Total cross-section measurements for e^-–CO scattering: 80–4000 eV

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Absolute total cross sections for electron scattering on CO molecules have been measured between 80 and 4000 eV. For N_2, new measurements without thermal transpiration error allowed us to renormalize previous data from our group. For both gases, good agreement with recent measurements and theory is observed. A semi-empirical fitting procedure allows us to reproduce the experimental data for both gases from 50 to 4000 eV. The fit permits us to extrapolate total cross sections into high energies; at this limit N_2 and CO total cross sections are equal within experimental uncertainties; the difference reported by García, Campos et al. has not been confirmed.

1. Introduction

It is known that CO molecules scatter electrons in a similar way as do the isoelectronic N_2 molecules (see ref. [1] and references therein). Comparative measurements of elastic differential cross sections [2] in the 20–100 eV energy range did not reveal statistically significant differences outside the experimental error. Minor differences have been noticed [3] at 300–500 eV energies, where, for small angle scattering, CO cross sections are higher than those of N_2. This has been attributed to the permanent dipole of the CO molecule.

In the total cross sections at low energies (≈ 2 eV) a prominent $^2\Pi$ resonance state is observable for both molecules [4,5]. A second maximum in the total cross sections occurs at about 20 eV [1]. In case of N_2 this peak is dominated by the $^2\Sigma_u$ resonance [6]. The total cross section for $e^- + CO$ above 50 eV is only 2% higher than that for $e^- + N_2$ [1]. Although the absolute values of cross sections from different apparatus [7–11] vary, this relative difference is maintained. In contrast, recent high-energy measurements [12,13] would suggest that total cross sections for these two molecules diverge above 500 eV, the difference being as high as 23% at 5000 eV. This result is not supported by the recent theoretical data of Jain and Baluja [14]. This discrepancy prompted the present work.

CO total cross sections were measured in the 1930s by Brüche [15] (1–50 eV) and by Ramsauer and Kollath [16] (0.2–1.5 eV). More recently, the measurements of Gus'kov et al. [17], Szmytkowski and Zubek [18], Hasted et al. [19], Buckman and Lohmann [5] have covered the energy range from 0.5 to 10 eV. The measurements by Kwan et al. [7], by Sueoka and Mori [11] and by Kanik et al. [9] have extended the energy range up to 500, 400 and 300 eV, respectively. The only results above 500 eV are those of García et al. [12].

2. Experimental

These measurements were performed with a modified Ramsauer-type electron spectrometer. The apparatus, the measurement procedure and the error evaluation have been described previously [20]. Here, we will summarize only those parameters which are relevant to the quality of the present measurement. The apparatus was capable of measurements from less than 100 to 4000 eV. The gas cell length was 140.2 mm. Division of the scattering cell into two parts improved the angular resolution. Both the

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transmitted current to the collector and the scattered current to the collision chamber were measured. The reduction formula was a modified de Beer–Lambert law [20]. The beam forming region and the interaction chamber were differentially pumped. The background pressure was kept constant during the measurement. Additionally, the emission current was stabilized electronically. These precautions improved the beam stability, minimizing gas–cathode interactions and allowing measurements for energies higher than 700 eV.

Pressure was measured with a Baratron capacitance meter. The apparatus is equipped with an electronic unit which allows the Baratron head to track the gas cell temperature to within 0.1 °C. Therefore no thermal transpiration correction was needed.

The angular acceptance of the collector was 4×10^{-4} sr. The associated angular resolution error was evaluated by using the differential elastic cross section data of DuBois and Rudd [21]. This error amounts to 0.3%, 0.7%, 1.0% of the total elastic cross section at 200, 500 and 800 eV, respectively. Due to the lack of appropriate data we can only estimate a similar figure for the angular resolution error caused by inelastic scattering. It is worth mentioning that our apparatus, due to the applied transverse magnetic field, performs partial screening against inelastic forward scattering.

The experiment was fully computer controlled. The present cross section values are the average of several (three or more) measurements for each energy. A single run averages cross sections obtained for several (usually seven) different pressures. The statistical error (one standard deviation of the average at each energy) is within 3% over the entire energy range. The possible systematical error was evaluated (see ref. [20]) as 3% in the lowest- and highest-energy regions; and 2.5% elsewhere.

