CRC Handbook of Laser Science and Technology

Volume II
Gas Lasers

Editor

Marvin J. Weber, Ph.D.

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CRC Press, Inc.
Boca Raton, Florida

Library of Congress Cataloging in Publication Data

Main entry under title:

Gas Lasers.

(Handbook of laser science and technology;
v. 2)
Bibliography: p.
Includes index.
1. Gas lasers. I. Weber, Marvin J.,
1932- . II. Series.
TA1695.G34 621.36'63 81-17087
ISBN 0-8493-3502-7 AACR2

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Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida, 33431.

International Standard Book Number 0-8493-3502-7

Library of Congress Card Number 81-17087
Printed in the United States

PREFACE

In the ten years since the publication of the *CRC Handbook of Lasers with Selected Data on Optical Technology,* the growth in the number and diversity of lasers and their applications has continued at a rapid pace. These developments have prompted an update and expansion of the original volume into the *CRC HANDBOOK SERIES OF LASER SCIENCE AND TECHNOLOGY.* The first two volumes of the series are devoted to lasers in all media. Later volumes are planned on optical materials and on laser instrumentation and operating techniques.

The object of this series is to provide a readily accessible and concise source of data in tabular and graphical form for workers in the areas of laser research and development. Volumes I and II contain extensive tables of experimental data on lasers and complete references to the original work. This is the primary emphasis. Many books and review articles describing the physics and operation of various lasers already exist. Therefore textual material is in general only that required to explain the data, to summarize the general operation and characteristics of each type of laser, and to describe important specific lasers or properties not covered elsewhere.

Of the various lasing media, gases contribute the largest number of laser transitions. This volume is devoted exclusively to gas lasers; other lasers and masers are covered in Volume I of this series. The coverage is divided into neutral atom, ion, and molecular lasers. The last group is further subdivided by whether the transition is between electronic, vibrational, or rotational states. A list of gas lasers arranged in order of wavelength is also provided.

It is a pleasure to acknowledge the efforts and cooperation of the contributors to this volume. Several chapters cover a vast body of data and required prodigious efforts to complete. The table of gas laser wavelengths was prepared with the assistance of Ann Weber and Eve Weber. The numerous suggestions and guidance of the Advisory Board throughout the preparation of this volume are greatly appreciated. Dr. Dean Hodges assisted with the initial arrangements for the preparation of the chapter on far-infrared lasers. Again, I wish to thank Marsha Baker and Pamela Woodcock of the CRC Press for their help and technical expertise in the editing of the series.

Marvin J. Weber
Danville, California
February, 1981

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In 1973, Dr. Weber joined the Laser Program of the Lawrence Livermore National Laboratory. His activities have included studies of the physics, characterization, and development of optical materials for high power lasers Dr. Weber has published numerous research papers and review articles in the areas of lasers, luminescence, optical spectroscopy, and magnetic resonance in solids and holds several patents on solid-state laser materials.

Dr. Weber is a Fellow of the American Physical Society and a member of the Optical Society of America and the American Ceramics Society. He has served as a consultant for the Division of Materials Research, National Science Foundation, and is a member of the Advisory Editorial Board of the *Journal of Non-Crystalline Solids.*

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Section 1
Neutral Gas Lasers

1. NEUTRAL GAS LASERS

Christopher C. Davis

INTRODUCTION

Since the first report of laser action in a gas discharge in a He-Ne mixture by Javan et al.[468] in 1961, oscillation in the neutral spectra of 50 elements on over 730 identified transitions has been reported. More than 90 additional, unidentified laser lines appear likely to originate from neutral species. Figure 1.1 shows that with the exception of Groups IIIB, IVB, VIB, and the actinides, laser action has been observed in all groups of the periodic table. The development of innovative pumping schemes has helped considerably in adding 21 elements to the list of neutral gas lasers in the last decade.

TABLES OF NEUTRAL LASER TRANSITIONS

Tables 1.1.1 to 1.10.1, which follow, contain details of all the identified neutral gas laser transitions and unidentified probable neutral gas laser transitions which have been reported in the literature, to our knowledge, through early 1980. Laser transitions are arranged according to groups, in order of increasing atomic number. Wavelengths of lines *in vacuo* are given in italics.

