

# **NONEQUILIBRIUM EFFECTS IN ION AND ELECTRON TRANSPORT**

**Edited by**

**Jean W. Gallagher**

*National Institute of Standards and Technology  
Gaithersburg, Maryland*

**David F. Hudson**

*Naval Surface Warfare Center  
Silver Spring, Maryland*

**Erich E. Kunhardt**

*Polytechnic University  
Farmingdale, New York*

**and**

**Richard J. Van Brunt**

*National Institute of Standards and Technology  
Gaithersburg, Maryland*

**PLENUM PRESS • NEW YORK AND LONDON**

Library of Congress Cataloging-in-Publication Data

---

International Swarm Seminar (6th : 1989 : Glen Cove, N.Y.)  
Nonequilibrium effects in ion and electron transport / edited by  
Jean W. Gallagher ... [et al.].  
p. cm.  
"Proceedings of the Sixth International Swarm Seminar, held August  
2-5, 1989, in Glen Cove, New York"--T.P. verso.  
Includes bibliographical references and index.  
ISBN 0-306-43713-9  
1. Ion swarms--Congresses. 2. Electron swarms--Congresses.  
I. Gallagher, Jean W. II. Title.  
QC702.7.I57I57 1989  
537.5'32--dc20

90-7893  
CIP

---

Proceedings of the Sixth International Swarm Seminar,  
held August 2-5, 1989, in Glen Cove, New York

ISBN 0-306-43713-9

© 1990 Plenum Press, New York  
A Division of Plenum Publishing Corporation  
233 Spring Street, New York, N.Y. 10013

All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted  
in any form or by any means, electronic, mechanical, photocopying, microfilming,  
recording, or otherwise, without written permission from the Publisher

Printed in the United States of America

## PREFACE

This volume presents the contributions of the participants in the Sixth International Swarm Seminar, held August 2-5, 1989, at the Webb Institute in Glen Cove, New York. The Swarm Seminars are traditionally held as relatively small satellite conferences of the International Conference on the Physics of Electronic and Atomic Collisions (ICPEAC) which occurs every two years. The 1989 ICPEAC took place in New York City prior to the Swarm Seminar. The focus of the Swarm Seminars has been on basic research relevant to understanding the transport of charged particles, mainly electrons and ions, in weakly ionized gases. This is a field that tends to bridge the gap between studies of fundamental binary atomic and molecular collision processes and studies of electrical breakdown or discharge phenomena in gases. Topics included in the 1989 seminar ranged the gamut from direct determinations of charged-particle collision cross sections to use of cross sections and swarm parameters to model the behavior of electrical gas discharges. Although the range of subjects covered was in many respects similar to that of previous seminars, there was an emphasis on certain selected themes that tended to give this seminar a distinctly different flavor. There was, for example, considerable discussion on the meaning of "equilibrium" and the conditions under which nonequilibrium effects become important in the transport of electrons through a gas. It is evident from work presented here that under certain gas discharge or plasma conditions nonequilibrium effects can be significant; therefore, application of swarm or transport parameters determined under equilibrium conditions to the modeling of such discharges or plasmas must be considered questionable. The discussions at this seminar, as represented by several of the invited papers, has helped to remove some of the confusion about the applicability of equilibrium assumptions and provided guidance for attempts to deal with nonequilibrium situations. The seminar also included discussions about the meaning and determination of higher order "diffusion coefficients" in electron transport and limitations on the range of validity of "modified effective range theory." Interesting new

developments on both topics were presented. Several of the invited papers were concerned with the peculiarities of ion transport in sulfur hexafluoride, a gas that has become increasingly important because of use in plasma processing of electronic materials and as a gaseous dielectric in electrical power systems. An attempt was made for the first time to include papers on electron transport in dense media, namely high-pressure gases and liquids.

The 1989 Swarm Seminar was sponsored jointly by the Polytechnic University of New York, the National Institute of Standards and Technology, and the Naval Surface Warfare Center. Financial support for the seminar was also provided by the U.S. Air Force Office of Scientific Research.



