RADIATION ACOUSTICS

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FOREWORD

Radiation acoustics is a new field of research developing at the interface of acoustics, nuclear physics, high energy physics, and the physics of elementary particles. It is founded upon studies and applications of radiation-acoustic effects arising in the process of interaction of penetrating radiation with matter.

The thermoradiation mechanism has been the best studied among the mechanisms of sound excitation by penetrating radiation in condensed media. According to this mechanism, sound generation is caused by thermal expansion of a medium, and the acoustic field can be described as a rule within the framework of linear theory.

The book considers mainly the processes of thermoradiation sound excitation in the case of continuous (modulated) and pulsed action of penetrating radiation on a substance. Basic laws of formation of acoustic signals are established and the bonds between the characteristics of these signals, radiation parameters, and thermodynamic, radiation, and acoustic properties of substances are revealed. The efficiency and optimal conditions of thermoradiation sound generation are considered. The particular features of sound generation by a particle beam moving along the surface of a liquid or solid at subsonic and supersonic velocities and an arbitrary form of modulation of radiation intensity in the beam are described. The possibility is discussed of the creation of virtual radiation-acoustic sources of sound in a wide frequency range (from sound to hypersound frequencies) with controlled parameters in liquids or solids

We consider the particular features of thermoradiation generation of sound by single particles Experimental results on sound excitation by beams of photons (laser radiation), electrons, protons, heavy ions, X-rays, and gamma-quanta are given Some other mechanisms of sound generation by single particles in the process of their absorption in a medium are considered apart from the thermoradiation mechanism, i.e., the mechanisms of microshock waves and the bubble, dynamic, Cherenkov, and striction mechanisms.

Applications of radiation acoustics are discussed. We have not tried to go into the details of many of them. Our purpose is to demonstrate the prospects of application of radiation acoustics to various fields from microelectronics (radiation-acoustic microscopy) to geophysics (neutrino-acoustic sounding of the Earth), and astrophysics (detection of cosmic neutrino and muons of super-high energy by huge acoustic detectors in the ocean).

We have not tried to review all papers on radiation acoustics. On the contrary, we have quite deliberately not included in the book the results of studies of nonlinear radiation-acoustic phenomena arising in the process of interaction of powerful radiation beams with matter. Although the role of nonlinear effects in future radiation-acoustic technologies will undoubtedly be essential (targeted action on physical, mechanical and chemical structure of substances, radiation-acoustic destruction of materials, etc.), investigation of these effects still continues.

The book may be useful not only to acousticians but also researchers and technicians specializing in adjacent and other fields as well as postgraduates and university students.

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L. M. Lyamshev

CONTENTS

INTRODUCTION 1

Chapter 1. PENETRATING RADIATION: GENERAL INFORMATION 7

1. Elementary particles: Fundamental laws of the microscopic world 7
2. Absorption of penetrating radiation in a condensed medium 13

Chapter 2. BASIC MECHANISMS OF SOUND GENERATION BY PENETRATING RADIATION IN CONDENSED MEDIA 23

1. Mechanisms connected with heat release 23
2. Thermoradiation generation of sound 24
3. Initiation of microshock waves 28
4. Bubble mechanism 30
5. The Cherenkov mechanism 31
6. Striction mechanism of sound generation 33
7. Sound generation in the process of pulsed radiolysis 35
8. Dynamic mechanism 35
9. Other mechanisms of sound generation 38

Chapter 3. THERMORADIATION EXCITATION OF SOUND IN A HOMOGENEOUS LIQUID 39

1. Equation of thermoradiation generation of sound 39
2. Reciprocity theorem in acoustics – Solution technique for boundary problems 42
3. Excitation of monochromatic sound in a liquid half-space with a free surface – The case of undisturbed surface 47
4. A liquid half-space with large-scale roughness of boundary 52

5. The case of small unevenness 61
6. Efficiency of thermoradiation excitation of sound in a liquid – Some estimates 72

Chapter 4. THERMORADIATION EXCITATION OF SOUND IN AN INHOMOGENEOUS MEDIUM 75

1. Sound excitation in a liquid half-space in the presence of a layer of another liquid at its boundary 75
2. Generation of sound in a liquid adjoining a solid layer 88
3. Liquid half-space with an inhomogeneous surface layer 96

Chapter 5. EXCITATION OF SOUND IN A LIQUID BY RADIATION PULSES 105

1. Sound generation in a liquid by rectangular pulses of radiation 106
2. A liquid with rough surface 113
3. Radiation pulses of arbitrary shape 116
4. Near wave field of thermoradiation pulsed source of sound 124
5. Sound generation in a liquid with gas bubbles 130

