [15] which do not correspond obviously to the idea of a liquid drop (see Fig. 1 in [15]).

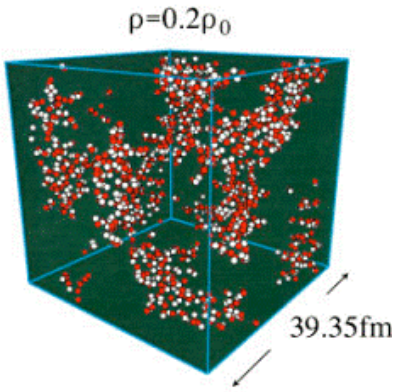

Fig. 1: Nuclear clusters in the form of a nuclear pasta (nuclear gel) [15]

Fig. 2: View of a typical cluster formed at the growth of a structure of solid particles [16]

In Fig. 2, we present a typical three-dimensional fractal cluster grown due to the Brownian process in the system "particles – cluster" with the probability for particles to stick to the cluster equal to 1 (see [16]). It is seen that the nuclear structure ensuring the minimum energy in the Hartree – Fock approximation constructed in [15] is very close by its spatial distribution to the classical fractal cluster of particles.

The notion of a fractal object was introduced by Mandelbrot [17] into science as an alternative to the regular geometrical and physical objects. In the Nature, we observe a lot of periodic regular phenomena: from the motion of a pendulum to the oscillations of atoms. Despite the absence of strictly periodic motions in the Nature (at least due to the boundedness in time), the periodicity turns out to be the exceptionally useful notion for the explanation of the basic laws and mechanisms in many branches of natural science. One of the reasons for the universality of harmonic motion is the quasilinearity of many physical systems and the invariance of laws guiding their behavior at shifts in space and in time. However, in the course of time, the dominance of linear ideas in science is broken now by the spreading of new nonlinear approaches to the real phenomena surrounding us. The new century has started under the sign of a total penetration of nonlinear phenomena, "nonlinear" thinking, and methods of nonlinear physics into all fields of knowledge.

In the majority of real phenomena, the linearity is violated, and, instead of the periodicity, we deal with aperiodic chaotic motions. In this case, the arising geometrical structures turn out irregular and rugged. At the huge variety of the behavior of nonlinear systems which appear as a result of the nonlinear evolution, there exist the general properties common for most of these systems such as the self-similarity and the invariance relative to a change of the scale (scaling). In other words, the main feature of nonlinear systems is not the invariance under additive shifts, but the invariance under multiplicative transformations of the scale and, hence, the specific role of fractal functions and distributions, rather than that of harmonic ones. Scaling is revealed in many nonlinear physical processes, especially at the study of critical phenomena characteristic of the behavior of substances in a neighborhood of phase transition points.

In the general case, one of the most considerable consequences of the self-similarity is the existence of objects with exceptionally irregular structure, which are called fractals [17]. In some meaning, the self-similarity is also a periodicity, but only on the logarithmic scale. The self-similarity—strict or approximate – plays the principal role in many fields, though it is revealed in very different ways. One of the last branches of physics, where the notion of a fractal is not yet used, is nuclear physics.

In the present work, we will construct a phenomenological theory of the binding energy of nuclear fractal structures, by considering them as the structures determined by their basic geometrical characteristic, namely by the fractal dimension D_f.

One of the power dependences characteristic of a fractal is that of the correlation function averaged over angles on the distance to its geometrical center. In this case, the mean density of particles in the cluster $\rho(r)$ varies, as a function of the distance r, inside the cluster by the law coinciding with the

law of decay of spatial correlations:

$$\rho\,(r) = \rho_{str}(R_{str}\,(A_{str})/r)^{3-D_f}. \tag{3}$$

These general consequences of the fractal geometry yield a simple relation between the mass number of a fractal cluster A, external size of the cluster R_A, and characteristic size $R_{str}\,(A_{str})$ of structureless elements, i.e., monomers with the mass number A_{str} and the density ρ_{str}, from which the fractal structure is built [16],

$$A = kA_{str}(R\,(A, A_{str}, \rho)/R_{str}\,(A_{str}))^{D_f}, \tag{4}$$

where the coefficient k has value of the order of 1 and is determined by a packing of monomers in the cluster. Relation (3) can be used to present the external radius of the cluster through its mass number and the fractal dimension:

$$R_A\,(A, A_{str}, D_f) = R_{str}(A/A_{str})^{1/D_f}. \tag{5}$$

As monomers, we can consider any nuclear structures with a sufficiently high stability or/and particles efficiently forming the condensate (particles which can participate in the evolutionary sequence of nuclear phase transitions). We may assume that monomers are, first of all, α-particles from the side of low-weight structures (see, e.g., [13]) and the nearest neighbors of helium nuclei in the Periodic Mendeleev table (i.e., stable light nuclei, which can form the condensate of particles with a high probability, e.g., lithium nuclei). From the side of heavier nuclei, the role of monomers can be played by the most stable nuclei such as nuclei of carbon, oxygen, and iron. Moreover, as will be shown below, the most probable monomer for a low-density structure of nucleons with $A \gg 5 \cdot 10^4$ immersed in the electron fluid is iron. As for the fractal dimension, the modeling of the processes of growth of clusters in the three-dimensional space at a high probability of the adhesion of monomers to one another shows that the fractal dimension of clusters is near $D_f = 2.39$.

For the further applications, it is convenient to use the following estimate of the surface area of a fractal cluster depending on the mass number of a structural unit A_{str} and the fractal dimension:

$$S\,(A; A_{str}, D_f) = 4\pi R_A^2 (A/A_{str})^{\gamma-2/3}. \tag{6}$$

The correction factor indicating the degree of growth of the surface area determined by the internal structure of a cluster depends on the number of structural elements and is equal to $\left(\dfrac{A}{A_{str}}\right)^{\gamma-2/3}$, $\quad \dfrac{2}{3} \leqslant \gamma \leqslant 1$. The coefficient $\gamma = 2/3$ for a continuous structure ($D_f = 3$) and $\gamma = 1$ for a developed system of nuclear "threads of a web" or "bubble" nuclei ($D_f = 2$) .

Relation (3) yields also the dependence of the fractal dimension of a cluster with the mass number A on the mean density and the mass number of structureless units forming the cluster:

$$D_f = 3\frac{\ln\,(A/A_{str})}{\ln\,(A/A_{str}) + \ln\,(\rho_{str}/\rho)}. \tag{7}$$

The natural attempt to use the conceptions of the fractal geometry in the model of a structure of multinucleon systems must obviously involve their following specific features:

- the appearance of the developed surface (and, hence, a decrease of the binding energy of a nuclear system due to the increase of its surface energy);
- The increase of characteristic sizes of a nuclear conglomerate, as the mean density of the nuclear matter decreases (i.e., a decrease of the Fermi energy of a system and, as it will be shown below, an increase of the binding energy of a nuclear cluster).

We may expect that the formation of the internal fractal structure in nuclear systems leads to a variation of their binding energy in very wide limits.

In the general case, the growth of structures and, hence, a decrease of the number of degrees of freedom of a system, are described by the appearance of two following components of the system: the structureless part and the coherent part in the form of a nuclear "web" constructed from monomers with the mass number A_{str} and some share of protons in monomers $y_{str} = Z_{str}/A_{str}$. In this case, we denote the mass of the coherent part by m_{cog} and the mass of the substance in the structureless liquid part by m_g and introduce the coherence parameter $\eta \approx m_{cog}/(m_{cog} + m_g)$.

The mean density of a system possessing the coherent part varies by the power law (6) due to correlations. Since the potential energy of the nuclear substance is proportional, in general, to the density, we may write

$$U(\rho) \propto U(r), \quad U(\alpha r) \propto r^{k_{sc}}, \quad k_{sc} = D_f - 3 \tag{8}$$

The value of coherence parameter can be estimated from the Lagrange theorem (virial theorem) for systems with the potential energy possessing the property of similarity, if we take into account that the coherent part is characterized mainly by the potential energy, whereas the whole kinetic energy is present in the structureless (liquid) part. Then the relation of the mean values of kinetic and potential energies

$$\frac{\overline{W_{kin}}}{\overline{U}} = \frac{D_f - 3}{2} \tag{9}$$

yields the formula for the coherence parameter

$$\eta \approx \frac{3 - D_f}{D_f - 1}, \quad D_f = \frac{3 + \eta}{1 + \eta}, \quad 0 \leqslant \eta \leqslant 1. \tag{10}$$

The contribution of the coherent part of the system to the binding energy by the relations $A_{cog} = \eta A$ and $Z_{cog} = y_{str} A_{cog}$, where $Acog$ is the mass number, and the mean density is determined by the fractal dimension (or the coherence parameter) according to relation (3).

3 Main contributions to the binding energy of nuclear systems

As is well known, the interaction of elements of a system causes the effective decrease of the mass of the system (the mass defect appears) with the appearance of the binding energy of the system determined by this mass defect.

For example, the total internal energy of a nucleon system including A nucleons (Z protons with mass m_p and $(A-Z)$ neutrons with mass m_n) can be written in the form: $W = Zm_pc^2 + (A-Z)\,m_nc^2 - B$, where B is the binding energy of the system, to which all basic interactions make contributions: $B = B_{Strong} + B_Q + B_{surf}$.

Here,

- $B_{strong} = B_{bulk} + B_{Fermi}$Z is the contribution of the strong interaction consisting of two terms: B_{bulk} bearing the bulk character (i.e., B_{bulk} is a strong-interaction-induced part of the binding energy which is proportional to the mass number A) and the term $B_{Fermi} \approx -A\dfrac{3}{5}E_f\,(\rho)$ which arises due to the Pauli principle and is proportional to $(N-Z)^2$;
- B_QZ is the contribution of the Coulomb interaction;
- B_{surf}Z is the contribution of the surface energy (i.e., energy related to the degree of inhomogeneity of the distribution of nucleons in space).

In order to estimate the contributions to the binding energy, we need the assumptions about the basic geometrical characteristics of a distribution of the nuclear matter in the system. The first efficient model of a distribution of the substance of a nucleus was the simplest model of a drop of the nuclear fluid, in which the mass number A and the radius of a nucleus are connected through relation (2).

At small excitations of a nucleus, the distribution of nucleons in the momentum space is usually considered homogeneous inside of the Fermi spherical surface with the radius in the momentum space equal to the Fermi momentum p_f:$f\,(p, E_f) = \begin{cases} 1,\ p < p_f \\ 0,\ p > p_f \end{cases}$ (degenerate Fermi distribution function), as well as in the volume of a nucleus V. The integration of the Fermi distributions over the phase space gives the relations between p_f and the densities of nucleons:

$$\begin{aligned} p_{fn} &= \left(3\pi^2\right)^{1/3}\hbar\rho_n^{1/3}, \quad \rho_n = \frac{A-Z}{A}\rho, \\ p_{fp} &= \left(3\pi^2\right)^{1/3}\hbar\rho_p^{1/3}, \quad \rho_p = \frac{Z}{A}\rho \end{aligned} \tag{11}$$

The Fermi surface radius (Fermi momentum) is connected with the Fermi energy E_f:

$$E_{f_p} = \frac{p_{fp}^2}{2\,m_p} = \frac{\left(3\pi^2\right)^{2/3}\hbar^2}{2\,m_p}\rho_p^{2/3}, \quad E_{f_n} = \frac{p_{fn}^2}{2\,m_n} = \frac{\left(3\pi^2\right)^{2/3}\hbar^2}{2\,m_n}\rho_n^{2/3}. \tag{12}$$

The kinetic energy $W_{kin}\,(A, Z)$ of the ensemble of nucleons in a nucleus with volume V is determined by their Fermi energy:

$$\begin{aligned} W_{kin}\,(A,Z) &= 2\frac{V}{(2\pi\hbar)^3}\int\left(\frac{p^2}{2\,M_{nuc}}\right)\left(f_p\left(p, E_{f_p}\right) + f_n\left(p, E_{f_n}\right)\right)d^3p \\ &= \frac{V}{5\pi^2\hbar^3}\left(p_{fn}^3E_{fn} + p_{fp}^3E_{fp}\right) = \frac{3}{5}\left((A-Z)\ E_{fn} + Z\,E_{fp}\right) \\ &= \frac{3}{5}\frac{\left(3\pi^2\hbar^3\right)^{2/3}}{2\,m_n}\rho_{nuc}^{2/3}\left(\left(1-\frac{Z}{A}\right)^{5/3} + \frac{m_n}{m_p}\left(\frac{Z}{A}\right)^{5/3}\right)A. \end{aligned} \tag{13}$$

The expansion of $W_{kin}\,(A, Z)$ in the small parameter $\varepsilon = \left(\frac{1}{2} - \frac{Z}{A}\right)$ leads to the expression

$$W_{kin}\,(A, Z, \rho_{nuc}) \approx \frac{\left(3\pi^2\hbar^3\right)^{2/3}}{2\,m_n}\rho_{nuc}^{2/3}\frac{2^{1/3}}{4}\left(1 + \frac{m_n}{m_p}\right)\left(\frac{3}{5} + \frac{1}{3}\left(1 - \frac{2Z}{A}\right)^2\right)A$$
$$= W_{kinBulk} + W_{kinSym},$$

where

$$\begin{aligned} W_{kinBulk} &= \frac{3}{5}\frac{\left(3\pi^2\hbar^3\right)^{2/3}}{2\,m_n}\rho_{nuc}^{2/3}\frac{2^{1/3}}{4}\left(1 + \frac{m_n}{m_p}\right)A, \\ W_{kinSym} &= \frac{1}{3}\frac{\left(3\pi^2\hbar^3\right)^{2/3}}{2\,m_n}\rho_{nuc}^{2/3}\frac{2^{1/3}}{4}\left(1 + \frac{m_n}{m_p}\right)\left(1 - \frac{2Z}{A}\right)^2 A. \end{aligned} \tag{14}$$

Thus, the formula for the kinetic energy contains the bulk term $W_{kinBulk}$ proportional to A and the term W_{kinSym}, which is proportional to $\left(1 - \frac{2Z}{A}\right)^2$ and determines the coefficient c_3 in the Bethe–Weizsäcker formula (1).

It is clear now that the coefficient c_0 in (1) consists of two terms:

$$\begin{aligned} c_0 &\approx U_{eff} - k_{vir}W_{kinBulk} \\ &\approx U_{eff} - \frac{3}{5}k_{vir}\frac{\left(3\pi^2\hbar^3\right)^{2/3}}{2\,m_n}\frac{2^{1/3}}{4}\left(1 + \frac{m_n}{m_p}\right)\rho_{nuc}^{2/3}. \end{aligned} \tag{15}$$

Here, U_{eff} is the depth of the potential well of the strong interaction of nucleons in a nucleus, k_{vir} is the virial coefficient determining the share of the kinetic energy that contributes to the binding energy. The value of U_{eff} can be calculated in the Fermi-fluid approximation, $U_{eff} \approx 58$ MeV (see, e.g., [10]). In this case, the coefficient c_3 reads

$$c_3 = \frac{1}{3}k_{vir}\frac{\left(3\pi^2\hbar^3\right)^{2/3}}{2\,m_n}\frac{2^{1/3}}{4}\left(1 + \frac{m_n}{m_p}\right)\rho_{nuc}^{2/3}. \tag{16}$$

It is seen that the negative contributions to the binding energy decrease, as the mean density of the nuclear substance $\approx {\rho_{nuc}}^{2/3}$ decreases. Therefore, the appearance of fractal structures in the nuclear matter (related to the enhancement of correlations) decreases its mean density and, hence, increases the binding energy of a nuclear structure. We choose k_{vir} so that the binding energy of the known "drop-like" nuclei is maximally exactly approximated. With regard for the geometrical properties of fractals (see relation (3) for the density of nuclear clusters), the above-presented relations yield finally the contribution of the strong interaction in the form

$$B_{Strong} \approx \left(c_0 - c_3\left(1 - \frac{2Z}{A}\right)^2\right)A, \tag{17}$$

$$c_0 \approx \left(58.4 - 42.6\left(\frac{A}{A_{str}}\right)^{-2\left(\frac{1}{D_f} - \frac{1}{3}\right)}\right), \quad c_3 \approx 23.7\left(\frac{A}{A_{str}}\right)^{-2\left(\frac{1}{D_f} - \frac{1}{3}\right)}.$$

It follows from (17) that, indeed, the appearance of fractal structures in the nuclear matter (related to the enhancement of correlations and to $D_f < 3$) decreases its mean density (in correspondence with (3)) and, hence, increases the bulk contribution of the strong interaction to the binding energy of a nuclear structure. As $D_f \to 3$, the contribution of the strong interaction tends to the bulk contribution in the ordinary Weizsäcker formula (1).

Since the nuclei are finite systems, there exists also the contribution of the strong interaction related to a great inhomogeneity of a distribution of the nuclear matter near the boundary of the system (surface energy of a liquid drop $W_{surf}(A, \rho_{nuc})$) [10]:

$$W_{surf}(A, \rho_{nuc}) = \int \lambda_N(\rho_{nuc})(\nabla \rho_{nuc})^2 d^3r.$$

For a step-like distribution, this contribution has naturally the form proportional to the surface area: $W_{surf}(A) = \sigma S(A) \approx c_1 A^{2/3}$. Here, the experimental value of the coefficient of surface tension σ amounts to about 1 MeV/fm2. The fractal structure of a nucleus causes, naturally, a change of the surface of a nuclear structure in agreement with formula (6) for the area of a cluster. With the use of the properties of the fractal geometry, we obtain

$$\begin{aligned} B_{surf}(A; A_{str}, D_f) &= -\sigma S(A; A_{str}, D_f) \approx -c_1(A; A_{str}, D_f) A^{2/3}, \\ c_1(A; A_{str}, D_f) &\approx 18.56 \left(\frac{A}{A_{str}}\right)^{2\left(\frac{1}{D_f} - \frac{1}{3}\right)}. \end{aligned} \tag{18}$$

Relations (18) imply that the fractality of a nuclear structure leads to an increase of the surface area (increase of the negative contribution to the binding energy) and, hence, to a decrease of the total binding energy of a cluster.

It is natural that the Coulomb energy of protons in a nucleus is expressed in terms of the nucleon distribution density and the Coulomb potential $U_Q(r, Z) = \dfrac{Ze}{r}$. For the drop model, the calculations are trivial:

$$\begin{aligned} W_Q(A, Z, \rho_{nuc}) &= \frac{1}{2} \int U_Q(r - r_1, Z) \frac{Ze}{A} \rho_{nuc}(r_1) \, d^3 r_1 \\ &= \frac{3}{5} Z(Z-1) \frac{e^2}{R_A} \approx c_2 \frac{Z^2}{A^{1/3}}. \end{aligned}$$

It is obvious that the influence of the fractal geometry on this contribution is manifested in its decrease due to an increase of the size of a nucleus. With regard for the dependence of the radius of a fractal cluster on its fractal dimension, we obtain the relation

$$\begin{aligned} B_Q(A, Z; A_{str}, D_f) &= -W_Q = -\frac{3}{5} \frac{e^2 Z(Z-1)}{R_A(A; Z, D_f)} \approx -c_2 \frac{Z(Z-1)}{A^{1/3}}, \\ c_2(A, A_{str}, D_f) &\approx 0.71 \left(\frac{A}{A_{str}}\right)^{-\left(\frac{1}{D_f} - \frac{1}{3}\right)}. \end{aligned} \tag{19}$$

The fractality of the structure causes the increase of its external radius, the decrease of the modulus of the negative contribution of the Coulomb energy to the binding energy of a cluster, and, hence, the increase of the total binding energy.

