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Angular distribution of electrons elastically scattered from gases: 1.5–400 eV on N_2. II

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Differential cross sections of electrons elastically (vibrationally) scattered from N_2 have been measured by a crossed-beam method. Energy and angular range of the measurements are 1.5 to 400 eV and $-96°$ to $+156°$, respectively, with an emphasis on the π_g shape-resonance region. The wide energy range of the measurements provides the basis for intercomparison of a large suite of similar measurements. The comparison shows generally good to excellent agreement. The comparison with theoretical calculations is less satisfactory with significant differences in the magnitudes of the cross sections and only fair agreement in shape. In the π_g shape-resonance region, the elastic cross sections appear to be one-half of the total cross sections, approximately. Inelastic cross sections, mainly vibrational excitations, would thus appear to have a magnitude near that of the elastic cross section suggesting the importance of an independent measurement of vibrational-excitation cross sections in the region of the π_g resonance.

I. INTRODUCTION

The elastic scattering of electrons from N_2 has been studied extensively by many authors since the early 1930's. Norman,[1] Brüche,[2] Aberth *et al.*,[3] Golden,[4] Bonham and Kennerly,[5] and Blaauw *et al.*[6] have measured the total scattering cross sections. Differential elastic-scattering cross sections (DCS) have been measured by Kollath,[7] Arnot,[8] Bullard and Massey,[9] Mohr and Nicoll,[10] Bromberg,[11] Ehrhardt and Willmann,[12] Kambara and Kuchitsu,[13] Comer and Read,[14] Pavlovic *et al.*,[15] Shyn *et al.*,[16] Truhlar *et al.*,[17] DuBois and Rudd,[18] Jansen *et al.*,[19] Finn and Doering,[20] Herrmann *et al.*,[21] and Srivastava *et al.*[22] Table I shows a summary of these DCS experiments and total cross sections for N_2. Theoretical calculations of the total and elastic-scattering cross sections by various approximations have been carried out by Stier,[23] Fisk,[24] Massey and Bullard,[25] Truhlar,[26] Wedde and Strand,[27] Siegel *et al.*,[28] Chandra and Temkin,[29] and Dubè and Herzenberg.[30] Table II shows a summary of those theoretical studies.

As shown in Table I, the energy ranges for the measurements are divided in two regions; one below 100 eV and the other above 100 eV. Therefore it is desirable to tie together the two regions with a single experiment.

The present paper is an extension of our earlier paper[16] on DCS of N_2. The energy range has been extended down to 1.5 eV and up to 400 eV and the results have been placed on an absolute scale using the elastic cross section of He at 10 eV calculated by LaBahn and Callaway.[31] The angular range covered was from $-96°$ to $+156°$.

The present results cover the two energy regions previously mentioned so that the resonance-scattering processes below 5 eV are compared with the previous measurements and theoretical calculations by various models and additionally the present results can be compared with the well-measured DCS at higher energies. It should be noted, however, that because of the energy resolution of the present experiments (60 meV), rotational excitations have not been discriminated against and the final results may be called vibrationally elastic cross sections.

II. APPARATUS AND PROCEDURES

A detailed description of the apparatus used for the present measurements can be found elsewhere.[16,33,34]

The procedure used for the present measurements was to integrate the signal for 10 s at each angle and each energy electrons elastically scattered from a vertically collimated N_2 beam. The electron beam was rotated in a horizontal plane and the angular range of $-96°$ to $+156°$ was scanned in $12°$ increments. Additional measurements were made at $\pm 6°$ for impact energies greater than 70 eV. The measurements were repeated with the N_2 beam off to obtain the background counts. The signal difference between the neutral beam on and off is the DCS of electrons elastically scattered from the N_2 beam. The signal to background count ratio (the background when the neutral beam is off) was typically in the order of 100 except for large angles (>140°) at high energies (>200 eV).

The volume correction (path length) of the final data due to the background gas density of 2×10^{-5} torr has been made. The signal from the background density has been measured to be $(34\pm 1)\%$ of the total signal at $90°$ after the neutral beam was displaced from the interaction region, and this correction has as uncertainty of $\pm 2\%$ in the final data. As described in detail elsewhere,[16,32]

TABLE I. A summary of DCS and total cross-section measurements on e-N_2.

