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Claus Grupen and Boris Shwartz
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PARTICLE DETECTORS

Second Edition

The scope of the detection techniques in particle detectors is very wide, depending on the aim of the measurement. Each physics phenomenon can be used as the basis for a particle detector. Elementary particles have to be identified with various techniques, and relevant quantities like time, energy, and spatial coordinates have to be measured. Particle physics requires extremely high accuracies for these quantities using multi-purpose installations as well as dedicated experimental set-ups. Depending on the aim of the measurement, different effects are used. Detectors cover the measurement of energies from very low energies (micro-electron-volts) to the highest of energies observed in cosmic rays.

Describing the current state-of-the-art instrumentation for experiments in high energy physics and astroparticle physics, this new edition covers track detectors, calorimeters, particle identification, neutrino detectors, momentum measurement, electronics and data analysis. It also discusses up-to-date applications of these detectors in other fields such as nuclear medicine, radiation protection and environmental science. Problem sets have been added to each chapter and additional instructive material has been provided, making this an excellent reference for graduate students and researchers in particle physics.

Claus Grupen is Professor Dr in the Department of Physics at Siegen University. He was awarded the Special High Energy and Particle Physics Prize of the European Physical Society for establishing the existence of the gluon in independent and simultaneous ways, as member of the PLUTO experiment at DESY in 1995.

Boris Shwartz is a Leading Researcher at the Budker Institute of Nuclear Physics. He has worked on the development and construction of the detectors used in several projects, including the KEDR and CMD-2 detectors, and WASA and Belle experiments.

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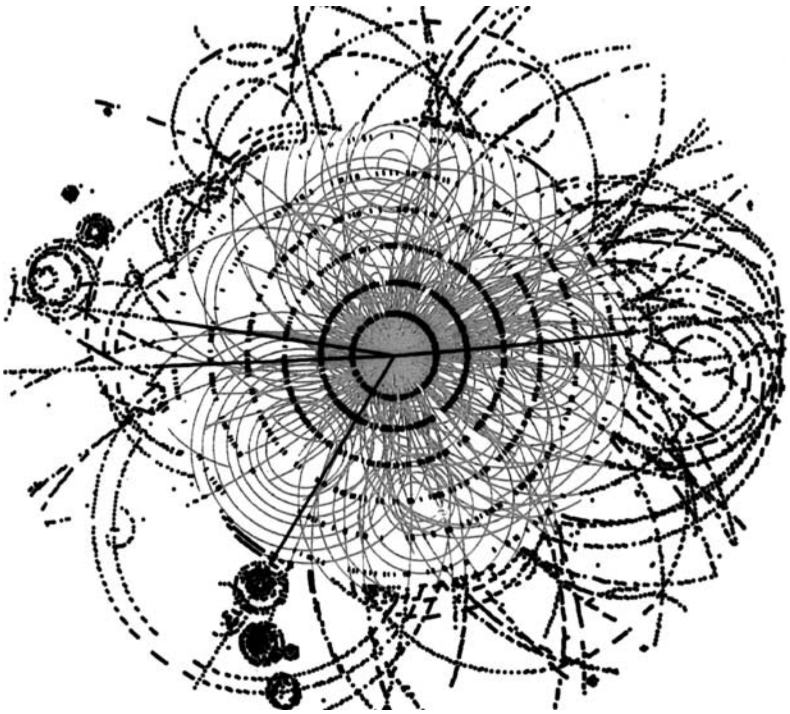
Simulation of a Higgs-boson production in proton–proton interactions in the ATLAS experiment at the Large Hadron Collider (LHC) at CERN. The Higgs decays into a pair of Z bosons, each of which decays in turn into muons pairs. The four muons are indicated by the four straight lines. The hadronic background originates from the interactions of spectator quarks and other interactions in the same beam crossing.
(With permission of the CERN photo archive.)



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Preface to the second edition

Scientific knowledge is a body of statements of varying degrees of certainty – some most unsure, some nearly sure, but none absolutely certain.

Richard Feynman

The book on Particle Detectors was originally published in German ('Teilchendetektoren') with the Bibliographisches Institut Mannheim in 1993. In 1996, it was translated and substantially updated by one of us (Claus Grupen) and published with Cambridge University Press. Since then many new detectors and substantial improvements of existing detectors have surfaced. In particular, the new proton collider under construction at CERN (the Large Hadron Collider LHC), the planning for new detectors at a future electron–positron linear collider, and experiments in astroparticle physics research require a further sophistication of existing and construction of novel particle detectors. With an ever increasing pace of development, the properties of modern detectors allow for high-precision measurements in fields like timing, spatial resolution, energy and momentum resolution, and particle identification.

