Differential cross sections for elastic and inelastic n=2 excitation of ground-state helium at 29.6 and 40.1 eV


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Differential cross sections for elastic and inelastic \( n = 2 \) excitation of ground-state helium at 29.6 and 40.1 eV

M J Brunger†, I E McCarthy, K Ratnavelu‡, P J O Teubner, A M Weigold§, Y Zhou and L J Allen

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Abstract. Differential cross sections have been measured for elastic and inelastic \( \left( 2^3S, 2^1S, 2^3P \text{ and } 2^1P \right) \) scattering of electrons by ground-state helium at 29.6 and 40.1 eV. The normalisation of the cross sections is discussed. Theoretical cross sections have been obtained using a ten-state coupled-channels-optical calculation. In general, there is good agreement between theory and experiment for singlet states but not for triplet.

1. Introduction

Up to now there have been significant differences between measured and calculated differential cross sections for electron scattering by ground-state helium to \( n = 2 \) states at incident energies \( E_0 \) of 29.6 and 40.1 eV. The recent inelastic experiments of Cartwright et al (1989) at 29.6 eV agree substantially with other data of Trajmar (1973) and Hall et al (1973) at 29.6 and 40.1 eV. Although there are a number of theoretical methods that have been applied to study this scattering system at the energies mentioned, the most successful has been the \( R \)-matrix technique. Even the simple five-state \( R \)-matrix calculation has done moderately well for most transitions at most angles except for the large-angle scattering in the \( 1^1S-2^1P \) transition (Fon et al 1979, 1980). The recent 19-state calculation of Fon et al (1988) has brought closer agreement to experiments at 29.6 eV.

In view of the success achieved in studying electron scattering by two-electron atoms using the coupled-channels-optical method (McCarthy et al 1988, 1989, Mitroy and McCarthy 1989), the present work reports the results of a ten-state coupled-channels-optical calculation of \( e-\text{He} \) scattering at 29.6 and 40.1 eV.

This paper also reports measurements of elastic and inelastic \( \left( 1^1S-2^{1,3}L \right) \) differential cross sections at energies of 18 (for elastic only), 30 and 40 eV following the technique of Brunger et al (1989).

2. Details of the calculations

The electron scattering calculations were done using the approach of McCarthy and Stelbovics (1983) as adapted for the use of large-dimension configuration-interaction...
wavefunctions by Mitroy et al (1987) and Bray et al (1989). The formalism of the optical-potential calculation for two-electron atoms is described by McCarthy et al (1988). The atomic states 1S, 2S, 3S; 2P, 3P; 3D were calculated using all allowed excitations in a basis formed by the 1s, 2s, 3s; 2p, 3p and 3d Hartree–Fock orbitals with higher excitations represented by 5s, 5p and 5d orbitals. Only the continuum optical potentials are included in the 1S-1S, 1S-2P, 2S-2S, 2S-2P, 2P-2P channel couplings. Optical potentials for discrete states outside the coupled space are not taken into account because the large set of discrete channels accounts for most of this coupling. Continuum optical potentials for the elastic channel are tested by how well they reproduce the total ionisation cross section. Theoretical and experimental (Montague et al 1984) values at 30 eV are respectively 0.09 $\sigma_0$ and 0.076 ± 0.003 $\sigma_0$.

The full coupled-channels-optical calculation is denoted by cco10. In order to assess the effect of the inclusion of the continuum a ten-channel calculation without optical potentials (cc10) is included.

3. Experimental details

The electron monochromator used in the present measurements has been described in detail previously (Brunger et al 1989). Briefly, a beam of helium atoms effusing from a molybdenum tube of internal diameter 0.6 mm is crossed with a beam of monoenergetic electrons of desired energy $E_0$. As required, elastically or inelastically scattered electrons at a particular scattering angle $\theta$ are energy analysed and detected. The resolution in the present measurements was typically 45 meV (FWHM) which was more than adequate to resolve the respective states of the $n=2$ manifold from each other and, of course, the elastic channel.

