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Bibliography of Electron and Photon Cross Sections with
Atoms and Molecules
Published in the 20th Centurey
– Carbon Dioxide –

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Bibliography of Electron and Photon Cross Sections With Atoms and Molecules Published in the 20th Century

—— Carbon Dioxide ——*

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A bibliography of original and review reports of experiments or theories of electron and photon cross sections and also electron swarm data are presented for atomic or molecular species with specified targets. These works covered 17 atoms and 51 molecules. The present bibliography is only for carbon dioxide (CO_2). About 1,240 papers were compiled. A comprehensive author index is included. The bibliography covers the period 1901 through 2000 for CO_2. Finally, author's comments for CO_2 electron collision cross sections are given.

Keywords : CO_2 molecule, collision cross section, electron, elastic scattering, rotational, vibrational and electronic excitations, dissociation, ionization, photon, photoabsorption, photodissociation, photoexcitation, photoionization, electron swarm, drift velocity, diffusion coefficient, ionization coefficient, excitation and ionization energies, transition probabilities, lifetimes of excited states

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Introduction

History

This bibliography is the result of a continuing literature survey which was begun around 1970 and originally encompassed only electron collision cross section and electron swarm data. The organization responsible for continuing this survey is Nagoya Institute of Technology, Nagoya. From 1994, the work continued to Gaseous Electronics Insititute, Nagoya. In 1997, the collection of photon cross section references was begun. The search for references in both cases was retrospective and included all papers reporting measurements, theoretical calculations or reviews and data compilations of such cross sections and electron swarm data.

Scope

This bibliography contains references to original research papers which report experiments or theoretical calculations of cross sections for electron and photon collisions with carbon dioxide CO_2. The review papers on this subject are also included. Some nitrogen molecule cluster papers are included. Some conference reports, company or agency reports and PhD thesis are included. Carbon dioxide ion papers and positron collision papers are not included in principle.

Papers reporting the following data are included.

For electron collision cross section :

1) elastic scattering
2) rotational excitation
3) vibrational excitation
4) electronic excitation
5) dissociation
6) ionization
7) attachment
8) grand total scattering (sum of elastic and inelastic cross sections)
9) metastable nitrogen molecules
10) electron swarm parameters (drift velocity, diffusion coefficient)
11) excitation and ionization coefficients

For photon collision cross section :

1) photoabsorption
2) photoexcitation and fluorescence
3) photodissociation
4) photoionization

For some related data :

1) excitation and ionization energies
2) transition probabilities
3) lifetimes of excited states
4) others

The energy range for electron cross section data is usually 0 - 10 keV, but some higher electron energy papers are included. The wavelength range for photon cross section data is from microwave to X-ray. Most papers are concerned with infrared, visible and ultraviolet ray region.

The bibliography includes the papers published in the 20th century, from 1901 to 2000. Oldest paper in this list is given by J. S. Townsend (1901). So for this carbon dioxide bibliography, published papers from 1901 to 1999 are compiled by alphabetical order of the first author's surname of the paper. And the references published in 2000 and plus some old papers found very recently after compilation are added as "Addenda of References for Carbon Dioxide Molecule". In total, about 1240 papers are compiled in the carbon dioxide molecule bibliography.

Organization

This report consists of four parts : introduction, the bibliography and its addenda, author index, and some comments on electron collision cross sections.

Bibliography

In this section the complete citation for all references are given. At first following classifications are shown :

E : Elastic collision
R : Rotational excitation
V : Vibrational excitation
EX : electronic EXcitation
D : Dissociation
I : Ionization
A : Attachment
ME : MEtastable argon
S : electron Swarm
O : Others (photon cross sections and the others)

All authors' initials and surname, journal name, volume, inclusive pages and year of publication are given as well as the title, and some additional information in the square bracket [ ]. E and T in the square bracket mean experiment and theory.

Bibliography for CO_2 are divided into two parts :

Part 1. 1900 - 1999 p. 1 - 88
Part 2. Addenda of References published in 2000, plus some old papers p. 89 - 106

Author Index

In this section all authors are listed alphabetically by surname. After each author's name is a list of page numbers indicating which references he or she authored or coauthored.

Part 1. 1900 - 1999 p. 1 - 17
Part 2. Addenda 1 p. 18 - 21

Some Comments on Electron Collision Cross Sections for CO_2

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References for CO_2 (1900 - 1999)

(Carbon dioxide, Carbonic acid)

E	: Elastic collision,	R	: Rotational excitation,
V	: Vibrational excitation,	EX	: Electronic excitation,
D	: Dissociation,	I	: Ionization,
A	: Attachment,	QT	: Grand total cross section,
S	: Swarm,	α	: Ionization coefficient,
O	: The others,	[ ]	: Additional informations, E : Exp., T : Theory.

The oldest paper in this list is given by J.S.Townsend (1901).

A R.Abouaf, R.Paineau and F.Fiquet-Fayard . J.Phys.B9, 303-314 (1976) K
Dissociative attachment in NO_2 and CO_2.
[E, CO_2, NO_2; 3 - 4.8 eV for CO_2]

O R.L.Abrams : Appl.Phys.Lett.25, 609-611 (1974)
Broadening coefficients for the P(20) CO_2 laser transition.
[E, hν, CO_2]

O M.S.Abubakar and J.H.Shaw : Appl.Opt.23, 3310-3315 (1984)
Analysis of carbon dioxide bands near 2.2 μm. [E, hν, CO_2]

O M.S.Abubakar : PhD Dissertation, Ohio State University (1985)
Carbon dioxide band intensities in the 12.7 to 7.7 μm region.
[E, hν, CO_2]

O M.S.Abubakar and J.H.Shaw : Appl.Opt.25, 1196-1203 (1986)
Carbon dioxide band intensities and line widths in the 8 - 12-μm region.
[E, hν, CO_2]