Already in the past, electron–positron storage rings, like LEP at CERN, have studied electroweak physics and quantum chromodynamics at energies around the electroweak scale ($\approx 100\,\text{GeV}$). The measurement of lifetimes in the region of picoseconds required high spatial resolutions on the order of a few microns. The Large Hadron Collider and the Tevatron at Fermilab will hopefully be able to solve the long-standing question of the generation of masses by finding evidence for particles in the Higgs sector. Also the question of supersymmetry will be addressed by these colliders. Detectors for these enterprises require precision calorimetry and high spatial resolution as well as unanticipated time resolution and extreme selectivity of events, to cope with high backgrounds. Particles in crowded jets have to be identified to allow for the invariant-mass reconstruction of short-lived particles. Radiation hardness is certainly also a hot topic for detectors at hadron colliders.

Particle detection in astroparticle physics also presents a challenge. The origin of the highest-energy cosmic rays, even in spite of recent indications of possible correlations with active galactic nuclei, is still an unsolved problem. Detectors like in the Auger experiment or possibly also the giant IceCube array under construction in Antarctica will very likely find the sources of energetic cosmic rays either in our galaxy or beyond. Also the interaction mechanisms at very high energies, which are inaccessible at present and future accelerators and storage rings, will be attacked by measuring the shape and the elemental composition of the primary cosmic-ray spectrum beyond the expected Greisen cutoff, where energetic protons or nuclei are assumed to lose significant energy, e.g. in proton–photon collisions with the omnipresent blackbody radiation.

These modern developments in the field of particle detection are included in the second edition which is substantially updated compared to the first English edition. Also new results on modern micropattern detectors only briefly mentioned in the first edition and chapters on accelerators and neutrino detectors are included. The chapters on 'Electronics' and 'Data analysis' are completely rewritten.

We would like to mention that excellent books on particle detectors already exist. Without trying to be exhaustive we would like to mention the books of Kleinknecht [1], Fernow [2], Gilmore [3], Sauli [4], Tait [5], Knoll [6], Leo [7], Green [8], Wigmans [9], and Leroy and Rancoita [10]. There are also many excellent review articles in this field published in the literature.

We gratefully acknowledge the help of many colleagues. In particular, we would like to thank Helmuth Spieler for contributing the chapter on 'Electronics'. Archana Sharma has contributed some ideas for micropattern detectors and muon momentum measurement. Steve Armstrong assisted in rewriting the chapter on 'Data analysis'. Iskander Ibragimov very carefully transformed those figures which were recycled from the first edition, where they were just pasted in manually, into an electronic format. He also took care of the labelling of all figures to make them look uniform. T. Tsubo-yama, Richard Wigmans and V. Zhilich provided a number of figures, and A. Buzulutskov and Lev Shekhtman explained us several details concerning microstrip detectors. They also suggested a couple of relevant references. Some useful discussions with A. Bondar, A. Kuzmin, T. Ohshima, A. Vorobiov and M. Yamauchi were very helpful. Simon Eidelman and Tilo Stroh have carefully read the whole book and checked all problems. Tilo Stroh has also taken over the Herculean task to set the text in LaTeX, to improve the figures, to arrange the layout, and prepare a comprehensive index. This was of enormous help to us.

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Preface to the first edition

The basic motive which drives the scientist to new discoveries and understanding of nature is curiosity. Progress is achieved by carefully directed questions to nature, by experiments. To be able to analyse these experiments, results must be recorded. The most simple instruments are the human senses, but for modern questions, these natural detection devices are not sufficiently sensitive or they have a range which is too limited. This becomes obvious if one considers the human eye. To have a visual impression of light, the eye requires approximately 20 photons. A photomultiplier, however, is able to 'see' single photons. The dynamical range of the human eye comprises half a frequency decade (wavelengths from 400 nm to 800 nm), while the spectrum of electromagnetic waves from domestic current over radio waves, microwaves, infrared radiation, visible light, ultraviolet light, X-rays and gamma rays covers 23 frequency decades!

