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Lecture Course "Modern Physics"

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Abstract

In the paper, the structure of the lecture course "Modern Physics" is described in detail. The course is based on a logical presentation of modern ideas about quantum-, atomic-, nuclear-, and molecular physics as well as astrophysics. A special attention is paid to a relatively new interdisciplinary research field, namely the physics of open systems, and to the study of clusters as one of the most promising scientific areas. Separate chapters of the textbook are devoted to nonlinear optics, quantum information, structure and dynamics of molecules. The fundamental laws and concepts of modern physics, their relationship and origin are comprehensively discussed. It is underlined that this lecture course is intended, first of all, for students of technical universities, postgraduate students of relevant specialties, as well as professors of vocation-related subjects. The inclusion of new sections of physics in the curricula of universities is rationalized, in particular, by the fact that physics is closely related to engineering. Due to this fact, the important role that physics plays in society becomes especially evident. The paper may also be of interest to those who are fond of physics and its state-of-the art.

Keywords

Modern physics, the physics of open systems, astrophysics, nonlinear optics, quantum information

1. Introduction

The introduction of new achievements in physics into the learning process, initiated more than twenty years ago by the authors' team (Voronov, Podoplelov, & Sagdeev), has allowed to prepare and publish several marked textbooks [1-5]. This work is carried out in accordance with the scientific and methodological research on the cognitive barriers of universities' students [6-8].

The first two books, originally published in 2005 and 2008, by the decision of the Publishing House, came out as the second edition in 2012 with the subtitle (as well as the last three books): "Physics at the Turn of the Millennium". The first of the above mentioned books were translated into English and Spanish. In 2018, an English edition of the third book was released.

The learning kit "Modern Physics" is regularly used in universities. It was highly appreciated by the scientific and educational community, as evidenced by the feedback received by the authors from Moscow, St. Petersburg, Rostov-on-Don, Petrozavodsk, Kazan, Ulyanovsk, Sevastopol, Novosibirsk, Tomsk, Abakan, Bratsk, and Baku. In opinion of Professor R.A. Brazhe, head of the Department of Physics at Ulyanovsk State Technical University, the uniqueness of the above learning kit is in the fact that it discloses for the first time the results of scientific research of recent decades in the field of physics of micro- and nanosystems, and adapts this information to real teaching process. It should be emphasized that high theoretical level of presentation is combined with readily understandable (mainly, for students) character of the book material. For the work "Creation of learning kit "Modern Physics" for technical and natural science specialties of universities", the authors' team including of V.K. Voronov (head of work), A. V. Podoplelov, and R. Z. Sagdeev was awarded the Prize of the Government of the Russian Federation in the field of education in 2015.

The above five books (five parts) were written on the basis of material selected from various sources (reviews, monographs, textbooks). The main source used by the authors is the papers articles in the journal "Advances of Physical Sciences", as well as in the Soros Educational Journal (for the first volume). References are given at the end of each chapter of the relevant volume. In a number of cases, additional references, which were not discussed in the text, were included. Such references could be helpful for an in-depth study of the material. This prompted us to expand the list of references, which finally contained more than five hundred and fifty publications in five volumes. Thus, readers get the access to impressive bank of literature references related to various sections of modern physics.

This lecture course consists of eleven chapters. The first chapter deals with nonlinear optics. The fundamental information about nonlinear optical effects, the generation of which depends on the intensity of light, is presented. The second chapter discloses the basic concepts of a relatively new interdisciplinary scientific direction, the physics of open systems, which was originated owing to the works of outstanding researchers of the nineteenth century. Among them are the physicist Ludwig Boltzmann, the mathematicians Henri Poincaré and Alexander Lyapunov, and the biologist Charles Darwin. The main features of self-organized systems are considered. The fractal geometry and bifurcation, a mathematical image corresponding to the rearrangement of the motion a real (physical, biological, etc.) system are discussed. Over the past sixty years, the already well-known objects of atomic physics were complemented with a number of new objects, which attract the ever-increasing research attention due to the variety of their physical properties and phenomena. The third chapter of the book describes some of such objects, acquaintance with which allows one to create an idea about one of the new areas of modern physics. The fourth chapter of the textbook is devoted to nuclear physics, the science dealing with the structure and properties of atomic nuclei, their interactions and transformations. This chapter briefly outlines ideas about the structure of atomic nuclei and their energy properties. Radioactive processes are also considered, and some fundamental problems of nuclear power engineering are covered.

The fifth chapter is dedicated to clusters, the study of which is one of the most promising areas in science about the fifth state of matter (solid, liquid, gas, plasma and clusters). The rapid development of cluster research gave rise to a number of new practically important scientific directions. The sixth chapter of the book describes physical properties of the condensed state. Among the main advances in the development of natural science over the past fifty years is the formation of a new field of knowledge (and hence a new field of research) at the intersection of several disciplines. In this regard, one can speak of a new molecular physics, which studies the structure and dynamics of molecules. The seventh chapter of the book summarizes the theoretical and experimental foundations of this new scientific direction.

