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The $1^1S \rightarrow 2^3S$ and $1^1S \rightarrow 2^3P$ excitation of helium by electron impact

W C Fon†, K A Berrington, P G Burke‡ and A E Kingston

Department of Applied Mathematics and Theoretical Physics, Queen's University, Belfast BT7 1NN, Northern Ireland

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Abstract. The R-matrix method calculations of Berrington *et al* and Fon *et al* are extended to the calculation of the integrated and differential cross sections for electron excitation of the ground-state helium atom to the 2^3S and 2^3P states in the energy ranges ($21{\cdot}4 \leqslant E \leqslant 30$ eV) and ($80 \leqslant E \leqslant 200$ eV). For intermediate energies ($30 \leqslant E \leqslant 80$ eV) pseudo-resonances arise which make accurate cross sections difficult to calculate and this region is therefore not considered. The calculations are compared with recent theoretical calculations and experimental measurements.

1. Introduction

Many theoretical models have been constructed to calculate the integrated and differential cross sections for excitation by electron impact of ground-state helium atoms to the $n = 2$ states. Reasonable success has been achieved with the theories (Thomas *et al* 1974, Madison and Shelton 1973) in predicting the differential cross sections for 2^1P excitation from the ground state. In the partial-wave expansion, a substantial contribution to the 2^1P excitation cross section comes from a large number of higher partial waves of large angular momentum (see Fon 1978) where less accurate methods (e.g. the distorted-wave approximation or even the Born approximation) may be valid. The demand for a high degree of accuracy in evaluating low partial waves is overshadowed by the predominance of the high partial-wave contribution. Hence it is comparatively easy to predict correctly the excitation cross sections for S–P optically allowed transitions like 2^1P excitation. On the other hand, cross sections for 2^3S and 2^3P excitations are more difficult to calculate, since excitation from the 1^1S ground state is spin-forbidden and thus the interaction contains only short-range exchange type terms. This implies that only a few low-lying partial waves contribute to the calculation of integrated and differential cross sections for these transitions. In addition the distortion of the atomic wavefunctions is most important in the short-range collision region. Thus it is here, for spin-forbidden transitions, that the quality of a theoretical model and the accuracy of the atomic wavefunctions are put to the most stringent test.

Berrington *et al* (1975) and Fon *et al* (1978) have calculated respectively the integrated and the differential cross sections for the $n = 2$ states of helium by using the

† On leave of absence from Department of Mathematics, University of Malaya, Pantai Valley, Kuala Lumpur, Malaysia.
‡ Also at the SRC Daresbury Laboratory, Daresbury, England.

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R-matrix method of Burke *et al* (1971). Agreement between the R-matrix method results and measurements is excellent; however, these calculations have only been carried out over a very narrow energy range (between the $n=2$ and $n=3$ excitation thresholds). In this paper, these calculations are extended to the calculation of $1^1S \to 2^3S$ and $1^1S \to 2^3P$ excitation cross sections over a greater energy range $21 \cdot 4 \leqslant E \leqslant 30$ eV and $80 \leqslant E \leqslant 200$ eV. The approximation is discussed in § 2 and the results are compared with recent calculations and experiments in § 3.

2. The approximation and its region of validity

In this paper we extend the earlier calculations of Berrington *et al* (1975) and Fon *et al* (1978) to energies up to 200 eV. We adopt the same R-matrix radius, $a = 16 \cdot 044$ au, but because of the larger energy range, we had to increase the number of continuum orbitals included for each angular momentum from 20 to 25. The calculations were carried out retaining the first five atomic eigenstates (1^1S, 2^3S, 2^1S, 2^3P and 2^1P) which were represented by the same CI wavefunctions as in the earlier work. We found that convergence was obtained for the differential cross section at the highest energy considered by including partial waves up to $L = 20$. For $L \leqslant 13$ these were calculated directly by the R-matrix program and for $L > 13$ they were obtained by extrapolation from lower L values.

One difficulty in our calculations, which has still not been satisfactorily solved, arises from the inclusion of correlation terms in the expansion of our total wavefunction. These terms are formed from the atomic orbitals alone and are given in the second expansion in equation (6) of Berrington *et al* (1975). These terms are included for completeness and in addition they allow for important correlation effects at low energies when all three electrons are close together near the nucleus. However in the intermediate energy range from about 30 to 80 eV they give rise to spurious resonances or pseudo-resonances which make the extraction of accurate results difficult.

It is important to emphasise at this stage that the difficulty at intermediate energies is by no means confined to the R-matrix method. Indeed pseudo-resonances have been observed by Burke and Taylor (1966) who included correlation terms in the close-coupling expansion for electron–hydrogen-atom scattering, and by Nesbet (1979) who used the matrix variational method. In our case, as in this earlier work, the pseudo-resonances arise because the correlation terms have significant components at short distances from highly excited and ionising channels which are not represented asymptotically in the wavefunction.