I B.Adamczyk, A.J.H.Boerboom and M.Lukasiewicz : Int.J.Mass Spectrom.Ion Phys. 9, 407-412 (1972)·K
Partial ionization cross sections of carbon dioxide by electrons (25 - 600 eV). [E, CO_2; CO_2^+, CO^+, O^+, C^+, O_2^+]

I B.Adamczyk, K.Bederski and L.Wojcik : Biomed.Environ.Mass Spectrom.16, 415-417 (1988)·
Mass spectrometric investigation of dissociative ionization of toxic gases by electrons at 20 - 1000 eV.
[E, CO_2, N_2O, NO, CO; partial ioniz.c.s., 20 - 1000 eV]

EX J.M.Ajello : J.Chem.Phys.55, 3169-3177 (1971) K
Emission cross sections of CO_2 by electron impact in the interval 1260 - 4500 A. II. [E, CO_2]

N.L Aleksandrov : High Energy Chem. 15, 237- (1981)

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Three-body electron attachment to a molecule. [review, CO_2, O_2, etc.]

S N.L. Aleksandrov and I.V. Kochetov : Sov. J. Plasma Phys. 18, 828-833 (1992)
Electron transport coefficients in a weakly ionized plasma with vibrationally excited molecules. [T, CO_2, N_2, CO]

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Electron transport parameters in a weakly ionized gas with vibrationally excited molecules. [T, CO_2, N_2, CO; 1 - 300 Td]

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Electron rate coefficients in gases under non-uniform field and electron density conditions. [T, CO_2, N_2, Ar]

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Ionization, attachment and negative ion reactions in carbon dioxide.
[E, CO_2]

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Molecular photoelectron spectroscopy. Part IV. The ionisation potentials and configurations of carbon dioxide, carbon oxysulphide, carbon disulphide, and nitrous oxide. [E, $h\nu$, CO_2, COS, CS_2, N_2O]

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Resonant excitation of high vibrational levels by slow electron collisions.
[E, CO_2, H_2, N_2, CO]

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Study of triplet states and short-lived negative ions by means of electron impact spectroscopy. [review, CO_2, N_2, CO, C_6H_6, etc.]

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Time of collection of electrons in ionization chambers. [, CO_2,

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Some measurements of electron drift velocities in compressed gases.
[E, CO_2, N_2, Ar]

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Metastable fragment production following electron impact on CO_2.
[E, CO_2]

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Experimental observation of autoionizing transitions from the decay of the $^{1,3}\Pi_u$ inner-shell excited states of carbon dioxide.
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Observation of electron-neutral inverse bremsstrahlung in an electron-beam-sustained discharge. [E, CO_2, N_2, H_2]

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On the cross section of low-energy electron collisions on CH_4 and CO_2.
[T, CO_2, CH_4; 0.01 - 20 eV for CO_2]

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Reaction of atomic oxygen with some simple alkenes. Part 2. — Reaction pathways involving ethene, propene and (E)-but-2-ene at atmospheric pressure.
[E, CO_2; production of O(g) from CO_2, $CO_2 + e \rightarrow [CO_2]^* \rightarrow CO + O$]

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Vibrational excitation of CO_2 by dipole interaction with slow electrons.
[E, CO_2: relative DCS, 1.9 eV, 0 - 30°]

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Streuung niederenergetischer Elektronen an Neonatomen und CO_2-Molekulen.
[E, CO_2, Ne]

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Angular distribution for the excitation of vibronic states by resonant electron molecule reactions. [T, CO_2; 3.6 eV, (100) and (010) modes]

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Ionization of gases by 266-nm ultraviolet light.
[E, $h\nu$, CO_2, N_2, O_2, C_2H_2; 295 K]

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Zur Lumineszenz einiger Molekulgase bei Anregung durch schnelle Elektronen. II. [E, CO_2, N_2, O_2, $N_2 + O_2$]

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V Rotational branch analysis of the excitation of the fundamental vibrational modes of CO_2 by slow electron collisions.
[E, CO_2; DCS, 1.1 - 3.8 eV]

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W. L. Mead (Ed), The Inst. of Petroleum 457-469 (1966)
Sur le seuil d'apparition des ions fragments produits avec exces d'energie cinetique. [review, CO_2, NO, N_2, C_3H_8]

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Spectroscopie par source laser. I. Etude experimentale des intensities et largeurs des raies de la transition $00^01-(10^00, 02^00)_I$ de CO_2.
[, $h\nu$, CO_2]

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CO_2 electron dissociation in the 18 - 46 eV range. A report of the O^+ and CO^+ abundances. [E, CO_2]

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Influence of secondary processes on the fragmentation pattern of CO_2 by electron impact. [E, CO_2; 18 - 44 eV]

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Dissociative ionization of CO_2 by electron impact in the range 40 - 150 eV. [E, CO_2; direct disso. and autoioniz.]

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Electron scattering in dense CO_2 gas : Photoionization spectra of CH_3I perturbed by CO_2. [E, CO_2]

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Electron attachment and ionization in oxygen, carbon monoxide and carbon dioxide. [E, CO_2, O_2, CO; th.- 100 eV for q_i]

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Measurement of electron attachment and ionisation cross sections in carbon dioxide. [E, CO_2; 13 - 90 eV for q_i, 2 - 9 eV for q_a]

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Autoionization and isotope effect in the threshold photoelectron spectrum of $^{12}CO_2$ and $^{13}CO_2$. [E, hν, CO_2]

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Photoelectron spectra and partial photoionization cross-sections for carbon dioxide. [E, hν, CO_2; 584 - 720 A]

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Photoelectron spectra and partial photoionization cross sections for NO, N_2O, CO, CO_2 and NH_3. [E, hν, CO_2, NO, N_2O, CO, NH_3]

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The behaviour of electrons in nitrous oxide. [E, N_2O; data compaired with CO_2]

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The behavior of electrons in chlorine. [E, CO_2 + Cl_2, Cl_2, Cl_2 + He]

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O Electron energy distributions, transport coefficients and electron excitation rates for RF excited CO_2 lasers. [T, CO_2]