The present measurements were taken with the monochromator operating in the energy-loss mode. Proper alignment of the monochromator and a generous half-cone viewing angle for the analyser ensured that no vignetting of the interaction volume occurred in the present system. Typical operating conditions of effusive gas flow and stable electron beam current were maintained throughout and double scattering effects were avoided by working in a region where the scattered intensity varied linearly with the target gas pressure.

As in previous measurements the true zero scattering angle was determined as that about which the elastic or 2P inelastic scattering intensity was symmetric. The estimated error in this determination was ±1°. The energy scale was calibrated against the well known 2S resonance of helium at 19.367 eV and is estimated to be accurate to better than 40 meV.

4. Results and discussion

4.1. Elastic scattering

The angular range of the current elastic differential cross sections was 5°–95° while the incident electron beam energies were 18, 30 and 40 eV. At each electron beam energy $E_0$, the experimental technique simply involved, for every $\theta$, scanning the energy loss through the elastic peak for a preset number of scans, initially with the target gas on and then with the target gas off. The gas on and gas off spectra were then subtracted
Differential cross sections for $e^- - \text{He}$ scattering

at each scattering angle to give an angular distribution. The measured angular distributions at 18, 30 and 40 eV were then corrected for angle-dependent effects.

The angular efficiency of the analyser was determined in a separate series of experiments which have been discussed in detail in an earlier publication (Brunger et al 1989). Briefly, however, the effective path-length correction factor was derived by comparing at 3 eV the known differential cross section for elastic scattering of electrons off helium, as calculated by Nesbet (1979), against that which we measured with the present scattering geometry.

The corrected angular distribution measurements at 18, 30 and 40 eV are placed on an absolute scale by normalising to the relevant data of Register et al (1980) at an arbitrary point. The normalisation at 18 and 30 eV is corrected by the factors $K$ of table 2. The present elastic differential cross sections are tabulated in table 1 and pictorially represented, for $E_0 = 30$ eV and 40 eV, in figure 1.

Table 1. Present experimental elastic differential cross sections. Units are $10^{-16}$ cm$^2$ sr$^{-1}$.

<table>
<thead>
<tr>
<th>Electron scattering angle $\theta$ (deg)</th>
<th>Electron beam energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18 eV</td>
</tr>
<tr>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>15</td>
<td>0.568</td>
</tr>
<tr>
<td>20</td>
<td>0.509</td>
</tr>
<tr>
<td>25</td>
<td>0.458</td>
</tr>
<tr>
<td>30</td>
<td>0.408</td>
</tr>
<tr>
<td>35</td>
<td>0.372</td>
</tr>
<tr>
<td>40</td>
<td>0.336</td>
</tr>
<tr>
<td>45</td>
<td>0.313</td>
</tr>
<tr>
<td>50</td>
<td>0.285</td>
</tr>
<tr>
<td>55</td>
<td>0.265</td>
</tr>
<tr>
<td>60</td>
<td>0.243</td>
</tr>
<tr>
<td>65</td>
<td>0.229</td>
</tr>
<tr>
<td>70</td>
<td>0.218</td>
</tr>
<tr>
<td>75</td>
<td>0.205</td>
</tr>
<tr>
<td>80</td>
<td>0.203</td>
</tr>
<tr>
<td>85</td>
<td>0.204</td>
</tr>
<tr>
<td>90</td>
<td>0.205</td>
</tr>
<tr>
<td>95</td>
<td>0.206</td>
</tr>
</tbody>
</table>

In each case the agreement between the present data and the earlier work of Register et al (1980) is seen to be good in terms of the shapes and absolute values of the differential cross sections. Furthermore, for each energy studied the angular distributions were repeated on several occasions at different gas pressures and on every occasion, for a given $E_0$, the shapes were found to be the same. We are therefore confident about the reproducibility of the present data.