Therefore, for many questions to nature, precise measurement devices or detectors had to be developed to deliver objective results over a large dynamical range. In this way, the human being has sharpened his 'senses' and has developed new ones. For many experiments, new and special detectors are required and these involve in most cases not only just one sort of measurement. However, a multifunctional detector which allows one to determine all parameters at the same time does not exist yet.

To peer into the world of the microcosm, one needs microscopes. Structures can only be resolved to the size of the wavelength used to observe them; for visible light this is about 0.5 μm. The microscopes of elementary particle physicists are the present day accelerators with their detectors. Because of the inverse proportionality between wavelengths and momentum (de Broglie relation), particles with high momentum allow small structures to be investigated. At the moment, resolutions of the order of 10^{-17} cm can be reached, which is an improvement compared to the optical microscope of a factor of 10^{13}.

To investigate the macrocosm, the structure of the universe, energies in the ranges between some one hundred micro-electron-volts (μeV, cosmic microwave background radiation) up to 10^{20} eV (high energy cosmic rays) must be recorded. To master all these problems, particle detectors are required which can measure parameters like time, energy, momentum, velocity and the spatial coordinates of particles and radiation. Furthermore, the nature of particles must be identified. This can be achieved by a combination of a number of different techniques.

In this book, particle detectors are described which are in use in elementary particle physics, in cosmic ray studies, in high energy astrophysics, nuclear physics, and in the fields of radiation protection, biology and medicine. Apart from the description of the working principles and characteristic properties of particle detectors, fields of application of these devices are also given.

This book originated from lectures which I have given over the past 20 years. In most cases these lectures were titled 'Particle Detectors'. However, also in other lectures like 'Introduction to Radiation Protection', 'Elementary Particle Processes in Cosmic Rays', 'Gamma Ray Astronomy' and 'Neutrino Astronomy', special aspects of particle detectors were described. This book is an attempt to present the different aspects of radiation and particle detection in a comprehensive manner. The application of particle detectors for experiments in elementary particle physics and cosmic rays is, however, one of the main aspects.

I would like to mention that excellent books on particle detectors do already exist. In particular, I want to emphasise the four editions of the book of Kleinknecht [1] and the slightly out-of-date book of Allkofer [2]. But also other presentations of the subject deserve attention [3–25].

Without the active support of many colleagues and students, the completion of this book would have been impossible. I thank Dr U. Schäfer and Dipl. Phys. S. Schmidt for many suggestions and proposals for improvement. Mr R. Pfitzner and Mr J. Dick have carefully done the proof reading of the manuscript. Dr G. Cowan and Dr H. Seywerd have significantly improved my translation of the book into English. I thank Mrs U. Bender, Mrs C. Tamarozzi and Mrs R. Sentker for the production of a ready-for-press manuscript and Mr M. Euteneuer, Mrs C. Tamarozzi as well as Mrs T. Stöcker for the production of the many drawings. I also acknowledge the help of Mr J. Dick, Dipl. Phys.-Ing. K. Reinsch, Dipl. Phys. T. Stroh, Mr R. Pfitzner, Dipl. Phys. G. Gillessen and Mr Cornelius Grupen for their help with the computer layout of the text and the figures.

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Introduction

Every act of seeing leads to consideration, consideration to reflection, reflection to combination, and thus it may be said that in every attentive look on nature we already theorise.

Johann Wolfgang von Goethe

The development of particle detectors practically starts with the discovery of radioactivity by Henri Becquerel in the year 1896. He noticed that the radiation emanating from uranium salts could blacken photosensitive paper. Almost at the same time X rays, which originated from materials after the bombardment by energetic electrons, were discovered by Wilhelm Conrad Röntgen.

The first nuclear particle detectors (X-ray films) were thus extremely simple. Also the zinc-sulfide scintillators in use at the beginning of the last century were very primitive. Studies of scattering processes – e.g. of α particles – required tedious and tiresome optical registration of scintillation light with the human eye. In this context, it is interesting to note that Sir William Crookes experimenting in 1903 in total darkness with a very expensive radioactive material, radium bromide, first saw flashes of light emitted from the radium salt. He had accidentally spilled a small quantity of this expensive material on a thin layer of activated zinc sulfide (ZnS). To make sure he had recovered every single speck of it, he used a magnifying glass when he noticed emissions of light occurring around each tiny grain of the radioactive material. This phenomenon was caused by individual α particles emitted from the radium compound, striking the activated zinc sulfide. The flashes of light were due to individual photons caused by the interaction of α particles in the zinc-sulfide screen. A particle detector based on this effect, the *spinthariscope*, is still in use today for demonstration experiments [1].