	Energy (eV)	θ (deg)	Nature of measurement
1. Kollath	1–36	90	absolute
2. Arnot	30–780	10–120	relative
3. Bullard and Massey	7–60	20–130	relative
4. Mohr and Nicoll	50, 84, and 100	30–160	relative
5. Bromberg	300–500	2–110	absolute
6. Ehrhardt and Willmann	1.4–3.9	10–110	relative
7. Kanbara and Kuchitsu	50–500	4–150	relative
8. Comer and Read	11.5	40–85	normalized
9. Pavlovic *et al.*	10–40	30	normalized
10. Shyn *et al.*	5–30	3–160	relative
11. Truhlar *et al.*	20	20–80	normalized
12. DuBois and Rudd	24–800	2–150	absolute
13. Jensen *et al.*	100–3000	5–55	normalized
14. Finn and Doering	13–100	5–90	relative
15. Herrmann *et al.*	90–1000	3–135	normalized
16. Srivastava *et al.*	5–75	20–135	normalized
17. Present paper	1.5–400	6–156	normalized
	Total cross sections E (eV)		
1. Norman	0.5–400		Total, absolute
2. Aberth *et al.*	1.5–25		Total, absolute
3. Brüche	1.5–60		Total, absolute
4. Golden	0.3–5.0		Total, absolute
5. Ehrhardt *et al.*	0.003–30		momentum transfer
6. Blaauw *et al.*	15–750		Total, absolute

it should be noted that the conventional sinθ path-length correction has been applied for the contribution of static gas background and this may cause an uncertainty of the differential cross sections below 12° as Trajmar *et al.*[36] and Vuskovic *et al.*[37] have pointed out. The estimated uncertainties were less than 10% at 6°, 5% at 12°, and 1% at larger angles (the geometry and dimension of the present apparatus resembles that of Vuskovic *et al.* as shown in Fig. 5 in their paper).

It is also noted that the electron monochrometer of the present apparatus has a focusing capability by an electron lens system to keep the interaction volume constant for all incident energies used.

III. EXPERIMENTAL RESULTS

DCS have been obtained at each of 20 impact energies (1.5, 1.9, 2.1, 2.4, 3.0, 4.0, 5.0, 7.0, 10.0, 15.0, 20.0, 30.0, 40.0, 50.0, 70.0, 100.0, 150.0, 200.0, 300.0, and 400.0 eV). Seven runs for energies less than 7 eV and five runs for the rest have been taken and averaged to obtain the final results for each incident energy. The results have been calibrated among the incident energies as follows: The scattered intensities at 36° and 60° have been normalized against the incident intensity of electron beam and the target gas density at each energy without the use of any electron lens

TABLE II. A summary of theoretical studies on e-N_2 scattering.

	E (eV)	Nature of calculation
1. Stier	2–4	Fixed-nuclei model
2. Fisk	0–40	Fixed-nuclei model
3. Massey and Bullard	above 200	Born approximation
4. Truhlar	30–83	Polarized Born approximation
5. Wedde and Strand	40–1000	Phase amplitude
6. Siegel *et al.*	0–30	Multiple scattering
7. Chandra and Temkin	0–5	Hybrid theory
8. L. Dubè and A. Herzenberg	0.5–4.5	Boomerang model

system in the detector in order to ensure a constant transmission of the detector. The transmission has been measured to be constant within ±5% down to 2 eV of electron energy. The signals at the angles (36° and 60°) in the normalization process may contain a component from the vibrational excitations because of the widening of the energy window of the analyzer as an expense of the constant transmission of the detector. However, the contribution is expected to be less than 1% of the elastic signals at the angles as calculated by Onda and Truhlar.[35] The normalized total elastic cross section of N_2 at 10 eV was calibrated against that of He at 10 eV by static gas experiments (volume experiment). The absolute pressures for both gases (He and N_2) were measured by a Bayard-Alpert gauge which was calibrated against a capacitance manometer (MKS Baratron) with an accuracy of ±5%. Thus the relatively normalized results of N_2 have been placed on an absolute scale. The final results are shown in Table III. The total cross section has been obtained after making an exponential extrapolation to 180°. The effect of the extrapolation is negligible due to the

TABLE III. DCS, $d\sigma/d\Omega$ (in units of 10^{-18} cm^2/srt). (The numbers in parenthesis represent extrapolated data points; σ_{el}, σ_{MT} in units of 10^{-16} cm^2.)

