ISSN 0915-6364

NATIONAL INSTITUTE FOR FUSION SCIENCE

Report on Cross Section Data Compilation for Electron and Ion Collisions with Molecules of Hydrogen, Hydrogen Isotopes, Nitrogen, Oxygen, Hydrocarbons, Water and Carbon Oxide

M. Kimura, A. Igarashi, M. Imai, Y. Itikawa, M. Kitajima, T. Kusakabe, K. Moribayashi, T. Morishita, K. Motohashi, L. Pichl, R. Suzuki, D. Kato, I, Murakami, T. Kato and M. Kato

(Received - July 6, 2006)

NIFS-DATA-98 Sep. 2006

RESEARCH REPORT
NIFS-DATA Series

TOKI, JAPAN

Report on Cross Section Data Compilation for Electron and Ion Collisions with Molecules of Hydrogen, Hydrogen Isotopes, Nitrogen, Oxygen, Hydrocarbons, Water and Carbon Oxide

Mineo Kimura,[1] Akinori Igarashi,[2] Makoto Imai,[3] Yukikazu Itikawa,[4] Masashi Kitajima,[5,*] Toshio Kusakabe,[6] Kengo Moribayashi,[7] Toru Morishita,[8] Kenji Motohashi,[9] Lukas Pichl,[10,†] Reiko Suzuki,[11] Daiji Kato,[12,‡] Izumi Murakami,[12] Takako Kato,[12] and Masatoshi Kato[12]

[1]*Kyushu University, Fukuoka 812-8581, Japan*

[2]*Miyazaki University, Miyazaki, 899-2192, Japan*

[3]*Kyoto University, Kyoto 606-8501, Japan*

[4]*Institute of Space and Astronautical Science, Sagamihara 229-8510, Japan*

[5]*Sophia University, Chiyoda-ku, Tokyo 102-8554, Japan*

[6]*Kinki University, Higashiosaka, Osaka 577-8502, Japan*

[7]*Japan Atomic Energy Agency, Kizu, Kyoto 619-0215, Japan*

[8]*The University of Electro-Communications, Chofu, Tokyo 182-8585, Japan*

[9]*Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan*

[10]*The University of Aizu, Aizu-Wakamatsu, Fukushima-ken 965-8580 Japan*

[11]*Hitotsubashi University, Kunitachi, Tokyo 186-8601, Japan*

[12]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*

Abstract

A working group searched and reviewed literatures relevant to cross section data for various processes of electron and ion collisions with molecules of hydrogen, hydrogen isotope, hydrocarbon, nitrogen, oxygen, carbon oxide, and water. New data collected by this working group were added to the NIFS (National Institute for Fusion Science) database (*https://dbshino.nifs.ac.jp*) for molecular target, i. e. AMOL (electron collision) and CMOL (ion collision). A new online bibliography database for electron-molecule scattering (*http://crdb.nifs.ac.jp/bib/iti/top.php*) was developed. This is a summary report of this work done by the working group in 2003-2004.

Keywords: electron-molecule collision, ion-molecule collision, cross section, database

*Present address: Tokyo Institute of Technology, Oh-okayama, Tokyo 152-8550, Japan

†Present address:International Christian University, Mitaka, Tokyo 181-8585, Japan

‡Corresponding author:kato.daiji@nifs.ac.jp

1. Introduction

During our '03-'04 activity, we have concentrated our effort on specifically aiming at molecular targets in fusion plasma. We have collected new data and evaluate them for a variety of molecules from hydrogen molecules to hydrocarbons both by electron and ionic impacts. There is a large volume of data collected from previous activities in NIFS for H_2 and D_2 targets. However, for these molecules in hydrogen family, we have found quite a few new experimental as well as theoretical data for various processes by electron and proton impacts and hence, have undertaken an effort of collecting and critically evaluating them and finally have updated our data base in NIFS. We were also concerned with fragmentation processes of molecules after ionization and charge transfer and collected a few new data for fragmentation and fragmented species, while from different perspective, we looked into water molecule since it is relevant to medical purpose as well. As a recent trend, coupled with rapid development of plasma-processing, vigorous experimental and theoretical studies have been performed for hydrocarbons by electron and ion impacts and as a consequence, a large volume of data have been found and collected. Even those molecules where no data is available for hydrocarbon molecules, our experimental members have carried out research to determine collision dynamics and provide accurate cross section data for as a wide energy range as possible. This aspect, that we are able to carry out own research for providing cross section data if necessary, is a part of our strengths and uniqueness of this working group.

The members of this working group are:

- Mineo Kimura (Ion collision: Kyushu University),
- Yukikazu Itikawa (Electron collision: Institute of Space and Astronautical Science, professor emeritus),
- Makoto Imai (Ion collision: Kyoto University),
- Toshio Kusakabe(Ion collision: Kinki University),
- Kenji Motohashi (Ion fragmentation: Tokyo University of Agriculture and Technology),
- Lukas Pichl (Ion collision: International Christian University),
- Reiko Suzuki (Ion collision: Hitotsubashi University),
- Akinori Igarashi (Electron collision: Miyazaki University),
- Daiji Kato (Electron collision: National Institute for Fusion Science),

- Masashi Kitajima (Electron collision: Sophia University),
- Kengo Moribayashi (Electron collision: Japan Atomic Energy Agency),
- Toru Morishita (Electron collision: University of Electro-Communications),
- Takako Kato (Coordinator: National Institute for Fusion Science),
- Izumi Murakami (Coordinator: National Institute for Fusion Science).

Below, each report from individual member is presented.

M. Kimura

2. Electron collisions

Electron collisions for molecules of H_2,D_2, HD, H_3^+,D_3^+, C_mH_n, O_2, H_2O and CO were considered in this work. There were several relevant data books published already. A list of the data books was prepared by Itikawa. Members of this subgroup reviewed the data books on the list. In addition, they searched new publications also which were not considered in the data books. Integrated cross sections of all fundamental processes by electron collision were collected in this work. The collected data were added to the AMOL database.

2.1 H_2, HD and D_2 (A. Igarashi)

We have added e^- + H_2 scattering cross sections to AMOL for total, elastic, momentum transfer, excitation, ionization, attachment, and photo emission. Data for other targets: $H_2^+, H_3^+, HD, HD^+, D_2, D_2^+, D_3^+$ were also included. The literatures are found in Refs. [1]-[12], and summarized in Table I.

TABLE I: Reference table for hydrogen molecule

Process	References
Total	[1], [13]-[24]
Elastic	[4, 9, 25–33]
Momentum transfer	[1, 3, 4, 8, 26, 27, 31–35]
Rotational excitation	[8, 9, 12, 28, 34, 36–39]
Vibrational excitation	[3, 8, 10, 12, 27, 28, 32–36],[40]-[48]
Electronic excitation	[9, 12, 31, 43], [49]-[63]
Ionization	[2, 5, 7, 9, 64–69]
Stopping	[8, 11]
Dissociation	[2, 5, 9]
Photo emission	[5, 9]

2.2 C_mH_n (M. Kitajima)

Electron collisions with hydro-carbons are known to play an important role in the edge of the fusion plasmas. In order to understand the plasmas and construct the modeling of the plasmas, a complete cross section database is necessary and, a number of experimental and theoretical cross section data have been reported. Compilation of these cross section data has been carried out periodically [70–72]. Analytic fit curves of the recommended electron impact cross sections for small hydro-carbons by Janev *et al.* [71] and Shirai *et al.* [72] have been stored into the new version of the cross section database, AMOL. Most of the cross section data reported up to 2004 other than compiled by Janev *et al.* [71] and Shirai *et al.* [72] have also been stored into the database. Molecules and processes for the stored cross section data sets are shown in Table II-IV.

TABLE II: Reference table for electron impact cross section data of C_mH_n ($m = 1$).

Molecule	Process	References
CH_4	total	V [72], E [73], T [74]
	elastic scattering	V [72]
	momentum transfer	V [72]
	total ionization	V [71], V [72], T [75], T [76], T [77], E [78], E [79], E [80], E [81]
	ionization	
	$CH_4 + e \rightarrow CH_4^+ + 2e$	V [71], V [72], E [80], E [81], E [82]
	dissociative ionization	
	$CH_4 + e \rightarrow CH_3^+$	V [71], V [72], E [80], E [81], E [82]
	$CH_4 + e \rightarrow CH_2^+$	V [71], V [72], E [80], E [81], E [82]
	$CH_4 + e \rightarrow CH^+$	V [71], V [72], E [80], E [81], E [82]
	$CH_4 + e \rightarrow C^+$	V [71], V [72], E [80], E [81], E [82]
	$CH_4 + e \rightarrow H_2^+$	V [71], V [72], E [81], E [82]
	$CH_4 + e \rightarrow H^+$	V [71], V [72], E [81], E [82]
	$CH_4 + e \rightarrow CH_2^+ + H^+$	E [83]
	$CH_4 + e \rightarrow CH^+ + H^+$	E [83]
	$CH_4 + e \rightarrow C^+ + H^+$	E [83]
	11 channels of ionic fragment pair production at 200eV	E [82]
	total dissociation	V [72]
	attachment	
	$CH_4 + e \rightarrow CH_4^-$	V [72]
CH_3	total	T [74]
	total ionization	V [71], T [84]
	ionization	
	$CH_3 + e \rightarrow CH_3^+ + 2e$	V [71]
	dissociative ionization	
	$CH_3 + e \rightarrow CH_2^+$	V [71]
	$CH_3 + e \rightarrow CH^+$	V [71]
	$CH_3 + e \rightarrow C^+$	V [71]
	$CH_3 + e \rightarrow H_2^+$	V [71]
	$CH_3 + e \rightarrow H^+$	V [71]
CH_2	total	T [74]
	total ionization	V [71], T [84]
	ionization	
	$CH_2 + e \rightarrow CH_2^+ + 2e$	V [71]
	dissociative ionization	
	$CH_2 + e \rightarrow CH^+$	V [71]
	$CH_2 + e \rightarrow C^+$	V [71]

(continued.)

Molecule	Process	References
	$CH_2 + e \rightarrow H_2^+$	V [71]
	$CH_2 + e \rightarrow H^+$	V [71]
CH	total	T [74]
	total ionization	V [71], T [86]
	ionization	
	$CH + e \rightarrow CH^+ + 2e$	V [71]
	dissociative ionization	
	$CH + e \rightarrow C^+$	V [71]
	$CH + e \rightarrow H^+$	V [71]
	excitation	
	$CH(X\ ^2\Pi) + e \rightarrow CH(A\ ^2\Delta)$	T [85]
	$CH(X\ ^2\Pi) + e \rightarrow CH(B\ ^2\Sigma^-)$	T [85]
	$CH(X\ ^2\Pi) + e \rightarrow CH(C\ ^2\Sigma^+)$	T [85]
	$CH(X\ ^2\Pi) + e \rightarrow CH(a\ ^4\Sigma^-)$	T [85]

TABLE III: Reference table for electron impact cross section data of C_mH_n ($m = 2$).

Molecule	Process	References
C_2H_6	total	V [72], E [73]
	elastic scattering	V [72]
	momentum transfer	V [72]
	total ionization	V [71], V [72], E [79], E [81]
	ionization	
	$C_2H_6 + e \rightarrow C_2H_6^+ + 2e$	V [71], V [72], E [81], E [82], E [87]
	dissociative ionization	
	$C_2H_6 + e \rightarrow C_2H_5^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow C_2H_4^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow C_2H_3^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow C_2H_2^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow C_2H^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow C_2^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow CH_3^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow CH_2^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow CH^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow C^+$	V [71], V [72], E [81], E [82], E [87]
	$C_2H_6 + e \rightarrow H_3^+$	V [72], E [82]
	$C_2H_6 + e \rightarrow H_2^+$	V [72], E [82]
	$C_2H_6 + e \rightarrow H^+$	V [72], E [82]
	$C_2H_6 + e \rightarrow C_2H_5^{2+}$	V [71], E [87]
	$C_2H_6 + e \rightarrow C_2H_3^{2+}$	E [87]
	42 channels of ionic fragment pair production at 200eV	E [82]
	total dissociation	V [72]
C_2H_5	total ionization	V [71]
	ionization	
	$C_2H_5 + e \rightarrow C_2H_5^+ + 2e$	V [71]
	dissociative ionization	
	$C_2H_5 + e \rightarrow C_2H_4^+$	V [71]
	$C_2H_5 + e \rightarrow C_2H_3^+$	V [71]
	$C_2H_5 + e \rightarrow C_2H_2^+$	V [71]
	$C_2H_5 + e \rightarrow C_2H^+$	V [71]
	$C_2H_5 + e \rightarrow CH_3^+$	V [71]
	$C_2H_5 + e \rightarrow CH_2^+$	V [71]
	$C_2H_5 + e \rightarrow CH^+$	V [71]
	$C_2H_5 + e \rightarrow C^+$	V [71]
C_2H_4	total	V [72], E [73], E [88]
	elastic scattering	E [89]
	momentum transfer	V [72], E [89]
	total ionization	V [71], V [72], E [84]

(continued.)

