Elastic scattering of 13 to 100 eV electrons from N_2*

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The cross section for elastic scattering of electrons from N_2 has been measured between 13 and 100 eV. The relative differential cross sections for elastic scattering and for excitation of the $C\,^3\Pi_u$ $v'=0$ and 1 bands were measured over the angular range from 20° to 90° in the 13–35 eV region and from 5° to 90° in the 40–100 eV region. The integrated cross sections were placed on an absolute basis by normalizing the $C\,^3\Pi_u$ $v'=0$ excitation cross section to the known emission cross section for the Second Positive system of nitrogen ($C\,^3\Pi_u \rightarrow B\,^3\Pi_g$) and by calibrating the electron spectrometer with respect to other electron scattering results. The total elastic scattering cross section varies from 12.3×10^{-16} cm^2 ($\pm 50\%$) at 13 eV to 3.9×10^{-16} cm^2 ($\pm50\%$) at 100 eV.

I. INTRODUCTION

There have been numerous investigations of the cross section for elastic scattering of electrons from N_2 at low energies. Some results, both experimental as well as theoretical, date from the 1930's. Brüche,[1] and later Normand,[2] measured the "absorption coefficient" of electrons at a particular energy as they passed through the gas. Arnot[3] measured the elastic differential cross section (DCS) over the angular range from 10°–120° at incident energies from 30–780 eV. Bullard and Massey[4] extended the elastic DCS measurements down to 7 eV. Mohr and Nicholl[5] measured elastic and inelastic scattering over the angular range from 20°–160° at incident energies of 50, 84, and 100 eV. Theoretical calculations of the total and differential elastic cross sections were carried out by Massey and Bullard,[6] Fisk,[7] and Stier.[8]

In recent years, Aberth, Sunshine, and Bederson[9] have used an atomic beam recoil technique to measure the total scattering cross section at energies from 1–25 eV. Bromberg[10] measured the DCS directly at incident energies of 300, 400, and 500 eV over the angular range from 2°–110°.

There have been four recent investigations in which the elastic differential cross section was determined by normalizing the data using other experimental or theoretical results. Pavlovic *et al.*[11] measured the elastic DCS between 21 and 25 eV over the angular range from 25°–90°. These results were placed on an absolute basis by calibrating the instrument with respect to the helium elastic DCS at energies from 10–40 eV as calculated by La Bahn and Callaway.[12] The same technique was used by Comer and Read,[13] who measured the DCS at 40° and 85° near 11.5 eV incident energy. Truhlar *et al.*[14] measured the elastic DCS at 20 eV from 20°–85° and by combining the total scattering cross section and the ionization cross section were able to determine the absolute elastic cross section at 20 eV.

The fourth experiment was performed by Shyn *et al.*,[15] who measured the angular distribution of elastically scattered electrons over the range from −114° to +162° at incident energies from 5–90 eV. In this experiment a crossed beam technique was used so that there was no correction necessary for variation of the scattering volume with scattering angle. The results were normalized to Fisk's[7] theoretical calculation of the elastic scattering cross section at 5 eV.

The total elastic cross section has been calculated from the DCS data by Shyn *et al.*[15] over the energy range 5–90 eV, by Truhlar *et al.*[14] at 20 eV, by Bromberg[10] at 500 eV, and by several of the early investigators. The results are in good agreement at low energies.

In the course of an investigation of electron scattering cross sections from N_2, it became apparent that a significant improvement in elastic cross section measurements in the 10–100 eV range might be possible by comparison of our inelastic scattering results for excitation of the N_2 $C\,^3\Pi_u$ state with the elastic scattering cross section and use of the well-measured electron impact optical excitation function for emissions from this state as well as the helium elastic DCS as secondary standards. The results of our investigation are presented in this paper.

II. EXPERIMENTAL

The apparatus used for these experiments has been previously described.[16,17] Briefly, it consists of a high energy resolution electron spectrometer coupled to an optical detection system. For the present experiments, the optical detection system was used only to determine the energy of the incident electron beam by monitoring the 14.02 (± 0.05) eV maximum of the N_2 second positive system (0, 0) band cross section.[17]

The complete electron impact spectrum of N_2 in the 11–12 eV energy range has been presented by Williams and Doering.[18] The first three vibrational bands of the $C\,^3\Pi_u$ state of N_2, which are the only inelastic features of interest in the present work, occur at energy losses of approximately 11.01, 11.28, and 11.50 eV, are free of interference from other transitions, and are easily measured with moderate energy resolution.