Unless stated otherwise, and with the exception of the lanthanides, identified transitions are assigned and their calculated wavelengths, *in vacuo*, given in accordance with energy level data given by Charlotte E. Moore in "Atomic Energy Levels," Volumes I, II, and III (1949, 1952, and 1958), National Bureau of Standards (NBS), National Standard Reference Data Series, NSRDS-NBS 34, reissued 1971, (originally issued as NBS Circ. 467) U.S. Government Printing Office, Washington, D.C. 20402. Calculated wavelengths and spectral assignments for the lanthanides are taken from Martin, Zalubas, and Hagan, "Atomic Energy Levels" — The Rare-Earth Elements, NSRDS-NBS 60, 1978. However, wherever possible the latest spectroscopic literature concerning each element that postdates "Atomic Energy Levels" has been consulted. In these cases, accurately measured values of the wavelengths in air of laser transitions observed in spontaneous emission are given in the table whenever possible, together with currently accepted transition assignments. Since most modern energy level data appears to be accurate to $\lesssim 10^{-3}$ cm^{-1}, several significant digits have been retained in calculated, *in vacuo*, wavelengths. The interested reader can easily convert these figures to air values by the use of Table of Wavenumbers[582] or by direct computation from Edlen's refractive index formula.[582]

The reference underlined for each laser transition is the reference in which oscillation was first reported. Additional references are not intended to be exhaustive, but represent selected important work both on the laser system itself and also frequently on the physical processes occurring within it. Substantial numbers of literature references are listed for those laser transitions of greatest practical importance. Typical conditions under which laser action has been obtained for each transition are given. If several significantly different pumping conditions exist, these are included. However, the implication that laser action occurs only under the specific conditions indicated is not intended. For further details, the interested reader should consult the individual references. A reference number indicated with (E) contains an incorrect wavelength and/or transition assignment.

Large numbers of the transitions listed have sufficiently high gain that they will

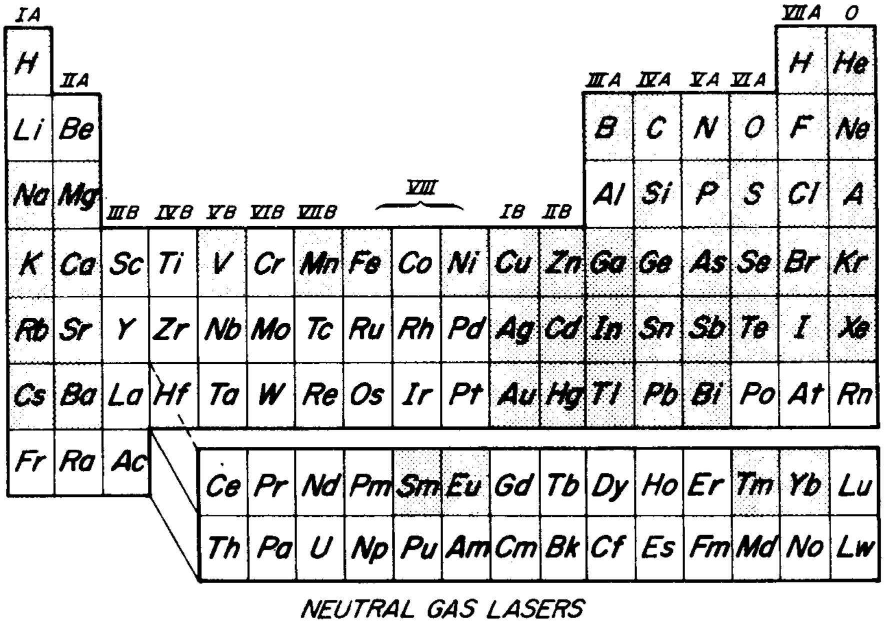


FIGURE 1.1. Periodic table of the elements showing those elements (shaded) in which laser oscillation in the neutral species has been reported.

generate coherent, directional laser output with only a single cavity reflector or with none at all. Lines which operate in this fashion generally amplify their own spontaneous emission up to the saturation intensity in a single pass. These lines which operate in an amplified spontaneous emission (ASE) mode[639-643] are designated as such to distinguish them from those few transitions which exhibit true cooperative emission (superfluorescence).