Molecule	Process	References
	ionization	
	$C_2H_4 + e \rightarrow C_2H_4^+ + 2e$	V [71], V [72]
	dissociative ionization	
	$C_2H_4 + e \rightarrow C_2H_3^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow C_2H_2^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow C_2H^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow C_2^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow CH_3^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow CH_2^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow CH^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow C^+$	V [71], V [72]
	$C_2H_4 + e \rightarrow H_2^+$	V [72]
	$C_2H_4 + e \rightarrow H^+$	V [72]
C_2H_3	total ionization	V [71]
	ionization	
	$C_2H_3 + e \rightarrow C_2H_3^+ + 2e$	V [71]
	dissociative ionization	
	$C_2H_3 + e \rightarrow C_2H_2^+$	V [71]
	$C_2H_3 + e \rightarrow C_2H^+$	V [71]
	$C_2H_3 + e \rightarrow C_2^+$	V [71]
	$C_2H_3 + e \rightarrow CH_2^+$	V [71]
	$C_2H_3 + e \rightarrow CH^+$	V [71]
	$C_2H_3 + e \rightarrow C^+$	V [71]
	$C_2H_3 + e \rightarrow H^+$	V [71]
C_2H_2	total	V [72], E [73], E [90]
	elastic scattering	V [72]
	momentum transfer	V [72]
	total ionization	V [71], V [72], T [86]
	ionization	
	$C_2H_2 + e \rightarrow C_2H_2^+ + 2e$	V [71], V [72]
	dissociative ionization	
	$C_2H_2 + e \rightarrow CH^+$	V [71], V [72]
	$C_2H_2 + e \rightarrow C_2H^+$	V [71], V [72]
	$C_2H_2 + e \rightarrow C_2H_2^{2+}$	V [71]
C_2H	total ionization	V [71]
	ionization	
	$C_2H + e \rightarrow C_2H^+ + 2e$	V [71]
	dissociative ionization	
	$C_2H + e \rightarrow C_2^+$	V [71]
	$C_2H + e \rightarrow CH^+$	V [71]
	$C_2H + e \rightarrow C^+$	V [71]
	$C_2H + e \rightarrow H^+$	V [71]

TABLE IV: Reference table for electron impact cross section data of C_mH_n ($m = 3$).

Molecule	Process	References
C_3H_8	total	V [72], E [91]
	elastic scattering	V [72]
	momentum transfer	V [72]
	total ionization	V [71], V [72], E [79]
	ionization	
	$C_3H_8 + e \rightarrow C_3H_8^+ + 2e$	V [71], V [72], E [92], E [82], E [93]
	dissociative ionization	
	$C_3H_8 + e \rightarrow C_3H_7^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_6^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_5^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_4^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_3^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_2^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_2H_5^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_2H_4^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_2H_3^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_2H_2^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_2H^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_2^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow CH_3^+$	V [71], V [72], E [92], E [82], E [93]
	$C_3H_8 + e \rightarrow CH_2^+$	V [71], V [72], E [92], E [82], E [93]
	$C_3H_8 + e \rightarrow CH^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C^+$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow H_3^+$	E [82], E [93]
	$C_3H_8 + e \rightarrow H_2^+$	E [82], E [93]
	$C_3H_8 + e \rightarrow H^+$	E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_5^{2+}$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_4^{2+}$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_3^{2+}$	V [71], V [72], E [82], E [93]
	$C_3H_8 + e \rightarrow C_3H_2^{2+}$	V [71], V [72], E [82], E [93]
	89 channels of ionic fragment pair production at 200eV	E [82], E [93]
C_3H_7	total ionization	V [71]
C_3H_6	total	V [72], E [94]
(propene)	total ionization	V [71], V [72]
C_3H_6	total	V [72], E [94]
(cyclopropane)	total ionization	V [72]
C_3H_5	total ionization	V [71]
C_3H_4	total	E [91], E [95]
(allene)	elastic scattering	E [95], T [96]
	momentum transfer	E [95], T [96]
C_3H_4	total	E [91], E [95]
(propyne)	total ionization	V [71]
	elastic scattering	E [95], T [96]
	momentum transfer	E [95], T [96]
C_3H_4	elastic scattering	T [96]
(cyclopropene)	momentum transfer	T [96]
C_3H_3	total ionization	V [71]
C_3H_2	total ionization	V [71]
C_3H	total ionization	V [71]

2.3 O_2 (D. Kato)

Cross section data were found in previous data compilations listed below.

- Hayashi (1981) [1] presented recommended values of integral and momentum-transfer cross sections for elastic collision and total scattering cross section by electron impact for energies of 10^{-3}eV to keV range. Estimated error of the momentum-transfer cross section was up to 20 %.

- Trajmar (1983) [3] compiled experimental cross section data for various processes which had become available since 1970.

- Tawara and Kato (1987) [7] compiled experimental cross section data for electron impact ionization. To that end, they surveyed relevant literatures up to mid-1986. Those numerical data are stored as one of our databases (AMDIS:Atomic and Molecular Data Interactive System).

- A comprehensive data compilation was reported by Itikawa *et al.* (1989) [97], which included total scattering, elastic scattering, momentum transfer, excitation of rotational, vibrational, and electronic states, dissociation, ionization, and attachment. Later, Itikawa (1994) [98] presented a set of cross section data updated.

- Kanik *et al.* (1993) [99] critically reviewed experimental cross section data for total and elastic scattering, excitation and ionization, and deduced a set of recommended cross sections.

- Zecca *et al.* (1996) [10] reviewed updated experimental data and presented available data for elastic and total scattering, vibrational and electronic excitation, dissociation and ionization cross sections at energies from 0.74 upto 1000 eV.

- Majeed and Strickland (1997) [100] surveyed cross section measurements in the late 1980s and early 1990s, and presented a recommended data set for total ionization and vibrational and electronic excitations.

- Brunger and Buckman (2002) [12] reported a data compilation at low to intermediate energies (10^{-3}eV-100eV) with the intention to update the data compilation by Trajmar *et al.* [3] in 1983.

The cross section data of the above compilations are summarized in Table V. Note this report presents experimental and recommended data only. In some cases, the same data of the identical

paper were included in different compilations. Measurement of ionization cross section by Tian and Vidal (1998) [101] is included in Table V. The data were added to the AMOL database.

Total cross sections and (gross) ionization cross sections are fairly accurate within 5-10 %.Elastic cross sections have uncertainty of 20 % due to lack of reliable differential cross sections.Electronic excitation cross section for vibrationally excited targets is scarce. In measurements of dissociation cross sections, fraction of fragment ion in a particular excited state is unknown. The total, elastic and excitation cross sections show broad maxima at electron energies of about 10 eV, while the ionization cross sections and the emission cross sections of dissociation fragments have maxima at about 100 eV.

TABLE V: Cross section data collection for electron collision with O_2. (E) stands for experimental data and (V) for recommended data.

Process	Electron Energy (eV)
Grand total	0.15-100(E) [12], 1-2000(V) [1], 0.5-1600(E) [3], 1-1000(V) [99], 0.1-1000(V) [97], 0.74-1000(E) [10]
Elastic	1-100(E) [12], 1-1000(V) [1], 2-500(E) [3], 1-1000(V) [99], 0.6-1000(V) [97], 0.74-1000(E) [10]
Elastic momentum transfer	1-100(E) [12], 0-1000(V) [1], 2-200(E) [3], 0.6-1000(V) [97]
Vibrational excitation	
sum of v'=1-12	4-45(E) [97]
v'=1,2,3,4	5-15, 20(E) [12]
total	1-30(V) [100], 0.74-15(E) [10]
Electronic excitation	
total	15-1000(E+V) [10]
$a^1\Delta_g$	2.6-28.6(E) [12], 1.5-200(E) [3, 97], 2-200(V) [100]
$b^1\Sigma_g^+$	5-20(E) [12], 2-150(E) [3, 97], 2-100(V) [100]
$A^3\Sigma_u^+ + C^3\Delta_u + c^1\Sigma_u^-$	20-500(E) [3], 9-20(E) [12], 10-500(E) [97], 6-200(V) [100]
Schumann-Runge continuum ($I^3\Pi_g$+$B^3\Sigma_u^-$+unknown)	20-500(E) [3, 97]
$B^3\Sigma_u^-$	15-50(E) [12], 9-1000(V) [100]
$I^3\Pi_g$	15-50(E) [12], 8-200(V) [100]
W=8.9 eV	9-1000(V) [100]
longest band (W=9.97 eV)	15-50(E) [12], 11-1000(V) [100]
second band (W=10.29 eV)	15-50(E) [12], 12-500(V) [100]
W=9.7-12.1 eV	20-100(E) [3, 97]
Rydberg	17-1000(V) [100]
Inelastic (elec. + rovib.)	4-1000(V) [99]
Ionization	

(continued.)

Process	Electron Energy (eV)
gross ionization	13-1000(E) [98], 13-1000(E) [100], 20-1000(E) [10]
total single-ionization	12.5-20000(E) [7], 15-1000(V) [99], 17.5-600(E) [101]
total double-ionization	45-600(E) [101]
total dissociative ionization	19-1000(V) [97]
O_2^+	13-500(E) [7], 17.5-600(E) [101], 13-170(V) [97]
	13-1000(V) [98]
O_2^{2+}	42-167(E) [7]
O^+	42-167(E) [7], 25-600(E) [101]
O^++O	25-600(E) [101]
O^++O^+	45-600(E) [101]
O^{2+}	70-600(E) [101], 55-1000(E) [98]
O^{2+}+O	100-600(E) [101]
O^{2+}+O^+	100-600(E) [101]
sum of O^+ and O_2^{2+}	18-1000(E) [98]
ionization excitation: $O_2^+(b^4\Sigma_g^-)$	20-5000(V) [97]
Emission cross section	
$O(2p^3 3s\ ^3S \rightarrow 2p^4\ ^3P$, 130.4 nm)	20-4000(E) [97]
$O(2p^3 3s\ ^3D \rightarrow 2p^4\ ^3P$, 98.9 nm)	25-400(E) [97]
$O(2p^3 3d\ ^3D \rightarrow 2p^4\ ^3P$, 102.7 nm)	25-400(E) [97]
$O(2p^3 3p\ ^3P \rightarrow 2p^3 3s\ ^3S$, 844.7 nm)	20-1000(E) [97]
$O_2^+(b\ ^4\Sigma_g^- \rightarrow a\ ^4\Pi_u)$	20-5000(E) [97]
O^+ $(2s2p^4\ ^4P \rightarrow 2s^2 2p^3\ ^4S$, 83.3 nm)	40-2000(E) [97]
Dissociation	
neutral products only	15-150(E) [10]
Dissociative attachment	
O^-+O	5-12(E) [97]

2.4 H_2O (K. Moribayashi)

There are a lot of data of electron impact cross sections of H_2O in Ref. [8, 102]. In addtition to the papers cited in Ref. [8, 102], we have found 19 papers which the cross sections for the processes of elastic scattering [103–107], dissociation and emission [108–111], ionization and dissociation [84, 112–117], and vibrational excitation [118, 119] were shown. It is noted that a data compilation updated by Itikawa and Mason [120] has been published after the present work. They assessed the data carefully and provided recommended data for all major processes. These cross sections are useful for the analysis of the radiation irradiation on the biological materials.

2.5 CO (T. Morishita)

Recently, Brunger and Buckman [12] reported a comprehensive study of experimental cross sections of electron collision with diatomic molecular targets at low to intermediate energies (10^{-3}eV-100eV). The author (TM) got cross section data of CO molecules on their report for elastic, rotational excitation, vibrational excitation and electronic excitation, and input the data into the AMOL database.