Several suggestions have been made to overcome this difficulty, but none has yet met with complete success, at least for inelastic collisions involving complex atoms. The simplest is just to leave out the awkward correlation terms from the wavefunction which could easily be done using the R-matrix method and the codes at our disposal. The method would then be equivalent to the close-coupling approximation. However careful study of the analogous situation for electron–hydrogen-atom scattering calculated in the 1s–2s–2p approximation has shown that the resultant excitation cross sections (1s–2s and 1s–2p) are too high in this energy range. There is no reason to suppose that the situation would be any different for helium. Another approach adopted by Burke and Webb (1970), Burke and Mitchell (1974), Callaway and Wooton (1974, 1975) and Callaway *et al* (1975) is to represent the infinity of omitted channels by a few well chosen pseudo-states. However these pseudo-states themselves introduce spurious thresholds and pseudo-resonances which have to be avoided or averaged over leading to inaccuracy in the cross section. Perhaps the best hope is to search for some averaging procedure over the pseudo-resonances similar to the moment T-matrix method used recently to extract total and elastic cross sections from L^2 wavefunctions (Winick and Reinhardt 1978a, b). Such approaches are under study but it is too early to say how successful they will be for inelastic transitions.

Finally we should mention some other completely independent approaches which have been mooted for this energy region. It is now generally agreed that perturbation series methods, such as the Born series or the eikonal–Born series, break down at substantially higher energies. Approaches based on distorted waves are becoming inaccurate at these energies since important final-state interaction effects involving the four $n=2$ states are neglected. Perhaps the most interesting alternative approach is that of Poet (1978) who has obtained exact excitation cross sections for electron–hydrogen-atom scattering in the radial limit at these energies. However it is not clear how his approach can be extended to treat complex atoms.

In conclusion therefore we see that in this intermediate energy region there is still no generally acceptable method available which will lead to accurate excitation cross sections. We have therefore decided to omit this region from consideration, rather than provide results of doubtful validity, with the hope that we will be able to complete the picture in the not too distant future.

3. Results and discussion

We have calculated the total and differential cross sections for the spin-forbidden transitions

$$\mathrm{e} + \mathrm{He}(1^1\mathrm{S}) \rightarrow \mathrm{e} + \mathrm{He}(2^3\mathrm{S})$$

and

$$\mathrm{e} + \mathrm{He}(1^1\mathrm{S}) \rightarrow \mathrm{e} + \mathrm{He}(2^3\mathrm{P})$$

at impact energies ranging from 21·4 to 200 eV. In presenting our results, we shall discuss $1^1\mathrm{S} \rightarrow 2^3\mathrm{S}$ and $1^1\mathrm{S} \rightarrow 2^3\mathrm{P}$ separately.

3.1.1. $1^1S \rightarrow 2^3S$ total cross section. Our calculated total cross sections for $2^3\mathrm{S}$ excitation are displayed in table 1. They are compared with the experimental measurements and other theoretical calculations in figure 1.

The experimental measurements of A Yagishita (1978, private communication), Trajmar (1973), Hall *et al* (1973) and Crooks (1972) are in general agreement among themselves but they are higher than the results of Vriens *et al* (1968). These data exhibit a peak at 26 eV and then begin a very steep descent consistent with the general characteristic of all spin-forbidden transitions.

Our R-matrix five-state calculation is in good agreement with the experiment of Brongersma *et al* (1972) (see Berrington *et al* 1975) and predicts a maximum at about 26 eV which is consistent with the experiments (Trajmar 1973, Hall *et al* 1973). For energies of 100 eV and above our calculation shows good agreement with the distorted-wave polarised-orbital calculations of Scott and McDowell (1975) and the second-order optical-potential distorted-wave model of Bransden and Winters (1975). All of these calculations are well within the experimental error bars of A Yagishita (1978,

Table 1. Total cross section in units of πa_0^2 for electron impact excitations of a helium atom from the ground state computed in the R-matrix method. The index denotes the power of ten by which the number should be multiplied.

E (eV)	2^3S	2^3P
22·95	$4{\cdot}858^{-2}$	$2{\cdot}754^{-2}$
26·5	$5{\cdot}872^{-2}$	$6{\cdot}221^{-2}$
29·6	$4{\cdot}779^{-2}$	$6{\cdot}782^{-2}$
81·63	$5{\cdot}353^{-3}$	$1{\cdot}041^{-2}$
100	$2{\cdot}300^{-3}$	$3{\cdot}767^{-3}$
120	$1{\cdot}392^{-3}$	$1{\cdot}829^{-3}$
150	$7{\cdot}825^{-4}$	$8{\cdot}208^{-4}$
200	$3{\cdot}634^{-4}$	$3{\cdot}103^{-4}$

