Electricity and Magnetism

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Preface

This course reflects the present level of advancement in science and takes into account the changes in the general physics curriculum.

Since the basic concepts of the theory of relativity are known from the course on mechanics, we can base the description of electric and magnetic phenomena on the relativistic nature of a magnetic field and present the mutual correspondence and unity of electric and magnetic fields. Hence we start this book not with electrostatics but with an analysis of basic concepts associated with charge, force, and electromagnetic field. With such an approach, the information about the laws of electromagnetism, accumulated by students from school-level physics, is transformed into modern scientific knowledge, and the theory is substantiated in the light of the current state of experimental foundations of electromagnetism, taking into account the limits of applicability of the concepts involved. Sometimes, this necessitates a transgression beyond the theory of electromagnetism in the strict sense of this word. For example, the experimental substantiation of Coulomb's law for large distances is impossible without mentioning its connection with the zero rest mass of photons. Although this question is discussed fully and rigorously in quantum electrodynamics, it is expedient to describe its main features in the classical theory of electromagnetism. This helps the student to acquire a general idea of the problem and of the connection of the material of this book with that of the future courses. The latter circumstance is quite significant from the methodological point of view.

This course mainly aims at the description of the experimental substantiation of the theory of electromagnetism and the formulation of the theory in the local form, i.e. in the form of relations between physical quantities at the same point in space and time. In most cases, these relations are expressed in the form of differential equations. However, it is not the differential form but the local nature which is important. Consequently, the end product of the course are Maxwell's equations obtained as a result of generalization and mathematical formulation of experimentally established regularities. Consequently, the analysis is mainly based on induction. This, however, does not exclude the application of the deductive method but rather presumes the combination of the two methods of analysis in accordance with the principles of scientific perception of physical laws. Hence, Maxwell's equations appear in this book not only as a result of mathematical formulation of experimentally established regularities but also as an instrument for investigating these laws.

The choice of experimental facts which can be used to substantiate the theory is not unique. Thus, the theory of electromagnetism is substantiated here with and without taking the theory of relativity into account. The former approach is preferable, since in this case the theory of relativity appears as a general space-time theory on which all physical theories must be based. Such a substantiation has become possible only within the framework of the new general physics curriculum.

An essential part of the theory is the determination of the limits of its applicability and the ranges of concepts and models employed in it. These questions, which are described in this book, are of vital importance. In particular, the analysis of the force of interaction between charges in the framework of the classical theory (i.e. without employing any quantum concepts) shows that the classical theory of electricity and magnetism cannot be applied for analyzing the interaction between isolated charged particles.

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A. Matveev

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Introduction

At present, four types of interactions between material bodies are known to exist, viz. gravitational, strong, weak, and electromagnetic interactions. They are manifested on different three-dimensional scales and are characterized by different intensities.

Gravitational interaction is noticeable only for bodies on astronomical scale. Strong interactions can be observed only between certain particles when they approach each other to quite small distances (10^{-15} m). Weak interactions are exhibited during mutual conversion of certain kinds of particles and become insignificant as the particles are separated by large distances. Only electromagnetic interactions are manifested in our everyday life. Practically, all "forces" which are involved in physical phenomena around us, except for gravitational forces, are ultimately electromagnetic forces. Naturally, all diverse relations and phenomena due to electromagnetic interactions cannot be described by the laws of electrodynamics since on each level of a phenomenon there exist specific features and regularities that cannot be reduced to regularities on another level. However, electromagnetic interactions on all levels are to a certain extent an elementary link with the help of which the entire chain of relations is formed. This makes electromagnetic phenomena important from a practical point of view.

The theory of electromagnetic phenomena plays an extremely important role. This theory is the first relativistically invariant theory, which played a decisive role in the creation and substantiation of the theory of relativity and served as the "training ground" on which many new ideas have been verified. Quantum electrodynamics is the most elaborate branch of quantum theory, whose predictions are in astonishingly good agreement with experiment, although at present it is still not complete and free of internal contradictions. The philosophical aspect of electromagnetism is also very important. For example, specific features of the field form of existence of matter are clearly manifested within the framework of electromagnetic phenomena. The mutual conversion of different forms of matter and energy is also clearly reflected in these phenomena.

The substantiation of the theory is presented in the book in two ways. When the theory is substantiated without taking into account relativistic effects, the experimental basis of the theory of electricity and magnetism is formed by the invariance of an elementary charge, Coulomb's law, the principle of superposition for electric fields, the Biot-Savart law, the superposition principle for magnetic fields, Lorentz force, Faraday's law of electromagnetic induction, Maxwell's displacement currents, and the laws of conservation of charge and energy. When relativistic effects are taken into account for substantiating the theory, the Biot-Savart law, the principle of superposition for magnetic fields, and the Lorentz force no longer serve as independent experimental facts in the formulation of the theory. The second way of substantiating the theory of electricity and magnetism is presented not as the main line but as a side track chosen so as to simplify the mathematical aspect of the problem. It includes the following stages.

