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Absolute Electron-Scattering Total Cross Section Measurements for Noble Gas Atoms and Diatomic Molecules

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Abstract

Absolute electron-scattering total cross sections for noble gas atoms (He, Ne, Ar, Kr, and Xe) and H_2, N_2, CO, NO, and O_2 molecules have been measured at impact energies between 0.5 and 250 eV by the linear transmission method with the same experimental set-up for all the investigated targets. Generally, our total cross sections have been found to be in good agreement with other data with respect to shape. Some systematic discrepancies in magnitude still exist between results of different groups, especially at the lowest applied energies and in the energy range where the cross sections peak. At these energies, new measurements should be carried out before establishing a reference set of data.

1. Introduction

Transmission of electrons through gaseous media (noble gases, air, hydrogen and nitrogen) was one of the first phenomena studied [1] shortly after the discovery of this elementary particle. Subsequently, total cross sections were the first parameters determined quantitatively for electron scattering in gases. Successful explanation of observed anomalies [2, 3] with respect to classically expected energeal dependences of cross sections [4] contributed to development of quantum mechanical methods [5].

Reliable, accurate experimental data concerning the electron-atom/molecule scattering are of great importance in understanding the atmospheric phenomena of Earth and other planets, aspects of interstellar matter, radiation chemistry, radiobiology, gaseous discharge plasma and electron impact-induced reactions on surfaces.

Among the measurable quantities describing the scattering processes, the grand total cross section is the most reliable because it can be determined without any normalization procedures. Therefore it may serve, inter alia, as a standard value (an upper limit) for the normalization of data for individual scattering processes and/or as a test of theoretical models. However, in spite of the conceptual simplicity of the methods used to determine electron scattering total cross sections and the efforts by many researchers, remarkable differences still exist in magnitude and/or shape of electron-energy dependences of the measured total cross sections for some targets (cf. [6, 7]).

The number of measurements of electron scattering total cross sections for the targets discussed in this paper, especially for lighter noble gas atoms, is remarkable. However, a thorough inspection of the available results shows that while the results from different laboratories are converging for lighter noble gases and H_2, the situation is not so favorable with heavier noble gases, even for the most recent data. Discrepancies between data from different laboratories for the same targets are in many cases outside the declared experimental uncertainties. Repeated measurement by various methods may help to find the source of systematic errors of a particular experiment. On the other hand, results obtained from the same apparatus for different targets and/or projectiles (electrons, positrons) are particularly useful in the analysis of the liability of cross sections concurrent with the change of the target and/or projectile.

Many of the previous measurements of absolute electron-scattering total cross sections for simple targets had been mainly concentrated in the very low energy range, i.e. below a few electronvolts (e.g. Ahmedabad [8–12], Bielefeld [13–18], Canberra [19–24], Gdańsk [25]), or in the high energy range (Trento [26–33], Sao Carlos [34], Madrid [35–37]). The present measurements were performed in the energy range between these two extremes. For convenience we present summaries of available experimental works on the total cross section for targets studied in the present work in Tables I and II (compare also Trajmar and McConkey [38]). Among the recent experiments, only those of the Pasadena [39–41] and Detroit [42–49] groups cover most of our energy range for the majority of gases under study. The Pasadena experiments are featured by the best angular resolution achieved which ensures good discrimination of electrons scattered in forward direction. Results from Detroit in many cases constitute the only absolute comparative data for electron and positron scattering. It may also be added, that in the majority of the experiments listed in Tables I and II total cross sections were obtained by the

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Table I. *Summary of available experimental work on total electron-scattering cross section for noble gas atoms (in chronological order).*