Chapter 6. GENERATION OF SOUND IN SOLIDS BY INTENSITY-MODULATED PENETRATING RADIATION 137

1. Basic equations 137
2. Boundary conditions 139
3. Method for solution of boundary problems 141
4. Thermoradiation generation of sound in a solid half-space with a free boundary 147
5. Particular features of excitation of Rayleigh waves 151
6. Solid half-space with a liquid layer at its surface 156
7. Efficiency of thermoradiation generation of sound 160
8. Influence of particular features of absorption of penetrating radiation on sound generation 164

Chapter 7. PULSED THERMORADIATION SOURCES OF SOUND IN SOLIDS 169

1. Sound generation by radiation pulses in a solid half-space 169
2. Excitation of Rayleigh waves by radiation pulses 184
3. Sound generation in a solid half-space in the presence of a liquid layer at its surface 186
4. Efficiency of sound generation 191
5. Influence of particular features of absorption of penetrating radiation 193
6. Thermoradiation generation of sound by pulses of non-relativistic protons 195

Chapter 8. MOVING THERMORADIATION SOURCES OF SOUND 201

1. Sound generation by a moving thermoradiation pulsed source in a liquid 202
2. Sound excitation by a moving thermoradiation pulsed source in solids 213

Chapter 9. SOUND GENERATION BY SINGLE HIGH-ENERGY PARTICLES 227

1. Sound generation by a particle in infinite space 227
2. Sound excitation by single particles in a solid half-space 234
3. Particular features of excitation of Rayleigh waves 237
4. Efficiency of sound generation 238

Chapter 10. EXPERIMENTAL STUDY OF THERMORADIATION EXCITATION OF SOUND 239

1. Laser thermooptical (thermoradiation) sources of harmonic sound oscillations in water 240
2. Sound excitation in water by laser pulses 248
3. Sound field excited by a sequence of laser pulses 252
4. Acoustic field of a moving laser thermoradiation source of sound in water 257

5. Laser thermooptical excitation of sound in solids – Excitation of surface waves 270
6. Sound excitation by X-rays (synchrotron radiation) in metals 281
7. Sound excitation by a proton beam 286
8. Excitation of acoustic waves in metals by electrons, positrons, and γ-quanta 298
9. Sound generation by an electron beam in water 302
10. Sound excitation by a beam of ions in metals 306

Chapter 11. SOME APPLICATIONS OF RADIATION ACOUSTICS 309

1. Scanning radiation-acoustic microscopy and visualization 310
2. Scanning laser-acoustic microscopy 311
3. Scanning electron-acoustic microscopy 314
4. X-ray – acoustic scanning visualization 318
5. Ion-acoustic microscopy and visualization 321
6. Acoustic detection of super-high-energy particles in cosmic rays – The DUMAND project 325
7. Neutrino for geoacoustics – The GENIUS project 330

Conclusion 339

References 343

Addendum. ACOUSTOOPTICS OF PENETRATING RADIATION 359

1. Diffraction of X-rays and neutrons by ultrasound in crystals 360
2. Scanning acoustic tunneling microscopy 361
3. Interferometers using matter waves – Atom interferometers 362

SUBJECT INDEX 367

INTRODUCTION

Investigation of radiation-acoustic effects was stimulated mainly by progress in the field of high-energy physics and the physics of elementary particles. The latter has advanced greatly during recent decades. Particles of tremendous energy of the order of magnitude of tens, hundreds, and thousands of gigaelectronvolts (GeV) were obtained with the help of accelerators and many new elementary particles subjected to amazing interactions and inter-transformations were discovered. Quantum chromodynamics and unified theory of electromagnetic and weak interactions appeared. The state-of-the-art is now that physics is on the verge of creating the unified theory of all the fundamental interactions — electromagnetic, strong (nuclear), weak, and gravitational interactions. Experimentation at even greater energy is needed for solution of this problem. This needs powerful accelerators of elementary particles, which would provide an opportunity to make the next step into the depth of the microscopic world [2, 76, 89, 176]. Such accelerators are under design and construction now.

As the construction of new, more powerful accelerators opens new opportunities for advancement of investigation of elementary particles into the field of larger and larger energies, the accelerators designed initially for purely basic studies, are applied to a greater and greater extent in research into the physics of solids, biology, chemistry, and medical science. They are utilized successfully in radiation technology, defectoscopy, analysis of rare minerals, and also (as it will be demonstrated below) in radiation-acoustic research and technology. As a rule, these are low-energy (about several megaelectronvolts (MeV)) accelerators like betatrons, linear accelerators, and microtrons [13]. Now more powerful accelerators (up to several gigaelectronvolts) of proton, meson, and ion beams and X-rays are being tried for these purposes.

