

Electron scattering from isoelectronic, $N_e = 18$, CH_3X molecules ($\text{X} = \text{F}, \text{OH}, \text{NH}_2$ and CH_3)

Czesław Szmytkowski and Andrzej M Krzysztofowicz

Faculty of Applied Physics and Mathematics, Technical University of Gdańsk, ul G Narutowicza 11/12, 80-952 Gdańsk, Poland

Received 6 June 1995

Abstract. Total cross sections for methanol, methylamine and ethane molecules were measured in a linear electron-transmission experiment for impact energies from nearly 1 eV up to 250 eV. Results show that for those targets and CH_3F , isoelectronic with them, between impact energies close to the cross section maximum and the highest energies applied, the total cross section increases with static electric dipole polarizability of the molecule.

1. Introduction

Relations between electron-scattering cross sections and physico-chemical parameters of target molecules have been searched for since the earliest systematic measurements of these cross sections (e.g. Brüche 1929). When found, such correlations may indicate the role of some microscopic target properties in the scattering process, while the semiempirical formulae describing these correlations should help to estimate total cross sections of targets that are still lacking in experimental data or calculations. To find such correlations an analysis of cross sections is needed for a group of targets of selected properties—if possible, of data taken on the same experimental setup.

Electron-scattering absolute grand-total cross sections at intermediate impact energies have recently been measured for families of targets to see how the cross sections vary from target to target. Floeder *et al* (1985) measured total cross sections for electron and positron scattering for a series of simple hydrocarbons and noticed that, for impact energies between 100 and 400 eV, the magnitude of total cross section for these targets is linearly correlated with the number of molecular electrons. Nishimura and Tawara (1991) established a connection between the magnitude of total cross section and the geometrical size of the target for a group of simple hydrocarbons, at intermediate energies. A strong correlation of total cross section with static electric dipole polarizability of the target was noted by Szmytkowski (1989) for a group of various atoms and molecules, in the energy range from 50 to 400 eV.

Recent calculations of Jain and Baluja (1992), performed for a large variety of molecules, have confirmed the correlation between the total cross section and the number of molecular electrons, but failed to confirm the target polarizability correlation.

It is a common and well-known feature of all the measured electron-scattering total cross sections that they decrease with increasing energy at intermediate and high electron impact energies. There is no agreement, however, about the character of this dependence (cf

Floeder *et al* 1985, Szmytkowski 1989, Nishimura and Sakae 1990, Nishimura and Tawara 1991, Karwasz *et al* 1993, Zecca *et al* 1992a, b, c, 1995).

The purpose of the reported work is the further investigation of how changes in some target parameters are reflected in the magnitude and energetic dependence of the electron impact total cross section. A set of molecules incorporating the methyl group (CH_3F , CH_3OH , CH_3NH_2 and C_2H_6) has been selected for the study, for which some correlations have already been investigated by Schmieder (1930). These molecules have the same number of molecular electrons, but vary in their permanent dipole moments and electric dipole polarizabilities. For the latter three targets, absolute total cross sections were measured for a wide range of impact energy. As far as we know, these are the first published electron-scattering absolute total cross sections for the methanol and methylamine molecules above 50 eV.

2. Experimental

2.1. Experimental procedure

The absolute total cross sections were determined by the linear transmission method. It is based on measurements of the attenuation of intensity of the projectile-particle beam transmitted through the target volume. The absolute total cross section $Q(E)$ for a given impact energy E may be, to the first approximation, derived from the Bouguer-de Beer-Lambert law

$$Q(E) = \frac{1}{nL} \ln \frac{I_0(E)}{I_p(E)} \quad (1)$$

where quantities measured directly in the present experiment are: projectile beam intensities at energy E in the presence, $I_p(E)$, and absence, $I_0(E)$, of the target in the scattering cell, and the length of the scattering volume, L . Density number n was determined from the ideal gas formula

$$n = \frac{p}{k} (T_t T_m)^{-0.5} \quad (2)$$

where p is pressure of the target as measured with a baratron and k is the Boltzmann constant. Expression (2) allows for the thermal transpiration effect (Knudsen 1910) due to a difference in temperature—usually of several degrees—between the collision chamber, T_t , and the manometer head, $T_m = 322$ K.