Target	Author(s)	References	Energy range (eV)
He	Mayer (1921)	[94]	0.2–8
	Ramsauer (1921)	[95]	0.75
	Ramsauer (1921)	[96]	0.75–51
	Brode (1925)	[101]	2–320
	Brüche *et al.* (1927)	[105]	1.3–46
	Ramsauer and Kollath (1929)	[98]	0.17–2.2
	Normand (1930)	[106]	0.5–400
	Golden and Bandel (1965)	[79]	0.3–28
	Baldwin and Friedman (1967)	[77]	0.16–1.38
	Blaauw *et al.* (1977)	[58]	15–750
	Kauppila *et al.* (1977)	[42]	1.6–29.5
	Szmytkowski and Zubek (1977)	[83]	2.5–42.5
	Stein *et al.* (1978)	[46]	1.7–29.4
	Kennerly and Bonham (1978)	[85]	0.5–50
	Gus'kov *et al.* (1978)	[91]	0.025–1.0
	Dalba *et al.* (1979)	[26]	100–1400
	Blaauw *et al.* (1980)	[59]	16–700
	Sinapius *et al.* (1980)	[14]	1–6
	Charlton *et al.* (1980)	[87]	2–50
	Ferch *et al.* (1980)	[13]	0.1–1.1
	Dalba *et al.* (1981)	[29]	300–2000
	Kauppila *et al.* (1981)	[47]	30–600
	Jones and Bonham (1982)	[65]	0.8–50
	Nickel *et al.* (1985)	[39]	4–300
	Mizogawa *et al.* (1985)	[111]	17–22
	Buckman and Lohmann (1986)	[19]	0.1–20
	Kumar *et al.* (1987)	[9]	0.73–9.14
	Szmytkowski *et al.* (1995)	[115]	0.5–20
Ne	Ramsauer (1921)	[96]	1.5–50
	Rusch (1925)	[102]	0.1–2
	Brüche *et al.* (1927)	[105]	0.8–48
	Ramsauer and Kollath (1929)	[98]	0.17–1.4
	Normand (1930)	[106]	0.5–400
	Salop and Nakano (1970)	[110]	0.37–20
	Szmytkowski and Zubek (1977)	[83]	2.5–42.5
	Gus'kov *et al.* (1978)	[91]	0.025–1.0
	Stein *et al.* (1978)	[46]	2.1–19.7
	Wagenaar and de Heer (1980)	[60]	22.5–750
	Sinapius *et al.* (1980)	[14]	1–6
	Kauppila *et al.* (1981)	[47]	20–700
	Nickel *et al.* (1985)	[39]	4–300
	García *et al.* (1986)	[35]	700–6000
	Kumar *et al.* (1987)	[9]	0.73–9.14
	Zecca *et al.* (1987)	[30]	100–3000
	Alle *et al.* (1993)	[23]	0.1–20
	Gulley *et al.* (1994)	[24]	0.1–5
	Szmytkowski *et al.* (1995)	[115]	0.5–220
Ar	Lenard (1903)	[1]	4–4000
	Mayer (1921)	[94]	0.2–40
	Ramsauer (1921)	[95]	0.8–1.1
	Ramsauer (1921)	[96]	0.75–36
	Ramsauer (1923)	[97]	0.75–64
	Brode (1925)	[101]	2–320
	Rusch (1925)	[102]	0.2–1.2
	Rusch (1926)	[103]	3.5–29
	Brüche *et al.* (1927)	[105]	1–47
	Ramsauer and Kollath (1929)	[98]	0.17–1.0
	Ramsauer and Kollath (1929)	[99]	0.17–36
	Normand (1930)	[106]	0.3–400
	Gaertner (1931)	[107]	0.2–6
	Golden and Bandel (1966)	[81]	0.1–21.6
	Baldwin and Friedman (1967)	[77]	0.18–1.38
	Kauppila *et al.* (1977)	[42]	1.3–15.5
	Szmytkowski and Zubek (1977)	[83]	2.5–42.5
	Gus'kov *et al.* (1978)	[91]	0.025–1.0
	Wagenaar and de Heer (1980)	[60]	15–750
	Sinapius *et al.* (1980)	[14]	1–6
	Charlton *et al.* (1980)	[87]	2–50
	Kauppila *et al.* (1981)	[47]	15–800
	Nogueira *et al.* (1982)	[34]	500–3000
	Jost *et al.* (1983)	[61]	0.1–60
	Wagenaar and de Heer (1985)	[63]	17.5–750
	Nickel *et al.* (1985)	[39]	4–300
	Ferch *et al.* (1985)	[16]	0.08–20
	García *et al.* (1986)	[35]	700–6000
	Buckman and Lohmann (1986)	[19]	0.12–20
	Subramanian and Kumar (1987)	[10]	0.73–9.14
	Zecca *et al.* (1987)	[30]	100–3000
	Nishimura and Yano (1988)	[62]	7–500
	Szmytkowski *et al.* (1989)	[57]	1–100
	Ce Ma *et al.* (1989)	[113]	300
	Szmytkowski *et al.* (1995)	[115]	0.5–220
Kr	Ramsauer (1923)	[97]	0.75–100
	Rusch (1925)	[102]	0.2–1.5
	Ramsauer and Kollath (1929)	[98]	0.18–1.6
	Ramsauer and Kollath (1929)	[99]	0.17–36
	Szmytkowski and Zubek (1977)	[83]	2.5–42.5
	Gus'kov *et al.* (1978)	[91]	0.025–1.0
	Wagenaar and de Heer (1980)	[60]	22.5–750
	Sinapius *et al.* (1980)	[14]	1–6
	Dababneh *et al.* (1980)	[45]	1.9–99.4
	Dababneh *et al.* (1982)	[44]	20–750
	Jost *et al.* (1983)	[61]	0.3–60
	Wagenaar and de Heer (1985)	[63]	20–750
	García *et al.* (1986)	[35]	700–6000
	Ferch *et al.* (1987)	[17]	0.3–5
	Buckman and Lohmann (1987)	[21]	0.175–20
	Subramanian and Kumar (1987)	[10]	0.73–9.14
	Szmytkowski *et al.* (1989)	[57]	1–100
	Zecca *et al.* (1991)	[31]	81–4000
	Kanik *et al.* (1992)	[40]	5–300
	Szmytkowski *et al.* (1995)	[115]	0.5–220
Xe	Ramsauer (1923)	[97]	0.75–100
	Ramsauer and Kollath (1929)	[98]	0.16–1.2
	Ramsauer and Kollath (1929)	[99]	0.17–36
	Szmytkowski and Zubek (1977)	[83]	2.5–42.5
	Gus'kov *et al.* (1978)	[91]	0.025–1.0
	Wagenaar and de Heer (1980)	[60]	17.5–750
	Sinapius *et al.* (1980)	[14]	1–6
	Dababneh *et al.* (1980)	[45]	2.8–49.6
	Dababneh *et al.* (1982)	[44]	20–750
	Jost *et al.* (1983)	[61]	0.2–60
	Wagenaar and de Heer (1985)	[63]	20–750
	Nickel *et al.* (1985)	[39]	4–300
	Ferch *et al.* (1987)	[17]	0.12–10
	Subramanian and Kumar (1987)	[10]	0.73–9.14
	Szmytkowski *et al.* (1989)	[57]	1–100
	Zecca *et al.* (1991)	[31]	81–4000
	Alle *et al.* (1993)	[23]	0.1–30
	Szmytkowski *et al.* (1995)	[115]	0.5–220

transmission method. Most of them involved magnetic fields, which may have added to experimental uncertainties [51, 52]. In the present work the nonmagnetic linear transmission method has been employed.

The results presented in this paper have been a part of a continuing program carried out in our laboratory for almost twenty years now and aimed at systematic measurements of absolute total electron scattering cross sections for

Table II. *Summary of total electron scattering cross section measurements on H_2, N_2, CO, NO and O_2 molecules (in chronological order).*