## CONTENTS

Non-Equilibrium Electrons Transport: ,A Brief Overview . . . . .	1
L.C. Pitchford, J.P. Boeuf, P. Segur and E. Marode	
Beam, Swarm and Theoretical Studies of Low-Energy Electron Scattering: Some Exemplars . . . . .	11
R.W. Crompton	
Coupled Solutions of Boltzmann Equation, Vibrational and Electronic Nonequilibrium Kinetics . . . . .	37
C. Gorse	
Higher-Order Electron Transport in Gases . . . . .	49
B.M. Penetrante and J.N. Bardsley	
Non-Local Descriptions of Electron Swarms in Space-Time . . . . .	67
H.A. Blevin and L.J. Kelly	
A Description of the Non-Equilibrium Behavior of Electrons in Gases: Macro-Kinetics . . . . .	83
E.E. Kunhardt	
Nonequilibrium Effects in Electron Transport at High E/n . . . . .	99
Y.M. Li	
Electron Collision Cross Sections for Processing Plasma Gases from Swarm and Discharge Data . . . . .	121
L.E. Kline	
When Can Swarm Data Be Used to Model Gas Discharges? . . . . .	143
M.J. McCaughey and M.J. Kushner	
Non-Equilibrium Effects in DC and RF Glow Discharges . . . . .	157
D.B. Graves and M. Surenda	
Measurement of Attachment Coefficients in the Presence of Ionization . . . . .	177
D.K. Davies	
Ion Transport and Ion-Molecule Reactions of Negative Ions in SF <sub>6</sub> . . . . .	197
Y. Nakamura	
A Survey of Recent Research on Ion Transport in SF <sub>6</sub> . . . . .	211
J. de Urquijo, I. Alvarez, C. Cisneros, and H. Martinez	

Collisional Electron-Detachment and Ion-Conversion Processes in SF <sub>6</sub> . . . . .	229
J.K. Olthoff, R.J. Van Brunt, Y. Wang, L.D. Doverspike and R.L. Champion	
A Close Encounter Between Theory and Experiment in Electron-Ion Collisions . . . . .	245
M.A. Hayes	
Electron-Ion, Ion-Ion, and Ion-Neutral Interactions . . . . .	261
R. Johnson	
Electron-Ion Recombination in Dense Molecular Media . . . . .	275
K. Shinsaka and Y. Hatano	
The Mobility of Electrons in Liquid Argon; Some Differences and Some Similarities with the Motion of Electrons in Crystals and Gases . . . . .	291
G. Ascarelli	
Ultrafast and Ultrasensitive Dielectric Liquids/Mixtures: Basic Measurements and Applications . . . . .	313
L.G. Christophorou, H. Faidas, and D.L. McCorkle	
Diffusion of Electrons in a Constant Field: Steady Stream Analysis . . . . .	329
J.H. Ingold	
Diffusion of Electrons in a Constant Field: TOF Analysis . . . . .	333
J.H. Ingold	
A Monte Carlo Simulation of Electron Drift Limited by Collisions in Gas Mixtures Using the Null Collision Method . . . . .	337
D. Ramos, E. Patrick, D. Abner, M. Andrews and A. Garscadden	
An Analysis of Transient Velocity Distribution of Electrons . . . . .	339
N. Ikuta, S. Nakajima and M. Fukutoku	
An Exact Theory for Transient Behavior of Electron Swarm Parameters . . . . .	343
P.J. Drallos and J.M. Wadehra	
Electron Transport Property Under Electric and Magnetic Fields Calculated by FTI Method . . . . .	345
N. Ikuta and Y. Sugai	
A Multigroup Approach to Electron Kinetics . . . . .	349
S. Clark and E.E. Kunhardt	
Integral Expansion Often Reducing to the Density Gradient Expansion, Extended to Nonmarkov Stochastic Processes. Consequent Stochastic Equation for Quantum Mechanics More Refined Than Schrodinger's . . . . .	351
G. Cavalleri and G. Mauri	
Generalized Diffusion Coefficients and 1/f Power Spectral Noise . . . . .	353
G.Cavalleri and G. Mauri	
Fokker-Planck Calculation of the Electron Swarm Energy Distribution Function . . . . .	355
N.J. Carron	

Nonlinear Diffusion . . . . .	357
E. E. Kunhardt	
Sensitive High-Temporal-Resolution TOF Electron Drift Tube; Asymmetrical Current Pulse Observation and Determination of $V_d$ , $D_L$ and $D_3$ . . . . .	359
C.A. Denman and L.A. Schlie	
The Characteristic Energy of Electrons in Hydrogen . . . . .	361
W. Roznerski, J. Mechlinska-Drewko, K. Leja and Z.Lj. Petrovic	
Electron Swarm Parameters in Krypton and Its Momentum Transfer Cross Sections . . . . .	363
Y. Nakamura	
The Electron-Mercury Momentum Transfer Cross Section at Low Energies . . . . .	367
J.P. England and M.T. Elford	
Longitudinal Diffusion to Mobility Ratios for Electrons in Noble Gases . . . . .	371
J.L. Pack, R.E. Voshall, A.V. Phelps and L.E. Kline	
Relations Between Electron Kinetics in DC ExB and Microwave Discharges . . . . .	373
G. Schaefer and P. Hui	
Computer Simulation of a Discharge in Crossed Electric and Magnetic Fields . . . . .	375
G.R. Govinda Raju and M.S. Dincer	
Structures of the Velocity Distributions and Transport Coefficients of the Electron Swarm in $CH_4$ in a DC Electric Field . . . . .	377
N. Shimura and T. Makabe	
Negative Ion Kinetics in $BCL_3$ Discharges . . . . .	381
Z.Lj. Petrovic, W.C. Wang, L.C. Lee, J.C. Han and M. Suto	
On the Mechanism of Thermal Electron Attachment to $SO_2$ . . . . .	385
H. Shimamori and Y. Nakatani	
Electron Attachment to $NF_3$ . . . . .	387
S.R. Hunter	
Electron-Energy Dependence of Electron Attachment to Molecules as Studied by a Pulse Radiolysis Microwave Cavity Technique . . . . .	389
H. Shimamori and Y. Nakatani	
Negative Ion Pulses Induced by Laser Irradiation of DC Discharge Media . . . . .	393
L.C. Lee, J.C. Han and M. Suto	
The Attachment of Electrons in Water Vapour at Low Values of $E/N$ . . . . .	395
J.C. Gibson and M.T. Elford	
Isotope Studies and Energy Dependences of Rate Constants for the Reaction $O^- + N_2O$ at Several Temperatures . . . . .	399
R.A. Morris, A.A. Viggiano and J.F. Paulson	