2.6 New bibliography databases (L. Pichl)

Upon suggestion of Professor Y. Itikawa, member of the data update working group, we have also developed a new bibliography database for electron-molecule scattering which is available online at the Coordination Research Center of NIFS [121, 122]. The online interface and sample data are shown in Fig. 1.

To this aim, the group of the University of Aizu set up a small database server for experimental purposes in cooperation with Dr. Daiji Kato. The bibliography database in novel by allowing the users to search for *target molecule* and *collision process* entries. The server also hosts other online databases and tools for cooperative projects with other database working groups, especially Dr. Akira Sasaki, JAEA and Dr. Lukáš Pichl, University of Aizu.

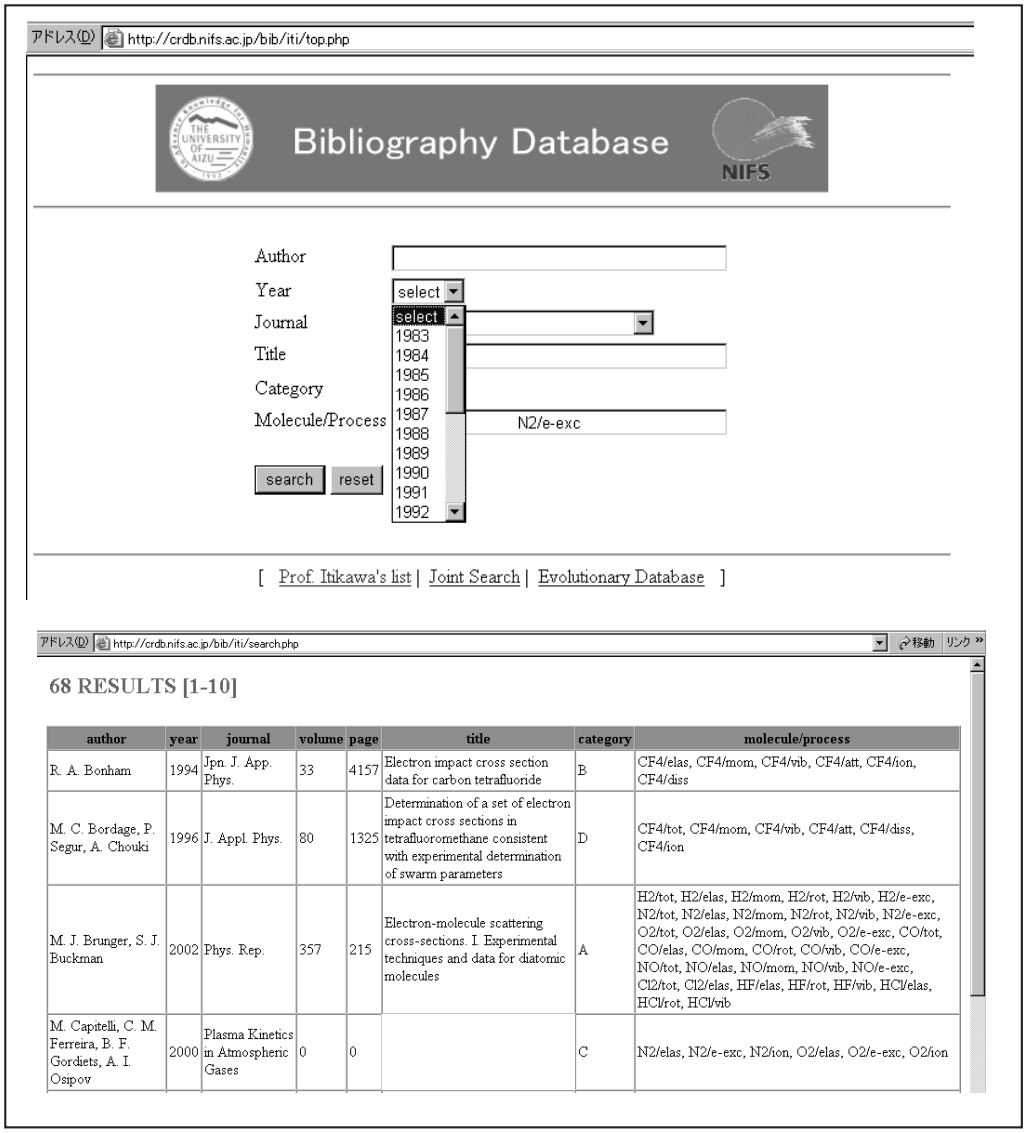

FIG. 1: Bibliography database for electron-molecule scattering with search capabilities for target molecules and collisional processes. Data by courtesy of Prof. Y. Itikawa. Available online at [121].

[1] M. Hayashi, IPPJ-AM-19 (Inst. Plasma Physics, 1981):
"Recommended Values of Transport Cross Sections for Elastic Collision and Total Collision Cross Section for Electrons in Atomic and Molecular Gases".

[2] D. A. Erwin and J. A. Kunk, IEEE Transaction on Plasma Science PS-11, 266 (1983):
"Rate Coefficients for Some Collisional Processes in High-Current Hydrogen Discharges".

[3] S. Trajmar, D. F. Register and A. Chutjian, Phys. Reports 97, 219 (1983):

"Electron Scattering by Molecules II. Experimental Methods and Data".

[4] S. J. Buckman and A. V. Phelps, JILA Information Center Report No. 27 (1985).

[5] H. Tawara, Y. Itikawa, Y. Itoh, T. Kato, H. Nishimura, S. Ohtani, H. Takagi, K. Takayanagi and M. Yoshino, IPPJ-AM-46 (Inst. Plasma Physics, 1986):
"Atomic Data Involving Hydrogens Relevant to Edge Plasmas".

[6] H. Tawara, Y. Itikawa, H. Nishimura and M. Yoshino, IPPJ-AM-55 (Inst. Plasma Physics, 1987):
"Atomic Data for Hydrogens in Collisions with Electrons -Addenda to IPPJ-AM-46".

[7] H. Tawara and T. Kato, Atomic Data and Nucl. Data Tables 36, 167 (1987):
"Total and Partial Ionization Cross Sections of Atoms and Ions by Electron Impact".

[8] I. Shimamura, Sci. Papers Inst. Phys. Chem. Res. 82, 1 (1989):
"Cross Sections for Collisions of Electrons with Atoms and Molecules".

[9] H. Tawara, Y. Itikawa, H. Nishimura and M. Yoshino, J. Phys. Chem. Ref. Data 19, 617 (1990):
"Cross Sections and Related Data for Electron Collisions with Hydrogen Molecules and Molecular Ions".

[10] A. Zecca, G. P. Karwasz and R. S. Brusa, La Rivusta del Nuovo Ciment 19, 1 (1996):
"One century of experiments on electron-atom and molecule scattering: a critical review of integral cross-sections. I. Atoms and diatomic molecules".

[11] A. Dalgarno, M. Yan and W. Liu, Astrophys. J. Supp. 125, 237 (1999):
"Electron energy deposition in a gas mixture of atomic and molecular hydrogen and helium".

[12] M. J. Brunger and S. J. Buckman, Phys. Reports 357, 215 (2002):
"Electron molecule scattering cross-sections. I. Experimental techniques and data for diatomic molecules".

[13] A. Deuring, *et al.*, J. Phys. B 16, 1633 (1983):
"Total Cross Section Measurements for Positron and Electron Scattering on Molecular Hydrogen Between 8 and 400 eV".

[14] R. K. Jones, Phys. Rev. A 31, 2898 (1985):
"Absolute Total Cross Section for Electron Scattering from Molecular Hydrogen from 1 to 50 eV".

[15] K. P. Subramanian, V. Kumar, J. Phys. B 22, 2387 (1989):
"Total electron scattering cross sections for molecular hydrogen at low electron energies".

[16] J. C. Nickel *et al.*, J. Phys. B 25, 2427 (1992):
"Total cross section measurements for electron scattering on H_2 and N_2 from 4 to 300 eV".

[17] J. Randnell *et al.*, J. Phys. B 27, 2369 (1994):

"Low energy electron scattering in H_2, N_2 and O_2".

[18] J. Ferch, W. Raith and K. Schroder, J. Phys. B 13, 1481 (1980):
"Total cross section measurements for electron scattering from molecular hydrogen at very low energies".

[19] Cz. Szmytkowski *et al.*, Phys. Scr. 54, 271 (1996): "Absolute electron-scattering total cross section measurements for noble gas atoms and diatomic molecules".

[20] G. Dalba *et al.*, J. Phys. B 13, 2836 (1980):
"Measurements of total absolute cross sections for 0.2-100 eV electrons on H_2".

[21] K. R. Hoffman *et al.*, Phys. Rev. A 25, 1393 (1982):
"Total-cross-section measurements for positrons and electrons colliding with H_2, N_2, and CO_2".

[22] A. Jain and K. L. Baluja, Phys. Rev. A 45, 202 (1992):
"Total (elastic plus inelastic) cross sections for electron scattering from diatomic and polyatomic molecules at 10-5000 eV: H_2, Li_2, HF, CH_4, N_2, CO, C_2H_2, HCN, O_2, HCl, H_2S, PH_3, SiH_4, and CO_2".

[23] B. van Wingerden *et al.*, J. Phys. B 13, 3481 (1980):
"Total cross sections for electron scattering by molecular hydrogen".

[24] J. W. Liu, Phys. Rev. A 35, 591 (1987):
"Total cross sections for high-energy electron scattering by $H_2(^1\Sigma_g^+)$, $N_2(^1\Sigma_g^+)$, and $O_2(^3\Sigma_g^-)$".

[25] B. van Wingerden *et al.*, J. Phys. B 10, 1345 (1977):
"Elastic scattering of electrons by molecular and atomic hydrogen".

[26] T. W. Shyn and W. E. Sharp, Phys. Rev. A 24, 1734 (1981):
"Angular distributions of electrons elastically scattered from H_2".

[27] H. Nishimura *et al.*, J. Phys. Soc. Jpn 54, 1757 (1985):
"Differential Cross Sections of Electron Scattering from Molecular Hydrogen I. Elastic Scattering and Vibrational Excitation ($X^1\Sigma_g^+, v = 0 \rightarrow 1$)".

[28] F. Linder and H. Schmidt and Z. Naturforschh. 26a, 1603 (1971):
"Rotational and Vibrational Excitation of H_2 by Slow Electron Impact".

[29] S. K. Srivastava *et al.*, J. Chem. Phys. 63, 2659 (1975):
"Absolute elastic differential electron scattering cross sections in the intermediate energy region. I. H_2".

[30] J. Furst *et al.*, Phys. Rev. A 30, 2256 (1984):
"Absolute total electronically elastic differential e^--H_2 scattering cross-section measurements from 1 to 19 eV".

[31] M. A. Khakoo and S. Trajmar, Phys. Rev. A 34, 146 (1986):

"Electron-impact excitation of the $a^3\Sigma_g^+$, $B^1\Sigma_u^+$, $c^3\Sigma_u$, and $C^1\Sigma_u$ states of H_2".

[32] M. J. Brunger *et al.*, Aust. J. Phys. 43, 665 (1990):
"Low energy electron scattering from H_2".

[33] M. J. Brunger *et al.*, J. Phys. B 24, 1435 (1991):
"Elastic scattering and rovibrational excitation of H_2 by low-energy electrons".

[34] J. P. England *et al.*, Aust. J. Phys. 41, 573 (1988):
"A study of the vibrational excitation of H_2 by measurements of the drift velocity of electrons in H_2-Ne mixtures".

[35] B. Schmidt *et al.*, Phys. Scr. 53, 30 (1994):
"New experimental techniques in the study of electron swarms in gases and their impact on the determination of low energy electron scattering cross sections".

[36] M. A. Morrison *et al.*, Aust. J. Phys. 40, 239 (1987):
"Near-threshold rotational and vibrational excitation of H_2 by electron impact: theory and experiment".

[37] R. W. Crompton *et al.*, Phys. Rev. A 2, 1386 (1970):
"Vibrational Excitation of H_2 by Low-Energy Electrons".

[38] R. W. Crompton *et al.*, Aust. J. Phys. 22 715-731 (1969):
"The Cross Section for the $J = 0 \rightarrow 2$ Rotational Excitation of Hydrogen by Slow Electrons".

[39] D. K. Gibson, Aust. J. Phys. 23, 683 (1970):
"The Cross Sections for Rotational Excitation of H_2 and D_2 by Low Energy Electrons".