Target	Author(s)	Reference	Energy range (eV)
H_2	Lenard (1903)	[1]	4–1000
	Mayer (1921)	[94]	0.2–8
	Ramsauer (1921)	[95]	0.85
	Brode (1925)	[101]	2–170
	Rusch (1925)	[102]	0–1.8
	Brüche (1927)	[104]	1.3–47.5
	Normand (1930)	[106]	0.4–400
	Ramsauer and Kollath (1930)	[100]	0.18–1.0
	Gaertner (1931)	[107]	0.2–6
	Golden *et al.* (1966)	[80]	0.25–15
	Ferch *et al.* (1980)	[13]	0.02–1.5
	Dalba *et al.* (1980)	[27]	0.2–100
	van Wingerden *et al.* (1980)	[66]	25–750
	Kumar and Krishnakumar (1981)	[8]	0.02–1.14
	Hoffman *et al.* (1982)	[43]	2–500
	Griffith *et al.* (1982)	[88]	2–52
	Deuring *et al.* (1983)	[86]	6–400
	Deuring *et al.* (1983)	[15]	1–8
	Jones (1985)	[68]	1–50
	Subramanian and Kumar (1989)	[11]	0.21–9.14
	Nickel *et al.* (1992)	[41]	4–300
	Zecca *et al.* (1994)	[33]	70–2750
	Randell *et al.* (1994)	[112]	0.01–0.175
	Szmytkowski *et al.* (1995)	[115]	0.4–250
N_2	Mayer (1921)	[94]	0.2–8
	Ramsauer (1921)	[95]	0.75
	Brode (1925)	[101]	2.2–320
	Brüche (1927)	[104]	0.95–47.5
	Normand (1930)	[106]	0.5–400
	Ramsauer and Kollath (1930)	[100]	0.18–1.4
	Golden (1966)	[82]	0.3–5
	Baldwin (1974)	[78]	0.3–1.56
	Mathur and Hasted (1977)	[75]	0.5–4
	Blaauw *et al.* (1977)	[58]	15–750
	Zubek and Szmytkowski (1978)	[84]	1.5–6.1
	Gus'kov *et al.* (1978)	[92]	0.04–3.7
	Hasted *et al.* (1979)	[76]	0.3–5
	Kennerly (1980)	[53]	0.52–51.3
	Dalba *et al.* (1980)	[28]	121–1600
	Blaauw *et al.* (1980)	[59]	12.5–750
	Hoffman *et al.* (1982)	[43]	2.2–700
	Griffith *et al.* (1982)	[88]	6.5–47.5
	Jost *et al.* (1983)	[61]	0.05–90
	Sueoka and Mori (1984)	[89]	1.15–403
	Mizogawa *et al.* (1985)	[111]	1–5.9
	Szmytkowski *et al.* (1988)	[56]	1–100
	García *et al.* (1988)	[36]	600–5000
	Nishimura and Yano (1988)	[62]	7–500
	Buckman (1989)	[22]	0.1–1.0
	Szmytkowski *et al.* (1989)	[57]	1–100
	Wan *et al.* (1989)	[108]	0.2–12
	Ferch *et al.* (1991)	[18]	0.1–2.6
	Nickel *et al.* (1992)	[41]	4–300
	Alle *et al.* (1993)	[23]	0.1–20
	Karwasz *et al.* (1993)	[32]	250–4000
	Randell *et al.* (1994)	[112]	0.01–0.175
	Szmytkowski *et al.* (1995)	[115]	0.4–250
CO	Brode (1925)	[101]	2–210
	Brüche (1927)	[70]	1.1–45
	Normand (1930)	[106]	0.5–400
	Ramsauer and Kollath (1930)	[100]	0.18–1.2
	Gus'kov *et al.* (1978)	[93]	0.1–2.0
	Szmytkowski and Zubek (1978)	[25]	1.3–5.6
	Hasted *et al.* (1979)	[76]	1–4.5
	Kwan *et al.* (1983)	[48]	1.08–500
	Sueoka and Mori (1984)	[89]	1.15–403
	Buckman and Lohmann (1986)	[20]	0.5–4.9
	García *et al.* (1990)	[37]	381–5254
	Kanik *et al.* (1992)	[40]	5–300
	Karwasz *et al.* (1993)	[32]	80–4000
	Xing *et al.* (1995)	[114]	400–2600
	Szmytkowski *et al.* (1995)	[115]	0.4–250
NO	Brüche (1927)	[70]	1–51
	Zecca *et al.* (1974)	[71]	0.025–9.6
	Dalba *et al.* (1980)	[28]	121–1444
	Szmytkowski and Maciąg (1991)	[69]	0.55–160
	Szmytkowski *et al.* (1995)	[115]	0.4–250
O_2	Brüche (1927)	[70]	1–46
	Ramsauer and Kollath (1930)	[100]	0.14–1.3
	Sunshine *et al.* (1967)	[109]	0.5–100
	Salop and Nakano (1970)	[110]	2.3–21
	Dalba *et al.* (1980)	[28]	100–1600
	Griffith *et al.* (1982)	[88]	2.5–52
	Katayama *et al.* (1985)	[90]	1.2–400
	Zecca *et al.* (1986)	[72]	0.23–100
	Dababneh *et al.* (1988)	[49]	5.2–500
	Williams and Allen (1989)	[74]	0.54–4.9
	Subramanian and Kumar (1990)	[12]	0.15–9.14
	Kanik *et al.* (1992)	[40]	5–300
	Randell *et al.* (1994)	[112]	0.01–0.175
	Szmytkowski *et al.* (1995)	[115]	0.4–250

atoms and molecules over low and intermediate energy range. Until now we have mainly presented meaurements for polyatomic molecules, and present data complete these with measurements for selected mono- and di-atomic targets.

2. Experimental

Our experimental procedure for the determination of electron impact absolute total cross sections is based on a simple conceptual idea. If a parallel and monoenergetic beam of projectiles (electrons) crosses a homogeneous gas-phase medium containing target particles, then attenuation of the projectile beam along its pathway is, to the first approximation, given by the Bouguer-de Beer-Lambert absorption law. Under these ideal experimental conditions one can determine the total cross section $\sigma(E)$ at a given impact energy E taking transmitted particle-beam intensities in the presence of the target, $I(E, n)$, or in its absence, $I(E, n = 0)$, and making use of the relationship

$$\frac{I(E, n)}{I(E, 0)} = \exp\,[-nl\sigma(E)], \tag{1}$$

where n is the scattering target density and l is the length of the beam's path of projectiles in the interaction volume.

Fulfilment of all the conditions at which the above relationship is justified is a rather difficult task. Actual experiments yield total cross sections which are to some degree influenced by substantial systematic errors which are difficult to estimate. It is thus a good practice to perform independent measurements varying such experimental conditions as the projectile current intensity, scattering chamber

geometry and/or beam attenuation rate. The main difficulties commonly experienced in total cross section experiments were analyzed in detail by Bederson and Kieffer [51] and Golden [52].

In the reported experiment, a quasimonoenergetic beam of electrons ($I \leqslant 200$ pA; $\Delta E = 70$ meV, fwhm) was produced by an electron gun, formed by means of electrostatic electron optics and a 127° electrostatic cylindrical dispersing element. The electron beam of the desired energy E was then injected into a collision chamber. Electrons leaving the reaction volume through the exit orifice were energy discriminated with a retarding field element followed by a Faraday cup detector.

The energy scale was calibrated with respect to the resonant features near 2.3 eV in N_2 and/or at 19.37 eV in He, visible in the transmitted electron currents when reference gas was admixed to the target gas. The dip in the transmission current corresponding to the highest, second maximum in the nitrogen total cross section was located at 2.22 eV (Kennerly [53]). Accuracy of the scale was ± 50 meV.

In the course of the experiment the target gas was let alternately into the scattering cell and the outer vacuum volume in such a way that the background pressure outside the scattering chamber, in the region of electron optics, was kept at the same value in both modes of operation. This enabled us to keep the conditions in the region of electron optics nearly constant and in consequence to reduce the influence of the target gas effusing from the collision chamber on the intensity of the primary electron beam and, therefore, on the measured cross section.

The gas effusing from the scattering chamber might seriously change the length over which scattering events take place in comparison to the geometrical size of the scattering container. For the same reason, the density distribution $n(z)$ of the target along the chamber is usually inhomogeneous. The product nl in eq. (1) should then be replaced with $(nl)_{\text{eff}} = \int n(z)\,\mathrm{d}z$, where integration is performed along the whole electron trajectory. Using the effective scattering path length calculations [55], we estimate that, in the present experimental arrangement, the effect of density drop accross the orifices is almost compensated by the longer electron path length in the target. As a result, within an accuracy of 0.5%, the product nL of gas density number n and geometrical size of the scattering cell L (= 30.5 mm) can be used in eq. (1).

