

Free electrons: fundamental interactions, applications and data needs

Loucas G. Christophorou

Abstract In spite of the important recent advances in the field of low-energy electron interactions with atoms and molecules, there still exist fundamental needs and challenges, some of which are generic in their basic and applied significance. These include measurements of cross sections for a number of fundamental low-energy electron-ground-state molecule interaction processes such as vibrational excitation (direct and indirect) and dissociation into neutral fragments, studies of low-energy electron-excited molecule interactions, investigations of low-energy electron interactions with radicals and transient species, and measurements of electron energy losses in electron-molecule collision processes. They also include studies for linking of knowledge on isolated electron-molecule interactions to that in the condensed phases of matter, and the systematic and quantitative exploration of the interactions of low-energy electrons with molecular and macromolecular biological structures.

Key words applications • data • interactions • low-energy electrons • molecules

Introduction

One hundred and five years have past since J. J. Thomson discovered the electron, the first elementary particle of the microcosmos. Although many other particles have since been discovered, the electron – especially the low-energy electron – still remains one of the most fundamental, abundant, reactive, and challenging particles in nature. In nature, electrons are either bound or free/quasi-free. This paper deals with the latter.

The systematic recent studies of low-energy electron-molecule interactions as a function of the electron energy, the internal energy of the molecule, and the nature, density, and state of the medium in which they occur has provided a wealth of basic knowledge which has advanced our understanding of the structure of atoms and molecules, the phenomena which accompany the interaction of ionizing radiation with matter and the deposition of energy by radiation in matter, the transport of electricity in gases, the interactions of electrons in plasmas, and the behavior of electrons in the condensed phases of matter. Concomitantly, this fundamental knowledge and understanding has underpinned and is underpinning the development of many of today's advanced technologies and is branching out into the environmental and life sciences.

Important as the recent advances have been there are still fundamental needs and challenges in this field, some of which are generic in their nature and in their basic and applied significance. A number of such areas are pointed out and are briefly discussed.

L. G. Christophorou
Academy of Athens,
28 Panepistimiou Str., Athens 106 79, Greece,
Tel.: +302/ 10 963 6825, Fax: +302/ 10 963 6707,
e-mail: lgchrist@otenet.gr

Received: 14 November 2002, Accepted: 24 February 2003

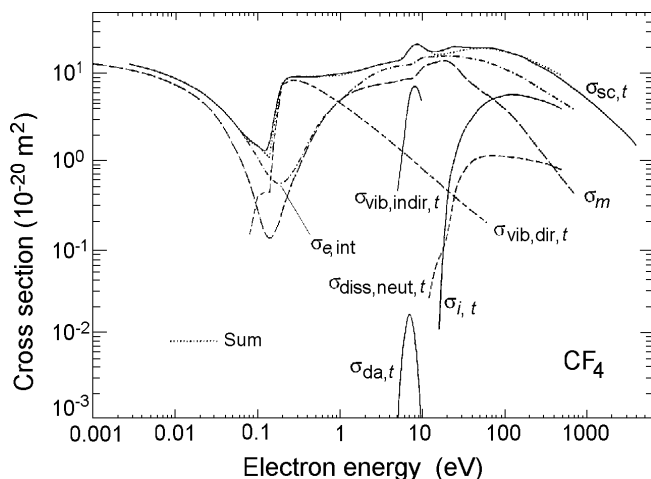


Fig. 1. Cross sections for direct and indirect electron collision processes in CF_4 . The symbols $\sigma_{\text{vib,dir,t}}$, $\sigma_{\text{diss,neut,t}}$, and $\sigma_{i,t}$ refer, respectively, to the total cross sections for direct vibrational excitation, dissociation into neutrals, and ionization of the CF_4 molecule. The symbols $\sigma_{\text{vib,indir,t}}$ and $\sigma_{\text{da,t}}$ refer, respectively, to the total cross sections for indirect vibrational excitation and dissociative electron attachment. The symbols σ_m , $\sigma_{e,\text{int}}$, and $\sigma_{\text{sc,t}}$ refer, respectively, to the cross sections for momentum transfer, integral elastic, and total electron scattering (from Ref. [14]).

Low-energy electron-ground-state molecule interactions

Absolute cross sections are now known for many electron-molecule collision processes for a large number of molecules [8, 15, 17, 28]. An example of the type of experimental data available is shown in Fig. 1. The data in this Figure are representative of the basic mechanisms via which energy is transferred from electrons to atoms and molecules and through which new particles are generated in matter. One of the most striking features of these cross-section data is the large magnitude of the cross sections for direct and indirect vibrational excitation of the CF_4 molecule. A consequence of such large cross sections for energy transfer from the electrons to vibrational excitation of

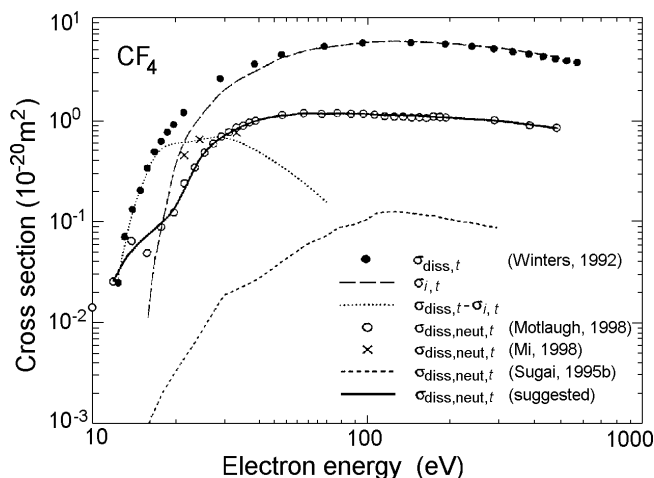


Fig. 2. Cross sections for electron-impact dissociation of the CF_4 molecule into neutrals. ---, $\sigma_{\text{diss,neut,t}}$ data of Nagano and Sugai as revised by Sugai *et al.* [35, 43]; , $\sigma_{\text{diss,t}} - \sigma_{i,t}$ Ref. [15]; \circ , $\sigma_{\text{diss,neut,t}}$ Ref. [34]; \times , $\sigma_{\text{diss,neut,t}}$ Ref. [30]; —, suggested values, Ref. [15]; \bullet , $\sigma_{\text{diss,t}}$ Ref. [46] ---, $\sigma_{i,t}$ Ref. [15] (from Ref. [15]).

molecules is the significant effect of vibrational excitation on the electron-slowng-down properties of gases and of the electron production and loss processes in them when they are electrically stressed, as, for instance, in low-density, low-temperature, non-equilibrium plasmas. However, accurate cross sections for vibrational excitation (direct and indirect) of molecules are very limited and so is our knowledge on the cross sections for other fundamental processes such as the electron-impact dissociation of molecules into neutrals [15, 17], and Fig. 2 shows an example of these data for the case of the CF_4 molecule.