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A A new apparatus for the study of pre-breakdown ionization growth in gases. [E, CO_2; E/N = 90.3 - 96.3 Td]

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The influence of ionization, electron attachment and detachment on electron swarms in gases. [E, CO_2]

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A high-pressure ionization chamber. [E, CO_2; E/N = 84.3 - 96.3 Td]

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Energy distribution in selected fragment vibrations in dissociation processes in polyatomic molecules. [T, hν, CO_2, HCN, DCN]

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O Calculation of vibrational excitation in CO_2, CO, N_2, He discharges. [T, CO_2, CO, N_2, He]

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Predicted angular distribution for resonant scattering of electrons by molecules. [T, CO_2, H_2, N_2, CO, NO, O_2, C_2H_2, C_6H_6]

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Negative ions of N_2O and CO_2. [T, CO_2, N_2O]

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Dissociative excitation of metastable fragments by electron impact on carbonyl sulphide, carbon dioxide and carbon monoxide. [E, CO_2, OCS, CO; 40 - 60 eV]

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K-shell photoabsorption coefficients of O_2, CO_2, CO, and N_2O. [E, hν, CO_2, O_2, CO, N_2O]

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A Electric dissociation of CO_2. [E, CO_2; 3 - 10 eV, dissociation th. energy 6.2 eV]

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A unified description of elastic high energy electron-molecule scattering [T, CO_2, CO, CH_4, C_2H_4, C_2H_6, N_2, O_2, H_2O]

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Measurement by cyclotron resonance of molecular cross sections for elastic collisions with 295°K electrons.
[E, CO_2, N_2, N_2O, NH_3, SO_2, H_2O, CF_3H, etc.]

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Cathode region of a transitory discharge in CO_2. I. Theory of cathode region. [T, CO_2]

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Cathode region of a transitory discharge in CO_2. II. Spatio-temporal evolution. [T, CO_2]

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A bibliography of electron swarm data. [compilation]

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Absolute intensities of CO_2 lines in the 3140 - 3410 cm^{-1} spectral region.
[E, $h\nu$, CO_2; V.M.Devi → V.Malathy Devi]

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Absorption coefficients and ionization yields of some small molecules at 58.4 nm. [E, $h\nu$, CO_2, Ar, CO, mostly; and review for many molecules]

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Evaluation of molecular quadrupole moments from broadening of microwave spectral lines. II. Calculation of the quadrupole moments and discussion.
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Synchrotron radiation study of photoionization and photodissociation processes of CO_2 in the 13 - 21 eV region. [E, $h\nu$, CO_2]

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Rydberg states of polyatomic molecules using model potentials.
[T, CO_2, N_2O, NO_2, C_2H_2, C_3H_4, H_2CO, etc.]

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Photodissociationen von H_2, N_2, O_2, NO, CO, H_2O, CO_2, und NH_3 in extremen Vakuum-UV. [E, $h\nu$, CO_2, NH_3, etc.; 1000 - 1500 A]

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Cross section measurements for photodetachment or photodissociation of ions produced in gaseous mixtures of O_2, CO_2, and H_2O.
[E, $h\nu$, CO_2, O_2, H_2O]

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Formation of negative ions upon irradiation of molecules by intense laser fields. [E, CO_2, CS_2, O_2]

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Accurate three-dimensional simulation of straw chambers using slow, medium and fast gas mixtures. [T, CO_2; cross section set for CO_2]

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Determination of the spectral dependence of the absolute quantum yields of $O(^1S)$ by the XeO^* luminescence method. I. Photolysis in CO_2 and N_2O. [E, hν, CO_2, N_2O]

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Vibrational contributions to molecular dipole polarizabilities. [compilation, CO_2, etc.]

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An absolute determination of the minimum ionizing energy of an electron, and the application of the theory of ionization by collision to mixtures of gases. [E, CO_2,

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The observation of resonance in the electron impact excitation intensities of the inner-shell states of CO_2. [E, CO_2; resonance at 313 eV]

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Angle-resolved electron-energy-loss study of core-level electron excitation in molecules : Determination of the generalized oscillator strength for carbon 1s($2\sigma_g \rightarrow 2\pi_u$) excitation in CO_2. [T, CO_2; 1290 eV, GOS]

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Compound state electron spectra of simple molecules.
[E, CO_2, N_2O, NO_2, NO, CO, O_2, N_2; 0 - 2.6 eV]

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Drift velocities of electrons in some commonly used counting gases.
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[T, CO_2; DCS. 20 - 1000 eV]

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[T, $(CO_2)_N$, $(H_2)_N$, $(N_2)_N$]

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[compilation, hν, CO_2]

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Calculation of the absorption coefficient in the microwindows of the CO_2 4.3-μm band. [T, hν, CO_2, $CO_2 + N_2$]

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Author Index for CO_2 References

Authour Index for CO_2 References. Addenda 1

Some Comments on Electron Collision Cross Sections for CO_2

The pioneer work on electron collision cross section set for CO_2 is given by J. J. Lowke in 1973. I have compiled the same set for CO_2 including new data many times. An example was shown in the book of NATO Meeting of Maratea (M. Hayashi, 1990). This cross section set is shown in Figure 1. The other cross section sets for CO_2 were presented by many authors, H. N. Kucukarpasi (1979), M. Yousfi (1987), S. E. Biagi (1991), and so on.

Now I do not like these cross section sets. Reasonable and correct cross section set have to calculate the temperature dependence of electron drift velocities at high E/N by B. Eq. and MCS method. We have solved this problem and reported at the 51th GEC Conference, Maui, as shown in this report.

Recently Michel Allan published the excellent experimental results for CO_2 + e collision data (2002), see p. 89 of this report. His used CO_2 molecules are mixture of $CO_2(g)$, $CO_2(r)$ and $CO_2(v)$. The letters in the bracket mean : g is ground state, r is rotationally excited state and v is vibrationally excited state. The concentration of $CO_2(g)$ is negligible small, and most interesting component in his experiment is the $CO_2(v_1)$. The $CO_2(v_1)$ of about 8 % concentation have dipole moment. Probably, concentration of $(CO_2)_2$ molecules are negligible small.

