国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

中外物理学精品书系

引进系列 · 15

The Elementary Process of Bremsstrahlung

韧致辐射基本过程

（影印版）

〔德〕豪格（E. Haug）
〔德〕纳克尔（W. Nakel） 著

北京大学出版社
PEKING UNIVERSITY PRESS

国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

中 外 物 理 学 精 品 书 系

引 进 系 列 · 15

The Elementary Process of Bremsstrahlung

韧致辐射基本过程

（影印版）

〔德〕豪格（E. Haug）
〔德〕纳克尔（W. Nakel） 著

北京大学出版社
PEKING UNIVERSITY PRESS

著作权合同登记号 图字:01-2012-2821
图书在版编目(CIP)数据

The Elementary Process of Bremsstrahlung = 韧致辐射基本过程:英文/(德)豪格(Haug,E.),(德)纳克尔(Nakel,W.)著.—影印本.—北京:北京大学出版社,2012.12

(中外物理学精品书系·引进系列)

ISBN 978-7-301-21937-9

I. ①韧… II. ①豪… ②纳… III. ①韧致辐射-研究-英文 IV. ①O571.43

中国版本图书馆 CIP 数据核字(2013)第 005563 号

书　　名: **The Elementary Process of Bremsstrahlung(韧致辐射基本过程)**(影印版)
著作责任者:〔德〕豪格(E. Haug)　〔德〕纳克尔(W. Nakel)　著
责任编辑:刘　啸
标准书号:ISBN 978-7-301-21937-9/O·0908
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　17.25印张　319千字
　　　　　2012年12月第1版　2012年12月第1次印刷
定　　价:46.00元

《中外物理学精品书系》
编 委 会

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

World Scientific Lecture Notes in Physics – Vol. 73

The Elementary Process of Bremsstrahlung

Eberhard Haug
Institut für Astronomie und Astrophysik
Universität Tübingen, Germany

Werner Nakel
Physikalisches Institut
Universität Tübingen, Germany

World Scientific

NEW JERSEY • LONDON • SINGAPORE • SHANGHAI • HONG KONG • TAIPEI • BANGALORE

Preface

This book is based on a review article about the elementary process of bremsstrahlung [W. Nakel, *Phys. Rep.* **243** (1994) 317]. When the author was encouraged by the editors of World Scientific to expand the review article to a lecture notes volume, he asked a colleague (E.H.) who has been working on the theory of bremsstrahlung, to be the co-author.

The aim of the book is to represent the theoretical and experimental developments in the elementary bremsstrahlung process, i.e., the triply differential cross section, and the status of the comparison and extent of agreement between them. It will be shown how far theory proceeded in the effort to describe the coupling of the radiation field to the electron-atom system. Although the main importance is attached to electron-atom bremsstrahlung, we also discuss electron-electron bremsstrahlung, electron-positron bremsstrahlung, and further bremsstrahlung processes.

The book is mainly addressed to graduate students and is therefore endowed with classical and semiclassical considerations on the bremsstrahlung process and with problems to be solved. But it will also be of interest to physicists who are actively engaged in research since it summarizes and discusses the extensive theoretical work in the original literature. Last but not least, the book is addressed to those readers who may want to get a more general view on this subject since bremsstrahlung is related to the fundamentals of theory and appears in many branches of physics and in technical applications.

The authors are indebted to Prof. H. Ruder, Prof. G.J. Wagner, and Dr. H. Lindel for their support of the work, and to Prof. P. Grabmayr for his valuable help in the preparation of this book. We are very grateful to

Prof. L.C. Maximon for helpful discussions. We wish to thank Dipl.-Phys. E. Gaertig, F. Engeser and U. Vogl for their extensive technical help in getting the manuscript into its final form.

We acknowledge the permission by Elsevier Science to reproduce the following figures from the article which appeared in *Physics Reports* [86]: Figs. 4.1, 4.2, 4.4, 4.5, 4.7 to 4.14, 4.16, 5.6, and 6.1 to 6.6.

Eberhard Haug
Werner Nakel

Universität Tübingen, *September 2003*

Note from the authors

The authors would be grateful if the readers would inform them about any errors which they may find. Corrections for this book which come to the authors' attention will be posted on the World Wide Web at
http://www.pit.physik.uni-tuebingen.de/nakel/nakel_ee.html
but can also be obtained by writing to the authors. The contact e-mail address is nakel@pit.physik.uni-tuebingen.de.

The Elementary Process of Bremsstrahlung

Contents

Chapter 1

Introduction

1.1 General introduction

The emission of a photon in the scattering of an electron from an atom is called bremsstrahlung (braking radiation). Apart from the interest in the nature of the process itself, there are a variety of reasons why the bremsstrahlung process occupies such an important place in physics. Firstly, the process is related to the fundamentals of the theory since it is a consequence of the general coupling of the electromagnetic field and matter fields. Therefore bremsstrahlung appears in nearly all branches of physics: atomic and nuclear, solid-state and elementary-particle physics. Moreover, bremsstrahlung is an important tool in many areas of experimental research, in the field of astrophysics, and it has a wide range of technical applications.

