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TECHNICAL REPORT RH—77—1

BIBLIOGRAPHY ON SOURCES OF INFORMATION ON PHENOMENA OF INTEREST IN GAS LASER RESEARCH AND DEVELOPMENT

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January 1977

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

Prepared for:

Army High Energy Laser Directorate
US Army Missile Research, Development and Engineering Laboratory
US Army Missile Command
Redstone Arsenal, Alabama 35809

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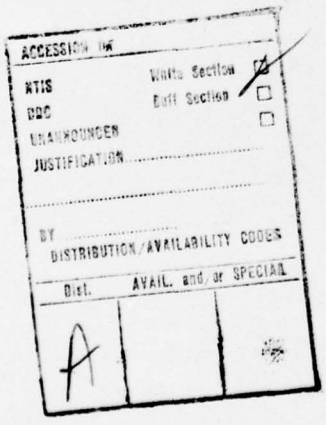

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Gas dynamics
Plasma physics and electrical discharges
Optical properties of solids
Surface physics and chemistry

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Persons engaged in gas laser research and development need data from many fields. This report was compiled in an effort to help fill this need.

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PREFACE

Persons engaged in gas laser research and development need data from many fields – atomic and molecular physics, gas-phase chemistry, optics and electromagnetic theory, quantum electronics, thermodynamics and heat transfer, gas dynamics, plasma physics and electrical discharges, optical properties of solids, surface physics and chemistry, and other branches of science and engineering. These data are required for the mathematical modeling of lasers, for the choice of materials in the construction of lasers, for the interpretation of laser performance, and for the study of the interaction of laser radiation with matter.

This bibliography was compiled in an effort to help fill this need, especially in atomic and molecular physics and gas-phase chemistry. It would have been far beyond our capacity in the available time to search out and list all (or even most) of the relevant research papers and other sources of information even in the restricted regime covered here. The number of entries would have been well in excess of 5×10^4. However, it was feasible for us to search out, categorize, and display most of the books, review articles, data compilations, and other bibliographies of use in gas laser research and development, and that is what we have done. A very small number of individual research papers that we consider to be of special interest are also included.

We may divide the references listed here into four main groups. The first deals with Atomic Collisions. Here we refer principally to two-body and three-body collisions between electrons,* atoms and molecules (neutral and ionized), and photons at impact energies sufficiently low that nuclear forces are unimportant. Hence, the center-of-mass impact energy ranges from thermal up into the low MeV range. Particle and photon impact on surfaces, and the passage of particles and photons through bulk matter are also included here, as are certain kinds of transport phenomena. Because of the large number of chemical references and their great importance in the present context, low-energy collisions between neutral structures are split off and labeled "chemical" whenever that appellation is considered appropriate.

The next main group of references deals with the structure and properties of atoms and molecules (neutral and ionized). Here we yielded to the temptation to insert a few references on exotic species (mesic atoms, muonium, and positronium). The topics covered include energy levels, spectral lines, line broadening and line shape, lifetimes, oscillator strengths, transition probabilities, and polarizabilities. There are also a few references on excitation, dissociation, and ionization of particles by electric and magnetic fields. In addition there are many items on spectroscopy, interaction potentials, and intermolecular forces.

The third group of references deals with lasers – the physics underlying their operation, laser theory, and applications of lasers.

The remaining references deal with a variety of subjects which we hope will be of interest and utility. Planetary atmospheres are included because the effect of laser radiation on a gaseous medium through which it is passing is important, as is the reaction of the medium on the radiation. Lasers are also used to monitor pollutants in the earth's atmosphere. Mass spectrometry is relevant to the rapidly developing interest in mass spectrometric sampling of operating gas lasers. The connection between electrical discharges and plasmas (included in the bibliography) and gas lasers is obvious to all. The relevance of lasers to thermonuclear fusion research also requires no elaboration. Much of the research on

* Poetic license is taken with the term "electron," which here means not only "negatron" and "positron," but also "muon," the latter particle sometimes being considered to be a heavy electron.

radiation chemistry, combustion and flames, and optical pumping is of direct importance to laser research and development, and hence many references are included here. The same comment can be made on many aspects of astrophysics, especially those related to the interaction of electromagnetic radiation with matter, plasma instabilities, and collisional and spectral properties of multiple ionized atoms. A few references are also included in other minor categories to demonstrate the utility of lasers in precise measurements of fundamental quantities.