All molecules have the same component M(g), M(r), M(v) and M_n (n = 2), depend on the pressure and temperature condition of the experiment. Most interesting experimental results occur in the triatomic molecules. The change from linear mode combination of three atoms to bend mode combination of three atoms, or vice versa, occur very easy in the triatomic molecules by vibrational excitation.

Almost theoretical results of electron collision cross sections for molecules are for M(g). Theoretical studies involving the M(r) and M(v) are urgently required for many molecules.

I have found the interesting paper of J. R. Locker (1983) * on photoabsorption cross sections of OCS. And I would like to say that three important pioneer works on CO_2 are carried out by G. N. Haddad (1979), M. T. Elford (1980) and S. J. Buckman (1987), all in Canberra, about 20 years ago.

I would like to present our recent three conference reports at the end of this report.

M. Hayashi and Y. Nakamura : 51th GEC, Maui 265-266 (1998)
M. Hayashi and Y. Nakamura : EMS-99, Tokyo 175-176 (1999)
S. Yoshinaga, Y. Nakamura and M. Hayashi : 25th ICPIG, Nagoya 285-286 (2001)

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* J. R. Locker, J. B. Burkholder, E. J. Bair and H. A. Webster III : J. Phys. Chem. 87, 1864-1868 (1983) [E, hν, OCS, 195 - 404 K at 226 nm]

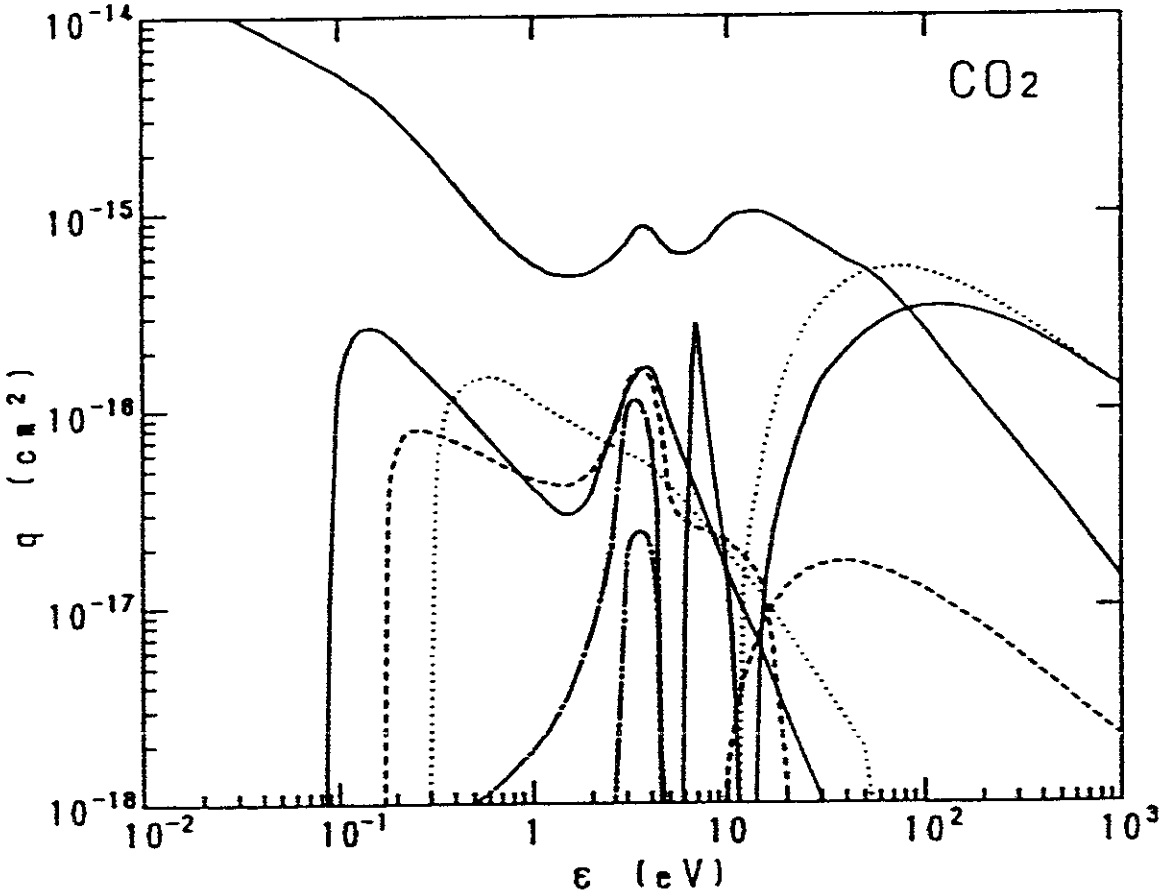

Figure 1. Electron collision cross section set for CO_2, assuming all CO_2 molecules are in CO_2(g) state (M. Hayashi, 1990). In all CO_2 + e experiments, CO_2 molecules are mixture of CO_2(r) and CO_2(v). So this cross section set is not applicable for exact calculations, and can use only for approximate applications.

JTP7.07

Temperature Dependence of Electron Drift Velocity and Electron Collision Cross Section Sets for Ground State and Vibrationally Excited State of the CO_2 Molecule

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The drift velocity of electrons in carbon dioxide have been calculated at gas temperatures ranging from 193 to 573 K and at E/N values up to 100 Td assuming that the gas was a mixture of the ground state molecules and the vibrationally excited molecules and its mix ratio depended on the temperature. The calculated drift velocities agreed well with the measurement of Elford (1980).