Low-energy electron-excited-state molecule interactions

Quantitative data on low-energy electron attachment to vibrationally excited molecules exist for a number of molecules [16]. However, similar knowledge for electronically excited molecules is meager and qualitative [16]. Oxygen is possibly the only molecule for which the cross sections for dissociative electron attachment to the ground-state molecule, to the vibrationally excited molecule, and

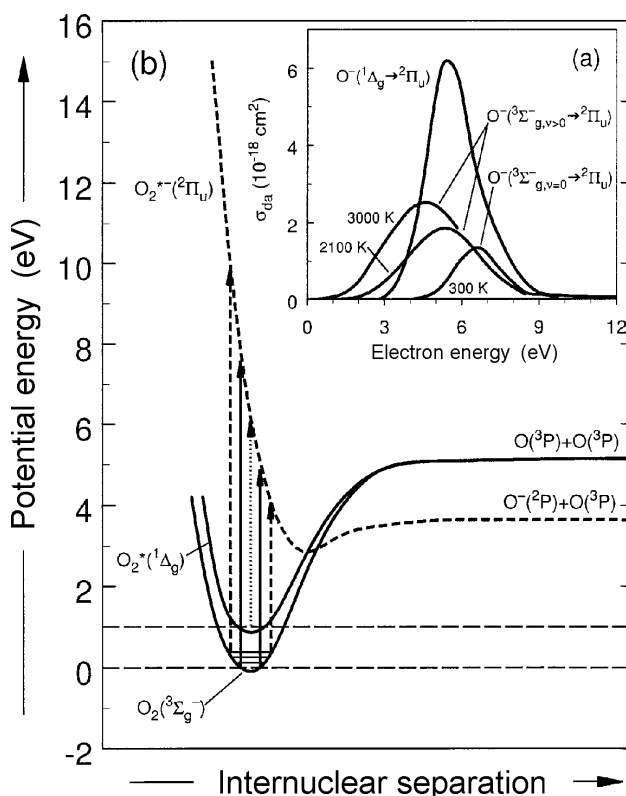


Fig. 3. (a) Comparison of the measured dissociative electron attachment cross sections for ground-state O_2 ($^3\Sigma_{g,v=0}^-$) (data of Ref. [37]), electronically excited (singlet) O_2 ($a^1\Delta_g$) (data of Ref. [26]), and vibrationally excited O_2 ($^3\Sigma_{g,v>0}^-$) oxygen molecules (from Ref. [16]). (b) Schematic potential energy curves for O_2 ($^3\Sigma_g^-$), O_2^+ ($a^1\Delta_g$), and O_2^- ($^2\Pi_u$), and transitions from the ground state O_2 ($^3\Sigma_{g,v=0}^-$) (solid arrows), electronically excited O_2 ($a^1\Delta_g$) (dotted arrow), and vibrationally excited O_2^+ ($^3\Sigma_{g,v>0}^-$) (broken arrows) species to the O_2^- ($^2\Pi_u$) negative ion state illustrating the processes of dissociative electron attachment to the ground state, lowest excited electronic state, and vibrationally excited states of O_2 .

to the electronically excited molecule have been accurately measured (Fig. 3). Experimental techniques are needed for quantitative studies of electron attachment to electronically excited molecules, especially since the cross sections for many electron–excited molecule collisions are very large and can have important applications [16].

The limited cross-section data on electron scattering from vibrationally excited molecules show that the cross sections for the excited species are larger than those for the ground state (Fig. 4). Similarly, the cross sections for electron-impact excitation and ionization of electronically excited atoms and molecules far exceed those for the ground state as can be seen from the data for the unexcited and excited Ar atom shown in Fig. 5. Data of this kind are limited for atoms and almost nonexistent for molecules. There is a need for experimental investigations in this area.

Low-energy electron–radical/transient species interactions

With the exemption of electron-impact ionization (e.g., see Tarnovsky *et al.* [44, 45]), there is almost complete lack of experimental data on the other electron-collision processes (e.g., electron attachment, elastic and inelastic electron scattering) for such species [15, 17]. Semiempirical calculations of electron-impact ionization (e.g., see [1, 18,

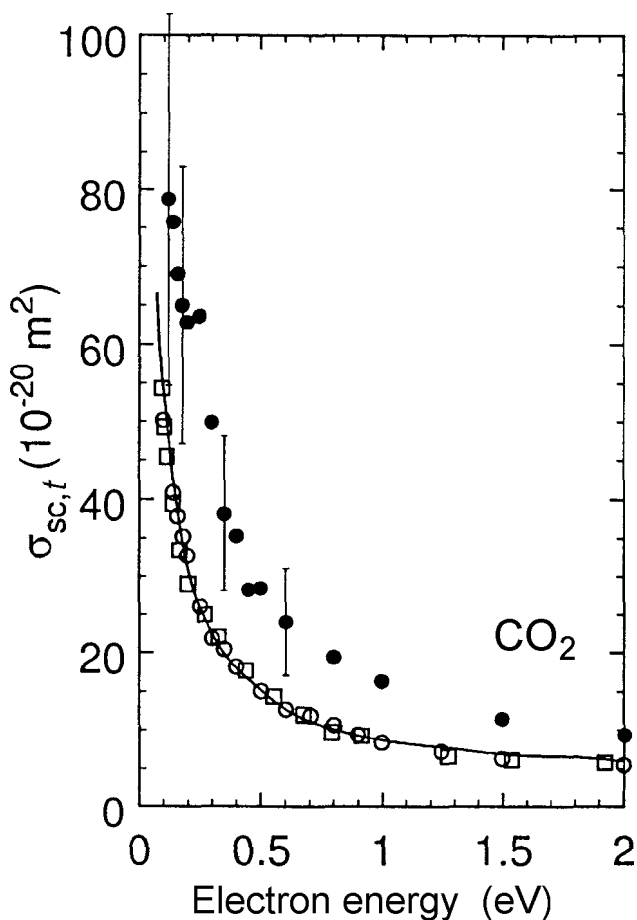


Fig. 4. Total cross section for electron scattering from the CO_2 molecule in the vibrational ground state (\circ , measurements of Ref. [5]; \square , measurements of Ref. [23]; —, calculated values of Ref. [33]), and from vibrationally excited CO_2 in the bending mode (\bullet , measurements of Ref. [5]).

