国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

中外物理学精品书系

引进系列·44

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极端相对论性重离子碰撞

（影印版）

〔美〕沃格特（R. Vogt）著

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著作权合同登记号　图字:01-2013-4068
图书在版编目(CIP)数据

极端相对论性重离子碰撞 = Ultrarelativistic heavy-ion collisions:英文/(美)沃格特(Vogt,R.)著.—影印本.—北京:北京大学出版社,2014.8
(中外物理学精品书系)
ISBN 978-7-301-24515-6

Ⅰ.①极…　Ⅱ.①沃…　Ⅲ.①重离子-碰撞(物理)-英文　Ⅳ.①O571.6

中国版本图书馆 CIP 数据核字(2014)第 159249 号

书　　名:**Ultrarelativistic Heavy-Ion Collisions(极端相对论性重离子碰撞)**(影印版)
著作责任者:〔美〕沃格特(R. Vogt)　著
责任编辑:刘　啸
标准书号:ISBN 978-7-301-24515-6/O・0979
出版发行:北京大学出版社
地　　址:北京市海淀区成府路 205 号　100871
网　　址:http://www.pup.cn
新浪微博:@北京大学出版社
电子信箱:zpup@pup.cn
电　　话:邮购部 62752015　发行部 62750672　编辑部 62752038　出版部 62754962
印 刷 者:北京中科印刷有限公司
经 销 者:新华书店
730 毫米×980 毫米　16 开本　30.75 印张　插页 1　586 千字
2014 年 8 月第 1 版　2014 年 8 月第 1 次印刷
定　　价:83.00 元

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
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Ultrarelativistic Heavy-Ion Collisions

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Amsterdam – Boston – Heidelberg – London – New York – Oxford – Paris
San Diego – San Francisco – Singapore – Sydney – Tokyo

Preface

This book is an extension of a course for advanced undergraduate and graduate students that I have taught at the University of California, Davis over the last ten years. It represents an attempt to gather useful information for new practitioners in the field of relativistic heavy-ion collisions in one place. As a resource for students, the text is on a rather basic level of theoretical depth. There is not a strong focus on data because the most recent data from the Relativistic Heavy Ion Collider is in a state of flux and no final conclusions have been drawn.

There are some excellent references that go beyond the scope of this book which can be used for more in-depth studies of theory. Cross sections and perturbative QCD is covered well in Halzen and Martin 'Quarks and Leptons: An Introductory Course in Modern Particle Physics', the CTEQ 'Handbook of Perturbative QCD' and, on a more phenomenological level, Perkins 'Introduction to High Energy Physics'. For more on ultraperipheral collisions, see the reviews by Baur *et al.* and Bertulani *et al.*. The review by Cleymans, Gavai and Suhonen 'Quarks And Gluons At High Temperatures And Densities' was very useful in preparation of the chapters on thermodynamics and hydrodynamics. The book 'Thermal Physics' by Kittel and Kroemer gives a good basic introduction to thermodynamics. The books 'Finite Temperature Field Theory' by Kapusta and 'Introduction to Relativistic Heavy Ion Collisions' by Csernai go further in depth in on these topics. Both Ramond 'Field Theory: A Modern Primer' and Cheng and Li 'Gauge Theory of Elementary Particle Physics' give good discussions of Grassman variables. Cheng and Li also have an excellent discussion of symmetries. A good early book on lattice gauge theory is 'Quarks, Gluons and Lattices' by Creutz. The earlier textbook, 'Introduction to High-Energy Heavy-Ion Collisions' by Wong has an understandable section on lattice gauge theory. For finite temperature on the lattice, there are a number of very good reviews by Karsch and by Gupta.

For a snapshot of the conclusions reached from the early RHIC runs with Au+Au, d+Au and *pp* collisions at 200 GeV in the center of mass, see Volume 757 of Nuclear Physics A containing reviews by all of the first four RHIC experiments. A compendium of new data is available in the proceedings of the Quark Matter conference series, the major meeting in this field.

This book is organized into two parts. The first part covers the basic physics of heavy ion collisions with chapters on kinematics, cross sections, geometry, thermodynamics, hydrodynamics and lattice gauge theory. It includes examples in the text and exercises at the end of each chapter. The second part includes several chapters that are more like extended examples using concepts developed in the first part. The chapters on high mass thermal dileptons and quarkonium cover two high energy probes in some depth. The third discusses fragmentation and hadronization of final state particles in proton-proton collisions.

