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Angular distribution of electrons elastically scattered from gases: 2–400 eV on He. I

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The angular distribution of electrons elastically scattered from He has been measured by electron impact utilizing a crossed-beam method. The energy and angular range measured were from 2.0 to 400 eV and from −96° to +156°, respectively. The present results have been normalized to LaBahn and Callaway's theoretical value at 10.0 eV. The present results agree, in general, with a few previous measurements; however, there are still discrepancies in a detailed shape and magnitude among the measurements. The various theories need more improvements, especially for the backward scattering. It is found that the Born approximation is not yet adequate at 400-eV incident energy.

I. INTRODUCTION

The elastic-scattering cross sections of helium by electron impact have been studied most extensively by many authors because of the fundamental nature in atomic physics and experimental feasibility. Theoretically, Mott[1] and Kim and Inokuti[2] had calculated the scattering cross sections by the Born approximation. Recently, Khare and Moiseiwitsch,[3] LaBahn and Callaway,[4] McCarthy *et al.*,[5] Byron and Joachain,[6] Winters *et al.*,[7] Dewangan and Walters,[8] Gien,[9] and Nesbet[10] have calculated the cross sections by various improved methods. Table I summarizes the theoretical studies of He by electron impact. Experimentally, many measurements have been made since the early 1930's. Brüche,[11] Ramsauer,[12] Golden and Bandel,[13] Kennerly and Bonham,[14] and Stein *et al.*[15] measured total cross sections.

For the measurements of differential cross sections (DCS), Bullard and Massey[16] and Hughes *et al.*[17] measured relative DCS in the early 1930's. Recently there has been renewed interest in the elastic cross sections of He; a number of investigations have been reported in two groups in terms of the energy range used, in general, i.e., the energy ranges below 100 eV and above 100 eV as shown in Table II along with total cross section measurements.

Below 100 eV, Gibson and Dolder[18] have measured a normalized DCS with a relatively small energy range from 3.1 to 19.1 eV and 25°–145° in the angular range which lacks information in the forward direction. Andrick and Bitsch[19] measured an absolute DCS with almost the same energy and angular range as Gibson and Dolder.[18] McConkey and Preston,[20] and Srivastava and Trajmar[21] have measured a normalized DCS below 100 eV with a very limited angular range, i.e., McConkey and Preston[20] [forward angles (20°–90°)] and Srivastava and Trajmar[21] [mostly backward angles (50°–135°)]. Also even in the region overlap, these measurements do not agree with each other, in some cases by as much as 50%.

Above 100-eV electron energy, Kurepa and Vuskovic[22] have measured the absolute DCS of 100–200-eV electron energy with the largest angular range (5°–150°). Vrien *et al.*,[23] Jansen *et al.*,[24] and Bromberg[25] have measured the DCS in the forward angular range. Sethuraman *et al.*[26] measured the normalized DCS in the energy range of 100–500 eV with the angular range 30°–150°,

TABLE I. Summary of the theoretical studies for He (elastic).

Authors	Model	Energy range (eV)
1. Mott	Born approximation	
2. Kim and Inokuti	Born approximation	
3. Khare and Moiseiwitsch	Static + exchange + polarization	25–700
4. LaBahn and Callaway	Extended polarization potential	1–500
5. Jhanwar and Khare	Buckingham-type polarization	200–500
6. McCarthy *et al.*	Local complex potential	20–3000
7. Gien	Modified Glauber	100–500
8. Byron and Joachain	Eikonal Born-series method	100–400
9. Winters *et al.*	Second-order potential approximation	50–500
10. Dewangan and Walters	Distorted-wave second Born approximation	100–3000
11. Nesbet	Variational calculation	1.7–18.4

TABLE II. The current status of the DCS and total cross section measurements for He by electron impact.