The CO gas was 99,95% commercial grade, with no further purification.

3. Results

Table 1 shows our measured values for CO and N_2 together with the statistical errors. The present results for CO are compared in fig. 1 with the data from other experimental groups [7,9,12] and with the theoretical results of Jain and Baluja [14]. The measurements of Sueoka and Mori [11] are not shown on the figure as they are considerably lower than the

Table 1
Total cross sections for electron scattering on CO (present data) and N_2 (present data and corrected values from our previous experiment [22] in 10^{-20} m^2. Statistical errors (in %) are given in parentheses

Energy (eV)	CO present	N_2 present	N_2 [22] renormalized
80	10.10 (1.3)		
90	9.74 (1.6)		
100	9.27 (0.9)		
121			8.59
125	8.18 (1.3)		
144			7.86
150	7.55 (3.3)		
175	7.05 (2.6)		
196			6.66
200	6.49 (1.5)		
250	5.63 (1.0)	5.53 (2.3)	
256			5.60
300	4.98 (0.7)	4.85 (2.9)	
324			4.88
350	4.50 (1.2)		
400	4.14 (0.6)		
484			3.65
500	3.56 (0.9)	3.58 (0.4)	
576			3.24
600	3.16 (2.0)		
676			2.86
700	2.80 (2.4)	2.79 (0.5)	
784			2.50
800	2.52 (2.5)		
900	2.29 (1.9)		2.23
1000	2.10 (1.6)	2.08 (0.5)	
1024			2.03
1100	1.91 (2.4)		
1156			1.82
1250	1.71 (1.6)		
1296			1.65
1444			1.49
1500	1.46 (1.2)		
1600		1.40 (0.2)	1.36
1750	1.26 (2.5)		
2000	1.11 (0.7)	1.13 (0.2)	
2250	0.992 (1.1)		
2500	0.890 (0.9)	0.890 (0.9)	
2750	0.819 (1.2)		
3000	0.755 (1.5)		
3250	0.706 (3.8)		
3500	0.654 (1.0)	0.649 (1.3)	
4000	0.565 (1.0)	0.585 (2.7)	

where E is the collision energy and A and B are fitting parameters. The fit apart from parameterizing the total cross section allows us to obtain quantitative information on the strength (V_0) and the range (a) of the molecular scattering potential (see ref. [29]),

$$V(r) = \frac{V_0}{r} \exp\left(-\frac{r}{a}\right),$$

$$A = \frac{\hbar^4}{16\pi m^2 a^4 V_0^2},$$

$$B = \frac{\hbar^2}{2\pi m a^2 V_0^2}. \qquad (2)$$

The continuous curves in fig. 1 are the best fits to formula (1). The experimental data of Jansen et al. [26], Kanik et al. [9,10] and the present results from 80 to 4000 eV have been used in the numerical algorithm. Both fits for CO and for N_2 succeed in reproducing experimental data between about 50 eV and the highest examined energy within measurement uncertainties. Between 20 and 50 eV the experimental values are slightly higher than the fitted values; this could be attributed to existence of resonant states centered between 20 and 30 eV [6,30,31] which cannot be reproduced by the Born-like model.

The parameters of the fit are presented in table 2; they are close for both gases. The 5% difference in the parameter A of the two fits reflects the fact that at low energies the CO cross section is higher than that of N_2. The parameters B determining the high-energy total cross sections are equal for CO and N_2, within the combined uncertainties of the experimental data and the fitting procedure. The minor difference indicating that at energies extrapolated up to tens of a keV the N_2 cross section would be 1% higher than that for CO, is a spurious effect to be attributed to a slightly higher angular resolution error in the CO measurements than for N_2. The parameters of the "effective" scattering potential are also close for both gases; the CO potential being only undistinguishably longer than that for N_2. It proves that the permanent dipole moment of the CO molecule is not reflected in the total cross section at intermediate energies.

Table 2
Parameters of the fit to the total cross sections (formula (1)), and of the effective scattering potential (formula (2))

Gas	A (A^{-2})	B (A^{-2} keV^{-1})	V_0 (au)	a (au)
CO	0.067	0.419	96.39	0.145
N_2	0.071	0.416	100.38	0.140

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