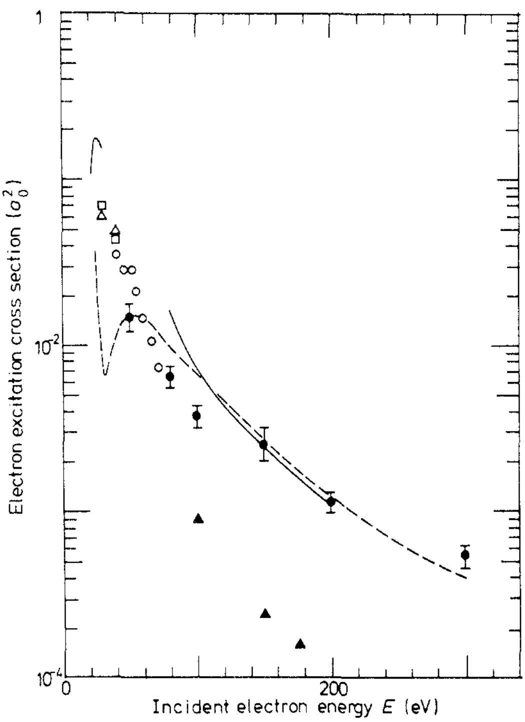

Figure 1. Total cross section for the process: $e+He(1^1S) \rightarrow e+He(2^3S)$. Theory: ——, present R-matrix five-state calculation; – – –, Scott and McDowell (1975). Experiment: ▲, Vriens *et al* (1968); □, Trajmar (1973); △, Hall *et al* (1973); ○, Crooks *et al* (1972); ♦, A Yagishita (1978, private communication).

private communication) at energies $150 \leqslant E \leqslant 200$ eV. Our calculation overestimates the 2^3S cross section at energies less than 100 eV but they are in close agreement with the many-body theory calculation of Thomas *et al* (1974).

3.1.2. $1^1S \rightarrow 2^3S$ differential cross section. Our calculated differential cross sections for 1^1S $\rightarrow$ 2^3S excitation by electron impact are displayed in table 2 and they are compared with experimental measurements and other theoretical calculations in figures 2, 3 and 4.

Table 2. Differential cross section for electron excitation of the 1^1S state of helium to the 2^3S state (in units of 10^{-19} cm^2 sr^{-1}).

Angle (deg)	Energy of incident electron E (eV)						
	26·5	29·6	81·63	100	120	150	200
0	4·71	8·32	3·85	1·88	1·15	$6{\cdot}40^{-1}$	$3{\cdot}01^{-1}$
10	4·38	7·78	3·03	1·32	$7{\cdot}32^{-1}$	$3{\cdot}65^{-1}$	$1{\cdot}50^{-1}$
20	3·56	6·33	1·49	$4{\cdot}93^{-1}$	$2{\cdot}52^{-1}$	$1{\cdot}45^{-1}$	$9{\cdot}53^{-2}$
30	2·66	4·50	$5{\cdot}14^{-1}$	$1{\cdot}84^{-1}$	$1{\cdot}59^{-1}$	$1{\cdot}41^{-1}$	$9{\cdot}89^{-2}$
40	2·25	3·03	$2{\cdot}27^{-1}$	$1{\cdot}58^{-1}$	$1{\cdot}55^{-1}$	$1{\cdot}23^{-1}$	$6{\cdot}92^{-2}$
50	2·73	2·44	$1{\cdot}96^{-1}$	$1{\cdot}49^{-1}$	$1{\cdot}25^{-1}$	$8{\cdot}45^{-2}$	$4{\cdot}06^{-2}$
60	4·05	2·72	$2{\cdot}05^{-1}$	$1{\cdot}22^{-1}$	$8{\cdot}95^{-2}$	$5{\cdot}41^{-2}$	$2{\cdot}37^{-2}$
70	5·67	3·38	$2{\cdot}14^{-1}$	$9{\cdot}91^{-2}$	$6{\cdot}50^{-2}$	$3{\cdot}67^{-2}$	$1{\cdot}52^{-2}$
80	6·78	3·77	$2{\cdot}26^{-1}$	$8{\cdot}84^{-2}$	$5{\cdot}37^{-2}$	$2{\cdot}88^{-2}$	$1{\cdot}14^{-2}$
90	6·76	3·52	$2{\cdot}44^{-1}$	$9{\cdot}04^{-2}$	$5{\cdot}20^{-2}$	$2{\cdot}64^{-2}$	$9{\cdot}89^{-3}$
100	5·53	2·67	$2{\cdot}71^{-1}$	$1{\cdot}02^{-1}$	$5{\cdot}57^{-2}$	$2{\cdot}65^{-2}$	$9{\cdot}29^{-3}$
110	3·61	1·68	$3{\cdot}01^{-1}$	$1{\cdot}17^{-1}$	$6{\cdot}15^{-2}$	$2{\cdot}77^{-2}$	$9{\cdot}08^{-3}$
120	1·86	1·17	$3{\cdot}34^{-1}$	$1{\cdot}35^{-1}$	$6{\cdot}82^{-2}$	$2{\cdot}92^{-2}$	$9{\cdot}00^{-3}$
140	1·80	3·18	$3{\cdot}90^{-1}$	$1{\cdot}65^{-1}$	$7{\cdot}93^{-2}$	$3{\cdot}15^{-2}$	$8{\cdot}90^{-3}$
160	6·11	7·99	$4{\cdot}26^{-1}$	$1{\cdot}84^{-1}$	$8{\cdot}61^{-2}$	$3{\cdot}29^{-2}$	$8{\cdot}80^{-3}$
180	8·84	$1{\cdot}06^{1}$	$4{\cdot}42^{-1}$	$1{\cdot}91^{-1}$	$8{\cdot}86^{-2}$	$3{\cdot}32^{-2}$	$8{\cdot}75^{-3}$

The superscript denotes the power of ten by which the number should be multiplied.