Finally, we arrive at the modified Weizsäcker formula for the binding energy of a nuclear cluster with the mass number A, charge Z, and fractal dimension D_f, which is built of nuclei with the mass number A_{str}, as the ordinary Weizsäcker formula (1), but with the coefficients c_0,c_1,c_2, and c_3, which are functions given by relations (17)–(19), rather than constants. Thus, a variation of the structure of a nuclear cluster leads to a change of the binding energy and the conditions for the stability of nuclear structures.

4 Stability of nuclear systems with different structures

The energy of a nuclear system depends usually only on the number of protons and neutrons in the system. The stable states of nuclei satisfy the conditions of positivity of the binding energy B, In this case, the condition of connectivity of neutrons and protons holds automatically, i.e., the relations

$$\mu_n = \left(\frac{\partial W}{\partial N}\right)_Z < 0, \quad \mu_p = \left(\frac{\partial W}{\partial Z}\right)_N < 0, \tag{20}$$

where μ_n and μ_p are the corresponding chemical potentials of the nuclear system, are valid. These conditions ensure the existence of a potential "well" by the parameters of the system, so that the most stable states are on the bottom of the potential "well" and are determined by the conditions for the appropriate potentials to be zero (derivatives of the binding energy with respect to the relevant parameters). For nuclear fractal clusters, the fractal dimension turns out to be a thermodynamical parameter. Therefore, the most stable nuclear structures are determined by two drip lines:

$$\partial B\,(A, Z, D_f)/\partial Z = 0, \quad \partial B\,(A, Z, D_f)/\partial D_f = 0. \tag{21}$$

The first equation yields the analytic formula for the drip line (which corresponds to the equilibrium relative to β-processes):

$$Z_{st}\,(A, D_f) = A\left(2 + 0.015A^{2/3}\left(\frac{A}{A_{str}}\right)^{\left(\frac{1}{D_f} - \frac{1}{3}\right)}\right)^{-1}. \tag{22}$$

To find the analytic solution of the second equation in (21) is a very difficult problem. Therefore, we find its solution numerically on the drip line (22) and obtain approximately:

$$D_{fst}\,(A) = 2.306(\lg(A))^{0.0415}. \tag{23}$$

The drip line (23) indicates the increase of the degree of saturation of stable nuclei by neutrons due to the appearance of spatial structures in a nucleus (and a decrease of the mean density of the nucleus for those structures).

In Fig. 3, we present the dependence of the fractal dimension of a nuclear cluster on its mass number on the drip line, and Fig. 4 shows the dependence of the mean density of the nuclear matter on the mass number on the same line.

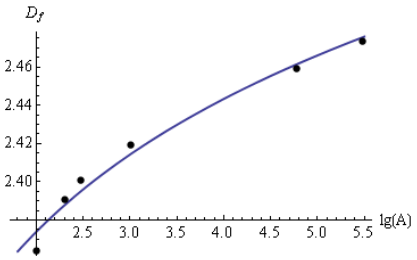

Fig. 3: Dependence of the fractal dimension on the mass number of a nuclear cluster on the drip line. Points are obtained by the numerical solution of the system of equations (21)

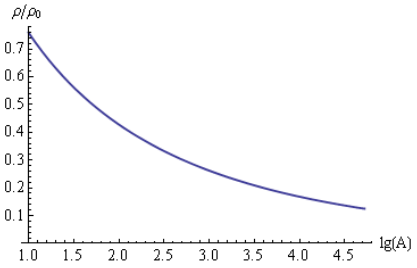

Fig. 4: Dependence of the mean density of the nuclear matter on the mass number on the drip line.

With the use of the drip line (23), relation (22) yields the dependence of Z/A for a stable nuclear structure on its mass number. This dependence is shown in Fig. 5.

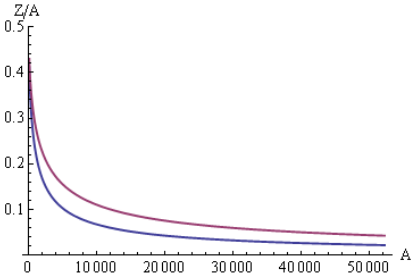

Fig. 5: Dependence of the relative charge of a nucleus on its mass number (upper curve corresponds to a nucleus in the form of a liquid drop; lower curve—to a fractal cluster).

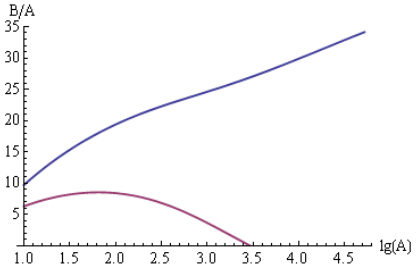

Fig. 6: Specific binding energy of fractal nuclear structures on the drip line. The lower curve corresponds to nuclei in the form of liquid drops.

Substituting the modified line of β-stability (22) and relation (23) in (1) with regard for (17)-(19) for the binding energy, we obtain the dependence of the specific binding energy on the mass number. This dependence is shown in Fig. 6. It is seen that the binding energy of stable fractal structures is, firstly, always higher than that of stable structures in the form of liquid drops, and, secondly, the region of stability of nuclear structures becomes wider.

It is necessary to consider the stability of nuclear systems not only relative to the balance of neutrons and protons in a nucleus, but relative to the processes of fission of nuclei. The process of spontaneous fission of a nucleus

is hampered by the presence of a potential barrier in the space of parameters which characterize a deformation of a nucleus; the fragments must pass through this barrier prior to their full separation [8].

In the model of a liquid drop, the fission of a nucleus should be preceded by some deformation. Firstly, an increase of the deformation is accompanied by an increase of the energy of a nucleus. At a deformation of the surface (proportional to a small parameter ε), the Coulomb energy tends to further increase the deformation (by pushing apart the perturbed sections), whereas the surface tension of the drop, which is defined as the derivative of the surface energy, tries to return the spherical shape to the drop. In this case, the energy of a deformation $\Delta W \approx (1/5)\left(2c_1A^{2/3} - c_2Z^2A^{-1/3}\right)\varepsilon^2$. The condition for the absence of decays on the drip line (positivity of the deformation energy) can be presented in the form $\dfrac{2c_1}{c_2} > \dfrac{Z^2}{A}$ and gives the following relation for the limiting value of the mass number A_b:

$$A_b\left(2 + 0.015A_b^{2/3}\left(\frac{A_b}{A_{str}}\right)^{\left(\frac{1}{D_f}-\frac{1}{3}\right)}\right)^{-2} = 50. \tag{24}$$

The stable nuclei can be observed in the region of mass numbers $A < A_b$. The appearance of a structure in the nuclear matter increases sharply its stability. Large nuclear structures with a sufficiently low density become stable also relative to decays, which is well seen from Fig. 7.

If the conditions of positiveness of the binding energy and the energy of excitation of surface oscillations are satisfied simultaneously, it is possible to determine the boundaries of stability by mass numbers at the given charge of a nucleus. The result of calculations is shown in Fig. 8. The value of mass number for a cluster with the optimum structure and with the maximum binding energy lies between these curves.

The boundaries of stability by the fractal dimension are shown in Fig. 9 as functions of the mass number of a cluster. On the same figure, we show the optimum dimension of such giant fractal clusters.

Work [18] reported on the discovery of stable isotopes of Th_{90} with the mass number 292, which were interpreted as superheavy elements with a charge of 122.

The analysis of Figs. 3, 7, and 8 allows us to propose another interpretation: the observed isotopes are, quite possibly, fractal isomers of nucleus Th_{90}, whose large mass number is related to the increase of the number of neutrons in them due to a low mean density of such nuclei, for example, to the formation of spatial structures with the fractal dimension $D_f \approx 2.1$ (quasibubble nuclei).

The possibility of the existence of stable nuclear clusters with the mass composed of tens of thousands of nucleons with a binding energy of about 1 MeV per nucleon and with the sufficiently low stability to the excitation of their surface (i.e., with the possibility of a decay induced by external physical actions) allows us to hope that such processes can release significant values of energy. As a result of the experiments on the self-organizing nucleosynthesis in solid targets with the use of hard-current diodes with a special construction [19],

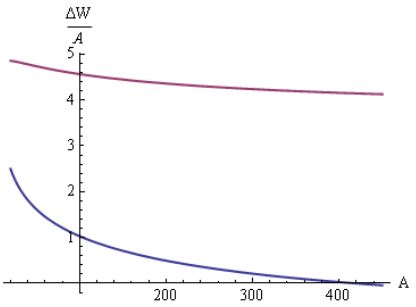

Fig. 7: Dependence of the energy of a deformation of a nucleus on its mass number. Lower curve corresponds to a liquid drop, and the upper one—to a fractal cluster.

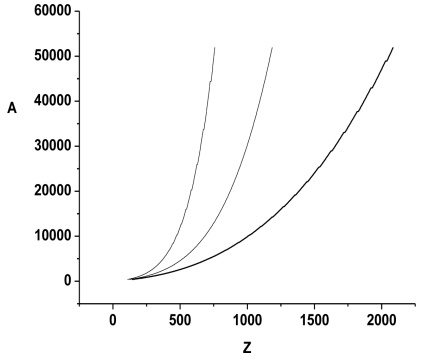

Fig. 8: Limiting curves indicating the dependences of the minimum and maximum mass numbers of clusters on the charge of a nucleus. Middle curve corresponds to optimum structures with the maximum binding energy.

a number of processes apparently related to the induced decay were registered in [20, 21].

For example, with the help of track detectors [22] positioned near the region, where the self-organizing nuclear processes are running, was registered the system of tracks of 276 nuclei of lithium and 276 nuclei of helium with an energy of about 1 MeV per nucleon, which escaped from a single center (Fig. 10.).

The appearance of such tracks can be a result of the spontaneous decay of a giant nuclear cluster of monomers (lithium and α-particles) created in the coherent nuclear processes:

$$^{19000}_{1580}A_{D_f=2.69} \rightarrow {}^{16240}_{200}A_{D_f=2.69} + 276\ {}^{4}_{2}He + 276\ {}^{6}_{3}Li + W_k.$$

We now clarify the above-used designations. The giant nuclear clusters are superheavy nuclear structure, whose composition includes two components: the coherent one in the form of nuclear "threads of a web" with the fractal

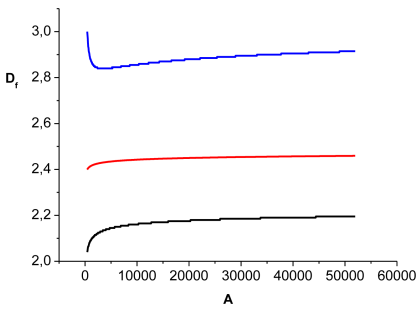

Fig. 9: Dependence of the limiting values of fractal dimension of a nuclear cluster on the mass number. Middle curve corresponds to the dimension of the cluster with the maximum binding energy.

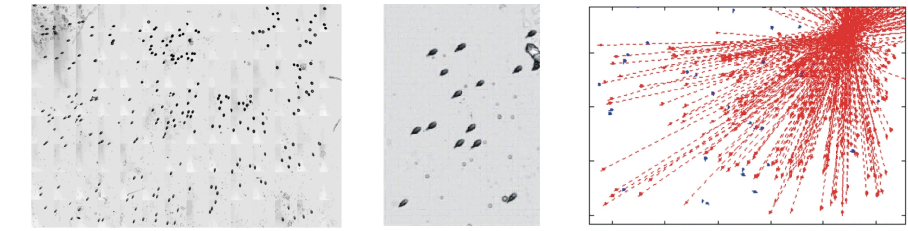

Fig. 10: Pattern of the filling of the detector by tracks with a "giant" cluster of 276 tracks (a); an individual fragment of the pattern (b); the diagram of track directions (c). Mean energy per particle in the cluster (lithium or α-particle) is of the order of 5 MeV.

dimension D_f (its value is given below on the right) formed by monomers with the nuclear density and the noncoherent component. The latter is a structureless part in the form of a nuclear fluid with a relatively low density, where nuclear "threads of a web" are positioned.

The nuclei of lithium and α- particles registered in a track detector are monomers, from which the coherent component ($276\ {}^4_2He + 276\ {}^6_3Li$) is constructed. Together with the nuclear fluid, the nuclear cluster is the structure with the mass number $Acl \approx 19000$, $Zcl \approx 1380$, and $D_f \approx 2.69$, which is denoted by ${}^{19000}_{1580}A_{D_f=2.69}$. It has a radius of about 45 fm and the stability reserve $\Delta W \leqslant 0.5$ MeV/nucleon. The kinetic energy released due to the decay, W_k, ensures an energy of the order of 1 MeV per nucleon for outgoing fragments. The cluster ${}^{16240}_{200}A_{D_f=2.69}$ formed after the decay has a higher specific binding energy per nucleon, than the initial structure ${}^{19000}_{1580}A_{D_f=2.69}$ due to the optimum density of protons in the cluster (see relations (22)–(23)).

The experiments performed much more earlier revealed some anomalies of tracks in nuclear emulsions (see, e.g., [30]), which can be considered as the registration of fractal isomers in the form of quasibubble nuclei with $D_f \approx 2.01$, $A \approx 60$, radius of about 10 fm, and the stability reserve of about 4 MeV/nucleon.

It follows from our studies that there exist the stable nuclei with a high concentration of neutrons and a high binding energy. Therefore, we need to consider the possibilities and the means of creation of stable nuclear structures different from nuclear drops and the set of types of the evolution of multiparticle systems to their equilibrium states.

The solution of this problem is difficult and is far from the completion. However, it is quite obvious that the creation of such superheavy nuclei by the fusion of low-mass nuclei moving with ultra-high energies in direct collisions is a low-efficiency improbable process due to a great excitation of the intermediate nuclear system formed in such collisions.

Works [21, 23–24] proposed a new class of nuclear processes, namely the collective coherent nuclear reactions, which do not require high energies for their realization and occur due to the appearance of long-range correlations in dynamical systems of nuclei with a variable structure. The new synergetic approach to nuclear processes comprehensively presented in [21] is based on such

synthetic sciences as the theory of control, self-organization, nonequilibrium thermodynamics of open systems [25-27], and the theory of fractals [17].

The conception of self-organizing synthesis is based on the quite general ideas of a structure of systems and on the comprehension of the fact that the dynamical systems of any nature are not solidified, but "alive" formations revealing the target "behavior". Moreover, their existence is continuously connected with their evolution. According to the conception, the whole observed variety of dynamical systems with various structures is a product of the evolution of the sets of interacting particles on the way of seeking such optimum structure of the system, which would correspond the highest stability and, hence, the largest chances to survive under dominating (i.e., most regular and/or most intense) external actions due to the improvement of the own internal structure.

The conception of self-organizing synthesis, like the scheme of inertial synthesis, considers a nonlinear wave propagating in a medium. In this case, the leading edge of the wave separates naturally the regions of a "fuel" entering into the wave and products of the combustion remaining behind the trailing edge. It is shown in [20, 21] that the analysis of a dynamical system formed by particles of the substance involved in a nonlinear wave leads to the general conclusion about the existence of a possibility to initiate the processes of self-organization in this system, which result in the synthesis of elements due to the "life activity" of the evolving system on the way from its creation to the decay.

By this conception, the realization of any scenario of the synthesis of elements is a collective process or a coherent nuclear reaction, in which a macroscopically large number of nucleons takes participation. A great number of "participants" of such a process corresponds to a huge amount of possibilities to realize the synthesis in the region of stable nuclei (it is proportional to the number of partitions of a very large integer into integer parts) with a minimum number of particles of a "superfluous" building material.

Book [21] contains a comprehensive description of base positions of the conception of self-organizing synthesis of nuclei and the great array of experimental results obtained as a result of the implementation of one of the scenarios of realization of the conception.

One of the most descriptive models of coherent nuclear reactions is the model of the filtration of a flux of initial nuclei through the growing macroscopic nuclear fractal cluster in the form of a moving and evolving shell of the electron—nucleus plasma.

The shell originates, when the correlations attain a critical level at some optimum density, which increases in the course of the evolution of the shell. The growth of the shell density occurs, because a part of the substance of a medium (through which the shell moves) enters the shell structure on its leading edge, whereas a part of the shell evaporates from the trailing edge (relative to its motion; see Fig. 11.).

The growth of the shell density is accompanied by a variation of its internal structure, the approaching of the fractal dimension to 3, and a decrease of the stability reserve up to the destruction of the shell and the formation of its fragments with various masses, i.e., up to the synthesis of a spectrum of nuclei.

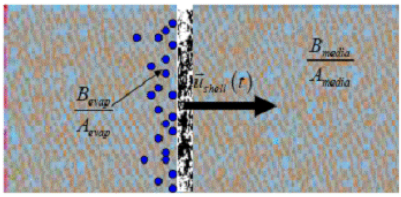

Fig. 11: Moving fractal shell in the form of a nuclear fractal membrane which filters the medium substance with the formation of new nuclei on the trailing edge of the wave-shell.

It is worth noting that the values of fractal dimension of a nuclear cluster (2.46 ± 0.05) presented in Fig. 3 correspond to the typical values of the dimension of clusters growing in the three-dimensional space, which are shown in Fig. 2.

If a cluster is created by the successive attachment of individual particles, its fractal dimension can be determined by the minimization of the free energy of the cluster within a simple model [28]:

$$D_f = \frac{4D_\omega + d\,(2D_\omega - 4) + 5d^2}{5D_\omega - 4 + 5d}. \tag{25}$$

Here, D_ω is the fractal dimension of the trajectories of particles, and d is the space dimensionality. For a Brownian trajectory with the dimension $D_\omega = 2$ in the three-dimensional space, we obtain $D_f = 2.5$, which is close to the dimension of nuclear clusters obtained by us from the condition for the binding energy to be maximum (see Fig. 3).