Authors	E (eV)	θ (degrees)	Nature of measurements
1. Bullard and Massey	4–50	20–120	Elastic, relative
2. Gibson and Dolder	3.1–19.1	25–145	Elastic, normalized
3. Andrick and Bitsch	2–19	15–145	Elastic, absolute
4. McConkey and Preston	1.5–100	20–90	Elastic, normalized
5. Srivastava and Trajmar	5.0–75	60–135	Elastic, normalized
6. Kurepa and Vuskovic	100–200	5–150	Elastic, absolute
7. Vrien *et al.*	100–400	5–30	Elastic, normalized
8. Sethuraman *et al.*	100–500	30–150	Elastic, normalized
9. Bromberg	200–700	2–30	Elastic, absolute
10. Jansen *et al.*	100–3000	5–55	Elastic, normalized
11. Hughes *et al.*	25–700	15–150	Elastic, relative
12. Present result	2.0–400	6–156	Elastic, normalized
13. Brüche	1.3–25		Total, absolute
14. Ramsauer	0.75–21		Total, absolute
15. Golden and Bandel	0.3–28		Total, absolute
16. Kennerly and Bonham	1.0–50		Total, absolute
17. Stein *et al.*	2.0–30		Total, absolute

which missed very important information about the strong forward peak. As pointed by Sethuraman *et al.*,[26] there is good agreement within an experimental uncertainty among the measurements above 300 eV, but below 300 eV there are two groups who do not agree with each other below 30° by as much as 40%.

Vrien *et al.*,[23] Jansen and DeHeer,[27] and Crooke and Rudd[28] have higher values than the other groups, which are Sethuraman *et al.*,[26] McConkey and Preston, and Vrien *et al.* (renormalized). It is thus clearly desirable to have a extensive measurement with a wide range of energy and angle to resolve the discrepancies among the existing measurements and, in addition, it can serve as reference data for other gases.

This paper presents an extensive experimental result from which the DCS of electrons elastically scattered from He by electron impact have been measured. A crossed-beam method was used. The angular and energy range measured were from 2.0 to 400 eV and from −96° to +156°, respectively. The present results have been normalized among themselves and have been placed on an absolute scale using theoretical values of total elastic cross sections at 10 eV calculated by LaBahn and Callaway.[4]

II. APPARATUS AND PROCEDURE

The apparatus used for the present measurements was the same as that used for the measurements[29-31] of electron-impact cross sections. A detailed description can be found in the above works. A brief description of the apparatus follows: a rotatable electron beam of 0.06 eV in energy half-width in a horizontal plane interacts with a vertically collimated neutral beam at 90°. The scattered electrons from the neutral beam were detected by a channeltron electron multiplier after energy analysis. Typically the electron beam current was 10^{-9} A.

The vacuum enclosure was pumped by a turbomolecular pump (pumping speed, 1500 s^{-1}) backed by a mechanical forepump and a background pressure of 10^{-8} torr was achieved without baking the system.

The magnetic fields have been reduced by three sets of Helmholz coils to less than 20 mG in all directions. The absolute energy scale was determined frequently to within 0.05 eV using the resonance at 19.35 eV.

The procedure used for the present measurements was as follows: the collimated beam of He was turned on at the background pressure of 10^{-4} torr and the signal count was integrated for 10 s for each angle from −96° to +156° in 12° increments for an incident energy. In addition, measurements were also made at ±6° for high impact energies (>70 eV). The measurements were repeated with the He beam off to obtain the background count. The difference between the two signals is the DCS electrons elastically scattered from the He beam. With the neutral He beam on, the density in the interaction region where the electron and neutral beam met was approximately three times larger than the overall background density. The ratio of the two signals (when the neutral beam is on and off) was typically in the order of 100 except for large angles (>120°) at high incident energies (>200 eV).

Since the half-width of electron beam (±2°) in the present apparatus is inside of the half-width of the collimated neutral beam, and the half-width of the neutral beam is well inside of the field of view of the detector system (±4°) as shown in Ref. 29, the angular dependence of the effective path length can be expressed, as a simple linear superposition of a static gas experiment and a pure beam experiment, by

$$1 - \sin\theta/(A + \sin\theta) \text{ for } 10° < \theta < 170°,$$

where A is the signal ratio of the volume scattered component to the component of a pure beam at 90°. In order to obtain the value A for the present experiment, the signal strength at 90° has been measured maintaining the same background pressure as the beam experiment after the neutral beam was displaced from the interaction region. The value A obtained from the measurement was 0.61 ± 0.02, which has an uncertainty of ±2% in the final result. It is noted, however, that a conventional $\sin\theta$ correction for the interaction volume for the background gas has been used. This may introduce an uncertainty in the differential cross section below 12° due to the departure from the $\sin\theta$ correction as Trajmar *et al.*[32] and Vuskovic *et al.*[33] have indicated. The uncertainties were estimated to be less than 10% at 6°, 5% at 12°, and 1% at larger angles (the geometry and dimension of the present apparatus resemble the example that Vuskovic *et al.* calculated and showed in Fig. 5 of their paper).