The physical reasonableness of the present data (and, by implication, the data of Register et al (1980) as agreement between the two sets is good) was investigated at 18 and 30 eV by the parametrised $S$-matrix technique. This method was described in detail by Allen et al (1987). We note that a critical aspect of the technique is that at
Table 2. Cross sections derived from the phaseshift analysis. Units are $a_{0}^{2}$. $Q_{tot}$ = total cross section, $Q_{MT}$ = momentum transfer cross section, $Q_{el}$ = integral elastic cross section and $Q_{abs}$ = absorption cross section. (a) $E_{0}$ = 18 eV. (b) $E_{0}$ = 30 eV.

(a)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{tot}$</td>
<td>$12.20 \pm 1.22$</td>
<td>$11.96 \pm 0.60$</td>
<td>$11.693$</td>
</tr>
<tr>
<td>$Q_{MT}$</td>
<td>$11.04 \pm 1.11$</td>
<td>$10.86 \pm 0.55$</td>
<td>$10.7$</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>$1.47$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$0.978$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{el}$</td>
<td>$6.99 \pm 1.4$</td>
<td>$7.54$</td>
<td>$-$</td>
<td>$7.98$</td>
</tr>
<tr>
<td>$Q_{abs}$</td>
<td>$1.49 \pm 0.3$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.81$</td>
</tr>
<tr>
<td>$Q_{tot}$</td>
<td>$8.48 \pm 1.7$</td>
<td>$-$</td>
<td>$8.43$</td>
<td>$8.79$</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>$1.76$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$1.13$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

![Figure 1. Differential cross section for elastic scattering on helium at (a) 30 eV, (b) 40 eV. Full circles, present experimental data; crosses, Register et al (1980); full curves, CCO10; broken curves, C10.](image)

For the present analysis the quantity which was minimised was

$$
\chi^2 = \frac{1}{M - CN} \sum_{i=1}^{M} \left[ \sigma_i - \kappa \sigma(\theta_i, a) \right]^2 / (\Delta \sigma_i)^2
$$

(1)

where $\sigma_i$ and $\Delta \sigma_i$ are respectively the experimental cross sections and statistical errors at $M$ angles $\theta_i$, $\sigma(\theta_i, a)$ is the cross section at $\theta_i$ calculated in terms of a set $a$ of $N$ free parameters, $\kappa$ is a renormalisation parameter which establishes the correct absolute
values of the differential cross sections, $C = 2$ for a real phaseshift analysis ($E_0 < \text{inelastic threshold}$) and $C = 4$ for a complex phaseshift analysis ($E_0 \geq \text{inelastic threshold}$). The results of the analysis are given in table 2 along with the relevant values of previously published work.

Clearly, $\kappa$ is close to unity at both energies which confirms both the present normalisation to Register et al. (1980) and their absolute values. Furthermore the good agreement at both energies between the derived cross sections of the current analysis and the previously published absolute values strongly suggests that the current elastic differential cross sections are physically reasonable.

The present theoretical elastic differential cross sections are shown together with the experimental results in figure 1. Clearly the inclusion of the optical potentials in $cCO$ has a large effect in bringing the ten-state coupled-channels calculation into reasonable agreement with experiment.

4.2. Ratios for the $n = 2$ manifold

The angular dependence of the $n = 2$ manifold states of helium at electron impact energies below 50 eV has been investigated by Trajmar (1973), Hall et al. (1973) and Cartwright et al. (1989). Trajmar (1973) measured the intensity ratios of the $2^3S$, $2^1S$ and $2^1P$ states to the $2^1P$ state for electrons of incident energies 29.6 eV and 40.1 eV over the angular range $3^\circ$ to $138^\circ$. These were subsequently placed on an absolute scale by utilising the previously determined $2^1P$ cross sections of Truhlar et al. (1973). Hall et al. (1973) measured the intensity ratios of the $2^3S$, $2^1S$, $2^1P$ and $2^3P$ states to the elastic peak and then made use of the known elastic cross section to obtain absolute differential cross sections for the $n = 2$ manifold states of helium over the angular range of $10^\circ$ to $125^\circ$ and at electron beam energies of 29.2, 39.2 and 48.2 eV. In table 1 of their paper, however, they also report the scattered intensity ratios of $2^3S$, $2^1S$ and $2^1P$ states with respect to the $2^1P$ state.

