Total cross section for electron scattering from N_2 in the energy range 600–5000 eV

G. García, A. Pérez, and J. Campos
Laboratorio de Física Atómica y Láseres del Centro de Investigaciones Energéticas Mediambientales y Technológicas and Cátedra de Física Atómica, Facultad de Ciencias Físicas, Universidad Complutense de Madrid, Ciudad Universitaria, 28040 Madrid, Spain
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Total cross sections for electron scattering by N_2 molecules in the energy range 600–5000 eV have been obtained from measurements of the attenuation of a linear electron beam. The results have been compared with available experimental cross sections and with theoretical calculations based on the first Born approximation. No previous experimental data have been found in the literature for impact energies above 1600 eV.

I. INTRODUCTION

There is a renewed interest in the study of the total cross sections of electron scattering by atoms and molecules as noted in recent articles.[1–3] Accurate measurements of total cross sections are required in several fields of physics (astrophysics, plasma physics, and atmospheric physics). In general, there are few data for energies of colliding electrons above 1000 eV. In the particular case of molecular nitrogen, most experiments were carried out at electron energies below 800 eV,[4–9] with the exception of the work of Dalba *et al.*[10] made in the range 100–1600 eV. The results of these experimental studies have been summarized by several authors (Hayashi,[11] Trajmar *et al.*,[12] and Itikawa *et al.*[13]).

As is well known, the first Born approximation and the Born-Bethe theory are extensively used for calculations of total cross sections of elastic and inelastic collisions of fast electrons with atoms and molecules.[14–17] Recently these approximations have been used by Liu[3,18] for H_2, N_2, and O_2 molecules. As has been pointed out by this author, accurate experimental data at energies above 1 keV are required to compare with the theoretical results.[3] The lack of experimental data for high-energy electron collisions has prompted the present experimental study.

In the present work total cross sections for electron scattering from N_2 have been measured in the energy range 600–5000 eV by a transmission-beam technique. Special care was taken to avoid systematic errors arising from forward electron scattering.

II. EXPERIMENTAL SETUP

The experimental arrangement is similar to that described in a previous work.[19] The basic scheme of the apparatus is shown in Fig. 1. The electron gun consists of a tungsten filament, extractive electrode, electrostatic lenses, and deflection plates. The pressure in the gun was maintained lower than 10^{-6} Torr. The collision chamber was limited by two apertures of 2 mm in diameter separated by a length (L) that was varied from 15 to 30 cm, according to the experimental requirements. The beam intensity in the scattering chamber was typically 10^{-9} A. The gas pressure was measured with a Thermovac TM202 thermal conductivity manometer, previously calibrated with a capacitance manometer (MKS Baratron 227 A). In order to discriminate the inelastically scattered electrons, a Comstock AC-901 double-focusing electrostatic analyzer was used. The entrance and exit apertures of the analyzer were 0.5 mm in diameter. The beam was focused at the entrance aperture by means of a three-element cylindrical lens. Under the conditions of this experiment the energy resolution was better than 0.2%. The transmitted electrons were collected on a Faraday cup and the intensity was measured with a Keithley 610 C electrometer. The Faraday cup and the energy analyzer were maintained at a pressure lower than 10^{-6} Torr.

III. PROCEDURE

The method is based on the measurement of the electron beam attenuation through the gas cell. The beam intensity follows the well-known law

$$I = I_0 \exp(-NL\sigma_T) ,$$

where I_0 is the intensity of the primary beam, I is the attenuated-beam intensity, L is the interaction-region length, N is the molecular density, and σ_T is the total cross section. N is obtained from the measurement of pressure and temperature in the gas cell. Each measure-

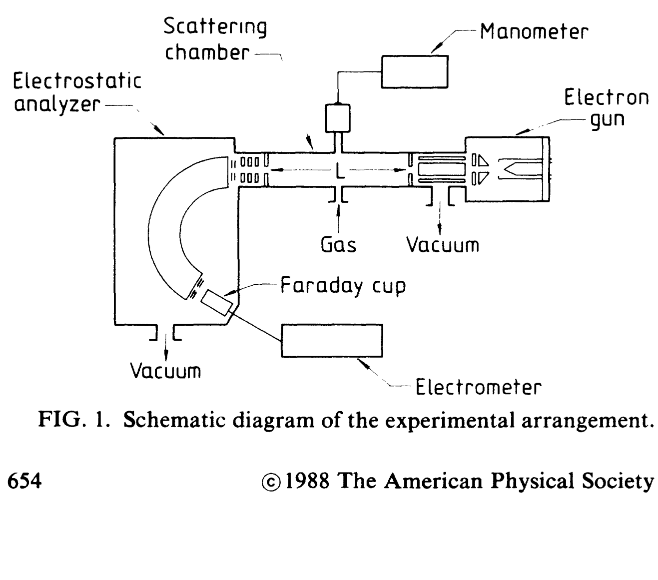

FIG. 1. Schematic diagram of the experimental arrangement.