It is also noted that the electron monochrometer has a focusing capability on the electron beam by an electron lens system to ensure the constant geometry of the interaction volume against the incident energies as indicated in Ref. 31.

At the background pressure of 10^{-4} torr when the neutral beam is on, the attenuation of scattered electrons from the interaction region to the detector has been calculated to be a maximum of 2% at 2.0 eV and smaller at higher energies. This will be included as a systematic uncertainty in the error analysis.

III. EXPERIMENTAL RESULTS

The DCS of electrons elastically scattered from He has been measured for 15 incident energies (2.0, 3.0, 5.0, 10.0, 15.0, 20.0, 30.0, 40.0, 50.0, 70.0, 100, 150, 200, 300, and 400 eV). The angular range measured was from −96° to +156°.

Five sets of data which had been taken for each incident energy have been taken and averaged to produce final results. The results have been calibrated among the incident energies as follows: The scattered intensities at 36° and 60° were calibrated with respect to the incident intensity and the target density at each energy without the use of any electron lens system in the detector in order to ensure a constant transmission against energy. The transmission of the detector system has been measured to be constant within 5%, down to an electron energy of 2 eV. The intensity of the well-collimated incident electron beam was measured by two Faraday cups which have measured the saturated current. Six sets of the relative calibration were taken to produce a final relative result. The results have been placed on an absolute scale using the theoretical value at 10 eV calculated by LaBahn and Callaway.[4] The reason to choose the theoretical value is that the theoretical angular distribution agrees best with that of the present result at 10 eV. Also the adopted value of total cross section agrees well, within 3%, with that of recent calculations by Nesbet[10] and the value measured by Kennerly and Bonham.[14] The results of angular distributions, total elastic cross sections, and momentum-transfer cross sections are shown in Table III. The total elastic cross sections have been obtained after making an exponential extrapolation to 0° and 180° in the angular distribution. The extrapolation procedure gives almost negligible effects (<1%) in the total cross section because of the $\sin\theta$ factor.

The statistical uncertainty (in standard deviation) in data points for low incident energies (<100 eV) is less than 2% and less than 4% for higher energies (>150 eV) at large angles (>90°). A 5% uncertainty exists in the calibration among the incident energies. There is an estimated 2% uncertainty in the volume correction except for 6° and 12°, and a 2% uncertainty in the attenuation factor. The transmission of the electrons through the detector system has been measured to be constant within 5% and the uncertainty of LaBahn and Callaway's theoretical value is ±5%. The resultant uncertainty (rms) for the present results is thus less than 10% except for 6° and 12° (14% at 6° and 11% at 12°).

Figure 1 shows a DCS of electrons elastically scattered from He at 2.0 eV along with the results of theoretical calculations by LaBahn and Callaway[4] and Nesbet,[10] and measurements of Andrick and Bitsch.[19] The present results show a good symmetry about zero angle which indicates negligible effects from stray electric and magnetic fields. The DCS has a pronounced backward scattering. This trend holds up to the incident energy of 5.0 eV. Agreement of the present results with the theoretical calculation by LaBahn and Callaway[4] is very good except for large angles (>145°),