The apparatus and experimental procedure used in the present measurements have already been intensively employed for the determination of absolute total cross sections in our laboratory. A more detailed description of the applied experimental system and the data-taking procedure can be found elsewhere (e.g. Krzysztofowicz and Szmytkowski 1995) and we give only a brief description here.

The sample in the scattering cell was irradiated with a quasimonoenergetic electron beam ($I \approx 10$ pA, fwhm ≈ 70 meV) from an electron gun coupled to an electrostatic cylinder deflector and a system of electron lenses. Those electrons which passed the exit orifice of the chamber were discriminated with a retarding element and detected by a Faraday cup with geometrical angular acceptance of 0.7 msr. No magnetic steering of electron beam was used in the spectrometer.

A gas handling system directs the target vapour or gas to the scattering chamber or, alternatively, into the background to ensure that conditions in the region of electron optics are stable throughout the experiment. The pressure range of the target in the scattering cell was chosen between 80 and 300 mPa, so that multiple scattering can be ignored.

An absolute energy scale for impinging electrons was established to within ± 60 meV with respect to the oscillatory resonant structure visible around 2 eV in the transmission current in nitrogen.

The measurements were carried out for a given energy in a series of runs. Within the limits of statistical uncertainties, results obtained in different series were independent of applied sample pressures and the electron beam controlling parameters. An averaging procedure with weights depending on the statistical uncertainty was applied to derive the final total cross section at a particular energy.

Methanol vapour was obtained from 99.8% pure liquid (Reanal) degassed each time using several freeze-pump-thaw cycles. The purities of methylamine (Merck-Schuchardt) and ethane (Matheson Gas Products) were 99.2% and 99.99%, respectively. These gases were used without any further purification.

2.2. Error estimation

Statistical uncertainties based on reproducibility (one standard deviation of the weighted mean values) are about 2% below 1 eV and never exceed 1.5% at higher energies.

Systematic errors in the absolute values of total cross sections originate mainly from the following:

(i) the inability to correctly determine the length of the interaction region in a target of usually inhomogeneous density is lower than 0.5% (see Nelson and Colgate 1973);

(ii) the imperfect discrimination of electrons scattered elastically and those scattered inelastically with small energy losses into small forward angles; it would lower the measured total cross section, compared with the actual value, by 1% at low energies and by 3% at the highest energies applied (the data were not corrected for this effect); and

(iii) the uncertainty of electron energy; at the lowest impact energies, where the cross section is a steep function of energy, possible drift in energy by 50 meV may cause a change in cross section of nearly 2%.

The sum of other possible systematic errors has been estimated to be less than 3%.

3. Results

In the reported experiment, absolute electron-scattering total cross sections for methanol, methylamine and ethane molecules have been measured with the same apparatus for energies ranging from a little less than 1 eV up to 250 eV. All obtained data are shown in numerical form in table 1.

3.1. CH₃OH

Our electron-methanol molecule absolute total cross section versus impact energy (0.8–250 eV) is plotted in figure 1 and compared with the early absolute results of Schmieder (1930) and the more recent normalized data of Sueoka *et al* (1985).

Three distinct regions can be discerned in the obtained cross section's energy dependence.

In the first region of the lowest applied energies, the cross section rapidly decreases with increasing impact energy—from 29×10^{-20} m² at 0.8 eV to 20×10^{-20} m² at around 2 eV. Such behaviour is characteristic of polar particles ($\mu_{\text{CH}_3\text{OH}} = 1.7$ D, Lide 1993–94) and related to direct scattering processes dominant at low impact energies (Itikawa 1978, Shimamura 1984).

Table 1. Measured absolute total cross sections (TCS) for electron impact of ethane, methylamine and methanol molecules in units of 10^{-20} m^2 .