Scintillations in the form of 'northern lights' (aurora borealis) had already been observed since long. As early as in 1733 this phenomenon was correctly interpreted as being due to radiation from the Sun (Jean-Jacques D'Ortous De Mairan). Without knowing anything about elementary particles, the atmosphere was realised to be a detector for solar electrons, protons and α particles. Also, already about 50 years before the discovery of *Cherenkov radiation*, Heaviside (1892) showed that charged particles moving faster than light emit an electromagnetic radiation at a certain angle with respect to the particle direction [2]. Lord Kelvin, too, maintained as early as 1901 that the emission of particles was possible at a speed greater than that of light [3, 4]. At the beginning of the twentieth century, in 1919, Madame Curie noticed a faint light emitted from concentrated solutions of radium in water thereby operating unknowingly the first Cherenkov detector. Similarly, Cherenkov radiation in water-cooled reactors or high-intensity radiation sources is fascinating, and sometimes extremely dangerous (e.g. in the Tokaimura nuclear reactor accident) to observe. The human eye can also act as Cherenkov detector, as the light flashes experienced by astronauts during their space mission with eyes closed have shown. These light emissions are caused by energetic primary cosmic rays passing through the vitreous body of the eye.

In the course of time the measurement methods have been greatly refined. Today, it is generally insufficient only to detect particles and radiation. One wants to identify their nature, i.e., one would like to know whether one is dealing, for example, with electrons, muons, pions or energetic γ rays. On top of that, an accurate energy and momentum measurement is often required. For the majority of applications an exact knowledge of the spatial coordinates of particle trajectories is of interest. From this information particle tracks can be reconstructed by means of optical (e.g. in spark chambers, streamer chambers, bubble and cloud chambers) or electronic (in multiwire proportional or drift chambers, micropattern or silicon pixel detectors) detection.

The trend of particle detection has shifted in the course of time from optical measurement to purely electronic means. In this development ever higher resolutions, e.g. of time (picoseconds), spatial reconstruction (micrometres), and energy resolutions (eV for γ rays) have been achieved. Early optical detectors, like cloud chambers, only allowed rates of one event per minute, while modern devices, like fast organic *scintillators*, can process data rates in the GHz regime. With GHz rates also new problems arise and questions of *radiation hardness* and *ageing* of detectors become an issue.

With such high data rates the electronic processing of signals from particle detectors plays an increasingly important rôle. Also the storage of data on magnetic disks or tapes and computer-aided preselection of data is already an integral part of complex detection systems.

Originally, particle detectors were used in cosmic rays and nuclear and particle physics. Meanwhile, these devices have found applications in medicine, biology, environmental science, oil exploration, civil engineering, archaeology, homeland security and arts, to name a few. While the most sophisticated detectors are still developed for particle physics and astroparticles, practical applications often require robust devices which also function in harsh environments.

Particle detectors have contributed significantly to the advancement of science. New detection techniques like cloud chambers, bubble chambers, multiwire proportional and drift chambers, and micropattern detectors allowed essential discoveries. The development of new techniques in this field was also recognised by a number of Nobel Prizes (C.T.R. Wilson, cloud chamber, 1927; P. Cherenkov, I. Frank, I. Tamm, Cherenkov effect, 1958; D. Glaser, bubble chamber, 1960; L. Alvarez, bubble-chamber analysis, 1968; G. Charpak, multiwire proportional chamber, 1992; R. Davis, M. Koshiba, neutrino detection, 2002).

In this book the chapters are ordered according to the object or type of measurement. However, most detectors are highlighted several times. First, their general properties are given, while in other places specific features, relevant to the dedicated subject described in special chapters, are discussed. The ordering principle is not necessarily unique because *solid-state detectors*, for example, in nuclear physics are used to make very precise energy measurements, but as solid-state strip or pixel detectors in elementary particle physics they are used for accurate track reconstruction.

The application of particle detectors in nuclear physics, elementary particle physics, in the physics of cosmic rays, astronomy, astrophysics and astroparticle physics as well as in biology and medicine or other applied fields are weighted in this book in a different manner. The main object of this presentation is the application of particle detectors in elementary particle physics with particular emphasis on modern fast high-resolution detector systems. This also includes astroparticle physics applications and techniques from the field of cosmic rays because these activities are very close to particle physics.

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