As shown by the Table of Contents, there are 71 categories in this bibliography. The number of bibliographic entries is approximately 2200. Many of these entries are review articles, which are mainly of tutorial value and do not contain much data or many references. Hence, in an effort to enable the user of this document to locate sources containing a large amount of data, we have placed the letter "D" in the left-hand margin alongside each reference of this type. Similarly, those items containing a large number of references are marked "R".

We would be grateful if users of this bibliography would point out omissions to us – a supplement or up-dated version may be in the offing. Finally, we would like to thank Charles Cason and David Howgate of Redstone Arsenal for their encouragement and help in this endeavor.

Earl W. McDaniel
Harry W. Ellis
Fred L. Eisele
Michael G. Thackston

School of Physics
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Atlanta, Ga., 30332
November, 1976

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A. ATOMIC COLLISIONS

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a. Elastic, Total, and Momentum Transfer Scattering

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ABSTRACT

Electrons colliding with atoms can form, at well-defined energies, compound states consisting of the target atom plus the incident electron. The compound states, which are also called "resonances" or "temporary negative ions," often dominate electron collision processes. In this review we discuss the experimental methods which are useful for studying these resonances, and review the results obtained by various investigators. We list the energies and the widths of resonances for H, He, Ne, Ar, Kr, Xe, Li, Na, Hg, and O. The configurations and other properties of resonances in atoms are discussed. Whenever applicable, results are presented in the form of tables and energy level diagrams.

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ABSTRACT

In this review we present the energies, configuration, and other properties of resonances (also called "compound states" and "temporary negative ions") in diatomic molecules. Much of the information is presented in the form of tables and energy level diagrams. Vibrational, rotational, and electronic excitation are discussed whenever these processes have given information on resonances; often these excitation processes proceed via resonances. The paper is divided according to molecular species (H_2 N_2, CO, NO, O_2), but the main conclusions are discussed by the nature of the processes involved.

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ABSTRACT

Rate coefficients for the excitation of the 4.3-μm bands of CO_2 have been measured using a drift-tube technique. The CO_2 density [(1.5 to 7) $\times$ 10^{17} molecules/cm^3] was chosen to maximize the radiation reaching the detector. Line-by-line transmission calculations were used to take into account the absorption of 4.3-μm radiation. A small fraction of the approximately 10^{-8} W of the 4.3-μm radiation produced by the approximately 10^{-7}-A electron current was incident on an InSb photovoltaic detector. The detector calibration and absorption calculations were checked by measuring the readily calculated excitation coefficients for vibrational excitation of N_2 containing a small concentration of CO_2. For pure CO_2 the number of molecules capable of emitting 4.3-μm radiation produced per cm of electron drift and per CO_2 molecule varied from 10^{-17} cm^{-2} at E/N = 6 $\times$ 10^{-17} V cm^2 to 5.4 $\times$ 10^{-16} cm^{-2} at E/N = 4 $\times$ 10^{-16} V cm^2. Here E is the electric field and N is total gas density. The excitation coefficients at lower E/N are much larger than estimated previously. A set of vibrational excitation cross sections is obtained for CO_2 which is consistent with the excitation coefficient data and with most of the published electron-beam data.

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The various experimental techniques used to obtain differential, total, and momentum-transfer electron-molecule scattering cross sections at low electron energies are reviewed, and observations are compared with theory, especially with theoretical calculations of rotational excitation cross sections for slow electrons incident on homonuclear diatomic molecules. A detailed discussion of the theory of rotational excitation by slow electrons is given, with particular attention to the merits and deficiencies of recent attempts to improve on the lowest-order Born approximation predictions, via the so-called rotational close coupling and adiabatic-nuclei approximations.