The tables of neutral gas laser transitions are arranged as follows:

GROUP IA

Table	Element
1.1.1	Hydrogen (3)
1.1.2	Sodium (4)
1.1.3	Potassium (15)
1.1.4	Rubidium (13)
1.1.5	Cesium (19)

GROUP IB

Table	Element
1.1.6	Copper (5)
1.1.7	Silver (2)
1.1.8	Gold (2)

GROUP IIA

Table	Element
1.2.1	Magnesium (6)
1.2.2	Calcium (4)
1.2.3	Strontium (4)
1.2.4	Barium (21)

GROUP IIB

Table	Element
1.2.5	Zinc (2)
1.2.6	Cadmium (17)
1.2.7	Mercury (31)

GROUP IIIA

Table	Element
1.3.1	Boron (1)
1.3.2	Gallium (5)
1.3.3	Indium (6)
1.3.4	Thallium (5)

GROUP IVA

Table	Element
1.4.1	Carbon (11)
1.4.2	Silicon (3)
1.4.3	Germanium (2)
1.4.4	Tin (4)
1.4.5	Lead (10)

GROUP VA and VB

Table	Element
1.5.1	Nitrogen (23)
1.5.2	Phosphorus (10)
1.5.3	Arsenic (15)
1.5.4	Antimony (1)
1.5.5	Bismuth (2)
1.5.6	Vanadium (2)

GROUP VIA

Table	Element
1.6.1	Oxygen (14)
1.6.2	Sulfur (9)
1.6.3	Selenium (3)
1.6.4	Tellurium (6)
1.6.5	Thulium (14)

GROUP VIIIA and VIIB

Table	Element
(See 1.1.1)	Hydrogen
1.7.1	Fluorine (18)
1.7.2	Chlorine (10)
1.7.3	Bromine (5)
1.7.4	Iodine (19)
1.7.5	Ytterbium (10)
1.7.6	Manganese (12)

GROUP VIII

Table	Element
1.8.1	Iron (7)
1.8.2	Nickel (2)
1.8.3	Samarium (8)
1.8.4	Europium (16)

GROUP 0

Table	Element
1.9.1	Helium (11)
1.9.2	Neon (200)
1.9.3	Argon (68)
1.9.4	Krypton (46)
1.9.5	Xenon (58)

Table 1.10.1
Miscellaneous and unidentified possible neutral laser transitions (45)

Note: Figures in parentheses indicate the number of laser lines in each table.

1.1A GROUP IA

Table 1.1.1
HYDROGEN[a] (FIGURE 1.2)

Wavelength (μm)	Transition assignment	Comments	Ref.
0.434046	5 → 2 (H-γ line, Balmer series)	As an impurity in a pulsed discharge in Ne at 1.5 torr; D = 25 mm; E/p = 140 V/cm torr	1
0.486132	4 → 2 (H-β line, Balmer series)	As an impurity in a pulsed discharge in Ne at 1.5 torr; D = 25 mm; E/p = 140 V/cm torr	1
1.87510	$4f\,^2F^o_{7/2} \rightarrow 3d\,^2D_{5/2}$ (P_α, first member of Paschen series, strongest fine-structure component)	Pulsed; as an impurity in 3.5 torr of He; optimum H pressure 0.01 torr; D = 7mm	1,2

[a] Measured wavelengths were taken from Wiese, W. L., Smith, M. W., and Glennon, B. M., *Natl. Stand. Ref. Data Ser. Natl. Bur. Stand.*, NSRDS-NBS4, 1966.