The pressure dependence of the scattered signal was studied to demonstrate the absence of multiple scattering. Analysis of the data up to pressures of 25 mtorr by the method of Lassettre and Francis[19] demonstrated the lack of multiple scattering in the elastic and inelastic $C\,^3\Pi_u$ channels. The ratio of elastic/$C\,^3\Pi_u$ signal was independent of pressure over the same pressure range. During the actual experiments, the pressure of the target gas was maintained at a few mtorr.

The general experimental procedure was measurement of the elastically scattered signal, the $C\,^3\Pi_u$ inelastic signal, and the elastic signal again. If the two elastic signals differed by more than 20%, the run was discarded. The magnitude of the elastically scattered signal and the $C\,^3\Pi_u$/elastic ratio were measured at each energy and angle. The results were normalized to constant pressure and incident beam current.

A similar procedure was used for the helium scattering and helium/nitrogen elastic scattering ratio experiments as described later. The absence of contamination of the helium by nitrogen in these experiments was verified by measurement of the helium $2\,^1P$ inelastic/elastic scattered intensity ratio. Satisfactory agreement was obtained with the results of Crooks,[20] indicating lack of nitrogen contamination.

For the experiments at incident energies from 40–100 eV, a small Faraday cup was used in the collision chamber to collect the incident beam current. This cup allowed us to go as low as 5° in scattering angle before it interfered with the scattering geometry. For the measurements below 40 eV, a larger Faraday cup was installed to improve the accuracy of the incident current collection. This cup, however, interfered with the scattering geometry of scattering angles less than 20°, so we present extrapolated values for angles less than 20° at energies below 40 eV.

III. RESULTS AND DISCUSSSION

A. Calculation of cross sections

Direct measurement of absolute scattering cross sections is not feasible with our apparatus for a number of reasons. For instance, because of interference from the optical system, we lack direct access to the collision chamber for the extremely accurate pressure measurements required for a direct measurement. We therefore examined a number of processes with known cross sections which might be used as secondary standards to put our relative cross section measurements on an absolute scale.

The electron impact optical excitation cross section for the $C\,^3\Pi_u\ v'=0$ state was adopted as a secondary standard for a number of reasons. The only known mode of decay from the $C\,^3\Pi_u$ excited state of N_2 is by an electric dipole transition to the $B\,^3\Pi_g$ state accompanied by emission of the prominent N_2 second positive system. Cascade contributions to the population of the $C\,^3\Pi_u$ state have been found to be small except near threshold.[17] Since cascades are negligible and the lifetime with respect to the transition $C\,^3\Pi_u \rightarrow B\,^3\Pi_g$ is short compared to all other deexcitation processes, the $C\,^3\Pi_u \rightarrow B\,^3\Pi_g$ electron-impact optical excitation cross section is equal to the $C\,^3\Pi_u$ electron impact excitation cross section. The cross section for N_2 second positive (0, 0) band emission by electron impact has been measured by Aarts and De Heer.[21] The total cross section for excitation of the $C\,^3\Pi_u\ (v'=0)$ level can be calculated from the (0, 0) band cross section by application of the branching ratios for the transition $C\,^3\Pi_u\ (v'=0) \rightarrow B\,^3\Pi_g\ (v'=0, 1, 2, \ldots)$ calculated by Nicholls[22] and measured by Shemansky and Broadfoot.[23] The branching ratios show that the excitation cross section of the $C\,^3\Pi_u(v'=0)$ level is 2.02 times the (0, 0) band cross section.