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Techniques for the determination of rotational and vibrational excitation cross sections of molecules by low-energy electrons are reviewed. The results of experiment are then compared with theory. High-energy resolution electron beam techniques are most useful for the measurement of the details of resonance-type, vibrational excitation cross sections. Cross section determinations

from analyses of electron transport coefficients are most successful at energies near the threshold of vibrational excitation and for rotational excitation. High-frequency energy relaxation studies provide data on rotational excitation. A comparison of presently available experimental and theoretical results shows that some of the excitation processes, e.g., rotational excitation of N_2 and CO and vibrational excitation of CO near threshold, are accurately described by the longest-range forces and Born approximation. In other cases, e.g., vibrational excitation of N_2 and CO near 2 eV, the excitation is best described in terms of an electron resonance with the molecular potential.

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ABSTRACT

Electrons colliding with atoms can form, at well-defined energies, compound states consisting of the target atom plus the incident electron. The compound states, which are also called "resonances" or "temporary negative ions," often dominate electron collision processes. In this review we discuss the experimental methods which are useful for studying these resonances, and review the results obtained by various investigators. We list the energies and the widths of resonances for H, He, Ne, Ar, Kr, Xe, Li, Na, Hg, and O. The configurations and other properties of resonances in atoms are discussed. Whenever applicable, results are presented in the form of tables and energy level diagrams.

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In this review we present the energies, configuration, and other properties of resonances (also called "compound states" and "temporary negative ions") in diatomic molecules. Much of the information is presented in the form of tables and energy level diagrams. Vibrational, rotational, and electronic excitation are discussed whenever these processes have given information on resonances; often these excitation processes proceed via resonances. The paper is divided according to molecular species (H_2, N_2, CO, NO, O_2), but the main conclusions are discussed by the nature of the processes involved.

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The first part of this article contains a summary of relevant collision theory methods. The second part is concerned with heavy particle collisions: excitation of H 1s hyperfine structure (hfs) states by H atomic impact; excitation of H_2 rotation by H and H_2 impact; H 2s→2p transitions produced by proton impact; charge exchange reactions; excitation of atomic levels by proton impact. The third part deals with inelastic collisions between atoms and electrons. Use of the Born and distorted wave approximations is discussed. Calculations of cross sections for excitation of forbidden lines in p^q configurations are reviewed and new results presented for O^{+2}, N^+, C^+, and Si^+, both variational and semiempirical methods being used. In the final section, concerned with atomic photoionization, new results are given for photoionization from $2p^q$ configurations.

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This review includes a compilation and critical evaluation of absolute cross sections for ionization of atoms and diatomic molecules by electron impact. Experimental techniques used for ionization are surveyed. Selected relative cross sections for production of multiply charged ions and a brief discussion of relative cross-section data near threshold are presented. Absolute limits are not set on the size of probable systematic errors in the various experiments.

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Electrons colliding with atoms can form, at well-defined energies, compound states consisting of the target atom plus the incident electron. The compound states, which are also called "resonances" or "temporary negative ions," often dominate electron collision processes. In this

review we discuss the experimental methods which are useful for studying these resonances, and review the results obtained by various investigators. We list the energies and the widths of resonances for H, He, Ne, Ar, Kr, Xe, Li, Na, Hg, and O. The configurations and other properties of resonances in atoms are discussed. Whenever applicable, results are presented in the form of tables and energy level diagrams.

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ABSTRACT

In this review we present the energies, configuration, and other properties of resonances (also called "compound states" and "temporary negative ions") in diatomic molecules. Much of the information is presented in the form of tables and energy level diagrams. Vibrational, rotational, and electronic excitation are discussed whenever these processes have given information on resonances; often these excitation processes proceed via resonances. The paper is divided according to molecular species (H_2, N_2, CO, NO, O_2), but the main conclusions are discussed by the nature of the processes involved.

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ABSTRACT

This paper is devoted to a critical review of photoabsorption cross sections for molecules of aeronomic and astrophysical interest at wavelengths less than 3000 A. A discussion of the relative merits of various experimental techniques is given along with possible systematic and random errors that may be associated with them. The problems in data analysis associated with finite spectral bandwidths are reviewed, with special emphasis on the interpretation of published absorption cross sections. This review does not contain a complete set of cross-section-versus-wavelength values for each molecule; the prepared figures are used to compare the results of several determinations or to point out where difficulties of interpretation might arise. However, references to all papers believed to contain the more reliable data are given.

