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A Modern Introduction to Particle Physics

3rd Edition

现代粒子物理学导论

第三版

（影印版）

〔巴基斯坦〕法耶兹丁（Fayyazuddin）
〔巴基斯坦〕里亚兹丁（Riazuddin） 著

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序　　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会 主任

中国科学院院士，北京大学教授

王恩哥

2010 年 5 月于燕园

A MODERN INTRODUCTION TO PARTICLE PHYSICS

Third Edition

Fayyazuddin
Riazuddin
National Centre for Physics, Pakistan

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Thou seest not in the creation of All-
merciful any imperfection.
Return thy gaze; seest thou any fissure?
Then return thy gaze again, and again and thy
gaze comes back to thee dazzled, aweary
Koran, The Kingdom LXVII.

To Masooda and Mumtaz

Preface

Preface for the Third Edition

The main aim in producing the third edition is to bring the book up to date and as such many chapters have been thoroughly revised. In particular the chapters on Heavy Flavors (Chap. 8), Neutrino Physics (Chap. 12), Electroweak Unification (Chap. 13), Weak Decays of Heavy Flavors (Chap. 15), Particle Mixing and CP-violation (Chap. 16), Grand Unification, Supersymmetry and Strings (Chap. 17) and Cosmology and Astroparticle Physics (Chap. 18) have gone through major revision with the addition of some new material. To make the book self-contained, appendix A has been extended. An important feature of the 3rd edition is the addition of a substantial number of new problems.

A number of typographical errors have been corrected and a number of figures have been streamlined, using Jaxodraw software.

We wish to express our deep sense of appreciation to Dr. Maqbool Ahmed and Mansoor-ur-Rehman for critically reading Chap. 18 on Cosmology and Astroparticle Physics, making many useful suggestions. We wish to express our deep thank to Aqeel Ahmed (our graduate student) for doing an excellent job in typing, drawing figures and carefully reading some of the chapters; without his help it was difficult to put the manuscript in the final form. Thanks are also due to Ishtiaq Ahmed, Jamil Aslam, M. Junaid, Ali Paracha and Abdur Rehman for assistance in typing the manuscript.

Finally we wish to acknowledge the permission granted by Particle Data Group for reproducing figures indicated in the text which are duely referred. One of us (F) would like to acknowledge the support of Higher Education Commission (HEC), Islamabad.

Fayyazuddin
Riazuddin

Preface for the Second Edition

Our aim in producing this new edition is to bring the book up to date and as such many chapters have been throughly revised. In particular, the chapters on Neutrino Physics, Partcle Mixing and CP–Violation and Weak Decays of Heavy Flavors have been mostly rewritten incorporating new material and new data. The heavy quark effective field theory has been included and a brief introductory section on supersymmetry and strings has been added. We wish to thank Ansar Fayyazuddin for writing this section.

A number of typographical errors have been corrected. Another change is that we have adopted a metric and notation for gamma matrices commonly used.[1]

Finally we wish to thank Mr. Amjad Hussain Gilani and Dr. Muhammad Nisar who did an excellent job in typing the manuscript; without their help it was difficult to put the manuscript in final shape.

Fayyazuddin
Riazuddin
Jan. 21, 2000

[1]See for example, J. D. Bjorken and S.D. Drell, Relativistic Quantum Mechanics, McGraw-Hill Book Co., New York (1965).

Preface for the First Edition

Particle physics has been one of the frontiers of science since J. J. Thompson's discovery of the electron about one hundred years ago. Since then physicists have been concerned with (i) attempts to discover the ultimate constituents of matter, (ii) the fundamental forces through which the fundamental constituents interact, and (iii) seeking a unification of the fundamental forces.

At the present level of experimental resolution, the smallest units of matter appear to be leptons and quarks, which are spin $1/2$ fermions. Hadrons (particles which feel the strong force) are composed of quarks. The evidence for this comes from the observed spectrum and static properties of hadrons and from high energy lepton-hadron scattering experiments involving large momentum transfers, which "prove" the actual existence of quarks within hadrons. As originally formulated, the quark model needed three flavors of quarks, up (u), down (d) and strangeness (s) not just u and d. The discoveries of the tau leptons and more flavors [charm (c) and bottom (b)] were to some extent welcomed and to some extent appeared to be there for no apparent reason since elementary building blocks of an atom are just u and d quarks and electrons. A charm quark was predicted to exist to remove all phenomenological obstacles to a proper and an elegant gauge theory of weak interaction. Without it, nonexistence of strangeness-changing neutral current posed a puzzle. This also restored the quark-lepton symmetry: for each pair of leptons of charges 0 and -1 there is a quark pair of charges $2/3$ and $-1/3$. The existence of τ-leptons and discovery of the b quark (charge $-1/3$) demand the existence of another quark (charge $2/3$), called the top quark, to again restore the quark-lepton symmetry. Indeed, six quark flavors have been proposed to incorporate violation of CP invariance in weak interaction.