The number density n of each gas target under study was derived from gas pressure p using the ideal gas law ($n = p/kT$). The absolute pressure in the scattering cell was measured with a capacitance manometer and was usually in the range of (50–300) mPa, while the electron optics was exposed to a background pressure nearly three orders of magnitude lower. The upper limit of the target gas pressure used for a particular target and a given incident energy was so chosen that multiple scattering effects could be ignored. The temperature of the scattering cell T_c was in the range of 305–315 K, while the manometer sensor head was kept at elevated temperature T_s (322 ± 1 K). This temperature difference was accounted for by applying the thermal transpiration correction [54]. The residual pressure in the vacuum chamber was about 20 μPa.

Another inevitable source of serious experimental error in every transmission experiment is incomplete discrimination of projectiles scattered in the small-angle forward direction by the detector system; a part of the scattered projectiles can be collected as an unscattered signal. The systematic lowering of the measured total cross section related to this effect usually increases with impact energy and depends on angular resolution of the detector system. For polar molecules the fraction of electrons scattered in the forward direction tends to increase with the increase in the electric dipole moment of the target molecule. In order to determine the extent to which small-angle scattering could affect measured total cross sections, absolute data on the angular distribution of scattered electrons (especially those scattered elastically) would be needed, for targets under study, at all energies used. Basing on the available, rather fragmentary data, we have estimated that, for the applied geometry of the detector system (solid angle subtended by the detector, averaged over the length of the scattering chamber, is 0.7 msr), the systematic error from forward scattering is less than 2% for nonpolar and up to 4% for polar targets over the entire energy range considered, for all targets studied in the present experiment.

The present data were accumulated over a long period of activity of our laboratory on the same experimental set-up (with minor changes only). Resulting cross sections at a given energy were calculated as weighted mean values from different series of measurements at the same energy. The weights were related to the uncertainties of each series. It was found that the total cross sections obtained in different series at the same energy were independent, within the limits of statistical uncertainties, of applied sample pressures, and the electron-beam-controlling parameters.

The statistical uncertainties (one standard deviation of weighted mean values) for all investigated targets are below 1%, save for the N_2 in the region of resonant oscillations around 2 eV and for the lowest energies in NO where they reach 3%.

Estimated systematic experimental error (the square root of the quadratic sum of all the single error contributions) does not exceed 4% at the lowest and 6% at the highest of the applied energies. At intermediate energies, the systematic error is about 3%. The uncertainties associated with a possible ±30 meV shift in the energy during the experiment close to resonant features in CO, N_2 and NO might amount up to 10%.

Gas samples of at least 99.9% purity were used without further purification.

Preliminary results of our measurements for N_2 have already been presented at SPIG'88 [56], while those for N_2 and heavier noble gases (Ar, Kr, Xe) at ECAMP'89 [57].

3. Results

Numerical results of the present measurements for noble gas atoms are summarized in the Table III and for diatomic molecules in the Table IV. Comparison with data of selected earlier experiments from other laboratories is shown in Figs 1 and 2. We must indicate that, for the sake of clarity, we present in the figures only data obtained in the very recent years and mainly from those laboratories where measurements were performed for the majority of targets presented here. For better presentation of discrepancies and agreements among different measurements, experimental points

Table III. *Measured total cross sections for electron impact on noble gas atoms (He, Ne, Ar, Kr and Xe) in units* $10^{-20}\,m^2$.

Impact energy (eV)	Total cross section				
	He	Ne	Ar	Kr	Xe
0.5	6.06	1.20	0.379	0.870	2.73
0.7	6.09		0.635	0.641	
0.8		1.42			1.40
1.0	6.13	1.51	1.18	0.835	1.79
1.2	6.11	1.65	1.57	1.15	3.55
1.4		1.75			
1.5	6.07		2.38	1.85	6.21
1.7		1.89			
2.0	6.02	1.99	3.39	3.07	10.1
2.5	5.92	2.20	4.22	4.87	14.9
3.0	5.79	2.35	4.99	6.61	20.4
3.5	5.69	2.47	5.97	9.15	24.9
4.0	5.56	2.60	6.88	11.0	30.1
4.5	5.43	2.72		13.4	34.8
5.0	5.30	2.80	8.71	15.3	37.8
5.5	5.22	2.91			41.4
6.0	5.15	3.02	10.8	19.2	42.4
6.5	5.11	3.08			43.4
7.0	5.01	3.15	12.6	22.1	43.3
7.5	4.90	3.19			43.0
8.0	4.81	3.22	15.1	25.1	42.6
8.5		3.30			42.1
9.0	4.65	3.32	17.3	26.5	41.5
9.5		3.40			41.0
10	4.37	3.43	19.1	28.0	40.5
11		3.51	20.9	28.2	
12	4.10	3.59	22.7	28.5	38.6
13		3.63	23.9	28.2	
15	3.61	3.68	23.8	26.8	36.7
17	3.41	3.73	21.8	25.2	36.2
20	3.05	3.75	18.2	23.5	34.7
22					31.9
25	2.65	3.78	15.8	20.8	27.2
30	2.37	3.76	14.1	18.7	20.0
35	2.18	3.73	12.8	16.9	17.5
38					16.4
40	2.01	3.67	11.8	16.0	15.6
42					14.9
50	1.74	3.62	10.3	14.4	13.7
60	1.57	3.50	9.60	13.5	12.8
70	1.40	3.41	9.14	12.6	12.5
80	1.28	3.29	8.59	11.8	12.3
90	1.21	3.20	8.22	11.2	12.0
100	1.14	3.05	7.95	10.7	11.7
110	1.11	2.90	7.69	10.3	11.5
120	1.02	2.83	7.55	9.59	11.1
140	0.924	2.60	7.13	9.05	10.7
160	0.895	2.47	6.81	8.58	10.4
180	0.818	2.35	6.32	8.01	10.1
200	0.769	2.23	5.98	7.53	9.51
220	0.708	2.10	5.78	7.11	8.97

from various laboratories are plotted in Figs 3 and 4 against scattering energy as percentage discrepancies between these measurements and the results obtained in our laboratory.

