国家出版基金项目
NATIONAL PUBLICATION FOUNDATION

中外物理学精品书系

引进系列 · 29

Introduction to Plasma Spectroscopy

等离子体光谱学导论

（影印版）

〔德〕孔策（H.-J. Kunze）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 · 29

Introduction to Plasma Spectroscopy

等离子体光谱学导论

(影印版)

〔德〕孔策（H.-J. Kunze）著

北京大学出版社
PEKING UNIVERSITY PRESS

著作权合同登记号　图字:01-2012-8659
图书在版编目(CIP)数据

等离子体光谱学导论 = Introduction to plasma spectroscopy:英文/(德)孔策(Kunze,H.-J.)著.—影印本.—北京:北京大学出版社,2013.7
(中外物理学精品书系・引进系列)
ISBN 978-7-301-22689-6

Ⅰ.①等…　Ⅱ.①孔…　Ⅲ.①等离子体诊断-光谱学-英文　Ⅳ.①O536

中国版本图书馆 CIP 数据核字(2013)第 137051 号

Reprint from English language edition:
Introduction to Plasma Spectroscopy
By Hans-Joachim Kunze

书　　　名:Introduction to Plasma Spectroscopy(等离子体光谱学导论)(影印版)
著作责任者:〔德〕孔策(H.-J. Kunze)　著
责 任 编 辑:刘　啸
标 准 书 号:ISBN 978-7-301-22689-6/O・0930
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
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　16.25 印张　插页 1　310 千字
2013 年 7 月第 1 版　2013 年 7 月第 1 次印刷
定　　　价:44.00 元

中外物理学精品书系

本书出版得到“国家出版基金”资助

“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

Hans-Joachim Kunze

Introduction to Plasma Spectroscopy

With 87 Figures

Springer

To Regina, Stefanie and Martina

Preface

This book is based on lectures given at the Ruhr-University of Bochum for graduate and postgraduates students starting their studies on plasma physics, but it is as well directed at established researchers who are newcomers to spectroscopy and need quick access to the diagnostics of plasmas ranging from low to high density technical systems at low temperatures as well from low to high density hot plasmas. Basic ideas and fundamental concepts are briefly introduced as is typical instrumentation from the X-ray to the infrared spectral regions. Examples, techniques, and methods illustrate the possibilities. The list of cited references is certainly not complete. Preference is given to either more recent publications since they usually refer to previous work or to reviews. I am grateful to Hans R. Griem and Andreas Dinklage for reading the manuscript and suggestions for improvement.

Bochum,
July 2009

Hans-Joachim Kunze

There is no lift to success,
you have to climb the stairs.
Emil Oesch

Contents

1

Introduction

Spectroscopic methods offer a large variety of possibilities to diagnose plasmas in the laboratory and in space, the apparatus required being one of the least complicated in many cases. Astronomical objects are the sun, the stars, and the interstellar matter. Plasmas in the laboratory range at low temperatures from low-density plasmas as nowadays mostly used for plasma processing to high density arcs and plasma torches at atmospheric pressure; at high temperatures pulsed but long-lived low density plasmas in magnetically confined fusion devices such as tokamaks and stellarators are at one end, short-lived inertially confined pellets having densities up to 100 times solid-state density represent the other end.

Specifically we talk of plasma *emission* spectroscopy if electromagnetic radiation emitted by the plasma is recorded, spectrally resolved, analyzed and interpreted in terms of either parameters of the plasma or characteristic parameters of the radiating atoms, ions or molecules. It is the most straightforward approach since only one port in otherwise closed systems is needed for radiation to escape. An inherent drawback is certainly the fact that the radiation detected and hence all information obtainable is integrated along the line of sight. This also holds for the supplementary approach of *absorption* spectroscopy. There radiation – in the most general case continuum radiation – is directed through the plasma, and the modification of the spectrum of the transmitted radiation by absorption and also by scattering contains the information on the plasma and its constituents. The application of fixed wavelength and tunable lasers as radiation sources utilizing both absorption and various scattering processes in the plasma is widespread and has developed into a field of its own described as laser spectroscopy. It is not a subject of this book and we refer to the relevant literature, for example to [1], or specifically with respect to the diagnostics of plasmas to [2]. Scattering by plasma electrons known as incoherent and collective Thomson scattering, one of the most powerful plasma diagnostic techniques [3–6] is also only mentioned here.