5 Fractal dipole resonance

The variation of the surfaces of giant charged nuclear clusters (their oscillations) leads, naturally, to the emission. For ordinary nuclei, the emission (giant dipole resonance) can be easily estimated in the approximation of drops of a charged fluid [7, 8]. Let us use this drop model for the estimation of the emission of fractal clusters. We denote a displacement of the surface of a cluster along the radius at a point (ϑ, φ) by $\xi\,(\vartheta, \varphi) = \xi_0\,(\vartheta, \varphi) \sin(\omega\, t)$. The density of the nuclear fluid can be considered constant, ρ_0, and let only the form of a nuclear cluster vary. Let the x-axis coincide with the polar axis $\vartheta = 0$. The quadrupole moment

$$e\, d_{xy} = \frac{eZ}{V_\delta} \int d\vartheta d\varphi \sin(\vartheta) \int\limits_{R-\delta}^{R+\xi_0(\vartheta,\varphi)} dr\, r^2 r^2 \cos(\vartheta) \sin(\vartheta) \cos(\varphi)\,. \tag{26}$$

The dependence of a displacement of the surface on the angles $\xi_0\,(\vartheta, \varphi)$ is described by the expansion in spherical modes (in spherical functions). The lowest nonzero mode is described by the expression

$$\xi_0\,(\vartheta, \varphi) = b \cos(\vartheta) \sin(\vartheta) \cos(\varphi)\,.$$

Therefore, the quadrupole moment (26) can be written as follows:

$$d_{xy} = \frac{Z\,R^2}{4\pi\delta} b \int\limits_0^{2\pi} d\varphi \cos^2(\varphi) \int\limits_0^{\pi} d\vartheta \cos^2(\vartheta) \sin^3(\vartheta) = \frac{Z\,R^2}{15\,\delta} b. \tag{27}$$

The conservation of the sum of the potential and kinetic energies of surface oscillations implies that the dispersion law of oscillations for the minimum frequency is given by the relation $\omega^2 = 8\left(\frac{1}{R}\right)^3 \left(\frac{\sigma(A, D_f)}{\rho}\right)$. In the first approximation (without a consideration of the distributions of protons and neutrons separately), the main contribution to the emission of surface oscillations is made by the quadrupole emission, whose intensity

$$I = e^2 \left(\frac{\omega^6}{4c^5}\right) d_{xy}^2. \tag{28}$$

The emission line width Γ_γ is equal to the product of $\hbar$ by the number of emitted quanta:

$$\Gamma_\gamma = \hbar \frac{I}{\hbar\omega} = e^2 \frac{1}{4} \left(\frac{\omega}{c}\right)^5 d_{xy}^2. \tag{29}$$

Using the dependences of the geometrical parameters of clusters on their dimension and the density, we can obtain the following dependence of the emission frequency of nuclear systems on the mass number, and the fractal dimension:

$$\omega = k^{3/2} \left(\frac{\sigma_s(\rho_A, \delta)}{\rho_A} \left(\frac{A}{A_{str}}\right)^{\gamma-2/3}\right)^{1/2} \approx \frac{\sqrt{8}}{R^{3/2}} \sqrt{\frac{\sigma_s(\rho_A, \delta)}{\rho_A} \left(\frac{A}{A_{str}}\right)^{\gamma-2/3}}. \tag{30}$$

In Fig. 12, we present the dependences of the emission frequency of nuclei due to the excitation of their surface on the mass number for ordinary nuclei and nuclei with the fractal structure.

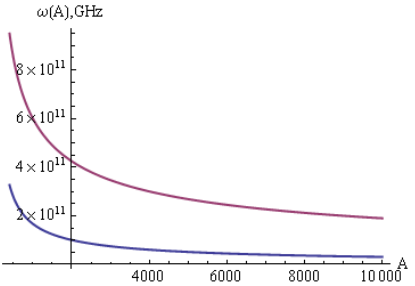

Fig. 12: Dependences of the emission frequency of nuclei due to the excitation of their surface on the mass number for ordinary nuclei (upper curve) and nuclei with the fractal structure (lower curve).

Since fractal structures are larger than liquid drops with the same mass, the emission frequencies of the former are significantly less, and the dependences of the emission frequency on the mass number are different. The experimental observation of the dipole resonance of fractal structures will allow one to determine the fractal dimension of nuclei and to classify structural nuclear isomers of the fractal type.

6 Fractal Thomson atoms

In the Nature, the charged nuclei capture the corresponding number of electrons and become the electrically neutral atoms. It is clear that the formed atoms can be stable (in the assumption of their planetary structure), if the radii of the electron orbits closest to the nucleus are larger than the nucleus radius $R\left(A_M; A_{str}, D_f\right)$:

$$\frac{a_0}{Z\left(A_M, A_{str}, D_f\right)} \geqslant R_{str}(A_M/A_{str})^{-D_f}. \tag{31}$$

This relation between the radii determines, in fact, the boundary of the Periodic Mendeleev table for the mass numbers of elements A_M. Relation (31) yields easily the estimate of the parameters of the limiting fractal nucleus: $A_M \approx 52000$, the charge $Z_M \approx 1180$, fractal dimension $D_f = 2.46$, specific binding energy per nucleon is of about 30 MeV, and size $R \approx 90$ fm.

For nuclear systems with large mass numbers ($A > A_M$), the quasistationary electroneutral formations will have the form of stable structures of the electron – nucleus plasma, rather than the planetary atoms. In other words, we may say that they will have the form of fractal Thomson atoms.

For the large values of mass numbers, $A > A_{\max M}$, the fractal electroneutral formations of the electron—nucleus plasma contain obligatorily the contribution of electrons. Their contribution to the energy of the degenerate electron Fermi-fluid can be presented with regard for the quasineutrality as a function of the density nuclear matter as follows:

$$W_{el}\left(A, Z; D_f\right) = \frac{3}{4} a_\varepsilon \, x_\rho^{4/3}\left(A; D_f\right)\left(\frac{Z}{A}\right)^{4/3}. \tag{32}$$

The binding energy of such formations differs from the binding energy of nuclei by the contribution of the electron Fermi-fluid. The density of the energy of such formations takes the form

$$\begin{aligned}\frac{W_{nuclei}\left(A, Z, x_\rho\right)}{\rho_{str}} = x_\rho \Bigg(& \left(M_n + c_3 - c_0\right) - \left(M_n - M_p + 4c_3\right)\frac{Z}{A} \\ & + c_1 \frac{1}{A^{1/3}} + c_2 \frac{Z^2}{A^{4/3}} + 4c_3 \frac{Z^2}{A^2}\Bigg) + \frac{W_{el}}{\rho_{str}}.\end{aligned} \tag{33}$$

The limiting Fermi energy of electrons increases with the substance density. Starting from the density which satisfies the condition

$$Z\varepsilon_e \geqslant \left(Am_n - M\left(A, Z\right)\right)c^2,$$

we obtain the possibility for the generation of stable free neutrons under conditions of thermodynamic equilibrium in the reactions $(A, Z) + Ze \to An + Z\nu_e$.

The requirement of a minimum of the internal energy $w\left(\rho, \rho_n, A, Z\right)$ of the nuclear matter with the mean density ρ, density of free neutrons ρ_n, and density of free electrons ρ_e under the condition of quasineutrality $\rho_e = \dfrac{Z}{A}\left(\rho - \rho_n\right)$ yields the equations

$$\left(\frac{\partial w}{\partial \rho_n}\right)_{\rho, A, Z} = 0; \qquad \left(\frac{\partial w}{\partial Z}\right)_{\rho, \rho_n, A} = 0. \tag{34}$$

With regard for (25) after the differentiation with respect to Z and A, the conditions of equilibrium (34) yield the equations

$$y_\beta = \frac{Z}{A} = \left(\frac{c_1}{2c_2}\right)^{1/2} \frac{1}{\sqrt{A}}; \tag{35}$$

$$x_p = \left((M_n - M_p + 4c_3)\left(\frac{2c_2}{c_1}A\right)^{1/6} - 2\left(\frac{c_1}{2c_2}\right)^{1/3}\left(4c_3\frac{1}{A^{1/3}} + c_2A^{1/3}\right)\right)^3 \frac{1}{a_\varepsilon^3}.$$

Thus, every density of nucleons corresponds to a single stable nucleus with $A(\rho)$ and $Z(\rho)$. It follows from the solution of Eqs. (35) that the mass number of a stable nucleus tends to the limit $A = 56$, as the density decreases. In this case, $\dfrac{Z}{A} \to \dfrac{26}{56}$. The energy density in the electron—nucleus plasma with regard for neutrons is as follows:

$$w = \frac{\rho - \rho_n}{A}\big((A-Z)\,M_n + Z\,M_p - B\,(A,Z)\big) + \rho_n\,W_n + \frac{3}{4}a_\varepsilon\left(\frac{Z}{A}\,(\rho-\rho_n)\right)^{4/3},$$

$$W_n \approx \rho_n\left(M_n + \frac{3}{5}\,\frac{a_\varepsilon^2}{2M_n}\,\rho_n^{2/3}\right). \tag{36}$$

The conditions of equilibrium take the form

$$\left(\frac{2M_n}{a_\varepsilon^2}\right)^{3/2}\left((c_3 - c_0) + \frac{1}{2}c_1A^{-1/3} - \frac{2c_1c_3}{c_2}\frac{1}{A}\right)^{3/2} = x_n, \tag{37}$$

$$\frac{1}{a_\varepsilon^3}\left(\frac{2c_2}{c_1}\right)^{1/2}\left((M_n - M_p + 4c_3)\,A^{1/6} - \sqrt{2c_1c_2}A^{1/3} - 8c_3\sqrt{\frac{c_1}{2c_2}}A^{-1/3}\right)^3 + x_n = x_\rho. \tag{38}$$

These equations allow one to calculate A and x_n for the given value of density x_ρ. As the density increases, the nucleus can be broken down. The threshold value of the ratio $y_{instab} = \dfrac{Z}{A}$ can be estimated from the requirement that the binding energy of nuclei be zero (see Fig. 11):

$$y_{instab} = \frac{2c_3 - \sqrt{4c_3^2 - \left(4c_3 + c_2A^{2/3}\right)\left(c_3 - c_0 + c_1A^{-1/3}\right)}}{4c_3 + c_2A^{2/3}}. \tag{39}$$

The plot of this function is shown in Fig. 13 together with the plot of $y_{st} = \sqrt{\dfrac{c_1}{2c_2}}A^{-1/2}$ for the most probable (stable) nucleus. The intersection of these plots determines the mass number of the most massive stable drop-like nucleus. In Fig. 14, we show the dependence of the mass number of the most probable nucleus on the logarithm of the mean density of the nuclear matter.

It is seen that the mass number of the most stable nucleus depends weakly on the density of the nuclear matter up to high densities and is equal to 56–60, but then it grows very rapidly.

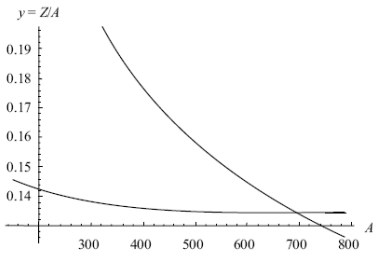

Fig. 13: Dependence of the quantity $y = Z/A$ on the mass number.

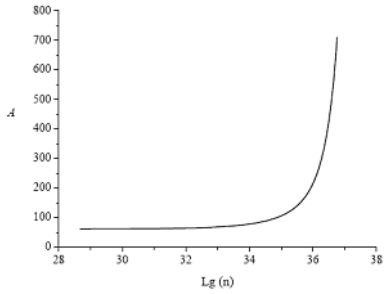

Fig. 14: Dependence of the mass number A of the most stable nucleus on the density of nucleons.

Conclusion. Potentialities of the energy release in nuclear processes.

In the framework of the conception of self-organizing synthesis of nuclei, we have introduced new important notions and presented some results, which would be applied in many fields of science and technique.

We have shown the efficiency of the use of such new states of the nuclear matter as the electron – nucleus plasma with strong correlations and the nuclear gel (cluster condensate with the fractal structure). As a result of the performed studies, it becomes clear that the fractal geometry in the Nature is spread onto the nuclear scale. Together with the mass and charge numbers, the nuclear structures are characterized by such fundamental parameters as the fractal dimension, correlation indices, and critical indices.

Based on the geometrical and physical relations involving the fractal geometry of a cluster structure and the Fermi statistics of nucleons, we have executed the estimates of the binding energy of fractal nuclear structures, predicted a high stability of superheavy nuclear clusters and their high binding energy, and obtained a generalization of the Bethe–Weizsäcker formula for superheavy fractal nuclear structures.

The expansion of the notions of the fractal geometry onto nuclear structures allows us to understand that the potentialities of nuclear processes and technologies as sources of energy are significantly greater than those considered in the modern nuclear physics. The conception of self-organizing synthesis leads us to the global conclusion that the future nuclear technologies will be based on multiparticle collective processes of synthesis-fission (coherent nuclear reactions) with a given energy directedness in a dense coherently correlated plasma (cluster condensate), rather than elementary two-particle collision nuclear reactions with overcoming the Coulomb barrier.

In order to develop the efficient technologies of the release and the accumulation of the nuclear energy, it is necessary to master the control over the self-organization of an internal structure of nuclei and their deformations. The main laws of the self-organization of nuclear structures and the methods of control will be considered in our future publications.

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Interdisciplinary Studies of Complex Systems
Vol. 1, No. 1 (2012) 81–84

Многокомпонентные случайные системы

Р. А. Минлос

От редакции. Редакция журнала обратилась к руководителю всемирно известной Добрушенской лаборатории Института Проблем Передачи Информации РАН Роберту Адольфовичу Минлосу с просьбой рассказать о научном направлении работы лаборатории, наиболее значимых результатах, полученных сотрудниками лаборатори, о том, какую роль играет сегодня математика в науке в целом. Данная публикация представляет ответы на эти вопросы.

Многокомпонентные случайные системы, — наименование одной из основных тем Добрушенской лаборатории ИППИ. Наименование — крайне удачное и емкое — было введено Р. Л. Добрушеным и объединяет многие направления, изучающие «большие» системы, т.е. системы с большим (в идеале бесконечным) числом элементов. В качестве примеров таких систем можно указать модели стохастической физики или квантовой теории поля, системы сетей связи, модели популяционной генетики, экологические модели и др.

Если говорить об основных особенностях этой науки, то следует привести характерные черты как самих многокомпонентных систем, так и принятых подходов к их изучению. Главная особенность таких систем проявляется (при некоторых условиях) в их «коллективном» поведении, возникающим из-за сильной скоррелированности всех элементов системы. Это приводит к таким, например, явлениям как фазовый переход, когда при незначительном изменении параметров системы она претерпевает резкую качественную перестройку своего состояния.

Другая важная черта больших систем, связанная уже со способом их описания и исследования, состоит во введение в это описание вероятностных представлений. Эта идея, впервые появившаяся в работах Больцмана, Максвелла и Гиббса, предлагает вместо того, чтобы детально следить за поведением каждой отдельной конфигурации элементов системы, ввести по определенному правилу распределение вероятностей на совокупности всех таких конфигураций, и изучать уже свойства этого распределения и, в частности, его эволюцию со временем. Такой подход избавляет нас от огромной и практически недоступной человеку информации, с которой пришлось бы оперировать при индивидуальном изучении каждой конфигурации. При этом львиная часть такой информации оказывается бесполезной, если нас интересует поведение системы «в целом», т.е. поведение ее наиболее вероятных (относительно введенного распределения) конфигураций...

Еще одна важная установка всех математических исследований многокомпонентных систем состоит в следующем. Исходная система всегда конечна — состоит из N элементов и исходное ее описание (пространство конфигураций, распределение вероятностей на этом пространстве и

т.д.) приспособлено именно к этому конечному случаю. Затем — поскольку N все-таки велико — для многих величин и соотношений, характеризующих состояние конечной системы, рассматривают их ассимптотику при N, стремящемся к бесконечности (этот предельный переход называют термодинамическим переходом). Естественно возникает мысль о том, чтобы построить некую идеализированную предельную систему с бесконечным числом элементов, т.е. предельное пространство их конфигураций и предельное распределение вероятностей на нем, так, чтобы асимптотические значения тех или иных величин, вычисляемых для конечной системы, совпали с соответствующими значениями, вычисленными уже для предельной системы. В большинстве математических работ по многокомпонентным системам это предельное образование так или иначе присутствует.

Что касается контретных направлений и тем из теории многокомпонентных систем, которыми занимаются в нашей лаборатории последнии годы и полученных результатах, то я хочу остановиться на следующих:

Статистическая физика. Исследовались предельные гиббсовские поля на решетке для некоторых сложных моделей; изучался модельный механизм формирования и роста кристаллов; были описаны и классифицированы связные состояния трансфер-матриц для двумерных и трехмерных решетчатых спиновых моделей; была вычислена высокотемпературная асимптотика убывания корреляций между далеко отстающими друг от друга спинами в модели Изинга.

Модели квантовой теории поля и квантовой теории твердого тела. Здесь были изучены нижние ветви спектра гамильтонианов в следующих моделях: модель Паули-Фирца (модель электромагнетизма); модель Нельсона (квантовая частица в безмассовом бозонном поле); модель полярона (электрон в бозонном поле); модель спин-бозона (единичный спин в бозонном поле). Во всех этих моделях были построены основные состояния и нижние (одночастные) ветви спектра возбуждений.

Теория сетей связи. Для больших сетей связи исследовались вопросы, связанные с т.н. пуассоновской гипотезой о том, что при низкой нагрузке сети ее элементы (серверы) почти независимы. Эта гипотеза была действительно подтверждена и, сверх того, было установлено, что для случая высокой нагрузки у некоторых классов цепей возникает сильная корреляция между элементами, что приводит к колебательному режиму в работе сети. Эта картина аналогична явлению фазового перехода в физике.

Стохастические динамики. Под стохастической динамикой обычно подразумевают какой-нибудь марковский процесс, имитирующий так или иначе определенную детерминированную динамику большой системы. Будучи удачно подобранным, этот марковский процесс хорошо улавливает свойства соответсвующей детерминированной динимики. Вот примеры стохастических динамик, изучавшихся в нашей лаборатории:

— стохастические динамики для бесконечного неидеального газа. Наиболее простым и хорошо изученным является т.н. «процесс рождения-гибели», в котором частицы могут лишь случайно рождаться в какой-нибудь точке пространства и затем, оставаясь все время в одном и том же месте, случайно гибнуть. Были изучены спектральные свойства генератора такой динамики, асимптотика убывания корреляций в ней и рассмотрены некоторые их применения в смежных науках (популяционная генетика, экология). Ряд методов и приемов, возникших при изучении такой динамики, успешно применяются в теории обработки изображения.

— другой пример стохастической динамики — это т.н. процесс с запретами в непрерывном пространстве (прежде такой процесс изучался всегда для решетчатых моделей). Следует также упомянуть интересную конструкцию стохастической динамики в пространстве бесконечных диаграмм Юнга. Полученные здесь результаты тесно связаны с теорией представлений бесконечной симметрической группы. Еще один пример изучавшейся у нас стохастической динамики — модель автомобильных потоков вдоль шоссе (стационарный режим, вероятности пробок и т.д.).

Эргодическая теория. Здесь довольно интенсивно изучались так называемые хаотические динамики. Под этим понимают такой класс динамических систем, траектории которых довольно густо покрывают все пространство динамической системы и тем самым подобны траекториям случайных процессов.

Следует так же отметить, что в нашей лаборатории рассматривались случайные блуждания одной или двух частиц в случайной среде. Рассматривались случайные блуждания по d-мерной решетке при фиксированной конфигурации случайного поля (среды) на этой решетке, меняющейся со временем.

Для полноты представления об общей многокомпонентной тематике, я хочу привести еще несколько сюжетов, традиционно причисляемых к этому направлению, хотя и не рассматриваемых в нашей лаборатории: редуцированное описание эволюции больших систем (уравнения гидродинамики, уравнение Больцмана и т.д.); детерминированная динамика бесконечного газа; ансамбль случайных матриц большого порядка; теория ренорм-группы; интегрируемые системы математической физики; спектральная теория для систем со случайным взаимодействием.