Quarks also have a hidden three valued degree of freedom known as color: each quark flavor comes in three colors. The antisymmetry of three-quark wave function of a baryon [e.g. proton] is attributed to color degree of freedom. The three number of colors also manifest themselves in π^0 decay and in the annihilation of lepton-antilepton into hadrons. We have encountered the following types of charges: gravitational, namely, mass, electric, flavor and color. The fundamental forces through which elementary fermions interact are then simply the forces of attraction or repulsion between these charges. The unification of forces is then sought by searching for a single entity of which the various charges are components in the sense that they can be transformed into one and another. In other words, they form generators of a gauge group G which is taken to be local so that a definite form of interaction between vector fields (which must exist and belong to the adjoint representation of G) and elementary fermions (which belong to the fundamental or trivial representation of G) is generated with a universal coupling constant. In this respect non-Abelian gauge field theories [Yang-Mills type] have played a major role. Here the field itself is a carrier of "charge" so that there are direct interactions between the field quanta.

Let us first discuss the strong quark interactions. The local gauge group is $SU_C(3)$ generated by three color charges, the field quanta are eight massless spin 1 color carrying gluons. The theory of quark interactions arising from the exchange of gluons is called quantum chromodynamics (QCD). The most striking physical properties of QCD are (i) the concept of a "running coupling constant $\alpha_s(q^2)$", depending on the amount of momentum transfer q^2. It goes to zero for high q^2 leading to asymptotic freedom and becomes large for low q^2, (ii) confinement of quarks and gluons in a hadron so that only color singlets can be produced and observed. Only the property (i) has a rigorous theoretical basis while the property (ii) finds support from hadron spectroscopy and lattice gauge simulations.

Weak and electromagnetic interactions result from a gauge group acting upon flavors. It is $SU_L(2)\times U(1)$ and is spontaneously broken rather than exact as was $SU_C(3)$.

The electroweak theory, together with the quark hypothesis and QCD, form the basis for the so called "Standard Model" of elementary particles. There have been many quantitative confirmations of the predictions of the standard model: existence of neutral weak current mediated by Z^0, discovery of weak vector bosons $W^{\pm}, Z^0$ at the predicated masses, precision determinations of electroweak parameters and coupling constants (e.g. $\sin^2\theta_W$ which comes out to be the same in all experiments) leading to one loop verification of the theory and providing constraints on the top quark and Higgs masses. Similarly there have been tests of QCD, verifying the running of the coupling constant $\alpha_s(q^2)$, q^2-dependence of structure functions in deep-inelastic lepton-nucleon scattering. Other evidences come from hadron spectroscopy and from high energy processes in which gluons play an essential role.

In spite of the above successes, many questions remain: replication of families and how many quarks and leptons are there? QCD does not throw any light on how many quark flavors there should be? Origin of fermion masses, which appear as free parameters since Higgs couplings with fermions contain as many arbitrary coupling constants as there are masses, is another unanswered question. Origin of CP violation at more fundamental level, rigorous basis of confinement and hadronization of quarks are other questions which await answers. Top quark and Higgs boson are still to be discovered.

Symmetry principles have played an important part in our understanding of particle physics. Thus Chapters 2-6 discuss global symmetries and flavor or classifications symmetries like SU(2) and SU(3) and quark model. Chapter 5 provides the necessary group theory and consequences of flavor SU(3). Chapters 2-6 together with Chapters 9, 10 and 11 on neutrino, weak interactions, properties of weak hadronic currents and chiral symmetry comprise mainly what is called old particle physics but include some new topics like neutrino oscillations and solar neutrino problem. These Chapters are included to provide necessary background to new particle physics, comprising mainly the standard model as defined above. The rest of the book is devoted to the standard model and the topics mentioned in paras 2-7 of the preface. Recently there has been an interface of particle physics with cosmology, providing not only an understanding of the history of very early universe but also shedding some light on questions such as dark matter and open or closed universe. Chapter 16 of the book is devoted to this interface.

Particle physics forms an essential part of physics curriculum. This book can be used as a text book, but it may also be useful for people working in the field. The book is so designed as to form one semester course for senior undergraduates (with suitable selection of the material) and one semester course for graduate students. Formal quantum field theory is not used; only a knowledge of non-relativistic quantum mechanics is required for some parts of the book. But for the remaining parts, the knowledge of relativistic quantum mechanics is essential. The familiarity with quantum field theory is an advantage and for this purpose two Appendicess which summarize the Feynman rules and renormalization group techniques, are added.

Initial incentive for this book came from the lectures which we have given at various places: Quaid-e-Azam University, Islamabad, Daresbury Nuclear Physics Laboratory (R), the University of Iowa (R), King Fahd University of Petroleum and Minerals, Dhahran (R) and King Abdulaziz University, Jeddah (F).

We have not prepared a bibliography of the original papers underlying the developments discussed in the book. Remedy for this can be found in the recent review articles and books listed at the end of each Chapter.

We wish to express our deep sense of appreciation to Dr. Ahmed Ali for critically reading the manuscript, for making many useful suggestions and for his help to update the data. We also wish to express our deep thanks to a colleague Mr. El hassan El aaud and a graduate student Mr. F. M. Al-Shamali [of one of us (R)], who drew diagrams and in general assisted in producing the final manuscript. In addition, the typing help provided by Mr. Mohammad Junaid at Research Institute of King Fahd University of Petroleum and Minerals was indispensable in getting the job done. Finally we wish to acknowledge the support of King Fahd University of Petroleum and Minerals for this project under Project No. PH/Particle/123.

We also take this opportunity to express our deep sense of gratitude to Prof. Abdus Salam, who first introduced us to this subject and for his encouragement throughout our work in this field.

Fayyazuddin
Riazuddin
March 4, 1992

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