3.1. *Noble gas atoms*

For lighter noble gas atoms, He and Ne, and at lower applied impact energies the agreement between the present data and the results from the laboratories in Detroit (Kauppila *et al.* [42] and Stein *et al.* [46]), Pasadena (Nickel *et al.* [39]) and Ahmedabad (Kumar *et al.* [9]) is excellent [Figs 1(a) and 1(b), respectively]. Differences [Figs 3(a) and 3(b)] do not exceed 3% and are well within the experimental

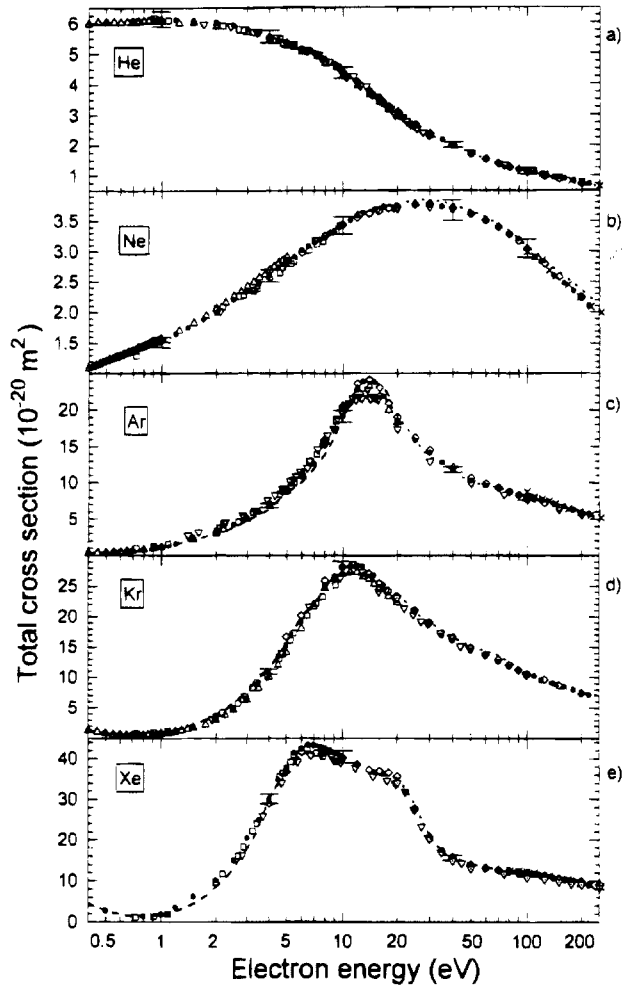

Fig. 1. Absolute electron-noble gas atoms scattering total cross sections (in $10^{-20}\,m^2$). Present results: ●, (a)–(e); the error bars correspond to the overall experimental uncertainties at some selected energies. Experiments of He, (a): ▽, Kauppila *et al.* [42]; ×, Dalba *et al.* [26]; – – – –, Blaauw *et al.* [59]; ◇, Nickel *et al.* [39]; △, Buckman and Lohmann [19]; □, Kumar *et al.* [9]. Experiments of Ne, (b): – – – –, Wagenaar and de Heer [60]; ▽, Kauppila *et al.* [47]; ◇, Nickel *et al.* [39]; □, Kumar *et al.* [9]; ×, Zecca *et al.* [30]; △, Gulley *et al.* [24]. Experiments of Ar, (c): ▽, Kauppila *et al.* [42, 47]; – – – –, Wagenaar and de Heer [60]; ◇, Nickel *et al.* [39]; — —, Ferch *et al.* [16]; △, Buckman and Lohmann [19]; □, Subramanian and Kumar [10]; ×, Zecca *et al.* [30]. Experiments of Kr, (d): ▽, Dababneh *et al.* [44, 45]; — —, Ferch *et al.* [17]; – – – –, Wagenaar and de Heer [63]; △, Buckman and Lohmann [21]; □, Subramanian and Kumar [10]; ×, Zecca *et al.* [31]; ◇, Kanik *et al.* [40]. Experiments of Xe, (e): ▽, Dababneh *et al.* [44, 45]; — —, Ferch *et al.* [17]; – – – –, Wagenaar and de Heer [63]; ◇, Nickel *et al.* [39]; □, Subramanian and Kumar [10]; ×, Zecca *et al.* [31].

uncertainty limits. The most recent results in Ne of Canberra group [24], obtained on the apparatus with improved resolution in respect to previous measurements [19–21], above 1 eV lie in average 4% over others.

For helium [Fig. 1(a)] at energies above 100 eV our data coincide within 2% with the intermediate energy part of the Dalba *et al.* [26, 29] experiments. More significant discrepancies with other recent results in helium are evident only at about 200 eV, where our results are higher than those reported by Kauppila *et al.* [47], Nickel *et al.* [39] and Blaauw *et al.* [58, 59] by 7, 5 and 6%, respectively.

For neon [Fig. 1(b)], at above 100 eV the present data agree well (within 2%) with all the most recent experimental results (Kauppila *et al.* [47], Nickel *et al.* [39], Zecca *et al.* [30]), while they are about 6% lower than earlier measurements of the Amsterdam group (Wagenaar and de Heer [60]).

Table IV. *Measured total cross sections for electron impact on H_2, N_2, CO, NO and O_2 molecules in units $10^{-20}\,m^2$.*

Impact energy (eV)	Total cross section					Energy (eV)	Total cross section				
	H_2	N_2	CO	NO	O_2		H_2	N_2	CO	NO	O_2
0.4	11.1	8.72	10.2	9.10	5.18	4.5	15.9		15.4		
0.5	11.5	9.13	11.1	9.25		4.6		12.4			
0.6	12.0	9.22		10.2	5.62	4.8		12.0			
0.65			12.1			5.0	15.4	11.5	15.1	9.30	7.18
0.7		9.21		10.8		5.5	15.0	11.2	13.8		
0.8	12.8	9.95	12.7	10.6	6.01	6.0	14.3	11.4	13.7		
0.9			13.3			6.5	13.8	11.4	13.3		8.22
1.0	13.5	10.2	14.0	11.4	6.12	6.8	13.6				
1.1		10.1	15.1			7.0		11.0	13.5		
1.2		10.2	16.2	12.3	6.18	7.5	12.8	11.2	13.4	9.58	8.52
1.3	14.2	10.4	18.1			8.0	12.4	11.6	13.2		
1.4	14.9	10.3	23.3			8.5	11.9	11.8			9.41
1.5		11.3	28.9	12.1	6.18	9.0	11.5	12.1	13.0		
1.6	15.2	12.4	35.1			9.5	11.2	12.2			
1.7		13.2	38.2			10	10.8	12.5	13.1	10.3	10.4
1.8	15.5	16.5	42.2			12	9.51	12.8	13.3	10.9	11.0
1.85		18.8				14	8.73	13.2			
1.9		22.0	43.8			15			14.2	11.6	10.8
1.95		26.1				16	7.82	13.1			
2.0	15.9	25.4	43.4	10.5	6.27	17			14.6		
2.05		24.7				18	7.16	13.6			
2.1		25.4	42.5			20	6.66	13.8	14.7	11.3	10.7
2.15		30.1				22			14.6		
2.2	16.3	34.2	40.8			23		13.9			
2.25		31.5				25	5.82		14.3	11.2	11.2
2.3		28.1	37.9			27		13.5			
2.35		26.9				30	4.88	13.1	13.7		
2.4	16.5	30.5	35.5			35	4.55	13.0	13.3	10.4	10.8
2.45		33.4				40	4.17	12.4	12.9		
2.5		29.8	33.0	9.68	6.29	45	3.99	11.9	12.4		
2.55		26.1				50	3.63	11.2	11.8	9.65	10.4
2.6	16.7	25.9	30.9			55		11.0			
2.65		28.1				60	3.36	10.7	11.1		
2.7		27.7	28.3			65		10.3			9.63
2.75		24.8				70	3.15	10.0	10.7		
2.8	16.7	23.1	26.5			75		9.69		8.91	9.33
2.85		22.7				80	2.93	9.45	10.2		
2.9		22.8	25.5			90	2.80	9.21	9.75		
2.95		22.2				100	2.61	8.85	9.47	8.41	8.52
3.0	16.8	20.3	23.6			110	2.43	8.46	9.11		8.23
3.1		19.3				120	2.25	8.09	8.54		7.95
3.2		17.9	21.0			125				7.95	
3.3		16.8				140	2.12	7.67	7.95		7.54
3.4		16.0				150				7.49	
3.5	16.8		18.7	9.25	6.62	160	1.96	7.22	7.47		7.13
3.6		14.3				175				7.05	
3.7			17.8			180	1.89	6.81	6.88		6.69
3.8	16.7	13.4				200	1.71	6.41	6.48	6.81	6.28
4.0	16.5	13.0	16.4			220	1.60	6.08	6.05		5.88
4.2		12.8				225				6.38	
4.4		12.4				250	1.49	5.67	5.59	6.02	5.41