Рассказывая о нашей лаборатории, ее тематике и результатах, нельзя не обратиться к истории, так как многокомпонентная тематика лаборатории имеет своим истоком многолетнюю работу семинара по статистической физике на механико-математическом факультете МГУ (1962–1994 гг., руководители Р. Л. Добрушин, Р. А. Минлос, В. А. Малышев, Я. Г. Синай). На этом семинаре было получено много первокласных результатов и возникло немало замечательных концепций и понятий. Здесь я приведу три на мой взгляд самых сильных работы, полученных на семинаре за все время его существования. Предельное распределение Гиббса. В начале своего рассказа, я уже говорил о том, что в работах по многокомпонентным системам стало обычаем обращаться к некоторой предельной системе. Впервые такой подход был предложен в шестидесятые годы прошлого века применительно к моделям равновесной статистической физики. В наиболее полном виде он был сформулирован в работах Р. Л. Добрушина, О. Ландфорда и Д. Рюэля и с тех пор известен под аббревиатурой ДЛР. Р. Л. Добрушин подробно изучил связанные с этим подходом понятия и конструкции и их разнообразные применения. Теория фазовых переходов. Такая теория была развита С. А. Пироговым и Я. Г. Синаем применительно к низкотемпературному решетчатому газу частиц с конечным числом состояний каждой отдельной частицы («конечный спин»). Построения этой теории существенно использует т.н. контурный метод, впервые примененный Р. Пайерлсом и усовершенствованный в работах Р. А. Минлоса и Я. Г. Синая. В дальнейших работах российских и зарубежных авторов теория Пирогова–Синая была обобщена на случай систем с бесконечными и даже непрерывными значениями спина. Хотя и существуют разные обходные (и более простые) методы уста-

новления фазового перехода, подход по теории Пирогова-Синая позволяет получить полную картину этого явления. «Капля» Вульфа. Рассмотрим решетчатый газ частиц при низкой температуре T, заключенный, скажем в квадрат $L \times L$ на двумерной решетке и имеюший фиксированную плотность r. Тогда при достаточно малых r типичная конфигурация состоит из мелких ($\ln L$) капелек, плавающих в пустоте. При возрастании плотности r после достижения некоторого порога $r'(T)$ в типичной конфигурации газа появляются единственная макроскопических размеров концентрация частиц — «капля», случайно расположенная в квадрате. Этот результат был получен Р. А. Минлосом и Я. Г. Синаем в шестидесятые годы. Через 20 лет Р. Л. Добрушин, Р. Котецкий и С. Б. Шлосман обратились снова к изучению «капли» и вывели, что ее форма имеет вид выпуклой фигуры, известной как «овал Вульфа» (напомним, что Вульф установил такую форму для «капли» из чисто феноменологических представлений). Результат Добрушена, Котецкого и Шлосмана, изложение которого заняло целую книгу, показывает мощь современной математической физики: с их помощью можно установить довольно тонкие факты, исходя из первоначальных физических постулатов.

Что касается вопроса о тенденции развития естественных наук и роли математики в этом развитии и, в частности, многокомпонентной тематики, то тема эта слишком обширна и мне вряд ли удастся ее объять. Могу только заметить, что сегодня в нашей лаборатории кроме всей «многокомпонентности» развиваются и многие другие направления: алгебра во всех ее разновидностях, теория информации, теория кодирования, математическая логика... Наряду с математиками старшего поколения у нас работает много талантливых молодых людей.

На вопрос о том, «растворяет» ли сегодня математика в себе философию, переводя вопросы веры и феноменологических представлений в конкретное знание, я могу ответить следующее: я часто размышляю о математике как об одном из способов постижения мира. Пока людям доступна лишь часть математики, применимая главным образом к описанию и изучению нашего мира. И то пока только к некоторым его областям. Однако, в современной математике уже есть много реалий, к нашей действительности повидимому не приложимых, но заставляющих думать о других мирах, организованных возможно иначе, чем наш, где все эти абстрактные структуры находят предметные воплощения.

Что касается других человеческих приемов познания, — в частности, философии, то мне она представляется далекой от математики. Философия есть способ логически зафиксировать то изумление, которое охватыет нас, когда мы задумываемся о природе всего сущего,- откуда и как оно пришло и почему, т.е. задумываемся о природе Бога. Поэтому, я бы отнес философию к некой разновидности поэзии.

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Перший комп'ютер в континентальній Європі був створений у Києві

The first computer in the continental Europe was created in Kiev

Б. Н. Малиновський
B. Malinovsky

«Зберігати довічно»

У грудні 1976 р. відбулося засідання вченої ради Інституту кібернетики АН УРСР, присвячене 25річчю введення в регулярну експлуатацію першої у континентальній Європі Малої електронної лічильної машини («МЭСМ»), створеної в Інституті електротехніки АН УРСР під керівництвом Сергія Олексійовича Лебедєва (1902–1974).

У своєму виступі на засіданні директор Інституту академік В. М. Глушков так оцінив його новаторське творче досягнення:

«Незалежно від зарубіжних учених С. О. Лебедєв розробив принципи побудови комп'ютера з програмою, яка зберігається в оперативній пам'яті. Під його керівництвом створено перший в континентальній Європі комп'ютер, у стислі строки розв'язано важливі науковотехнічні завдання, чим було закладено радянську школу програмування. Опис «МЭСМ» — перший у країні підручник з обчислювальної техніки. «МЭСМ» стала прототипом великої електронної лічильної машини «БЭСМ». Лабораторія С. О. Лебедєва — це організаційний зародок Обчислювального центру — пізніше Інституту кібернетики АН УРСР».

Твердження В. М. Глушкова про те, що С. О. Лебедєв, незалежно від учених Заходу, розробив принципи по-

"Story eternally"

In December 1976 the academic council conference of the Institute of Cybernetics Academy of Science of the Ukrainian SSR was devoted to the 25 years of exploitation of the first in the continental Europe Small Electronic Computing machine (MESM), which was created in the Institute of Electrical Engineering AS Ukr.SSR under the Sergei Lebedev leadership (1902–1974).

The head of the Institute academician Victor Glushkov evaluated Lebedev's innovative and creative achievements in the following words: "Independently of foreign scientists, S. Lebedev elaborated the construction principles for the computer with program that can be stored in operating memory. Under his supervision the first computer in the continental Europe was created, important scientific and technical tasks were resolved in the short terms and the Soviet school of programming was founded. The MESM description became the first country textbook on computer engineering. The MESM served as prototype for the Big Electronic Computing Machine BESM. The laboratory of S. Lebedev is the Computing Center organizational germ, that later transformed into the Institute of Cybernetics".

будови комп'ютера з програмою, яка зберігається в пам'яті — принципово важливий момент. Саме зберігання програми в оперативній пам'яті стало завершальним кроком у розвитку перших комп'ютерів. На Заході цей етап пов'язують з ім'ям Джона фон Неймана. Оскільки висловлювання В. М. Глушкова підтверджено низкою архівних документів і спогадами людей, які працювали з С. О. Лебедєвим, можна стверджувати, що поряд із Джоном фон Нейманом С. О. Лебедєв є розробником принципу збереження програми в оперативній пам'яті комп'ютера.

На засіданні закритої вченої ради інститутів електротехніки і теплоенергетики АН УРСР від 8 січня 1951 р. (протокол №1) С. О. Лебедєв, відповідаючи на поставлені йому запитання після доповіді про «МЭСМ», сказав:

«У мене є дані по 18 машинах, розроблених американцями, ці дані мають характер реклами, без будьяких відомостей, як машини побудовані», і далі: «Використовувати зарубіжний досвід важко, оскільки опубліковані відомості дуже скупі».

У короткій записці, надісланій в АН СРСР на початку 1957 р., С. О. Лебедєв констатує: «У 1948–1949 рр. мною були розроблені основні принципи побудови подібних машин. Враховуючи їхнє виняткове значення для народного господарства, а також відсутність в СРСР будьякого досвіду їх побудови та експлуатації, я прийняв рішення якнайшвидше створити малу електронну лічильну машину, на якій можна було б досліджувати основні принципи побудови, перевірити методику розв'язання окремих задач і нагромадити експлуатаційний досвід».

Не випадково «МЭСМ» спочатку розшифровувалася як «Модель электронной счетной машины», і лише пізніше слово «Модель» було замінено на слово «Малая».

У згаданому вище протоколі С. О. Лебедєв відзначив: «За даними зарубіжної літератури, проектування і створення машини триває 510 років,

The statement that S. Lebedev elaborated the construction principles for the computer with a program stored in memory independently of western scientists, expressed by V. Glushkov, is fundamentally important. Namely, storage of the program in the operating memory was the final step in the first computers development. In western countries this stage is linked to the name of John von Neumann. And as the words of V. Glushkov are supported by the series of archival documents and his colleagues' statements, we can assert that Lebedev was a developer of the stored-program computer principle as well as John von Neumann.

On January 8, 1951, at the Institute of Electrical Engineering and the Institute of Heat and Power Engineering, AS Ukr.SSR, academic council private session (minutes 1) Lebedev reported on MESM and gave the following answer to the question from the audience: "I have got the data on 18 machines, elaborated by Americans. This data is a kind of advertising material and does not include any facts about the construction of the machines", and then: "It is really hard to use the foreign achievements, because the published information is very limited."

In a short note, sent to the Acaldemy of Science of the USSR in the beginning of 1957, S. Lebedev states: "In 1948–1949 I elaborated the main construction principles of such machines. Taking into account their significance for national economy and being aware of the fact that there is no experience of such machine building and exploitation in the USSR, I decided to create a small computing machine, which would be used to investigate the main construction principles, to check the problem solving techniques and to accumulate the experience of exploitation".

Not by chance MESM was deciphered at first as "Model Electronic Computing Machine", and later the

ми маємо намір побудувати машину за 2 роки».

Неймовірно, але вченому вдалося реалізувати цей проект за такий короткий строк. Роботи було розпочато в 1948 р., а вже наприкінці 1950го запрацював макет «МЭСМ». У 1951 р. «МЭСМ» здали для регулярної експлуатації. На ній, єдиній на той час машині такого класу, протягом 1952 р. розв'язувалися найважливіші задачі: фрагменти розрахунків термоядерних процесів, космічних польотів і ракетної техніки, дальніх ліній електропередачі тощо.

Досвід створення та експлуатації «МЭСМ» дав змогу С. О. Лебедєву за короткий час (наступні два роки!) створити «Большую электронную счетную машину» — «БЭСМ».

У статті «Біля колиски першої ЕОМ» (ЕОМ — електронна обчислювальна машина, назва статті російською мовою «Около колыбели первой ЭВМ», ЭВМ — электронная вычислительная машина) С. О. Лебедєв назвав «МЭСМ» «первістком радянської обчислювальної техніки». «БЭСМ» Сергій Олексійович характеризував так: «Коли машина була створена, вона нічим не поступалася новітнім американським зразкам і являла собою справжнє торжество ідей її творців».

Основні принципи побудови «МЭСМ» містяться у книзі (раніше секретній) «Мала електронна лічильна машина» (автори С. О. Лебедєв, Л. Н. Дашевський, К. О. Шкабара, 1952 р.). Ось ці принципи:

1. В машині використовується двійкова система числення.

2. До складу машини входять п'ять пристроїв — арифметичний, пам'яті, керування, вводу та виводу.

3. Програма обчислень кодується і зберігається в пам'яті так само, як і числа.

4. Обчислення здійснюються автоматично на основі програми, яка зберігається в пам'яті машини.

5. Крім арифметичних, машина виконує логічні операції — порівняння, умовного та безумовного переходів.

word "model" was replaced by the word "small".

In the abovementioned minutes S. Lebedev pointed out: "According to the foreign literature data, the projecting and construction of the machine last for 510 years. We intend to build a machine in 2year term."

Incredibly, but scientist managed to realize this project in such a short-term. The work was started in 1948, and MESM began functioning in the end of 1950. In 1951 MESM was handed over for regular commission. It was the only machine of such class at the time and during 1952 it was used to solve the most important problems: calculation fragments for the thermonuclear processes, space flights and jet engineering, power lines, etc.

The experience of MESM construction and exploitation made it possible for Lebedev to create in the next two years a Big Electronic Computing Machine—BESM.

In the article "At the Cradle of the first Computer" Lebedev called MESM a "firstling of the Soviet computer engineering". He described BESM in the following words: "When the machine was created, it was comparable to the latest American models. It was a triumph of ideas of its creators."

The main principles of MESM construction can be found in the previously classified book "Small Electronic Computing Machine" authored by

S. Lebedev, L. Dashevsky and E. Shkabara (1952). Here are those principles:

1. Machine uses binary notation.

2. Machine consists of five devices: arithmetic, memory, operational, input and output.

3. Computing program encoded and kept in the memory, as well as data.

4. Calculations implemented automatically on the basis of the memory-stored program.

5. Besides arithmetic operations, machine implements the logical ones:

6. Пам'ять будується за ієрархічним принципом.

7. Для обчислень використовуються числові методи розв'язання задач.

У 1955 р. на конференції у Дармштадті доповідь С. О. Лебедєва про «БЭСМ» викликала сенсацію: мало кому відома за межами СРСР машина була визнана найбільш швидкодіючою у Європі.

Судячи зі спогадів сучасників, задум створити цифрову обчислювальну машину виник у вченого ще до війни, коли він жив у Москві.

Професор А. В. Нетушил, який закінчив Московський енергетичний інститут за кілька років до війни, згадує: «Результатом моїх досліджень стала кандидатська дисертація на тему: «Аналіз тригерних елементів швидкодіючих лічильників імпульсів». Як відомо, електронні тригери стали пізніше основними елементами цифрової обчислювальної техніки. Від самого початку цієї роботи в 1939 р. і до захисту С. О. Лебедєв з увагою і схваленням ставився до моїх досліджень.

Він погодився бути опонентом з дисертації, захист якої відбувся наприкінці 1945 р. На той час ще ніхто не підозрював, що С. О. Лебедєв виношує ідеї створення цифрових обчислювальних машин».

Дружина вченого А. Г. Лебедєва розповідала, як восени 1941 р., коли Москва поринала у темряву через нальоти фашистської авіації, чоловік надовго зачинявся у ванній кімнаті, де можна було без побоювання вмикати світло, і годинами писав у товстому зошиті незрозумілі їй кружечки і рисочки (нулі та одиниці, які використовуються у двійковій системі числення).

Заступник С. О. Лебедєва по лабораторії, де створювалася «БЭСМ», доктор технічних наук В. В. Бардиж свідчить, що мав з учнем розмову, під час якої Сергій Олексійович сказав, що якби не війна, то роботу зі створення цифрової електронної обчислювальної машини він розпочав би значно раніше.

Нагадаємо, що в 1939–1947 рр. в

comparisons, conditional and unconditional transitions.

6. Memory built on the hierarchy principle.

7. Calculations done by digital tasks solving techniques.

At the 1955 conference in Darmstadt Lebedev's report about BESM caused a sensation. The machine, unknown outside the USSR, was recognized as the most fastacting in Europe.

According to the references of Lebedev's contemporaries, the idea to create the digital computing machine came to his mind before the war, when scientist lived in Moscow.

Professor Anatoliy Netushyl, who had graduated from the Moscow Energy Institute several years before the war, recalls: My research resulted in the Ph.D. thesis "Analysis of the trigger elements of fastacting impulse counters". It is known that later electronic triggers became the basic elements of the digital computer devices. From the very beginning of the work in 1939 till its defense, S. Lebedev treated my research with attention and approval. He had agreed to serve as opponent during the thesis defense, which took place in the end of 1945. At that time nobody suspected that S. Lebedev was elaborating the idea of digital computing machine creation."

Scientist's wife Alice Lebedeva used to say that in autumn of 1941, when attacks of fascist air forces plunged Moscow into the darkness, her husband closed himself in the bathroom, where he could safely switch on the light, and was writing for hours in his thick notebook some strange circles and sticks (zeros and ones, which are used in the binary notation).

Doctor of technical science Vsevolod Bardyzh, who was Lebedev's deputy in the laboratory, where BESM was created, recalls that during the conversation with a student

S. Lebedev mentioned that, if not the war, he would have started working on the digital computer construction much earlier.

СРСР жодних публікацій про двійкову систему числення, методику арифметичних операцій з двійковими числами і структуру цифрової обчислювальної машини ще не було. У відомих на той час релейній обчислювальній машині «Марк1» (США, 1944 р.), електронній обчислювальній машині «ЭНИАК» (США, 1946 р.) використовувалися десяткові системи числення. У релейних машинах К.р Цузе «Z1» (Німеччина, 1937 р.), «Z2» (Німеччина, 1938 р.), «Z3» (Німеччина, 1941 р.) використовувалася двійкова система числення, однак публікації про ці машини з'явилися лише за кілька років після Другої світової війни. Саме у довоєнні й перші повоєнні роки С. О. Лебедєв незалежно від закордонних вчених розробив методику операцій щодо двійкової системи числення, структуру та архітектуру «МЭСМ». Створення її було дуже непростим завданням, з яким учений блискуче впорався.

В архіві Інституту електродинаміки (раніше електротехніки) АН УРСР зберігається папка з документами про створення «МЭСМ». Чиясь турботлива рука понад піввіку тому написала на ній слова «Зберігати довічно». Вони виявилися пророчими.

We should be reminded that in 1939–1947 there were no publications about binary notation, principles of arithmetic operations with binary code and computer structure yet. Decimal notation was used in the machines known at that time, which were the relay computing machine Mark1 (USA, 1944) and the electronic computing machine ENIAC (Electronic Numerical Integrator and Computer, USA, 1946). Namely during the prewar and early postwar years S. Lebedev elaborated the principles of operations with binary notation and the structure and architecture of MESM. Its creation was a really hard task, but the scientist managed to solve it brilliantly.

In the archive of the Institute of Electrodynamics (formerly electrical engineering), AS Ukr.SSR, there is a folder containing documents about MESM development. Somebody's caring hand wrote prophetic words on it: "Store eternally."

Сучасники С. О. Лебедєва — піонери комп'ютерної техніки за кордоном

Поява наприкінці 40х років комп'ютерів із програмою, яка зберігається в пам'яті, була завершальним і дуже важливим кроком у розвитку цифрової обчислювальної техніки. До цього досягнення причетні у світі лише кілька видатних учених: у США — Джон фон Нейман, угорець за походженням (1903–1957), Джон Мочлі (1907–1980) і Преспер Еккерт (1919–1975), у Великобританії — Алан Тьюринг (1912–1954), Том Кілбурн (нар. 1921) і Моріс Уілкс (нар. 1913), в СРСР — Сергій Лебедєв (1902–1974), Ісаак Брук (1902–1974).

Кожен з них зробив свій внесок у створення перших комп'ютерів і ста-

Lebedev's contemporaries—pioneers of the computer engineering abroad

The rise of a programstored computers in the end of 1940s was the final and very important step in the development of digital computer engineering. Only few key scientists in the world were involved into this process. They were John von Neumann (Hungarian by birth, 1903–1957), John W. Mauchly (1907–1980) and J. Presper Eckert (1919–1995) from the USA, Alan Turing (1912–1954), Tom Kilburn (1921–2001) and Maurice V. Wilkes (1913) from the United Kingdom, Sergei Lebedev (1902–1974) and Isaac Brouk (1902–1974) from the USSR.

Each of them made a contribu-

новлення інформаційних технологій. Алан Тьюринг ще в 1936 р. у статті «Про зчисленні числа» довів можливість обчислення суто механічним шляхом будьякого алгоритму, який має розв'язок. Запропонована ним з цією метою гіпотетична універсальна машина, що отримала назву «машина Тьюринга», могла запам'ятовувати послідовність дій під час виконання алгоритму.