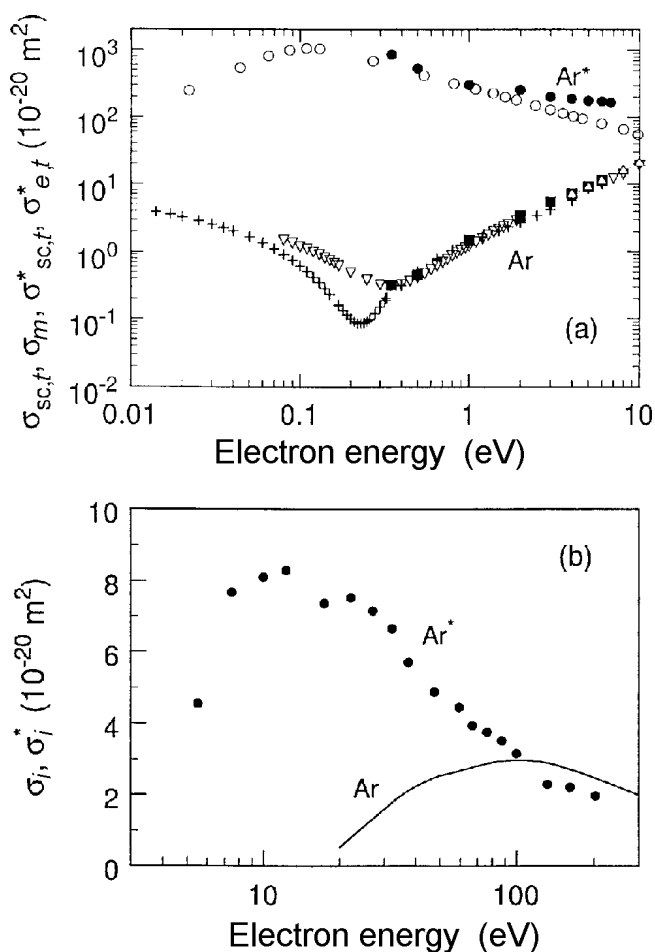


Fig. 5. (a) Comparison of the cross section for electron scattering from the excited Ar^+ ($4^3P_2 + 4^3P_2$) argon atom, and from the unexcited Ar (3^1S_0) argon atom. Total electron scattering cross section of the excited atom, $\sigma_{sc,t}^*(\epsilon)$ ($4^3P_2 + 4^3P_2$): \bullet , measurements of Ref. [6]. Total elastic electron scattering cross section of the excited atom, $\sigma_{e,t}^*(\epsilon)$ (4^3P_2): \circ , calculated values of Ref. [38]. Total electron scattering cross section of the ground-state atom, $\sigma_{sc,t}(\epsilon)$ (3^1S_0): measurements of Ref. [27] (\blacksquare), Ref. [36] (\triangle), Ref. [22] (∇). Momentum transfer cross section for the ground-state atom, $\sigma_m(\epsilon)$ (3^1S_0): $+$, measurements of Ref. [32]. (b) Cross section for electron-impact ionization of metastable Ar^+ , $\sigma_i^*(\epsilon)$ (\bullet , Ref. [19]) in comparison with the cross section, $\sigma_i(\epsilon)$, for electron-impact ionization of the ground state Ar (—, measurements of Ref. [29]).

25, 44]) are rather successful in providing total ionization cross sections for radicals. An example [1] of these data is shown in Fig. 6 for a number of radicals generated by electron impact on SF_6 .

Specific processes of generic interest, energy losses, correlations

One fundamental process which needs further attention is the photodetachment of atomic and molecular negative ions of interest to technology (e.g., photodetachment cross sections and energetics for negative ions such as CF^- , CF_2^- , CF_3^- , and C_2F_5^- which are important in plasma diagnostics). In this connection, the method developed by Sowada and Holroyd [41] for photodetachment from negative ions in nonpolar liquids, and the method developed more recently

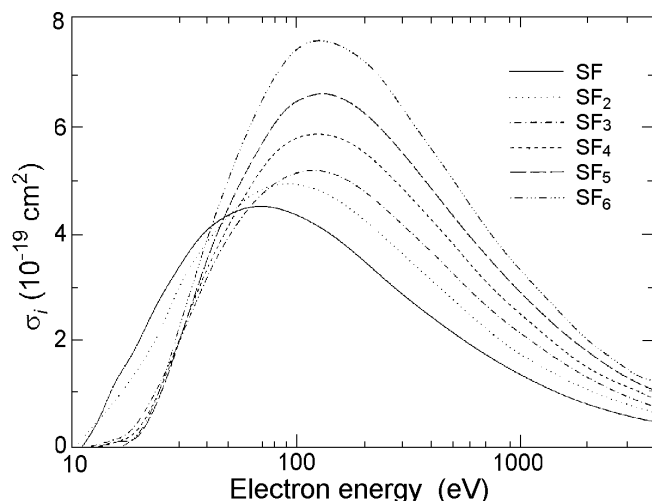


Fig. 6. Calculated total electron-impact ionization cross sections for the SF_x ($x = 1$ to 5) radicals (Ref. [1]).