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IV. HEAVY PARTICLE IMPACT ON HEAVY PARTICLES

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Charge changing processes of hydrogen beams in gases (H_2, He, N_2, O_2, Ne, Ar, Kr, Xe), atomic hydrogen, alkali metal vapors (Li, Na, Mg, K, Cs), and gaseous carbon are reviewed primarily from an experimental point of view. Following a simple description of charge changing phenomena and typical techniques of measurement, problems associated with the experiments are discussed.

Experimental cross-section results for the various charge changing processes are presented in figures with critical comments. A brief review of the theoretical developments relevant to the charge changing processes of hydrogen beams is also presented.

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ABSTRACT

The current understanding is summarized from a unified point of view, which Bethe initiated four decades ago and which enables one to put a variety of theoretical and experimental data into a coherent picture. Properties of the generalized oscillator strength, which plays the central role in the theory, are treated in detail. The integrated cross section for inelastic scattering and related quantities at the high-velocity limit also are discussed. The theory provides a series of criteria for testing the compatibility of cross-section data and atomic (or molecular) properties that may be obtained from theory or independent experiments.

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ABSTRACT

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ABSTRACT

Vibrational relaxation data are surveyed in order to provide the rates of vibrational energy transfer for processes important in the CO_2–N_2 laser. A kinetic model is assumed for the vibrational energy transfer into and within the various vibrational modes of the molecules that make up a CO_2–N_2 laser, including the species H_2O, O_2, He, and H_2. Experimental data are assembled and interpreted for the rate constants and the probabilities per collision for the various kinetic processes of the assumed mechanism as a function of temperature. For certain processes, the experimental data are reinterpreted in terms of more recent knowledge of vibrational energy transfer. The data are compared with theoretical calculations and various anomalies in those comparisons are discussed. The significance of the various vibrational energy transfer processes for understanding the operation of the CO_2–N_2 laser are contrasted with the state of knowledge of the rate information.

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$CO + OD = CO_2 + D$
$CO + O = CO_2 + h\nu$
$CO + O = CO_2$
$CO + O + M = CO_2 + M$
$CO_2 + H = CO + OH$
$CO_2 + O = CO + O_2$
$CO_2 + M = CO + O + M$

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$H_2 + O = H + OH$
$H + OH = H_2 + O$
$H_2 + OH = H_2O + H$
$H_2O + H = H_2 + OH$
$H_2O + O = OH + OH$
$OH + OH = H_2O + O$
$H_2O + M = H + OH + M$
$H + OH + M = H_2O + M$

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$O_2 + H = O + OH$
$O + OH = O_2 + H$
$O_2 + H + M = HO_2 + M$
$HO_2 + M = O_2 + H + M$
$H_2O_2 + H = H_2 + HO_2$
$H_2 + HO_2 = H_2O_2 + H$
$H_2O_2 + H = H_2O + OH$
$H_2O + OH = H_2O_2 + H$
$H_2O_2 + OH = H_2O + HO_2$
$H_2O + HO_2 = H_2O_2 + OH$; $H_2O_2 + M = OH + OH + M$; $OH + OH + M = H_2O_2 + M$

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B. EXCITATION, DISSOCIATION, AND IONIZATION OF PARTICLES BY ELECTRIC AND MAGNETIC FIELDS

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C. INNER-SHELL PROCESSES (ESP. EXCITATION, IONIZATION, AUGER EFFECT)

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ABSTRACT

The present status of the field of fluorescence yields, radiationless (Auger and Coster-Kronig) and radiative transition probabilities is summarized. Tables of experimental and theoretical results are included, and tables of "best values" of important quantities are presented.

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ABSTRACT

Volume 1 (1969) deals with elastic and inelastic collisions of electrons with atoms; volume 2 (1969) with electron collisions with molecules, photoionization, photodetachment of electrons from negative ions, radiative recombination, and bremsstrahlung. All kinds of electron collisions are discussed: elastic scattering; rotational, vibrational, and electronic excitation; dissociation; ionization; spin exchange; negative ion formation; and electron-ion recombination. Also included are electron transport phenomena. Volume 3 (1971) is concerned with thermal energy collisions involving neutral and ionized atoms and molecules, diffusion, and ionic mobilities. Volume 4 (1974) covers higher energy collisions involving neutral and ionized atoms and molecules, electron-ion recombination, and ion-ion recombination. The higher energy phenomena that are treated include elastic scattering, excitation, ionization, charge transfer, dissociation, and ion-atom interchange at impact energies up into the MeV range. Volume 5 (1975) deals with positrons,

positronium, muons, muonium, and mesic atoms, and it also contains extensive notes on recent advances in the entire field of atomic collisions. The experimental sections of each volume are full of detail and contain many graphs and tables of data. The theory is presented in less detail and in simpler form than in "The Theory of Atomic Collisions" by Mott and Massey.