Generally, target molecule M in beam and swarm experiments consists of the mixture of different states:

$$M = M(g) + M(r_j) + M(v_i) + M_N ,$$

where M(g), $M(r_j)$, $M(v_i)$ and M_N represent the ground state molecules, the rotationally excited molecules, the vibrationally excited molecules and the van der Waals clusters consisting of N molecules (N≥2), respectively. It is known that the concentration of $M(v_i)$ increases with temperature. For example, the concentration of $CO_2(v_i)$ in CO_2 has been calculated to be 8.4 % at 313 K and 26.5 % at 673 K, respectively [1,2]. This is due to the low threshold energy (0.083 eV) of the lowest vibrational excited level (010) mode. The concentrations of rotationally excited molecules are much larger than of the vibrationally excited molecules. The concentration of the clusters are important at low temperature and high pressure conditions.

Most of theoretical calculations of electron collision cross sections have been performed for pure M(g) target, not for the M(v) molecules.

A number of different electron collision cross sections for molecules have been determined with beam and swarm experiments. So far, in most of the experiments it is implicitly assumed that the target molecules are all in the ground state, or electron collision cross section set of M(g), M(r) and M(v) are almost the same. Strictly speaking, this assumption is not correct, and in particular, cannot be applied to the molecules which have temperature dependence in electron collision cross sections.

Take the CO_2 molecule. The ground state $CO_2(g)$ is linear, but $CO_2(010)$ is bent and this has a dipole moment. Electron collision cross section set of $CO_2(g)$ and $CO_2(v)$ are expected to be different each other. In fact, Buckman [3], Ferch [1] and Strakeljahn [4] have determined the grand total cross section Q_T for $CO_2(g)$ and $CO_2(v)$ and found that $Q_T(v)$ of CO_2 are larger than $Q_T(g)$ at the electron energies lower than about 10 eV.

It seems to be quite difficult to determine directly the electron collision cross section sets of $CO_2(g)$ and $CO_2(v)$ from the beam and swarm experiments. However, if the cross section sets of $CO_2(g)$ and $CO_2(v)$ are available, we can calculate the electron swarm parameters of a known concentration of $CO_2(g)$ and $CO_2(v)$ very easily. Momentum transfer cross sections q_m for $CO_2(g)$ and $CO_2(v)$, which have been based on the compilation of Hayashi [5] and recent experiments of Nakamura [6] and Strakeljahn [4], are shown in Fig. 1. Tentatively, we have assumed that all other inelastic cross sections of $CO_2(g)$ and $CO_2(v)$ are practically the same [7,8]. At a given temperature, the concentrations of $CO_2(g)$ and $CO_2(v)$ are known, then we have calculated the values of electron drift velocity W in CO_2. The results are shown in Fig. 2. The calculated W values at three temperatures are in general agreement with the experimental data of Elford [9].

Haddad [10] have discussed the importance of the populations of vibrationally excited CO_2 molecules already. They also have mentioned the contributions due to CO_2 molecules in rotational states and have concluded that such states are not likely to play a significant role compared with vibrationally excited molecules. But they could not reproduce their experimental data for W at high E/N from the analysis.

A similar analysis on $H_2(g)$, $H_2(r\ )$ and $H_2(v)$

also have to be started. The H_2 molecule have the famous long-standing controversy in the vibrational excitation cross section [11]. In the present paper, we propose to investigate and to measure the cross sections for molecules not only in the ground state but also in the excited states which should have different cross sections from those in the ground state. Although the difference among the cross section sets for $H_2(g)$, $H_2(r)$ and $H_2(v)$ may be small compared with the CO_2 molecule since the H_2 molecule is diatomic. Theoretical studies involving the excited species are urgently required.

The term "*temperature dependence* of cross section" may not be appropriate. The molecules, $CO_2(g)$, $CO_2(r)$ and $CO_2(v)$, have the definite and individual cross section sets, and their concentrations change with temperature. The temperature dependence is caused through different concentration of the excited components at different temperatures. Attachment cross section of the excited molecules is quite different from the ground state molecules for many attaching gases.

We wish to thank Professor H. Tawara for valuable comments.

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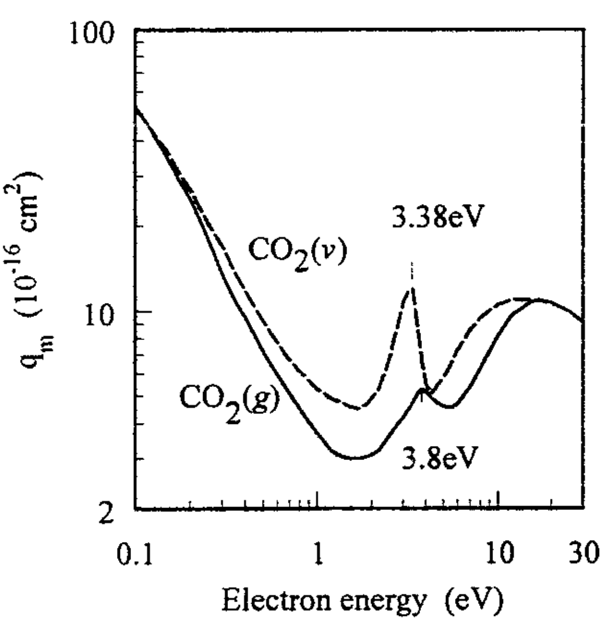

Fig. 1. The assumed elastic momentum transfer cross sections for the ground state (solid curve) and vibrationally excited CO_2 molecules (broken curve).