[40] H. Ehrhardt *et al.*, Phys. Rev. 173, 222 (1968):
"Resonance Scattering of Slow Electrons from H_2 and CO Angular Distributions".

[41] T. N. Rescigno *et al.*, J. Phys. B 26, L567 (1993):
"An ab initio treatment of near-threshold vibrational excitation of H_2 by electron impact: new perspectives on discrepancies between crossed-beam and swarm data".

[42] M. Allan, J. Phys. B 18, L451 (1985):
"Experimental observation of structures in the energy dependence of vibrational excitation in H_2 by electron impact in the $^2\Sigma_u^+$ resonance region".

[43] R. I. Hall and L. Andric, J. Phys. B 17, 3815 (1984):
"Electron impact excitation of H_2 (D_2). Resonance phenomena associated with the $X^2\Sigma_u^+$ and $B^2\Sigma_g^+$ states of H_2^- in the 10 eV region".

[44] S. F. Wong and G. J. Schulz, Phys. Rev. Lett. 32, 1089 (1974):
"Rotational and Vibrational Excitation of H_2 by Electron Impact at 4.5 eV: Angular Distributions".

[45] C. Mundel *et al.*, Phys. Rev. A 32, 181 (1985):
" Nuclear dynamics in resonant electron-molecule scattering beyond the local approximation: Vibrational excitation and dissociative attachment in H_2 and D_2".

[46] W. F. Chan *et al.*, Chem. Phys. 168, 375 (1992):
"Absolute optical oscillator strengths (11-20 eV) and transition moments for the photoabsorption of molecular hydrogen in the Lyman and Werner bands".

[47] M. Cacciatore *et al.*, Chem. Phys. 55, 67 (1981):
"Cross sections and rate coefficients for electronic excitation of the triplet states of the hydrogen molecule in different vibrational levels".

[48] J. N. Bardsley *et al.*, Phys. Rev. A 20, 1398 (1979):
"Dissociative attachment and vibrational excitation in low-energy collisions of electrons with H_2 and D_2".

[49] S. K. Srivastava and S. Jensen, J. Phys. B 10, 3341 (1977):
"Experimental differential and integral electron impact cross sections for the $B^1\Sigma_u^+$ state of H_2 in the intermediate-energy region".

[50] T. L. Gibson *et al.*, Phys. Rev. A 35, 2473 (1987):
"Application of the Schwinger multichannel formulation to electron-impact excitation of the $B^1\Sigma_u^+$ state of H_2".

[51] H. Nishimura and A. Danjo, J. Phys. Soc. Jpn 55, 3031 (1986):
"Differential Cross Section of Electron Scattering from Molecular Hydrogen. II. $b^3\Sigma_u^+$ Excitation".

[52] M. A. Khakoo *et al.*, Phys. Rev. A 35, 2832 (1987):
"Electron-impact excitation cross sections for the $b^3\Sigma_u^+$ state of H_2".

[53] M. A. Khakoo and J. Segura, J. Phys. B 27, 2355 (1994):
"Differential cross sections for the electron impact excitation of the $b^3\Sigma_u^+$ continuum of molecular hydrogen".

[54] M. A. P. Lima *et al.*, Phys. Rev. A 38, 4527 (1988):
" Cross sections for excitation of the $b^3\Sigma_u^+$, $a^3\Sigma_g^+$, and $c^3\Sigma_u$ states of H_2 by low-energy electrons".

[55] J. M. Ajello *et al.*, EOS Transaction Am. Geophys. Union 66 (1985) 989.

[56] J. M. Ajello *et al.*, Phys. Rev. A 29, 636 (1984):
"Studies of extreme-ultraviolet emission from Rydberg series of H_2 by electron impact".

[57] F. J. de Heer, J. D. Carrier, J. Chem. Phys. 55, 3829 (1971):
"Emission of the Werner Band System and Lyman-α Radiation for 0.05-6-keV Electrons in H_2".

[58] M. -T. Lee *et al.*, Phys. Rev. A 26, 3240 (1982):
"Electron-impact excitation and dissociation processes in H_2".

[59] T. N. Rescigno *et al.*, Phys. Rev. A 13, 216 (1976):
"Low-energy electron-impact excitation of the hydrogen molecule".

[60] S. Chung and C. C. Lin, Phys. Rev. A 17, 1874 (1978):
"Application of the close-coupling method to excitation of electronic states and dissociation of H_2 by electron impact".

[61] S. J. B. Corrigan, J. Chem. Phys. 43, 4381 (1965):
"Dissociation of Molecular Hydrogen by Electron Impact".

[62] T. N. Rescigno and B. I. Schneider, J. Phys. B 21, L691 (1988):
"Electron-impact excitation of the $b^3\Sigma_u^+$ state of H_2 using the complex Kohn method: R dependence of the cross section".

[63] M. A. P. Lima *et al.*, J. Phys. B 18, L865 (1988):
"Cross sections for electron impact excitation of the $b^3\Sigma_u^+$ state of H_2: an application of the Schwinger multichannel variational method".

[64] I. R. Cowling *et al.*, J. Phys. B 6, 665 (1973):
"Electron-molecule collision ionization in hydrogen and deuterium".

[65] B. L. Schram *et al.*, Physica 32, 734 (1966): "Ionization Cross Sections for Electrons (100-600eV) in Noble and Diatomic Gases".

[66] D. Rapp and P. Englander-Gorden, J. Chem. Phys. 43, 1464 (1965):
"Total Cross Sections for Ionization and Attachment in Gases by Electron Impact. I. Positive Ionization".

[67] B. L. Schram *et al.*, Physica 31, 94 (1965): "Ionization Cross Sections for Electrons (0.6-20 keV) in Noble and Diatomic Gases".

[68] J. T. Tate and P. T. Smith, Phys. Rev. 39, 270 (1932):
"The Efficiencies of Ionization and Ionization Potentials of Various Gases Under Electron Impact".

[69] R. L. Boyd and G. W. Green, Proc. Phys. Soc. 71, 351 (1958): "Electron Ionization Cross Sections using Chopped Beams".

[70] H. Tawara, Y. Itikawa, H. Nishimura, H. Tanaka and Y. Nakamura, NIFS-DATA-6 (National Institute for Fusion Science, 1990):
"Collision Data Involving Hydro-Carbon Molecules".

[71] R. K. Janev, J. G. Wang, I. Murakami and T. Kato, NIFS-DATA-68 (National Institute for Fusion

Science, 2001):

"Cross Sections and Rate Coefficients for Electron-Impact Ionization of Hydrocarbon Molecules".

[72] T. Shirai, T. Tabata, H. Tawara and Y. Itikawa, At. Data Nucl. Data Tables 80, 147 (2002):

"Analytic Cross Sections for Electron Collisions with Hydrocarbons: CH_4, C_2H_6, C_2H_4, C_2H_2, C_3H_8, AND C_3H_6".

[73] W. M. Ariyasinghe and D. Powers, Phys. Rev. A 66, 052716 (2002):

"Total electron scattering cross sections of CH_4, C_2H_2, C_2H_4, and C_2H_6 in the energy range 200-1400 eV".

[74] K. N. Joshipura, M. Vinodkumar and U. M. Patel, J. Phys. B 34, 509 (2001):

"Electron impact total cross sections of CH_x, NH_x and OH radicals vis-à-vis their parent molecules".

[75] W. M. Huo, Phys. Rev. A 64, 042719 (2001).

"Convergent series representation for the generalized oscillator strength of electron-impact ionization and an improved binary-encounter-dipole model".

[76] S. P. Khare, M. K. Sharma and S. Tomar, J. Phys. B 32, 3147 (1999):

"Electron impact ionization of methane".

[77] Y. -K. Kim, W. Hwang, N. M. Weinberger, M. A. Ali and M. E. Rudd, J. Chem. Phys. 106, 1026 (1997):

"Electron-impact ionization cross sections of atmospheric molecules".

[78] C. Vallance, S. A. Harris, J. E. Hudson and P. W. Harland, J. Phys. B 30, 2465 (1997): "Absolute electron impact ionization cross sections for CH_3, where X = H, F, Cl, Br, and I".

[79] N. Durić, I. Cádež and M. Kurepa, Int. J. Mass. Spectrom. Ion Processes 108, R1 (1991):

"Electron impact total ionization cross-sections for methane, ethane and propane".

[80] O. J. Orient and L. K. Srivastava, J. Phys. B 20, 3923 (1987):

"Electron impact ionisation of H_2O, CO, CO_2 and CH_4".

[81] H. Chatham, D. Hils, R. Robertson and A. Gallagher, J. Chem. Phys. 81, 1770 (1984):

"Electron impact ionization of H_2O, CO, CO_2, and CH_4".

[82] P. Wang and C. R. Vidal, Chem. Phys. 280, 309 (2002):

"Dissociation of multiply ionized alkanes from methane to n-butane due to electron impact".

[83] B. G. Lindsay, R. Rejoub and R. F. Stebbings, J. Chem. Phys. 114, 10225 (2001):

"Production of positive ion pairs by electron-impact ionization of CH_4".

[84] W. Hwang, Y. -K. Kim and M. E. Rudd, J. Chem. Phys. 104, 2956 (1996):

"New model for electron-impact ionization cross sections of molecules".

[85] K. L. Baluja and A. Z. Msezane, J. Phys. B 34, 3157 (2001):
"Electron collisions with methylidyne (CH) radical using the R-matrix method".

[86] Y. -K. Kim, M. A. Ali and M. E. Rudd, J. Res. Natl. Inst. Stand. Technol. 102, 693 (1997):
"Electron-impact total ionization cross sections oh CH and C_2H_2".

[87] V. Grill, G. Walder, P. Scheier, M. Kurdel and T. D. Mark, Int. J. Mass Spectrom. Ion Processes 129, 31 (1993):
"Absolute partial and total electron impact ionization cross sections for C_2H_6 from threshold up to 950 eV".

[88] Cz. Szmytkowski, S. Kwitnewski and E. Ptasinska-Denga, Phys. Rev. A 68, 032715 (2003):
"Electron collisions with tetrafluoroethylene (C_2F_4) and ethylene (C_2H_4) molecules".

[89] R. Panajotovic, M. Kitajima, H. Tanaka, M. Jelisavcic, J. Lower, L. Campbell, M. J. Brunger and S. J. Buckman, J. Phys. B 36, 1615 (2003):
"Electron collisions with ethylene".

[90] O. Sueoka and S. Mori, J. Phys. B 22, 963 (1989):
"Total cross section measurements for 1-400 eV positrons and electrons in C_2H_2".

[91] Cz. Szmytkowski and S. Kwitnewski, J. Phys. B 35, 3781 (2002):
"Total cross sections for electron scattering with some C_3 hydrocarbons".

[92] V. Grill, G. Walder, D. Margreiter, T. Rauth, H. U. Poll, P. Scheier and T. D. Mark, Z. Phys. D 25, 217 (1993):
"Absolute partial and total electron impact ionization cross sections for C_3H_8 from threshold up to 950 eV".

[93] P. Wang and C. R. Vidal, J. Chem. Phys. 116, 123 (2002):
"Single to triple ionization of propane due to electron impact: Cross sections for the different dissociation channels".

[94] Cz. Szmytkowski and S. Kwitnewski, J. Phys. B 35, 2613 (2002):
"Electron scattering on C_3H_6 isomers".

[95] C. Makochekanwa, H. Kawate, O. Sueoka, M. Kimura, M. Kitajima, M. Hoshino and H. Tanaka, Chem. Phys. Lett. 368, 82 (2003):
"Total and elastic cross-sections of electron and positron scattering from C_3H_4 molecules (allene and propyne)".

[96] A. R. Lopes and M. H. F. Bettega, Phys. Rev. A 67, 032711 (2003):
"Elastic scattering of low-energy electrons by C_3H_4 isomers".

[97] Y. Itikawa *et al.*, J. Phys. Chem. Ref. Data 18, 23-42 (1989):
"Cross sections for collisions of electrons and photons with oxygen molecules".

[98] Y. Itikawa, Adv. At. Mol. Opt. Phys. 33, 253 (1994):
"Electron collisions with N_2, O_2, and O: What we do and do not know".

[99] I. Kanik, S. Trajmar and J. C. Nickel, J. Geophys. Res. 98, 7447-7460 (1993):
"Total electron scattering and electronic state excitations cross sections for O_2, CO and CH_4".

[100] A. Majeed and D. J. Strickland, J. Phys. Chem. Ref. Data 26, 335 (1997):
"New survey of electron impact cross sections for photoelectron and auroral electron energy loss calculations".