Джон Мочлі і Преспер Еккерт у 1946 р. створили комп'ютер «ЭНИАК», що керувався програмою, команди якої встановлювалися за допомогою механічних перемикачів. Це потребувало дуже багато часу й обмежувало автоматизацію обчислень. Зрозумівши це, вчені під час проектування наступного комп'ютера «ЭДВАК» передбачили зберігання програми в оперативній пам'яті. На етапі завершення робіт з «ЭНИАК» і проектування «ЭДВАК» з ними почав співпрацювати відомий учений Джон фон Нейман, який на той час брав участь у Манхетенському проекті зі створення атомної бомби і був зацікавлений у розробці ефективної обчислювальної техніки для виконання своїх розрахунків.

Блискуче освічений учений, видатний математик зумів узагальнити досвід, отриманий під час розробки машин, і виклав його у вигляді основних принципів побудови цифрових електронних обчислювальних машин у звіті, складеному в 1945 р. і розповсюдженому Г. Голдстайном. Ці принципи були застосовані для побудови машини «ДЖОНИАК» (названа на честь Джона фон Неймана). Матеріали звіту не друкувалися у відкритій пресі до кінця 50х років, але їх передали ряду фірм США та Великобританії. Популярність фон Неймана як видатного вченого відіграла свою роль — викладені ним принципи і структура комп'ютера отримали назву нейманівських, хоча їхніми співавторами були також Мочлі та Еккерт, а С. О. Лебедєв незалежно від цих учених реалізував такі самі принципи у «МЭСМ». На той час «МЭСМ» зали-

tion into creation of the first computers and the emerging of the Information Technologies. Alan Turing in his 1936 article "On Computable Numbers" proved the possibility to calculate mechanically any algorithm that is solvable. A hypothetical universal machine, which he proposed for this purpose, was called "Turing machine" and was able to memorize the order of actions during the algorithm performance.

In 1946 John Mauchly and Presper Eckert constructed computer ENIAC, which was operated by a program with commands performed by the mechanical switches. It took too much time and limited calculations automation. The scientists realized it and implemented stored program, while projecting the next computer EDVAC. A famous scientist John von Neumann started collaborating with them at the final stage of ENIAC construction and EDVAC projecting. At that time Neumann participated in the Manhattan project on atomic bomb creation and was interested in elaborating effective computer device for his calculations.

Being a brilliantly educated scientist, an outstanding mathematician managed to summarize the experience, accumulated during the machine elaboration process. He described it as the main principles of computer architecture in the 1945 report introduced to the public by Herman H. Goldstine. These principles were used to build the computer IAC under the direction of von Neumann. Materials of the report hadn't been published in press until the end of 1950s, but they were transmitted to several companies in the US and Great Britain. The principles and structure of the computer were called after von Neumann, though Mauchly and Eckert were the real inventors and S. Lebedev realized the same principles in his MESM independently from these scientists. That happened due to von Neumann's popularity. At that time MECM still remained classified

шалася засекреченою і блискуче досягнення С. О. Лебедєва не було відоме західним ученим. Слід зазначити, що машина «ДЖОНИАК», створена під керівництвом фон Неймана, почала працювати через рік після появи «МЭСМ».

Вчені університету в Манчестері Фредерік Вільямс і Том Кілбурн у 1948 р. створили примітивний комп'ютер під назвою «Baby» (дитина). Для запису даних і програми розв'язання задачі вони використали електронно-променеву трубку і першими довели можливість зберігати числа та програми у загальній пам'яті машини. Через рік Моріс Уілкс, який працював в університеті в Кембриджі й прослухав у 1946 р. лекції Мочлі та Еккерта, зумів випередити своїх учителів: у 1949 р. він створив перший у світі комп'ютер «ЭДСАК» з програмою, яка зберігається в пам'яті, здатну, на відміну від «Baby», розв'язувати не лише тестові задачі.

Про те, що було зроблено С. О. Лебедєвим у ті роки, сказано вище. І. С. Брук у 1950–1952 рр. створив першу в Російській Федерації цифрову електронну обчислювальну машину «М1».

Подальша творча доля «чудової сімки» склалася порізному. Алан Тьюринг у роки Другої світової війни брав участь у створенні комп'ютера «Колосс», призначеного для розшифрування радіограм німецького вермахту. «Не Тьюринг, звісно, виграв війну, але без нього ми могли б її програти», — підкреслив один із його соратників зі створення машини. Рання смерть не дала можливості цьому геніальному вченому повною мірою реалізувати свої наміри.

Долю Тьюринга розділив фон Нейман: він помер на 54му році життя, так і не побачивши другу, спроектовану під його керівництвом машину «ДЖОНИАК».

Джон Мочлі і Проспер Еккерт продовжили роботи зі створення комп'ютерів. У 1951 р. їм вдалося розробити першу в США серійну машину «УНИ-

and the western scientists were not aware of the brilliant achievement of Lebedev. It should be mentioned, that Neuman's machine IAC started working a year after MESM creation.

In 1948 University of Manchester scientists Frederic C. Williams and Tom Kilburn constructed a primitive computer called Baby. They used CRT (Cathode Ray Tube) for data and problem solving program recording. The scientists were the first to prove that it was possible to store data and programs in the machine's common memory. A year later Maurice Wilkes, who worked at the Cambridge University and attended lectures of Mauchly and Eckert in 1946, managed to leave his teachers behind. In 1949 he created the first computer EDSAC with a stored program memory capacity, which, in contrast to "Baby", was able to solve more then just test tasks.

The work of Lebedev during those years is described above. In 1950–1952 I. Brouk created the first computer M1 in Russia.

The later fate of "magnificent seven" was different. During the Second World War Alan Turing participated in construction of the "Colossus" computer, which was used to decipher the radiograms of the German Wehrmacht. One of his colleagues noted: "Of course it was not Turing who won the war. But we could have lost it without him". His early death disabled this genius scientist from complete realization of his intentions.

John von Neumann had a similar fate. He died at the age of 53 without seeing the second computer, projected under his direction. The computer was called "JOHNIAC" after the scientist.

John Mauchly and Presper Eckert went on working on the computer design. In 1951 they managed to create the first serial computer UNIVAC (UNIVersal Automatic Computer) in the USA. In 1952 they finished working on EDVAC (Electronic Discrete Variable Automatic Computer). Later

ВАК», а в 1952 р. — завершити роботи з «ЭДВАК». Згодом вони стали керівниками заснованих ними комп'ютерних фірм.

Том Кілбурн і Моріс Уілкс досягли блискучих успіхів у своїй подальшій науковій діяльності. У 1953 р. запрацював макет першої у світі обчислювальної машини на точкових транзисторах, розробленої Кілбурном. Робота була завершена в 1955 р. У машині використовувалися 200 транзисторів і 1300 германієвих діодів. У 60ті роки під керівництвом Тома Кілбурна було створено досить досконалу обчислювальну машину «АТЛАС» на транзисторах. Використання у ній віртуальної пам'яті і мультипрограмної роботи мало великий резонанс серед розробників комп'ютерів.

Моріс Уілкс став визначним ученим. Під його керівництвом було створено ще одну лампову машину «ЭДСАК2» з мікропрограмним керуванням, уперше запропонованим вченим у 1951 р. У подальшому він працював у галузі програмування, автоматизації проектування комп'ютерів, заклав основи мультипрограмної роботи електронних обчислювальних машин, консультував багато проектів і отримав світове визнання як видатний учений сучасності. Сьогодні Моріс Уілкс — почесний професор університету в Кембриджі і консультант однієї з найбільших американських фірм (ITT). Президія НАН України присвоїла йому звання почесного доктора (1998).

they headed computer companies they founded.

Tom Kilburn and Maurice Wilkes brilliantly succeeded in their scientific efforts. In 1953 the first model computer on point transistors elaborated by Kilburn was tested. The work was finished in 1955. There were 200 transistors and 1300 germanium diodes used in the machine. In 1960s there was created the quite perfect computer ATLAS under the direction of Tom Kilburn. Virtual memory and multiple program usage in the machine had a great response among the computer designers.

Maurice Wilkes became an outstanding scientist. Another vacuum tube computer "EDSAC2" with microprogramming control was created under his direction and presented in 1951. Later on he worked in the field of programming and computer construction automation. He laid the basis for multiprogrammed functioning of the computers, consulted many projects and obtained the recognition as a prominent scientist of the present. Today ninetyyearold Maurice Wilkes is the honorary professor in Cambridge and a consultant of the one of the biggest American companies (ITT). Presidium of the Ukrainian Academy of Science granted him the rank of honorable doctor of the Academy in 1998.

Становлення вітчизняного комп'ютеробудування

Навіть на тлі цих видатних досягнень західних учених результати наукової діяльності С. О. Лебедєва в галузі комп'ютеробудування у наступні двадцять років (після створення «МЭСМ» і «БЭСМ») вражають своїми масштабами. Під його керівництвом і за безпосередньої участі було створено ще 18 (!) комп'ютерів, при-

Emerging of the national computer building

Taking to the account these outstanding achievements of the western scientists, the scientific outcome and the magnitude of Lebedev's activity in the field of computer building during the next 20 years (after MESM and BESM creation) still impresses anyone. He participated in and directed the construction of 18 (!) more computers,

чому 15 з них випускалися великими серіями. І це за технологічної відсталості СРСР (тоді ще невеликої). Не випадково учень Сергія Олексійовича академік В. А. Мельников підкреслював: «Геніальність С. О. Лебедєва полягала саме в тому, що він визначав мету з урахуванням перспективи розвитку структури майбутньої машини, вмів правильно обрати засоби для її реалізації відповідно до можливостей вітчизняної промисловості» (журнал «УСиМ», 1976, №6). Під керівництвом С. О. Лебедєва було розроблено суперкомп'ютери для обчислювальних центрів, комп'ютери для протиракетних систем і для ракет, які використовувались у системах протиповітряної оборони.

Інтерес С. О. Лебедєва до цифрової обчислювальної техніки не був випадковим. Він стимулювався тим, що перші двадцять років своєї творчої діяльності (до 1946 р.), працюючи в галузі енергетики, вчений постійно стикався з необхідністю складних розрахунків і намагався автоматизувати їх на базі засобів аналогової обчислювальної техніки, в чому досяг чималих успіхів, але переконався в обмежених можливостях цього напряму техніки.

Діяльність ученого після переїзду в Москву почалася з лампових машин, які виконували десятки тисяч операцій. На той час це були суперкомп'ютери. Створені в 1958 і 1959 роках «М40» і «М50» виявилися найбільш швидкодіючими в світі. З появою напівпровідникових і магнітних елементів Сергій Олексійович перейшов до розробки суперкомп'ютерів другого покоління. Створена в 1967 р. «БЭСМ6» з продуктивністю мільйон операцій на секунду випускалася 17 років. Нею були оснащені кращі обчислювальні центри СРСР. «БЭСМ6» посіла гідне місце у світовому комп'ютеробудуванні: недарма Лондонський музей науки в 1972 р. придбав цю машину, щоб зберегти її для історії. Завершенням яскравої наукової діяльності С. О. Лебедєва стало створення суперкомп'ютерів на інтегральних схемах продуand 15 of them were produced in big lots, despite of moderate technological backwardness of the USSR at that time. Lebedev's disciple, academician

V. Melnikov stressed out that: "Lebedev's genius laid in his ability to set up the aim, taking into account the prospects of future machine structure development, being able to choose the methods correctly to achieve the aim in conformity with national industrial potential." (cited according to the "USM" journal, 1976, 6). S. Lebedev directed construction of the supercomputers for computer facilities, computers for the antimissile systems and the antiairplane rocket weapons.

Lebedev's interest in the digital computer engineering was not accidental. During the first 20 years of his creative career (until 1946) Lebedev worked in the field of power engineering and he constantly faced the necessity to do complex calculations. He successfully tried to automate them using analog devices, but quickly realized that the abilities of these techniques were limited.

His scientific work started with the vacuum tube machines that carried out ten thousands operations. At the time they were supercomputers. Computers M40 and M50, created in 1958 and 1959, were the most fastacting computers in the world. With the advent of semiconductors and magnetic elements

S. Lebedev switched to the elaboration of the second generation supercomputers. The 1967 BESM6, with a million of operations per second efficiency, was manufactured for 17 years. The best computer facilities in the USSR were equipped with this machine. The BESM6 took a worthy place in the world computer building. In 1972 London Museum of Science bought the machine to save it for the history. Lebedev's bright scientific career was concluded with construction of the supercomputers based on integrated circuits (microchip) devices that managed millions operations per

ктивністю мільйони операцій на секунду. Два з них після модернізації досі використовуються в системах протиракетної і протилітакової оборони. Кожний комп'ютер був новим словом в обчислювальній техніці — більш продуктивний, більш надійний і зручний в експлуатації. Головним принципом побудови всіх машин стало розпаралелювання обчислювального процесу. У «МЭСМ» і «БЭСМ» із цією метою використовувалися арифметичні пристрої паралельної дії. У «М20», «М40», «М50» додалася можливість роботи зовнішніх пристроїв паралельно з процесором. У «БЭСМ6» з'явився конвеєрний (або «водопровідний», як назвав його Лебедєв) спосіб виконання обчислень. У наступних комп'ютерах використовувалася багатопроцесорність та інші вдосконалення. Всі машини, розроблені під керівництвом С. О. Лебедєва, випускалися промисловістю СРСР великими серіями.

«Вміти дати напрямок — ознака геніальності», — цю фразу Ф. Ніцше цілком можна віднести до С. О. Лебедєва.

Новаторська творча діяльність ученого сприяла створенню потужної комп'ютерної промисловості, а керований ним Інститут точної механіки та обчислювальної техніки АН СРСР став провідним у СРСР. У 50–70ті роки за рівнем своїх досягнень він не поступався відомій американській фірмі «IBM».

Характеризуючи наукові здобутки С. О. Лебедєва, президент НАН України академік Б. Є. Патон підкреслив: «Ми завжди будемо пишатися тим, що саме в Академії наук України, у нашому рідному Києві, розкрився талант С. О. Лебедєва як видатного вченого в галузі обчислювальної техніки і математики, а також найбільших автоматизованих систем. Він започаткував створення в Києві відомої школи в галузі інформатики. Його естафету підхопив В. М. Глушков. І тепер у нас плідно працює Інститут кібернетики імені В. М. Глушкова — одна з найбільших у світі установ цього профілю.

second. Two of them after update are still in use in antimissile and antiairplane defense systems. Every computer was a new step in computer engineering. Every next one was more productive, more reliable and suitable in exploitation. The main principle of machines construction was paralleling of the calculation process. In MESM and BESM they used arithmetic parallel devices for this purpose. In M20, M40 and M50 external devices worked in parallel with a processor. Conveyer calculation method (Lebedev called it waterpipe) was introduced into BECM6. In the following computer models they used multiple processors and other improvements. All the machines projected under Lebedev's direction were on big serial production in the USSR.

The pioneering work of Lebedev contributed into the formation of powerful computer industry. The Institute of Precision Mechanics and Computer Engineering Academy of Science of the USSR, headed by Lebedev, became the leading one in the country. In 1950s–1970s its achievements were as significant as ones of the American company IBM.

Characterizing scientific attainments of

S. Lebedev, the President of National Academy of Science of Ukraine Boris Paton stressed out: "We would always be proud that in our very Academy of Science of Ukraine, in our beloved Kiev, the Lebedev's talent unfolded to become a prominent scientist in the field of computer engineering and mathematics, and the largest computerbased systems. He founded the famous school of thought in the field of computer science in Kiev. V. Glushkov carried on his work. And now we have productive

V. Glushkov Institute of Cybernetics, NASU, one among the largest in the world.

One of Lebedev's wonderful qualities was his care of and trust to the

Чудовою рисою С. О. Лебедєва була його турбота про молодь, довіра до неї. Молодим він доручав розв'язання найскладніших задач. Цьому сприяв неабиякий педагогічний талант Сергія Олексійовича. Багато його учнів стали видатними вченими і розвивають свої наукові школи.

Усе життя С. О. Лебедєва — це героїчний приклад служіння науці, своєму народові. Він завжди прагнув поєднувати найвищу науку з практикою, з інженерними завданнями.

Він жив і працював у період бурхливого розвитку електроніки, обчислювальної техніки, ракетобудування, освоєння космосу та атомної енергії. Будучи патріотом своєї країни, Сергій Олексійович брав участь у найбільших проектах І. В. Курчатова, С. П. Корольова, М. В. Келдиша, які забезпечили створення надійного щита Батьківщини. В усіх цих роботах особлива роль належала електронним обчислювальним машинам, створеним С. О. Лебедєвим.

Його видатні праці назавжди ввійдуть до скарбниці світової науки і техніки, а його ім'я стоятиме поряд з іменами цих великих учених».

Виняткова скромність С. О. Лебедєва, секретність значної частини його робіт призвели до того, що в західних країнах про геніального вченого мало що відомо: до кінця 90х років XX ст. змістовних публікацій там практично не було. У книзі американського історика Джона Лі «Комп'ютерні піонери» (1995), де вміщено понад 200 біографій учених, імені С. О. Лебедєва не знайти.

Лише у 95ту річницю від дня народження С. О. Лебедєва його заслуги визнали і за кордоном. Як піонер обчислювальної техніки він був відзначений медаллю Міжнародного комп'ютерного товариства з написом: «Сергій Олексійович Лебедєв. 1902–1974. Розробник і конструктор першого комп'ютера в Радянському Союзі. Засновник радянського комп'ютеробудування».

youth. He put them in charge of solving the most difficult problems. He possessed an outstanding pedagogical talent. A lot of his disciples became prominent scientists. They developed their own scientific schools.

His whole life is a heroic example of the devotion to science and to his people. He always aspired to combine noble science with practice and engineering tasks.

He lived and worked in the period of stormy development of electronics, computer engineering, rocket production, space exploration and atomic energy. Being a patriot of his country, Lebedev participated in the biggest projects of I. Kurchatov, S. Korolyov and M. Keldysh, who created a reliable shield for the Motherland. In all these works the computers constructed by Lebedev played a special role.

His prominent works will enrich the treasury of the world science and technology, and his name will stand together with the names of the greatest scientists forever."

Due to the Lebedev's extraordinary modesty and classified nature of the significant part of his works, it is very little known in the western countries about this genius scientists. Until the end of 1990s there were almost no substantial publications. In the 1995 book "Computer Pioneers" by John Lee, which contains over 200 biographies of the scientists, Lebedev's name is not mentioned.

Only on 95th birthday anniversary his achievements were recognized abroad. He was recognized as a pioneer of computer engineering with a medal from the International Computer Society. Its legend states: "Sergei Alekseyevich Lebedev 1902–1074. Developer and designer of the first computer in the USSR. Founder of the Soviet computer building".