For Ar [Fig. 1(c), see also Fig. 3(c)] at energies just above the Ramsauer minimum our data agree quite reasonably with the results of Buckman and Lohmann [19], but are 10% lower than those of Ferch *et al.* [16] and, on average, 20% lower than those of Jost *et al.* [61] (not presented in Figs 1 and 3). The largest discrepancies occur in the region of fast rise of the cross section with energy. Around 7 eV the data of Kauppila *et al.* [42] are higher than those here by about 10% and this discrepancy increases towards lower energies. Near 10 eV present results agree well with the measurements of Ferch *et al.* [16] but are 5–8% lower than those of Buckman and Lohmann [19], Nickel *et al.* [39] and Subramanian and Kumar [10], and 20% lower than those of Jost *et al.* [61]. One reason for this discrepancy could be an error in energy determination, which propagates directly into the total cross section when it is a steep function of energy. However, as already stated by Buckman and Lohmann [19], the discrepancy between two time-of-flight experiments (Ferch *et al.* [16], Buckman and Lohmann [19]), in which energy is intrinsically determined, is somewhat disturbing. In the vicinity of the maximum our data are closest to the prior measurements of Nickel *et al.* [39], Ferch *et al.* [16] and Nishimura and Yano [62], solely being 8% higher than those of Kauppila *et al.* [42]. It is worth noting, that the more recent measurements of the Detroit group [50] for e^+–Ar scattering have yielded total

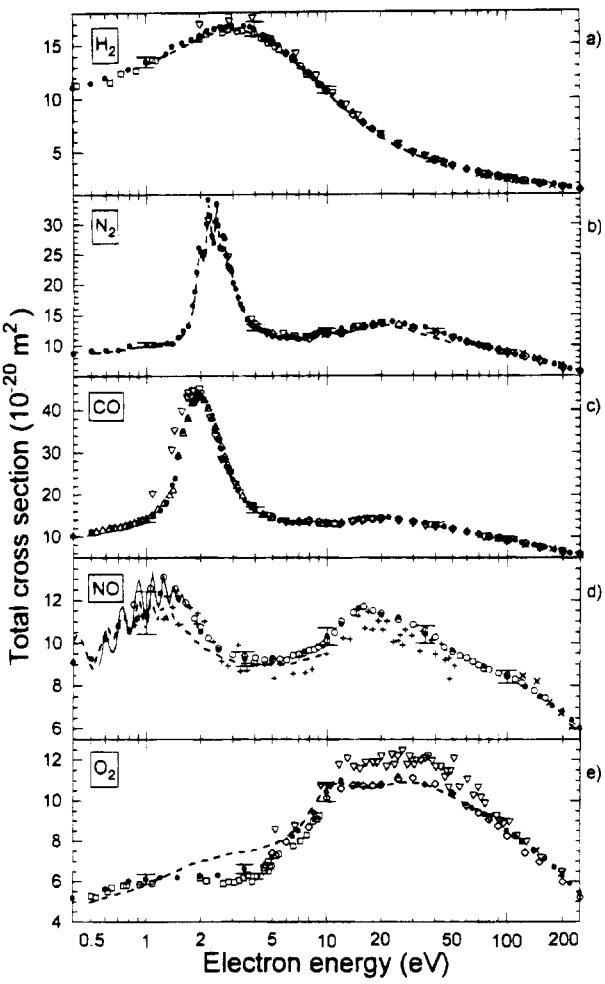

Fig. 2. Absolute electron-diatomic molecules scattering total cross sections (in 10^{-20} m^2). Present results: ●, (a)–(e); the error bars correspond to the overall experimental uncertainties at some selected energies. Experiments of H_2, (a): ▽, Hoffman *et al.* [43]; — —, Jones [68]; □, Subramanian and Kumar [11]; ◇, Nickel *et al.* [41]; ×, Zecca *et al.* [33]. Experiments of N_2, (b): — —, Kennerly [53]; ×, Dalba *et al.* [28]; ▽, Hoffman *et al.* [43]; ◇, Nickel *et al.* [41]. Experiments of CO, (c): ▽, Kwan *et al.* [48]; △, Buckman and Lohmann [20]; ◇, Kanik *et al.* [40]. ×, Karwasz *et al.* [32]. Experiments of NO, (d): +, Brüche [70]; — —, Zecca *et al.* [71]; ×, Dalba *et al.* [28]; ○, Szmytkowski and Maciąg [69]. Experiments of O_2, (e): ×, Dalba *et al.* [28]; — —, Zecca *et al.* [72]; ▽, Dababneh *et al.* [49]; □, Subramanian and Kumar [12]; ◇, Kanik *et al.* [40].