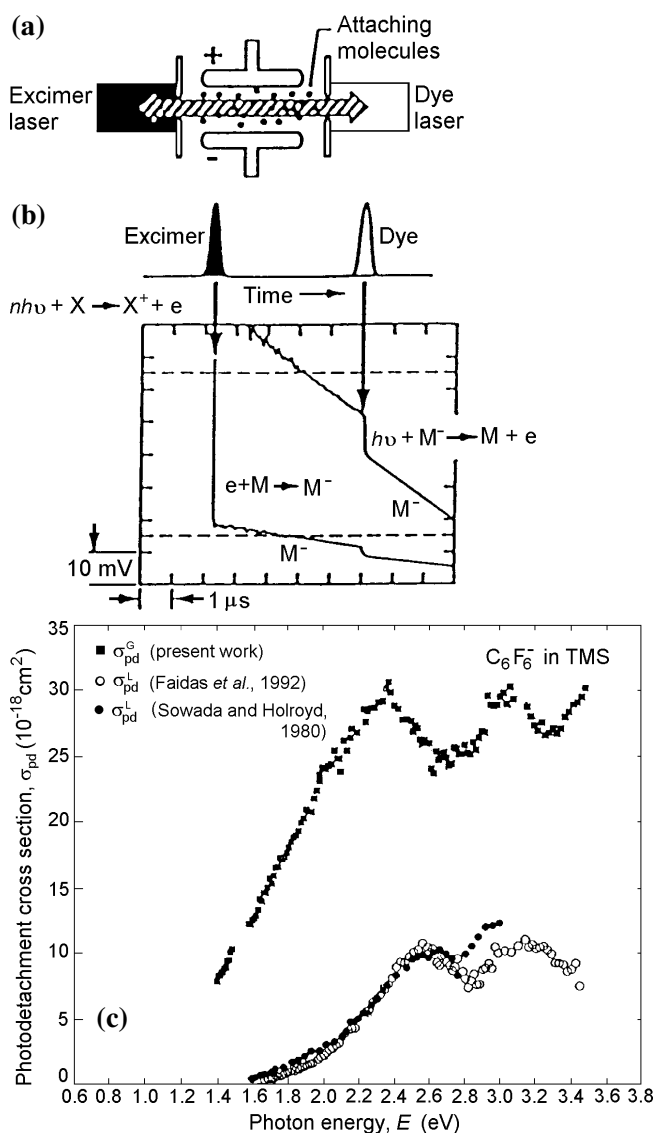


Fig. 7. (a), (b) Schematic diagram illustrating the two-laser photodetachment method of Christophorou and collaborators [11]. (c) Photodetachment cross section, σ_{pd}^G , for the $C_6F_6^-$ ion in gaseous tetramethylsilane (TMS) (\blacksquare , Ref. [11]), and, σ_{pd}^L , in liquid TMS (\circ , Ref. [20]; \bullet , Ref. [42]).

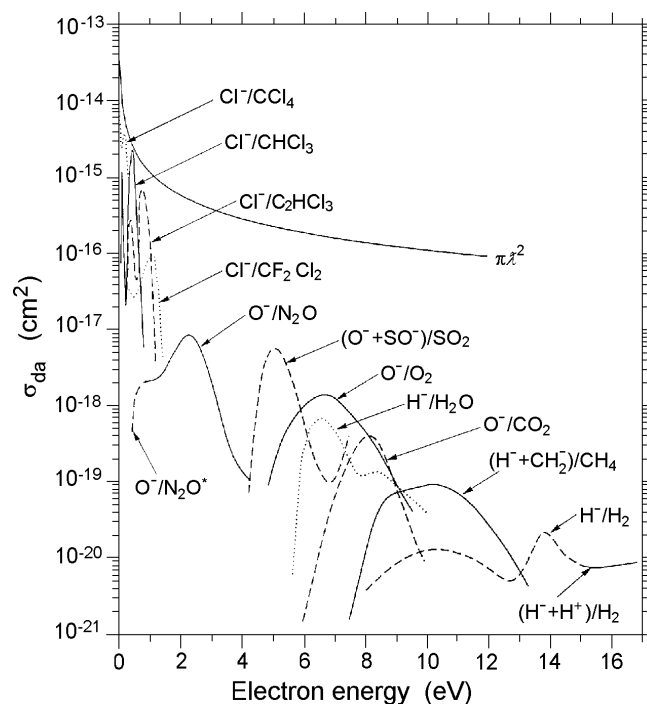


Fig. 8. Dissociative electron attachment cross sections as a function of the electron energy for a number of molecules. The line designated by $\pi\lambda^2$ is the s -wave capture cross section (from Ref. [13]).

by Christophorou and collaborators [11] for the measurement of the photodetachment cross sections and the photodetachment onsets in gases and liquids may be of interest. The principle of the method of Christophorou and collaborators is shown in Fig. 7, and an example of the results obtained is given in the lower part of Fig. 7 for the case of $C_6F_6^-$ in the gaseous and in the liquid state of matter.

Furthermore, besides the need of cross-section data for the various electron collision processes, data are needed (e.g., in computational models) for the associated electron energy losses, that is, for the energy which is transferred by the electron to the molecule in each individual electron-molecule collision process.

Systematic studies are necessary to establish correlations of, and trends in, the data with predictive capability (e.g., see Fig. 8 for electron attachment).

Linking knowledge on the isolated low-energy electron-molecule interactions to that in the condensed phase

Until recently, most of the fundamental understanding on low-energy electron-molecule interactions has been derived from studies on electron interactions with isolated molecules (i.e., from studies on electron interactions with molecules in low pressure gases). Considerable progress has been made in recent years [12] in unraveling and quantifying the effects on electron-molecule interactions of the nature, density, and state of the medium in which these interactions occur. A number of methods have been devised which provide most useful information on low-energy electron-molecule interactions in low-, high-, and very-high-pressure gases, in clusters, at surfaces, and in

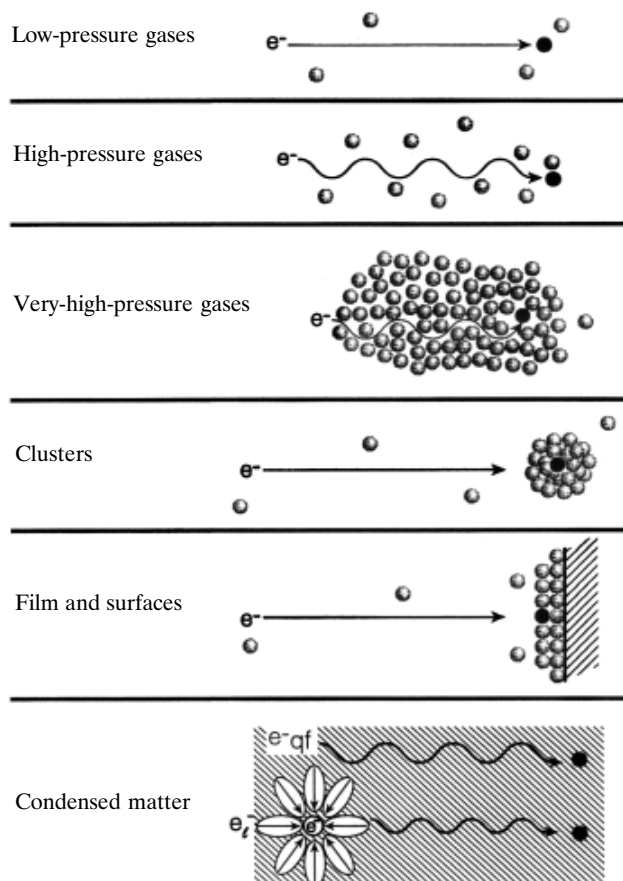


Fig. 9. Schematic illustrations of electron–molecule interactions in low-, high-, and very-high-pressure gases, in clusters, at surfaces, and in condensed matter.