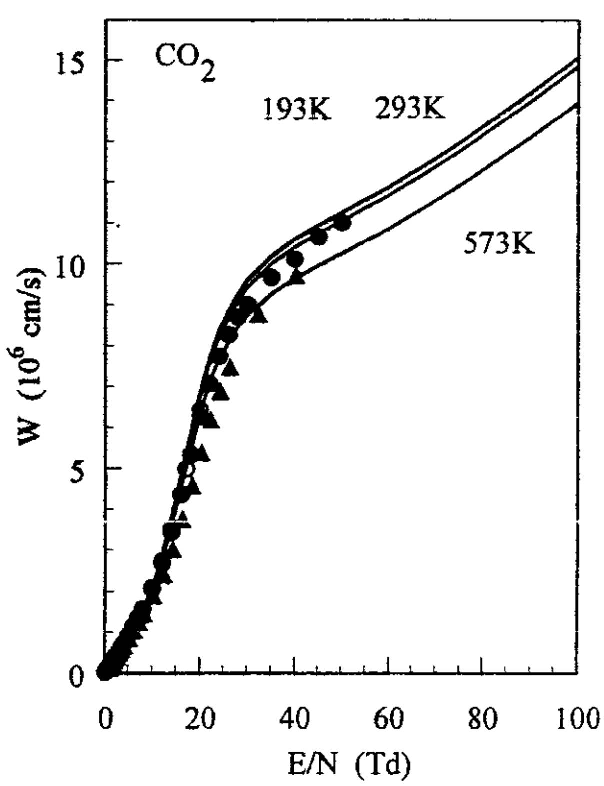

Fig. 2. Calculated electron drift velocities in CO_2 at different temperatures. Open and closed circles and closed triangles show the measurements of Elford [9] at 193, 293 and 573 K, respectively.

May We Measure the Exact Values of Electron Collision Cross Sections for Molecules by Beam and Swarm Experiments ?

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We cannot measure the exact values of DCS for molecules intrinsically. Of course, we can measure the approximate values of DCS for molecules, but can measure the exact values of DCS for atoms. The reason is very simple.

Target molecule M in both beam and swarm experiments consists of the mixture of different states :

$$M = M(g) + M(r_J) + M(v_1) + M_N$$

where $M(g)$, $M(r_J)$, $M(v_1)$ and M_N represent the completely ground state molecules, the rotationally excited molecules, the vibrationally excited molecules and the van der Waals clusters consisting of N molecules ($N \geqq 2$), respectively. Usually beam and swarm experiments are carried out at about 300 K. The concentration of $M(g)$ is small compared to $M(r_J)$ (except H_2 molecules) at 300 K. Then the molecule M is always mixture of $M(r_J)$ and $M(v_1)$, and the concentration of $M(r_J)$ and $M(v_1)$ changes with temperature. And electron collision cross section sets from elastic to inelastic collision processes for $M(r)$ and $M(v)$ are different each other. The target molecules M in the beam and swarm experiments are always mixtures of different molecules $M(r_J)$ and $M(v_1)$. In the case of H_2, the target gas consists of $M(g)$ and $M(r_J)$, especially $M(g)$ and $M(r_1)$ at 78 K.

Most clear change of cross sections of $M(r_J)$ and $M(v_1)$ will occur for triatomic molecules, CO_2, N_2O and so on. Triatomic molecules can change from linear to bend, or vice versa easily. The authors [1] have presented the different elastic momentum transfer cross sections q_{mr} and q_{mv} for $CO_2(r)$ and $CO_2(v)$, where they assumed that all other inelastic cross sections of $CO_2(r)$ and $CO_2(v)$ are practically the same. Then they have calculated the electron drift velocity W as a function of gas temperature T. When T increas, concentrations of $CO_2(v)$ increases, then W decreases with T at the same E/N, the electric field over the gas number density, around 50 Td.

We have a comment to the interesting and important paper of W. Johnstone, et al. [2]. They have measured the temperature dependence of elastic DCS for CO_2 at 4.0 eV. Unfortunitly, q_{mv} for $CO_2(v)$ at 4 eV is almost equal to q_{mr} for $CO_2(r)$ [1]. Then we propose the same experiments at about 3.4 eV for CO_2, because the temperature dependence of DCS seems to be very large there.

Winstead and McKoy [3] calculated the elastic DCS for $N_2O(g)$ at low electron energies and compare the experimental DCS data for $N_2O(r)$ + $N_2O(v)$ mixture at 300 K. We can see large discrepancy between them at lower than about 10 eV. We urge Winstead and Mckoy to calculate the DCS for $N_2O(v)$ and also $N_2O(r)$ for comparison. We can see the same discrepancy of DCS for CO_2 [4] [5] at low electron energies..

H_2 molecules have the famous long standing controversy in the vibrational excitation cross section [6]. A possible way to solve the problem may be as follows. At first, theoreticians calculate the q_{mg}, q_{mr}, q_{mv}, q_{rg}, q_{rr}, q_{rv}, q_{vg}, q_{vr}, and q_{vv} for $H_2(g)$, $H_2(r_1)$ and $H_2(v_1)$, as a function of electron energies. Using these data, we calculate the electron swarm parameters. From beam experiments, we cannot determine the values of q_{mg}, q_{mr}, q_{rg}, q_{rr} for $H_2(g)$ and $H_2(r_1)$ at the same time. It is clear that the threshold energies of q_r and q_v for $H_2(g)$ and $H_2(r_1)$ are different. Bhattacharyya, et al. [7] have shown that elastic integral cross sections q_{tr} are larger than q_{tg} for 20 to 200 eV for $H_2(g)$ and $H_2(r_1)$. We want the elastic DCS values for $H_2(g)$ and $H_2(r_1)$ at low electron energies lower than 10 eV. Swarm experiments also carried out in the mixtures of $H_2(g)$ and $H_2(r_1)$, except for para-$H_2(g)$ at 78 K (concentration of $H_2(g)$ is 99.3 %). We compare the experimental and calculated swarm parameters at given conditions.

Usually, theoreticians calculate the DCS for M(g), not for $M(r_j)$ and $M(v_i)$, for most molecules. Theoretical studies involving the rotationally and vibrationally excited species are urgently required for many molecules. There is a interesting paper given by A. Jain [8].

If we have the cross section sets for excited inert gas clusters, we can calculate the electron swarm parameters of inert gases at high pressure and low temperature conditions. The concentration of the clusters for atoms and molecules are important at low temperature and high pressure conditions.