Most spectroscopic methods utilize the radiation emitted by atoms, ions, or molecules being present in the specific plasma either as impurities or being

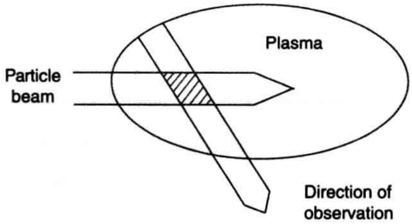

Fig. 1.1. Injection of a particle beam into a plasma

intentionally added to the plasma for specific purposes such as radiation cooling or diagnostics. In recent years, the injection of atomic beams has been advanced: they enter the plasma more or less on a straight path till they are ionized. As Fig. 1.1 reveals, observation of the emission from the beam particles now yields *local* information from the hatched region, background radiation naturally still being collected along the line of sight.

The present monograph intends to give an introduction to plasma spectroscopy, and the two books by Griem [7, 8] remain the standard references for this field. The monograph by Fujimoto [9] emphasizes the theoretical framework for the population density distribution in plasmas. For a general introduction to spectroscopic principles and techniques, the monograph [10] may be consulted. Spectroscopic methods are also discussed in books on plasmas diagnostics [11, 12].

Spectral Regions

With increasing temperature of a plasma the maximum of the continuum radiation and the strong lines emitted occur at shorter wavelengths, and typically plasma spectroscopy has to cover the spectral range from the infra-red down to X-rays. Although the physical concepts underlying the emission of radiation are more or less the same over this spectral range, different experimental techniques have to be employed, resulting in a corresponding partition into several spectral ranges.

380–750 nm is the visible. This spectral region is well defined by the sensitivity curve of the eye. Radiation is transmitted through air with practically no losses; this also holds for the adjacent regions toward shorter and longer wavelengths. The *infra-red* IR extends from the *near infra-red* to the *far infra-red* FIR adjacent to the microwave region, which starts around wavelengths of 1 mm, but transmission through air can be influenced by absorption within molecular bands of water vapor, carbon dioxide and other molecular constituents or pollutants. In addition, absorption by windows has to be considered, which also occurs when going to wavelengths below the visible. Flint glass, for example, starts to absorb already around 380 nm, and for shorter wavelengths windows of quartz are advised; ordinary quartz cuts off at around 210 nm, but best quartz is satisfactory down to just below 180 nm. The spectral range 200–380 nm is known as the *ultraviolet* UV.

Below 200 nm electromagnetic radiation is absorbed by air, first by oxygen starting at around 195 nm and then by nitrogen at 145 nm, and transmission through air occurs again only below 0.15 nm, where 30% of the radiation starts to be transmitted through 1 m of air at atmospheric pressure. To avoid this absorption in air, the spectrographic system and path of the radiation from the plasma have to be evacuated. For that reason, the spectral range 200–0.15 nm has been named the *vacuum-ultraviolet or vacuum-UV* VUV. Traditionally, this range is subdivided according to the optics which has to be employed. *Vacuum–UV* is thus specifically used for the range 200–105 nm, where transparent window materials (LiF cuts off at 105 nm) and hence also lens optics exist.

The range 105–0.15 nm is customarily named *extreme-ultraviolet* EUV or XUV, and it includes *the soft X-rays* from 30 to 0.15 nm.

Below 0.15 nm the region of the *hard X-rays* starts, where it is more practical to use the photon-energy unit in kilo electron volts instead of the wavelength. Hard x-rays overlap with the broad range of γ*-rays* from about 10 keV to 250 MeV; γ-quanta are typically emitted by nuclei.

Spectroscopic Units

The electromagnetic radiation flux from a surface element plotted as function of frequency ν or wavelength λ is known as *spectrum*. Both are related to each other by

$$\lambda_{\text{vac}} = c/\nu \,, \tag{1.1}$$

where c and λ_{vac} are velocity of light and wavelength in vacuum, respectively, and ν is in Hertz ($1\,\text{Hz} = 1\,\text{s}^{-1}$). The most common wavelength units are the nanometer (nm), the Ångström ($1\,\text{Å} = 10^{-1}\,\text{nm}$) and the micrometer (µm). The wavenumber σ defined by

$$\sigma = 1/\lambda_{\text{vac}} = \nu/c \tag{1.2}$$

is more commonly used at long wavelengths, especially when dealing with molecular transitions. Its unit is the inverse meter, but in practice wavenumbers are usually expressed in inverse centimeters (cm^{-1}). This unit has been named Kayser (K), $1\,\text{K} = 1\,\text{cm}^{-1}$.

At short wavelengths the photon energy $E = h\nu$ is preferred in the unit electron volt (eV). Wavelength in vacuum – we omit the subscript "vacuum" from hereon – and energy are thus related by

$$\frac{h\nu}{\text{eV}}\,\frac{\lambda_{\text{vac}}}{\text{nm}} = 1239.842 \,. \tag{1.3}$$