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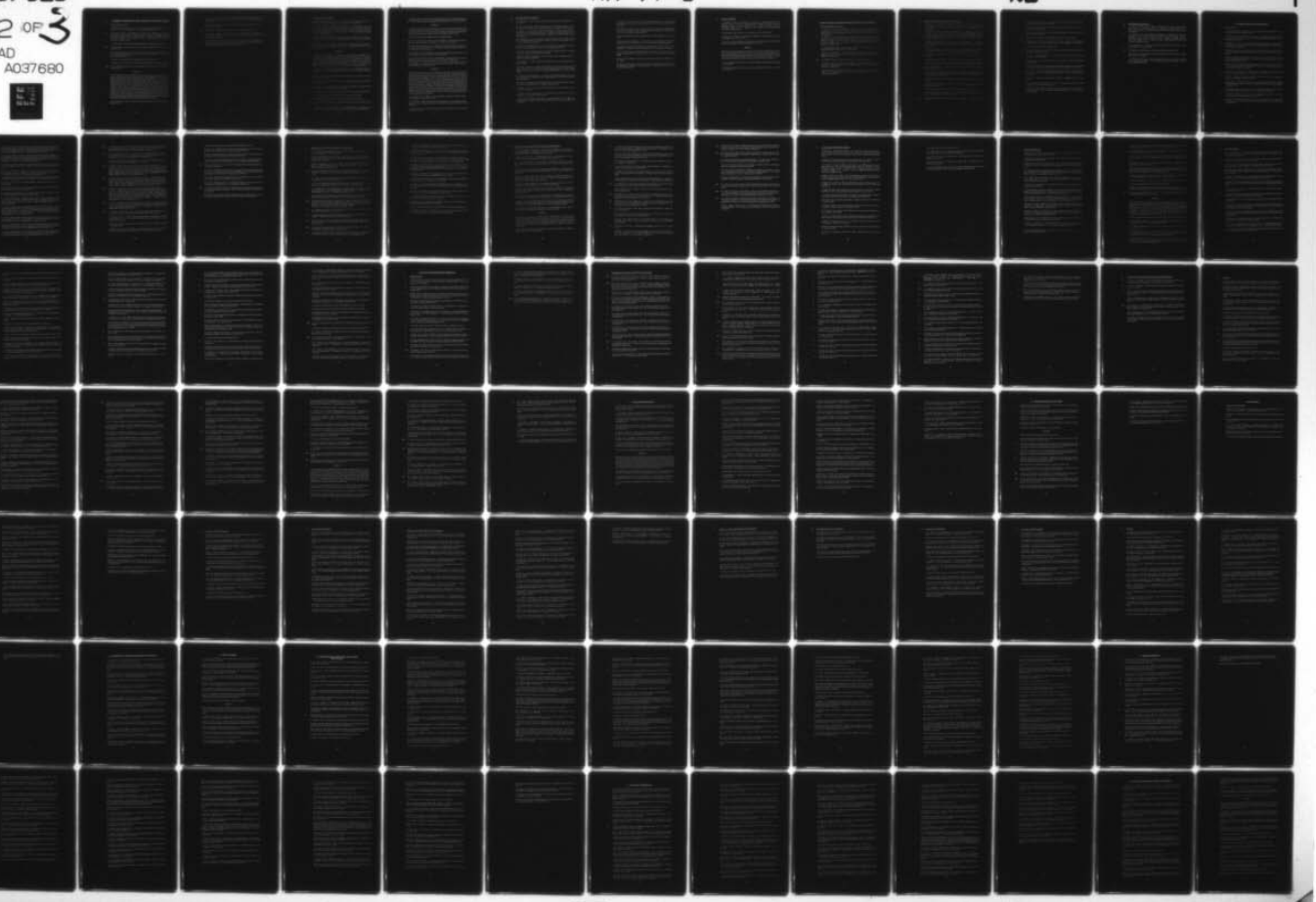