Energy (eV)	TCS			Energy (eV)	TCS		
	C ₂ H ₆	CH ₃ NH ₂	CH ₃ OH		C ₂ H ₆	CH ₃ NH ₂	CH ₃ OH
0.6	3.11			11	31.7		
0.7	4.37	29.7		11.5		27.0	24.9
0.8	5.05	28.2	28.2	12	30.8		
0.9		27.0		12.5		26.4	
1.0	6.50	26.2	25.6	13.5			24.1
1.1		25.1		14	29.5		
1.2	7.97	24.4	23.6	14.5		25.3	
1.3		23.3		15.5			23.1
1.4	9.13	22.7	22.1	16	28.3		
1.5		22.4		16.5		24.6	
1.6	10.2	21.8	21.3	17.5			22.4
1.7		21.3		18	28.2		
1.8	10.8	21.0		18.5		23.5	
1.9		20.7	19.7	20	27.6	22.8	21.8
2.0	11.9	20.1		22			21.1
2.1		20.0		23		22.2	
2.2			19.7	25	26.6	21.7	20.0
2.3		19.9		27			19.2
2.5	14.5	19.8	19.6	28		21.0	
2.8		19.9		30	24.5	20.5	18.4
3.0	16.0	19.9	19.8	35	23.0	19.3	17.5
3.2		20.2		40	21.9	18.4	16.7
3.5	17.9	20.6	20.2	45	21.1	18.1	16.1
4	20.2	21.5	21.6	50	20.2	17.4	15.7
4.5	23.0	22.4	22.3	60	19.2	16.7	14.9
5	25.1	23.6	23.7	70	18.3	16.2	14.3
5.5	27.2	24.8	24.7	80	17.3	15.6	13.5
6	29.4	25.8		90	16.4	14.6	12.9
6.5	32.0	27.3	25.8	100	15.4	14.0	12.4
7	33.9			110	14.2	13.6	11.9
7.5	34.7	29.1	26.5	120	13.7	13.1	11.4
8	34.6			140	12.8	12.0	10.7
8.5	34.2	29.2	26.8	160	12.1	11.3	10.1
9	33.6			180	11.3	10.7	9.4
9.5		28.5	26.2	200	10.5	9.76	8.81
10	32.5			220	9.90	9.09	8.28
10.5		27.9	25.9	250	9.26	8.38	7.55

Beyond 3 eV, the cross section increases and assumes the form of a very wide maximum with no apparent structure, centred near 9 eV. Similar maxima, of varying distinctness, occur in this energy range for most of the targets hitherto examined. Satisfactory explanation of their origin would demand a detailed experimental and/or theoretical study of possible processes at work in each particular case. However, due to a vast number of open channels in this energy range it proves to be a most demanding task even for the simplest molecules. For most of the molecules, including CH₃OH, such data are still highly insufficient in quantity. Trepka and Neuert (1963) and more recently Kühn *et al* (1988) investigated the processes of negative-ion formation due to electron collisions with methanol molecules. Their results demonstrate that, in the region of the above mentioned maximum, the registered negative ions are mainly a result of temporary ion resonant states while at higher energies, direct

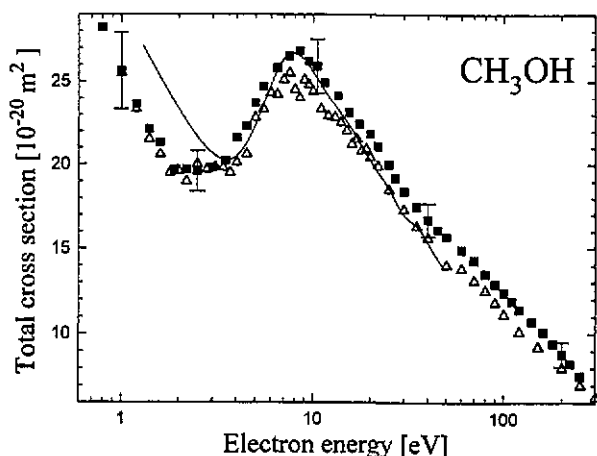


Figure 1. Absolute e^- - CH_3OH scattering total cross sections: (■), present, absolute; (—), Schmieder (1930), absolute; (Δ), Sueoka *et al* (1985), normalized. The error bars correspond to overall experimental uncertainties estimated at selected points.

processes seem to prevail.