The bremsstrahlung process is generally considered to be well understood. However, the comparisons between experiment and theory have for the most part been made for cases where only the emitted photons are considered, disregarding the decelerated outgoing electrons. Thus the results are necessarily integrated over all electron scattering angles, whereby important features are lost and the check of the theory is not as strong as it could be. When, on the other hand, the bremsstrahlung photons are detected in coincidence with the decelerated electrons scattered into a fixed direction, information on the elementary process of bremsstrahlung can be obtained and a more stringent check of the theoretical work becomes possible.

The quantity measured in the coincidence experiments and calculated by the pertinent theory is the triply differential cross section, differential in photon energy and angle, and in the scattering angle of the outgoing electron. However, the most detailed independently observable quantity is the triply differential cross section including all polarization correlations, corresponding to an electron-photon coincidence experiment with a spin-polarized primary beam and detectors sensitive to polarization of the photons and of the outgoing electrons. Such a complete scattering experiment has not yet been done, but several experiments including single polarization variables were performed, providing benchmarks for comparison with theoretical predictions.

The main force acting by the atom on the incident electron, leading to bremsstrahlung emission, is due to the Coulomb field of the nuclear charge. The effect of the atomic electrons is two-fold: on the one hand, the atomic electrons screen the Coulomb field of the nucleus as a static charge distribution and reduce the cross section for bremsstrahlung emission. The recoil momentum is taken up by the atom as a whole. On the other hand, the atomic electrons act as individual particles and the bremsstrahlung process may also take place in the collision with an atomic electron which then absorbs the recoil momentum and is ejected. This process is called electron-electron bremsstrahlung. With the aid of coincidence experiments it is possible to differentiate exactly between these two components.

The book is organized as follows: Chapter 2 is devoted to classical and semiclassical considerations on the bremsstrahlung process. In four main sections (Chapters 3 to 6) we will deal with the elementary processes of (screened) electron-nucleus bremsstrahlung and of electron-electron bremsstrahlung. We start in Chapter 3 with the discussion of theoretical predictions for relativistic electron-nucleus bremsstrahlung. Electron-photon coincidence experiments on electron-nucleus bremsstrahlung are discussed in Chapter 4. In all the experiments it turned out that there is a strong angular correlation with the photons emitted on the same side relative to the primary beam as the decelerated outgoing electrons (Section 4.2.1). A measured angular distribution of decelerated electrons for fixed photon direction shows a sharp forward peaking (Section 4.2.2).

Only two coincidence experiments were done for electron-nucleus bremsstrahlung including measurements of the polarizational variables. We first discuss measurements of linear polarization of bremsstrahlung emitted by unpolarized electrons (Section 4.3.1). Here the radiation was found to be almost completely polarized with the electric vector in the emission plane. Decreases of the degree of polarization were attributed to spin-flip radiation processes. In Section 4.3.2 we discuss the measurements of the photon emission asymmetry of bremsstrahlung from transversely polarized electrons, where spin-orbit effects are observed which are usually masked in non-coincidence experiments. Even in the case of zero deflection of the decelerated outgoing electrons a non-zero photon emission asymmetry was observed.

Further polarization correlations for which the elementary process has not yet been measured, are discussed in Section 4.3.3. In all experiments no spin analysis of the outgoing electrons is performed to date.

Section 4.4 deals with the application of the coincidence technique in producing quasimonochromatic photon beams, so-called tagged photons.

In Chapters 5 and 6 we investigate the process of electron-electron bremsstrahlung. In contrast to the electron-nucleus system the electron-electron system has no electric dipole moment and the electron-electron bremsstrahlung shows features of quadrupole radiation. The theoretical part starts with the kinematics of the process (Section 5.2). The calculation of the elementary radiation process in free electron-electron collisions is a straightforward application of quantum electrodynamics. However, the cross section becomes extremely complicated due to recoil and exchange effects even in lowest-order perturbation theory (Section 5.3). The radiative collision of a free electron with an initially bound atomic electron is calculated using the impulse approximation (Section 5.4). The electron-photon coincidence technique enables one to differentiate completely between electron-electron and electron-nucleus bremsstrahlung. Experiments without regard to polarization variables (Section 6.1) yield the angular distribution of photons for fixed direction of outgoing electrons (Section 6.1.1) and the energy distribution (Section 6.1.2). A measurement of the photon linear polarization of the elementary process of bremsstrahlung (Section 6.2) is the only polarization measurement on electron-electron bremsstrahlung so far.

We do not discuss in detail the integrated cross sections (doubly differential angular distribution, singly differential energy spectrum, and total energy loss). Only a summary of this subject is given in Chapter 7. In addition, further bremsstrahlung processes are mentioned, such as positron-nucleus bremsstrahlung, electron-positron bremsstrahlung, two-photon bremsstrahlung, polarization bremsstrahlung, coherent bremsstrahlung from crystalline targets, bremsstrahlung from heavier particles, bremsstrahlung in nuclear decays, and bremsstrahlung in magnetic fields.