There is some disagreement in the measured values of the second positive system emission cross section near 100 eV. The values obtained by Aarts and De Heer[21] and more recently by Imami and Borst[24] are much lower than those obtained by previous investigators.[25,26] By investigating the pressure dependence of the apparent emission cross section, Aarts and De Heer[20] concluded that the higher results of previous investigators were caused by the presence of low energy secondary electrons in the apparatus. However, in view of the disagreement, we felt that it was neccessary to make an independent measurement of the cross section at 100 eV. To perform this measurement, we calibrated our apparatus by repeating the experiments of Vriens *et al*,[27] Chamberlain *et al.*,[28] and Crooks,[20] who measured the DCS for elastic scattering and excitation of the $2\,^1P$ state of helium at 100 eV, and measuring the ratio of the helium scattering to $N_2\ C\,^3\Pi_u$ excitation. The $C\,^3\Pi_u$ cross section was calculated from the measured ratio at 100 eV. The results are given in Table I. The results of our measurement agree with those of Aarts and De Heer[21] and Imami and Borst,[24] whereas those of other investigators are much larger. We therefore used the values of Aarts and De Heer for our calculations.

Since our apparatus allowed the measurement of the elastic and $C\,^3\Pi_u$ DCS over an angular range between 5° or 20° and 90°, it was obviously necessary to use some sort of extrapolation procedure for both the calculation of the $C\,^3\Pi_u$ total cross section for comparison with the optical excitation cross section and calculation of the total elastic scattering cross section. For all elastic scattering measurements, the DCS was extrapolated between the lowest scattering angle measured and 0° by plotting the intensity vs scattering angle on semilog graph paper and making a linear extrapolation to 0°. With a few exceptions (see Table II), this extrapolation procedure was therefore used over the angular range 0°–5° above 40 eV incident energy

TABLE I. $C\,^3\Pi_u\ (v'=0)$ excitation cross section at 100 eV.

Investigator	Result
Present results[a]	2.6×10^{-19} cm^2
Present results[b]	3.5
Imami and Borst[24]	2.9
Aarts and De Heer[21]	3.6
Burns *et al.*[25]	21
Jobe *et al.*[26]	18 (at 90 eV)

[a]Obtained by using helium cross sections of Chamberlain *et al.*[28]
[b]Obtained by using helium cross sections of Crooks.[20]

TABLE II. Relative elastic differential scattering cross section ($d\sigma/d\Omega$).

Scattering angle degrees degrees	5	7.5	10	12	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
Energy (eV)																				
13	(4.4)[a]		(3.9)		(3.1)	2.9	2.6	2.2	2.0	1.8	1.6	1.4	1.2	0.98	0.79	0.64	0.53	0.44	0.37	0.31
15	(5.1)		(4.6)		3.7	3.1	2.8	2.4	2.0	1.7	1.5	1.3	1.1	0.94	0.77	0.61	0.46	0.37	0.31	0.29
18	(6.8)		(5.7)		4.8	3.9	2.9	2.4	2.0	1.7	1.4	1.1	0.90	0.72	0.59	0.48	0.40	0.33	0.28	0.24
20	(8.3)		(6.6)		(5.2)	4.0	3.3	2.6	2.0	1.7	1.4	1.1	0.90	0.72	0.55	0.42	0.35	0.29	0.26	0.24
22	(8.8)		(7.0)		(5.3)	4.2	3.3	2.6	2.0	1.6	1.3	1.0	0.81	0.64	0.50	0.40	0.31	0.28	0.24	0.22
24	(9.8)		(7.7)		(5.9)	4.6	3.5	2.8	2.2	1.6	1.3	0.94	0.74	0.59	0.44	0.37	0.31	0.28	0.24	0.22
30	(8.4)		(6.6)		(5.2)	3.9	2.9	2.2	1.7	1.4	1.0	0.77	0.59	0.44	0.37	0.28	0.22	0.20	0.17	0.16
35	(11.0)		(7.7)		(5.5)	3.9	2.8	2.0	1.4	1.1	0.81	0.59	0.44	0.33	0.26	0.20	0.16	0.13	0.11	0.098
40	10.0		7.4		5.1	3.7	2.6	1.8	1.2	0.86	0.61	0.42	0.31	0.22	0.18	0.15	0.12	0.11	0.096	0.086
50	(11.0)		(7.1)		(5.0)	3.3	2.2	1.5	1.0	0.64	0.42	0.31	0.24	0.18	0.14	0.11	0.096	0.081	0.077	0.068
60	(9.4)	(7.5)	(6.3)	(5.2)	(3.9)	2.6	1.7	1.1	0.72	0.46	0.31	0.22	0.16	0.13	0.099	0.081	0.070	0.063	0.059	0.059
75	8.8	7.5	6.4	6.1	4.6	2.9	1.7	1.0	0.63	0.42	0.29	0.20	0.16	0.13	0.01	0.094	0.083	0.077	0.075	0.077
90	11.0	7.7	5.9	5.0	3.9	2.2	1.3	0.79	0.52	0.33	0.24	0.18	0.14	0.12	0.10	0.088	0.077	0.072	0.068	0.066
100	11.0	8.1	6.3	5.0	3.5	2.0	1.2	0.74	0.46	0.29	0.22	0.16	0.13	0.12	0.10	0.090	0.085	0.081	0.079	0.079