In the present study we have measured energy-loss spectra which encompass the $n = 2$ manifold of helium at fixed scattering angles ranging from $2^\circ$ to $90^\circ$ and at electron impact energies of 29.6 eV and 40.1 eV respectively. Each energy-loss spectrum was collected and stored with the aid of a multichannel scaler until adequate signal-to-noise conditions for all the features in the spectrum were achieved. A typical spectrum is shown in figure 2.

The transmission efficiency of the analyser was determined by a technique first explored by Pichou et al. (1976) and which was discussed in detail previously by Brunger et al. (1989). Consequently we are confident that the present data do not suffer from any serious transmission effects.

The ratios of the $2^3S$, $2^1S$ and $2^3P$ cross sections to the $2^1P$ cross section were determined by measuring the heights of the individual peaks above the background. This is a justifiable procedure under the current experimental conditions as the signal-to-noise ratio in all cases was excellent. It was further verified by integrating the area under the peaks for a few specific cases. Tabulated values of the ratios for the present experiment are given in table 3.

The current measurements agree reasonably well in terms of shape and magnitude, at both energies studied and across the overlapping angular range, with Trajmar (1973) and Hall et al. (1973). Trajmar (1973) reports complicated structure in his 29.6 eV $2^3S/2^1P$ ratio curve which is not seen in either the present study nor in the earlier work of Hall et al. (1973).
Figure 2. A typical energy-loss spectrum for the $n = 3$ manifold in helium. The incident electron beam energy was 35 eV and the electron scattering angle 5°.

Table 3. Scattered intensity ratios (to $2^1P$) at 29.6 eV and 40.1 eV incident energies. The errors represent plus and minus one standard deviation.

