# Elastic electron scattering from neon at backward angles

H. Cho*
*Physics Department, Chungnam National University, Daejeon 305-764, Korea*

R. P. McEachran and S. J. Buckman
*Atomic and Molecular Physics Laboratories, Research School of Physical Sciences and Engineering, Australian National University, Canberra, Australian Capital Territory 0200, Australia*

H. Tanaka
*Department of Physics, Sophia University, Chiyoda-ku, Tokyo, Japan*
(Received 4 June 2008; published 11 September 2008)

We present experimental and theoretical differential cross sections for the elastic scattering of electrons from neon at four incident electron energies from 5 to 50 eV. The magnetic angle-changing device has been used to extend the present measurements from mid-angles to backward angles up to 180°. The results reveal some small differences between experiment and theory at backward angles in some cases; however, the agreement at 5 and 50 eV is excellent.

DOI: 10.1103/PhysRevA.78.034702 PACS number(s): 34.80.Bm

## I. INTRODUCTION

There have been many experimental investigations of electron-neon scattering. Focusing on only those which are relevant to the present study, the results of Register and Trajmar [1] cover elastic differential cross sections (DCSs) for 11 incident electron energies from 5 to 100 eV and for scattering angles in the range of 10°–145°. Shi and Burrow [2] measured the DCS in the very low-energy region of 0.25–7.0 eV for scattering angles from 30° to 120°. Gulley *et al.* [3] also did measurements in the low-energy range from 0.1 to 7.0 eV and for angles up to 130°.

Zubek and co-workers [4] reported measurements that are more relevant to this experiment. They measured the elastic DCS for neon at the two electron energies of 5 and 7 eV from 130° to 180° using an angle-changing device, which is basically the same as the device we used in this experiment. However, their DCSs increased rapidly toward backward angles at both incident energies, a trend that was unexpected. Later, in 2006, the same group reported a new set of DCSs at 7, 10, and 15 eV for the backward angles [5]. In this new result at 7 eV, the previous increase at backward angles was no longer observed, and, consequently, the puzzle was partially resolved. However, the puzzle at 5 eV still persists and this was, in part, a direct motivation for the present study.

On the theoretical side, there have also been many studies, the most successful of which are those of Fon and Berrington [6], McEachran and Stauffer [7], and Saha [8]. An extensive review of all previous theoretical work on neon is provided in Ref. [5].

In this paper, we present absolute measurements as well as theoretical calculations of the differential cross section for elastic scattering from neon at four incident electron energies from 5 to 50 V and for scattering angles from mid-angles (90°, 100°, or 120°) to 180°. This will be the final in a series of reports on the elastic DCSs of the rare gases, which have been published over the last several years [9–11].

## II. EXPERIMENT

Since the experimental study is focused on measuring the DCS at backward angles up to 180°, where cross-section measurements are typically inaccessible due to the mechanical constraints of the electron spectrometer, a version of the magnetic angle-changing device developed by Read and Channing [12] has been used with a conventional electron spectrometer. The electron spectrometer used in the present experiment is described in detail elsewhere [13,14]. Relative measurements of the angular distribution are placed on an absolute scale by the use of the relative flow technique, which relies on measurements of the ratio of scattered electron intensities for the gas of interest relative to that for a standard gas, in our case helium. In using this technique, the

TABLE I. Differential cross sections for elastic electron scattering (in units of $10^{-16}$ cm$^2$ sr$^{-1}$) from neon. Figures in parentheses indicate estimated percentage uncertainties.

| Angle (deg) | Energy (eV) 5 | 10 | 20 | 50 |
|---|---|---|---|---|
| 90 | | | | 0.050 (15) |
| 100 | | | 0.136 (12) | 0.014 (17) |
| 110 | | | 0.085 (13) | 0.014 (15) |
| 120 | 0.120 (15) | 0.082 (14) | 0.073 (16) | 0.080 (13) |
| 130 | 0.087 (16) | 0.073 (14) | 0.107 (15) | 0.196 (15) |
| 140 | 0.066 (16) | 0.076 (13) | 0.191 (14) | 0.311 (14) |
| 150 | 0.055 (15) | 0.093 (14) | 0.242 (14) | 0.449 (14) |
| 160 | 0.051 (15) | 0.109 (15) | 0.325 (12) | 0.559 (13) |
| 170 | 0.049 (16) | 0.121 (13) | 0.397 (13) | 0.653 (12) |
| 180 | 0.047 (17) | 0.126 (13) | 0.432 (12) | 0.770 (10) |