Recent FALP Studies of Dissociative Recombination and Electron Attachment . . . . .	401
N.G. Adams, D. Smith and C.R. Herd	
Recent Sift Studies of Ion-Molecule Reactions: A Deuteration of Interstellar Molecules . . . . .	403
K. Giles, D. Smith and N.G. Adams	
Reactions of Several Hydrocarbon Ions with Atomic Hydrogen and Atomic Nitrogen . . . . .	407
W. Lindinger, A. Hansel, W. Freysinger and E.E. Ferguson	
Quenching of $\text{NO}^+$ ( $v=1,3$ ) in Low Energy Collisions with $\text{CH}_4$ and He . . . . .	409
A. Hansel, N. Oberhofer and W. Lindinger	
Rotational Energy Effects in Ion-Molecule Reactions . . . . .	411
A.A. Viggiano, R.A. Morris, T. Su and J.F. Paulson	
The Application of a Selected Ion Flow Drift Tube to the Determination of Proton Affinity Differences . . . . .	413
M. Tichy, G. Javahery, N.D. Twiddy, E.E. Ferguson	
Energy Dependences of Rate Constants for the Reaction $^{22}\text{Ne}^+ + ^{20}\text{Ne}$ at Several Temperatures . . . . .	415
R.A. Morris, T. Su, A.A. Viggiano and J.F. Paulson	
Deexcitation of $\text{He}(2^1\text{P})$ in Collisions with Rare Gas Atoms . . . . .	417
M. Ukai, H. Yoshida, Y. Morishima, H. Nakazawa, K. Shinsaka and Y. Hatano	
Measurements of $D_T/K$ for Sodium Ions Drifting in Argon . . . . .	419
M.J. Hogan and P.P. Ong	
Transverse Diffusion of Neon Ions in Neon . . . . .	421
T. Stefansson	
Helium Ion Clusters $\text{He}_n^+$ ( $n \leq 16$ ) Formed in a Liquid Helium Cooled Drift Tube . . . . .	423
T. Kojima, N. Kobayashi and Y. Kaneko	
Ion and Fast Neutral Model for Nitrogen at Very High $E/N$ . . . . .	427
A.V. Phelps	
Study of the Electron Transport in an RF Discharge in Ar and $\text{CH}_4/\text{H}_2$ by Optical Emission Spectroscopy . . . . .	429
F. Tochikubo, T. Kokubo and T. Makabe	
$\text{H}_\beta$ Line Shapes in RF Discharges in $\text{CHClF}_2$ and $\text{H}_2$ . . . . .	433
S. Radovanov, S. Vrhovac, Z. Petrovic and B. Jelenkovic	
Time-Resolved Investigations of $\text{H}_2$ and $\text{H}_2:\text{CH}_4$ RF Plasmas . . . . .	435
S.C. Haydon, W. Hugrass and H. Itoh	
Scattering of Electrons of High-Molecular Rydbergs in Dense Atomic and Molecular Gases . . . . .	439
U. Asaf, K. Rupnik, W.S. Felps and S.P. McGlynn	



A Constant Ratio Approximation Theory of the Cylindrical Positive Column of a Glow Discharge . . . . .	441
T. Dote and M. Shimada	
Laser-Induced Opto-Galvanic Studies of Pre-Breakdown Swarm Phenomena . . . . .	445
A. Ernest, M. Fewell and S.C. Haydon	
Influence of Negative Ion and Metastable Transport on the Stochastic Behavior of Negative Corona (Trichel) Pulses . . .	449
S.V. Kulkarni and R.J. Van Brunt	
Improvement in the Breakdown Strength of $SF_6/N_2$ Mixtures-A Physical Approach . . . . .	451
D. Raghavender and M.S. Naidu	
Geometry-Dependent Displacement Current in the Pulsed-Townsend Drift Tube . . . . .	453
E. Patrick, D. Abner, D. Ramos, M. Andrews and A. Garscadden	
List of Attendees . . . . .	455
Index . . . . .	461