For energies above 10 eV, the cross section is a monotonically slowly decreasing function of energy, with a slight change of slope around 80 eV, possibly related to a maximum of the ionization cross section occurring around 90 eV (Durić *et al* 1989). With growing impact energy, the role of ionization effects in the scattering process increases. At around 100 eV the total ionization cross section in CH_3OH scattering constitutes slightly less than one-quarter of the grand-total cross section and reaches slightly over one-third for the highest applied energy, viz 250 eV.

All results shown in figure 1 exhibit the same energy dependence. The normalized data of Sueoka *et al* (1985) are lower than ours, throughout the energy range, by 5% for the lower energies and up to 15% beyond 50 eV. A similar discrepancy of up to 15% occurs below 3 eV in the case of the Schmieder (1930) results. However, the apparent discrepancies among results from different laboratories are always within the limits of combined experimental uncertainties.

3.2. CH_3NH_2

The absolute grand-total cross section measured for methylamine in the reported experiment as a function of electron impact energy (0.8–250 eV) is presented in figure 2, along with the only other published total cross section (Schmieder 1930). Essential discrepancies between the two experiments are clearly visible. The Schmieder results for energies below 8 eV are constantly decreasing towards lower energies, while the present cross section has a distinct minimum at around 2.5 eV. There is also a significant systematic difference in magnitude (up to 25%) between the two sets of results.

The cross section measured for methylamine rapidly decreases from $30 \times 10^{-20} \text{ m}^2$ at 0.7 eV to nearly $20 \times 10^{-20} \text{ m}^2$ at 2 eV, then increases rather slowly to reach a maximum of almost $30 \times 10^{-20} \text{ m}^2$ at 8.5 eV. In the region of the total cross section maximum, Collin *et al* (1968), Hubin-Franskin and Collin (1971), Abuain *et al* (1984), and—more recently—Yalcin and Suzer (1992) have all registered negative ions as products of electron scattering on the methylamine molecule. Some of them are produced in resonant

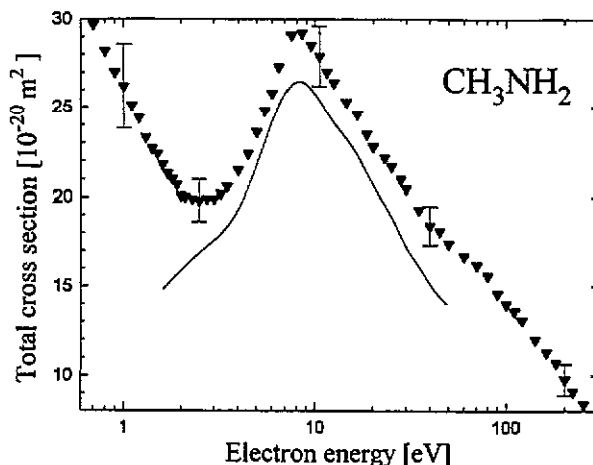


Figure 2. Absolute e^- - CH_3NH_2 scattering total cross sections: (\blacktriangledown), present, absolute; (—), Schmieder (1930), absolute. The error bars correspond to overall experimental uncertainties estimated at selected points.

processes, via transient negative parent ions formed on electron attachment, while others are due to direct processes. Motte-Tollet *et al* (1990) have also noticed a very broad enhancement in vibrational excitation functions centred at 7.5 eV and assigned it to scattering processes occurring via shape resonance built on the electronic ground state of the molecule. Another shape resonance of different symmetry is most probably located near 8.5 eV. The relative experiments of Motte-Tollet *et al* (1990, 1992) suggest that due to a relatively high permanent dipole moment of the methylamine molecule ($\mu_{\text{CH}_3\text{NH}_2} = 1.3$ D, Lide 1993-94), the intensities of resonant and non-resonant vibrational excitation in the region of the RCS maximum are similar to each other, while for higher energies direct processes are definitely dominant. However, to ascertain the roles of particular processes in the scattering one would also need absolute values of partial cross sections.

