

Preface

The phenomena that referred to the notion of *magnetic resonance* are related to *quantum radiophysics*. Quantum Radiophysics as a branch of science was formed in the beginning of the 1960s. In this field of physics, one studies the phenomena accompanied with the emission or absorption of electromagnetic waves of radio-frequency diapason by quantum systems (nuclei, electrons, atoms, molecules, etc.). These phenomena, the physical nature of which is of independent interest, provided the basis of radiospectroscopic methods for studying the structure of matter and physicochemical processes in it. They are also used for the creation of quantum generators, amplifiers, and magnetometers. Thus, the quantum radiophysics consists of *radiospectroscopy* and *radioelectronics*.

For the first time, the selective absorption of radio waves due to the magnetic properties of electron shells was observed in 1913 by B. K. Arkad'ev, Professor of Moscow University. In 1934, C. E. Cleeton and N. H. Williams observed inversion spectra of ammonia in the range of radio frequencies (Phys. Rev., 1934, v. 45, p. 234). In 1938, I. Rabi registered the first nuclear magnetic resonance (NMR) spectra in experiments with atomic beams (Phys. Rev., 1939, v. 55, p. 526).

The particularly intensive development of radiospectroscopic methods began after 1944, when E. K. Zavoiskii, Professor of Kazan State University (Russian Federation), discovered the phenomenon of electron paramagnetic resonance—EPR (Thesis for Doctor of Science, 1944). In 1946, two scientific teams of American scientists, headed by F. Bloch and E. M. Purcell, published articles on the observation of nuclear magnetic resonance in condensed matter (Phys. Rev., 1946, v. 69, p. 127 and *ibid.*, p. 37, consequently). In 1950, H. G. Dehmelt and G. Krueger obtained spectra of nuclear quadrupole resonance—NQR (Naturwissenschaften, 1950, Bd. 37, S. 111).

At present the latest technical achievements, including in the areas of processing and cryogenic technologies, are used in radiospectroscopy. Devices developed on the basis of these achievements have extremely high sensitivity and resolution. For example, in NMR one records quantum transitions with energies $10^{-24} \div 10^{-25}$ erg ($10^{-31} \div 10^{-32}$ J) and resolves two neighboring spectral lines separated by less than 0.1 Hz. Thus, the radiospectroscopy allows the investigation of processes that lead to the finest changes in the electronic structure of atoms and molecules.

Magnetic relaxation—the achievement of the equilibrium state of nuclear or electronic macroscopic magnetization in a static magnetic field—has no direct analogs in physical phenomena which determine spectra in infrared, visible, and more shortwave diapasons, when an equilibrium state is achieved mainly due to the spontaneous transitions from excited states. The magnetic relaxation processes are determined by the intensity of fluctuating electromagnetic fields in matter. Thus, the investigation of these processes is the study of interactions of nuclei and electrons with the fluctuating electromagnetic fields in close interweaving with the study of the nature and velocity of thermal molecular motion which produces those fluctuating fields. It should be noted that magnetic relaxation is sensitive to molecular motions in a very wide range: $10^3 \div 10^{11}$ Hz. Most often, the study of spectral and relaxation characteristics of magnetic resonance have been held separately, and only in relatively rare original works attempts were made to carry out their complex analysis. However, the latter trend is increasing and no doubt in the nearest future these characteristics will be widely considered using common programs for the interpretation of responses of magnetic resonances at certain impacts on substances (or spin systems). The confirmation of this can be found in developing applications of double, ternary, and more complex resonances (2-, 3-, multidimensional spectroscopies), in which the relaxation processes are responsible for the transfer of spin polarization from one spin system to another.

The radiospectroscopic methods are widely used in molecular physics, chemistry, biology, medicine, and other sciences. In recent years, the methods of quantum radiophysics are used in engineering and industry, as well as for control of technological processes. Thus, in Russia, the NMR method is used for oil well logging, for the laboratory analysis of productivity oil collectors, and for the analysis of oil content and moisture in seeds; the ESR methods were developed for geological research, nondestructive testing of precious stones, etc.

An important step in the formation of quantum radiophysics is connected with the publication of the articles of American physicists (J. P. Gordon, H. J. Zeiger, C. H. Townes. *Phys. Rev.*, 1955, v. 99, p. 1264) and Soviet physicists (N. G. Basov, A. M. Prokhorov. *Physics-Uspkhi* (Advances in Physical Sciences), 1955, v. 57, No 3, p. 481), who had independently created the first quantum generators with a beam of ammonia molecules. Both groups noted that the initial purpose of their work was the creation of high-resolution radiospectroscopes on the basis of molecular radiation, but much greater influence on the development of quantum radiophysics produced a “collateral” effect associated with the oscillating mode of the device, i.e., with its conversion in the quantum generator. Quantum generators with beams of atoms and molecules immediately attracted attention due to their unique properties: even the first devices provided the relative instability of the frequency of the order 10^{-8} (approximate level of the precision of astronomical methods of timing) and soon achieved indicators of $10^{-12} \div 10^{-13}$. At present, the generator on a beam of hydrogen atoms is characterized by the frequency instability $2 \cdot 10^{-14}$ per day and the frequency reproducibility of $\pm 5 \cdot 10^{-13}$. The high

frequency stability of quantum generators has determined their use as devices of storage precise time:time and frequency standards.