θ(deg) \ E (eV)	1.5	1.9	2.1	2.4	3.0	4.0	5.0	7.0	10.0	15.0
6										
12	98.8	275.4	329.3	340.4	298.8	184.2	158.7	210.9	255.2	463.0
18										
24	73.2	213.3	253.3	271.9	262.0	162.9	161.7	202.8	240.1	314.7
30										
36	49.4	151.2	177.3	209.9	212.2	159.4	159.9	191.3	199.1	196.8
48	54.5	106.7	125.4	139.2	155.9	125.7	134.8	169.7	153.5	126.2
60	64.7	94.5	100.1	99.0	108.3	95.1	103.0	129.9	103.2	75.3
72	78.3	101.3	92.5	82.7	77.9	71.4	77.9	88.1	62.7	44.7
84	86.8	104.0	92.5	74.0	66.0	56.1	62.9	67.5	46.9	24.5
96	86.6	99.9	87.4	69.6	61.7	50.2	57.5	55.9	36.1	26.2
108	81.7	94.5	82.3	69.6	68.2	52.5	56.9	59.9	45.0	38.6
120	71.5	90.5	88.7	87.0	79.0	59.6	61.1	71.5	60.3	50.0
132	64.7	121.5	127.9	128.3	115.8	73.8	70.7	82.6	76.4	72.6
144	68.1	190.4	216.6	211.0	174.3	92.1	87.5	101.7	93.7	92.2
156	102.1	278.1	325.5	332.8	237.1	116.9	100.6	110.8	108.0	108.7
168	(140.0)	(363.2)	(402.8)	(463.3)	(300.0)	(141.7)	(113.8)	(120.3)	(121.9)	(125.1)
σ_{el}	9.6	16.7	17.5	17.4	14.8	11.1	11.2	12.5	11.7	11.3
σ_{MT}	10.0	17.1	18.1	16.8	12.6	9.6	9.2	10.8	9.3	8.2

θ(deg) \ E (eV)	20	30	40	50	70	100	150	200	300	400
6					1655.4	1592.6	1429.7	1348.9	1129.1	1063.7
12	674.8	875.8	991.0	1047.5	1102.2	934.3	740.8	629.4	414.8	380.4
18					552.2	429.5	323.8	256.0	152.1	117.3
24	421.1	408.5	403.1	360.1	297.9	212.7	138.3	96.8	57.1	51.6
30					139.2	90.3	64.0	45.6	32.0	31.2
36	216.2	182.6	144.0	105.4	77.8	48.4	33.0	26.9	21.7	20.9
48	117.7	75.6	53.0	38.0	26.7	19.5	16.4	14.6	11.0	9.0
60	63.3	35.1	23.7	17.7	13.3	10.9	10.5	9.6	5.8	4.7
72	33.3	19.1	13.5	10.2	7.4	7.5	7.4	6.0	3.8	3.6
84	19.6	13.3	8.5	6.6	6.3	7.3	5.9	4.5	3.4	2.6
96	22.1	12.4	7.9	6.6	7.5	7.4	5.7	4.1	3.0	2.0
108	34.8	18.4	12.3	11.0	10.8	8.2	6.3	4.3	2.4	1.7
120	52.5	30.8	24.2	21.4	17.6	10.5	7.3	4.8	2.3	1.6
132	70.0	50.6	42.8	35.8	24.5	13.6	8.6	5.2	2.4	1.6
144	93.5	77.6	65.1	51.6	31.7	18.0	9.5	5.2	2.5	1.6
156	121.2	104.2	90.4	67.7	39.2	22.6	10.7	5.1	2.5	1.6
168	(148.8)	(130.9)	(115.8)	(83.7)	(46.6)	(28.1)	(11.8)	(5.1)	(2.5)	(1.6)
σ_{el}	12.1	10.3	9.4	8.5	7.3	5.6	4.5	3.7	2.6	2.3
σ_{MT}	8.3	6.0	4.7	4.1	2.8	1.76	1.17	0.75	0.46	0.35

TABLE IV. Sources of uncertainties in the inter-gas (He-N_2) calibration (measurement of the ratio of elastic total cross section).