For energies above 10 eV the total cross section descends monotonically with energy to nearly $9 \times 10^{-20} \text{ m}^2$ at 250 eV.

3.3. C_2H_6

Absolute total cross sections for electron scattering on the ethane molecule had been measured by Brüche (1930) and Schmieder (1930), with recent experiments by Floeder *et al* (1985) and Nishimura and Tawara (1991). Normalized cross sections were obtained by Sueoka and Mori (1986) and, for very low energies, by Lunt *et al* (1994). In the present experiment, data were taken between 0.6 and 250 eV. All the hitherto published absolute results are of the same shape (see figure 3) and differ in magnitude only. The largest discrepancies occur for energies close to the maximum (up to 20%), which may be related to relatively high uncertainties of the different experimental techniques employed. The present experimental data distribute between those of Nishimura and Tawara (1991) and those of Floeder *et al* (1985).

At the lowest energy of the present experiment, i.e. 0.6 eV, the C_2H_6 molecule is very transparent for electrons and the total scattering cross section is a mere $3 \times 10^{-20} \text{ m}^2$. The most recent measurements of Lunt *et al* (1994) suggest that below 0.5 eV the cross section has a Ramsauer-Townsend minimum, characteristic of non-polar targets with relatively high

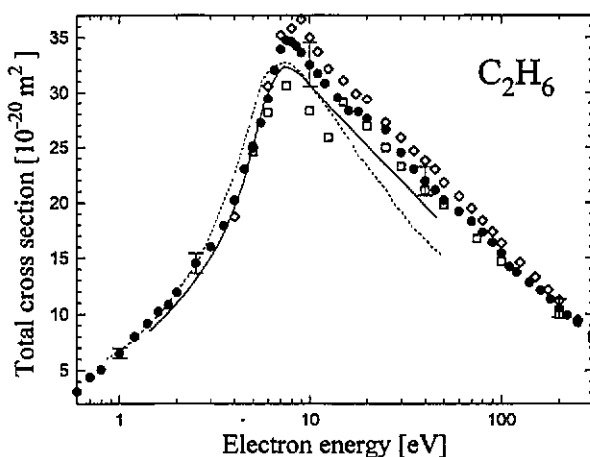


Figure 3. Absolute e^- - C_2H_6 scattering total cross sections: (●), present; (---), Brüche (1930); (—), Schmieder (1930); (□), Floeder *et al* (1985); (◇), Nishimura and Tawara (1991). The error bars correspond to overall experimental uncertainties estimated at selected points.

polarizability. A minimum just above 0.1 eV is also visible in the momentum-transfer cross section derived from swarm experiments by Cottrell and Walker (1965, 1967), Duncan and Walker (1974) and McCorkle *et al* (1978) and nicely reproduced in the recent calculations of Sun *et al* (1992).

The cross section increases sharply with energy and has a structureless maximum of $35 \times 10^{-20} \text{ m}^2$ near 8 eV. Both the experimental elastic (Matsunaga *et al* 1981, Curry *et al* 1985, Tanaka *et al* 1988, Mapstone and Newell 1992) and the vibrationally inelastic differential cross sections (Kubo *et al* 1981, Curry *et al* 1985, Mapstone and Newell 1987, Boesten *et al* 1990) indicate the presence of an f-wave short-lived shape resonance, centred near 7.5 eV. The share of vibrational excitation processes reaches about 10% of the total cross section between 5 and 10 eV (Boesten *et al* 1990). Trepka and Neuert (1963) and Rutkowsky *et al* (1980) have observed negative ions at this maximum, originating via a dissociative attachment channel. The presence of a broad shape resonance—though shifted near 12 eV—also follows from the theoretical static-exchange studies of Winstead *et al* (1991), while continuum multiple scattering investigations of Boesten *et al* (1990) and complex Kohn calculations of Sun *et al* (1992) locate the resonance close to 7.5 eV, in good agreement with experimental data.