[a]( ) Indicates extrapolated values.

and 0°–20° below 40 eV.

Since the measurements of Shyn *et al.*[15] have shown that the elastic DCS rises in the angular range 90°–160°, we estimated the backscattered contribution to the total cross section by fitting our DCS results to those of Shyn *et al.* in the 55°–90° angular range and using their results normalized to ours from 90°–160°. The contribution from 160°–180° was again estimated by a simple extrapolation as described above. The 90°–180° contribution to the total cross section we calculate is shown separately in Table IV for each energy. This backward hemisphere percentage, which we calculate but do not measure, ranges from 39% at 13 eV to 18% at 100 eV.

The $C\,^3\Pi_u$ total cross section was calculated by using an extrapolation between the smallest angle measured and 0° as described above as well as the assumption of a constant DCS vs scattering angle from 90°–180°.

The $C\,^3\Pi_u$ optical excitation cross section was used as a calibration standard for impact energies above 24 eV. Below 24 eV, two problems arose which prevented the use of this cross section as a standard. First, the electrons which had excited the $C\,^3\Pi_u$ state at 11 eV had only a few eV energy left and were hard to measure accurately. Second, the maximum in the $C\,^3\Pi_u$ DCS moves to a progressively higher scattering angle as the energy approaches threshold (See Fig. 3 and the discussion below) and the contribution of the DCS between 90° and 180°, which we can only estimate, becomes increasingly important. We therefore devised an internal calibration method for use below 24 eV which did not require accurate measurements of the $C\,^3\Pi_u$ transition.

The internal calibration method consisted of four parts. First, the energy dependence of the relative elastic DCS was measured from 13–30 eV at a fixed scattering angle of 38°. Second, the relative elastic DCS from 5°–90° was measured at each energy. Third, all the relative DCS measurements were related to each other by normalizing them at 38° to the 38° scattering vs energy measurement. Fourth, the total cross sections for elastic scattering were calculated and normalized to the values obtained by the $C\,^3\Pi_u$ emission cross section measurement at 24 and 30 eV. All the results shown later between 13 and 20 eV were obtained using this method and are so indicated.

B. Relative elastic differential cross section

The relative elastic differential cross section has been measured at 14 different energies between 13 and 100 eV. The results are given in Table II. In Fig. 1, our results are compared to the results of Truhlar *et al.*,[14] Shyn *et al.*,[15] and Pavlovic *et al.*[11] All four sets of data in Fig. 1 have been forced to agree at a scattering angle of 40°.

The agreement with the results of Truhlar *et al.*[14] is good over the whole angular range from 20°–80°. The results of Shyn *et al.*[15] are steeper than ours, but nowhere is the deviation greater than about 50%. It is interesting to note that in each of these three experiments, a different method was used to obtain the