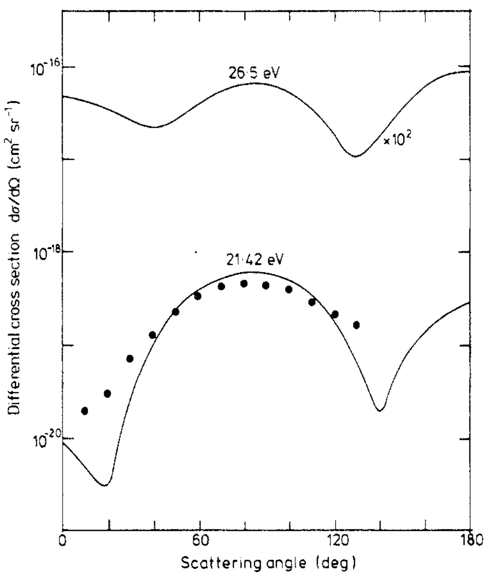

Figure 2. Differential cross section for the process: $e + He(1^1S) \rightarrow e + He(2^3S)$ at low impact energies. Theory: ——, present R-matrix five-state calculation. Experiment: ●, Pichou *et al* (1976).

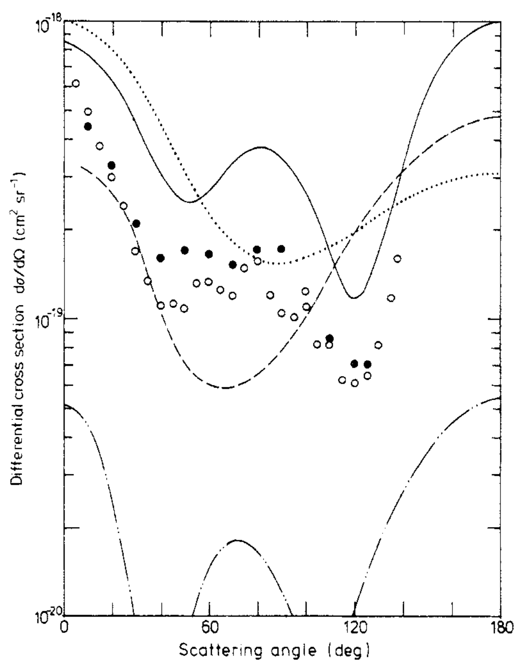

Figure 3. Same as figure 2 except here the energy is 29·6 eV. Theory: ——, present R-matrix five-state calculation; · · · , Thomas *et al* (1974); - - -, Shelton *et al* (1973); – · · – · · –, Scott and McDowell (1975). Experiment: ●, Hall *et al* (1973); ○, Trajmar (1973).