All the results shown in figure 3 exhibit a change in the slope of the cross section function around 20 eV, similar to that of Xe. The origin of this effect remains to be investigated. For higher energies, the cross section decreases steadily along with energy and at above 100 eV the share of ionization processes in the scattering—the total ionization cross section—is nearly a half of the total cross section (Lampe *et al* 1957, Chatham *et al* 1984).

4. Final remarks

Absolute total cross sections for electron scattering on 18-electron molecules incorporating the methyl group are summarized in figure 4, while their selected parameters are shown in table 2. The data of H_2S and Ar have been added to table 2. No theoretical total cross sections are available for comparison.

The most outstanding feature of these cross section functions is the fact that their

overall shape is remarkably similar for all the investigated polar molecules (CH_3F , CH_3OH and CH_3NH_2) throughout the examined energy range. The long-range interaction due to the targets' permanent dipole moment is especially apparent at the lowest energies, when the cross sections for polar molecules increase sharply, while decreasing for the non-polar C_2H_6 molecule. The same difference is clearly observable for other families of isoelectronic targets (e.g. Ne , H_2O , NH_3 and CH_4 , Szmytkowski 1990).

The target polarization induced by the incident electron seems to have an appreciable effect on the magnitude of the total cross section at higher impact energies. Both in the vicinity of the maximum (about 8 eV) and for the higher energies, the total cross section of isoelectronic molecules tends to increase with their growing polarizability. Such behaviour contradicts the conclusions of Jain and Baluja (1992) but confirms the trend observed by Szmytkowski (1989). On the other hand, according to the investigations of Floeder *et al* (1985), the total cross section for targets of the same number of molecular electrons should have the same value for any given intermediate energy.

Figure 5 shows the total cross sections of the measured targets plotted at selected energies against target polarizability. For energies between several times the ionization potential and

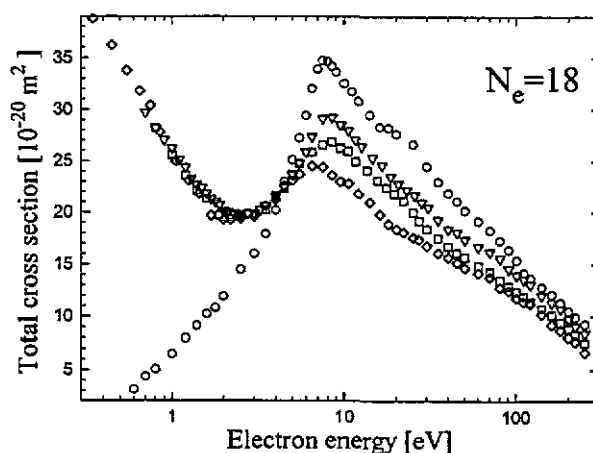


Figure 4. Total cross sections for electron scattering on 18-electron targets incorporating the methyl group: (\circ), C_2H_6 , present; (∇), CH_3NH_2 , present; (\square), CH_3OH , present; (\diamond), CH_3F , Krzysztofowicz and Szmytkowski (1995).

Table 2. Selected parameters of 18-electron targets.

Target	Dipole moment ^a (D)	Polarizability ^b (10^{-30} m^3)
C_2H_6	—	4.47
CH_3NH_2	1.31	4.01
CH_3OH	1.70	3.29
CH_3F	1.858	2.97
Ar	—	1.6411
H_2S	0.97	3.78

^aLide (1993–1994).

^bMiller (1993–1994).