condensed matter (see Fig. 9 for a schematic illustration of these environments). For instance, it has been established that negative ion resonances occur in all states of matter. Figure 10 shows the 2.3 eV negative ion state of N_2 as it has been observed in solid N_2 [40]. In general, while negative

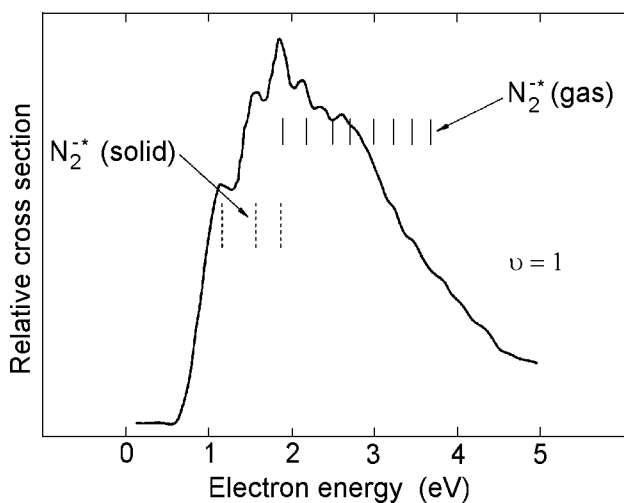


Fig. 10. Relative cross section for indirect scattering of low-energy electrons via the $N_2^{-*}({}^2\Pi_g)$ negative ion state of N_2 in solid N_2 film leaving the N_2 molecule excited in the first vibrational level. The broken vertical lines indicate the positions of the peaks in the cross section as measured in the film, and the solid vertical lines indicate the corresponding positions as measured in the gas (based on data in Ref. [40]).

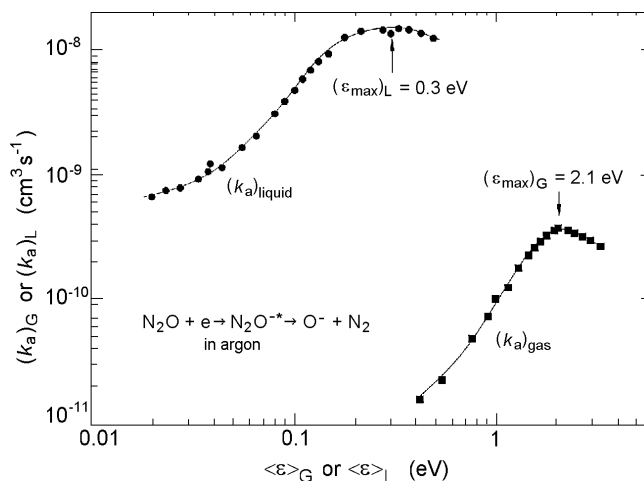


Fig. 11. Electron attachment rate constant for the production of O^- from N_2O in gaseous, $(k_a)_G$, and in liquid Ar, $(k_a)_L$, plotted as a function of the respective, $\langle \epsilon \rangle_G$ and $\langle \epsilon \rangle_L$, mean electron energies (from Ref. [10], the $(k_a)_L$ data are from Ref. [3]).

ion resonances occur in all molecules and in all states of matter, the medium introduces significant changes in the energetics of their formation, as well as in other of their physical properties such as their lifetimes and decay channels [10].

Table 1. Approximate relations between the energetics of photoionization, photodetachment, and electron attachment in the gaseous and the liquid state of matter.

Process*	Approximate relation ^{+,#}
Photoionization	
$M_G + nh\nu \rightarrow M_G^+ + e_G$	I_G
$M_L + nh\nu \rightarrow M_L^+ + e_L$	$I_L = I_G + P^+ + V_0$
Photodetachment	
$M_G^- + h\nu \rightarrow M_G + e_G$	$(E_{th})_G = VDE_G = EA_G + \Delta E_G$
$M_L^- + nh\nu \rightarrow M_L + e_L$	$(E_{th})_L = VDE_L = EA_G + V_0 - P^- + \Delta E_L$ ($EA_L \cong EA_G + V_0 - P^-$)
Electron attachment	
$M_G + e_G \rightarrow M_G^{-*}$	$VAE_G \approx (E_{NIS})_G = -VEA_G$
$M_L + e_L \rightarrow M_L^{-*}$	$VAE_L \approx (E_{NIS})_L \approx (E_{NIS})_G - (V_0 - P_{NIS}^-)$

* The notation is as follows: e_G , M_G , M_G^- , M_G^{-*} , and M_G^+ refer, respectively, to the electron, molecule, negative ion, transient negative ion, and positive ion in a low pressure gas. e_L , M_L , M_L^- , M_L^{-*} , and M_L^+ refer, respectively, to the same quantities in the liquid. The symbol $nh\nu$ represents n number of photons.

⁺ The notation I_G , $(E_{th})_G$, EA_G , VEA_G , VAE_G , $(E_{NIS})_G$, and VDE_G refers, respectively, to the ionization threshold energy, detachment threshold energy, adiabatic electron affinity, vertical electron affinity, vertical attachment energy, energy of the negative ion state, and vertical detachment energy in a low pressure gas. I_L , $(E_{th})_L$, EA_L , VEA_L , VAE_L , $(E_{NIS})_L$, and VDE_L refer, respectively, to the same quantities in the liquid. ΔE is a quantity which depends on the relative positions of the potential energy curves (surfaces) of M and M^- .