1. Uncertainty in the ratio of measured pressure		± 5%
2. Uncertainty in the incident electron beam current		± 2%
3. Uncertainty in data points		± 3%
	Subtotal	±10%

$\sin\theta$ factor in the calculation of the total elastic cross section.

The statistical uncertainty (in standard deviation) in data points is less than ±3% and there is a 6% uncertainty (in standard deviation) in the normalization process among the incident energies. The calibration between He and N_2 contains uncertainties of ±10% as shown in Table IV. There is uncertainty of ±2% in the path-length correction, ±5% uncertainty in transmission of the detector, and ±5% uncertainty in the adopted value of He at 10 eV. Therefore the resultant uncertainty in root mean square for the present results is ±14% except for 6° (17% at 6°).

Figure 1 shows the π_g shape-resonance structure of the elastic scattering from 1.5 to 5.0 eV at 144°. The first peak appears at 1.9 and then at 2.1, 2.4, and 2.6 eV. The energy scale had been determined by the He resonance at 19.35 eV. Figure 2 shows the three dimensional perspective diagram of the DCS over the shape resonance region (1.5–5.0 eV). The DCS had been measured at each resonance peak. This figure shows clearly a transition of DCS from a symmetric scattering with a maximum near 90° at 1.5 eV to a dominant forward scattering at 5.0 eV through a strongly peaked forward and backward scattering (π_g shape resonance near 2.4 eV). The maximum near 90° at 1.5 eV disappears and DCS has a single minimum near 110° at 5.0 eV.

Figure 3 shows DCS at 2.4-eV incident energy along with the measurement of Ehrhardt and Willmann[12] and the theoretical values calculated by Siegel *et al.*[28] and Chandra and Temkin.[29] For comparison, the measurement of Ehrhardt and Willmann was normalized with the present results at 60°. The agreement between the present results and that of Ehrhardt and Willmann[12] is quite good below 60°, but differ for higher values, above 60°, by about 10%. The theoretical results of Chandra and Temkin agree relatively well for values beyond 80°, but below 80° their values are larger than the present results by about 50%. The result of Siegel *et al.*[28] is in agreement in shape except near 90°, but the magnitude is almost twice as great as the present results.

Figure 4 shows DCS at 20 eV together with various measurements and a theoretical calculation by Siegel *et al.* Agreement among the measurements is fairly good except at extreme angles. The re-

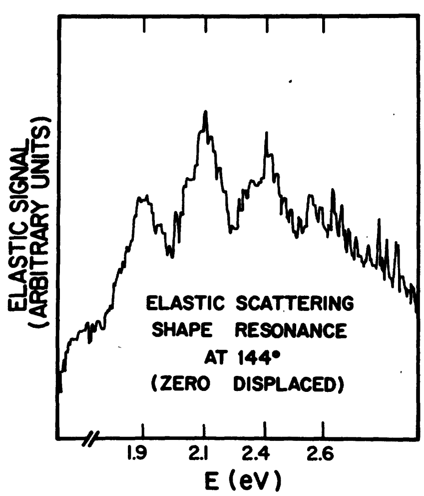

FIG. 1. Energy spectrum 1.5–5.0 eV at 144° (shape resonance).