The eighth chapter of this book deals with quantum information, a new branch of physics that was arisen due to the development of the fundamental ideas of quantum mechanics. At present, quantum information commonly includes the issues related to possible design of a quantum computer, quantum teleportation and quantum cryptography. These issues are briefly analyzed in this section of the book. A separate paragraph is devoted to new sections of quantum information. The ninth chapter describes the main characteristics of some new instruments and analytical methods employed mainly for the study the condensed state. The tenth chapter highlights the fresh achievements of astrophysics in the investigation of the Universe and its objects. The past fifty years witness real breakthrough in this field of research. This progress became possible due to unique measurements from spacecraft during flight to various bodies of the Solar System, observations of the outer bodies of the Solar System and exoplanets using space and ground-based telescopes, as well as owing to the development of mathematical simulation methods. Finally, the last, eleventh chapter is devoted to the development of ideas about the structure and evolution of the Universe. Each chapter ends with test questions. A list of references is given at the end of the book.

2. Content of the lecture course

2.1 Chapter 1. Nonlinear Optics

1.1 Multiphoton processes; Photoionization; Photoemission threshold; Laser light scattering; Generation of higher harmonics; Excitation of summation oscillations; Coherent radiation in the ultraviolet spectral region; Parametric light generation; Non-linear refraction; The effect of laser beam self-focusing; Light pressure; Method to cooling and trap atoms with laser light. 1.2. Non-stationary effects; Superradiation; Inverted states of the atomic system; Self-induced transparency; Coherent non-stationary response of a resonant medium; Solitons; Inverse scattering method; Group solitons; Generation of ultrashort optical pulses; Femtosecond laser spectroscopy; Chemical dynamics of the transition state.

2.2 Chapter 2. Physics of Open Systems

2.1. Features of self-organized structures; Belousov-Zhabotinsky reaction; Benard effect; Open systems; The idea of non-equilibrium dynamics or the physics of open systems; Dissipative structures; Processes of structural self-organization, threshold nature of self-organization; Synergetics. 2.2. Fractals. The main distinctive feature of fractal structures; Self-similarity of fractals; Fractal dimension. 2.3. Feigenbaum scenario; Bifurcation, bifurcation diagram; Stable position of the system.

2.3 Chapter 3 Atomic Physics

3.1. Rydberg atom; Excited atoms; Hydrogen-like ion. States with a large value of the principal quantum number; Sources of data on Rydberg atoms; Generation of Rydberg atoms; Rydberg atom-based detectors; Evidence for the existence of Rydberg atoms in space. 3.2. Excimer molecules; Chemical features of excimer molecules. Excimer lasers as unique sources of high-power ultraviolet radiation; Areas of potential application of excimer lasers. 3.3. Exotic atoms. Atoms containing an antiproton or a negative ion instead of one electron; Antiprotonic helium as a typical example of an exotic atom.

2.4 Chapter 4. Nuclear Physics

4.1. Nuclear quarks; Virtual particles; The color of quarks; The idea of gluonic field. 4.2. Energy properties of nuclei; The nature of forces acting between nucleons; Relationship between the mean bond energy and the value of the mass number. 4.3. Radioactivity; General description of radioactive processes; Types of radioactive decays; Beta decay; Cluster radioactivity; Nucleon clusters; Gamma decay;

Discovery and study of radioactivity: historical review; Fundamental aspects of nuclear engineering; Chain fission reaction; Nuclear fusion; Nuclear explosion; Uranium-graphite pile; Practical utilization of thermonuclear energy; Neutronless thermonuclear reactors.

2.5 Chapter 5. Cluster State of the Matter

5.1. Methods for preparation of clusters; Gas aggregation; Preparation of cluster beams; Laser method for preparation of clusters. 5.2. Practical application of cluster beams; Film deposition; Design of new materials; Surface treatment; 5.3. Fullerenes as unique carbon-containing structures; Synthesis of polyatomic carbon molecules; Euler's formula; The main chemical features of buckminsterfullerene C_{60}. 5.4. Endohedral compounds; Synthesis and structural features of endohedral fullerenes; Endohedral fullerenes as a new class of synthetically and practically valuable nanostructures. 5.5. Carbon nanotubes; Structural features of single-layer nanotubes; Multilayer nanotubes; Methods for the synthesis of nanotubes; Prospects for the application of carbon nanotubes. 5.6. 2D Nanostructures; Graphene as the first representative of a new class of materials, two-dimensional crystals; The electronic structure of grapheme, an allotrope of carbon. Prospects for the practical application of graphene.