[101] C. Tian and C. R. Vidal, J. Phys. B 31, 5369-5381 (1998):
"Electron impact ionization of N_2 and O_2: contributions from different dissociation channels of multiply ionized molecules".

[102] T. Shirai, T. Tabata and H. Tawara, At. Data Nucl. Data Tables 79 (2001) 143.

[103] W. M. Johnston and W. R. Newell, J. Phys. B 24, 3633 (1991):
"Absolute vibrationally elastic cross sections for electrons scattered from water molecules between 6 eV and 50 eV".

[104] A. Danjo and H. Nishimura, J. Phys. Soc. Jpn. 54, 1224 (1985):
"Elastic Scattering of Electrons from H_2O Molecule".

[105] T. W. Shyn and A. Grafe, Phys. Rev. A 46, 4406 (1992):
"Angular distribution of electrons elastically scattered from water vapor".

[106] T. W. Shyn and S. Y. Cho, Phys. Rev. A 36, 5138 (1987):
"Vibrationally elastic scattering cross section of water vapor by electron impact".

[107] A. Katase, K. Ishibashi, Y. Matsumoto, T. Sakae, S. Maezono, E. Murakami, K. Watanabe, H. Maki, J. Phys. B 19, 2715 (1986):
"Elastic scattering of electrons by water molecules over the range 100-1000 eV".

[108] T. Ogawa, S. Ihara, N. Yonekura, T. Yasuda and K. Nakashima, Chem. Phys. 168, 145 (1992):
"Formation cross sections, emission cross sections and Fano plots of translational-energy-separated excited hydrogen atoms ($n = 3, 4$) produced in e-H_2O collisions".

[109] G. R. Mohlmann, K. H. Shima and F. J. De Heer, Chem. Phys. 28, 331 (1978):
"Production of H, D(2s, 2p) by electron impact (0-2000 eV) on simple hydrogen containing molecules".

[110] D. A. Vroom and F. J. De Heer, J. Chem. Phys. 50, 1883 (1969):
"Production of Excited Hydrogen Atoms by Impact of Fast Electrons on Water Vapor".

[111] G. R. Mohlmann and F. J. De Heer, Chem. Phys. 40, 157 (1979):
"Production of Balmer radiation by electron impact (0-2000 eV) on small hydrogen containing molecules".

[112] J. Schutten, F. J. De Heer, H. R. Moustafa, A. J. H. Boerboom and J. Kistemaker, J. Chem. Phys. 44, 3924 (1966):
"Gross- and Partial-Ionization Cross Sections for Electrons on Water Vapor in the Energy Range 0.1-20 keV".

[113] H. C. Straub, B. G. Lindsay, K. A. Smith and R. F. Stebbings, J. Chem. Phys. 108, 109 (1998):
"Absolute partial cross sections for electron-impact ionization of H_2O and D_2O from threshold to 1000 eV".

[114] N. J. Djuric, I. M. Cadez and M. V. Kurepa, Int. J. Mass. Spectrom. Ion Processes 83, R7 (1988):
"H_2O and D_2O total ionization cross-sections by electron impact".

[115] M. A. Bolorizadeh and M. E. Rudd, Phys. Rev. A 33, 882 (1986):
"Angular and energy dependence of cross sections for ejection of electrons from water vapor. I. 50-2000 eV electron impact".

[116] C. I. M. Beenakker, F. J. De Heer, H. B. Krop and G. R. Mohlmann, Chem. Phys. 6, 445 (1974):
"Dissociative excitation of water by electron impact".

[117] T. D. Mark and F. Egger, Int. J. Mass. Spectrom. Ion Processes 20, 89 (1976):
"Cross-Section for Single Ionization of H_2O and D_2O nu Electron Impact from Threshold up to 170 eV".

[118] T. W. Shyn, S. Y. Cho and T. E. Cravens, Phys. Rev. A 38, 678 (1988):
"Vibrational-excitation cross sections of water molecules by electron impact".

[119] G. Seng and F. Linder, J. Phys. B 9, 2539 (1976):
"Vibrational excitation of polar molecules by electron impact. II. Direct and resonant excitation in H_2O".

[120] Y. Itikawa and N. Mason, J. Phys. Ref. Data 34, 1 (2005):
"Cross Section for Electron Collisions with Water Molecules".

[121] Bibliography database for electron - molecule scattering (data by courtesy of Prof. Y. Itikawa), http://crdb.nifs.ac.jp/bib/iti/top.php

[122] L. Pichl, M. Suzuki, H. Kashiwagi, K. Joe, D. Kato and A. Sasaki, GESTS International Transaction on Computer Science and Engineering 12(No. 1), 93 (2005).

3. Ion collisions

Following sections concern ion-molecule collision. Cross section data compilation for target molecules of H_2, HD, D_2,N_2, O_2, C_mH_n, CO and CO_2 is presented. The data were added to the CMOL database.

3.1 H - Ne projectiles colliding with H_2, D_2, N_2 and O_2 (M. Imai)

In the present work, new data were added for collision systems of atoms and ions of H - Ne projectiles colliding with molecules of hydrogen, deuterium, nitrogen and oxygen with intention to update Table 13 of the previous report (NIFS-DATA-70 [1]). Data for state-selective collisions are also included [3],[8]. Note that Dmitriev *et al.* [7] have studied single electron capture by helium-like projectiles of Li, Be and N ions at the ground and metastable(1s2s) states from N_2 molecules.

Projectile ionic species	Target molecular species	References
H^0, H^+, D^+	H_2, HD, D_2	[4, 6, 10]
N^{5+}	H_2	[3, 8]
O^{q+}(q=0,2-6)	H_2	[5, 9]
He^{2+}	O_2	[2]
Li^+	N_2	[7]
Be^{2+}	N_2	[7]
N^{5+}	N_2	[7]
O^0	N_2, O_2	[9]

3.2 Dissociative charge exchange of H_2, N_2, O_2, CO, CO_2 and C_nH_m (K. Motohashi)

Data of ion-production cross sections, emission cross sections and branching ratios for dissociative charge exchange in ion-molecule collisions in the impact-energy range from 1 eV to 100 keV were compiled and analyzed. Papers on cross sections, branching ratios and the kinetic energy release (KER) of fragment ions in "Journal of Physics B", "Physical Review A", "Physical Review Letters" and "The Journal of Chemical Physics" in 1969 to 1999 were collected.

Fragmentation or dissociation of molecule is one of the most fundamental processes among chemical reactions. Dissociation via the charge exchange of ion-molecule collisions is especially important

in the plasma of ionosphere and nuclear fusion because of their large cross sections. There have been very scarce, however, of quantitative studies on dissociative ion-molecule collisions in low energy (from 1 eV to 100 keV). In this report, the data on cross sections, branching ratios of ion production, and KERs of fragment ions in dissociative charge exchange processes of ion-molecule collisions are compiled and summarized.

Studies on dissociative charge exchange of ion-molecule collisions reported in 1969 to 1999 were found in "Journal of Physics B", "Physical Review A", "Physical Review Letters" and "The Journal of Chemical Physics". In the present research, incident ions of H^+, C^{q+}, N^{q+}, O^{q+}, and rare gas ions were considered. Target molecules were H_2, N_2, O_2, CO, CO_2 and the simple hydrocarbon molecules. Collision energy is in the range from 1 eV to 100 keV. Charge exchange process is dominant in this energy range.

The cross-section measurements of dissociative charge transfer in ion-molecule collisions are listed in Table VI. Five papers in keV energy range and four papers in eV energy range are included. All of them are experimental studies. Detected particles are fragment ions except for the study of reference [16]. Absolute cross sections of secondary ion formation from many kinds of simple molecules were measured by Gilbody's group [11–13]. The cross sections were obtained by normalizing the values of total cross sections of secondary ion formation to ones measured by de Heer *et al.* [20]. Errors of their cross sections were estimated to be less than 20%. This value includes reading error of about 7% associated with relative measurements and uncertainty of 10% in normalization procedure. Lindsay *et al.* [14] measured relative differential cross sections for the production of secondary protons from the specific states of H_2^+* in 5-25 keV H^+-H_2 collisions by coincidence technique with a time-of-flight mass separator and a parallel plate energy analyzer. Inouye *et al.* [16] measured relative optical emission cross sections of excited CH* and CH^+ radicals produced in collisions of He^+ and Ar^+ with acetylene. Only relative cross sections were measured because absolute values of detection efficiency of their optical system were unknown. Absolute state-selected cross sections for abstraction-charge transfer reactions were measured by a group of Iowa State University [17–19]. The state-selected measurements were carried out by use of reactant ions (C^+ and O^+) produced by a high-pressure ion source or a VUV photoionization ion source.

In general, measured cross sections for production of secondary particles have relatively large errors because of large uncertainties of detection efficiencies. The detection efficiency generally depends on energies and angles of particles to be detected. It is also difficult to determine absolute values because normalization procedures have uncertainties.

TABLE VI: Cross section measurements of dissociative charge transfer in ion-molecule collisions.

Incident ions	Target molecules	Species	Collision energy	Partial cross sections of	Ref.
H^+	O_2, N_2, CO, and CH_4	O^+, O^{2+}, N^+, N^{2+}, C^+, C^{2+}, CH^+, CH_2^+, CH_3^+, H^+, H_2^+	5-45 keV	Secondary ion formation	[11]
He^+	H_2, N_2, O_2, CO, CO_2, and CH_4	H^+, N^+, N^{2+}, O^+ O^{2+}, C^+, C^{2+}, CO^+, CH^+, CH_2^+, CH_3^+, and H_2^+	5-45 keV (LAB)	Secondary ion formation	[12]
Ne^+ and Na^+	H_2, N_2, O_2, and CO	H^+, N^+, N^{2+}, O^+, O^{2+}, C^+, and C^{2+}	5-45 keV (LAB)	Secondary ion formation	[13]
H^+	H_2	H^+	5-25 keV (LAB)	State-selected fragmentation	[14]
H^+	N_2	N^+	5-25 keV	Ion-pair formation	[15]
He^+ and Ar^+	C_2H_2	CH*(A-X), (B-X), and CH^+*(B-A)	30-300 eV (LAB)	Optical emission	[16]
C^+	N_2	N^+ and CN^+	4-8 eV (CM)	Abstraction-charge transfer	[17]
O^+	H_2 and D_2	H^+, D^+, OH^+ and OD^+	0.02-12 eV (CM)	Abstraction-charge transfer	[18]
O^+	N_2	N^+ and NO^+	0.06-40 eV (CM)	Abstraction-charge transfer	[19]

3.3 Charge transfer of C_mH_n (T. Kusakabe)

Collision processes between ions and molecules are important in basic research and in a number of applications such as astrophysics, plasma science and material science. However, the present knowledge of collisions processes involving molecular targets is limited and the amount of collision data is very scarce. Collision data of charge transfer processes by slow ions from molecular targets are urgently required in many applied fields because charge transfer makes a dominant contribution at energies below 100 keV/u. Among many types of molecules, various hydrocarbons, such as CH_4, C_2H_2, C_2H_4 and so forth, have been observed near the divertor edge. Hence, charge transfer processes for these large hydrocarbons (C_mH_n, where $m = 1 - 4$) are also important which provide essential ingredients for the modeling of plasma and carbon behavior. Here we attempt to review cases of some selective hydrocarbons as shown in the following Table.

We searched not only some research journals, but also consulted some data books [21–23]. For hydrocarbons, very few investigations have been carried out. We found only 4 publications [24–27]. Therefore, we undertook the effort to carry out a joint experimental and theoretical study of charge transfer from these hydrocarbons by H^+, He^{2+}, C^{q+} ($q = 1-3$), Ne^{q+} ($q = 2-6$) and Ar^{q+} ($q = 2-9$)

Projectile ionic species:	All species of atomic ions
Target molecular species:	Hydrocarbon molecules (C_mH_n, where $m = 1 - 4$)
Energy region:	a few eV - a few MeV
Search of papers published:	Primarily before 2003,
	but recent interval (2000 - 2003) for light ions (H^+ - Ne^{q+}).
References:	[21]-[27]

ion impacts below 10 keV. We have also carried out a careful study on the effect of vibrational states and isomer of the target. Results will be published elsewhere.