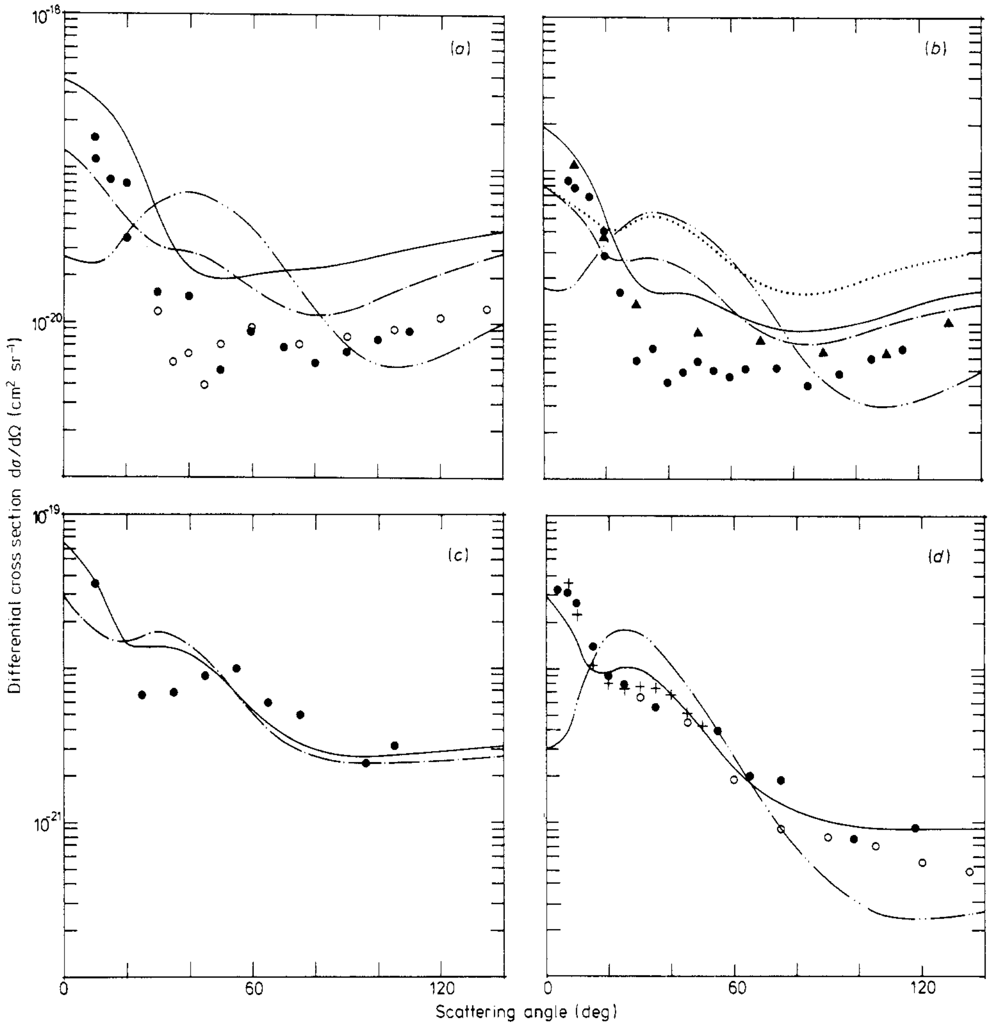

Figure 4. Same as figure 2 except here the energies are (*a*) 81·63 eV; (*b*) 100 eV; (*c*) 150 eV; (*d*) 200 eV. Theory: ——, present R-matrix five-state calculation; – · – · –, Bransden and Winters (1975); – · · – · · –, Scott and McDowell (1975); · · · , Thomas *et al* (1974). Experiment: ●, Yagishita *et al* (1976); ○, Opal and Beaty (1972); ▲, Crooks (1972); +, Dillon (1975).

The angular dependence for the 2^3S excitation is very complicated and it is not easy to derive any systematic variation of angular dependence with collision energy. In accordance with the present R-matrix method results, the general features can be observed as (i) a sharp forward peak at all energies; and (ii) the presence of two minima at low energies.

In figure 3, our calculations for 2^3S excitation at 29·6 eV are compared with the experiments of Hall *et al* (1973) and Trajmar (1973) and theoretical results calculated by the distorted-wave approximation (Shelton *et al* 1973); the many-body Green's function theory (Thomas *et al* 1974), and the distorted-wave polarised-orbital method (Scott and McDowell 1975). The experiments are in good agreement with each other.

However, the theoretical calculations show considerable divergence. While the calculations of Shelton *et al* (1973) and Thomas *et al* (1974) predict a single broad minimum, the results of Scott and McDowell (1975) show two pronounced minima. The overall agreement between these calculations and the experiments is very poor both in shape and in magnitude. Our present calculation predicts two pronounced dips at angles of 50° and 120° which is consistent with the experiments, but our calculation is considerably higher than both sets of experimental data.

Our calculations at 29·6 eV shown in figure 3 manifest distinctly the forward-peaking behaviour and show the unmistaken presence of two minima. The forward-peaking behaviour persists at all energies considered and the two pronounced dips also show up in our calculations at much lower energies (see figure 2) even in the neighbourhood of the 2^3S threshold. At higher energies, as the incident electron energy increases, the first dip becomes shallower and turns into a bend as observed by Yagishita *et al* (1976), while the second dip fades away slowly but a trace of the second dip can still be recognised even at incident energies as high as 200 eV.

At incident electron energies above 81·6 eV, it seems that the quantitative discrepancy between our calculations and the experiments of Hall *et al* (1973) and Trajmar (1973) shown at 29 eV gradually disappears as the incident energy increases. Our calculations are in better agreement with the measurements of Crooks (1972) and Dillon (1975) (see figures 4(*b*) and (*d*)) than with those of Yagishita *et al* (1976). At these energies, the calculation of Thomas *et al* (1974) appears to be rather high at large angles and underestimates the differential cross section at small angles. The agreement between our calculations and those of Bransden and Winters (1975) is excellent at large angles but their method seems to underestimate the differential cross sections at small angles. The calculation of Scott and McDowell (1975) is also shown in figure 4. They do not reproduce the sharp increase in the differential cross section at small angles of scattering.

3.2.1. $1^1S \to 2^3P$ total cross section. Our calculated total cross sections for 2^3P excitation are also displayed in table 1. They are compared with the experimental measurements and other theoretical calculations in figure 5.

