

Springer Series on

Atoms+Plasmas

18

Editor: I.I. Sobel'man

Springer-Verlag Berlin Heidelberg GmbH

Springer Series on

Atoms+Plasmas

Editors: G. Ecker P. Lambropoulos I.I. Sobel'man H. Walther

Managing Editor: H.K.V. Lotsch

- 1 **Polarized Electrons**
2nd Edition
By J. Kessler
- 2 **Multiphoton Processes**
Editors: P. Lambropoulos and S.J. Smith
- 3 **Atomic Many-Body Theory**
2nd Edition
By I. Lindgren and J. Morrison
- 4 **Elementary Processes in Hydrogen-Helium Plasmas**
Cross Sections and Reaction Rate Coefficients
By R.K. Janev, W.D. Langer, K. Evans, Jr. and D.E. Post, Jr.
- 5 **Pulsed Electrical Discharge in Vacuum**
By G.A. Mesyats and D.I. Proskurovsky
- 6 **Atomic and Molecular Spectroscopy** 2nd Edition
Basic Aspects and Practical Applications
By S. Svanberg
- 7 **Interference of Atomic States**
By E.B. Alexandrov, M.P. Chaika and G.I. Khvostenko
- 8 **Plasma Physics** 2nd Edition
Basic Theory with Fusion Applications
By K. Nishikawa and M. Wakatani
- 9 **Plasma Spectroscopy**
The Influence of Microwave and Laser Fields
By E. Oks
- 10 **Film Deposition by Plasma Techniques**
By M. Konuma
- 11 **Resonance Phenomena in Electron-Atom Collisions**
By V.I. Lengyel, V.T. Navrotsky and E.P. Sabad
- 12 **Atomic Spectra and Radiative Transitions** 2nd Edition
By I.I. Sobel'man
- 13 **Multiphoton Processes in Atoms**
By N.B. Delone and V.P. Krainov
- 14 **Atoms in Plasmas**
By V.S. Lisitsa
- 15 **Excitation of Atoms and Broadening of Spectral Lines**
By I.I. Sobel'man, L. Vainshtein and E. Yukov
- 16 **Reference Data on Multicharged Ions**
By V.G. Pal'chikov and V. Shevelko
- 17 **Lectures on Non-linear Plasma Kinetics**
By V.N. Tsytovich
- 18 **Atoms and Their Spectroscopic Properties**
By V.P. Shevelko

V.P. Shevelko

Atoms and Their Spectroscopic Properties

With 69 Figures and 74 Tables



Springer

Dr. Viatcheslav P. Shevelko
P.N. Lebedev Physics Institute
Optical Division
Russian Academy of Sciences
117924 Moscow, Russia

Series Editors:

Professor Dr. Günter Ecker
Ruhr-Universität Bochum, Fakultät für Physik und Astronomie,
Lehrstuhl für Theoretische Physik I, Universitätsstrasse 150, D-44801 Bochum, Germany

Professor Peter Lambropoulos, Ph.D.
Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany, and
Foundation for Research and Technology – Hellas (F.O.R.T.H.),
Institute of Electronic Structure & Laser (IESL),
University of Crete, PO Box 1527, Heraklion, Crete 71110, Greece

Professor Igor I. Sobel'man
Lebedev Physics Institute, Optical Division, Russian Academy of Sciences,
Leninsky Prospekt 53, 117924 Moscow, Russia

Professor Dr. Herbert Walther
Sektion Physik der Universität München, Am Coulombwall 1,
D-85748 Garching/München, Germany

Managing Editor: **Dr.-Ing. Helmut K.V. Lotsch**
Springer-Verlag, Tiergartenstrasse 17, D-69121 Heidelberg, Germany

ISSN 0177-6495

ISBN 978-3-642-08274-0

CIP-data applied for

Die Deutsche Bibliothek – CIP-Einheitsaufnahme
Sevelko, Vjačeslav P.:
Atoms and their spectroscopic properties: with 74 tables/V.
P. Shevelko.

(Springer series on atoms + plasmas; 18)

ISBN 978-3-642-08274-0 ISBN 978-3-662-03434-7 (eBook)

DOI 10.1007/978-3-662-03434-7

NE: GT

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag Berlin Heidelberg GmbH. Violations are liable for prosecution under the German Copyright Law.

© Springer-Verlag Berlin Heidelberg 1997.