<table>
<thead>
<tr>
<th>$\theta$ (deg)</th>
<th>$E_0 = 29.6$ eV</th>
<th></th>
<th>$E_0 = 40.1$ eV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>$2^1S$</td>
<td>$2^3S$</td>
<td>$2^3P$</td>
<td>$2^1S$</td>
</tr>
<tr>
<td>2.0</td>
<td>0.547 ± 0.027</td>
<td>—</td>
<td>—</td>
<td>0.2456 ± 0.007</td>
</tr>
<tr>
<td>2.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>5.0</td>
<td>0.503 ± 0.04</td>
<td>0.078 ± 0.009</td>
<td>0.0431 ± 0.003</td>
<td>—</td>
</tr>
<tr>
<td>7.5</td>
<td>0.453 ± 0.023</td>
<td>—</td>
<td>—</td>
<td>0.224 ± 0.0067</td>
</tr>
<tr>
<td>10.0</td>
<td>0.426 ± 0.042</td>
<td>0.082 ± 0.009</td>
<td>0.0522 ± 0.004</td>
<td>—</td>
</tr>
<tr>
<td>12.5</td>
<td>0.412 ± 0.031</td>
<td>—</td>
<td>—</td>
<td>0.183 ± 0.0073</td>
</tr>
<tr>
<td>15.0</td>
<td>0.378 ± 0.037</td>
<td>0.091 ± 0.01</td>
<td>0.067 ± 0.005</td>
<td>—</td>
</tr>
<tr>
<td>17.5</td>
<td>0.350 ± 0.038</td>
<td>—</td>
<td>—</td>
<td>0.143 ± 0.0057</td>
</tr>
<tr>
<td>20.0</td>
<td>0.309 ± 0.034</td>
<td>0.104 ± 0.011</td>
<td>0.104 ± 0.008</td>
<td>—</td>
</tr>
<tr>
<td>22.5</td>
<td>0.238 ± 0.028</td>
<td>0.134 ± 0.015</td>
<td>0.151 ± 0.014</td>
<td>—</td>
</tr>
<tr>
<td>25.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.07641 ± 0.0038</td>
</tr>
<tr>
<td>27.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30.0</td>
<td>0.1698 ± 0.020</td>
<td>0.160 ± 0.017</td>
<td>0.242 ± 0.022</td>
<td>—</td>
</tr>
<tr>
<td>32.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.05525 ± 0.0028</td>
</tr>
<tr>
<td>35.0</td>
<td>—</td>
<td>0.199 ± 0.022</td>
<td>0.322 ± 0.029</td>
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<tr>
<td>37.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.03845 ± 0.0019</td>
</tr>
<tr>
<td>40.0</td>
<td>0.0711 ± 0.009</td>
<td>0.256 ± 0.031</td>
<td>0.475 ± 0.042</td>
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<tr>
<td>42.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.022 ± 0.0011</td>
</tr>
<tr>
<td>45.0</td>
<td>0.053 ± 0.007</td>
<td>0.325 ± 0.039</td>
<td>0.696 ± 0.063</td>
<td>—</td>
</tr>
<tr>
<td>47.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.0138 ± 0.0015</td>
</tr>
<tr>
<td>50.0</td>
<td>0.066 ± 0.009</td>
<td>0.435 ± 0.052</td>
<td>0.935 ± 0.084</td>
<td>—</td>
</tr>
<tr>
<td>52.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.01568 ± 0.0017</td>
</tr>
<tr>
<td>55.0</td>
<td>0.124 ± 0.014</td>
<td>0.636 ± 0.076</td>
<td>1.060 ± 0.106</td>
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</tr>
<tr>
<td>57.5</td>
<td>0.145 ± 0.017</td>
<td>—</td>
<td>—</td>
<td>0.03724 ± 0.0041</td>
</tr>
<tr>
<td>60.0</td>
<td>0.166 ± 0.019</td>
<td>1.203 ± 0.120</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>65.0</td>
<td>0.234 ± 0.027</td>
<td>0.966 ± 0.119</td>
<td>1.290 ± 0.141</td>
<td>—</td>
</tr>
<tr>
<td>67.5</td>
<td>0.284 ± 0.031</td>
<td>—</td>
<td>—</td>
<td>0.159 ± 0.0099</td>
</tr>
<tr>
<td>70.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.568 ± 0.172</td>
</tr>
<tr>
<td>75.0</td>
<td>0.373 ± 0.041</td>
<td>1.390 ± 0.153</td>
<td>1.620 ± 0.128</td>
<td>—</td>
</tr>
<tr>
<td>77.5</td>
<td>0.418 ± 0.041</td>
<td>—</td>
<td>—</td>
<td>0.369 ± 0.022</td>
</tr>
<tr>
<td>80.0</td>
<td>0.497 ± 0.045</td>
<td>1.61 ± 0.177</td>
<td>1.872 ± 0.206</td>
<td>—</td>
</tr>
<tr>
<td>87.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.711 ± 0.043</td>
</tr>
<tr>
<td>90.0</td>
<td>0.892 ± 0.088</td>
<td>1.60 ± 0.176</td>
<td>2.34 ± 0.234</td>
<td>—</td>
</tr>
</tbody>
</table>
The value of the minimum in Trajmar's 2S/2P ratio curve at 29.6 eV is smaller than that observed in the present study. At first sight this observation could be explained if the angular resolution of Trajmar's apparatus was much better than that used in the current measurements. Buckman (1985) estimates the angular resolution of the present analyser to be of the order of 2°. This is very similar to that quoted by Trajmar who calculated the angular resolution of his analyser on the basis of extreme geometrical considerations. This similarity in angular resolution is supported by the excellent agreement at 40.1 eV for the 2S/2P ratios of all the experiments at the minimum. Unfortunately Hall et al (1973) did not report a ratio of the apparent minimum at 29.6 eV and so this matter remains experimentally unresolved.