The beginning of radiation acoustics is connected in a broad sense with the discovery by A. Bell, W. Roentgen, and J. Tyndall [180, 195, 245] of the optoacoustic (photoacoustic) effect, that is sound generation in a gas volume due to intermittent (modulated) light passage or, in other words, due to interaction of modulated optical radiation (modulated photon beam) with a substance (gas). At the same time Bell discussed the problem of construction of a radiophone, "a device for producing sound by radiation of any kind" [195]. Further studies of the optoacoustic effect and its applications served, as is known, as the basis for the development of optoacoustics (photoacoustics) including optoacoustic spectroscopy of gases and condensed media [74, 126]. A powerful stimulus for the development of this field in recent decades was the construction of lasers (see [96, 127] for example).

The first studies of radiation-acoustic effects were conducted in the 1950s and 1960s. So, for example, in 1956 Kaganov, Lifshits, and Tanatarov considered sound radiation in a solid by a uniformly moving electron and showed that at an electron velocity greater than the sound velocity in a medium (lattice), the Cherenkov radiation of sound (phonons) occurs [101]. The analogous problem was considered earlier (1953) by Buckingham [203].

In 1955 Glaser and Rahm reported observation of tracks of particles in the process of their passage through a metastable boiling-up liquid in a bubble chamber according to sound (vibration) signals arising as a result of the birth and development of bubbles [209]. In 1957—1959 Askar'yan considered radiation of ultrasonic and hypersonic waves by charged particles in dense media due to local heating and formation of microscopic cavities along particle tracks. Excitation of surface and bulk waves under the impact of a non-relativistic electron flux upon the surface of a dense medium was considered and the problem of utilization of acoustic signals generated by particles for detection of particles was discussed [6, 7][1]. In 1963 White investigated sound generation by an electron beam in a solid [260][2]. Somewhat later (1967) Graham and Hutchison [216] measured

[1] In contrast to Glaser and Rahm [209], who discussed sound radiation due to the rise of bubbles at particle tracks in metastable media, Askar'yan [6, 7] considered local heating arising at particle tracks in dense stable media and producing sound pulses, as well as the bubbles generating hypersonic waves. He proposed also acoustic detection of particles and noted the possibility of manifestation of hypersonic pulses in the process of biological action of radiation on cells and chromosomes (as a part of destructive effect).

[2] We must note that at the same time, White conducted the first experiments on laser generation of sound in solids. Somewhat earlier the first widely known experiments

mechanical oscillations in quartz crystals, sapphire, etc., on their being irradiated by electron beam pulses, and in 1969 Beron and Hofstadter, as Askar'yan before them [6, 196], suggested that not only electrons but also other particles can generate mechanical vibrations[3].

Numerous studies of sound excitation in condensed media by electron and proton beams and by single particles were conducted in the 1970s by Borshkovskii, Volovik, Zalyubovskii, Kalinichenko, Lazurik, and others, and in the 1980s, by Lyamshev and Chelnokov (see [155, 156]). Various mechanisms of sound excitation in condensed media by penetrating radiation were considered. The major results of these studies and the bibliography can be found in the book [97]. The publications of many researchers on possible applications of the radiation-acoustic effects date to the same period (see, for example, F. Perry et al. on the application of these effects to the dosimetry of pulsed beams of accelerated particles and to obtaining data on the depth distribution of irradiation dose in a target [242]).

A powerful stimulus for development of research in radiation acoustics were ideas to use radiation-acoustic effects for detection of super-high-energy muons and neutrinos at a large depth in the ocean [8, 199], to develop a radiation-acoustic microscope [207], and finally, the suggestion to "sound" the Earth (using a radiation-acoustic technique) by a super-high-energy neutrino beam from super-powerful (for super-high energy of particles) proton accelerators of future generation named tevatrons [248]. Further publications (see, for example, [15, 151 – 154, 184]) were connected in this or that way with these aspects. Investigations performed in the 1950s and 1980s have been described to some extent in the book [97] mentioned above and in a collection of articles [173].