Випередив час

«Я хочу сказати ще і ще раз, і буду все життя повторювати, що Віктор Михайлович Глушков — надзвичайно талановита людина, а в деяких сферах, чисто наукових, на мій погляд — геніальна людина, яка зробила величезний вклад у нашу науку, техніку, у наше громадське життя, і переоцінити важливість цього внеску для нашої країни просто неможливо.» (*Із інтерв'ю Бориса Євгеновича Патона для телефільму про В. М. Глушкова. «Нова студія», документальний цикл «Таємниці України». Київ, 2007 р.*)

Сучасникам не завжди вдається повною мірою збагнути значення діяльності того чи іншого вченого. Справжня оцінка часто з'являється значно пізніше, коли наукові результати і висловлені ідеї вже перевірені часом. Видатний внесок Віктора Михайловича Глушкова (1923–1982) у математику, кібернетику та обчислювальну техніку був високо оцінений ще за життя вченого. Але чим далі, тим очевиднішим стає те, що в процесі своєї творчої діяльності він зумів випередити час, зорієнтувавши створений ним у 1962 р. Інститут кіберне тики АН УРСР на перехід від обчислюваль ної техніки до інформатики, а далі — до інформаційних технологій. В. М. Глушков став фундатором цього надзвичайно важ ливого напряму розвитку науки і техніки в Україні і колишньому Радянському Союзі. Підготувавши необхідні кадри фахівців, він створив могутню наукову школу з цього напряму.

Поняття «інформаційні технології» з'явилося в науці в останні роки XX ст. Доти вживали терміни «інформатика» або «комп'ютерна наука», а ще раніше — «обчислювальна техніка», що визначали вужче коло проблем. Інформаційні технології, будучи високими технологіями, охоплюють широкий спектр наукових, конструкторських, технологічних і виробничих напрямів: проектування та виробництво комп'ютерів, периферійних

He was ahead of time

"I want to say again and again, and will repeat all my life that Victor Mikhaylovich Glushkov is annormally talented man, and in some fields, purely scientific, by my opinion, is a genius, who made an incredible contribution to the science, technics, community life of our country. it is impossible to overstimate this." (*From Boris Paton's interview for a television movie about V. G. Glushkov. "New studio", a documentary serial "Secrets of Ukraine". Kiev, 2007*)

The significance of scientist's work is not always recognized fully by contemporaries. Real evaluation appears much later, when the scientific results and the expressed ideas are verified by the time. The prominent contribution of Victor Glushkov (1923–1982) into mathematics, cybernetics and computer engineering was highly appreciated when he was still alive. But with the time passing by, it became evident that in the process of his creative activity he managed to stay ahead of time and oriented his Institute of Cybernetics of the Academy of Science of the Ukrainian SSR, which he founded and supervised, for the transition from computer engineering to computer science, and then—to information technologies (IT).

Glushkov became a founder of this incredibly important field of science and technologies in Ukraine and in the former USSR. He have trained the necessary cohort of experts and created a powerful scientific school in this field.

The term "information technologies" appeared in science in the last years of XX century. Earlier the terms "informatics" or "computer engineering" were used, that defined narrower problem circle. Being high technologies, information technologies cover wide range of scientific, design, technological and industrial directions: design and construction of computers, periphery devices, elemental base,

пристроїв, елементної бази, мережевого устаткування, системного програмного забезпечення, розробку і створення автоматизованих та автоматичних цифрових систем різного призначення і прикладного програмного забезпечення до них. Усі ці напрями почали розвиватися ще в 60–70х роках в Інституті кібернетики АН УРСР.

Видатні досягнення наукової школи В. М. Глушкова в галузі інформаційних технологій стали фундаментом для подальшого становлення в Інституті наукових шкіл його учнів і послідовників по ряду напрямів інформаційних технологій. У цій книзі відображено, в основному, історію розвитку основних напрямів у галузі комп'ютеробудування.

Ламповий комп'ютер «Киев» з «адресною мовою» програмування

Після від'їзду С. О. Лебедєва до Москви його учні в Києві — Л. Н. Дашевський, К. О. Шкабара, С. Б. Погребинський та інші — під керівництвом академіка Б. В. Гнєденка, директора Інституту математики АН УРСР, куди передали лабораторію С. О. Лебедєва, розпочали розробку комп'ютера «Киев» на електронних лампах із пам'яттю на магнітних осердях. Машина хоч і поступалася за характеристиками новому комп'ютеру «М20», розробленому під керівництвом С. О. Лебедєва в АН СРСР, але цілком відповідала вимогам того часу. В ній уперше використали «адресну мову», запропоновану К. О. Ющенко та В. С. Королюком, що суттєво спрощувало програмування.

Коли в 1956 р. колишню лабораторію С. О. Лебедєва очолив В. М. Глушков, під його керівництвом розробку комп'ютера «Киев» було успішно завершено. Він тривалий час використовувався в Обчислювальному центрі АН УРСР, створеному на базі лабораторії в 1957 р. Другу таку машину придбав Об'єднаний інститут ядерних досліджень у Дубні, де вона також довnetwork equipment, system software, elaboration and creation of automated and automatic numeric systems of different destination and their application software. All these directions have been developed since 196070s in the Institute of Cybernetics of the Academy of Science of the Ukrainian SSR, created in 1962 by V. Glushkov.

Outstanding scientific achievements of Glushkov's school in the field of IT became the foundation for the further development of scientific schools in the Institute under the direction of his followers. They developed diverse directions of IT. History of main directions of digital, analog and cybernetic computer devices is reflected in this book.

Vacuum tubes Computer "Kiev" with "address programming language"

After S. Lebedev left for Moscow, his colleagues in Kiev, among whom were L. Dashevsky, E. Shkabara, S. Pogrebinsky and others, under the supervision of academician B. Gnedenko, director of the Institute of Mathematics, AS Ukr.SSR, where Lebedev's laboratory was placed, started to elaborate computer "Kiev" with electronic tubes on magnetic cores. The machine "Kiev" yielded to the characteristics of new Lebedev's computer M20, but was surely uptodate. They used for the first time the "address programming language", which simplified the programming.

In 1956 V. Glushkov took the former laboratory of Lebedev. Under his supervision the elaboration of computer "Kiev" was successfully finished. This computer was in long use in the Computer Center of the Academy of Science of Ukraine, created on the base of the laboratory. The second machine of such kind was bought by the United Institute of Nuclear Investigations in Dubna, where it was exploited for a while. In 1962 the Computer Center

го експлуатувалася. Директором Обчислювального центру АН УРСР було призначено В. М. Глушкова.

Напівпровідникова керуюча машина широкого призначення «Днепр»

Наступною після комп'ютера «Киев» в Обчислювальному центрі АН УРСР було розроблено першу в Україні (і в СРСР) напівпровідникову керуючу машину широкого призначення «Днепр». Ідея її створення належить В. М. Глушкову, головний конструктор — Б. М. Малиновський. «Днепр» виготовили за рекордно короткий час: усього за три роки, і в липні 1961 р. дослідні зразки встановили на ряді виробництв. Цей результат тоді був світовим рекордом швидкості розробки і впровадження подібних машин. Пояснюючи фактори успіху, В. М. Глушков згадував: «Паралельно зі створенням «Днепра» ми провели за участю ряду підприємств України велику підготовчу роботу щодо застосування машини для керування складними технологічними процесами. Разом із співробітниками Металургійного заводу ім. Дзержинського (Дніпродзержинськ) досліджували питання керування процесом виплавки сталі у бесемерівських конверторах, із співробітниками содового заводу в Слов'янську — колоною карбонізації тощо. Як експеримент уперше в Європі за моєю ініціативою було здійснено дистанційне керування бесемерівським процесом протягом кількох діб поспіль у режимі порадника майстра. Машина «Днепр» використовувалася для автоматизації плазових робіт на Миколаївському заводі ім. 61 комунара. Згодом з'ясувалося, що американці дещо раніше від нас розпочали роботи зі створення універсальної керуючої напівпровідникової машини «RW300», аналогічної «Днепру», але запустили її у виробництво в червні 1961 р., водночас з нами. Це був саме той момент, коли нам вдалося

was transformed into the Institute of Cybernetics, which is now called after its founder academician V. Glushkov.

Transistor based control computer of broad application "Dnepr"

Following computer "Kiev" first in Ukraine (and in the USSR) transistor based control computer "Dnepr" was developed at the Computer Center of the AS Ukr.SSR. The idea of its creation belongs to Victor Glushkov. Boris Malinovsky (author of this book) was the chief designer of the machine. The machine was manufactured in record short time, only in three years, and in July 1961 it was installed at the selected factories. At that time this result was the world speed record of elaboration and implementation of the control machine. Explaining the factors of success, V. Glushkov recalled: "In parallel with "Dnepr" creation we had carried out a serious preparatory work on the machine utilization to control difficult technological processes together with several Ukrainian companies. Together with the employees of the Dzerzhinsky Metallurgical plant (Dneprodzerjynsk) we investigated control process over steel smelting in Bessemer converters, together with the workers of Soda plant in Slovyansk worked on carbonization column etc. I initiated the first experiment in Europe on remote control over Bessemer process, that lasted for several days in the regime of Master consultant.

The "Dnepr" machine was used to automate ship projecting works at Nikolaev "61 Communards" plant. Later we found out that the Americans had started earlier working on universal transistor control machine RW300, which was similar to "Dnepr", but put it into production in June 1961, at the same time with us. It was that very moment when we managed to

скоротити до нуля розрив між рівнем нашої та американської техніки, нехай лише в одному, але дуже важливому напрямі. До того ж «Днепр» був першою вітчизняною напівпровідниковою машиною (якщо не брати до уваги спецмашини). Згодом з'ясувалося, що вона чудово витримує різні кліматичні умови, вібрацію тощо. Коли під час спільного космічного польоту «СоюзАполлон» треба було впорядкувати демонстраційний зал у Центрі керування польотами, то після тривалого вибору всетаки зупинилися на «Днепре». Дві такі машини керували великим екраном, на якому відтворювався політ і стикування космічних кораблів».

Ця перша запущена в серійне виробництво напівпровідникова керуюча машина побила й інший рекорд — промислового довголіття, оскільки випускали її впродовж десяти років (1961–1971), тоді як зазвичай через п'ятьшість років потрібна вже серйозна модернізація.

Машини «Днепр» використовувалися в багатьох піонерських цифрових системах керування виробничими процесами, складними фізичними експериментами, під час випробовувань складних об'єктів нової техніки та не лише постачалися вітчизняним споживачам, а й експортувалися до багатьох країн Ради Економічної Взаємодопомоги (РЕВ).

Слід зауважити, що семирічним планом розвитку СРСР (1958–1965) будівництво приладобудівних заводів в Україні не передбачалося. Перші машини «Днепр» випускав Київський завод «Радіоприлад». З ініціативи В. М. Глушкова, підтриманої урядом, одночасно з розробкою машини «Днепр» у Києві розпочали спорудження заводу обчислювальних і керуючих машин — нині «Електронмаш». Отже, розробка «Днепра» стимулювала будівництво великого заводу з виробництва комп'ютерів.

Колектив творців машини «Днепр» і керуючих систем на її базі (керівник роботи Б. М. Малиновський, учасники М. З. Котляревський (від заво-

reduce to zero the gap between the level of American technology development and ours in one very important field. Besides, our computer was the first national transistor machine (if not to take into account specialized machines).

Later it was verified that the machine beautifully tolerates different climatic conditions, vibration, etc. When during the joint space mission "Soyuz–Apollo" it was necessary to equip the showroom in the Space flights operational center, after long discussions computer "Dnepr" was chosen. Two machines operated the big screen, on which the flight and docking was reproduced."

This first serial transistor control machine also broke the record of industrial longevity, as it was in production for ten years (1961–1971). In other cases serious modernization was usually needed after fivesix years.

"Dnepr" machines were used in many industrial processes pioneering digital control systems, complicated physical experiments, during the new sophisticated technology testings. The machines were supplied not only to national users, but were exported to many states of Council for Mutual Economic Assistance (CMEA or Comcon).

It should be mentioned, that the specialized plant construction in Ukraine was not included into the USSR sevenyear plan (1958–1965). The first "Dnepr" computers were produced by the Kiev plant "Radiopribor". V. Glushkov promoted construction of the plant for computers and digital control machines assembly ("Electronmash" now) in Kiev at the same time with "Dnepr" development. Government supported this initiative. Thus, "Dnepr" creation stimulated the construction of a big computer plant.

The creators of the digital control machine "Dnepr" and the control systems on its basis (B. Malinovsky— principal investigator and chief ex-

ду обчислювальних і керуючих машин), Г. О. Михайлов, М. М. Павлов, А. Г. Кухарчук, Л. О. Коритна, Ю. Т. Митулінський, І. Д. Войтович, Ф. Н. Зиков, В. С. Каленчук та ін.) був представлений на Ленінську премію. Однак роботи набагато випередили час. Новаторів не зрозуміли і представлення на премію відхилили, так само, як щодо «МЭСМ» у 1952 р.

У 1968 р. Інститут кібернетики АН УРСР разом із Київським заводом обчислювальних та керуючих машин розробив і випустив малою серією напівпровідникову машину «Днепр2», призначену для розв'язання широкого кола завдань: плановоекономічних, керування виробничими процесами і складними фізичними експериментами. Керували роботами В. М. Глушков і А. О. Стогній, головним конструктором був А. Г. Кухарчук. Машина складалася з обчислювальної частини «Днепр21» і керуючого комплексу «Днепр22». Науковим керівником робіт зі створення «Днепр22» був Б. М. Малиновський, головним конструктором — В. М. Єгипко. Машина «Днепр2» мала розвинуте математичне забезпечення, що постачалося замовникові. На жаль, випуск «Днепр2» за рішенням Міністерства приладобудування СРСР невдовзі було припинено.

Аналогова обчислювальна техніка

У 1959 р. колектив Обчислювального центру АН УРСР поповнився відділом математичного моделювання. Його керівником став талановитий 43літній учений професор Георгій Євгенович Пухов. Раніше він працював (з 1957 р.) завідувачем кафедри теоретичної і загальної електротехніки Київського інституту цивільної авіації і залишився на цій посаді за сумісництвом. Г. Є. Пухов зумів зібрати у відділ своїх кращих учнів — колишніх студентів і співробітників ка федри й розгорнув великі та глибокі до слідження в галу-

ecutive officer, participants M. Kotlyarevsky, G. Mykhaylov, N. Pavlov, A. Kukharchuk, Y. Mitulinsky and others) were nominated for a Lenin prize. However, work was so innovative, that its meaning were not comprehended by authorities, and the nomination was called off in the same way it was done with MESM in 1952.

In 1968 the Institute of Cybernetics in collaboration with the Kiev computers and control machines plant elaborated and produced a small series of transistor computer "Dnepr2". It was designed to solve a wide range of problems, such as planning, economic, controling over industrial processes and difficult physical experiments. V. Glushkov and A. Stogniy led the project; A. Kukharchuk was a principal designer. The machine consisted of a computing part "Dnepr21" and a control complex "Dnepr22". B. Malinovsky supervised works on "Dnepr22". The machine "Dnepr2" had comprehensive software that was supplied to the customer. Unfortunately, "Dnepr2" production was soon stopped with the resolution of Ministry of Instrumentmaking of the USSR.

Analog Engineering

In 1959 a new department of mathematical modeling was created in the AS Ukr.SSR Computing Center. Its chief was a talented 43yearsold scientist, professor Georgiy Pukhov. Earlier (since 1957) he served as chairman for the department of theoretical and general electrical engineering at the Institute of Civil Aviation in Kiev. He retained this post as adjunct chairman. G. Pukhov managed to attract the best students and former employees to the department. He developed broad and profound research in

зі аналогової і квазіана логової техніки спочатку в Обчислюваль ному центрі, а потім в Інституті кібернети ки АН УРСР, створивши наукову школу. Усього через рік відділ розробив спеціалізовану машину «ЭМСС7» для розрахунку різних будівельних конструкцій (Є. А. Проскурін та ін.), потім машину «ЭМСС7М» (В. В. Васильєв та ін.), «ЭМСС8 Альфа» (А. Є. Степанов та ін.). Пізніше були створені машини: «Итератор» для розв'язання систем лінійних диференціальних рівнянь з лінійними граничними умовами (Г. І. Грездов та ін.); «Аркус» — для розв'язання лінійних і нелінійних диференціальних рівнянь з лінійними і нелінійними крайовими умовами (Г. І. Грездов); «Оптимум2» для розв'язання транспортної задачі лінійного програмування (В. В. Васильєв); «Асор1» для розв'язання задач сіткового планування (В. В. Васильєв та ін.); «УСМ1» для розв'язання диференціальних рівнянь у частинних похідних еліптичного і параболічного типу (Г. Є. Пухов та ін.).

Усі машини, розроблені у відділі Г. Є. Пухова, випускалися малими серіями на заводах України.

У 1961 р. Г. Є. Пухова обрали членомкореспондентом АН УРСР. У 1966 р. Георгія Євгеновича було призначено першим заступником директора Інституту кібернетики АН УРСР. У цей час з ініціативи В. М. Глушкова численні відділи Інституту було згруповано в чотири відділення — теоретичної й економічної кібернетики, кібернетичної техніки, технічної кібернетики, медичної і біологічної кібернетики, а також обчислювальний центр. Відділення мали велику самостійність. Ними керували провідні вчені: О. О. Бакаєв, Г. Є. Пухов, О. І. Кухтенко, М. М. Амосов. Це давало змогу В. М. Глушкову майже не втручатися в роботу відділень, приділяючи основний час на рішення дуже важливих задач зі зв'язку Інституту з керівними органами країни, підключення Інституту до постанов уряду, що забезпечувало подальший розвиток матеріаль-

the field of analog and quasi analogue technology at the Computing Center, and then—at the Institute of Cybernetics, established the scientific school. After just a year the department elaborated its first specialized machine EMSS7 for different building constructions calculations (E. Proskurin and others), and then—a machine EMSS7M (V. Vasiliev and others), later—EMSS8 Alfa (A. Stepanov and others). Later the following machines were built: "Iterator" to solve systems of linear differential equations with linear boundary data (G. Grezdov and others), "Arkus" to solve linear and nonlinear differential equations with linear and nonlinear boundary data (G. Grezdov); "Omtimum2" to solve transportation problem of linear programming (V. Vasiliev); "Asor1" to solve the problems of net planning (V. Vasiliev and others); USM1 to solve differential equations in partial derivatives of elliptic and parabolic types (G. Pukhov and others).

All the machines, elaborated at the Pukhov's department, were manufactured in small lots by the Ukrainian plants.

In 1961 G. Pukhov was elected a Corresponding Member of the AS Ukr.SSR. In 1966 he was appointed the first deputy director of the Institute if Cybernetics, AS Ukr.SSR. At that time V. Glushkov initiated the process of merger of the numerous Institute departments into four sections: theoretical and economic cybernetics; cybernetic technologies; technical cybernetics; medical and biological cybernetics; and also Computing Center. The sections were independent and headed by prominent scientists A. Bakaev, G. Pukhov, A. Kukhtenko and N. Amosov.

V. Glushkov did not interfere much with the work of sections and could spend most of time to solve very important tasks on governmental affairs, on the state cooperation with the institute, its relevance to the government decisions. It ensured the further

ної, науковотехнічної і кадрової бази Інституту.

Г. Є. Пухову було доручено керівництво відділенням кібернетичної техніки Інституту. Своїм заступником він призначив Б. М. Малиновського і дав йому доручення координувати роботу технічних відділів: керуючих машин (Б. М. Малиновського), арифметичних і запам'ятовуючих пристроїв обчислювальних машин (Г. О. Михайлова), теорії цифрових обчислювальних машин (З. Л. Рабіновича), фізичних і технологічних основ цифрових обчислювальних машин (В. П. Деркача), перетворювачів форми інформації (А. І. Кондалєва), передачі інформації (А. М. Лучука), теорії і розрахунку електромагнітних пристроїв (О. В. Тозоні), медичної кібернетичної техніки (Л. С. Алєєва).