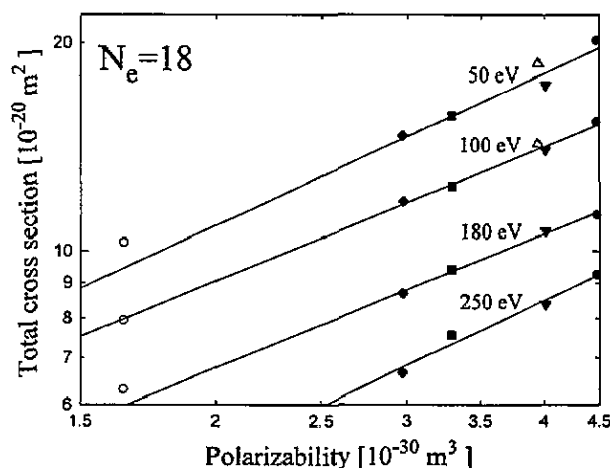


Figure 5. Absolute total cross sections versus electric dipole polarizability of molecule for isoelectronic targets: (●), C₂H₆; (▼), CH₃NH₂; (■), CH₃OH; (◆), CH₃F, Krzysztofowicz and Szmytkowski (1995). Regression lines have been traced. Earlier data from the same laboratory are also marked: (Δ), H₂S, Szmytkowski and Maciąg (1986); and (○), Ar, Szmytkowski *et al* (1995).

250 eV, the dependence of cross section on polarizability α can be expressed as: $Q \sim \alpha^s$, where $s \simeq 0.7$ is close to the 0.5 value of the Vogt and Wannier (1954) formula derived for pure polarization interactions. Results for other isoelectronic targets, Ar and H₂S, attached in figure 5, also lie near the regression lines.

It should be noted here that certain dependence of the total electron-impact ionization cross section, which is an essential component of the grand-total cross section at intermediate energies, on polarizability has also been observed for hydrocarbons by Nishimura and Tawara (1994).

The noticed correlation between total cross section and target polarizability allows us to estimate roughly the former at any intermediate energy with only one target parameter given.

Between 100 and 250 eV, the cross section versus energy dependence has the form $Q \sim E^{-0.5}$ for the investigated molecules. This means that for these energies, the total cross section is proportional to the time spent by the incident electron in the region of target molecule.

Acknowledgments

We would like to thank Grzegorz Kasperski and Paweł Możejko for their assistance in the final episodes of this project. This work was in part sponsored by Komitet Badań Naukowych.

References

- Abuain T, Walker I C and Dance D F 1984 *J. Chem. Soc. Faraday Trans. II* **80** 641-5
- Boesten L, Tanaka H, Kubo M, Sato H, Kimura M, Dillon M A and Spence D 1990 *J. Phys. B: At. Mol. Opt. Phys.* **23** 1905-13
- Brüche E 1929 *Ergebnisse der exakten Naturwissenschaften* **8** 185-228