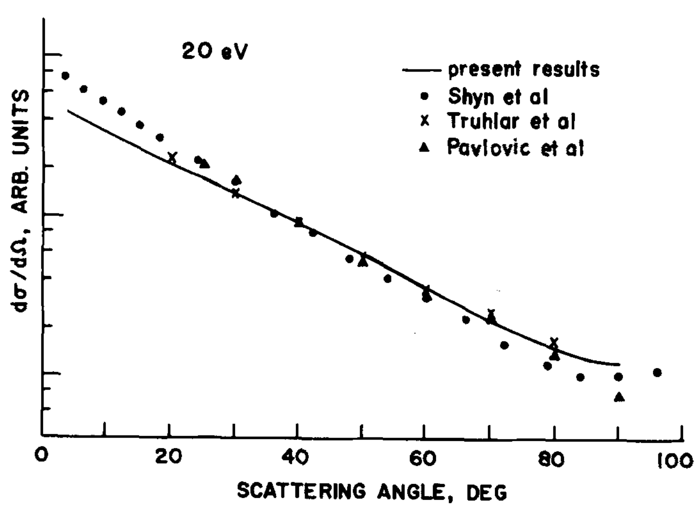

FIG. 1. Relative elastic DCS for electrons on N_2 at 20 eV. The present results are compared to those of Shyn *et al.*,[15] Truhlar *et al.*,[14] and Pavlovic *et al.*[11] All four measurements have been normalized at a scattering angle of 40°. Note that the present results are calculated from an extrapolation below 20°. The results of Shyn *et al.* are extrapolated below 18°.

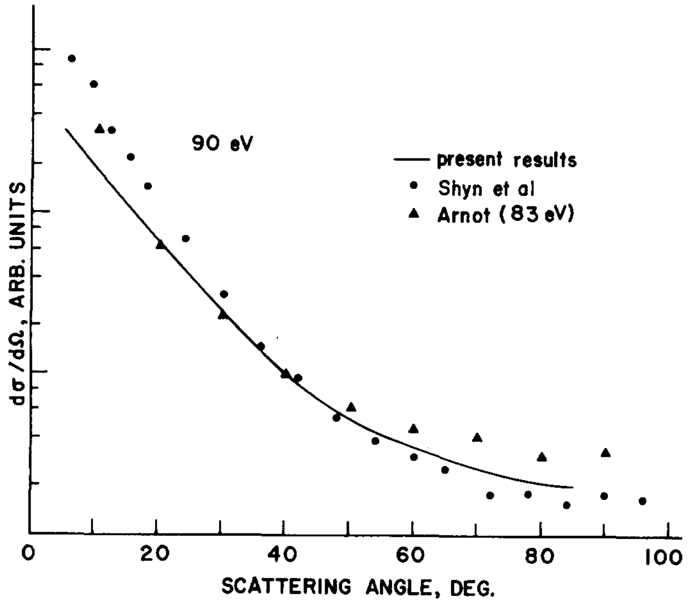

FIG. 2. Relative elastic DCS for electrons on N_2 at 90 eV. The present results are compared to those of Shyn *et al.*[15] and Arnot.[3] All three measurements have been normalized at a scattering angle of 40°. Note that the present results are calculated from an extrapolation below 5°. The results of Shyn *et al.* are extrapolated below 9°.

relative elastic differential cross sections. Pavlovic *et al.*[11] normalized the results at each angle to the theoretical values of La Bahn and Callaway.[12] Truhlar *et al.*[14] applied a correction for the variation of the effective path length of the electron beam as a function of scattering angle. Shyn *et al.*[15] used a molecular beam experiment so that no angular correction was necessary and the differential cross sections could be obtained directly from the relative intensity data. It is important to note, however, that since all the 20 eV results shown in Fig. 1 for scattering angles less than 18° were obtained by extrapolation, they must obviously be accepted with some caution.

In Fig. 2 our results are compared to those of Shyn *et al.*[15] and Arnot[3] at an energy of 90 eV. As for the 20 eV results, our results are smaller than those of Shyn *et al.*[15] at small angles. Note that our results are extrapolated below 5° and those of Shyn *et al.*[15] below 9°. The values of Arnot agree well with ours except at 10°.