*Corresponding author. FAX: +82 42 823 0919. hcho@cnu.ac.kr

 

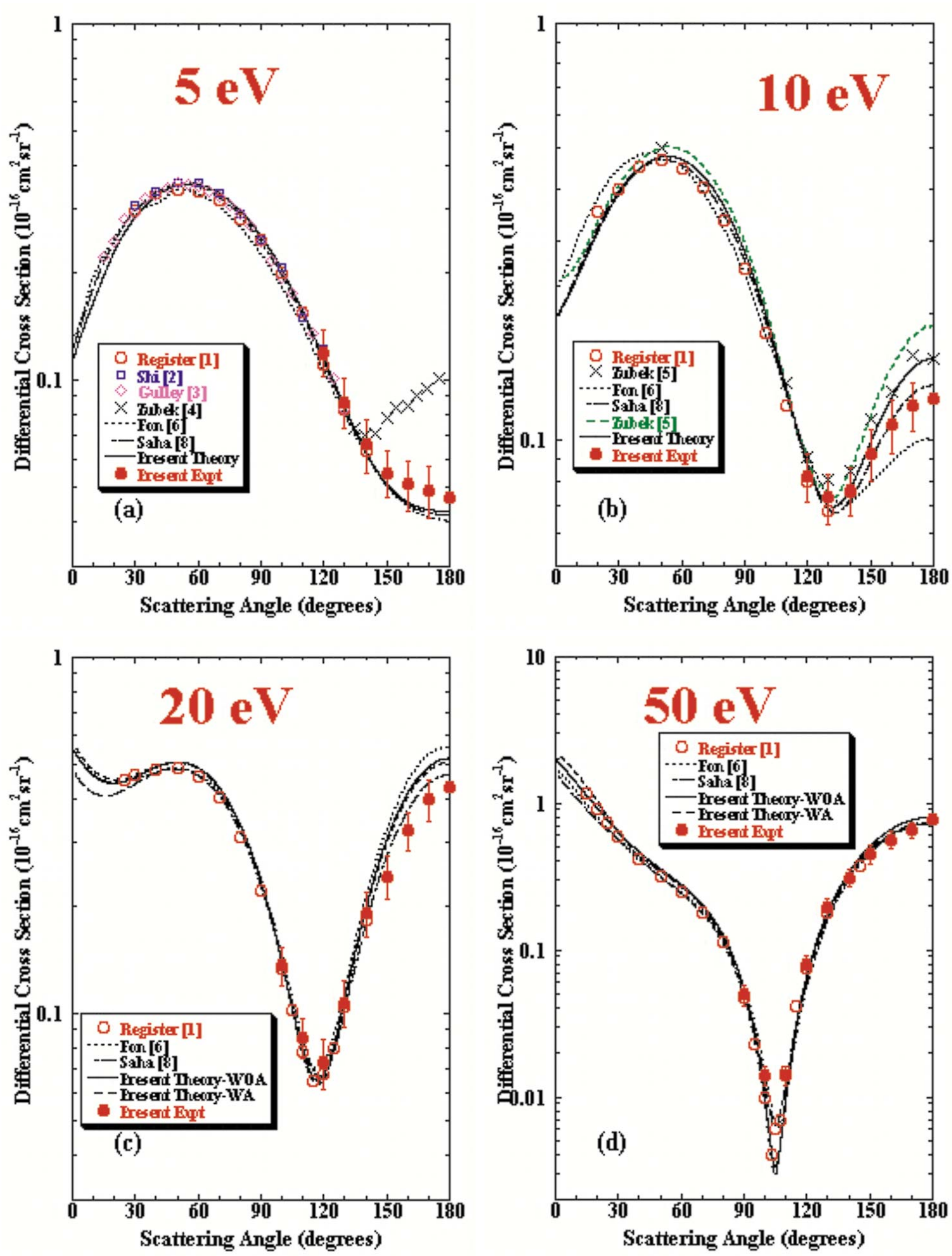


FIG. 1. (Color online) Absolute differential cross section for elastic electron scattering from neon at (a) 5, (b) 10, (c) 20, and (d) 50 eV.

ratio of the driving pressures is determined from values of the molecular diameters of helium and neon of $2.18\times10^{-8}$ and $2.59\times10^{-8}$ cm, respectively [15]. For the present angular differential measurements, we have used the recommended helium elastic differential cross sections of Boesten and Tanaka [16]. The electron energy was calibrated with respect to the 19.37 eV resonance in He and with respect to the $^2\Pi_g$ resonance of $N_2$. The experimental uncertainties in the present DCS measurements vary typically from 10% to 17%. Conservative estimates of the uncertainties in the integral (ICS) and momentum transfer cross sections (MTCS) are around 25%, but vary slightly depending on the uncertainties in the DCS.