Finally, I would like to thank my colleagues at UC Davis and the students in the class that have helped make this course better. In particular I would like to mention Daniel Cebra, Mike Anderson and Brooke Haag. Roppon Picha was great help, putting all the equations in my hand-written lecture notes into LaTeX. I would like to thank Frithjof Karsch for discussions about the lattice chapter. I also thank Jean Cleymans, Vesa Ruuskanen and Bengt Friman for discussions on other sections and Joe Kapusta for useful remarks. I thanks Carl Schwarz at Elsevier for originally suggesting that I do this book and enthusiasm about the project. Last but not least I thank Jørgen and Kristina for their patience during the completion of the book.

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Part I

Basics

Chapter 1

Kinematics and invariants

1.1 Introduction

Over the years, nuclear collision energies have increased from beam kinetic energies of a few MeV/nucleon on fixed targets in small university laboratories to, at present, collider energies at large laboratories with international collaborations. As the energy is increased, the relevant degrees of freedom change. At the lowest energies, the nucleus may remain intact or be broken up into light nuclear fragments. As various thresholds for particle production are reached, some of the energy of the system may go into producing new particles, such as pions or kaons. At high enough energies, the relevant degrees of freedom are expected to be quarks and gluons rather than hadrons, forming the quark-gluon plasma.

The modern era of heavy-ion collisions arrived with beam energies of 10-200 GeV/nucleon at fixed-target facilities: the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) and the Super Proton Synchrotron (SPS) at the European Center for Nuclear Research (CERN). Both the AGS and the SPS accelerated protons and several types of ions onto fixed targets of heavy nuclei. While the AGS accelerated silicon, Si, and gold, Au, ions, the SPS provided oxygen, O, sulfur, S, and lead, Pb, beams as well as, more recently, indium, In. Proton-proton (pp) and proton-nucleus (pA) interactions are used as baseline comparison measurements to distinguish true dense matter effects in nucleus-nucleus (AB) collisions from those already present in pp and pA collisions. For gold ions (nuclear mass number, A, of 197), the maximum energy at the BNL AGS was 10 GeV/nucleon while the maximum lead ion ($A = 208$) energy at the CERN SPS was 158 GeV/nucleon. Lower energy ion beams were also used to perform energy scans, down to 2 GeV/nucleon at the AGS and 20 GeV/nucleon at the SPS.

Note that the maximum energy per nucleon of the heaviest ion beam is not as high as the maximum possible proton beam energy, $E_{\rm max}$. The maximum energy for ions is $E_{\rm max}Z/A$ where Z is the proton number (nuclear charge). Protons and lighter ions can be accelerated to higher energies per nucleon, E/A, due to their larger charge-to-mass ratio, Z/A. The Z/A ratio determines the acceleration capability because while the uncharged neutrons are unaffected by the electromagnetic fields, they remain bound in the nucleus. The maximum possible center-of-mass energy for these fixed-target machines is rather low, 4.4 GeV/nucleon for Au+Au collisions at the AGS and 16.8 GeV/nucleon for Pb+Pb collisions at the SPS.

Now, two nuclear colliders take heavy-ion physics to the next level. In a collider, both collision partners, the 'projectile' and 'target' are accelerated, leading to much higher energies than those possible at fixed-target facilities. The Relativistic Heavy-Ion Collider (RHIC) at BNL and the Large Hadron Collider (LHC) at CERN produce Au+Au and Pb+Pb collisions at energies up to 200 GeV/nucleon and 5500 GeV/nucleon respectively in the center of mass. Diagrams of the RHIC and LHC accelerator complexes are shown in Figs. 1.1 and 1.2. These high energies, far above production threshold for most particles, make it possible to study the production of rare particles not accessible at lower energy facilities.

At the RHIC complex, the atoms are stripped of some of their electrons, leaving a positive charge which is accelerated by an electric field in the Tandem van de Graaff. The ions are then sent through a beam line in vacuum at 5% the velocity of light via a magnetic field. Protons are accelerated by the Linac and then sent to the Booster. Both ions and protons are further accelerated by the Booster and then