4.3. Differential cross sections for the n = 2 manifold

We have measured differential cross sections at 29.6 eV for excitation of the 2P, 2S, 2S and 2P states in helium. This was achieved by using the relevant ratios of table 3 and by measuring, in another series of experiments, the differential cross sections for the excitation of the 2P state. The technique for measuring the 2P angular distribution is identical to that previously employed for elastic scattering except that now the energy loss is set at 21.2 eV.

The present 2P angular distribution is integrated by Simpson's rule and then normalised to the preferred value of the integral cross section at 29.6 eV as given by de Heer and Jansen (1977). The results of this procedure are given in table 4 and pictorially represented in figure 3(a) along with earlier experimental data, the 19-state R-matrix calculation and the present cco and cco10 calculations.

<table>
<thead>
<tr>
<th>θ (deg)</th>
<th>σ(θ)(10^{-18} cm^2 sr^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.031 ± 12.3%</td>
</tr>
<tr>
<td>10</td>
<td>3.686 ± 12.4%</td>
</tr>
<tr>
<td>15</td>
<td>3.046 ± 12.4%</td>
</tr>
<tr>
<td>20</td>
<td>2.329 ± 12.5%</td>
</tr>
<tr>
<td>30</td>
<td>1.385 ± 12.7%</td>
</tr>
<tr>
<td>40</td>
<td>0.677 ± 13.2%</td>
</tr>
<tr>
<td>50</td>
<td>0.323 ± 14.4%</td>
</tr>
<tr>
<td>60</td>
<td>0.155 ± 16.6%</td>
</tr>
<tr>
<td>70</td>
<td>0.104 ± 18.3%</td>
</tr>
<tr>
<td>80</td>
<td>0.087 ± 19.3%</td>
</tr>
<tr>
<td>90</td>
<td>0.082 ± 19.7%</td>
</tr>
<tr>
<td>100</td>
<td>0.078 ± 20.0%</td>
</tr>
</tbody>
</table>

The uncertainties in the 2P data are in the quadrature sum of the statistical uncertainty in the angular distribution at each angle, uncertainties in atomic beam density fluctuations and electron beam current fluctuations (4%) and an uncertainty due to the truncation of the Simpson's integral to 100°. This latter uncertainty is of the order of 11.5% as this is precisely the contribution that the 100°-180° differential data of the cco10 calculation make to the value of the integral cross section.

We have checked the absolute value of the 2P data at 30° by performing another experiment that was first suggested by Hall et al (1973) and which nicely accounts for
potential transmission problems. We measured the intensity of the inelastic $2^1P$ signal at 29.6 eV and then the intensity of the elastic signal at $E_0 = 29.6 - 21.2 = 8.4$ eV. Care was taken to ensure that the primary beam current and the atomic beam density remain constant throughout. The ratio of these intensities is then simply related to the ratio of the differential cross sections. Hence given the absolute value of the elastic differential cross section at 8.4 eV and 30° (Nesbet 1979) we immediately find the absolute value of the $2^1P$ differential cross section at $E_0 = 29.6$ eV; $\theta = 30^\circ$. The value obtained by this method agreed with that given in table 4 to better than 4% and so we are confident that our absolute values for the $2^1P$ differential cross sections are reasonable.

The data of table 4 (and values interpolated from these data) can now be combined with the relevant numbers in table 3 to generate the required differential cross sections for the $2^3S$, $2^1S$ and $2^3P$ states. These are presented in figures 4(a)-6(a), respectively, along with the measurements of Cartwright et al (1989), the 19-state $R$-matrix calculation of Fon et al (1989) and the present $CC10$ and $CC010$ results.

At 40.1 eV the $2^1P$ differential cross section has not been measured. Differential cross sections for the $2^3S$, $2^1S$ and $2^3P$ states have been estimated by multiplying the ratios of table 3 with the differential cross section for $2^1P$ calculated by the $CC010$ method (figure 3(b)). It is assumed that the calculation, which gives a complete description of the data within experimental error at 29.6 eV, is equally valid at 40.1 eV. The results are shown in figures 4(b)-6(b). They can be considered as a comparison with theory of the ratios of the respective excitations to $2^1P$.

