The Elementary Process of Bremsstrahlung

World Scientific Lecture Notes in Physics

Published

- Vol. 49: Field Theory, Disorder and Simulations
G Parisi
- Vol. 50: The Quark Structure of Matter
M Jacob
- Vol. 51: Selected Topics on the General Properties of Quantum Field Theory
F Strocchi
- Vol. 52: Field Theory: A Path Integral Approach
A Das
- Vol. 53: Introduction to Nonlinear Dynamics for Physicists
H D I Abarbanel, et al.
- Vol. 54: Introduction to the Theory of Spin Glasses and Neural Networks
V Dotsenko
- Vol. 55: Lectures in Particle Physics
D Green
- Vol. 56: Chaos and Gauge Field Theory
T S Biro, et al.
- Vol. 57: Foundations of Quantum Chromodynamics (2nd ed.)
T Muta
- Vol. 59: Lattice Gauge Theories: An Introduction (2nd ed.)
H J Rothe
- Vol. 60: Massive Neutrinos in Physics and Astrophysics
R N Mohapatra and P B Pal
- Vol. 61: Modern Differential Geometry for Physicists (2nd ed.)
C J Isham
- Vol. 62: ITP Lectures on Particle Physics and Field Theory (In 2 Volumes)
M A Shifman
- Vol. 64: Fluctuations and Localization in Mesoscopic Electron Systems
M Janssen
- Vol. 65: Universal Fluctuations: The Phenomenology of Hadronic Matter
R Botet and M Ploszajczak
- Vol. 66: Microcanonical Thermodynamics: Phase Transitions in "Small" Systems
D H E Gross
- Vol. 67: Quantum Scaling in Many-Body Systems
M A Continentino
- Vol. 69: Deparametrization and Path Integral Quantization of Cosmological Models
C Simeone
- Vol. 70: Noise Sustained Patterns
Markus Loecher
- Vol. 73: The Elementary Process of Bremsstrahlung
W. Nakel and E. Haug

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

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: Suite 202, 1060 Main Street, River Edge, NJ 07661

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

THE ELEMENTARY PROCESS OF BREMSSTRAHLUNG

Copyright © 2004 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN 981-238-578-9

Printed in Singapore by World Scientific Printers (S) Pte Ltd

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.

Contents

Preface	v
Chapter 1. Introduction	1
1.1 General introduction	1
1.2 Short historical note	4
1.3 Notations and definitions	5
Chapter 2. Classical and semiclassical considerations on the bremsstrahlung process	9
2.1 Electron-nucleus bremsstrahlung	9
2.1.1 Screening effects	16
2.1.2 Bremsstrahlung linear polarization	18
2.1.3 Bremsstrahlung from transversely polarized electrons .	22
2.2 Electron-electron bremsstrahlung	23
2.3 Weizsäcker-Williams method of virtual quanta	26
Chapter 3. Theory of the elementary process of electron- nucleus bremsstrahlung	27
3.1 Introduction	27
3.2 Bremsstrahlung cross section	28
3.3 Born approximation (Bethe-Heitler formula)	32
3.3.1 Atomic screening	47
3.3.2 Nuclear recoil effects	50
3.3.3 Effects of nuclear structure	51
3.4 Approximations with the Sommerfeld-Maue wave function . . .	55

3.4.1	Sommerfeld-Maue wave function	55
3.4.2	Spin formalism	61
3.4.3	Cross section	63
3.4.4	Nonrelativistic approximation	71
3.4.5	The short-wavelength limit	72
3.4.6	Approximation for the long-wavelength limit and for high electron energies	74
3.4.7	Cross section in second Born approximation	76
3.5	Calculation using relativistic partial-wave expansions	79
3.5.1	Partial wave expansion	79
3.5.2	Calculations with a relativistic self-consistent-field potential	89
3.5.3	Calculation for a pure Coulomb potential	93
3.6	Spin-dependent cross section and bremsstrahlung asymmetry .	97
3.7	Bremsstrahlung polarization	104
3.7.1	General polarization correlation	104
3.7.2	Linear polarization in Born approximation	108
3.7.3	Circular polarization from polarized electrons in Born approximation	112
3.8	Radiative corrections to bremsstrahlung	115
Chapter 4. Experiments on the elementary process of electron-nucleus bremsstrahlung		119
4.1	Survey of experimental devices	119
4.2	Electron-photon coincidence experiments without regard to polarization variables	121
4.2.1	Angular distributions of photons for fixed directions of outgoing electrons	121
4.2.2	Angular distributions of electrons for fixed photon directions	123
4.2.3	Energy distributions for fixed electron and photon directions	125
4.2.4	Wide-angle bremsstrahlung experiments at very high energies	127
4.3	Electron-photon coincidence experiments including polarization variables	128
4.3.1	Linear polarization of bremsstrahlung emitted by unpolarized electrons	128

4.3.2	Photon emission asymmetry of bremsstrahlung from transversely polarized electrons	136
4.3.3	Further polarization correlations	141
4.4	Tagged photons	143

Chapter 5. Theory of the elementary process of electron-electron bremsstrahlung 147

5.1	Introduction	147
5.2	Kinematics	148
5.2.1	Center-of-mass system	151
5.2.2	Laboratory system	152
5.3	Cross section	157
5.3.1	Laboratory system	161
5.3.2	Center-of-mass system	162
5.3.3	Center-of-mass system of the outgoing electrons	162
5.4	Bremsstrahlung in the field of bound electrons	165

Chapter 6. Experiments on the elementary process of electron-electron bremsstrahlung 175

6.1	Electron-photon coincidence experiments without regard to polarization variables	175
6.1.1	Angular distribution of photons for fixed electron direction	176
6.1.2	Energy distributions	178
6.2	Electron-photon coincidence experiments including polarization variables	182
6.2.1	Linear polarization of electron-electron bremsstrahlung emitted by unpolarized electrons	182
6.2.2	Further polarization correlations	185

Chapter 7. Some remarks on integrated cross sections and further bremsstrahlung processes 187

7.1	Integrated cross sections	187
7.2	Positron-nucleus bremsstrahlung	190
7.3	Electron-positron bremsstrahlung	192
7.4	Two-photon bremsstrahlung	196
7.5	Polarization bremsstrahlung	203
7.6	Crystalline targets: coherent bremsstrahlung	206

7.7 Bremsstrahlung from heavy particles 206

7.8 Bremsstrahlung in nuclear decays 207

 7.8.1 Bremsstrahlung in β decay 207

 7.8.2 Bremsstrahlung in orbital-electron capture 207

 7.8.3 Bremsstrahlung in α decay 207

7.9 Bremsstrahlung in magnetic fields 208

 7.9.1 Electron-nucleus bremsstrahlung in strong magnetic
 fields 208

 7.9.2 Synchrotron radiation (magnetobremsstrahlung) 210

7.10 Stimulated bremsstrahlung 210

Conclusion 211

Appendix A Problems 213

**Appendix B Squared matrix element of electron-electron
 bremsstrahlung 241**

Bibliography 249

Index 257