F. TRANSPORT PHENOMENA IN GASES, ENERGY DISTRIBUTIONS, SWARMS

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ABSTRACT

The book begins with an interesting history of electron and ion swarm research, and certain other aspects of atomic physics, that carries the reader up to the Second World War. Then follows a detailed and extensive theoretical treatment of electron drift and diffusion in static electric and magnetic fields, electron motion in high-frequency electric fields, and the effects of inelastic collisions on electron transport. Next comes an authoritative and comprehensive discussion of experimental techniques used to measure electron drift velocities, diffusion coefficients, "magnetic" drift velocities, and electron attachment coefficients. Analytical methods are then described for deriving elastic and inelastic cross sections from the results of electron swarm experiments. Such experiments can provide information on electron collisions for impact energies ranging from thermal values up into the eV region (tens of eV in certain cases). The book concludes with a chapter containing carefully selected and evaluated data on electron transport coefficients and elastic and inelastic cross sections for He, Ne, Ar, Kr, Xe, H_2, D_2, N_2, O_2, air, CO_2, CO, and water vapor. A little information is presented on other gases. The data are presented in both graphical and tabular form and constitute the best collection available.

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ABSTRACT

A compilation of experimental data is presented for the mobilities of mass-identified ions in neutral gases at room temperature as a function of the ionic energy parameter E/N, the ratio of electric field strength to neutral gas number density. The literature has been covered to February 1976. In addition, a recently developed theory of gaseous ion mobility is used to compute, for each ion-gas combination, the zero-field reduced mobility as a function of the common ion-gas temperature. Finally, it is shown how the tabulated data can be used to estimate the ionic diffusion coefficients and to obtain information about the ion-neutral interaction potential.

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ABSTRACT

A generalized Einstein relation for gaseous ions is shown to be accurate even at high electric field strengths, provided care is taken in the evaluation of the ion temperature. Comparison with experiment is made for K^+ ions in He, Ne, and Ar. The validity of this relation means that gaseous ion diffusion coefficients can be calculated from the more easily measured mobilities.

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ABSTRACT

The first rigorous kinetic theory of ion mobility in neutral gases, valid for electric fields of arbitrary strength without restriction on the ion-neutral mass ratio or interaction potential, is presented. The theory is based on the use of a set of basis functions in which the ions are allowed to have a temperature different from that of the neutral gas. The convergence of a series of approximations for the mobility is good, and the resulting expressions are not expansions in powers of the field strength. In lowest approximation, the equation for the mobility is nearly the same as that obtained from an approximate free-flight theory, except for the appearance of an effective temperature in the diffusion, or momentum-transfer, collision integral. This difference is the crucial point that allows experimental measurements of ion mobility as a function of field strength to be used to obtain information on ion-neutral potentials. Data on K^+ ions in He, Ne, and Ar are analyzed as an example; the range of effective temperatures is approximately 100 to 20,000°K. At high effective temperatures the results agree with similar information obtained from the scattering of ion beams in gas targets.

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G. IMPACT OF PARTICLES AND RADIATION ON SURFACES, CHANNELING

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ABSTRACT

Information on the spectrum of oscillator strength for neutral atoms in their ground states is surveyed with particular regard to recent progress in the far uv-soft x-ray range and to the theoretical interpretation of data from experiments and from numerical calculations. The analysis brings out numerous aspects of atomic mechanics and problems that remain unsolved. An effort is made to interconnect different theoretical approaches within the framework of the theory of atomic spectra.

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ABSTRACT

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I. MOLECULAR STRUCTURE AND PROPERTIES

I. ENERGY LEVELS

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ABSTRACT

Optical pumping of ground-state and metastable atoms and ions is reviewed. We present a critical survey of the literature on pumping mechanisms, light propagation, relaxation mechanisms, spin exchange, and experimental details on the various atomic species which have been successfully pumped.

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ABSTRACT

The use of intense laser light to bring about thermonuclear reactions in a plasma is of considerable current interest. We present detailed analytical and computational studies which show the feasibility of laser-driven fusion. The required laser technology and the presently anticipated practical difficulties are discussed in outline.

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