The experimental measurements of A Yagishita (1978, private communication), Trajmar (1973), Hall *et al* (1973), Jobe and St John (1967) are in general agreement among themselves, showing a maximum at about 30 eV. At higher energies, the experiments show a steep descent as the incident energy increases, although the slope of descent for the 2^3P excitation is not as steep as that for the 2^3S excitation. Our *R*-matrix five-state calculation is in accord with the DWPO I calculations of Scott and McDowell (1976) throughout the energy range. Both of these calculations are within the experimental error bars of A Yagishita (1978, private communication) at energies greater than 150 eV, while they overestimate the 2^3P total cross section for energies less than 100 eV.

3.2.2. $1^1S \to 2^3P$ differential cross section. Our calculated differential cross sections for $1^1S \to 2^3P$ excitation are displayed in table 3 and they are compared with experimental measurements and other theoretical calculations in figures 6, 7 and 8.

At high impact energies the angular dependence of our differential cross sections for the 2^3P excitation is found to be in complete contrast to that of the 2^3S excitation. Instead of showing a strong forward peak, the differential cross sections for the $1^1S \to 2^3P$ transition is shown to decrease rapidly at small scattering angles and gives rise

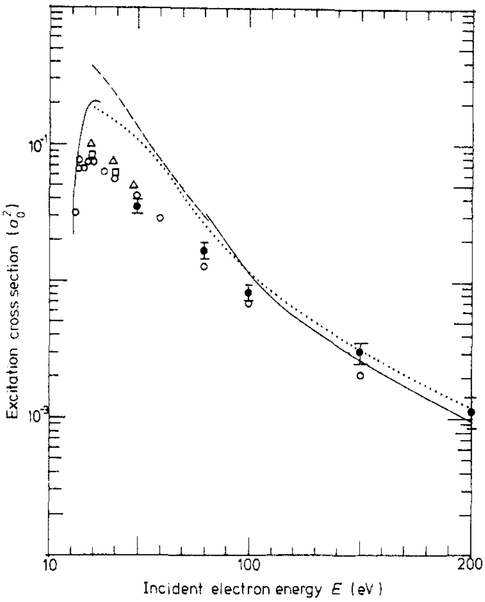

Figure 5. Total cross section for the process: $e+He(1^1S) \rightarrow e+He(2^3P)$. Theory: ——, present R-matrix five-state calculation; · · ·, Scott (1976); – – –, Thomas *et al* (1974). Experiment: □, Trajmar (1973); △, Hall *et al* (1973); ○, Jobe and St John (1967); ●, A Yagishita (1978, private communication).

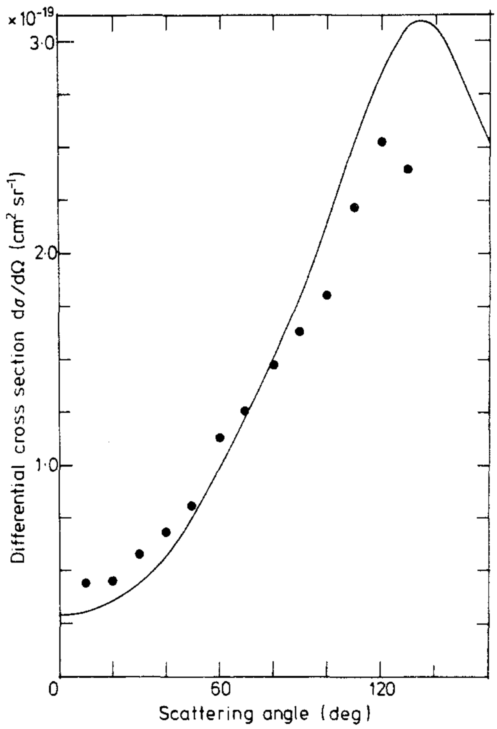

Figure 6. Differential cross section for the process: $e+He(1^1S) \rightarrow e+He(2^3P)$ at an electron impact energy 2 eV above the 2^3P threshold. Theory: ——, present R-matrix five-state calculation. Experiment: ●, Pichou *et al* (1976).

to a clear maximum at angles of a few tens of degrees; this maximum moves to smaller values as the impact energy increases. For impact energies above 100 eV, very good agreement is observed between our calculation and the experiments of Yagishita *et al* (1976). For energies below 81·6 eV, the agreement is not so good (see figures 7 and 8(a)); however, among many calculations (Scott and McDowell 1976, Thomas *et al* 1974, Shelton *et al* 1973), our calculation gives somewhat better qualitative agreement with the experiments (Hall *et al* 1973, Trajmar 1973, Chutjian and Srivastava 1975, Yagishita *et al* 1976). However as the energy of the incident electron increases it appears that results of Scott and McDowell and Thomas *et al* and the present results tend to come closer to each other. Figure 6 shows that there is good agreement between our calculation and the experimental data of Pichou *et al* (1976).