2.6 Chapter 6. Physical Properties of the Condensed State

6.1. Disordered condensed systems; Long-range order and disorder in condensed media; Structural features of disordered systems; Amorphous metal materials; Amorphous ferromagnets; Practical application of amorphous alloys. 6.2. Liquid-crystal state of matter; Types of liquid-crystal phases. Physical properties of liquid-crystal state; Optimization of the physical characteristics of nematics; Types of polymer-dispersed liquid crystals; Improvement of such liquid crystals using nanoobjects; 6.3. Semiconductors. Heterosystems of reduced dimension. Size quantization of electron energy;

Quasiparticles as separate elementary excitations; Excitons in low-dimensional structures; Physical foundations of nanostructures formation; Quantum wells, quantum threads, quantum dots; Practical application of nanostructures; Laser in a quantum well. 6.4. Introduction to acoustoelectronics; Main features of high frequency acoustic (sound) waves; Surface and bulk acoustic waves; Amplification of acoustic waves in semiconductors and in layered structures "piezoelectric-semiconductor"; Prospective devices on the basis of surface acoustic waves. 6.5. Physical foundations of superconducting electronics; Josephson effect; Josephson contacts; Switching cell; Squids; Superconductivity and magnetism in heterostructures ferromagnet/superconductor. 6.6. Artificial materials with pronounced resonant properties; Photonic crystals; Metamaterials; 2D metamaterials (metasurfaces). 6.7. New applications of laser irradiation; New types of lasers; Free electron lasers; Laser irradiation for high-precision measurements; Sources of extreme ultraviolet laser irradiation for lithography; High precision frequency and time measurements. Ultra-fast structural dynamics of matter in real time; Laser cooling of molecules.

2.7 Chapter 7. Structure and Dynamics of Molecules

7.1. High resolution nuclear magnetic resonance spectroscopy; The nature of NMR phenomenon; Sources of information about molecular structure; Chemical shift; Spin-spin coupling; Introscopy of nuclear magnetic resonance (MR-tomography); 7.2. Quantum-chemical models of molecular structure and dynamics; Molecular orbitals; Ruthan equations; Hartree-Fock method; Semiempirical and ab initio quantum-chemical calculations of spatial and electronic structure of molecules.

2.8 Chapter 8. Quantum Information

8.1. Superposition, entangled states; Mixed states. 8.2. Quantum computers; Record of the initial state; Physical objects that implement q-bits, quantum bits of information; Computation; Output of results. 8.3. Quantum cryptography. 8.4. Quantum teleportation. 8.5. New sections of quantum information; Quantum biomicroscopy; The role of perception in physical experiments with a quantum system.

2.9 Chapter 9. Instruments and Research Methods

9.1. Thermal imagers. 9.2. Biosensors for determination of biologically active and toxic compounds. 9.3. Multimode acoustic sensors and systems. 9.4. X-ray diffractometry for structural diagnostics of materials. 9.5. Muonic radiography. 9.6. Ptychography as a new branch of lensless optics. 9.7. Additive or 3D technologies for layering materials. *2.10 Chapter 10. New Things in Astrophysics*

10.1. Solar cosmic rays. 10.2. Fundamentals of the Earth's magnetic field physics.10.3. Accelerated expansion of visible Universe. 10.4. Black holes, wormholes and a time machine. 10.5. Exoplanet research. 10.6. The evolution of galaxies. Star formation.

2.11 Chapter 11. the Development of Ideas about the Structure and Evolution of the Universe: Historical Review

11.1. The beginning of astronomical observations; Anaximander's model of the universe. 11.2. Geocentric picture of the world; Schools of Pythagor, Aristotle, Ptolemy. 11.3. Formation of ideas about the geocentric system of the world in the works of Nicolaus Copernicus, Galileo Galilei, Giordano Bruno. 11.4. The contribution of Isaac Newton, Edwin Hubble, Albert Einstein, Georgy Gamow to the development of ideas about the structure and evolution of the Universe. 11.5. Fundamentals of modern astronomy.

3. Conclusions

The learning kit "Physics at the Turn of the Millennium" is intended mainly for senior students of engineering degree, whose future professional activity is connected with industrial production, as well as research in academic institutes. At the same time, there are virtually no course books on modern sections of natural science for university students of other specialties, in particular, economic and humanitarian ones. This circumstance prompted us to prepare a lecture course, the material of which would be understandable for the first and (or) second year students of most universities. Such course is based on the material selected from the above five books of the series "Physics at the Turn of the Millennium". As for technical and natural science specialties, this course of modern physics (in the form of lectures) could be given to second-year students after the mandatory classes (lectures, seminars, and laboratory works) in classical physics. It is worthwhile to note here that it is impossible to include new material related to sections of modern physics in the curricula instead of the classical material, which is usually given by departments of physics. The classical material is, figuratively speaking, the foundation that is necessary for the acquisition of new knowledge, especially those related to the micro- and nanoworld. If we take into account a low level of proficiency of high school graduates in the natural science and mathematics, it becomes even more evident that it is impossible to replace the traditional lecture course by novel sections. As for the third- and fourth-year students, undergraduates and postgraduates of natural science and technical specialties, it would be reasonable, after reading the lecture course of modern physics mentioned above, to prepare for them special courses in physics based on the material selected from the above "Physics at the Turn of the Millennium ".

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