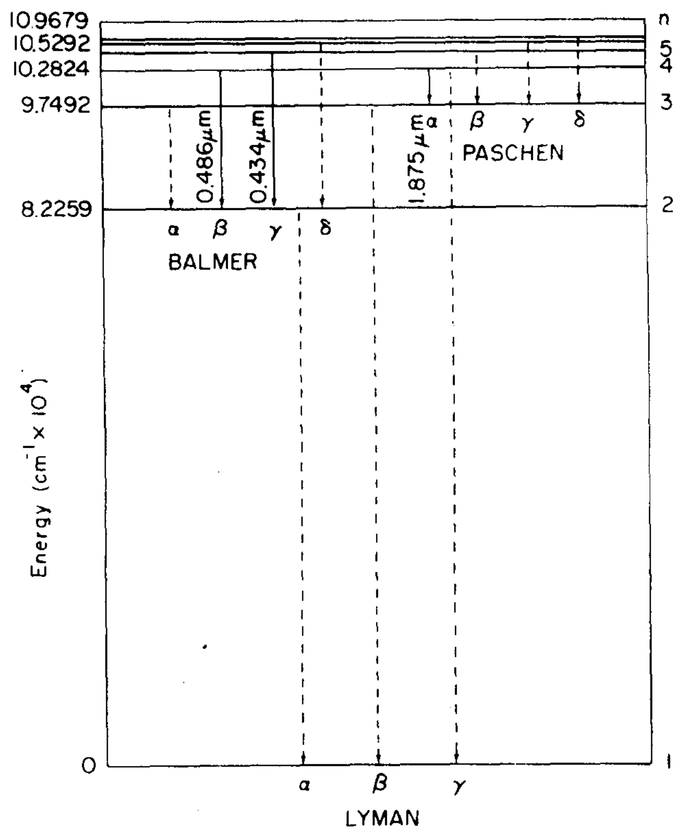
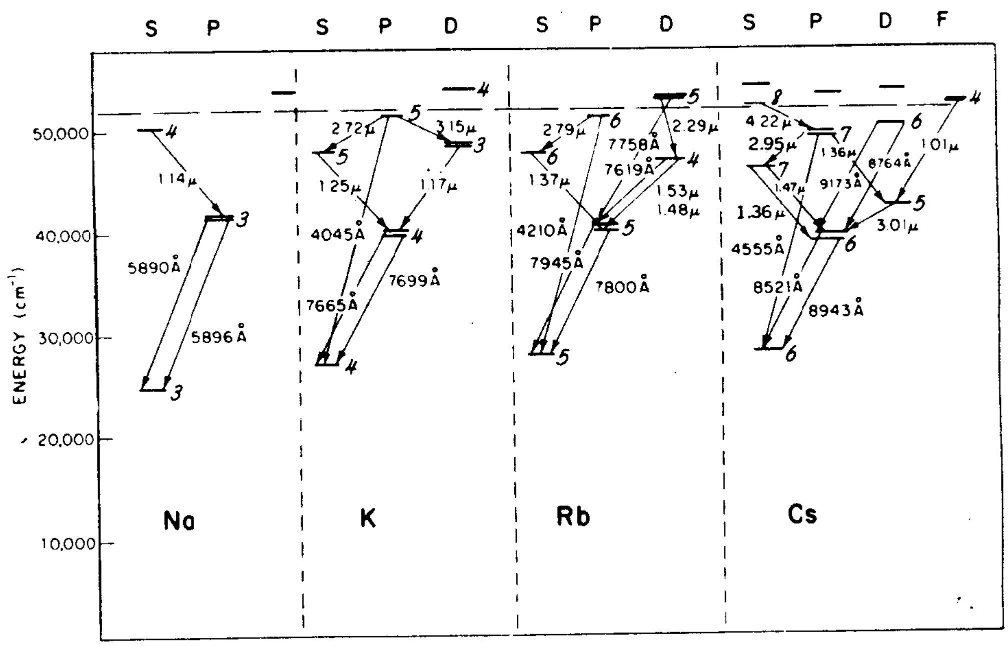


FIGURE 1.2. Partial energy level diagram of atomic H showing the reported laser transitions.

Table 1.1.2
SODIUM[a] (FIGURE 1.3)

Wavelength (μm)	Transition assignment	Comments	Ref.
0.58959236	$3p\ ^2P^o_{1/2} \rightarrow 3s\ ^2S_{1/2}$[b]	Pulsed; operates in an ASE mode following photodissociation of NaI with the fifth harmonic of a Q-switched Nd/YAG laser at 0.2128 μm; NaI in a cell at 600°C with 10 torr of Ar; NaI density $1.1 \pm 0.3 \times 10^{15}$ cm^{-3};[c] also with ArF laser pumping (193 nm) of NaI or NaBr heated in an oven at temperatures up to 1000°C, generally operated at 500—700°C which corresponds to $10^{-4} - 5 \times 10^{-1}$ torr vapor pressure; no buffer gas used	3,4
0.58899504	$3p\ ^2P^o_{3/2} \rightarrow 3s\ ^2S_{1/2}$[b]	Pulsed under the same operating conditions as the second conditions listed above	3
1.138145	$4s\ ^2S_{1/2} \rightarrow 3p\ ^2P^o_{1/2}$[d]	Pulsed; 0.001—0.003 torr of Na with 1—10 torr of H; D = 12 mm	5-8
1.140378	$4s\ ^2S_{1/2} \rightarrow 3p\ ^2P^o_{3/2}$[d]	Pulsed; 0.001—0.003 torr of Na with 1-10 torr of H; D = 12 mm	5-8

[a] Wavelength and spectral assignments were taken from Risberg, P., *Ark. Fys.*, 10, 583—606, 1956.
[b] Resonance line.
[c] Excitation results from the reaction NaI $\xrightarrow{h\nu}$ Na(3p $^2P^o$) + I(5p^5 $^2P_{3/2}$).
[d] Selective excitation occurs via the two-body recombination reaction; $Na^+ + H^- \rightarrow Na(4s\ ^2S_{1/2})$ + H.