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on interaction of laser radiation with a liquid were conducted in the Lebedev Physical Institute of the USSR Academy of Sciences (see G. A. Askar'yan, A. M. Prokhorov, G. F. Chanturiya, and G. P. Shipulo, Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 1963, v. 44, No. 6, pp. 2180 – 2182) which led to the discovery of the light-hydraulic effect. This paper played a fundamental role in the development of laser and radiation acoustics.

[3] Recently detection of an acoustic signal from a muon beam at the neutrino channel of the U-70 accelerator of the Institute of High-Energy Physics (Moscow) was reported (see A. B. Borisov et al., Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 1991, v. 100, p. 112). Acoustic signals from a muon flux in the muon filter of the neutrino channel were studied. Results of measurements of signals and theoretical estimates based on the thermoradiation mechanism of sound generation were given. A satisfactory agreement between experimental and theoretical results was noted that was the evidence of the dominant role of the thermoradiation mechanism in the process of sound generation. The possibility of application of the radiation-acoustic technique to remote determination of the characteristics of particle beams from the accelerator was considered.

A definite concept has been formed by now about the mechanisms of sound generation by penetrating radiation. They are connected usually with the physical phenomena (processes) resulting in the conversion of penetrating radiation energy into acoustic energy. These processes depend on the radiation type, on the target substance in which this radiation is absorbed, and on the energy release mode in the absorption region. The mechanisms of sound generation are numerous and not equal in their efficiency [155].

Heat release is one of the most universal physical phenomena taking place due to absorption of penetrating radiation. Thermal energy can transform partially into sound wave energy in different ways. At moderate released energy densities, when no phase changes occur in a substance, the main contribution to the sound generation process arises from the thermal expansion of a medium. This is the thermoradiation (thermoelastic) mechanism of sound generation. In this case the sound fields can be described within the framework of linear theory which has been developed extensively in recent years [156].

The pattern of sound generation looks much more complex in the case of large densities of penetrating radiation energy released in a medium. In this case the phenomena arising are nonlinear. The effects caused by the growth of the expansion rate of the heated region of a medium (hydrodynamic nonlinearity) and the change of thermodynamic parameters of a substance in the process of action of penetrating radiation (thermal nonlinearity) turn out to be substantial. If the density of released thermal energy increases further, more complex processes of sound generation develop, which are connected with phase transitions, for example, in the conditions of bubble mechanism of sound generation by penetrating radiation [6, 64] and the mechanism of formation of shock waves [4, 72][4]. There are also "non-thermal" mechanisms of sound generation: the Cherenkov, dynamic, striction, and other mechanisms. However, the thermoradiation mechanism is the one best-studied up to now.

Research on radiation-acoustic effects could hardly have drawn the attention of physicists in recent decades if it was not connected with the prospects of its practical applications. Examples are scanning radiation-acoustic microscopy of condensed media [157, 201, 206, 257], acoustic detection of super-high-energy particles (the DUMAND project — Deep Underwater Muon and Neutrino Detection) [9, 56, 67, 200, 239], research

[4] We should note that discussion on the density of the energy released in a medium in the process of absorption of penetrating radiation concerns first of all laser (optical) radiation (photon beams). However, in a certain sense they are valid also for particle beams and a single particle or a group of particles. In the latter cases we can discuss the peaks of local heating and overheating leading to formation of acoustic compression waves, microshock waves, microcavitation, and microbubbles.

on the role of the radiation-acoustic mechanism in underwater noise generation in calm ocean [149], and also the opportunities opening up for the application of new generations of proton and linear super-powerful accelerators of future generations to the production of super-high-energy neutrino beams and the application of these beams in geoacoustics (neutrino geoacoustics, the GENIUS project — Geological Exploration of Neutrino-Induced Underground Sound) [185, 248] and in neutrino-acoustic ocean tomography [236]. We should note also the important role of radiation-acoustic effects in investigation and prediction of radiation blistering [80].

The book consists of eleven chapters. The first two chapters give data on elementary particles, absorption of penetrating radiation in a substance, and mechanisms of radiation excitation of sound. The next seven chapters of the book contain the results of the theoretical treatment of thermoradiation sound generation in condensed media, i.e., in homogeneous and inhomogeneous liquids and solids, under the action of modulated penetrating radiation and radiation pulses on a substance. Particular features of the acoustic fields of moving thermoradiation sound sources are considered. Sound excitation by single high-energy particles is analyzed. The efficiency and optimal conditions of thermoradiation sound generation are discussed. The theoretical consideration is based on the solutions of boundary-value problems for the inhomogeneous wave equation with the right-hand side in the form of the function of power density of sound sources produced by radiation absorption in a substance. It is assumed that this absorption obeys the exponential law, which is valid for laser (optical), X-ray, and electromagnetic (in general) beams and with certain limitations for beams of relativistic electrons. This has provided an opportunity to obtain results in the final form and compare them to experimental data. At the same time, the role of the law of radiation absorption in formation of acoustic field of a thermoradiation sound source is analyzed, and the conditions when the absorption law does not play a considerable role are determined. Corresponding analytical expressions are given.