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

θ (deg) \ E (eV)	2.0	3.0	5.0	10.0	15.0	20.0	30.0	50.0	70.0	100	150	200	300	400
6									92.1	68.3	60.6	49.5	32.0	27.5
12	22.4	23.0	29.2	38.9	54.6	68.8	79.1	75.1	72.6	47.1	40.7	32.7	20.3	17.3
18						59.0	68.4	58.5	53.3	35.1	27.1	23.1	12.6	10.1
24	26.2	25.6	28.3	33.6	45.4	53.6	57.5	46.6	41.2	27.2	18.2	14.0	7.9	6.1
30						41.0	47.3	35.6	31.0	18.6	12.2	10.0	5.0	3.5
36	30.1	28.5	27.8	30.8	36.7	40.3	39.4	28.3	23.1	14.0	8.5	6.2	3.3	2.1
48	32.7	30.7	28.4	27.6	29.3	30.4	26.7	17.6	13.6	7.8	4.3	3.0	1.5	0.92
60	35.6	32.2	29.8	26.6	23.3	23.8	18.8	11.5	8.6	4.8	2.4	1.6	0.79	0.47
72	38.0	37.0	32.4	26.4	21.3	19.6	13.9	8.3	5.9	3.0	1.4	0.94	0.50	0.24
84	41.8	41.3	35.5	27.1	21.8	17.7	11.8	6.4	4.4	2.1	1.05	0.63	0.33	0.15
96	45.1	45.8	40.3	29.5	22.0	17.1	10.8	5.4	3.5	1.7	0.73	0.44	0.24	0.10
108	50.3	52.2	45.0	33.8	24.5	17.5	10.8	4.9	3.0	1.4	0.57	0.33	0.18	0.070
120	56.2	57.7	51.6	38.4	27.8	19.0	11.1	4.9	2.8	1.3	0.47	0.28	0.16	0.055
132	63.5	62.1	57.2	43.7	31.0	20.2	12.2	4.9	2.7	1.1	0.44	0.25	0.14	0.054
144	66.1	66.5	59.5	48.8	34.8	21.5	12.9	5.3	2.8	1.2	0.41	0.24	0.12	0.047
156	69.7	68.4	68.8	53.9	38.5	22.8	13.9	5.6	2.9	1.2	0.41	0.23	0.11	0.047
168	(74.9)	(73.5)	(73.0)	(58.1)	(43.5)	(24.5)	(15.4)	(6.1)	(3.0)	(1.2)	(0.40)	(0.22)	(0.10)	(0.046)
σ_{el}	5.75	5.69	5.26	4.28	3.59	3.04	2.37	1.46	1.08	0.66	0.41	0.30	0.17	0.12
σ_{MT}	6.74	6.71	6.12	4.78	3.58	2.56	1.68	0.82	0.53	0.26	0.12	0.08	0.044	0.022

where the theoretical value is smaller than the present results by about 10%. The experimental results by Andrick and Bitsch[19] and Nesbet's theoretical values agree very well in shape but are larger in magnitude by 10% than the present results.

Figure 2 shows DCS for 10 eV along with other experimental and theoretical results by LaBahn and Callaway.[4] A pronounced forward scattering appeared in addition to the backward scattering and the angular distribution has a minimum near 60°. As the energy increases the forward scattering becomes stronger and the backward scattering reduces. Also the minimum point in DCS moves toward a larger angle as the energy increases. Agreement of the present results with the theoretical calculation is excellent in the forward direction, but the theoretical calculation shows larger values near 90° (about 8%) and smaller values in extreme angles (>145°) by 10% than the present results. Measurements by McConkey and Preston[20] (9.1 eV) are in good

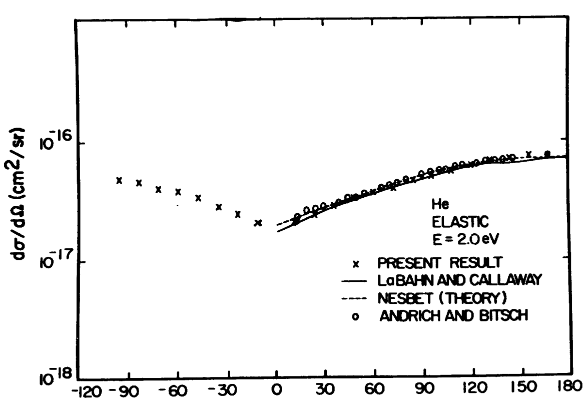

FIG. 1. Angular distribution per solid angle $d\sigma/d\Omega$ of 2.0-eV electron impact. Dot is an extrapolated point.

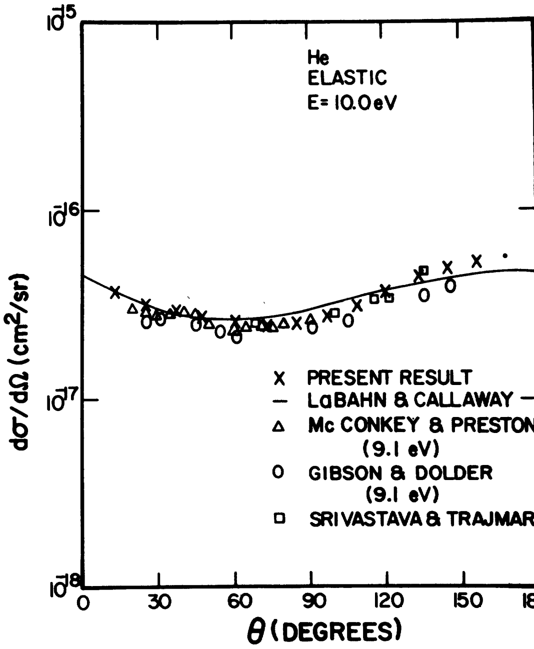

FIG. 2. Angular distribution $d\sigma/d\Omega$ of 10.0-eV electron impact. Dot is an extrapolated point.

agreement with the present results except for small angles (<24°). Gibson and Dolder's measurements[18] are in relatively good agreement with the present results except for extreme angles. The experimental results of Srivastava and Trajmar[21] have larger values than the present results as the angle increased.