Quantum amplifiers were created almost simultaneously with quantum generators. The main advantage of quantum amplifiers is an extremely low level of set (equivalent input) noises. The most perspective of these were devices created on the basis of electron paramagnetic resonance in solids. In 1956, N. Bloembergen showed that in systems with several energy levels it was possible to create a steady-state quantum amplifier if one used an auxiliary radiation for the polarization of electron spins. It should be noted that for the first time the method of inversion of level populations with pumping radiation was proposed by N. G. Basov and A. M. Prokhorov in 1955. Quantum amplifiers have provided new possibilities in many areas of science and technology. For example, in 1963, the first in the history of television images were transmitted from America to Europe using an artificial Earth satellite (a metallic sphere of 30 m in diameter) as a passive reflector of radio waves and using a quantum amplifier as a receiver (the first translation was devoted to the funeral ceremony for American President John Fitzgerald Kennedy). Now, using quantum amplifiers, the radiolocation of all inner planets of the Solar System has been made (in order that a reader can imagine the difficulties in receiving signals reflected from planets, we indicate that the signal which passed the way to Venus and back, is weakened at 10^{27} times). Based on the revised estimations of the relative positions of planets the new theory of planetary motion in the Solar System was developed in the late 1960s. Quantum paramagnetic amplifiers are widely applied in systems of Deep Space communications and radio astronomy, where they are used as input stages of low noise receivers.

On the basis of quantum electronics devices magnetometers have been created, which have extremely high sensitivity and high accuracy measurements of magnetic fields. Using quantum magnetometers, variations of the Earth's magnetic field can be registered in limits of $10^{-7} \div 10^{-8}$, i. e., approximately $0.5 \cdot 10^{-7}$ G ($0.5 \cdot 10^{-11}$ T). Quantum magnetometers are widely used for the study of fluctuations of the Earth's magnetic field due to the change in conditions in the ionosphere and to internal processes in the globe depths, for registration of spatial variations of the geomagnetic field in geological survey, archeology, and military applications.

An important event that brought general recognition to quantum radiophysics was the invention of lasers. In 1958, for the development of ideas of quantum radioelectronics, A. L. Schawlow and C. H. Townes proposed a quantum generator of light and considered general problems related to the generation and amplification of electromagnetic waves in the optical range (Phys. Rev., 1958, v. 112, p. 940). The first pulsed optical generator was created in 1960 (T. H. Maiman. Nature, 1960, v. 187, p. 493) and the first steady-state one was realized in 1961 (A. Javan, W. R. Bennett, D. R. Herriott. Phys. Rev. Lett., 1961, v. 6, p. 106). The appearance of coherent high power light sources resulted in a colossal leap in researches on nonlinear effects in physical optics, as well as in many technical applications.

In different scientific schools, the development of the theory and experimental methods occurred with certain peculiarities that derive from the historical and

economical conditions of research teams. This circumstance may lend some peculiarities of our book but we tried to be objective. In this book, we try to give a circumstantial account of the principles of magnetic resonance and its applications in accordance with our vision of the subject, our possibilities, and abilities. We tried to create a universal book but certainly some particular questions have remained out of the book. In accordance with the chosen style of the book, we have decided to follow the opinion of the great A. Abragam, who reckoned that as opposed to an article it is not necessary in a book to cite initial publications on questions. Now there are many hundreds and even thousands of important articles on each question and it is difficult to give preference to only some of them. After each chapter we suggest the list of books and reviews recommended for further reading (excuse us if we did not indicate some excellent ones).

This book is written on the basis of a few dozens of lecture courses, which have been prepared and delivered by the authors at the Faculty of Physics of Saint-Petersburg State University (Department of Quantum Magnetic Phenomena: BULLETIN DU GROUPEMENT AMPERE, October–December 2010, No. 241, <http://www.ampere.ethz.ch/>) for students who are taught at the directions “Physics” and “Applied Mathematics and Physics,” according to the undergraduate and Master’s programs “Magnetic Resonance, Physical aspects and applications,” “Tomographic technologies in modern medical diagnostics,” and “Quantum Radiophysics.” The material is disposed so that the book would be of interest to scientists and students of physical, chemical, biological, and geological specialities.

The book contains 5 parts and 21 chapters: Alexey Donets wrote Chap. 1; Yurii Chernyshev wrote Chap. 2; Vladimir Chizhik wrote Sects. 2.7 and 2.8, Chap. 3, Sect. 4.4 (partly), Chaps. 15, 19–21; Andrey Komolkin wrote Chaps. 4 and 6; Marina Shelyapina wrote Sects. 1.9–1.11, Chaps. 5, 7–9, 17; Vyacheslav Frolov wrote Sect. 2.9, Chaps. 10–14, 16. Andrei Komolkin made the key contribution to the preparation of the book as a whole, Alexey Donets edited all the figures in the book.

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Chizhik, V.I.; Chernyshev, Y.S.; Donets, A.V.; Frolov, V.;

Komolkin, A.; Shelyapina, M.G.

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