3.2.3. $1^1S \rightarrow 2^3P$ *orientation and alignment parameters.* If b_m ($m = 0, \pm 1$) denotes the amplitude for scattering to the magnetic sublevels, then the differential cross sections σ_m for excitation to the magnetic sublevels are

$$\sigma_0 = |b_0|^2 \qquad \sigma_1 = \sigma_{-1} = |b_1|^2$$

and the total differential cross section $\sigma = \sigma_0 + 2\sigma_1$. In general b_m is complex and can be written as $b_m = |b_m|\, e^{i\chi_m}$ where χ is the phase. The orientation and alignment parameters λ and χ are then defined as

$$\lambda = \sigma_0/\sigma \qquad (0 \leq \lambda \leq 1)$$

$$\chi = \chi_1 - \chi_0 \qquad (-\pi < \chi \leq \pi).$$

Table 3. Differential cross section for electron excitation of the 1^1S state of helium to the 2^3P state (in units of 10^{-19} cm^2 sr^{-1}).

Angle (deg)	Energy of incident electron E (eV) 26·5	29·6	81·63	100	120	150	200
0	1·97	4·29	2·28	$9{\cdot}51^{-1}$	$5{\cdot}10^{-1}$	$2{\cdot}58^{-1}$	$1{\cdot}11^{-1}$
10	2·05	4·37	2·87	1·44	$9{\cdot}07^{-1}$	$5{\cdot}63^{-1}$	$3{\cdot}19^{-1}$
20	2·31	4·61	3·61	1·86	1·13	$6{\cdot}23^{-1}$	$2{\cdot}77^{-1}$
30	2·74	4·97	3·25	1·44	$7{\cdot}41^{-1}$	$3{\cdot}27^{-1}$	$1{\cdot}09^{-1}$
40	3·19	5·22	2·26	$8{\cdot}18^{-1}$	$3{\cdot}59^{-1}$	$1{\cdot}32^{-1}$	$3{\cdot}49^{-2}$
50	3·49	5·17	1·40	$4{\cdot}17^{-1}$	$1{\cdot}59^{-1}$	$5{\cdot}03^{-2}$	$1{\cdot}12^{-2}$
60	3·55	4·79	$8{\cdot}40^{-1}$	$2{\cdot}08^{-1}$	$7{\cdot}10^{-2}$	$2{\cdot}03^{-2}$	$4{\cdot}19^{-3}$
70	3·49	4·28	$5{\cdot}12^{-1}$	$1{\cdot}10^{-1}$	$3{\cdot}54^{-2}$	$9{\cdot}98^{-3}$	$2{\cdot}11^{-3}$
80	3·55	3·94	$3{\cdot}36^{-1}$	$6{\cdot}73^{-2}$	$2{\cdot}19^{-2}$	$6{\cdot}44^{-3}$	$1{\cdot}44^{-3}$
90	3·98	4·02	$2{\cdot}43^{-1}$	$5{\cdot}02^{-2}$	$1{\cdot}71^{-2}$	$5{\cdot}16^{-3}$	$1{\cdot}21^{-3}$
100	4·80	4·57	$1{\cdot}91^{-1}$	$4{\cdot}22^{-2}$	$1{\cdot}49^{-2}$	$4{\cdot}57^{-3}$	$1{\cdot}09^{-3}$
110	5·82	5·38	$1{\cdot}58^{-1}$	$3{\cdot}75^{-2}$	$1{\cdot}35^{-2}$	$4{\cdot}18^{-3}$	$9{\cdot}89^{-4}$
120	6·61	6·06	$1{\cdot}32^{-1}$	$3{\cdot}34^{-2}$	$1{\cdot}22^{-2}$	$3{\cdot}81^{-3}$	$8{\cdot}98^{-4}$
140	6·11	5·49	$8{\cdot}68^{-2}$	$2{\cdot}45^{-2}$	$9{\cdot}57^{-3}$	$3{\cdot}16^{-3}$	$7{\cdot}44^{-4}$
160	3·12	2·43	$5{\cdot}32^{-2}$	$1{\cdot}73^{-2}$	$7{\cdot}77^{-3}$	$2{\cdot}74^{-3}$	$6{\cdot}58^{-4}$
180	1·33	$5{\cdot}66^{-1}$	$4{\cdot}06^{-2}$	$1{\cdot}44^{-2}$	$7{\cdot}12^{-3}$	$2{\cdot}59^{-3}$	$6{\cdot}32^{-4}$

The superscript denotes the power of ten by which the number should be multiplied.