### III. THEORY

The theoretical approach used here is a relativistic extension of the previous nonrelativistic work on neon by McEachran and Stauffer [7,17] which also includes, when appropriate, a relativistic and nonlocal *ab initio* absorption potential [18]. The determination of this absorption potential is based upon a close-coupling ansatz in which the total wave function is expanded in terms of a summation and integration over products of scattering wave functions and atomic bound as well as continuum wave functions. In the elastic or ground state channel, all the potential and exchange terms are retained except for the exchange terms with the excited states. On the other hand, in the excited state channels, only the coupling potentials with the ground state are kept. In this manner, it is then possible to formally solve the differential equations for the scattering wave functions in the excited state channels in terms of complex Green's functions. These scattering wave functions are then substituted into the coupling potentials in the ground state channel to form a complex optical potential. The real part of this poten-

TABLE II. Elastic integral (ICSs) and elastic momentum transfer cross sections (MTCSs), respectively, in units of $10^{-16}$ cm$^2$ for neon. The estimated uncertainty on the integral and the momentum transfer cross sections is $\pm 25\%$. "Expt." means present experiment, and "Theory WA" and "Theory WOA" indicate present theory calculated with and without absorption effects included, respectively.

| | ICS | | | MTCS | | |
|---|---|---|---|---|---|---|
| Energy (eV) | Expt | Theory WOA | Theory WA | Expt | Theory WOA | Theory WA |
| 5 | 2.72 | 2.74 | | 2.04 | 2.06 | |
| 10 | 3.24 | 3.37 | | 2.26 | 2.41 | |
| 20 | 3.57 | 3.76 | 3.74 | 2.71 | 2.95 | 2.91 |
| 50 | 3.17 | 3.43 | 3.27 | 2.57 | 2.79 | 2.53 |

tial describes the polarization interaction while the imaginary part simulates inelastic absorption processes. The Dirac-Fock scattering equations for the ground state channel can then be solved for the scattering phase shifts.

In practice, it is often found that the real part of the optical potential does not adequately describe the polarization interaction [19,20]. It is then better to replace the real part of the optical potential by a local polarization potential. We have followed this procedure here and used a dipole polarization potential which was scaled to yield the best experimental value for the dipole polarizability $\alpha_d=2.6690$ [21]; see Ref. [7] for details.

Although neon is a very light atom, the excited bound and continuum states of neon, which are used in this absorption potential, are best described in terms of intermediate coupling for which a relativistic *j*-*j* coupling scheme is the most appropriate approach. Thus, the bound excited state wave functions for neon were determined using the multiconfiguration Dirac-Fock code of Grant *et al.* [22], while the continuum wave functions for neon were calculated in the field of the static potential of the appropriate ion.

At 5 and 10 eV there are no inelastic channels open and the phase shifts are real quantities. The cross sections can then be determined in the usual manner. However, at 20 and 50 eV, when absorption effects were included in the calculation, the phase shifts now become complex. The elastic and momentum transfer cross sections were then determined in terms of the real and imaginary parts of these phase shifts using Eqs. (11a) and 11(b) of Ref. [23]. In particular, at 20 eV there are only nine bound excited states of neon, having direct matrix elements with the ground state, which are open. In intermediate coupling notation, these bound states are $3s[3/2]_1$, $3s[1/2]_1$, $3p[1/2]_0$, $3\bar{p}[1/2]_0$, $3p[5/2]_2$, $3p[3/2]_2$, $3\bar{p}[3/2]_2$, $4s[3/2]_1$, and $4s[1/2]_1$, and they were all incorporated in the formation of the absorption potential. However, at 50 eV all inelastic channels are open, with the continuum channels, which simulate ionization, being the most important. The absorption potential then included an additional six bound states, namely, $3\bar{d}[1/2]_1$, $3d[3/2]_1$, $3\bar{d}[3/2]_1$, $3d[7/2]_3$, $3d[5/2]_3$, and $3\bar{d}[5/2]_3$ as well as $25s,p,\bar{p},\ldots,g$, and $\bar{g}$ continuum states. In order to check the convergence with respect to the number of bound and continuum wave functions in the absorption potential, the calculation at 50 eV was repeated without the six additional bound states and without the $g$ and $\bar{g}$ continuum waves. When this was done, the elastic cross section increased by only 0.03%.