Originally published by Springer-Verlag Berlin Heidelberg New York in 1997

Softcover reprint of the hardcover 1st edition 1997

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Design & Production GmbH, Heidelberg
Typesetting: Asco Trade Typesetting Ltd., Hong Kong

SPIN: 10009991

54/3144/SPS – 5 4 3 2 1 0 – Printed on acid-free paper

Preface

Atomic spectroscopy and the physics of atomic collisions have many applications in investigation of confined plasmas, thermonuclear fusion, laser-produced plasmas, the upper planetary atmosphere, plasma diagnostics, and many others.

The aim of this reference book is to give brief information on atomic radiative characteristics and elementary processes occurring in astrophysical and laboratory plasmas. These topics include energy levels, transition probabilities, oscillator strengths, electric multipole polarizabilities, photoionization, excitation, ionization and charge transfer cross sections.

This monograph deals mainly with the interaction of neutral atoms with photons, electrons and ions. Some elementary atomic processes involving negative and positive ions are discussed.

The book can be conditionally divided into two main parts. The first one contains information on the energy-level transition probabilities, atomic polarizabilities, fine and hyperfine structure, angular momenta coupling schemes and selection rules. The second part comprises data on collisional characteristics such as cross sections and the corresponding Maxwellian rate coefficients for different elementary processes: photoionization, excitation, single and multi-electron ionization and electron capture. In the last chapter, recent data on collisions involving H^- ions are considered.

The monograph does not contain a detailed description of complicated theoretical approaches and formulas. It presents data in a dense form using figures, tables and simple analytical formulas, which allows one to estimate the atomic characteristics without resorting to computers. This may be of a special interest to experimentalists working in some fields of atomic physics. As well as the pure atomic data, a brief physical background of specific problems is presented.

I am very grateful to Professor H.-J. Kluge (Gesellschaft für Schwerionenforschung, Darmstadt, Germany) and Professor Hiro Tawara (National Institute for Fusion Science, Nagoya, Japan) for their hospitality during my stays at GSI (October 1994 to February 1995) and NIFS (March 1995 to August 1995), where the major part of this book was written.

It is a great pleasure to thank my colleagues for their help during the writing of this book, especially I.L. Beigman, H.F. Beyer, B.N. Chichkov, V.S. Lebedev, V.G. Pal'chikov, L.P. Presnyakov, E. Salzborn, I.Yu. Tolstikhina, O.I. Tolstikhin, D.B. Uskov, L.A. Vainshtein and E.A. Yukov.

Special thanks are addressed to M.A. Evteeva and N.V. Kozulina for expertly typing the manuscript and to T.A. Shergina for preparing the figures.

Moscow-Darmstadt-Nagoya
June 1996

V.P. Shevelko

Contents

Introduction	1
1 Atomic Structure and Spectra	3
1.1 Classification of Spectral Lines	3
1.1.1 Notations	3
1.1.2 Spectral Series of Hydrogen Atom	4
1.1.3 Spectra of Alkali Elements	6
1.2 Coupling Schemes	7
1.3 Ionization Potentials and Binding Energies	9
1.4 Electron Affinity	14
1.5 Fine and Hyperfine Structure	14
1.6 Isotope Shift	18
1.7 Lamb Shift	27
1.8 Radial Analytical Wave Functions	33
1.8.1 Hydrogen-like Wave Functions	33
1.8.2 The Slater Wave Functions and Potential	37
1.8.3 Bates-Damgaard Approximation	39
2 Oscillator Strengths and Transition Probabilities	40
2.1 Basic Relations	40
2.2 Selection Rules	41
2.3 Oscillator Strengths and Transition Probabilities	44
2.3.1 Three Representations of the Oscillator Strength. Sum Rules	44
2.3.2 Recommended Data for Wavelengths, Energy Levels and Transition Probabilities	45
2.3.3 Tables for f and W in H, He and Light Atoms	48
2.3.4 Oscillator Strengths in Alkali Atoms	51
2.4 Lifetimes of Excited States	52
2.5 Autoionizing States	61
2.6 Asymptotic Formulas	70
2.6.1 Quasiclassical Formulas	70
2.6.2 Bates-Damgaard Tables for Dipole and Quadrupole Matrix Elements	71
2.7 Angular Coefficients	84
2.7.1 LS -coupling	84