- 1930 *Ann. Phys., Lpz.* 4 387–408
- Chatham H, Hils D, Robertson R and Gallagher A 1984 *J. Chem. Phys.* 81 1770–7
- Collin J E, Hubin-Franskin M-J and D'Or L 1968 *Adv. Mass Spectrom.* 4 713–26
- Cottrell T L and Walker I C 1965 *Trans. Faraday Soc.* 61 1585–93
- 1967 *Trans. Faraday Soc.* 63 549–54
- Curry P J, Newell W R and Smith A C H 1985 *J. Phys. B: At. Mol. Phys.* 18 2303–18
- Duncan C W and Walker I C 1974 *J. Chem. Soc. Faraday Trans. II* 70 577–85
- Durić N, Čadež I and Kurepa M 1989 *Fizika* 21 339–43
- Floeder K, Fromme D, Raith W, Schwab A and Sinapius G 1985 *J. Phys. B: At. Mol. Phys.* 18 3347–59
- Hubin-Franskin M-J and Collin J E 1971 *Bull. Soc. R. Sci. Liège* 40 502–17
- Itikawa Y 1978 *Phys. Rep.* 46 117–64
- Jain A and Baluja K L 1992 *Phys. Rev. A* 45 202–18
- Karwasz G, Brusa G P, Gasparoli A and Zecca A 1993 *Chem. Phys. Lett.* 211 529–33
- Knudsen M 1910 *Ann. Phys., Lpz.* 31 205–29
- Krzysztofowicz A M and Szmytkowski Cz 1995 *J. Phys. B: At. Mol. Opt. Phys.* 28 1593–602
- Kubo M, Matsunaga D and Tanaka H 1981 *Proc. 12th Int. Conf. on the Physics of Electronic and Atomic Collisions (Gatlinburg)* ed S Datz (Amsterdam: North-Holland) Abstracts p 344
- Kühn A, Fenzlaff H-P and Illenberger E 1988 *J. Chem. Phys.* 88 7453–8
- Lampe F W, Franklin J L and Field F H 1957 *J. Am. Chem. Soc.* 79 6129–32
- Lide D R 1993–1994 *CRC Handbook of Chemistry and Physics* 74th edn (Boca Raton, FL: Chemical Rubber Company) pp 9–42
- Lunt S L, Randell J, Ziesel J P, Mrotzek G and Field D 1994 *J. Phys. B: At. Mol. Opt. Phys.* 27 1407–22
- Mapstone I M and Newell W R 1987 *Proc. 15th Int. Conf. on the Physics of Electronic and Atomic Collisions (Brighton)* ed J Geddes, H B Gilbody, A E Kingston, C J Latimer and H J R Walters (Amsterdam: North-Holland) Abstracts p 275
- Mapstone B and Newell W R 1992 *J. Phys. B: At. Mol. Opt. Phys.* 25 491–506
- Matsunaga D, Kubo M and Tanaka H 1981 *Proc. 12th Int. Conf. on the Physics of Electronic and Atomic Collisions (Gatlinburg)* ed S Datz (Amsterdam: North-Holland) Abstracts p 358
- McCorkle D L, Christophorou L G, Maxey D V and Carter J G 1978 *J. Phys. B: At. Mol. Phys.* 11 3067–79
- Miller T M 1993–1994 *CRC Handbook of Chemistry and Physics* 74th edn (Boca Raton, FL: Chemical Rubber Company) pp 10–192
- Motte-Tollet F, Hubin-Franskin M-J and Collin J E 1990 *J. Chem. Phys.* 93 7843–50
- 1992 *J. Chem. Phys.* 97 7314–22
- Nelson R N and Colgate S O 1973 *Phys. Rev. A* 8 3045–9
- Nishimura H and Sakae T 1990 *Japan. J. Appl. Phys.* 29 1372–6
- Nishimura H and Tawara H 1991 *J. Phys. B: At. Mol. Opt. Phys.* 24 L363–6
- 1994 *J. Phys. B: At. Mol. Opt. Phys.* 27 2063–74
- Rutkowski J, Drost H and Spangenberg H-J 1980 *Ann. Phys., Lpz.* 37 259–70
- Schmieder F 1930 *Z. Elektrochem.* 36 700–4
- Shimamura I 1984 *Electron-Molecule Collisions* ed I Shimamura and K Takayanagi (New York: Plenum) pp 89–189
- Sueoka O, Katayama Y and Mori S 1985 *At. Coll. Res. Japan, Prog. Rep.* 11 17–8
- Sueoka O and Mori S 1986 *J. Phys. B: At. Mol. Phys.* 19 4035–50
- Sun W, McCurdy C W and Lengsfeld B H III 1992 *J. Chem. Phys.* 97 5480–8
- Szmytkowski Cz 1989 *Z. Phys. D* 13 69–73
- 1990 *Z. Nauk. P. G.: Fizyka* 26 3–75
- Szmytkowski Cz and Maciąg K 1986 *Chem. Phys. Lett.* 129 321–4
- Szmytkowski Cz, Maciąg K and Karwasz G P 1995 to be published
- Tanaka H, Boesten L, Matsunaga D and Kudo T 1988 *J. Phys. B: At. Mol. Opt. Phys.* 21 1255–63
- Trepka L and Neuert H 1963 *Z. Naturf. a* 18 1295–303
- Vogt E and Wannier G H 1954 *Phys. Rev.* 95 1190–8
- Winstead C, Hipes P G, Lima M A P and McKoy V 1991 *J. Chem. Phys.* 94 5455–61
- Yalcin T and Suzer S 1992 *J. Mol. Struct.* 266 353–6
- Zecca A, Karwasz G P and Brusa R S 1992a *Phys. Rev. A* 45 2777–83
- 1992b *Phys. Rev. A* 46 3877–82
- 1992c *Chem. Phys. Lett.* 199 423–5
- Zecca A, Nogueira J C, Karwasz G P and Brusa R S 1995 *J. Phys. B: At. Mol. Opt. Phys.* 28 477–86