3.4 Charge transfer in collisions of O^{q+} ions with $H_2(1s^2 X^1\Sigma_g^+)$ (L. Pichl)

There have been two theoretical papers on electron capture in O^{q+} collisions with the H_2 molecule published in 2004 [28, 41]. Pichl *et al.* [28] calculated the state-resolved and total cross sections with $q = 1$ for the ground-state $O^+(^4S)/H_2$ collision using the electronic-state molecular orbital approximation (quantal and semiclassical) with the projectile energy ranging between 50 eV/u and 10 keV/u. They also extrapolated the theoretical method beyond this interval. The results in [28] agree well with different sets of experimental data below and above the projectile energy of 100 eV/u as shown in Fig. 2.

Wang *et al.* [41] calculated the state-resolved and total cross section for the ground-state $O^{3+}(^2P)/H_2$ collision including target vibrations to some extent while neglecting the possibility of multiple electron capture and Coulomb explosion of the target. The results for fixed H_2 internuclear distance including a comparison to semiclassical results by L. Pichl and M. Kimura are shown in Fig. 3. Final geometry-averaged data including state-resolved cross-section and comparison of various theoretical approaches were also published [41]. Note the agreement of the full-quantal cross sections computed in Stancil's group in University of Georgia with the semiclassical results by Pichl *et al.* in the energy range of 0.1 to 1.0 keV, where both methods apply (cf. Fig. 3).

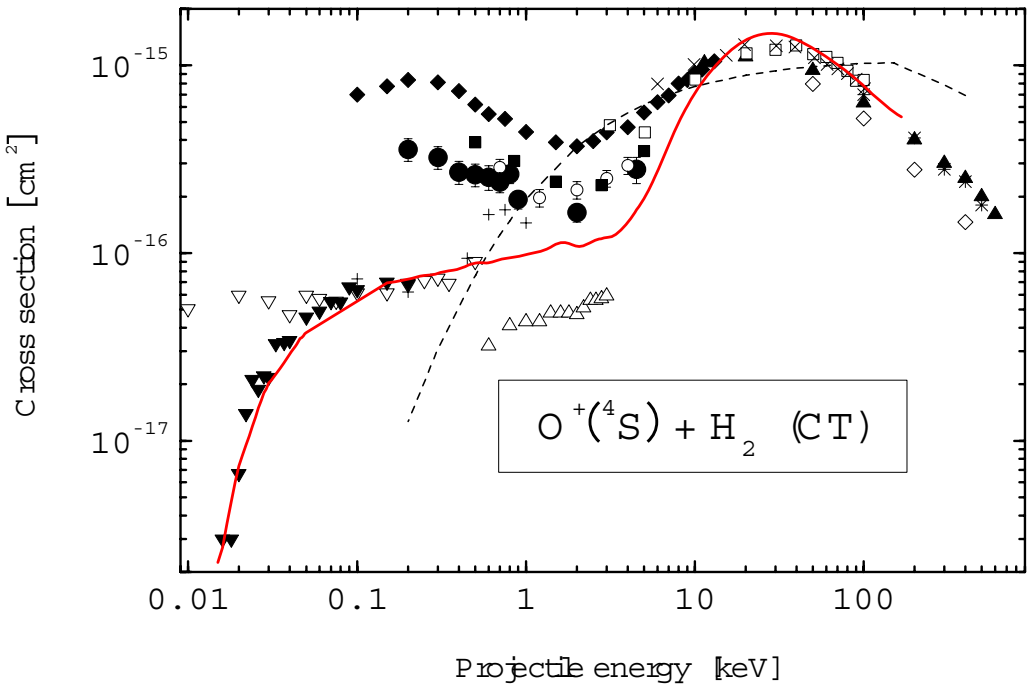

FIG. 2: Total charge transfer cross section for collisions of $O^+(^4S)$ with the ground-state H_2 (full line) and various experimental data. Solid circle: Kusakabe *et al.* [29], open circle: Kusakabe *et al.* [30], solid square: Sieglaff *et al.* [31], +: Irvine and Latimer [32], solid down triangle: Flesch and Ng [39], open down triangle: Xu *et al.* [33], open square: Hoffman *et al.* [34], solid diamond: Nutt *et al.* [35], solid triangle: Phaneuf *et al.* [36], ×: Lockwood *et al.* [37], and open triangle: Moran and Wilcox [38]. Dashed line: Olson formula [40] and solid line: our calculation [28].

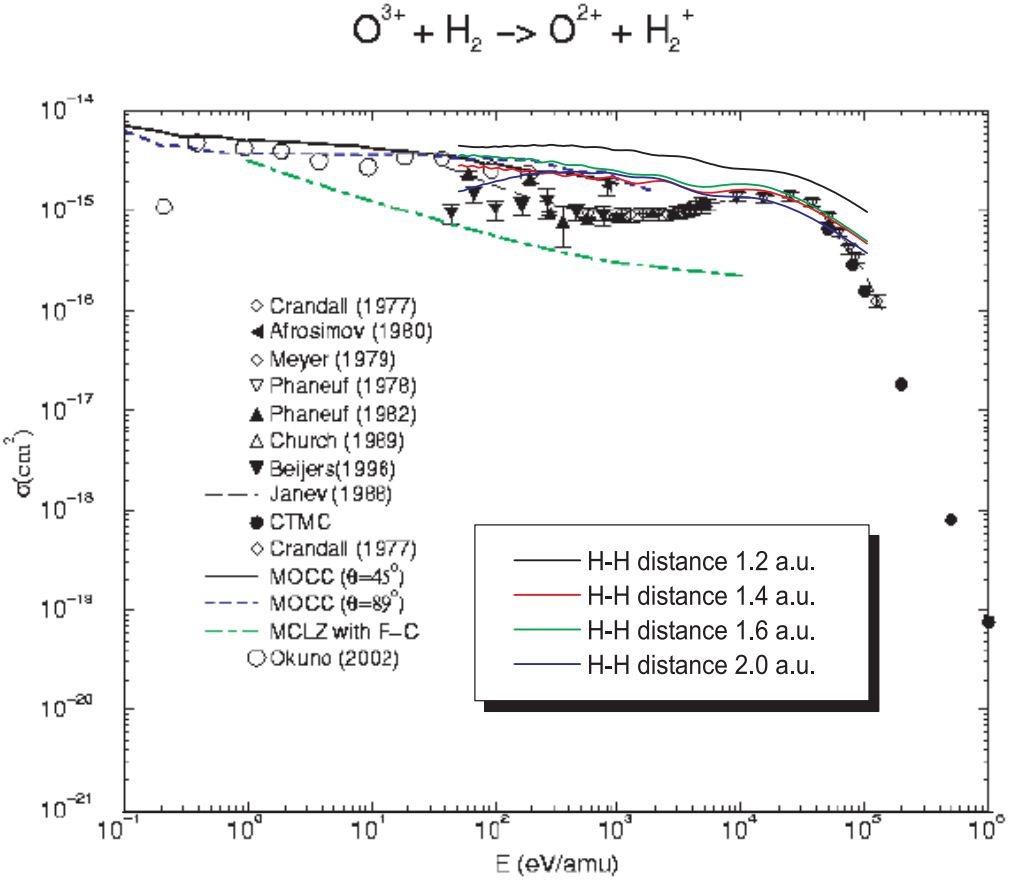

FIG. 3: Single electron capture in collisions of $O^{3+}(^2P)$ with ground-state H_2 for various target internuclear separation and collision angles. The lines show semiclassical approximation by L. Pichl and M. Kimura. The final data for averaged geometries are given in [41].

3.5 Evaluation and fitting formulas for H^+,O^+/H,O,N_2,O_2 charge-transfer cross sections (L. Pichl)

As a part of our data evaluation effort, we have compiled the evaluation of charge transfer cross sections in collisions of H^+,O^+/H,O,N_2,O_2 (including data resolved with respect to the ground-state $O^+(^4S)$ and the metastable $O^+(^2D,^2P)$ ions) in the energy range of 1 eV to 200 keV, which was recently published by Lindsay and Stebbings [42]. Table VII shows the fitting formulas [42] of the Rice University group. The values of the parameters and the applicable energy ranges are listed in Table VIII.

In addition, the integral cross sections for direct scattering of ground-state O^+ ions on He, H_2, O_2 and N_2 measured in the same group are shown in Table IX. The cross sections include contributions from all elastic and inelastic processes resulting in a fast O^+ ion. These data complement the charge-transfer cross sections included in the NIFS database. The experimental conditions for the direct scattering measurements [43] were as follows. For H_2, N_2 , and O_2 at energies of 0.5 - 5 keV, the angular range is 0.18 - 4.82 degs. The corresponding angular range for He is 0.22 - 4.82 degs. The angular range for the 0.1 keV data is 1.0 - 20 degs.

TABLE VII: Functional form of the charge transfer cross sections in 10^{-16}cm^2. E is projectile energy in keV.

Process	$f(E)$
H^+-H	$(a_1 - a_2 \ln E)^2(1 - e^{-a_3/E})^{4.5}$
H^+-O	$(a_1 - a_2 \ln E)^2(1 - e^{-a_3/E})^2 + (a_4 - a_5 \ln E)(1 - e^{-a_6/E})^2$
O^+-H	$(a_1 - a_2 \ln E)^2(1 - e^{-a_3/E})^{0.8}$
$O^+(^4S)$-H	$(a_1 - a_2 \ln E)^2$
O^+-O	$(a_1 - a_2 \ln E)^2(1 - e^{-a_3/E})^{0.8}$
$O^+(^4S)$-O	$(a_1 - a_2 \ln E)^2$
$O^+(^2D,^2P)$-O	$(a_1 - a_2 \ln E)^2$
H^+-N_2	$a_1 e^{-(\ln E - a_2)^2/a_3}(1 - e^{-E/a_4})^2 + (a_5 - a_6 \ln E)^2(1 - e^{-a_7/E})^2$
H^+-O_2	$(a_1 - a_2 \ln E)^2(1 - e^{-a_3/E})^{1.5} + (a_4 - a_5 \ln E)^2(1 - e^{-a_6/E})$
$O^+(^4S)$-N_2	$(a_1 - a_2 \ln E)(1 - e^{-a_3/E})^{1.7} + a_4(1 - e^{-a_5/E})^4(1 - e^{-E/a_6})^3$
$O^+(^2D,^2P)$-N_2	$(a_1 - a_2 \ln E)^2(1 - e^{-a_3/E})^{0.5} + (a_4 - a_5 \ln E)^2(1 - e^{-a_6/E})^{1.5}$
$O^+(^4S)$-O_2	$a_1(1 - e^{-a_2/E})^2 + (a_3 - a_4 \ln E)^2(1 - e^{-E/a_5})^4$
$O^+(^2D,^2P)$-O_2	$(a_1 - a_2 \ln E)^2$

TABLE VIII: Fitting parameters and the applicable energy range for Table VII

Process	Parameters $(a_1, a_2, ...)$	Range (keV)
H^+-H	4.15, 0.531, 67.3	0.005 - 250
H^+-O	2.91, 0.0886, 50.9, 4.73, -0.862, 0.0306	0.002 - 100
O^+-H	3.13, 0.170, 87.5	0.025 - 600
$O^+(^4S)$	3.74, 0.143	0.004 - 0.4
O^+-O	4.07, 0.269, 415	0.04 - 380
$O^+(^4S)$-O	4.75, 0.601	0.5 - 5
$O^+(^2D,^2P)$-O	3.92, 0.392	0.5 - 5
H^+-N_2	12.5, 1.52, 3.97, 0.360, -1.20, 0.208, 0.741	0.1 - 100
H^+-O_2	1.83, -0.545, 15.8, 6.35, -0.801, 0.240	0.05 - 100
$O^+(^4S)$-N_2	0.800, -1.60, 20.4, 0.453, 0.400, 0.00833	0.01 - 185
$O^+(^2D,^2P)$-N_2	8.46, -1.07, 0.155, 0.919, -1.08, 12.2	0.01 - 185
$O^+(^4S)$-O_2	2.16, 0.250, 2.85, -0.103, 0.144	0.01 - 5
$O^+(^2D,^2P)$-O_2	4.19, 0.0315	0.005 - 5

TABLE IX: Integral cross sections of $O^+(^4S)$ direct scattering

E(keV)	He (10^{-16}cm^2)	H_2 (10^{-16}cm^2)	N_2 (10^{-16}cm^2)	O_2 (10^{-16}cm^2)
0.1	5.2	-	5.9	7.6
0.5	4.81 ± 0.48	3.09 ± 0.77	5.63 ± 1.24	6.41 ± 0.96
1.5	4.40 ± 0.44	2.73 ± 0.41	3.72 ± 0.45	5.30 ± 0.53
5.0	2.31 ± 0.28	1.68 ± 0.42	2.64 ± 0.45	3.75 ± 0.38

3.6 Charge transfer in collisions of H^+ with C_mH_n (R. Suzuki)

As a part of our ongoing study on various physical phenomena in collisions of positively charged heavy ions with molecules [6, 44–47], here we report our results on the total charge transfer cross sections in collisions of protons with hydrocarbons. In particular, we review our charge transfer cross sections for the C_2H_4 and C_2H_6 targets, and the overall qualitative trend in the capture cross sections as a function of the number of carbon atoms in the target C_mH_n molecule.