Although much of the available data was obtained by extrapolation procedures, we feel that the disagreement between our results and those of Shyn *et al.*[15] at angles less than 20° is significant since, as we shall see later, our total elastic scattering cross section is smaller than that of Shyn *et al.*,[15] especially at the higher energies. The observed disagreement could arise if the correction for the angular dependence of the scattering volume which we applied to our data were incorrect. The angular dependence of the scattering volume in our apparatus is unusually complicated because the electron-optic axis does not lie in the analyzer rotation plane.[16] The angular scattering volume correction has been described in detail by Finn.[29] However, we felt that an experimental verification of this correction would be desirable so we repeated the experiment of Vriens *et al.*[27] who measured the differential cross section for elastic scattering of 100 eV electrons from helium. An analysis of the data, which is summarized in Table III, indicates that our cross sections have an angular dependence similar to that of Vriens *et al.* over the range from 5–30° except at $\theta = 10°$, where the cross section is significantly less. The discrepancy at 10° is probably due to interference from the Faraday cup. Since this cup was replaced by a larger version as discussed above, the interference effect might have been somewhat greater for the later measurements, but could not have accounted for all the disagreement between our results and those of Shyn *et al.*[15] below 20°.

In spite of the above differences with the results of Shyn *et al.*,[15] the over all agreement between the various experiments performed to date is impressive.

C. Relative differential cross sections for excitation of the $C\,^3\Pi_u$ state

As mentioned above, the cross section for excitation of the first two vibrational levels of the $C\,^3\Pi_u$ state was measured relative to the elastic DCS at each energy and scattering angle. The results for the relative $C\,^3\Pi_u$ state DCS are shown in Fig. 3. At 100 eV, the cross section is forward peaked, except for the single data point at 5°, which may be in error. The cross section clearly becomes more isotropic at low energies. Such behavior is to be expected. The results of Lassettre[30] and Aarts and De Heer[21] suggest that the $C\,^3\Pi_u$ state may have a mixed singlet–triplet character since the cross section for electron impact excitation for this state does not decrease with increasing energy as rapidly as expected for a pure singlet–triplet transition.

D. Total elastic scattering cross section

The total elastic scattering cross sections were calculated from the relative cross sections for elastic scattering and excitation of the $C\,^3\Pi_u$ states and the N_2 second positive system ($C\,^3\Pi_u \rightarrow B\,^3\Pi_g$) emission cross section measured by Aarts and De Heer[21] for impact energies greater than 22 eV and by the relative internal calibration method at lower energies. The total elastic scattering cross section is given in Table IV, where we have tabulated the elastic cross section and the percent contribution from the backward hemisphere (90°–180° scattering angle) which we have calculated from our measurements and the results of Shyn *et al.*[15]

TABLE III. Helium relative DCS at 100 eV.

θ (deg)	Average DCS[a]	No. of measurements	Average deviation (%)	Vriens *et al.*[27]	Present results / Vriens *et al.*
5	2.5	4	18	2.6	0.96
7.5	1.9	6	14	2.2	0.86
10	1.3	7	13	1.9	0.68
15	1.4	6	7	1.4	1.0
20	1.0	7	...	1.0[a]	1.0
25	0.72	7	11	0.74	0.97
30	0.52	7	11	0.55	0.95

[a]Normalized to 1.0 at $\theta = 20°$.

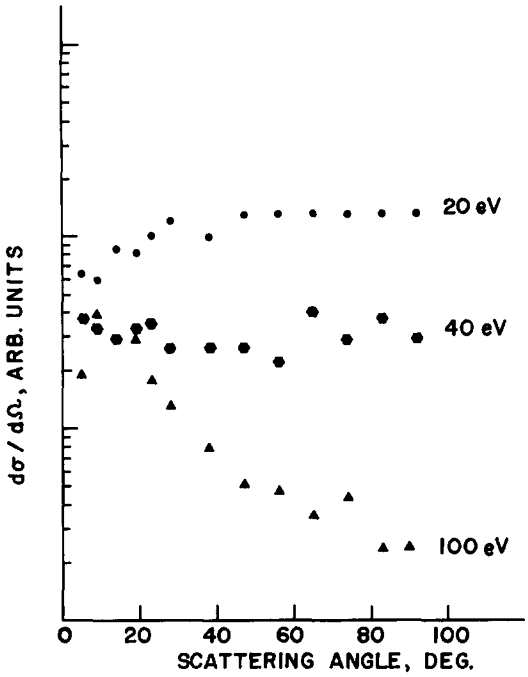

FIG. 3. Relative inelastic DCS for excitation of the $C\,^3\Pi_u$ ($v'=0$) state of N_2 by 20, 40, and 100 eV electrons. The same units were used for each energy.