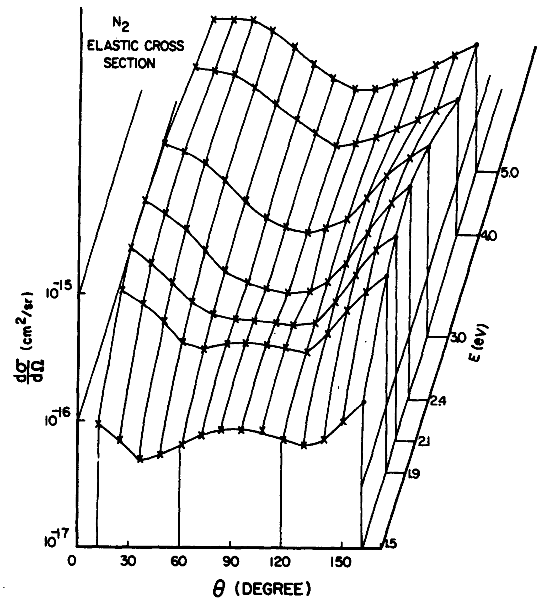

FIG. 2. Three-dimensional perspective diagram near resonance region (1.5–5.0 eV).

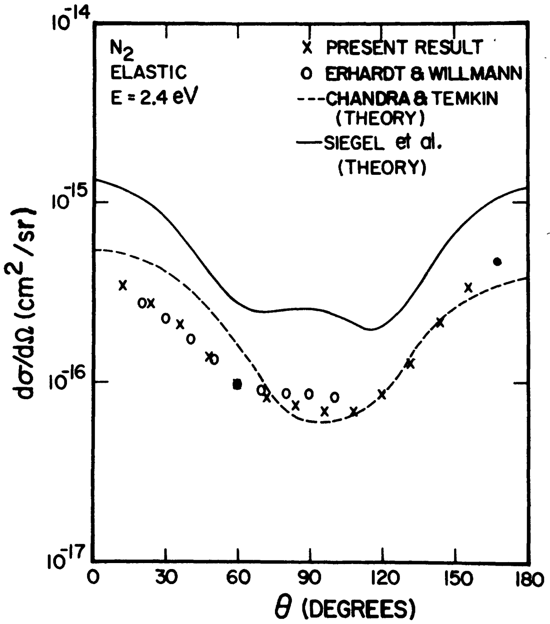

FIG. 3. Angular distribution $d\sigma/d\Omega$ of 2.4-eV electron impact. Dot is an extrapolated point.

sults of DuBois and Rudd[18] show smaller values below 60° and above 140° than the present results by about 10%. The theoretical calculation by Siegel *et al.* is in a fair agreement with the present results except near 90° where the theoretical

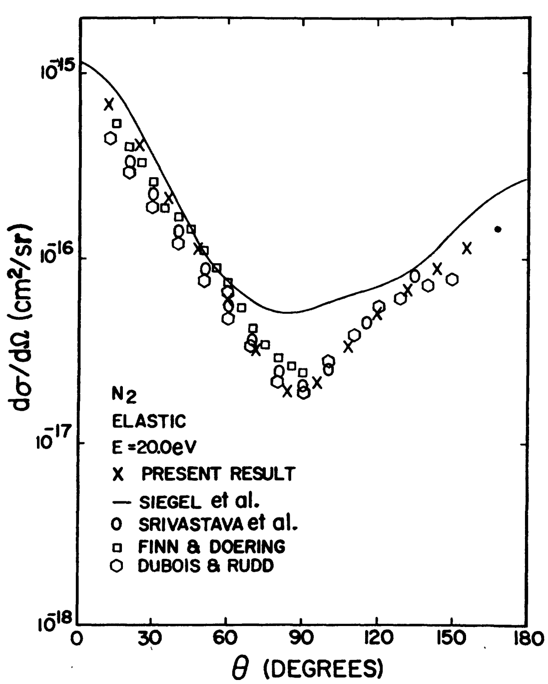

FIG. 4. Angular distribution $d\sigma/d\Omega$ of 20.0-eV electron impact. Dot is an extrapolated point.