First, we have studied the electron capture and direct elastic scattering in collisions of H^+ ions with C_2H_4 below 10 keV [48]. Within the molecular representation, both the semiclassical as well

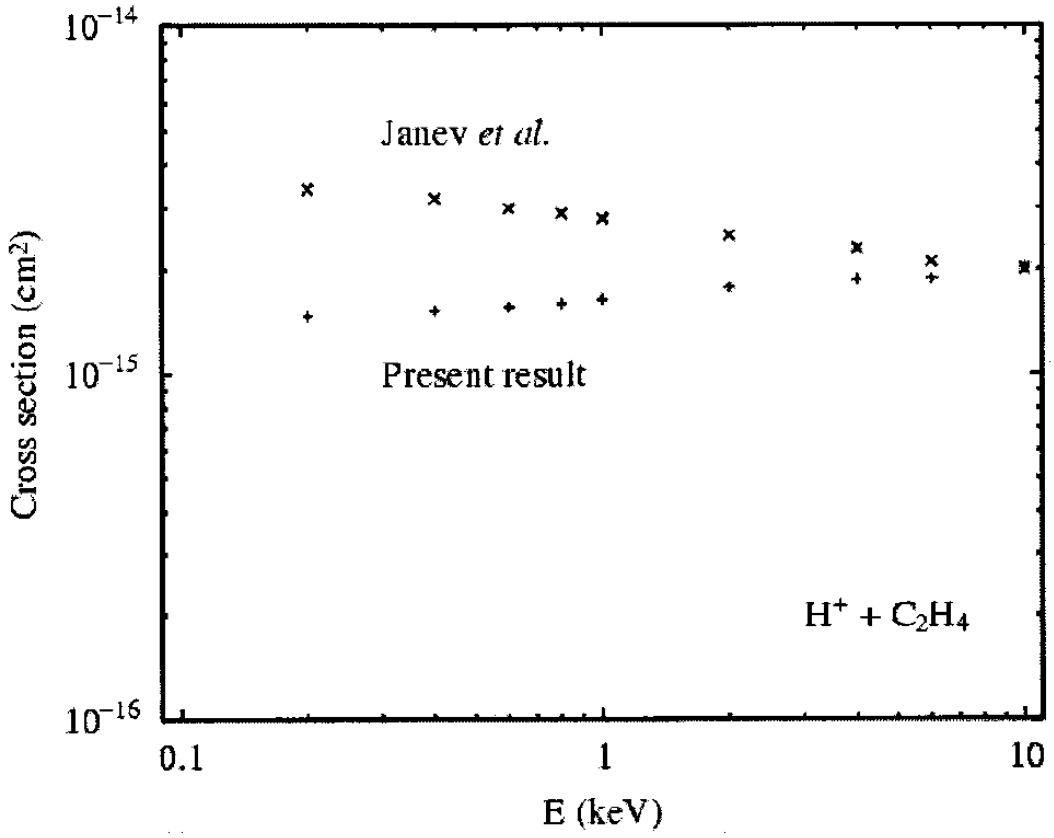

FIG. 4: Total charge transfer cross section for the collision of H^+ with C_2H_4.

as fully quantum-mechanical approaches were used. In order to account for the steric effect, the calculations were carried out at three different molecular configurations, in which H^+ approaches (i) parallel and (ii) perpendicular to the C=C axis in the molecular plane, and (iii) perpendicular to this plane. We find that electron capture in the (iii) configuration takes place preferentially over that in the (i) and (ii) configurations at scattering angles above 15 degs, while the results for (i) and (ii) are comparable in magnitude below 10 degs, although (ii) dominates slightly at still smaller angles. The total capture cross sections for the (iii) and (ii) configurations differ by a factor of 4 above 500 eV, while those for (i) lie between these values. Below 500 eV, the results for (i) and (iii) are similar in magnitude, while that for the (ii) configuration sharply decreases. The total capture cross section is shown in Fig. 4

As the next target system with larger number of hydrogen atoms, we theoretically studied charge-transfer processes in the collisions of H^+ ions with C_2H_6 molecules below 10-keV collision energies, and obtained the converged total as well as differential cross sections in this energy range. The present collision system suggests that the combination of the Demkov-type and Landau-Zener type

mechanisms primarily governs the scattering dynamics for the flux exit from the initial channel. The charge-transfer cross sections were found to agree very well with all available experimental data below a few keV, but begin to deviate above 3 keV, in which case the present results slowly decrease, while the measurements stay nearly constant. From the study of the electronic state calculation, we have also provided some information on the fragmented species, which elucidates the fragmentation mechanism of the $C_2H_6^+$ ions produced by the charge transfer. The vibrational effect of the initial target to charge transfer has also been qualitatively examined. The total charge transfer cross section as a function of energy is plotted in Fig. 5.

For the sake of applications including the modeling of energy balance in the fusion edge plasmas, it is important to assess the trends in the electron capture cross sections over a wide range of hydrocarbons. Fig. 6 summarizes our results for various hydrocarbons molecules at the collision energy below 10 keV. Further details are given in References [48, 49].

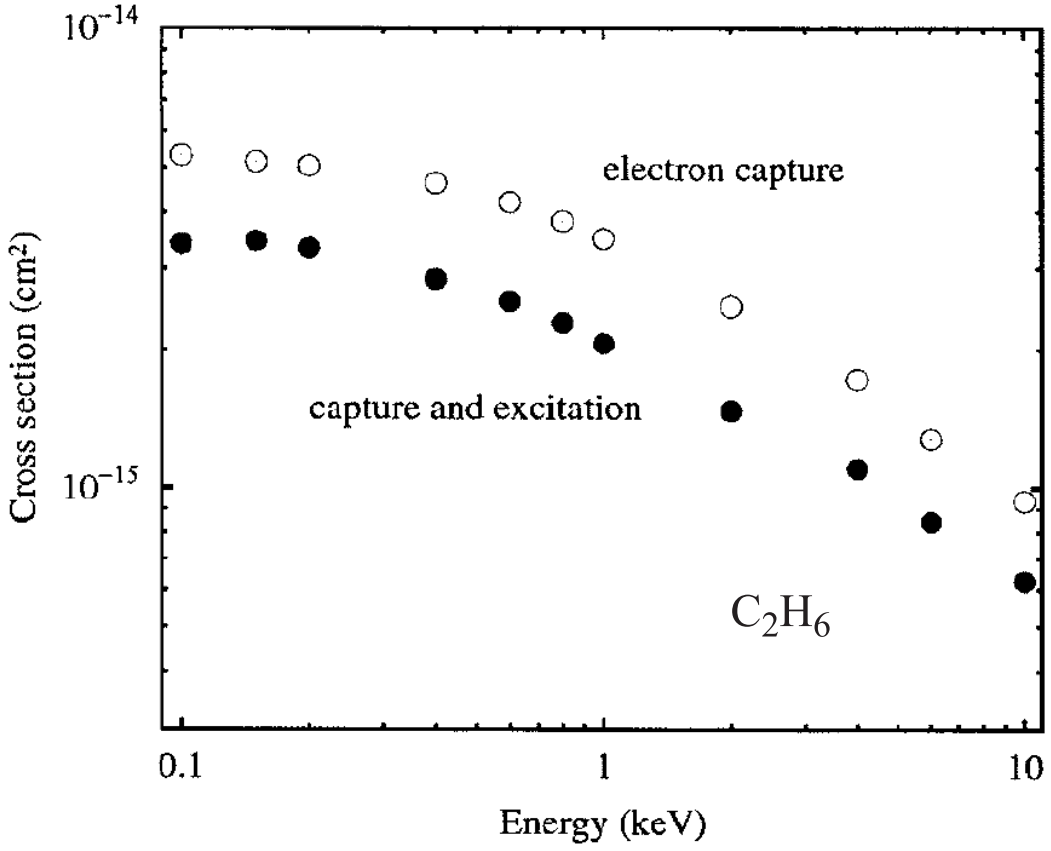

FIG. 5: Total electron capture and simultaneous target excitation cross sections for the collision of H^+ with C_2H_6.

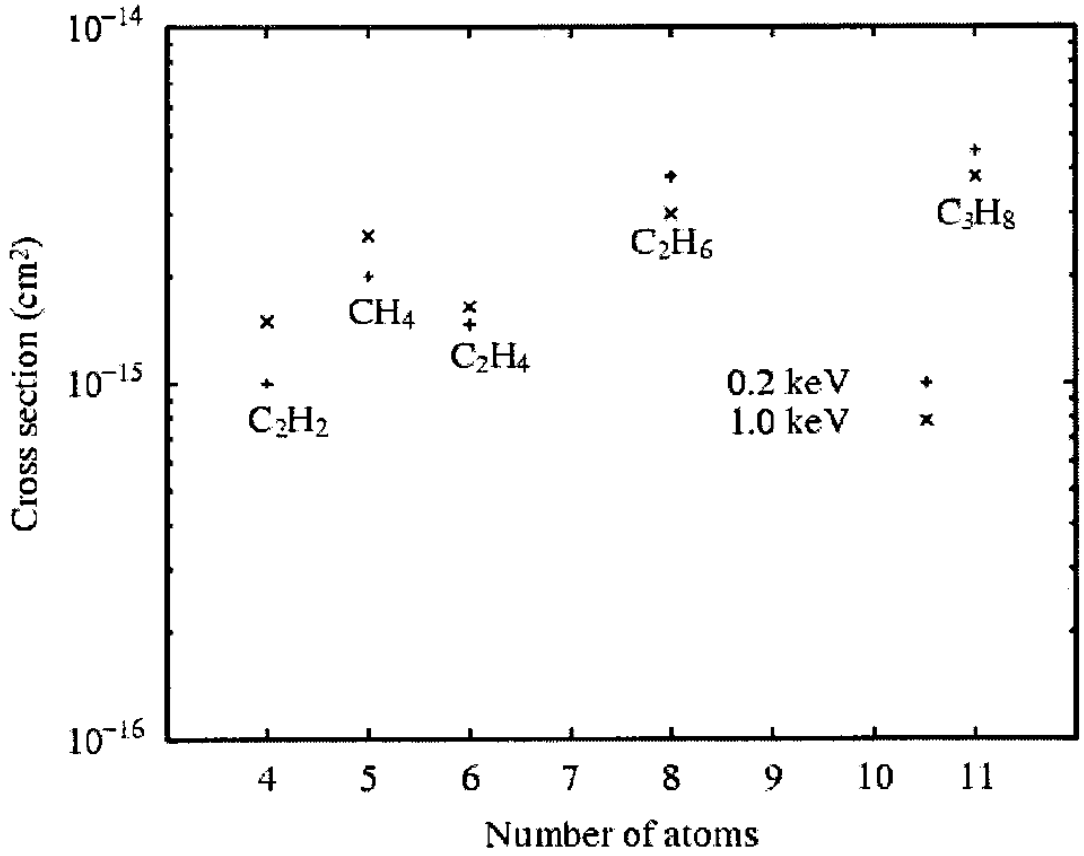

FIG. 6: Trends in the total charge transfer cross sections for collisions of H^+ with hydrocarbons at specific energies as shown.

Acknowledgments

This work was carried out under the collaborating research program at National Institute for Fusion Science: Molecular Processes Data Compilation for NIFS Data Center (M. Kimura, 2003-2004).

[1] I. Murakami, T. Kato, A. Igarashi, M. Imai, Y. Itikawa, D. Kato, M. Kimura, T. Kusakabe, K. Moribayashi, T. Morishita, K. Motohashi and L. Pichl, NIFS-DATA-70 (National Institute for Fusion Science, 2002):
"AMDIS and CHART update (I)".