[#] V_0 is the ground-state energy of the electron in the medium and $P^{+,-}$ is the polarization energy of the positive or negative ion in the medium and is normally approximated by the Born expression $P^{+,-} = -e^2 / [(2R)(1 - 1/\epsilon_{opt})]$, where R is the effective radius of the ion cavity and ϵ_{opt} is the optical dielectric constant of the medium.

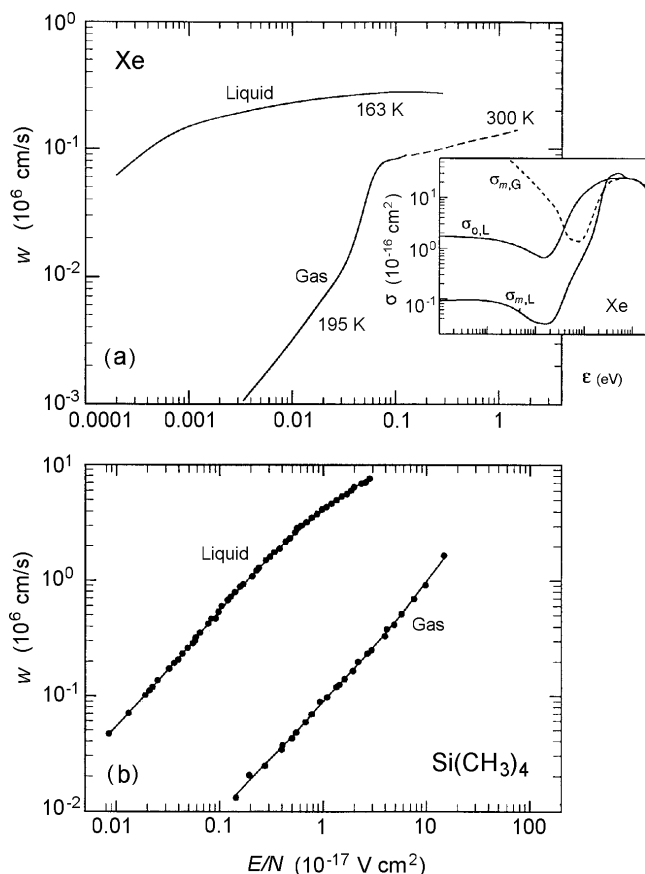


Fig. 12. (a) Electron drift velocity $w(E/N)$ in liquid [31] and gaseous [24] Xe (from Ref. [10]). The inset compares the elastic momentum transfer cross section in gaseous ($\sigma_{m,G}(\epsilon)$) and in liquid ($\sigma_{m,L}(\epsilon)$) xenon; $\sigma_{o,L}(\epsilon)$ is the cross section for elastic energy loss [39]. (b) Electron drift velocity $w(E/N)$ in liquid and gaseous TMS (from Refs. [10, 21]).

With regard to the energetics of electron interactions in various media, the critical role of the polarization energy has been demonstrated from studies on the energetics of electron attachment, photodetachment, and photoionization. Figure 11 shows one such example for the case of dissociative electron attachment to N_2O producing O^- . The

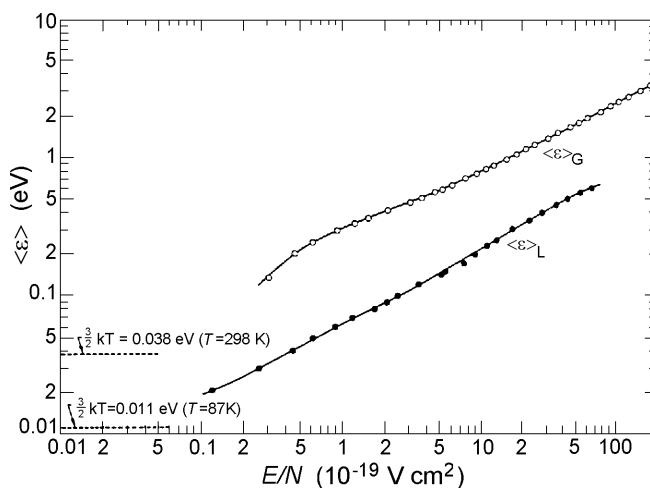


Fig. 13. Mean electron energy in gaseous, $\langle \epsilon \rangle_G$, and liquid, $\langle \epsilon \rangle_L$, Ar (from Ref. [9]).

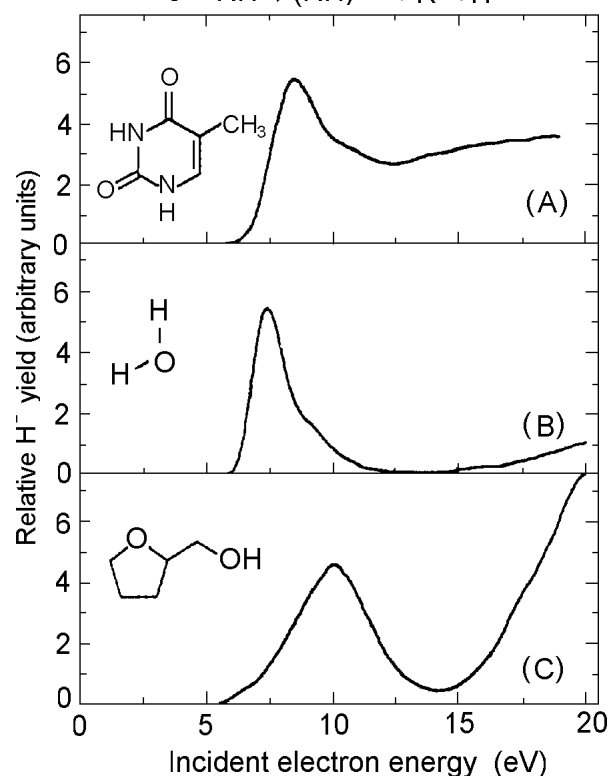
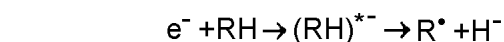
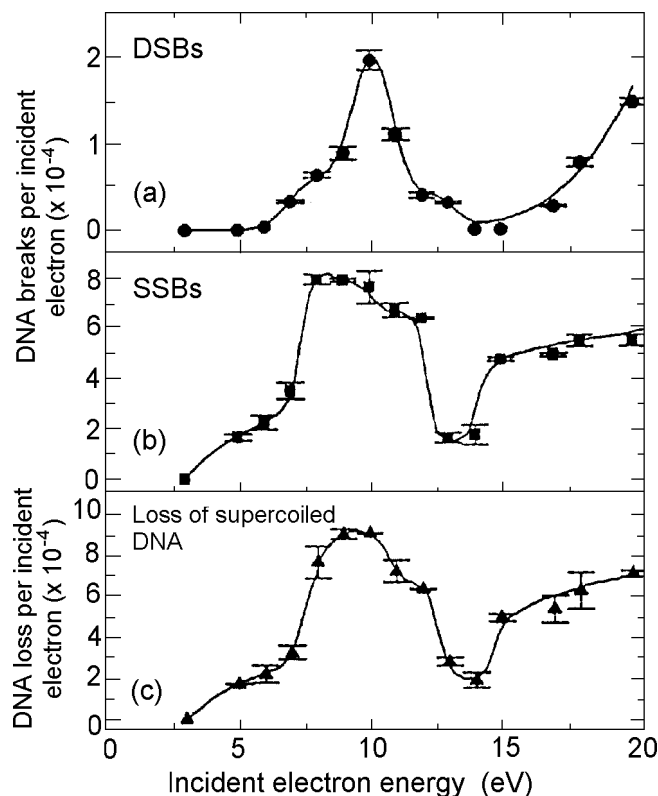