The relativistic nature of the magnetic field is demonstrated in Sec. 8, where the formula for interaction of currents flowing in infinitely long parallel conductors is derived and Lorentz force is obtained from electric interaction of charges. The field interpretation of these results allows us to find the magnetic induction of current passing through an infinitely long conductor. The principle of superposition for a magnetic field now becomes a corollary of the principle of superposition for an electric field. The transition to magnetic induction for arbitrary currents and the derivation of the corresponding equations are given in Sec. 35, where the independence of local relations from the values of physical quantities at other points is effectively used. After this, the Biot-Savart law is theoretically derived in Sec. 37, thus concluding the analysis of the connection existing in the relativistic concept of space and time between the invariance of an elementary electric charge, Coulomb's law, the principle of superposition for an electric field and the Biot-Savart law, as well as between the Lorentz force and the principle of superposition for a magnetic field.

CHAPTER 1

Charge. Field. Force

Charge is the source and the object of action of an electromagnetic field.
Field is the material carrier of electromagnetic interactions between charges, and is a form of the existence of matter.
Force is a quantitative measure of the intensity of interaction between charges.
Charges, fields, and forces are inseparably linked with space, time, and motion of matter.
Their interrelation cannot be understood without taking into account the connection with space, time and motion.

Sec. 1. Microscopic Charge Carriers

The properties of basic microscopic charge carriers are described. The distribution of electric charge in a proton and a neutron is discussed, and the physical meaning of electric charge is analyzed.

Classification. By microscopic charge carriers we mean charged particles and ions which can carry both positive and negative charge. The numerical value of a charge can only be an integral multiple of the elementary charge

$$|e| = 1.6021892(46)\cdot 10^{-19}\ \text{C}. \tag{1.1}$$

In spite of persistent experimental attempts, it has not been possible so far to detect microscopic carriers with a fractional charge (see Sec. 3).

About 200 particles and an enormous number of ions, atoms, and molecules are known at present. A large number of particles exist only for a short time after their creation and then disintegrate into other particles. In other words, *particles have a finite lifetime.* In most cases, this lifetime is extremely small and is of the order of a very small fraction of a second. *Only a small number of charged particles have an infinite lifetime. These are the electron, the proton, and their antiparticles.* Atomic nuclei contain protons, while the electron shells of atoms contain electrons. It is these particles that are responsible for almost all phenomena analyzed in a course on electricity and magnetism. In addition to protons, nuclei also contain neutrons. These are electrically neutral and have an infinite lifetime in nuclei. However, their average lifetime outside nuclei is about 17 min, after which they disintegrate into protons, electrons, and antineutrinos.

The charge of ions is due to the fact that the electron shell of the corresponding atom or molecule lacks one or several electrons (positive ions) or, on the contrary, has extra electrons (negative ions). Consequently, the treatment of ions as microscopic charge carriers boils down to an investigation of electron and proton charges.

Electron. An electron is the material carrier of an elementary negative charge. *It is usually assumed that an electron is a structureless point particle*, i.e. the entire charge of an electron is concentrated at a point. *Such a representation is intrinsically contradictory* since the energy of the electric field created by a point charge is infinite, and hence the inertial mass of the point charge must also be infinite. This is in contradiction with the experiment since the electron rest mass is $m_e = 9.1 \times 10^{-31}$ kg. *However, we must reconcile ourselves with this contradiction in the absence of a more satisfactory and less contradictory view on the structure (or absence of a structure) of electron.* The difficulties associated with an infinite rest mass can be successfully overcome in calculation of various effects with the help of **mass renormalization** which essentially consists in the following. Suppose that it is required to calculate a certain effect and an infinite rest mass appears in the calculations. The quantity obtained as a result of calculations is infinite and is consequently devoid of any physical meaning. In order to obtain a physically reasonable result, another calculation is carried out, in which all factors, except those associated with the phenomenon under consideration, are present. This calculation also includes an infinite rest mass and leads to an infinite result. Subtraction of the second infinite result from the first leads to the cancellation of infinite quantities associated with the rest mass. The remaining quantity is finite and characterizes the phenomenon being considered. Thus, we can get rid of the infinite rest mass and obtain physically reasonable results which are confirmed by experiment. Such a method is used, for example, to calculate the energy of an electric field (see Sec. 18).

Proton. A proton is the carrier of a positive elementary charge. Unlike an electron, a proton is not considered as a point particle. The distribution of the electric charge in a proton has been thoroughly investigated in experiments. The method of investigation is similar to that used at the beginning of this century by Rutherford in investigations of the atomic structure, which led to the discovery of the nucleus. The collisions between electrons and protons are analyzed. If we assume the proton to be a *spherically symmetric* distribution of charge in a finite volume, *the electron trajectory which does not pass through this volume is independent of the law of charge distribution*, and is the same as if the entire charge of the proton were concentrated at its centre. *The trajectories of electrons passing through the volume of the proton depend on the specific form of charge distribution in it.* These trajectories can be calculated. Hence, by carrying out quite a large number of observations of the results of collisions between electrons and protons, we can draw conclusion about the charge distribution inside the proton. Since very small volumes in space are involved, electrons with very high energies are required for experiments. This necessity is