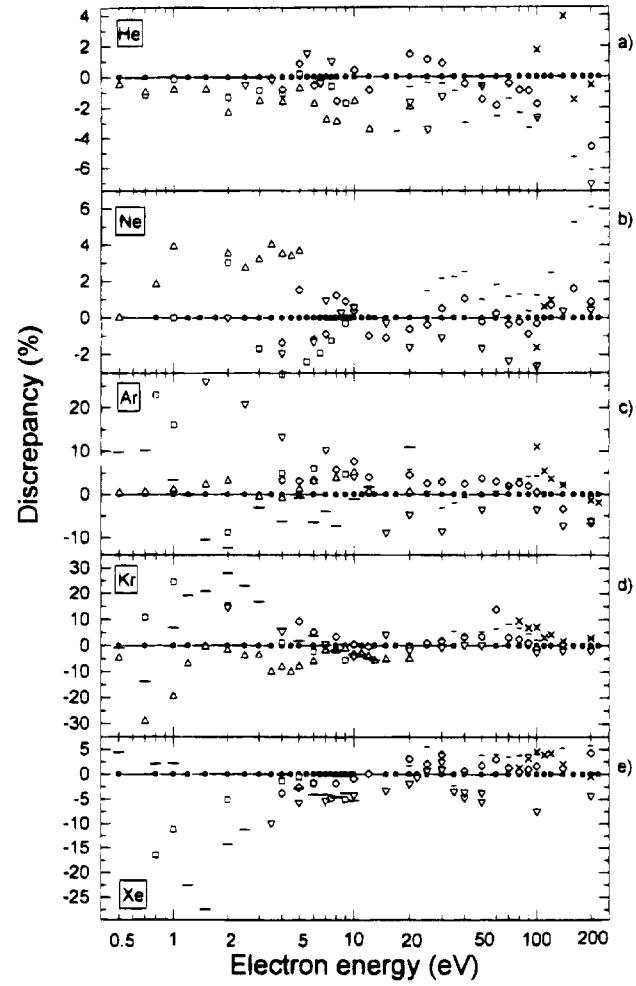

Fig. 3. Discrepancies (in %) between experimental electron-scattering total cross sections for noble gas atoms from different laboratories and the present results (horizontal reference points). Data plotted with a positive discrepancy are higher than the present results. Symbols are the same as in Fig. 1. When energies at which the present and other measurements were taken do not coincide, the respective total cross section values have been estimated from interpolation.

cross sections higher than given in Ref. [42] and a similar effect might be expected for e^-–Ar. Present data at 100 eV are bounded by 5% limits: by results of Zecca *et al.* [30] and of Wagenaar and de Heer [63] from upper side and those of Kauppila *et al.* [47] from below.

For krypton [Fig. 1(d)] the discrepancies [Fig. 3(d)] between results of various experiments are much higher. In the region of the Ramsauer minimum our data are about 10% higher than those of Ferch *et al.* [17] and as much as 30% higher than those of Buckman and Lohmann [21], but are more than 20% lower than the data of Jost *et al.* [61]. Just above 1 eV the results of Ferch *et al.* [17] are 20–30% higher than the present data and the measurements of Buckman and Lohmann [21]. At some energies around 5 eV, the present results are even up to 10% higher than that of Buckman and Lohmann [21], 4% higher than those of Subramanian and Kumar [10], 3–5% lower than data of Ferch *et al.* [17] and about 6% lower than those of Dababneh *et al.* [45] and Kanik *et al.* [40]. At the maximum, our results agree well with the data of Dababneh *et al.* [45] and of Kanik *et al.* [40], while they are systematically some 5% higher than the data of Ferch *et al.* [17] and of Buckman and Lohman [21]. Around 60 eV, the remeasurements of Wagenaar and de Heer [63], although being lower than the previous data from this group [60], are still visibly higher than all other results. At energies close to 100 eV, the Trento results (Zecca *et al.* [31]) are clearly above those of the others. All the experimental results tend to merge within 5% error bar at 200 eV.

A somewhat better agreement between different experiments is visible for Xe [Fig. 1(e), cf. Fig. 3(e)]. At the Ramsauer minimum our data agree well with measurements of Ferch *et al.* [17] but, unlike those for Ar and Kr, are 5% higher than the data of Jost *et al.* [61]. For energies between 1 and 3 eV results from Bielefeld [17] are almost 10–20% lower than ours and 20% below the data of Jost *et al.* [61]. At the maximum, our results are about 4% higher than most of the recent measurements. Only the data of Jost *et al.* [61] are higher than ours. Around 100 eV, the present measurements exceed the results of Dababneh *et al.* [44] by about 7% and are only slightly (4%) lower than other results (Zecca *et al.* [31], Wagenaar and de Heer [63], Nickel *et al.* [39]).

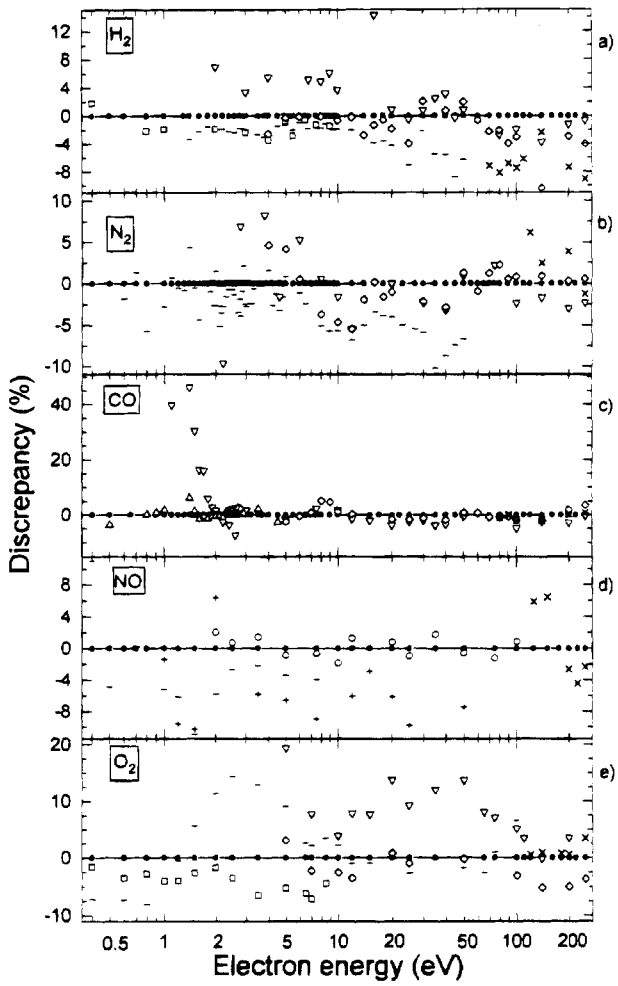

Fig. 4. Discrepancies (in %) between experimental electron-scattering total cross sections for diatomic molecules from different laboratories and the present results (horizontal reference points). Data plotted with a positive discrepancy are higher than the present results. Symbols are the same as in Fig. 2.