Fig. 14. (Upper part) Measured yields, per incident electron, for the induction of (a) double-strand breaks (DSBs), (b) single-strand breaks (SSBs), and (c) loss of supercoiled DNA, in DNA solid films by low-energy electron irradiation, as a function of the incident electron energy. (Lower part) Electron damage to condensed films of (A) thymine, (B) water, and (C) tetrahydrofurfuryl alcohol exemplified by the yield of H^- desorption as a function of the incident electron energy (from Ref. [4]).

cross section for the production of O^- by dissociative electron attachment to N_2O is much larger when the reaction takes place in liquid argon as opposed to gaseous Ar. The shift of the resonance to lower energy is due to the polarization energy of the medium and is common for other reactions involving negative ion states, and charge-separated and quasi-charge-separated states. This has been indicated by studies on molecular clusters and by comparisons of measurements in the gaseous, the condensed, and the interphase states of matter.

Table 1 shows the approximate energetic relations that have been indicated from studies of the energetics of electron attachment, photodetachment, and photoionization of molecules in gases and liquids.

In addition, it has clearly been shown that electrons can have high mobilities in nonpolar liquids with negative V_0 values. Figure 12 shows this for liquid Xe and liquid TMS (tetramethylsilane). Furthermore, as in gases, quasi-free electrons in electrically stressed rare gas liquids can have energies considerably in excess of thermal (Fig. 13).

In spite of this progress, this field remains a virtually unexplored territory of utmost importance. Knowledge of the behavior of slow electrons in all states of matter and the region between the phases (interphase physics/clusters) will allow us to link the abundant knowledge in the gaseous phase with the scarce knowledge in the condensed phases of matter. Such unification of our knowledge on the fundamental electron–molecule interactions in all states of matter is of basic and applied significance and a prerequisite of bringing physics closer to biology.

Low-energy electron interactions with molecular and macromolecular structures of biological interest

There is a need to develop a physicochemical foundation of biological action. To accomplish this goal, low-energy electron and ion physics must be brought closer to biological materials and environments.

Efforts along these lines trace many years. For instance, in my 1971 book [7] I have indicated the possibility of establishing a toxicity index for molecules based on their electron-capture rate constants, which later Bakale and collaborators [2] have shown possible. The role of slow electrons in radiation damage has been conjectured during at least the last 50 years, and has recently been indicated by experiments [4] (see Fig. 14). The field is however virgin and the physics of life sciences is wide open and challenging. The low-energy electron and its interactions with molecules lie at the very basis of the physicochemical foundation of life sciences, which is yet to be developed.

References

1. Ali MA, Irikura KK, Kim Y-K (2000) Electron-impact total ionization cross sections of SF_x ($x = 1-5$). *Int J Mass Spectrom* 201:187–195
2. Bakale G, McCreary RD (1987) A physico-chemical screening test for chemical carcinogenesis: the k_e . *Carcinogenesis* 8:253–264
3. Bakale G, Sowada U, Schmidt WF (1976) Effect of an electric field on electron attachment to SF_6 , N_2O , and O_2 in liquid argon and xenon. *J Phys Chem* 80:2556–2559
4. Boudaiffa B, Cloutier P, Hunting D, Huels MA, Sanche L (2000) Resonant formation of DNA strand breaks by low-energy (3 to 20 eV) electrons. *Science* 287:1658–1660
5. Buckman SJ, Elford MT, Newman DS (1987) Electron scattering from vibrationally excited CO_2 . *J Phys B: At Mol Opt Phys* 20:5175–5182
6. Celotta R, Brown H, Molof R, Bederson B (1971) Measurements of the total cross section for the scattering of low-energy electrons by metastable argon. *Phys Rev A* 3:1622–1628
7. Christophorou LG (1971) *Atomic and molecular radiation physics*. Wiley Interscience, New York
8. Christophorou LG (ed.) (1984) *Electron–molecule interactions and their applications*, Vols 1–2. Academic Press, New York
9. Christophorou LG (1985) Mean energy of excess electrons in liquid Ar as a function of E/N ; electron attachment to N_2O in gaseous and liquid Ar. *Chem Phys Lett* 121:408–411
10. Christophorou LG (1994) Linking the gaseous and the condensed phases of matter: the slow electron and its interactions. In: Christophorou LG, Illenberger E, Schmidt WF (eds) *Linking the gaseous and the condensed phases of matter: the behavior of slow electrons*. Plenum Press, New York, pp 3–30
11. Christophorou LG, Datskos PG, Faidas H (1994) Photodetachment in the gaseous, liquid, and solid states of matter. *J Chem Phys* 101:6728–6742
12. Christophorou LG, Illenberger E, Schmidt WF (eds) (1994) *Linking the gaseous and the condensed phases of matter: the behavior of slow electrons*. Plenum Press, New York
13. Christophorou LG, McCorkle DL, Christodoulides AA (1984) Electron attachment processes. In: Christophorou LG (ed) *Electron–molecule interactions and their applications*. Academic Press, New York. Vol. 1, chapter 6, pp 477–617
14. Christophorou LG, Olthoff JK (1999) Electron interactions with plasma processing gases: an update for CF_4 , CHF_3 , C_2F_6 , and C_3F_8 . *J Phys Chem Ref Data* 28:967–982
15. Christophorou LG, Olthoff JK (2000) Electron collision data for plasma-processing gases. *Adv At Mol Opt Phys* 44:59–98
16. Christophorou LG, Olthoff JK (2000) Electron interactions with excited atoms and molecules. *Adv At Mol Opt Phys* 44:155–293
17. Christophorou LG, Olthoff JK (2003) *Fundamental electron interactions with plasma processing gases*. Kluwer Academic/Plenum Publishers, New York (in print)
18. Deutsch H, Becker K, Matt S, Märk TD (2000) Theoretical determination of absolute electron-impact ionization cross sections of molecules. *Int J Mass Spectrom Ion Processes* 197:37–69
19. Dixon AJ, Harrison MFA, Smith ACH (1973) Ionization of metastable rare gas atoms by electron impact. In: Cobic BC, Kurepa MV (eds) *Proc of the VIII Int Conf on the Physics of Electronic and Atomic Collisions*, Belgrade, pp 405–406
20. Faidas H, Christophorou LG, McCorkle DL (1992) Laser photodetachment in liquids: $C_6F_6^-$ in tetramethylsilane. *Chem Phys Lett* 193:487–492
21. Faidas H, Christophorou LG, McCorkle DL, Carter JG (1990) Electron drift velocities and electron mobilities in fast room temperature dielectric liquids and their corresponding vapors. *Nucl Instrum Meth Phys Res A* 294:575–582
22. Ferch J, Granitzka B, Masche C, Raith W (1985) Electron-argon total cross section measurements at low energies by time-of-flight spectroscopy. *J Phys B: At Mol Opt Phys* 18:967–983
23. Ferch J, Masche C, Raith W (1981) Total cross section measurement for $e-CO_2$ scattering down to 0.07 eV. *J Phys B: At Mol Opt Phys* 14:L97–L100
24. Hunter SR, Carter JG, Christophorou LG (1988) Low-energy electron drift and scattering in krypton and xenon. *Phys Rev A* 38:5539–5551

