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Bibliography of Electron and Photon Cross Sections
with Atoms and Molecules
Published in the 20th Century
– Nitrogen Molecule –

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Bibliography of Electron and Photon Cross Sections

With Atoms and Molecules

Published in the 20th Century

—— Nitrogen Molecule ——*

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(Gaseous Electronics Institute)

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 nitrogen molecule (N₂). About 2240 papers were compiled. A comprehensive author index is included. The bibliography covers the period 1906 through 2000 for N₂. Finally, author's comments for N₂ electron collision cross section are given.

Keywords : N₂ 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 nitrogen molecule, N_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. Nitrogen 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. Famous authors C. Ramsauer, J. S. Townsend and L. B. Loeb's papers were published in 1921 independently. But oldest paper in this list is given by H. E. Hurst (1906). So for this nitrogen molecule bibliography, published papers from 1906 to 1999 are compiled in alphabetical order of the first author's surname of the paper. References published in 2000 and plus some old papers found very recently after compilation are added as "Addenda of References for Nitrogen Molecule". In total, about 2240 papers are compiled in the nitrogen 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 N₂ are divided into four parts :

- Part 1. 1990 - 1999 p. 1 - 31
- Part 2. 1980 - 1989 p. 32 - 75
- Part 3. 1906 - 1979 p. 76 - 163
- Part 4. Addenda of References (1) published in 2000, plus some old papers p. 164 - 183
- Addenda of References (2) published in 2000, plus some old papers p. 184 - 189

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.

Some Comments on Electron Collision Cross Sections for N₂

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References for N₂ (1990 - 1999)

(Nitrogen)

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.

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Study of rigid-rotor exact exchange electron - N₂ scattering using the
first-order non-degenerate adiabatic theory.
[T, N₂; 0.0027 - 13.6 eV]
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Absolute cross section for the formation of N₂⁺ (X²Σ_u⁺) ions produced by
electron impact on N₂. [E, N₂; th. - 200 eV]
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147-153 (1999b)
Cross section for the production of N₂⁺ (X²Σ_u⁺) ions by electron impact
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[E, N₂]
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High resolution EUV emission spectroscopy of the N₂ c' ¹Σ_u⁺ v' = 3
and 4 levels by electron impact. [E, N₂; 100 eV]
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[T, N₂ + O₂]
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Electron transport coefficients in a weakly ionized plasma with
vibrationally excited molecules. [T, N₂, CO₂, CO]
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Electron transport parameters in a weakly ionized gas with vibrationally
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Ionization and deionization of electron beam disturbed air.
[compilation, N₂ + O₂]
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Electron-impact excitation of the $x^1\Sigma_g^-$, $y^1\Pi_g$ and $o_3^1\Pi_u$ Rydberg electronic states of the nitrogen molecule.
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[E, N_2]
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(Nitrogen)

E : Elastic collision,	R : Rotational excitation,
V : Vibrational excitation,	EX : Electronic excitation,
D : Dissociation,	I : Ionization,
A : Attachment,	QT : Grand total cross section,
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(Nitrogen)

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,
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Some Comments on Electron Collision Cross Sections for N₂

Electron collision cross section set of elastic, rotational excitation, vibrational excitation, electronic excitation, dissociation and ionization collision for nitrogen molecule are reported by many authors. An example is given by A. V. Phelps (1985a) and (1985b). Another one is given by Y. Itikawa (1986).

Recently, we have pointed out at International Symposium on Electron-Molecule Collisions and Swarms, Tokyo that we cannot measure the exact values of electron collision cross sections for all molecules at present (M. Hayashi (1999)). For N₂, target molecules of beam and swarm experiments are mixture of N₂(g), N₂(r) and small amount of N₂(v) molecules. The concentration of N₂(v) increases with high temperature. Electron collision cross section sets for N₂(g), N₂(r) and N₂(v) are different each other. Nitrogen is the homonuclear diatomic molecule. Then differences of cross section sets for N₂(g), N₂(r) and N₂(v) are not so large, compared with triatomic or polyatomic molecules, and concentration of N₂(v) is little. So we can assume that all cross section sets of N₂(g), N₂(r) and N₂(v) are equal approximately. We can use these cross section sets of N₂ for many applications. But if we want more exact cross section sets for N₂, we have to determine these cross section sets separately and independently.

Theoreticians calculate the cross section set for M(g), not for M(r) and M(v) for most molecules. Theoretical values for M(r) and M(v) are urgently required for many molecules.

The experiments of N₂ + hν are also carried out in the mixtures of N₂(g), N₂(r) and N₂(v) molecules. Then obtained results have the temperature dependence. But temperature effects are also not so large for N₂, compared with triatomic or polyatomic molecules.

Author would like to present our conference report at the end of this report.

M. Hayashi and Y. Nakamura : International Symposium on Electron-Molecule Collisions and Swarms, EMS-99, Tokyo 175-176 (1999)

The review paper,

Y. Itikawa, et al. : J. Phys. Chem. Ref. Data 15, 985-1010 (1986)
is a useful and convenient report for N₂ molecule. This report is not shown here.

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 ($N \geq 2$), 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 increases, 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. Unfortunately, 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_{ms} , 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_{ms} , 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 $M(v_1)$, 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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Atoms (17)		Molecules (51)					
A + e.	A + h ν		M + e.	M + h ν .			
He 2	2170 *	2	H ₂ , D ₂	1870	5	CH ₄	780
Ne 10	1140 *		N ₂	2240			
Ar 18	1960		O ₂	1700		CF ₄	390
Kr 36	900		CO	1190		CCl ₄	210
Xe 54	1040		NO	880		CCl ₂ F ₂	250
						CH ₃ Cl	90
Li 3	450		F ₂	190		SiH ₄	230
Na 11	800		Cl ₂	360		SiF ₄	140
K 19	370		Br ₂	140		GeH ₄	50
Rb 37	220		I ₂	240			
Cs 55	370				6	C ₂ H ₄	370
			HF	260		CH ₃ OH	240
O 8	390		HCl	320			
			HBr	190			
F 9	90		HI	130	7	SF ₆	920
Cl 17	130						
		3	CO ₂	1240			
			H ₂ O	850	8	C ₂ H ₆	260
Cu 29	180		O ₃	480		C ₂ F ₆	150
Cd 48	210		N ₂ O	450		Si ₂ H ₆	70
Ba 56	320		NO ₂	300	9	C ₃ H ₆	120
			H ₂ S	270		C ₂ H ₅ OH	60
Hg 80	600		SO ₂	260			
			CS ₂	260			
			OCS	240	11	C ₃ H ₈	190
not final, but finished mostly		4	C ₂ H ₂	390		C ₃ F ₈	100
			NH ₃	400	12	C ₄ F ₈	100
include electron swarm papers			NF ₃	110		C ₆ H ₆	240
			BF ₃	110		C ₆ F ₆	100
include review papers			BCl ₃	90	60	C ₆₀	300
			PH ₃	80			
			H ₂ CO	180		M _r + M _v	850

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

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