Most interesting temperature dependence occur for attachment cross sections q_a [9]-[13]. The values of non-dissociative q_{an} and dissociative q_{ad} are quite different for M(r) and M(v), and M(r) and M(v) have the definit and individual cross sections, independ on the temperature. Apparent temperature dependence of attachment cross section is caused through different concentration of the excited components M(r) and M(v) at different temperatures.

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A Measurement of Temperature dependence of Electron Transport Parameters in CO_2

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1. Introduction

CO_2 in the ground state is a linear molecule, but the vibrationally excited CO_2 has a temporal electric dipole moment and its electron collision cross section is expected to be different from that of the ground state. The CO_2 gas at elevated temperature naturally consists of not only the ground state molecules but also molecules in different vibrationally excited states and electron transport parameters are again expected to have temperature-dependence. Haddad and Elford measured the electron drift velocity in CO_2 at 193, 293 and 573K up to E/N=40Td (where E is the electric field and N the gas number density, and $1\text{Td}=1\times10^{-17}$ $\text{V}\cdot\text{cm}^2$) and actually observed temperature dependent drift velocity [1]. Buckman *et al* measured the total cross section for electrons from vibrationally excited (principally 010) CO_2 molecules in the energy range 0.12-2.0 eV [2] and confirmed enhanced total cross section for the excited molecules up to about factor 2.4 of the ground state molecule.

In the present study we constructed a drift tube capable of measuring the parameters at elevated gas temperature up to about 500K, and measured the drift velocity and the longitudinal diffusion coefficient in CO_2 over the E/N range 8-300 Td at 273, 373, 423 and 473K.

2. Experimental description

Figure 1 shows the cross sectional diagram of the present electron drift apparatus. It consists of a double-shutter electron drift tube with variable drift distance, a non-inductive theathed heater-winding and a four-hold heat reflector. The drift distance is varied from 1 to 5cm by using a linear-motion feedthrough. The diameter of the drift volume is 5cm. Two pairs of thermocouples were installed at the top of the drift tube and under the electron collector and they were used to monitor and to control the inside gas temperature. The gas pressure was measured by an MKS Baratron (10 Torr Head) at cold point and the gas number density in the drift volume was determined from the monitored temperature.

Prior to actual measurement in CO_2 we measured the transport parameters in pure N_2, which are not expected to have any temperature dependence in the present E/N range, in order to confirm the determined gas number density at elevated temperatures between 293 and 473K. Figure 2 shows the measured temperature dependence of the electron drift velocity W and the product of the longitudinal diffusion coefficient and the gas number density ND_L in N_2 between 293 and 473K at several E/N. Both parameters were almost independent on the gas temperature over the present temperature range. They also agreed very well with our previous measurement [3], and it was actually confirmed that we were able to determine the correct E/N values in the measurements.

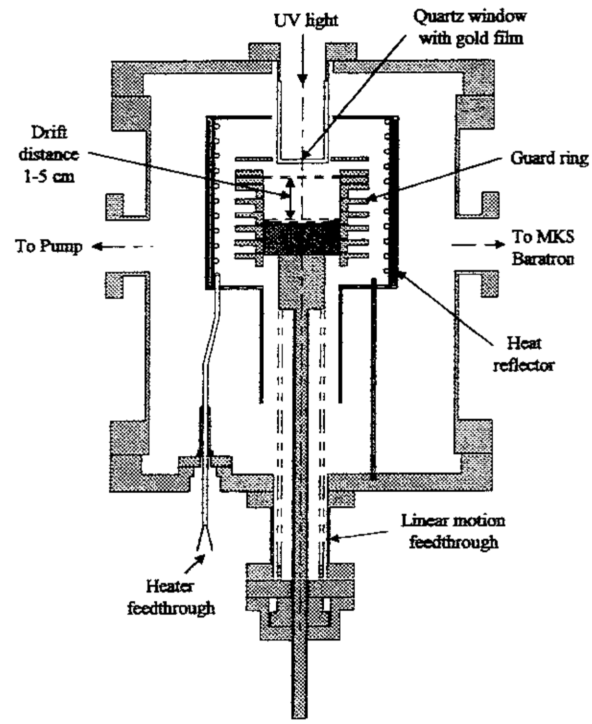

Figure 1. The cross sectional diagram of the electron drift apparatus

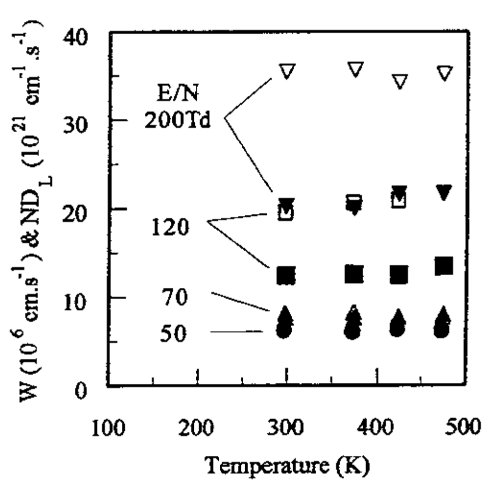

Figure 2. Temperature dependence of transport parameters in N_2. Solid and open symbols show W and ND_L, respectively.

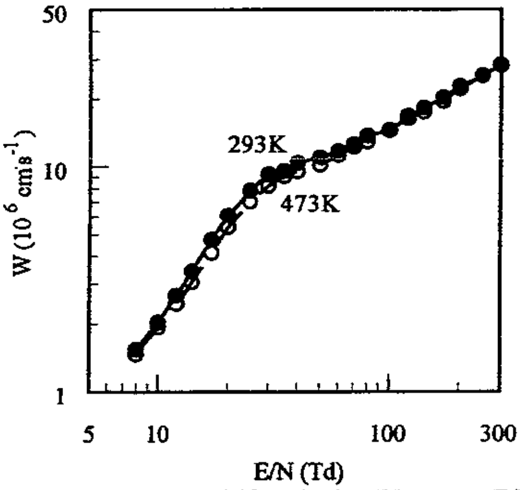

Figure 3. The electron drift velocity W versus E/N at 293K and 473K.