ALKALI DISSOCIATION LASERS

FIGURE 1.3. Laser transitions observed in the neutral alkali metals following ArF laser dissociation of alkali-iodide salts. The script numbers to the right of the levels are principal quantum numbers. (From Ehrlich D. J. and Osgood, R. M., Jr., *Appl. Phys. Lett.*, 34, 655, 1979. With permission.)

Table 1.1.3
POTASSIUM[a] (FIGURE 1.3)

Wavelength (μm)	Transition assignment	Comments	Ref.
0.4044136	$5p\ ^2P^o_{3/2} \rightarrow 4s\ ^2S_{1/2}$[b]	Pulsed; pumped with an ArF laser (193 nm) using KI or KBr heated in a cell to 500—700°C without buffer gas	3
0.40472602	$5p\ ^2P^o_{1/2} \rightarrow 4s\ ^2S_{1/2}$[b]	Pulsed; pumped with an ArF laser (193 nm) using KI or KBr heated in a cell to 500—700°C without buffer gas	3
0.7664899	$4p\ ^2P^o_{3/2} \rightarrow 4s\ ^2S_{1/2}$	Pulsed; pumped with an ArF laser (193 nm) using KI or KBr heated in a cell to 500—700°C without buffer gas	3
0.7698959	$4p\ ^2P^o_{1/2} \rightarrow 4s\ ^2S_{1/2}$	Pulsed; pumped with an ArF laser (193 nm) using KI or KBr heated in a cell to 500—700°C without buffer gas	3
1.177283	$3d\ ^2D_{5/2} \rightarrow 4p\ ^2P^o_{3/2}$	Pulsed; pumped with an ArF laser (193 nm) using KI or KBr heated in a cell to 500—700·C without buffer gas	3
1.243224	$5s\ ^2S_{1/2} \rightarrow 4p\ ^2P^o_{1/2}$	Pulsed; 0.1 torr of K with 3—5 torr of H[f]	7
1.252211	$5s\ ^2S_{1/2} \rightarrow 4p\ ^2P^o_{3/2}$	Pulsed; as for the two lines immediately above	3,7
3.1415224	$5p\ ^2P^o_{3/2} \rightarrow 3d\ ^2D_{3/2}$[c]	Pulsed; K vapor excited with a Q-switched ruby laser (694.3 nm); also as for 1.177-μm line	3,9
3.1601267	$5p\ ^2P^o_{1/2} \rightarrow 3d\ ^2D_{3/2}$[c]	Pulsed; K vapor excited with a Q-switched ruby laser (694.3 nm); also as for 1.177-μm line	3,9
6.422525	$6p\ ^2P^o_{3/2} \rightarrow 6s\ ^2S_{1/2}$[d]	Pulsed; K vapor discharge in a heat pipe at 370°C (1 torr vapor pressure) pumped with a flashlamp pumped coumarin dye laser (534.31 nm)	10,11
6.4575288	$6p\ ^2P^o_{1/2} \rightarrow 6s\ ^2S_{1/2}$[d]	Pulsed; K vapor discharge in a heat pipe at 370°C (1 torr vapor pressure) pumped with a flashlamp pumped coumarin dye laser (534.31 nm)	10,11
7.8953393	$7s\ ^2S_{1/2} \rightarrow 6p\ ^2P^o_{3/2}$	Pulsed; K vapor discharge in a heat pipe at 370°C (1 torr vapor pressure) pumped with a flashlamp pumped coumarin dye laser (534.31 nm)	10,11
9.1791962	$6d\ ^2D_{3/2} \rightarrow 5f\ ^2F^o$[e]	Pulsed; K vapor discharge in a heat pipe at 370°C (1 torr vapor pressure) pumped with a flashlamp pumped coumarin dye laser (534.3) nm)	10,11
12.568814	$7p\ ^2P^o_{1/2} \rightarrow 7s\ ^2S_{1/2}$	Pulsed; K vapor discharge in a heat pipe at 370°C (1 torr vapor pressure) pumped with a flashlamp pumped coumarin dye laser (534.31 nm)	10,11