In general, the present results for noble gas atoms are in quite good agreement with the majority of recent measurements, especially regarding the shape of the curves. The most serious discrepancies in the magnitude of the cross section occur at the Ramsauer minimum in Kr, and to lesser extent, also in Xe and the rapidly rising parts of total cross section curves in Ar, Kr and Xe. At the maximum, most of the recent sets of data agree reasonably well; however, the present data tend to constitute their upper limit. That our results around maxima are usually among the highest ever obtained has been also observed in previous Gdańsk measurements (e.g., for H_2O [64]); we have no plausible explanation for this effect.

With this exception though, exact trends indicating systematic differences between the present and other measurements are hardly visible. It can be partially due to the fact, that results for different targets in the same laboratory were usually obtained within large intervals of time and, in many cases, the apparatuses underwent some minor changes in the meantime.

Generally, the present results for noble gases are in the best agreement with linear transmission experiments from Pasadena and Canberra. The data of Jost *et al.* [61] are higher everywhere, apart from the Ramsauer minimum in Xe. This systematic disagreement could be attributed to the extrapolation procedure adopted by Jost *et al.* [61] in order to eliminate the angular resolution error. This procedure although essentially correct, depends strongly on the assumed zero-angle differential cross section. However, experimental values of these cross sections are known only by extrapolation, and their measured total behavior varies from target to target.

Another systematic difference regards results from the Amsterdam laboratory. Wagenaar and de Heer [63], also working in a linear geometry, used a very short scattering cell ($\leqslant 10$ mm) and so the effects of gas effusion could have caused overestimation of their measured total cross sections.

At the ends of the apparatuses' energy ranges other systematic discrepancies can emerge. In the TOF experiments at their high-energy limit (above 10 eV), measured cross sections tend to be underestimated, probably due to cumulation of different forward scattering effects [65]. On the other hand, high energy experiments from Trento usually give overestimated cross sections below 150 eV due, as stated by Zecca *et al.* [31], to electron-beam instabilities.

3.2. *Diatomic molecules*

The high accuracy and reliability required for results in hydrogen is partly related to their frequent use for testing models describing processes in gas discharges and plasmas. The present $e^- - H_2$ total cross sections agree well (within 3%) with the data from Pasadena [41] and Amsterdam [66] (below 20 eV), constituting once more rather the upper limit of the existing experimental results [Fig. 2(a), see also Fig. 4(a)]. The data of Hoffman *et al.* [43] between 2 and 20 eV are higher than the present by about 6%. The results of Dalba *et al.* [27], save for energies below 2 eV, are also in very good agreement with the present measurements.

A remarkable number of measurements has been performed for N_2. Present results in all the overlaping energy ranges are by 3–5% higher than measurements of Kennerly [53] [Figs. 2(b) and 4(b)], which are frequently used as standards. Similar discrepancies between measurements from that laboratory and our own have also been observed for the chlorofluoromethanes [67] and can be attributed to scattering on exit orifices in the apparatus of Bonham and co-workers (see Jones [68]). For energies below 10 eV the results of Hoffman *et al.* [43] are a few percent higher than the present measurements. At about 100 eV the results of Dalba *et al.* [28] are higher than all others; however, their renormalization by 6%, as stated by Karwasz *et al.* [32], brings also these data into good agreement with other experimental results (Nickel *et al.* [41], Nishimura and Yano [62]).

Very good agreement between the present data and results of the most recent measurements from other laboratories exists also for CO [Figs 2(c) and 4(c)]. This time, only the low energy (below 2 eV) data of the Detroit group (Kwan *et al.* [48]) are much higher, up to 40%, than others. This discrepancy diminishes substantially if one shifts the results from Detroit by 0.10–0.15 eV towards higher energies.

Few data have been published so far for absolute total cross section measurements in NO. The present cross sections agree well with independent measurements from the same laboratory [69] and are usually higher from the pioneering experiment of Brüche [70] performed at our University nearly 70 years ago [Fig. 2(d)]. It is worth noting that the results of Brüche are also always lower for other

targets discussed here. A better agreement, especially in shape, is observable with the normalized results of Zecca *et al.* [71]; the existing discrepancy [Fig. 4(d)] in magnitude may be due to indirect pressure evaluation (by ionization gauge read-out) in their experiment. Near 100 eV, the results of Dalba *et al.* [28] are 6% higher than ours.

The biggest discrepancies between results from different laboratories are visible for O_2 [see Figs 2(e) and 4(e)]. Good agreement exists among the present results, those of Kanik *et al.* [40] (within 4%) and Zecca *et al.* [72] (within 3% above 6 eV). For energies below 100 eV, the measurements of Dababneh *et al.* [49] are visibly higher than others; the discrepancy reaches about 15% between 10 and 40 eV. The results of Subramanian and Kumar [12] are lower than the present ones by 5–8%.

It has been noticed by Dalba *et al.* [28] in their measurements between 100 and 1400 eV that total cross section for the N_2–NO–O_2 series decreases as follow $\sigma(N_2) > \sigma(NO) > \sigma(O_2)$. At 5 eV, as it is evident from the present data, the NO cross section equals almost exactly the arithmetical average of the N_2 and O_2 values. According to our measurements, the NO cross section colocates between N_2 and O_2 up to 25 eV, then drops below O_2 up to 100 eV and rises above N_2 at higher energies. However, these latter differences do not exceed our overall experimental error. Additionally, recent calculations [73] for the 100–1000 eV energy range, although giving overestimated results for all the three targets considered, rather confirm the conclusion of Dalba *et al.* [28]. Therefore, additional, comparative measurements would be required for the N_2–NO–O_2 series between 20 and 200 eV.

In general, the agreement between cross sections from different laboratories is somehow poorer for molecules than for noble gases. The most serious discrepancies exist in the regions of the total cross section's maxima what may be related to different energy resolution of experimental arrangements used in different laboratories and/or to influence of the target-molecules (especially O_2 and NO) on electron optics.

4. Summary

Absolute electron-scattering total cross sections have been measured for noble gas-atoms (He, Ne, Ar, Kr and Xe) and diatomic molecules (H_2, N_2, CO, NO and O_2). The same apparatus has been employed over a wide energy range, between 0.5 and 250 eV. A critical comparison has been made with absolute results from various laboratories. The best agreement is with the Pasadena data in the energy range of overlap. Differences between existing data (in some cases exceeding the declared error bars) are particularly evident at the lowest impact energies, below 1 eV, and in the energy range where the cross sections rise sharply. A large discrepancy still remains around the maximum of the total cross section for O_2. In many cases, the existing differences can be fully explained by possible systematic errors like angular resolution [42, 61, 68], end effects [63, 65], contact potentials [47, 48] or beam instabilities [31].

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