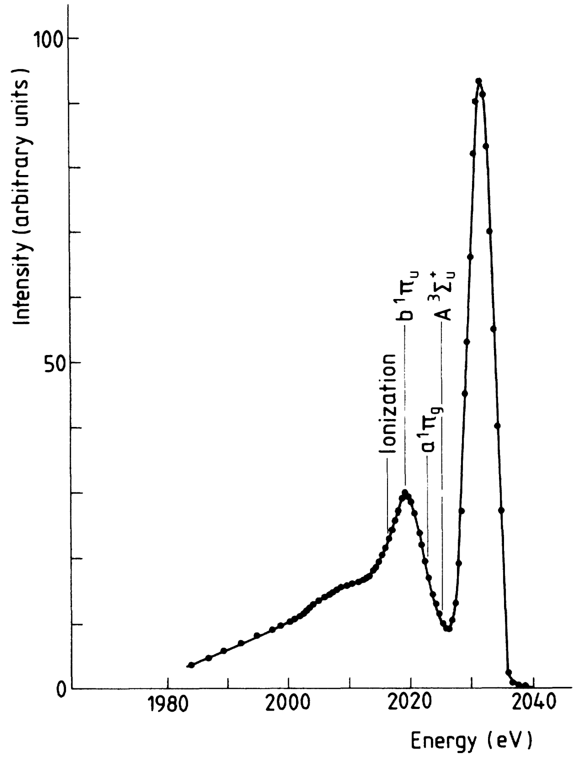

FIG. 2. Energy spectrum of electrons after crossing the collision chamber at 50-mTorr N_2 pressure. Positions of characteristic energy levels of N_2 are shown with vertical lines.

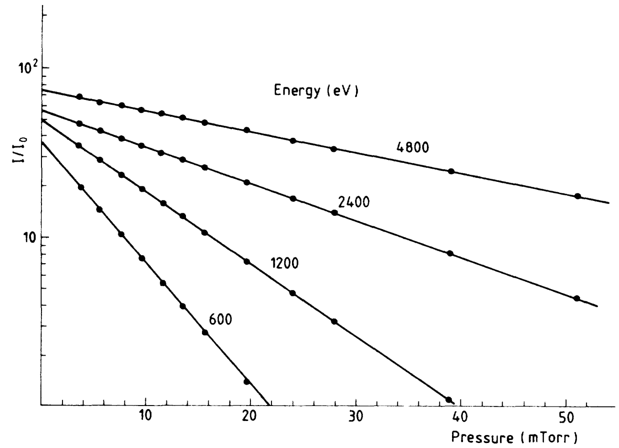

FIG. 3. Transmitted-electron-beam intensity vs N_2 pressure for energies ranging from 600 to 4800 eV.

ment was performed at pressures ranging from 4 to 66 mTorr. It was ensured that pressure gradients did not contribute to the experimental errors by measuring the pressure at several points along the cell. The accuracy on the pressure measurements is determined by the calibration of the MKS Baratron 227 A. Taking into account the data of the manufacturer, the temperature coefficients, and the zero drift, we have estimated an accuracy on the pressure determinations better than 1%.

To measure accurately the attenuation of the electron beam it is necessary to discriminate the forward inelastically scattered electrons. For this reason we used an electrostatic analyzer to study the energy spectrum of the electrons reaching the detector. A typical result for 2032-eV electrons and 50-mTorr N_2 pressure in the collision chamber is plotted in Fig. 2. As this figure shows, the energy resolution used in this experiment was enough to avoid the aforementioned systematic error.

The elastically scattered electrons in the forward direction are not discriminated by the analyzer. However, this error contribution can be neglected by using appropriate angular resolution. In the conditions of our experiment the solid angle subtended by the entrance aperture of the analyzer as seen from the center of the gas cell was typically about 10^{-5} sr. By extrapolating the elastic differential cross sections experimentally determined by Jansen *et al.*[20] and Du Bois and Rudd[21] to zero angle, we have obtained an error in our measurements due to forward elastic scattering of less than 0.1%.

Figure 3 shows a typical semilogarithmic plot of the transmitted-beam intensity versus pressure. The experimental points lie on a straight line whose slope gives the total cross section. Measurements were performed for electron currents from 10^{-9} to 10^{-11} A. In this range no dependence of total cross sections on the current was found. In order to check that our measured length L corresponds to the actual absorption length, we changed the collision-chamber length from 15 to 30 cm. The total cross sections were found to be independent of L within statistical uncertainties, namely, 2%.

IV. RESULTS AND DISCUSSION

The experimental results of total cross sections for electron scattering on N_2 in the impact-energy range 600–5000 eV are shown in Table I. By combining the error contributions previously mentioned, we have estimated a total error of 3% in these values. Experimental results of Refs. 7, 8, and 10 are included in Table I for comparison. As may be seen in Table I there is agreement between the present measurements and those obtained by other authors in the overlapping energy range.