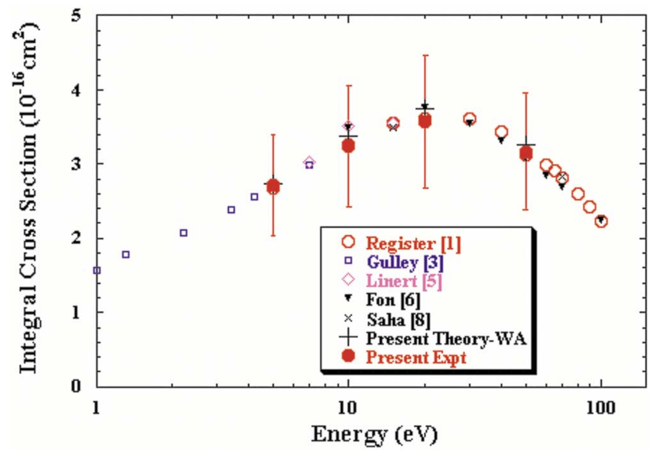


FIG. 2. (Color online) Elastic integral cross section for neon.

## IV. RESULTS AND DISCUSSION

In this study, we measured the absolute differential cross section for elastic scattering at 5, 10, 20, and 50 eV and for scattering angles ranging from either 90°, 100°, or 120°, depending on the positions of the DCS minima, to 180°. These data are presented in Table I and Fig. 1. The experimental uncertainties on each measured point are indicated in the table as percentages. The reason for not measuring in the low- to mid-angular range is simply to cut the data acquisition time and to concentrate on the backward angle region in which we have the most interest. Furthermore, there are many experimental and theoretical data in these angular regions and they agree fairly well with each other. However, we choose the starting angles so that we include the DCS minima in the measurements.

The DCS result at 5 eV is of particular interest, since the results of Zubek and co-workers show a marked difference from our experimental and theoretical results at backward angles. As discussed in Sec. I, the 7 eV data reported by Zubek and co-workers in [4] showed a similar behavior, but their later result in 2006 [5] did not show any such increase at large angles. Therefore, judging from our present results at 5 eV and the later results of Zubek *et al.* at 7 eV, the increasing tail of Zubek *et al.* at 5 eV seems to be an artifact.

As noted above, there are no absorption effects for 5 and 10 eV, since these energies are below the first excitation threshold. For 20 and 50 eV, we show calculations both with and without the absorption effects included. For 10 and 20 eV, the present theoretical results deviate from the present experimental results to varying extents at angles near 180°. However, at 5 eV the agreement between experiment and theory is excellent, as well as at 50 eV when absorption effects are included. Also shown in Fig. 1 are the *R*-matrix calculations of Fon and Berrington [6] and the multiconfigu-

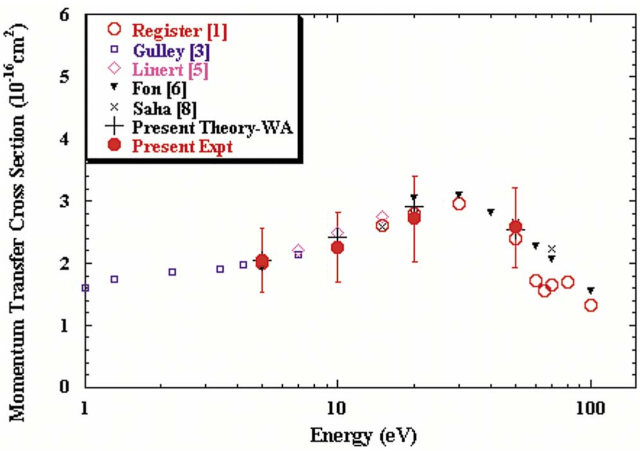


FIG. 3. (Color online) Momentum transfer cross section for neon.

ration Hartree-Fock calculations of Saha [8]. There is excellent agreement between the present experimental and theoretical results, with absorption when appropriate, and those of Saha at all energies and angles. The agreement of our results with the calculations of Fon and Berrington is slightly less satisfactory.