Features of the comparison of experiment and theory in figures 4-6 are that the $CC010$ calculation for singlet states agrees well with the present experiment. The optical potential makes a large difference and is responsible for the good agreement. This is particularly notable for the $2^1S$ state at 29.6 eV. The calculation of this excitation is
Differential cross sections for $e^{-}$-He scattering

Figure 4. As figure 3 for the $2^3S$ excitation.

Figure 5. As figure 3 for the $2^1S$ excitation.

extremely sensitive to details of the theory. Where the present experimental data differ noticeably from previous data they are closer to the $c_{CO10}$ calculation. There is no serious quantitative agreement for the $R$-matrix calculation. For triplet excitations there is no quantitative agreement between theory and experiment.
Figure 6. As figure 3 for the $2^3\text{P}$ excitation.

Table 5. Integrated cross sections ($\pi a_0^2$) for $e$–He channels at 30 and 40 eV. Experimental error estimates are given in parentheses for the last significant digits.

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Channel</th>
<th>$\pi$</th>
<th>$\pi_{CO}$</th>
<th>$R$ matrix</th>
<th>Expt$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Elastic</td>
<td>2.219</td>
<td>2.549</td>
<td>2.540$^b$</td>
<td>2.542</td>
</tr>
<tr>
<td></td>
<td>$2^3\text{S}$</td>
<td>0.042</td>
<td>0.059</td>
<td>0.043$^c$</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>$2^1\text{S}$</td>
<td>0.047</td>
<td>0.038</td>
<td>0.037$^c$</td>
<td>0.02461 (492)</td>
</tr>
<tr>
<td></td>
<td>$2^3\text{P}$</td>
<td>0.084</td>
<td>0.059</td>
<td>0.023$^c$</td>
<td>0.0272</td>
</tr>
<tr>
<td></td>
<td>$2^1\text{P}$</td>
<td>0.088</td>
<td>0.048</td>
<td>0.054$^d$</td>
<td>0.0426 (21)</td>
</tr>
<tr>
<td>40</td>
<td>Elastic</td>
<td>1.707</td>
<td>1.926</td>
<td>—</td>
<td>1.797$^e$ (1.910$^f$)</td>
</tr>
<tr>
<td></td>
<td>$2^3\text{S}$</td>
<td>0.017</td>
<td>0.012</td>
<td>—</td>
<td>0.016$^f$</td>
</tr>
<tr>
<td></td>
<td>$2^1\text{S}$</td>
<td>0.040</td>
<td>0.027</td>
<td>—</td>
<td>0.024$^f$</td>
</tr>
<tr>
<td></td>
<td>$2^3\text{P}$</td>
<td>0.033</td>
<td>0.026</td>
<td>—</td>
<td>0.024$^f$</td>
</tr>
<tr>
<td></td>
<td>$2^1\text{P}$</td>
<td>0.120</td>
<td>0.091</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>


5. Conclusions

Electron–helium scattering is a prototype for theories of scattering from multielectron atoms at intermediate energies. It has the essential features that configuration interaction is important and that there is a significant total ionisation cross section, suggesting that it is an important test of methods for taking the continuum into account in the scattering calculation.

The present experimental data agree with data from other laboratories except in some details. For singlet states the coupled-channels–optical calculations agree very well with the present experiment, particularly at angles where the present data differ from other data. For triplet states no calculation shows serious quantitative agreement with experiment.

In the present calculations the target states involved in the lowest dipole excitations from the $n = 1$ and 2 states are explicitly coupled. The continuum is represented by
Differential cross sections for $e^- - He$ scattering

the half-shell potential, which makes a very large difference to the differential cross sections.

The present coupled-channels-optical method is confirmed as a very good method for calculating singlet excitations of multielectron atoms. The most inaccurate feature of the method is its treatment of exchange, for which the amplitudes are calculated in the Bonham–Ochkur peaking approximation. This is a likely reason for the poorer agreement with experiment for triplet excitations.

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