Figure 3 shows the DCS for 50 eV impact along with LaBahn and Callaway's theoretical results and other experimental measurements. The theoretical results have smaller values at small angles (<60°) and large angles (>140°) and larger values near 90° than the present results. This trend is generally true for the incident energy larger than 10 eV. Measurements of McConkey and Preston[20] and that of Srivastava and Trajmar[21] are in good agreement with the present results in the angular range from 45° to 105°; but there are smaller values at small angles (<45°) by McConkey and Preston and larger values at large angles in the measurements by Srivastava and Trajmar (>105°) than the present results.

Figure 4 shows the DCS for 100-eV impact along with various theoretical calculations and other experimental results. The DCS shows a dominant forward scattering without a minimum point. The optical model calculation by McCarthy *et al.*[5] has the best agreement with the present results in the forward direction; however, they cannot produce a high backward scattering. The first Born approximation has a very low forward scattering compared to the experimental results. Byron and Joachain's[6] calculation gives higher forward scattering and lower values in the backward scattering than the present results. The experimental results of Jansen *et al.*[24] and Sethuraman *et al.*[25] agree well with the present results in shape, but not in magnitude. Their values are lower than the present results. The results of McConkey and Preston[20] do not agree with the present results in shape as well as in magnitude. Their values are lower than the present results by 65% near 90°. The result of Chamberlain *et al.*[32] at 5° agrees with the present results within the experimental uncertainty.

Figure 5 shows the DCS of 400-eV electron impact along with the theoretical and other experimental results. In the angular range from 60° to 120°, the results of the Born approximation and optical model by McCarthy *et al.*[5] agree very well with the present results. But the Born approximation gives still smaller values and the optical model predicts larger values than the present results for small angles (<60°), and both theories give smaller values for large angles (>120°). The present results agree very well with the results of Bromberg,[25] Jansen *et al.*,[24] and Chamberlain *et al.*[32] within the experimental uncertainty.

Finally, Fig. 6 shows the total elastic-scattering cross sections along with other experimental results and theoretical values. The theoretical

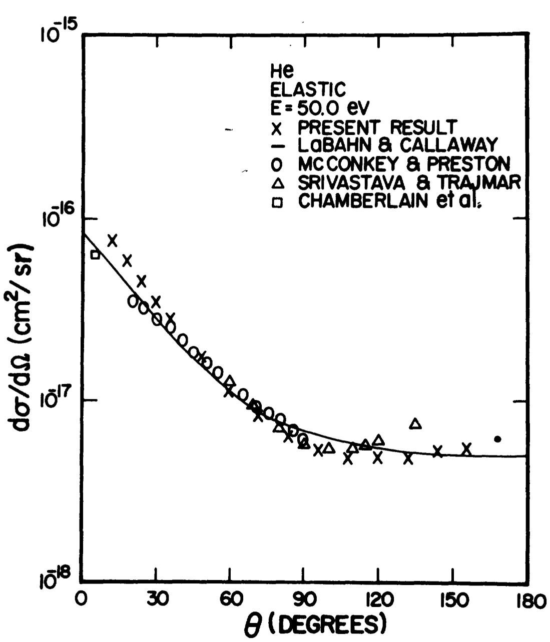

FIG. 3. Angular distribution $d\sigma/d\Omega$ of 50-eV electron impact. Dot is an extrapolated point.