Experimentally estimated and theoretically calculated elastic integral cross sections and momentum transfer cross sections are presented in Table II and Figs. 2 and 3. In order to estimate experimental ICSs and MTCSs, we used theoretical numbers for the angular regions where we have not measured the elastic DCSs. Perhaps not surprisingly, given the level of agreement at the DCS level, the experimental ICSs and MTCSs are in generally good agreement with previous results at all energies. It is worth noting, however, that the present results, particularly for the MTCS, which is more strongly weighted toward contributions from backscattering, should have less uncertainty than most previous results, given the extension of the present DCS results to 180°. In particular, our MTCS at 5 eV is in excellent agreement with the value of $2.070 \times 10^{-16}$ cm$^2$ for this cross section as determined from drift velocity measurements by Robertson [24]. It should also be noted that the present theoretical values of the MTCS agree with those of Robertson from his highest measurement at 7 eV down to 0.5 eV within the stated experimental error of 3%.

## V. CONCLUSIONS

Absolute differential cross sections for the elastic scattering of electrons from neon have been measured and calculated at energies of 5, 10, 20, and 50 eV over an extended angular range up to 180°. At 10 and 20 eV, all the present theoretical results deviate from the present experimental results to a small extent at some backward angles. At 5 eV, however, the agreement between experiment and theory is excellent, as well as at 50 eV when absorption effects are included. At the integral cross section level, the present results are in good agreement with previous experiment and theory.

## ACKNOWLEDGMENT

This work was supported by KOSEF (Grant No. R01-2007-000-10034-0).

[1] D. F. Register and S. Trajmar, Phys. Rev. A **29**, 1785 (1984).
[2] X. Shi and P. D. Burrow, J. Phys. B **25**, 4273 (1992).
[3] R. J. Gulley, D. T. Alle, M. J. Brennan, M. J. Brunger, and S. J. Buckman, J. Phys. B **27**, 2593 (1994).
[4] B. Mielewska, I. Linert, G. C. King, and M. Zubek, in *Abstracts of the XXIV International Conference on Photonic Electronic and Atomic Collisions, Rosario, Argentina 2005* (unpublished).
[5] I. Linert, B. Mielewska, G. C. King, and M. Zubek, Phys. Rev. A **74**, 042701 (2006).
[6] W. C. Fon and K. A. Berrington, J. Phys. B **14**, 323 (1981).
[7] R. P. McEachran and A. D. Stauffer, Phys. Lett. **107A**, 397 (1985).
[8] H. P. Saha, Phys. Rev. A **39**, 5048 (1989).
[9] H. Cho, R. J. Gulley, and S. J. Buckman, J. Korean Phys. Soc. **42**, 71 (2003).
[10] H. Cho, R. P. McEachran, H. Tanaka, and S. J. Buckman, J. Phys. B **37**, 4639 (2004).
[11] H. Cho, R. P. McEachran, S. J. Buckman, D. M. Filipovic, V. Rejcev, B. P. Marinkovic, H. Tanaka, A. D. Stauffer, and E. C. Jung, J. Phys. B **39**, 3781 (2006).
[12] F. H. Read and J. M. Channing, Rev. Sci. Instrum. **67**, 2372 (1996).
[13] S. K. Srivastava, A. Chutjian, and S. J. Trajmar, J. Chem. Phys. **63**, 2659 (1975).
[14] H. Cho, H. Lee, and Y. S. Park, J. Korean Phys. Soc. **43**, 40 (2003).
[15] J. F. O'Hanlon, *A User's Guide to Vacuum Technology* (Wiley, New Jersey, 2003).
[16] L. Boesten and H. Tanaka, At. Data Nucl. Data Tables **52**, 25 (1992).
[17] R. P. McEachran and A. D. Stauffer, J. Phys. B **16**, 4023 (1983).
[18] S. Chen, R. P. McEachran, and A. D. Stauffer, J. Phys. B **41**, 025201 (2008).
[19] K. Bartschat, R. P. McEachran, and A. D. Stauffer, J. Phys. B **21**, 2789 (1988).
[20] K. Bartschat, R. P. McEachran, and A. D. Stauffer, J. Phys. B **23**, 2349 (1990).
[21] T. M. Miller and B. Bederson, Adv. At. Mol. Phys. **13**, 1 (1977).
[22] I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, and N. C. Pyper, Comput. Phys. Commun. **21**, 207 (1980).
[23] R. P. McEachran and A. D. Stauffer, J. Phys. B **36**, 3977 (2003).
[24] A. G. Robertson, J. Phys. B **5**, 648 (1972).