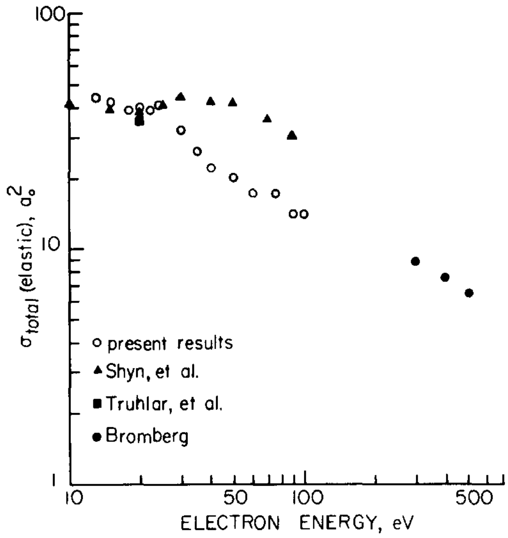

FIG. 4. Total elastic scattering cross section for electrons on N_2. The results of the present experiment are compared to those of Shyn *et al.*,[15] Truhlar *et al.*,[14] and Bromberg.[10,31]

The total elastic cross section results are compared to the results of other investigators in Fig. 4. All the measurements are in excellent agreement below 25 eV. Above this energy, our cross section is significantly smaller than the results of Shyn *et al.*[15] Bromberg's[10] measurement at 500 eV is shown as well as values at 300 and 400 eV which we have obtained by integration of Bromberg's 300 and 400 eV differential cross section.[31] It is important to note, in view of past confusion, that Bromberg's total cross sections[10] are $\sigma/4\pi a_0^2$.[31] We therefore multiply Bromberg's results by 4π for comparison with ours in Fig. 4, where units of a_0^2 are used. We have presented our results in units of a_0^2 in Fig. 4 and in cm^2 in Table IV. Figure 4 shows that our results extrapolate to 300 eV in excellent agreement with Bromberg's results.

TABLE IV. Total elastic cross section.

Energy (eV)	Elastic cross section ($\times 10^{-16}$ cm^2)	Calculated 90°–180° contribution[b]
13	12.4[a]	39%
15	11.8[a]	37%
18	10.9[a]	34%
20	11.2[a]	33%
22	10.9[a]	30%
24	11.5	33%
30	8.8	27%
35	7.2	23%
40	6.4	21%
50	5.7	20%
60	4.7	19%
75	4.7	22%
90	3.9	17%
100	3.8	18%

[a]The cross section at these energies is obtained using the internal calibration method (i.e., the relative energy dependence of the elastic cross section at 38°) rather than the elastic/$C\,^3\Pi_u$ ratio.
[b]The 90°–180° contribution to the total elastic cross section was calculated using our results to 90° and those of Shyn *et al.*[15] beyond 90° (see text).

We estimate the error in our total cross section measurement as follows: the uncertainty in the $C\,^3\Pi_u$ (0, 0) cross section as measured by Aarts and De Heer,[21] (15%); the uncertainty in the total $C\,^3\Pi_u$ cross section between 90° and 180° (20%), the random and statistical errors derived from measuring the $C\,^3\Pi_u$ to elastic ratio (10%), and the elastic DCS (5%). Consideration of all the expected uncertainties leads us to an estimate of total error of ±50% in the total scattering cross sections.

IV. CONCLUSIONS

The elastic scattering cross section of nitrogen has been measured from 13–100 eV. The relative DCS for elastic scattering has been integrated from 0°–180° with the aid of extrapolations from 5°–0° and the data of Shyn *et al.*[15] from 90° to 180°. The relative results have been placed on an absolute scale by comparison of the elastic scattering intensity to the intensity of the N_2 $C\,^3\Pi_u$ inelastic process at each energy and scattering angle and use of the measured optical emission cross section for the $C\,^3\Pi_u \rightarrow B\,^3\Pi_g$ transition as a secondary standard. The results are in good agreement with previous results in the 13–20 eV region but somewhat lower at the higher energies up to 100 eV. Extrapolation of the present measurements to 300 eV gives excellent agreement with the measurements of Bromberg.[10,31] The uncertainty in the cross section measurement is estimated to be ±50%.

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