Chapter 1
Introduction

Geometrical charged-particle optics describes the motion of charged particles in *macroscopic* electromagnetic fields by employing the well-established notations and concepts of *light* optics. Macroscopic fields are produced by macroscopic elements, such as solenoids, electric, and magnetic multipoles, or by voltages applied to conducting devices, for example, cylinders or apertures. We define the atomic fields within solid or biological objects as *microscopic* fields. The propagation of the particles in these fields will not be considered within the frame of *geometrical charged-particle optics*.

The description of the particle motion from the point of view of light optics is reasonable because the elementary particles have particle and wave properties. The similarity between the propagation of light and particles is documented by the equivalent mathematical treatments [29]. Moreover, the properties of particle-optical instruments and their constituent components are described most appropriately in light-optical terms, which have been established at a time when charged particles were still unknown. The treatment of particle motion by means of optical concepts has been proven extremely useful for the design of beam-guiding systems, the electron microscope in particular. This microscope has developed over the years from an image-forming system to a sophisticated analytical instrument yielding structural and chemical information about the object on an atomic scale.

Within the frame of validity of charged-particle optics, we describe electrons and ions by the same formalism because their propagation in macroscopic fields depends only on their mass and charge, respectively. The effect of the spin on the motion of charged particle is of the same order of magnitude as that resulting from diffraction. The influence of diffraction becomes negligibly small in the limit that the index of refraction does not change appreciably over a distance of several wavelengths λ. The limit $\lambda \rightarrow 0$ represents the domain of *geometrical charged-particle optics*.

For reasons of simplicity, we restrict our further investigations to electrons. Nevertheless, we can use all results for ions as well if we substitute their charge and rest mass for the corresponding quantities of the electron. Geometrical light optics describes the properties of optical elements by means of their effects on the light rays along which the point-like *photons* propagate. The rays form straight lines

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in the region outside the lenses. These rays are either refracted at the surfaces of the lenses where the index of refraction changes abruptly or are deflected steadily if the index of refraction changes gradually, as in the case of the atmosphere due to the varying density with respect to the distance from the earth. The so-called *gradient-index* lenses have an index of refraction, which increases quadratic with the distance from their *optic axis*.

In close analogy to light optics, geometrical electron optics conceives the path of an electron as a geometrical line or trajectory, respectively. However, contrary to light optics, all electron optical elements form gradient-index lenses because the electrons must travel in vacuum where the electromagnetic fields produced by the exterior currents and charges vary continuously. The word electron originates from the Greek word $\eta\lambda\varepsilon\kappa\tau\rho o\nu$ meaning amber. In 1890, *Stony* introduced this word for denoting the elementary charge because amber charges up by friction.

Electron optics is based on two fundamental discoveries made in 1924 by *Louis de Broglie* [2] and in 1926 by *Hans Busch* [3]. De Broglie postulated on ground of theoretical considerations that one must attribute a wave to each elementary particle. At about the same time, Busch discovered that the magnetic field of a solenoid acts on electrons in exactly the same way as a glass lens on the light rays. It had been these two important discoveries, which lead *Ernst Ruska* to the conclusion that it must be possible to build a microscope, which uses electrons instead of photons. He realized successfully the first electron microscope in 1931 [30]. The development of the electron microscope, oscillographs, and cathode-ray tubes gave rise to the science of electron optics. The guiding of charged particles is also of great importance in accelerators and spectrometers employed in nuclear physics [31, 32]. However, the close analogy between these instruments and the classical electron optical devices was not widely recognized. For the development of the latter instruments, it proved extremely useful to utilize the concepts and notations employed in light optics. Subsequently, one applied and expanded these methods in the context of designing aberration correctors, monochromators, and imaging energy filters composed of non-rotationally symmetric elements such as dipoles and quadrupoles. Unfortunately, the designers of accelerators and spectrometers in nuclear physics did not take notice of these developments established much earlier. As a result, different notations exist for the same device or property. This unfortunate situation causes quite often confusion among the nonexperts. This situation dates back from the early days of charged-particle optics, when each group entering this field of research introduced its own nomenclature. In this book, we use the notation and terminology introduced by Scherzer [6, 33]. Within the frame of this terminology, we distinguish between *planes* and *sections*. Planes are plane surfaces perpendicular to the optic axis regardless of whether it is straight or curved. Sections are surfaces which contain the optic axis. Unlike a plane, a section can be curved, as what happens in systems with curved axis.

The main task of charged-particle optics is the manipulation of ensembles of rays each originating from a common point. Important collective properties of optical elements are, for example, the focusing of homocentric bundles of rays in order to form an image and the guiding of particles in accelerators or storage rings [34], respectively. We do not consider methods for producing charged particles in the frame of geometrical charged-particle optics. Although this approximation is well suited to describe the action of optical elements, it fails to provide information about the intensity in the region of the caustic formed by the loci of the intersections of rays emanating from the same origin. Because a plane partial wave is associated to each trajectory, strong interference effects arise at the vicinity of the caustic, as it is the case in the image plane of an electron microscope.

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