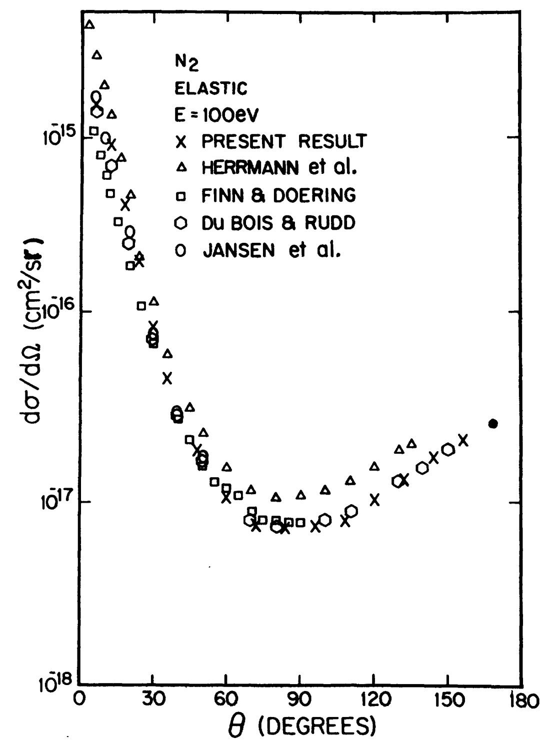

FIG. 5. Angular distribution $d\sigma/d\Omega$ of 100-eV electron impact. Dot is an extrapolated point.

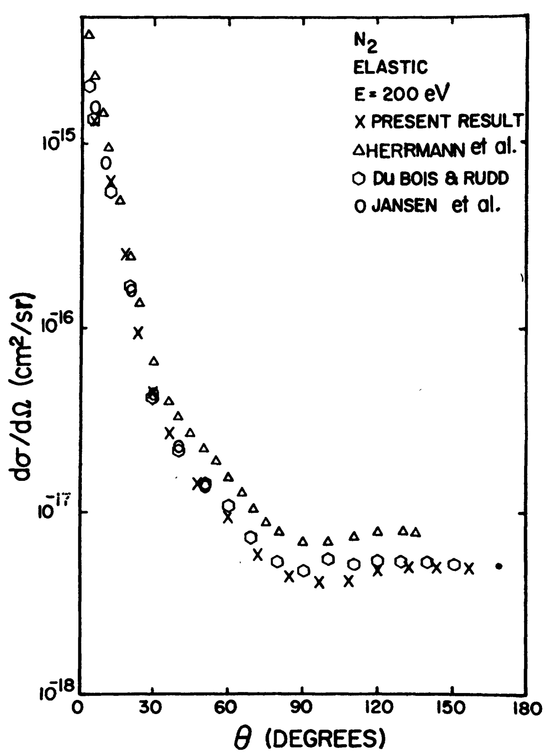

FIG. 6. Angular distribution $d\sigma/d\Omega$ of 200-eV electron impact. Dot is an extrapolated point.

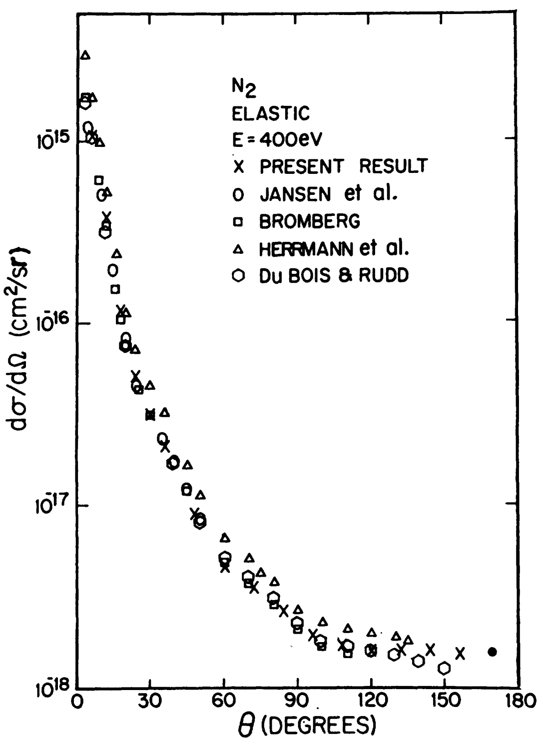

FIG. 7. Angular distribution $d\sigma/d\Omega$ of 400-eV electron impact. Dot is an extrapolated point.

values are larger by more than 50%.