Our experimental results have been compared with theoretical predictions. Inokuti and McDowell[16] have shown that elastic cross sections for electron scattering by atoms and molecules in the first Born approximation, σ_{el}, are given by

$$\frac{E_0}{R}\frac{\sigma_{el}}{a_0^2}=\pi\left[A+B\frac{R}{E_0}+\cdots\right], \tag{1}$$

where E_0/R is the energy of incident electrons in Rydberg units and a_0 is the Bohr radius. The constants A and B for N_2 have been calculated by Liu.[3] On the other hand, the total inelastic cross sections σ_{inel} have been given by Inokuti[14] according to Born-Bethe theory as

$$\frac{E_0}{R}\frac{\sigma_{inel}}{a_0^2}=4\pi\left[M_{tot}^2\ln\left[4C_{tot}\frac{E_0}{R}\right]+\gamma_{tot}\frac{R}{E_0}+\cdots\right], \tag{2}$$

TABLE I. Experimental cross sections (a_0^2) for electron scattering from N_2.

E_0 (eV)	This work[a]	Ref. 7[b]	Ref. 8[c]	Ref. 10[d]
600	11.6	11.4	11.07	
650		10.6		
676				10.68
700	10.2	9.89	10.1	
750		9.36		
784				9.36
850	8.80			
900				8.32
1000	7.62			
1024				7.57
1156				6.82
1200	6.69			
1296				6.14
1444				5.57
1600	5.00			5.07
2000	4.18			
2400	3.52			
2800	3.20			
3200	2.76			
3600	2.54			
4000	2.35			
4400	2.08			
4800	1.95			
5000	1.85			

[a]Experimental error, 3%.
[b]Experimental error, 4%.
[c]Statistical uncertainty, 2%.
[d]Experimental error, 2.5%.

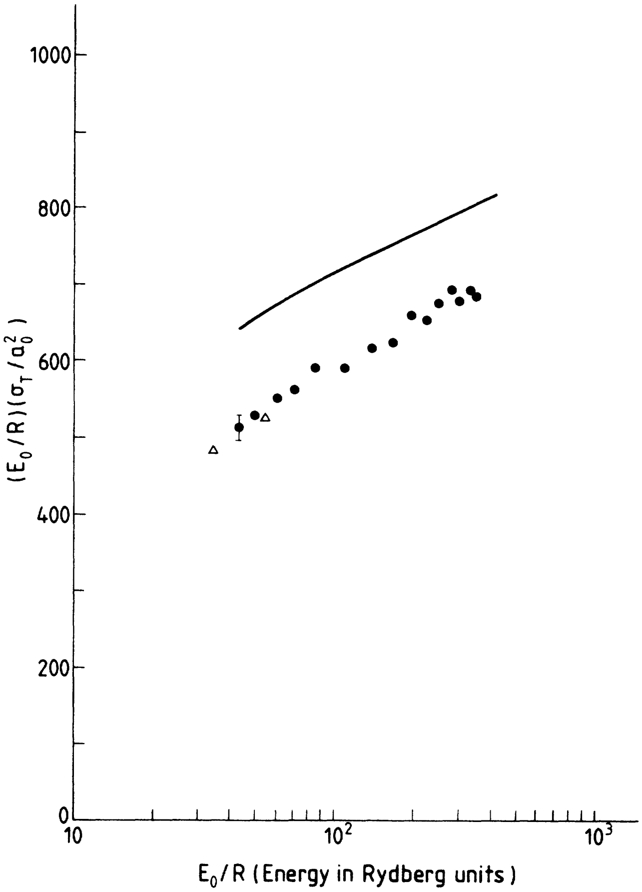

FIG. 4. $E_0\sigma_T R^{-1}a_0^{-2}$ plotted vs E_0R^{-1} for N_2. ●, present work (3% experimental error). —, Born σ_{el} plus Born-Bethe σ_{inel} from Ref. 3. △, experimental σ_{el} given in Ref. 21 plus Born-Bethe σ_{inel} from Ref. 3.

where the constants M_{tot}^2, C_{tot}, and γ_{tot} have been calculated by Liu[3] for N_2. The total cross sections σ_T were obtained in Ref. 3 for high-energy electron scattering from N_2 by adding the results for σ_{el} and σ_{inel} of expressions (1) and (2). In Fig. 4, $(E_0/R)(\sigma_T/a_0^2)$ is plotted versus $\ln(E_0/R)$ for our experimental results and for the theoretical data given by Liu.[3] As may be seen, the total cross sections experimentally determined in this work are lower than those deduced from the Born approximation. However, the total cross sections obtained by adding, where possible, the inelastic cross sections given by the Born-Bethe theory with the elastic cross sections measured by Du Bois and Rudd[21] are in agreement with the present results. Therefore it may be inferred that the Born approximation overestimates the elastic cross sections for electron scattering from N_2 even at 5000 eV impact energy. This situation has been previously shown[19,22] in electron-atom collision experiments.

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