Між «цифровиками» і «аналоговиками» йшло негласне (але добре!) змагання. Пік успіхів колективу відділу Г. Є. Пухова припав на 60ті роки. Творчий внесок самого Г. Є. Пухова важко переоцінити. Але стрімкий розвиток цифрової техніки призвів, практично, до згортання досліджень в галузі аналогової і квазіаналогової техніки. У 1971 р. Г. Є. Пухов разом зі своїм відділом перейшов з Інституту кібернетики АН УРСР до Інституту електродинаміки АН УРСР. Пізніше він створив Інститут проблем моделювання в енергетиці АН УРСР.

У 1971 р., після переходу Г. Є. Пухова до іншого інституту, керівником відділення кібернетичної техніки став Б. М. Малиновський (на громадських засадах), залишаючись завідувачем відділу керуючих машин.

Попередники персональних комп'ютерів

Ще в 1959 р. у В. М. Глушкова виникла ідея створити машину для інженерних розрахунків. У 1963 р. під його на-

development of the material, scientific, technical and cadre basis of the institute, and also his own department of digital automation.

G. Pukhov was entrusted to lead the section of cybernetic technology of the institute. He appointed B. Malinovsky his deputy in charge of coordination of the following technical departments: department of operational machines (B. Malinovsky); department of computer arithmetic and storage devices (G. Mikhaylov); department of computer theory (Z. Rabinovich); department of physical and technological computer foundations (A. Kondalev); department of information transfer (A. Luchuk); department of theory and development of electromagnetic devices (O. Tozoni); department of medical computer devices (L. Aleev).

There was an unpublicized (however a positive!) competition between the "digital" and "analog" scientists. The peak of success of Pukhov's section took place in 1960s. The personal contribution of G. Pukhov was enormous. But the speedy development of digital engineering brought to the end research in the field of analog and quasianalog technology. In 1971 G. Pukhov moved his section from the Institute of Cybernetics to the Institute of Electrodynamics, AS Ukr.SSR. Later he created the Institute of Modeling Problems in Energetic, AS Ukr.SSR.

In 1971 after G. Pukhov's departure to another institute, B. Malinovsky became the head of the cybernetic technology section (on a voluntary basis), maintaining supervisory position in the control machines department.

Predecessors of personal computers

In 1959 V. Glushkov decided to create the machine for engineering calculations. Such machine called "Promin"

ковим керівництвом було розроблено і запущено в серійне виробництво створену в Інституті разом зі Спеціальним конструкторським бюро (СКБ) машину «Промінь». Її почав випускати Сєвєродонецький завод обчислювальних машин. «Промінь» була, по суті, новим словом у світовій практиці, мала у технічному плані цілу низку нововведень, зокрема пам'ять на металізованих картах. Але найголовніше — це була перша машина з так званим ступінчастим мікропрограмним керуванням (на яке В. М. Глушков пізніше одержав авторське свідоцтво).

Згодом ступінчасте мікропрограмне керування використали в машині для інженерних розрахунків, скорочено — «МИР1», створеній слідом за «Промінь» (1965). У 1967 р. на виставці в Лондоні, де демонструвалася «МИР1», її придбала американська фірма «IBM» — найбільша у США, яка постачала майже 80% обчислювальної техніки для всього капіталістичного світу. Це був перший (і, на жаль, останній) випадок купівлі радянської електронної машини американською компанією.

Розробники «МИР1» отримали Державну премію СРСР (В. М. Глушков, Ю. В. Благовещенський, О. А. Летичевський, В. Д. Лосєв, І. М. Молчанов, С. Б. Погребинський, А. О. Стогній). У 1969 р. прийняли до виробництва нову, досконалішу «МИР2», а потім — «МИР3». За швидкістю виконання аналітичних перетворень цим машинам не було конкурентів. «МИР2», наприклад, успішно змагалася з універсальними машинами звичайної структури, які перевищували її за номінальною швидкодією та обсягами пам'яті у багато разів. На цій машині вперше у практиці вітчизняного математичного машинобудування було реалізовано діалоговий режим роботи, де використовувався дисплей зі світловим пером. Кожна з цих машин стала кроком уперед на шляху побудови розумної машини — стратегічного напряму в розвитку комп'ю-

was elaborated in the Institute of Cybernetics and its SDB. In 1963 its serial production was started at the Severodonetsk computer plant. The computer "Promin" was a breakthrough in the world practice. It included many technical innovations, particularly memory on metallic cards. But the main thing was that it was the first machine with a socalled piggyback firmware control (later V. Glushkov received an author's certificate for it).

Some time later firmware control was used in the machine for engineering calculations MIR1, which was created after the "Promin" computer (1965). In 1967 MIR1 was exhibited in London where it was bought by the American company IBM—the largest in the USA supplier of about 80% of all computer technique for the capitalist world. It was the first and unfortunately the last time when the American company bought a Soviet computer.

MIR1 creators were awarded with the USSR State prize (V. Glushkov, Y. Blagoveshensky, A. Letichevsky, V. Losev, I. Molchanov, S. Pogrebinsky, and A. Stogniy). In 1969 improved computer MIR2, then—MIR3 were manufactured. These machines had no competitors for the speed of analytic conversion. For example, MIR2 successfully competed with universal computers of ordinary structure that rated many times higher in speed and memory capacity. Namely, on this machine for the first time in the history of national machinebuilding, they realized the dialog mode of work, where they used display with light pen. Each of these machines was a step forward creation of an intellectual machine, along a strategic direction in computer development proposed by V. Glushkov.

At that time it was considered that machine language should be as simple as possible, and the rest would be done by programs. "Address lan-

терів, запропонованого В. М. Глушковим.

На той час у світі панувала думка, що машинна мова має бути якомога простішою, а все інше зроблять програми. Такою була «адресна мова» для комп'ютера «Киев», розроблена В. С. Королюком і К. Л. Ющенко.

Проектуючи машини «МИР», В. М. Глушков ставив інше завдання — зробити машинну мову якомога ближчою до людської (мається на увазі математична, а не розмовна мова). І така мова — «Аналітик» — була створена (О. А. Летичевський) і підтримана оригінальною внутрішньомашинною системою її інтерпретації. Машини «МИР» використовувалися в усіх куточках Радянського Союзу. Головним конструктором комп'ютерів «Промінь» та «МИР» був С. Б. Погребинський.

guage" for the "Kiev" computer designed by V. Korolyuk and E. Yuschenko was of such kind.

Designing machines MIR, V. Glushkov set another aim—create machine language similar to the human one (meaning the mathematic, not the spoken language). Such language "Analitic" was created by O. Letichevsky and supported by the original internal system of interpretation. MIR machines were used in all parts of the USSR.

Кібернетична техніка

Термін «кібернетична техніка» з ініціативи Б. М. Малиновського затвердився в 1978 р. У «Енциклопедії кібернетики» (головний редактор В. М. Глушков), виданій у 1976 р., цей термін ще не згадувався. На відміну від обчислювальної, кібернетична техніка стала важливим напрямом у науці та техніці, пов'язаним із завданням зі створення технічних засобів для побудови керуючих, вимірювальних, контролюючих, автоматичних і автоматизованих систем і приладів з використанням комп'ютерів. Її попередниця технічна кібернетика була спрямована не на створення технічних засобів, а на розробку теорії систем керування, у першу чергу наукових основ автоматичного керування.

Виникненню кібернетичної техніки послужили створення і численні застосування керуючого комп'ютера «Днепр». Надалі відділення кібернетичної техніки почало займатися розробкою не тільки керуючих обчислювальних машин і спеціалізованих обчислювальних пристроїв, а й засобів передачі інформації, засобів спілкува-

Cybernetic techniques

The term "cybernetic technique" proposed by B. Malinovsky was established in 1978. In the "Encyclopedia of Cybernetics" (1976, editor—V. Glushkov) this term is not mentioned. Unlike the computational techniques, cybernetic technique became an important direction of science, connected with the task of facilities creation for control, measuring, automatic and automated systems and devices with a use of computers. Its predecessor—technical cybernetics, was aimed to elaborate the theory of control systems, first of all the scientific basis for automatic control, but not to create technical facilities to make them.

Creation and numerous usage of the machine "Dnepr" positively influenced the emerging of cybernetic technique. Later on, the Section of Cybernetic Techniques began to elaborate not only the control computers and specialized computing devices, but also information transmission media, communication facilities for the control systems operators, and the is-

ння оператора із системами керування, а також питаннями їхнього застосування для керування різними процесами, автоматизації складних експериментів і вимірювальних приладів.

Поява кібернетичної техніки була об'єктивно обумовлена швидким зростанням потреб в засобах автоматизації, прагненням мати ефективні, максимально дешеві, надійні, зручні в експлуатації технічні засоби для побудови автоматичних і автоматизованих систем у різних галузях народного господарства, науки і техніки, у військовій справі, у приладобудуванні, що вирішує задачі, дуже далекі від тих, котрі вирішуються звичайною обчислювальною технікою в обчислювальних центрах або за допомогою персональних та інших обчислювальних засобів. Основою кібернетичної техніки, породженої в надрах обчислювальної техніки, стала також автоматика, телемеханіка, автоматичне керування, вимірювальна техніка — на їхній базі кібернетична техніка здобула самостійність.

Рушійною силою розвитку обчислювальної техніки стала потреба, що дедалі зростала, в обчисленнях (найрізноманітніших) у науці та техніці. Звідси й удосконалення засобів обчислювальної техніки пішло по лінії створення могутніх універсальних машин, машин для інженернотехнічних розрахунків, термінальних комп'ютерів для обчислювальних систем колективного користування, а також по лінії розвитку обчислювальної техніки для індивідуального користування інженерами, студентами, школярами, адміністраторами й ін. Основні вимоги до засобів обчислювальної техніки — це якнайвища продуктивність, зручність в обслуговуванні як великих колективів — споживачів обчислювальної техніки, так і окремих користувачів, простота спілкування людини з машиною. Обчислювальна техніка, як відомо, створюється для використання її людиною в якості могутнього обчислювального інструмента і засобу автоматизації інтелектуальної діяльності.

Розвиток кібернетичної техніки

sues of their usage to control different processes, automation of difficult experiments and measuring devices.

The appearance of cybernetic technique was fairly caused by increasing demand for the automated facilities, by aspiration for having the effective, cheap, reliable, easytouse technical devices to construct the automatic and automated systems in different fields of economy, science and technology, in the military service, in the instrumentmaking industry. These devices would solve the problems different from ones, which are usually solved by ordinary computers in the computing centers or with the help of personal or other calculators. The foundation of cybernetic technique, which first came out from the computing techniques, was also automation, telemechanics, automatic control, measuring technique. On their basis cybernetic technique acquired independence.

A growing demand for various calculations in science and technology became the driving force in computing technique development. The improvement of computing technique devices developed into two directions: creation of the powerful universal computers, computers for technical and engineering calculations, terminal computers for the shared computation systems; and also into development of computer technique for personal use by engineers, students, schoolchildren, administrators etc. The main requirements to the computing technique devices were highest productivity, usability, comfortable service for both collective and individual users, simplicity in communication between human and machine. As we know, computing technique is created to provide a powerful calculation and intellectual activity automation means to the people.

The driving force for cybernetic technique development was the intention to automate different technological and measuring processes, daytoday industrial management, control over

був обумовлений прагненням автоматизувати різні технологічні і вимірювальні процеси, оперативне керування виробництвом, керування енергетичними, транспортними й іншими об'єктами, у тому числі в сфері озброєння й у космосі (процеси розпізнавання і т. д.) з метою вилучення людини з галузі контролю і керування цими процесами. У таких застосуваннях виконання обчислень є лише частиною загального комплексу інформаційних процесів, що підлягають автоматизації. У зв'язку з цим комп'ютери, хоча і виконують роль центральної інтелектуальної частини систем, але вже не є єдиним засобом для їхньої побудови. Для цього потрібні також засоби автоматичного обміну інформацією між об'єктами й комп'ютерами, передачі інформації (як цифрової, так і аналогової) на відстань, відображення ходу процесу оператору, втручання оператора в процеси й ін. Таким чином, склад засобів кібернетичної техніки виявився значно ширшим, ніж засобів власне обчислювальної техніки. Для деяких застосувань частка засобів останньої виявилася взагалі незначною порівняно з великим обсягом іншої апаратури, такої, наприклад, як засоби зв'язку з об'єктом.

Крім того, до обчислювальних засобів, що входять до складу засобів кібернетичної техніки, виникли свої, особливі вимоги. Висока швидкість виконання обчислювальних операцій у ряді випадків перестала бути основним критерієм їхньої якості. Якщо він і задавався, то, як правило, доповнювався цілою низкою інших вимог з оперативності обробки, вартості, розмірів апаратури, надійності й ін. З'явилися особливі вимоги до організації обчислювального процесу. Головними стали вимога обробки інформації в реальному масштабі часу, циклічне повторення тих самих програм, тільки з різними початковими умовами, орієнтація обчислювальних засобів на визначені класи обчислень та ін. Можливі випадки, що вимагають надвисокої швидкості обчислень для визначених груп

energy, transport and other objects, including ones in the field of armament and space exploration (recognition processes) with the aim to eliminate human from the control and management over these processes. For such purpose calculation is only a part of the whole complex of information processes, which are to be automated. In such a view the computers are not a unique means for their construction, though they play a role of a central intellectual part of the systems. Besides, for these purposes there should be means of automatic information exchange between the computer and other objects, distant information transmission (both digital and analog), report on processes to the operator's display, operator's interference with the processes, etc. Thus, the composition of cybernetic facilities was much broader than ones of computing techniques. In some applications, for instance, in the facilities for communications with object, the part of computing technique devices was minimal compared with the great range of other equipment.

Besides, there appeared special demands for the computing devices, which are to be included into the cybernetic technique. The high speed of calculation operations was no longer the main criteria of their qualities in some cases. If it was hallmarked, it was usually compiled with other demands for processor efficiency, cost, size of device, reliability, etc. There were special demands for organization of the computing process. Among them: information processing in a real time scale, cyclic repetition of the same programs but with different initial conditions, selection of computing devices toward definite classes of calculations, etc. The opportunity to apply extreme speed of calculations for definite groups of applications. It is often needed to disperse the computing devices in the cybernetic systems, according to the process specificity, which should be automated. That also

застосувань тощо. Обчислювальні засоби в кібернетичних системах часто потрібно розосередити, залежно від специфіки процесу, який автоматизується, при цьому виникає необхідність у побудові розподілених, ієрархічних, однорідних, кільцевих та інших обчислювальних структур. Крім алгоритмічної універсальності (у визначених межах, обумовлених класами застосувань), від обчислювальних засобів, що входять до складу кібернетичної техніки, потребували системної універсальності (у рамках намічених застосувань), що внесло свої особливості в принципи її побудови (модульність, інтерфейси для підключення пристроїв зв'язку з об'єктом та ін.).

Математичне забезпечення засобів кібернетичної техніки також має певні особливості (стандартні програми і мови, орієнтовані на області застосувань, жорсткі програми, підготовка програм на універсальних машинах, схемна реалізація програм, усічена операційна система й ін.).

Значний внесок у проведені дослідження зробили технічні відділи Обчислювального центру АН УРСР і відділення кібернетичної техніки Інституту кібернетики АН УРСР, що виросло за двадцять років — з 1962 по 1982 — до 500 наукових співробітників, інженерів, лаборантів і техніків.

Прикладами можуть бути такі масштабні роботи, як створення і широке використання на промислових підприємствах і в багатьох науководослідних організаціях Радянського Союзу декількох сотень керуючих машин «Днепр»; розробка і промисловий випуск разом із Науковиробничим об'єднанням «Светлана» (м. Ленінград) першого в СРСР сімейства мікрокомп'ютерів широкого призначення «Электроника С5»; розробка разом з Виробничим об'єднанням ім. С. П. Корольова в інтересах цілої галузі промисловості засобів зв'язку СРСР керуючих комп'ютерів «СОУ1» і «СОУ2», комплексу мікропроцесорних засобів, у тому числі професійно орієнтованого персонального комп'ютера «Нейbrings necessity to build the parted hierarchic, homogenous, circular and other computing structures. In addition to algorithmic universality (in fixed limits, caused by the application classes), there should be system universality on behalf of computing devices that were part of cybernetic technique (within the limits of planned applications), which brought peculiarities into the principles of its construction (modularity, interfaces to link with object communication devices, etc.)

Mathematical foundation of the cybernetic technique also has its own peculiarities (standard programs and languages oriented on application fields, hardware programs, programs preparation on universal computers, circuit programs implementation, truncated operating system, etc.)

A significant contribution into the research was made by the technical departments of the Computing Center of the AS Ukr.SSR and by the Section of Cybernetic Techniques of the Institute of Cybernetics, AS Ukr.SSR, whose staff increased to 500 scientists, engineers, laboratory assistants and technicians in 20 years (1962–1982).

Following profound works can serve as an examples: creation and wide use of several hundreds of "Dnepr" machines at the industrial enterprises and many research organizations of the Soviet Union; development and production of the first Soviet family of universal microcomputers "Electronica S5" (together with scientific production association "Svetlana", StPetersburg, Russia); development (in collaboration with Kiev S. Korolev Production association) and wide usage of control machines SOU1 and SOU2, of microprocessorbased complex facilities, including a professionally oriented PC "Neuron", modular set of microprocessorbased tuning devices SO01—SO04 for the benefit of the whole communication facilities industry of the USSR; elaboration of the professionallyoriented PC ES1841 (to-

рон», модульного набору засобів налагодження мікропроцесорної техніки «СО01» — «СО04»; розробка професійно орієнтованого персонального комп'ютера «ЕС1841» (разом із Науководослідним інститутом керуючих обчислювальних машин Радіопрому СРСР), створення процесорів цифрової обробки сигналів, суперпродуктивних спеціалізованих засобів розпізнавання образів, цифрових спеціалізованих пристроїв контролю і керування швидкоплинучими фізичними процесами, відеокомп'ютерних терміналів, систем автоматизації інженерної праці, знанняорієнтованих інтелектуальних систем, могутніх кластерних обчислювальних комплексів, систем автоматизації наукових експериментів в установах Академії наук УРСР, унікальних керуючих систем різного, в тому числі оборонного призначення й ін.

У підсумку загальні зусилля колективу відділення кібернетичної техніки сприяли становленню й успішній роботі наукової школи в цій дуже важливій галузі знань.

gether with the research institute of Radioprom of the USSR), creation of signal digital processing, devices super productive facilities for pattern recognition, digital specialized devices for control over highspeed physical processes, videocomputer terminals, systems of engineering works automation, knowledgeoriented intellectual systems, powerful clustered computing complexes, systems of scientific experiments automation for the organizations of the Academy of Science Ukr.SSR, unique control systems of different applications, including military, etc.

Great collective efforts of the Section of the cybernetic technique staff furthered the formation and successful work of the scientific school in this incredibly important field of knowledge.

Interdisciplinary Studies of Complex Systems
Vol. 1, No. 1 (2012) 109–115

О некоторых памятных датах и юбилеях 2012–2013 гг.