25. Huo WM, Tarnovsky V, Becker K (2002) Total electron-impact ionization cross-sections of CF_x and NF_x ($x = 1-3$). *Chem Phys Lett* 358:328–336
26. Jaffke T, Meinke M, Hashemi R, Christophorou LG, Illenberger E (1992) Dissociative electron attachment to singlet oxygen. *Chem Phys Lett* 193:62–68
27. Jost K, Bishing PGF, Erchen F, Felsmann M, Walther J (1983). In: *Proceedings of the XIII Int Conf on the Physics of Electronic and Atomic Collisions*, p 91
28. Karwasz GP, Brusa RS, Zecca A (2001) One century of experiments on electron-atom and molecule scattering: a critical review of integral cross sections. *Riv Nuovo Cimento* 24:4:1–101
29. Krishnakumar E, Srivastava SK (1988) Ionization cross sections of rare-gas atoms by electron impact. *J Phys B: At Mol Opt Phys* 21:1055–1082
30. Mi L, Bonham RA (1998) Electron-ion coincidence measurements: the neutral dissociation cross section of CF_4 . *J Chem Phys* 108:1910–1914
31. Miller LS, Howe S, Spear WE (1968) Charge transport in solid and liquid Ar, Kr, and Xe. *Phys Rev* 166:871
32. Milloy HB, Crompton RW, Rees JA, Robertson AG (1977) The momentum transfer cross section for electrons in argon in the energy range 0–4 eV. *Austr J Phys* 30:61–72
33. Morrison MA, Lane NF, Collins LA (1977) Low-energy electron-molecule scattering: application of closed-channel theory to e - CO_2 collisions. *Phys Rev A* 15:2186–2201
34. Motlagh S, Moore JH (1998) Cross sections for radicals from electron impact on methane and fluoroalkanes. *J Chem Phys* 109:432–438
35. Nakano T, Sugai H (1992) Partial cross sections for electron impact dissociation of CF_4 into neutral radicals. *Jpn J Appl Phys, Part 1* 31:2919–2924
36. Nickel JC, Imre K, Register DF, Trajmar S (1985) Total electron scattering cross sections: I. He, Ne, Ar, Xe. *J Phys B: At Mol Opt Phys* 18:125–133
37. Rapp D, Briglia DD (1965) Total cross sections for ionization and attachment in gases by electron impact. II. Negative-ion formation. *J Chem Phys* 43:1480–1489
38. Robinson EJ (1969) Electron scattering by metastable rare gases. *Phys Rev* 182:196–200
39. Sakai Y, Nakamura S, Tagashira H (1985) Drift velocity of hot electrons in liquid Ar, Kr, and Xe. *IEEE Trans Elect Insul* 20:133–137
40. Sanche L (1991) Primary interactions of low-energy electrons in condensed matter. In: Ferradini C, Jay-Gerin J-P (eds) *Excess electrons in dielectric media*. CRC Press, Boca Raton, chapter 1
41. Sowada U, Holroyd RA (1979) Laser photodetachment from O_2 in non-polar liquids. *J Chem Phys* 70:3586–3591
42. Sowada U, Holroyd RA (1980) Laser photodetachment spectra of $C_6F_6^-$ in nonpolar liquids. *J Phys Chem* 84:1150
43. Sugai H, Toyoda H, Nakano T, Goto M (1995) Absolute cross sections for the electron-impact dissociation of CF_4 and CHF_3 into the CF_x ($x = 1-3$) neutral radicals. *Contrib Plasma Phys* 35:415–420
44. Tarnovsky V, Deutsch H, Martus KE, Becker K (1998) Electron impact ionization of the SF_2 and SF_3 free radicals. *J Chem Phys* 109:6596–6600
45. Tarnovsky V, Kurunzi P, Rogozhnikov D, Becker K (1993) Absolute cross sections for dissociative electron impact ionization of the CF_x ($x = 1-3$) free radicals. *Int J Mass Spectrom Ion Processes* 128:181–194
46. Winters HF, Inokuti M (1982) Total dissociation cross section of CF_4 and other fluoroalkanes for electron impact. *Phys Rev A* 25:1420–1430