Figures 5–7 show the measured DCS at 100, 200, and 400 eV, respectively. Other measurements are plotted for comparison. In general, the results of Jansen *et al.*[19] and DuBois and Rudd[18]

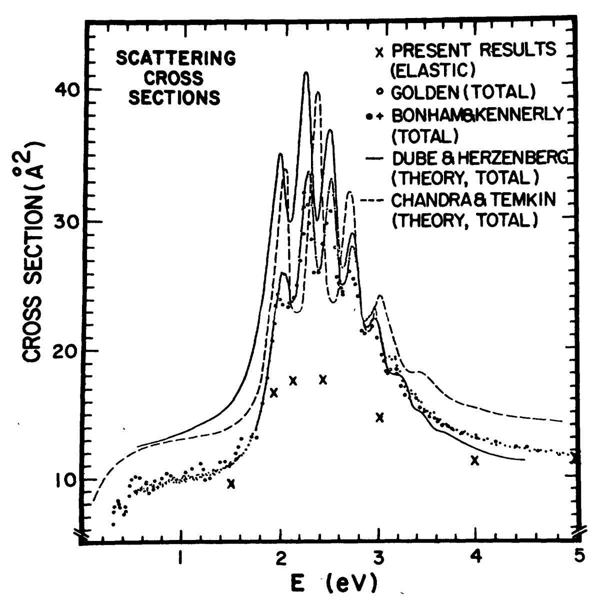

FIG. 8. Elastic cross section near π_g shape-resonance region.

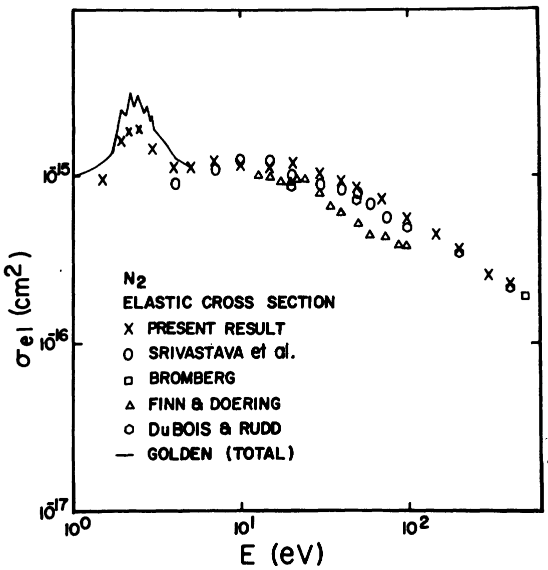

FIG. 9. Elastic-scattering cross section $\sigma_{el}(E)$.

agree well with the present results; the results of Herrmann *et al.*[21] agree with the present results in shape, but their results are larger than the present results by about 40%. The results of Finn and Doering[20] at 100 eV agree with the present results except for small angles (<30°). Bromberg's results at 400 eV agree very well with the present results.

Figure 8 shows the integrated elastic cross section over angles, along with the two measurements for the total cross section and two theoretical calculations for the total cross sections near the π_g shape-resonance region. The theoretical values are generally much larger than those measured values. Since the magnitude of the measured total cross sections is almost twice that of the present results, which is near the resonance region for elastic scattering, the inelastic excitation cross sections, mainly vibrational excitations, should have the same order of magnitude as those of the elastic-scattering cross sections. It thus appears very desirable to measure independently the total vibrational-excitation cross sections near the π_g resonance region.

Finally, Fig. 9 shows the integrated elastic cross section along with other previous measurements. The results of Srivastava *et al.*[22] have the best agreement with the present results, and the results of DuBois and Rudd[18] agree very well with the present results above 100 eV. Finn and Doering's results have smaller values than the present results by as much as 50%. The results of Bromberg at 500 eV is in apparent agreement with the present results (after a 4π factor correction of Bromberg's original result).

IV. SUMMARY

This paper presents the angular distribution of electrons elastically scattered from N_2 in the energy range 1.5–400 eV with angular range from $-96°$ to $+156°$. The elastic-scattering cross sections (20 incident energies) have been placed on an absolute scale by normalizing with He elastic cross section at 10 eV. The angular distributions were also used to determine the momentum-transfer cross sections. The resultant uncertainty of the present results is believed to be less than ±14% in standard deviation.

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