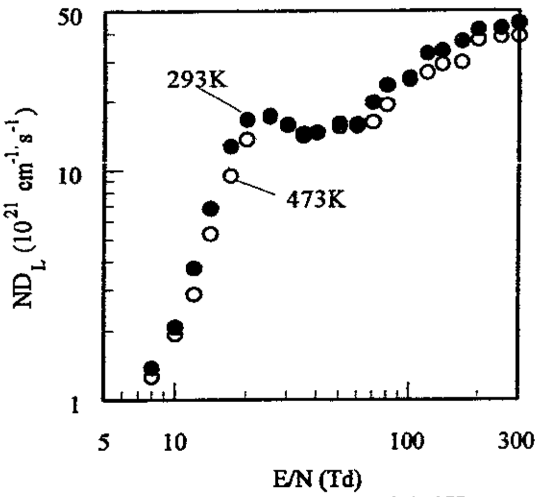

Figure 5. ND_L versus E/N at 293K and 473K.

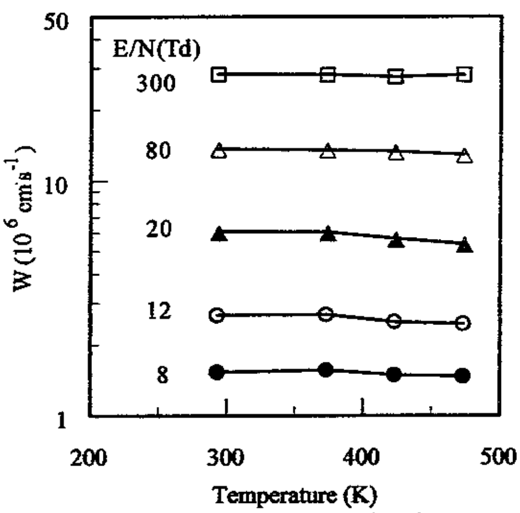

Figure 4. Temperature dependence of W in CO_2.

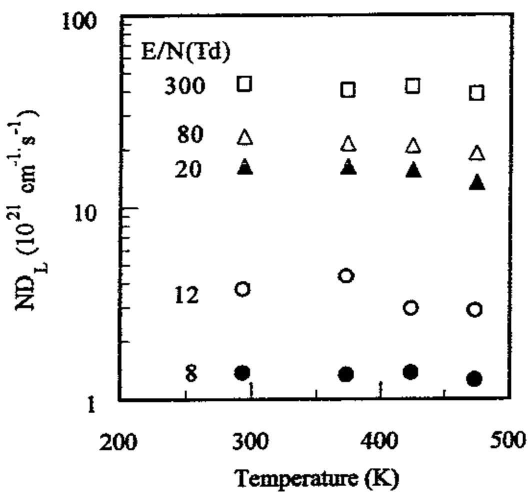

Figure 6. Temperature dependence of ND_L in CO_2.

3. Results and discussions

Figure 3 shows the present electron drift velocities measured at 293 and 473K. At the lowest and highest E/N the drift velocity is almost independent on temperature, but it evidently decreases at higher temperature at E/N range 17-200Td.

Figure 4 shows the temperature dependence of W. The estimated error limit in W is ±5% and monotonic decrease in W with temperature is evident at intermediate E/N. At E/N=8 and 300Td W is almost independent on gas temperature.

Figure 5 shows the present ND_L at 293 and 473K, and Figure 6 shows its temperature dependence. The estimated error limit is ±15%, but still the temperature dependence similar to the drift velocity is evident.

Mean energy of electrons participating this temperature dependence should extend up to a few eV. The dependence due to rotational excitation and deexcitation should appear even lower E/N and vibrational deexcitation should affect only very low energy electrons. Therefore, the observed gas temperature dependence should be related to the presence of the vibrationally excited molecules with enhanced elastic cross section due to their temporal dipole moment [2].

4. Conclusions

The drift velocity and the product of the longitudinal diffusion coefficient of electrons in carbon dioxide were measured at 293, 373, 423 and 473K over the E/N range 8-300Td. A monotonic decrease with the gas temperature was observed in both transport parameters over the E/N measured except at E/N=8 and 300Td.

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Numbers of References

on Electron and Photon Collisions with Atoms and Molecules published in the 20th Century

Atoms (17)			Molecules (51)					
A + e, A + hν			M + e, M + hν,					
He	2	2170 *	2	H_2, D_2	1870	5	CH_4	750
Ne	10	1140 *		N_2	2180			
Ar	18	1960		O_2	1700		CF_4	390
Kr	36	790		CO	1190		CCl_4	210
Xe	54	940		NO	880		CCl_2F_2	250
							CH_3Cl	90
Li	3	450		F_2	170		SiH_4	230
Na	11	800		Cl_2	330		SiF_4	140
K	19	370		Br_2	130		GeH_4	50
Rb	37	220		I_2	240			
Cs	55	370				6	C_2H_4	370
				HF	260		CH_3OH	240
O	8	390		HCl	320			
				HBr	190			
F	9	90		HI	130	7	SF_6	780
Cl	17	130						
			3	CO_2	1240			
						8	C_2H_6	260
Cu	29	180		H_2O	850		C_2F_6	150
Cd	48	210		O_3	480		Si_2H_6	70
Ba	56	320		N_2O	450			
				NO_2	300	9	C_3H_6	120
Hg	80	600		H_2S	270		C_2H_5OH	60
				SO_2	260			
				CS_2	240			
				OCS	240	11	C_3H_8	190
							C_3F_8	100
			4	C_2H_2	390			
						12	C_4F_8	100
				NH_3	400		C_6H_6	240
				NF_3	110		C_6F_6	100
				BF_3	110			
				BCl_3	90	60	C_{60}	300
				PH_3	80			
				H_2CO	180		$M_r + M_v$	700

not final, but finished mostly

include electron swarm papers

include review papers

* He(Ne) + e only. Not include He(Ne) + hν papers.

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