Chapter 10 presents the results of numerous experiments conducted and published by many researchers and concerning thermoradiation excitation of sound by modulated laser radiation and laser pulses in the cases of stationary and moving laser beams, beams of protons and electrons in water, and by electron, positron, proton, ion, and X-ray beams and gamma-quanta in metals. We have to note here that comparison of these results to theoretical conclusions proves the validity of the thermoradiation theory.

Some applications of radiation acoustics are discussed in Chapter 11. The purpose of this chapter is to demonstrate not only the variety of already existing applications but their "large scale". We mean both radiation-acoustic microscopy and immense projects of the future like the DUMAND and GENIUS projects.

CHAPTER 1

Penetrating Radiation: General Information

This chapter provides information on particles constituting penetrating radiation, and absorption of penetrating radiation in the process of its interaction with a substance. Only the most general concepts are presented here. Detailed information may be found in specialized books on particle and nuclear physics.

1. ELEMENTARY PARTICLES: FUNDAMENTAL LAWS OF THE MICROSCOPIC WORLD

The material world is "constructed" from elementary particles. This means that their properties, laws of motion, and forces between them determine the diversity of physical phenomena. Commonly the particles which cannot be separated into components are called elementary particles. This definition applies to electrons, protons, and neutrons, but not atoms and atomic nuclei. Protons and neutrons together are called nucleons. Another common and well-known particle is a light particle, i.e., photon. An electrically neutral particle, i.e., neutrino, is much less known. It is very difficult to detect, as it interacts with electrons and nucleons very weakly and therefore, goes through a tremendous thickness of substance almost freely. Knowledge on the structure of the microscopic world, i.e., physics of elementary particles, is the basis for the whole of modern science. Studies of atomic structure provided an opportunity to discover extraordinary properties of elementary particles and develop a theory of motion, i.e., quantum mechanics.

Quantum mechanics and the theory of relativity are the two pillars supporting the whole of modern physics. Such a general concept as symmetry, which to a significant degree determines the structure of particles and their interactions, is also fundamental for modern physics. Modern models and theories of physics of elementary particles are formulated in the mathematical language of the apparatus of symmetry, i.e., theory of groups. One of the most important parameters in quantum mechanics is spin. All particles are separated into classes depending on the value of their spin: particles with half-integer spins are fermions or Fermi particles and particles with integer spins are bosons or Bose particles. The description of spin using the mathematical apparatus of the theory of groups became the starting point of many theories, i.e., so-called internal symmetries. Development of symmetry schemes unifying fermions and bosons is the goal of the supersymmetry trend and finally, the Grand Unification Theory.

Let us turn to history. It was discovered in the first decade of the last century that an atom consists of a nucleus and electrons. As it turned out, a nucleus has the dimensions of 10^{-13} cm and the whole atomic mass is contained in it. The density of matter is extremely high in a nucleus and is equal to 10^{14} g/cm^3. The charge of the nucleus is positive. Electrons move around a nucleus at a distance of 10^{-8} cm. It was determined in the 1930s that a nucleus consists of protons and neutrons. The last do not have any charge. Electrons are held within an atom by electric forces. Physicists call the forces binding positively charged protons with neutral neutrons nuclear forces, due to their nature.

Pauli had predicted the existence of the neutrino already in the 1920s. It only became possible to observe this particle experimentally twenty years after it had been discovered because of its "ability" almost not to interact with matter. Physicists associated this feature with forces of weak coupling in contrast to nuclear forces, i.e., forces of strong coupling. Further research, and first of all the studies of the nature of nuclear forces, led to the discovery of a huge number of particles, their interaction, and interconversion. Quantum electrodynamics, quantum chromodynamics, and the unified theory of electric weak interaction were developed.

All particles are divided into hadrons and leptons depending on processes they take part in. Fundamental interactions of only four types stand behind all processes observed up to now, i.e., electromagnetic, weak, strong, and gravitational couplings. Gravitation is universal. All elementary particles take part in it. Sources of electromagnetic field are charges. Neutral particles, which do not have any charge, interact with an electromagnetic field only due to their complex structure or quantum