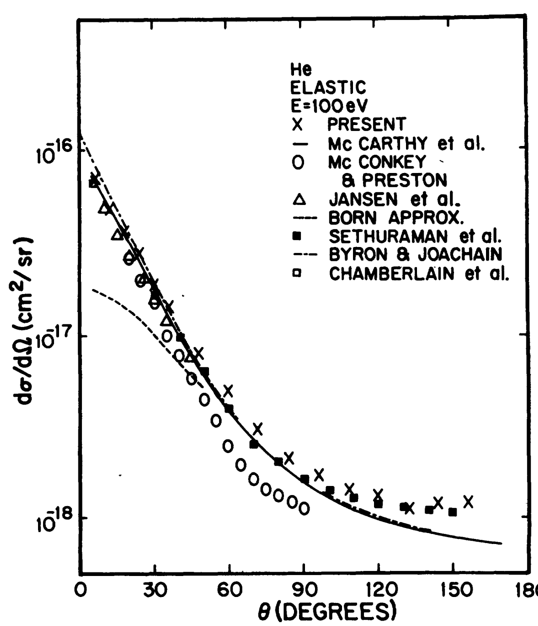

FIG. 4. Angular distribution $d\sigma/d\Omega$ of 100-eV electron impact. Dot is an extrapolated point.

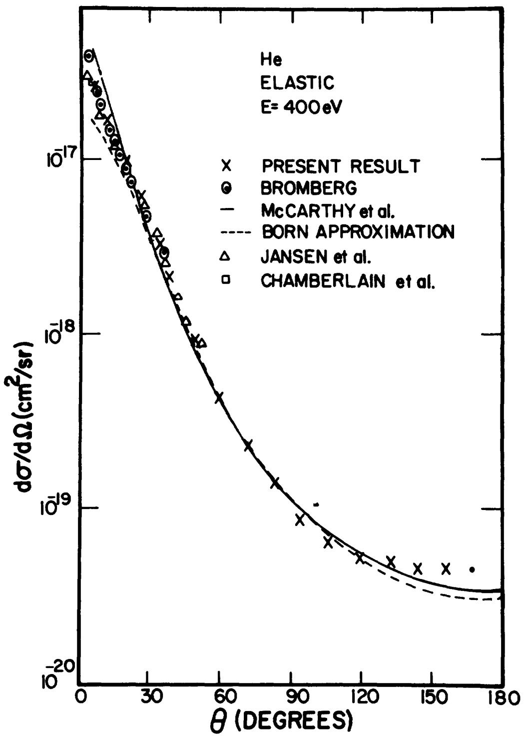

FIG. 5. Angular distribution $d\sigma/d\Omega$ of 400-eV electron impact. Dot is an extrapolated point.

calculation by LaBahn and Callaway[4] agrees very well with the present results below 20 eV and above 300 eV, but not between 20 and 300 eV. Theoretical values calculated by Winters *et al.*[7] agree very well with the present results (50–500 eV). Also, the values of Byron and Joachain's[6] calculation by the eikonal Born-series method agree very well with the present results (100–400 eV). The first Born approximation gives smaller values than the present results. However, it is interesting to note that the value of the Born approximation approaches the experimental values

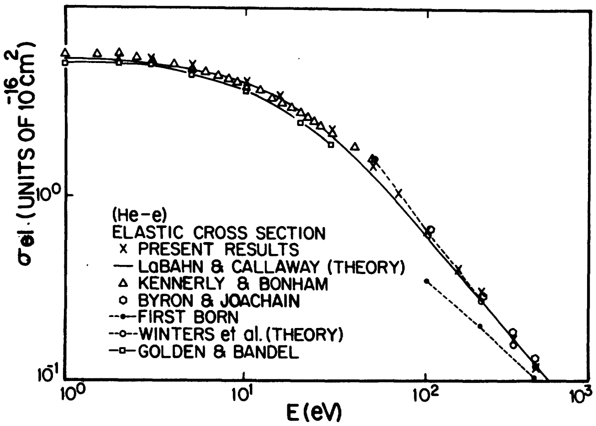

FIG. 6. Elastic-scattering cross section $\sigma_{el}(E)$.

as the incident energy increases. The Born approximation is not good enough yet at 400-eV incident energy. The values of Golden and Bandel's[13] measurements by an improved Ramsauer[12] method are smaller than the present results by approximately 15%. Agreement between the present results and those of Kennerly and Bonham[14] is excellent except at 50 eV, where their value is larger than the present results by approximately 14%.

IV. SUMMARY

This paper presents the angular distribution of electrons elastically scattered from He by electron impact. The energy and angular range measured were from 2.0 to 400 eV and from −96° to +156°, respectively. The present results have been placed on an absolute scale utilizing the theoretical value at 10.0 eV calculated by LaBahn and Callaway.[4] The angular distributions were used to determine total elastic-scattering cross sections and the momentum-transfer cross sections. The resultant uncertainty of the present results is ±10%.

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