2.7.2 <i>jl</i> -coupling	88
2.7.3 Arbitrary Coupling	89
3 Radiative Characteristics	90
3.1 Photoionization and Radiative Recombination	90
3.2 The Kramers Formulas and the Gaunt Factor	101
3.3 Polarizabilities	104
3.3.1 Dipole Polarizability. Basic Relations	105
3.3.2 Static Dipole Polarizabilities of Atoms and Ions	108
3.3.3 Multipole Static Polarizabilities. Boundary Radii	108
3.4 Bremsstrahlung	116
3.4.1 Basic Formulas	117
4 Electron–Atom Collisions	120
4.1 Excitation	120
4.1.1 Basic Relations	120
4.1.2 Transitions in Hydrogen	122
4.1.3 Transitions in Helium	122
4.1.4 Dipole Transitions. Model Potentials	126
4.1.5 Transitions Between Rydberg States	135
4.1.6 Intercombination Transitions	137
4.2 Single Ionization	141
4.2.1 General Properties	142
4.2.2 Approximation Formulas	146
4.2.3 Fitting Parameters for H-like Ions. High-Energy Behavior	149
4.3 Multiple Ionization	153
5 Ion–Atom Collisions	161
5.1 Excitation	161
5.2 Ionization	166
5.2.1 Single Ionization	166
5.2.2 Double Ionization of He	168
5.2.3 Multiple Ionization	170
5.3 Electron Capture	173
5.4 Collisions Involving H ⁻ ions	181
5.4.1 H ⁺ + H ⁻ Collisions	182
5.4.2 H ⁻ + H ⁻ Collisions	183
5.4.3 Collisions of H ⁻ with Multicharged Ions	184
References	189
Subject Index	200

Glossary of Terms

Units

The system of atomic units (a.u.) is used: $e^2 = m = \hbar = 1$.

Length (Bohr radius)	$a_0 = 0.529\ 177\ 249(24) \times 10^{-8}$ cm
Energy	$E_0 = e^2/a_0 = 27.211\ 3961(81)$ eV = 2Ry
Rydberg	1 Ry = $me^4/2\hbar^2 = 13.605\ 6981(40)$ eV = $109\ 737.315\ 34(13)$ cm ⁻¹
Time	$\tau_0 = \hbar^3/me^4 = a_0/v_0$ = $2.418\ 88433(11) \times 10^{-17}$ s
Velocity	$v_0 = e^2\hbar = 2.187\ 691\ 417(98) \times 10^8$ cm/s
Cross section	$\pi a_0^2 = 0.879\ 735\ 6696(80) \times 10^{-16}$ cm ²
Fine-structure constant	$\alpha = e^2/\hbar c = 1/137.035\ 9895(61)$
Velocity of light	$c = 1/\alpha = 137.035\ 9895(61)$ a.u. = $2.997\ 92458 \times 10^{10}$ cm/s

The values of the fundamental physical constants are given in a report of the CODATA Task Group on Fundamental Constants, CODATA Bulletin No. 63, E.R. Cohen, B.N. Taylor: Rev. Mod. Phys. **59**, 1121 (1987).

List of Symbols

<i>A</i>	Autoionization transition probability
[<i>A</i>]	Ions of the isoelectronic sequence of an atom A or A-like ions
<i>E</i>	Incident particle energy
<i>E_{cm}</i>	Center-of-mass energy
<i>Eχ</i>	Electric 2 ^{χ} -pole transition
<i>f</i>	Oscillator strength
<i>I</i>	Binding energy; ionization potential
<i>l</i>	Orbital quantum number
<i>M</i>	Nuclear mass
<i>Mχ</i>	Magnetic 2 ^{χ} -pole transition
<i>m</i>	Electron mass
<i>N</i>	Total number of atomic electrons
<i>n</i>	Principal quantum number
<i>q</i>	Number of equivalent electrons

X Glossary of Terms

T	Electron or ion temperature
v	Relative velocity
$\langle v\sigma \rangle$	Maxwellian rate coefficient
X_z	Ion with a charge $z - 1$: $X_z = X^{(z-1)+}$
W	Radiative transition probability
Z	Nuclear charge
z	Spectroscopic symbol: $z = Z - N + 1$
β_x	Electric 2^x -pole polarizability
ΔE	Transition energy, energy shift
γ	Hyperpolarizability
κ	Multiplicity
κ_r	Radiative recombination rate coefficient
λ	Wavelength
μ	Reduced mass
σ	Cross section
σ_+	Net (gross) ionization cross section

Special mathematical functions used in the book can be found in *Handbook of Mathematical Functions*, ed. by N. Abramowitz, I.A. Stegun (Constable, London 1970).