Н. Кондратьева

Если бы не было памятных и юбилейных дат, мы многое бы забыли. Эти дни не только дань признательности великим людям за проделанный ими труд, но и размышления о сути этого труда, его историческом значении и его значении для будущего.

В 2013 году исполняется 150 лет со дня рождения великого ученого, первого Президента Украинской Академии Наук Владимира Ивановича Вернадского. Основатель новых наук, таких как биогеохимия, генетическая минералогия, радиогеология и ряда других, В. И. Вернадский известен, в первую очередь, как автор учения о биосфере. Учение Вернадского о биосфере явилось синтезом идей и исследований, относящихся к десяткам наук.

Понятие биосферы, поверхности геологической оболочки Земли на которой сосредоточена область жизни, было введено в биологию Ламарком в начале XIX века, а в геологию Зюссом в конце XIX века. В учении Вернадского биосфера получила новое понимание. Биосфера выявилась как планетное явление космического характера. Вернадский писал: «Космические излучения вечно и непрерывно льют на лик Земли мощный поток сил, придающий совершенно особый, новый характер частям планеты, граничащей с космическим пространством... Вещество биосферы благодаря этим излучениям проникнуто энергией, оно становиться активным, собирает и распределяет в биосфере полученную в форме излучения энергию, превращая ее в энергию в земной среде свободную, способную производить работу. Земная поверхностная оболочка не может, таким образом, рассматриваться как область только вещества; это область энергии, источник изменения планеты внешними космическими силами». [1]

Вернадский также отмечал, что человечество не только часть биосферы, но и носитель планетарного разума. Он указывал, что историю научной мысли «нельзя рассматривать только как историю одной из гуманитарных наук. Это история есть одновременно история создания в биосфере новой геологической силы — научной мысли, раньше в биосфере отсутствовавшей». Владимир Иванович Вернадский создал новое учение о Природе, рассматривающее единство жизни, сознания и мысли. Жизни, как бесконечного многообразия сложных биологических систем; сознания, как способности воспринимать и перерабатывать информацию; мысли как творческой силы и закона мира.

Направлением развития учения Вернадского можно рассматривать науку синергетику. Одному из основателей этой науки, Герману Хакене-

ну, в этом году исполняется 85 лет. Рассматривая процесс возникновения смысла (саморождение смысла) в сложной биологической системе, Герман Хакен дает следующую ее характеристику: «Одна из наиболее поразительных особенностей любой биологической системы — необычайно высокая степень координации между ее отдельными частями. В клетке одновременно и согласовано могут происходить тысячи метаболических процессов. У животных от нескольких миллионов до нескольких миллиардов нейронов и мышечных клеток своими согласованными действиями обеспечивают координированные движения, сердцебиение, дыхание и кровообращение. Распознавание образов процесс в высшей степени кооперативный, равно как и речь и мышление у людей.

Совершенно очевидно, что все эти высоко координированные когерентные процессы становяться возможными только путем обмена информацией, которая должна быть произведена, передана, принята, обработана, преобразована в новые формы информации и должна участвовать в обмене информацией между различными частями системы и вместе с тем между различными иерархическими уровнями. Так мы приходим к неприложному выводу о том, что информация (сознание) является решающим элементом существования жизни». [2] Заглядывая в будущее, ученый пишет: «. . . мы надеемся, что, когда нам удастся найти законы, применимые к широкому кругу самых различных сложных систем, на нас снизойдет озарение и мы сможем постичь их внутреннюю сущность».

В XX веке в естественные науки пришли новые направления, среди них вопросы искусственного интеллекта, информационных технологий, «управления и связей в животном и машинах». В этом и следующем году научное сообщество отмечает юбилеи целого ряда пионеров этих напралений: 100-летие со дня рождения Алана Тьюринга и Мориса Уилкса, 110-летие со дня рождения Джона фон Неймана, Сергея Лебедева, Исаака Брука, Юджина Вигнера, 90-летие со дня рождения Виктора Глушкова.

Алан Тьюринг в 1934 г. в статье «О вычислимых числах» доказал возможность выполнения чисто механическим путем любого имеющего решение алгоритма. Предложенная им для этой цели гипотетическая цифровая универсальная машина, получившая название машины Тьюринга, имела память для запоминания последовательности действий, т.е. программу выполнения алгоритмов.

Независимо от западных ученых, принципы малой электронной счетной машины МЭСМ были разработаны академиком Украинской Академии Наук и АН СССР Сергеем Лебедевым. МЭСМ Лебедева бала первым созданным в континентальной Европе компьютером. Первая ЭВМ Джона фон Неймана начала работать через год.

Нельзя не упомянуть о предложенной Джоном фон Нейманом концепции клеточных автоматов, поставившей вопрос о возможности развития жизни из неживых клеток, учитывая, что неживые клетки могут хранить информацию — программу, способную менять мир. Сегодня теория клеточных автоматов рассматривается как один из возможных путей исследования поведения сложных систем.

Две работы Юджина Вигнера (о непостижимой эффективности математики в естественных науках (1960 г.) и о роли сознания в квантовых

измерениях (1961 г.)) вызвали бурную дискуссию в научной среде и заставили задуматься о важных вопросах: о сознании (мышлении) как предмете науки и о математике как способе адаптации идей и законов к человеческому мышлению. Во многом эти работы были написаны Вигнером под впечатлением величайшего научного открытия XX века — квантовой теории поля. Здесь, конечно, нужно отметить, что родоначальник квантовой теории поля П. А. М. Дирак, как и Ю. Вигнер родился 110 лет назад, в августе 1902 года. Вышеуказанные работы Вигнера породили так же дискуссию о возможности влияния сознания (мышления) на окружающий мир и дискуссию о проблеме интеграции всех естественных наук, где главную роль играет математика. [3]

Законы, применимые к самым различным сложным системам могут быть найдемы путем построения математических моделей этих систем и их анализа. Это сложная задача требует как новых математических методов и техник, так и нового математического мышления. Для описания широкого спектра сложных систем математика должна входить как аппарат исследования в самые различные науки и отыскивать аналогии и созвучия между ними. Математические структуры и модели сложных систем требуют от математиков понимания сути их природы. Одних математических уравнений уже недостаточно. На то, что «математики знают больше математику чем природу» сетовал еще в XVI веке Джордано Бруно: «. . . математики — как бы посредники, переводящие с одного языка на другой; но затем другие вникают в смысл, а не они сами». Выдающийся математик XX века Израиль Моисеевич Гельфанд, в 2003 году в юбилейной речи своего 90-летия говорил: «Важная черта математики состоит в том, что она является адекватным языком многих различных областей: физики, инженерии, биологии. Это очень важное понятие: адекватный язык. . . . Сейчас время радикальной перестройки фундаментального языка математики. . . . Через 10–15 лет математика будет совсем другой.»

В сентябре 2013 года научное сообщество будет отмечать 100 лет со дня рождения великого математика.

Израиль Гельфанд говорил, что если мы начнем вникать в понятие адекватного языка, то мы сможем открыть для себя неожиданные вещи.

Математика — язык символический. Развитие математики характеризует рост сознания земного человечества. И, возможно, в символах больше не будет нужды, когда человечество осознает общность бытия, единство всего сущего. И математика выполнит свою миссию, растворясь во множестве наук, и став самой наукой, найдет самую красивую и единую формулу Бытия.

Научные прозрения, как правило, опережают свое время. Иногда на целые столетия. 800 лет назад, о том, что элементарные вихри есть первоматерия или свет духовный, сказал в своей работе «De Luche» первый канцлер Оксфорда Роберт Гроссетест. Трактат «De Luche» («Свет») признан одной из самых красивых научных работ раннего средневековья.

Роберт Гроссетест разделил свет на видимый lux и невидимый lumen. Видимый свет он призвал изучать экспериментально с использованием геометрии. Вместе со своим учеником Роджером Бэконом, Гроссетест заложил основы геометрической оптики. А на базе своего учения о невидимом свете,

первичных световых вихрях, — тончайшей субстанции, Роберт Гроссетест развил свою космогонию и космологию. Гроссетест увидел в метафизике света, по крайней мере, частичное проникновение в суть божественного создания физической вселенной. Он считал, что в начале возникла Точка света как первая форма и первоматерия слитые воедино. Из этой Точки по законам излучения свет начал процесс эманации. Согласно Гроссетесту, первая форма и первая материя (lumen) сами по себе должны быть простыми и неделимыми. Он так же считал,что конечное умножение простого не может создать что-то определенное, имеющее размер (квант). Но что бесконечное умножение простого может привести к созданию определенного кванта. Таким образом, через бесконечное умножение первой формы (структуры) в первоматерии появились природные объекты, возникло мироздание. Бесконечное самоумножение света расширило материю до сферической формы, так как свет рассеивается сферически, поэтому космос — сфера. [4]

Процесс образования телесных форм Роберт Гроссетест рассматривал как процесс образования протяженности. Он также пояснял, почему небесные тела могут двигаться только круговыми движениями, указывал, что небесные сферы могут получать движение только от «мыслительной движущей силы», которой является разум. Роберт Гроссетест считал, что мыслительная сила движет всем во Вселенной и порождает в ней физический мир. Он как бы раскрывал тезис Платона: «Мысли правят миром». И включил этот тезис в свою теорию творения мира: «Разум вращает сферы в круговороте, вглядываясь назад в себя, выраженного в материальной форме».

Гроссетест стал первым в средневековой Европе, кто предложил теорию о неравной бесконечности. В своей работе «Свет» он писал, что есть бесконечные числа, отличающиеся по величине: «Сумма всех четных и нечетных чисел бесконечна и, следовательно, больше чем сумма всех четных чисел на сумму всех нечетных чисел. Так же не равны бесконечные числа точек на несоизмеримых линиях. . . ». Теория неравных бесконечностей легла, в свою очередь, в основу теории измерения мира, в которой Гроссетест указывал на относительный характер измерения времени и размера, базирующихся на ежедневных движениях небесных тел или единицах измерения пространственных масштабов.

Ровно 100 лет назад, в 1912 году работа Роберта Гроссетесте была переведена на немецкий язык.

В это время широко обсуждалась выдвинутая Альбертом Эйнштейном теория о квантах света. Эйнштейн писал, что волновая теория света, оперирующая непрерывными функциями, прекрасно оправдывается при описании чисто оптических явлений, таких как дифракция,преломления, дисперсия,. . . Но, что не следует забывать о том, что эти оптический наблюдения относятся не к мгновенным, а к средним по времени величинам. И может оказаться, что теория света, оперирующая непрерывными пространственными функциями, приведет к противоречию с опытами, когда ее будут применять к явлениям возникновения и превращения света.

В это же время инженер и философ Константин Циолковский разработал конструкцию лучшего в мире дирижабля, рассчитал космические

скорости и создал теорию космических эр и лучистой телепативности. Теорию лучистой телепативности Циолковского записал его ученик, выдающийся ученый, основатель космической биологии А. Л. Чижевский. В своей теории, Циолковский рассматривал не только процесс возникновения физической вселенной, но и обратный процесс — процесс возвращения вселенной в нефизическое состояние, которое он называл лучистой телепативностью. Циолковский считал, что эти циклические процессы должны занимать миллиарды лет и порождать каждый раз все более и более развитое человечество.

Циолковский указывал, что вещество в Космосе занимает исчезающе малый объем по сравнению с объемом «полевого» пространства или вакуума. Малость же вещества говорит о его временности, так как все временное имеет малую или исчезающе малую величину. Малые формы поглощаются без остатка большими. Следовательно, можно сделать вывод, что физическая (косная) материя преобразуется в лучевую энергию или какую иную. Думая о лучистой энергии, Циолковский думал о ней как об энергии мыслительной. Он говорил:«Мысли передаются на расстояния молниеносно, мгновенно. Мгновенность — это самое удивительное. Мгновенность и проницаемость повсюду. Второе качество обязательно сопровождает первое. Мыслительное общение есть мировое явление. Когда — нибудь все придет в состояние лучистого телепативного поля мира». [5]

В это же время философ, математик и богослов Павел Флоренский, проанализировав специальную теорию относительности Эйнштейна, пришел к выводу, что скорость света — $3 \cdot 10^8$ м/с — есть граница между миром земным и небесным, физическим и духовным, lux и lumen. Мир физических явлений останавливается на границе скорости света, но наши мысли могутд переходить эту границу и посещать миры более высоких измерений. [6]

В этом году исполняется 155 лет со дня рождения Константина Циолковского и 130 лет со дня рождения Павла Флоренского.

В 1931 году, журнал «Everyday Seience and Mechanics» напечатал статью Николая Теслы «Энергия нашего будущего». В этой статье Николай Тесла писал: «...я обнаружил, что от Солнца действительно исходит излучение, замечательное непостижимо малой величиной составляющих его частиц и скоростью их движения, безмерно превышающей скорость света. Это излучение, сталкиваясь с космической пылью, генерирует вторичное излучение, сравнительно слабое, но явно обладающее проникающей способностью, интенсивность которого почти одинакова во всех направлениях».

А в 1956 году ученые зафиксировали элементарный вихрь — частицу без электрического заряда, с нулевой массой, имеющей только спин — момент вращения. Эту частицу назвали нейтрино. Начиналась эра исследования «тонкой материи», невидимого света lumen.

И только уже в нашем веке, в 2003 году, в памятный день 750-летия со дня смерти Роберта Гроссетеста, в английском городе Линкольн, состоялась посвященная ему международная конференция. В кафедральном Соборе Линкольна, где похоронен Роберт Гроссетест, была вывешена мемориальная доска в его честь. Это памятное событие пробудило интерес к работам великого философа и ученого. И в 2007 году работа «Свет» была

переведена учеными Стенфордского университета на английский язык с адаптацией терминологии к языку современной физики.

Памятные дни и юбилеи являются частью научной жизни, благодаря им научные теории получают дополнительный импульс распространения и развития. В. И. Вернадский писал: «Научная мысль сама по себе не существует, она создается живой человеческой личностью, есть ее проявление. В мире реально существуют только личности, создающие и высказывающие научную мысль, проявляющие научное творчество — духовную энергию. Ими созданные невесомые ценности — научная мысль и научное открытие — в дальнейшем меняют ход процессов биосферы, окружающей нас природы». Отсюда и история научной мысли имеет страницы, как романтические так и драматические, и героические ибо творится людьми. И памятные дни подчас становятся торжеством справедливости или данью героическому подвигу, или тому и другому вместе.

В 2013 году исполняется 470 лет со дня смерти Николая Коперника и 470 лет со дня выхода из печати его главного труда «О вращении небесных тел», с этого момента датируется начало первой научной революции. Через пять лет после смерти Коперника, в мир пришел Джордано Бруно. Во времена Николая Коперника Земля стояла на месте, как центр мира, а Солнце вращалось вокруг нее. И Коперник понимал какой нелепостью должно было казаться его учение, где все было наоборот. Он долго не решался его опубликовать и думал не лучше ли передать свое учение устно, только друзьям, как Пифагор. Ученик Коперника Ретик приложил немало труда, чтобы труд учителя был напечатан. Этому помогло и анонимное предисловие к первому изданию, в котором говорилось, что гелиоцентрическая модель мира есть только условный математический прием, придуманный для упрощения вычислений.

Для того, чтобы новое учение стало осознаваться, входить в жизнь, нужен был бесстрашный человек, готовый отдать жизнь за истину. Им стал Джордано Бруно. С определенной долей фанатизма, Бруно проповедовал учение Коперника по всей Европе, он так же говорил о бесконечности Вселенной и называл звезды далекими солнцами. Несколько лет тюрьмы не заставили его отречься от своих убеждений, и когда суд инквизиции потребовал для него сожжение на костре, он ответил своим судьям: «Сжечь — не значит опровергнуть!». В 1600 г. в Риме, на площади Цветов, Джордано Бруно сожгли на костре. К памятной дате 300-летия смерти Джордано Бруно, в Риме, на площади Цветов был установлен памятник с надписью: «Джордано Бруно — от столетия, которое он предвидел, на том месте, где был зажжен костер».

История начала первой научной революции будет неполной без упоминания великого ученого того времени, современника Джордано Бруно, Галилео Галилея. В этом году исполняется 370 лет со дня смерти ученого. Двадцать лет назад, в памятный год 350-летия со дня смерти Галилея, Папа Иоанн Павел II официально признал, что инквизиция совершила ошибку, силой вынудив ученого отречся от признания гелиоцентрический модели мира. Уже в преклонном возрасте, пройдя через тюрьму, угрозы, находясь под домашним арестом и слежкой, ослепнув, Галилео Галилей продолжал писать свои бесценные научные труды.

В начале XIII века, Роберт Гроссетест призвал научный мир изучать природу экспериментально и с использованием математики. Однако, до Галилея, в реализации этого призыва было мало продвижения. Галилео Галилей считается основателем экспериментальной физики. Ученый говорил, что природу нужно не просто наблюдать, — ей нужно ставить вопросы, а получив на них ответ, их нужно анализировать — аналитически, чувственно, абстрактно. Изучая природу, Галилей заложил основы классической механики.

800 лет назад Роберт Гроссетест в работе «De Iride» писал: «Оптика поможет нам видеть то, что находится очень далеко так, как будто это находится совсем близко. Рассматривать маленькие вещи в любом размере, который мы захотим. Возможно, мы сможем получать информацию с невероятных расстояний...». Галилео Галилей сделал первый шаг в реализации и этого предвидения. Он сконструировал телескоп и направил его в небо и первый написал об этом. Небо стало ближе к Земле и это повергло ученых в изумление. Короли стали просить, чтобы для них открывали новые звезды...

Среди сутолоки жизни, в памятные и юбилейные дни, мы отрываем наши взгляды от земли и смотрим на небо: там в удивительном индиго светятся лунные кратеры Коперника и Джордано Бруно, летят Галилеевы спутники, астероид (10204) Алана Тьюринга, малая планета 1590 Циолковского...

24 марта 2012

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Зміст

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Тематика та мета журналу

«Міждисципрлінарні дослідження складних систем» — це рецензований журнал із вільним доступом, що публікує дослідницькі статті, огляди, повідомлення, дискусійні листи, історичні та філософські студії в усіх областях теорії складних систем для впровадження взаємодії між науковцями з різних галузей математики, фізики, біології, хімії, інформатики, соціології, економіки та ін. Ми бажаємо запропонувати істотне джерело актуальної інформації про світ складних систем. Журнал має стати частиною наукового форуму, відкритого та цікавого як для експертів з різних областей, так і для широкої аудиторії читачів: від студентів до досвідчених дослідників. Журнал надає можливість для науковців з різних галузей презентувати нові ідеї, гіпотези, піонерські дослідження. Особливо запрошуються до публікації автори наукових статтей та (але не тільки) наукових оглядів, проте статті з історії та філософії науки, інформації про наукові події, дискусійні повідомлення також вітаються.

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Міждисциплінарні дослідження складних систем

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Підписано до друку 28 листопада 2012 р. Формат $70 \times 108/16$. Папір офсетний. Гарнітура ComputerModern. Друк офсетний. Умовн. друк. аркушів 10,5. Облік. видав. арк. 8,35.

ВИДАВНИЦТВО
Національного педагогічного університету імені М. П. Драгоманова.
01030, м. Київ, вул. Пирогова, 9.
Свідоцтво про реєстрацію № 1101 від 29. 10. 2002
(044) тел. 239-30-85