[2] E. Y. Kamber, O. Abu-Haija and S. M. Ferguson, Phys. Rev. A 65, 062717 (2002):
"Competition between dissociative and nondissociative single-electron capture in He^{2+} - O_2 collisions".

[3] D. M. Kearns, R. W. McCullough and H. B. Gilbody, J. Phys. B 35, 4335-4346 (2002):
"Experimental study of the collision mechanisms involved in one-electron capture by slow N^{5+} ions in atomic and molecular hydrogen".

[4] J. M. Sanders, S. L. Varghese, C. H. Fleming and G. A. Soosai, J. Phys. B 36, 3835-3846 (2003):
"Electron capture by protons and electron loss from hydrogen atoms in collisions with hydrocarbon and hydrogen molecules in the 60-120 keV energy range".

[5] W. Liu, G. Imbriani, L. Buchmann, A. A. Chen, J. M. D'Auria, A. D'Onofrio, S. Engel, L. Gialanella, U. Greife, D. Hunter, A. Hussein, D. A. Hutcheon, A. Olin, D. Ottewell, D. Rogalla, J. Rogers, M. Romano, G. Roy and F. Terrasi, Nucl. Instr. Meth. A 496, 198-214 (2003):
"Charge state studies of low energy heavy ions passing through hydrogen and helium gas".

[6] T. Kusakabe, M. Kimura, L. Pichl, R. J. Buenker and H. Tawara, Phys. Rev. A 68, 050701 (2003):
"Observation of significant differences in charge transfer between collisions of H^+ ions with H_2 and with D_2 molecules in the high-eV to low-keV range".

[7] I. S. Dmitriev, Ya. A. Teplova, Yu. A. Fainberg and Yu. A. Belkova, Phys. Scripta 68, 383-387 (2003):
"Formation of Metastable States of Light Ions in Ion-Atom Collisions".

[8] R. W. McCullough, D. M. Kearns, J. B. Greenwood and H. B. Gilbody, Nucl. Instr. Meth. B 205, 581-585 (2003):
"Studies of state selective electron capture processes by helium-like ions in H and H_2".

[9] B. G. Lindsay, W. S. Yu, K. F. McDonald and R. F. Stebbings, Phys. Rev. A 70, 042701 (2004):
"Electron capture and loss by kilo-electron-volt oxygen atoms in collisions with He, H_2, N_2, and O_2".

[10] T. Kusakabe, L. Pichl, R. J. Buenker, M. Kimura and H. Tawara, Phys. Rev. A 70, 052710 (2004):
"Isotope effect in charge-transfer collisions of slow H^+ and D^+ ions with H_2, HD, and D_2 molecules".

[11] R. Browning and H. B. Gilbody, J. Phys. B 1, 1149-1156 (1968):
"Fragmentation of molecular gases by 5-45 keV protons".

[12] R. Browning, C. J. Latimer and H. B. Gilbody, J. Phys. B 2, 534-540 (1969):
"Fragmentation of molecular gases by 5-45 keV He^+ ions".

[13] W. G. Graham, C. J. Latimer, R. Browning and H. B. Gilbody, J. Phys. B 6, 2641-2652 (1973):
"Ionization of fragmentation of diatomic molecular gases by 5-45 keV Ne^+ and Na^+ ions and Ne atoms".

[14] B. G. Lindsay, F. B. Yousif, F. R. Simpson and C. J. Latimer, J. Phys. B 20, 2759-2771 (1987):
"The dissociative ionisation of hydrogen by 5-25 keV protons: energy spectra and angular distribution of fragment ions".

[15] F. B. Yousif, B. G. Lindsay and C. J. Latimer, J. Phys. B 23, 495-504 (1990):
"The formation of quasi-bound states of N_2^{2+} in H^+-N_2 collisions".

[16] H. Inouye, N. Shimakura and H. Sasaki, J. Phys. B 15, 2423-2437 (1982):
"Excitational dissociation of C_2H_2 molecules by impact of He^+ and Ar^+ ions in the energy range 30-300 eV".

[17] J. D. Burley, L. S. Sunderlin and P. B. Armentrout, J. Chem. Phys. 94, 1939-1946 (1991):
"Kinetic-energy dependence of the reactions of $C^+(^2P)$ + N_2 from threshold to 28 eV CM".

[18] X. Li, Y. -L. Huang, G. D. Flesch and C. Y. Ng, J. Chem. Phys. 106, 564-571 (1997):
"Absolute state-selected total cross sections for the ion-molecule reactions O^+ $(^4S,^2D,^2P)$+$H_2(D_2)$".

[19] X. Li, Y. -L. Huang, G. D. Flesch and C. Y. Ng, J. Chem. Phys. 106, 1373-1381 (1997):
"A state-selected study of the ion-molecule reactions $O^+(^4S,^2D,^2P)$ + N_2".

[20] F. J. de Heer, J. Schutten and H. Moustafa, Physica 32, 1766-1792 (1966):
"Ionization and Electron Capture Cross Sections for Protons Incident on Noble and Diatomic Gases".

[21] International Bulletin on Atomic and Molecular Data for Fusion: IEEA, No. 42 (1991) - 62 (2003).

[22] CIAMDA98 An Index to the Literature on Atomic and Molecular Collision Data Relevant to Fusion Research: IAEA(1998).

[23] H. Tawara, NIFS-DATA-42 (National Institute for Fusion Science, 1997):
"Bibliography on Electron Transfer Processes in Ion - Ion / Atom / Molecule Collisions - Updated 1997 -".

[24] J. M. Sanders, S. L. Varghese, C. H. Fleming and G. A. Soosal, J. Phys. B 36, 3835-3846 (2003):
"Electron capture by protons and electron loss from hydrogen atoms in collisions with hydrocarbon and hydrogen molecules in the 60 - 120 keV energy range". [60 - 120 keV H^+ / CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8]

[25] K. Hosaka, H. Tawara, I. Yamada, H. Sakaue, F. Krok, F. J. Currell, N. Nakamura, S. Ohtani, H. Watanabe, A. Danjo, M. Kimura, A. Matsumoto, M. Sakurai and M. Yoshino, Phys. Scripta T73, 273-275

(1997):

"Multiple Electron Capture Processes between Highly Charged Ions and Molecules". [$1.5 \times q$ keV I^{q+} $(q = 10, 15, 20, 25, 30)$ / CH_4]

[26] T. Kusakabe, T. Horiuchi, N. Nagai, H. Hanaki, I. Konomi and M. Sakisaka, J. Phys. B 19, 2165-2174 (1986):

"Charge Transfer of Multiply Charged Argon, Krypton and Xenon Ions on Atomic and Molecular Targets. Single-Charge Transfer Cross Sections". [0.286 keV/u $Kr^{2+\sim 9+}$, $Xe^{2+\sim 11+}$ / CH_4, C_2H_6, C_3H_8]

[27] E. Salzborn and A. Muller, *Electronic and Atomic Collisions*, eds. N. Oda and K. Takayanagi, pp. 407-426 (Amsterdam, North-Holland, 1980):

"Electron Capture by Multi-Charged Ions Colliding with Multi-Electron Targets". [30 keV $Ar^{2+\sim 7+}$ / CH_4]

[28] L. Pichl, Y. Li, H. -P. Liebermann, R. J. Buenker and M. Kimura, Phys. Rev. A 69, 062715 (2004):

"Electron capture and excitation in collisions of $O^+(^4S,^2D,^2P)$ with H_2 molecules".

[29] T. Kusakabe *et al.*, J. Phys. B 34, 4809 (2001) :

"Charge transfer cross sections in collisions of ground state $O^+(^4S)$ ions with H_2 and various carbon-containing molecules in the low-energy region".

[30] T. Kusakabe, Y. Mizumoto, K. Katsurayama and H. Tawara, J. Phys. Soc. Jpn. 59, 1987 (1990):

"Electron Capture by C^+, N^+ and O^+ Ions in Collisions with H_2 Molecules and He Atoms at Low keV Energies".

[31] D. R. Sieglaff, B. G. Lindsay, K. A. Smith and R. F. Stebbings, Phys. Rev. A 59, 3538 (1999):

"Absolute differential and total cross sections for charge transfer of O^+ with H_2".

[32] A. D. Irvine and C. J. Latimer, J. Phys. B 24, L145 (1991):

"Charge transfer reactions of ground state O^+ ions with H_2 molecules".

[33] Y. Xu, E. W. Thomas and T. F. Moran, J. Phys. B 23, 1235 (1990):

"Charge transfer reactions of ground $O^+(^4S)$ and metastable $O^+(^2D,^2P)$ ions with H_2 molecules".

[34] J. M. Hoffman, G. H. Miller and L. Lockwood, Phys. Rev. A 25, 1930 (1982):

" Charge transfer of ground-state C^+, N^+, and O^+ in N_2 and H_2".

[35] W. L. Nutt, R. W. McCullogh and H. B. Gilbody, J. Phys. B 12, L157 (1979):

"Electron capture by 0.1-13 keV C^+, N^+ and O^+ ions in H and H_2".

[36] R. A. Phaneuf, F. W. Meyer and R. H. McKnight, Phys. Rev. A 17, 534 (1978):

"Single-electron capture by multiply charged ions of carbon, nitrogen, and oxygen in atomic and molecular hydrogen".

[37] G. J. Lockwood, G. H. Miller and J. M. Hoffman, Phys. Rev. A 18, 935 (1978):
"Charge transfer of C^+, N^+, and O^+ in N_2 and H_2".

[38] T. X. Moran and J. B. Wilcox, J. Chem. Phys. 69, 1397 (1978):
"Charge transfer reactions of ground O^+ (^4S) and excited O^+ (^2D) state ions with neutral molecules".

[39] G. D. Flesch and C. Y. Ng, J. Chem. Phys. 94, 2372 (1991); J. Geophys. Res. 96, 21403 (1991):
"Absolute total cross sections for the charge transfer and dissociative charge transfer channels in the collisions of $O^+(^4S)$+H_2".

[40] R. E. Olson, Phys. Rev. A 6, 1822 (1972):
"Charge Transfer at Large Internuclear Distances: Application to Asymmetric Alkali-Ion-Alkali-Atom Systems".

[41] J. G. Wang, P. C. Stancil, A. R. Turner and D. L. Cooper, Phys. Rev. A 69, 062702 (2004):
"Vibrationally resolved charge transfer of O^{3+} with molecular hydrogen".

[42] B. G. Lindsay and R. F. Stebbings, J. Geophys. Res. 110, A12213 (2005):
"Charge transfer cross sections for energetic neutral atom data analysis".

[43] B. G. Lindsay, J. Geophys. Res. 109, A08305 (2004):
"Absolute differential cross sections for direct scattering of keV O^+ ions by He, H_2, N_2, and O_2".

[44] M. Kimura, Y. Li, G. Hirsch and R. J. Buenker, Phys. Rev. A 52, 1196 (1995):
"Elastic and inelastic processes in H^++CH_4 collisions in the low-kilo-electron-volt regime".

[45] M. Kimura, Y. Li, G. Hirsch and R. J. Buenker, Phys. Rev. A 54, 5019 (1996):
"Elastic and inelastic processes in H^++C_2H_2 collisions below the 1.5-keV regime".

[46] T. Kusakabe, K. Asahina, A. Iida, Y. Tanaka, Y. Li, G. Hirsch, R. J. Buenker, M. Kimura, H. Tawara and Y. Nakai, Phys. Rev. A 62, 062715 (2000):
"Charge-transfer processes in collisions of slow H^+ ions with hydrocarbon molecules: CH_4, C_2H_2, C_2H_6, and C_3H_8".

[47] T. Kusakabe, K. Asahina, J. P. Gu, G. Hirsch, R. J. Buenker, M. Kimura, H. Tawara and Y. Nakai, Phys. Rev. A 62, 062714 (2000):
" Charge-transfer processes in collisions of H^+ ions with H_2, D_2, CO, and CO_2 molecules in the energy range 0.2-4.0 keV".

[48] R. Suzuki, N. S. Rai, H. -P. Liebermann, R. J. Buenker, L. Pichl and M. Kimura, Phys. Rev. A 71, 032710 (2005):
"Elastic and electron-capture processes in H^+ + C_2H_4 collisions below the 10-keV regime".

[49] R. Suzuki, S. N. Rai, H. -P. Liebermann, R. J. Buenker, L. Pichl and M. Kimura, Phys. Rev. A 72,

052710 (2005):

"Elastic and inelastic processes in $H^+ + C_2H_6$ collision below the 10-keV regime".