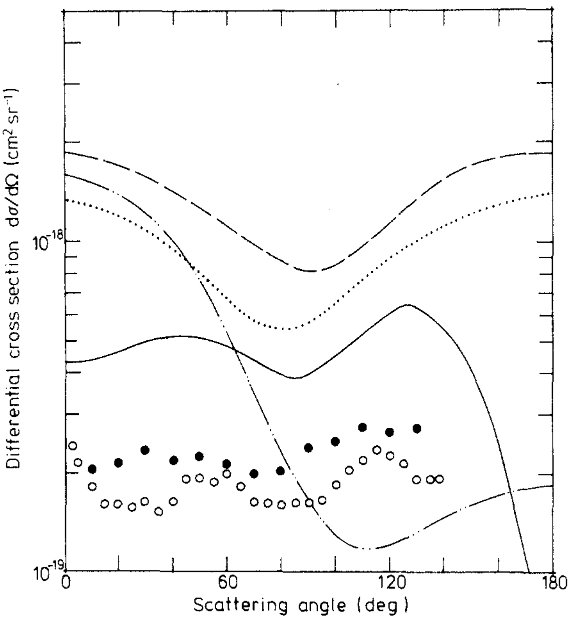

Figure 7. $1^1S \rightarrow 2^3P$ differential cross section at 29·6 eV. Theory: ——, present R-matrix five-state calculation; · · · , Thomas *et al* (1974); – – –, Shelton *et al* (1973); – · · – · · –, Scott and McDowell (1975), Scott (1976). Experiment: ●, Hall *et al* (1973); ○, Trajmar (1973).

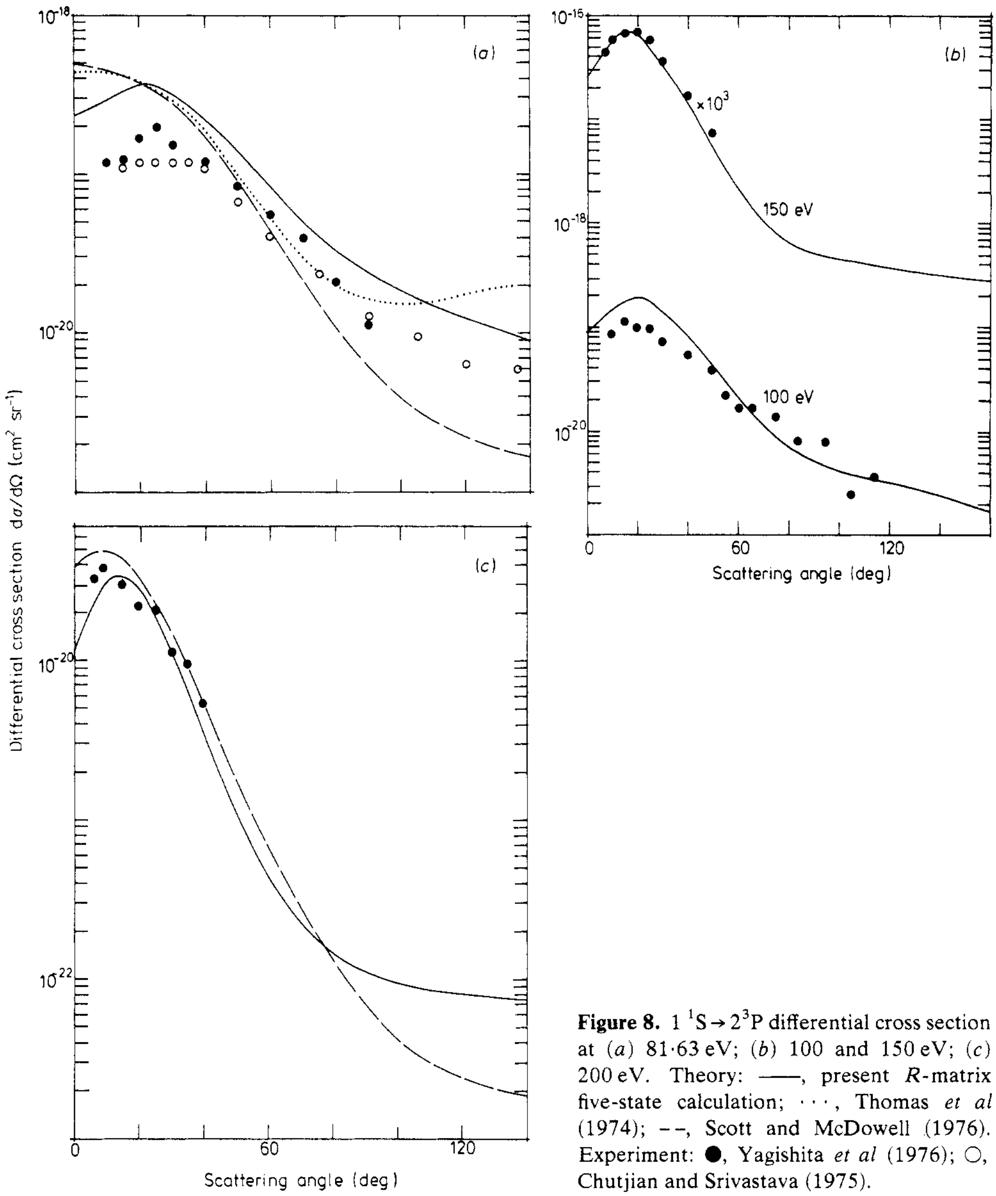

Figure 8. $1\,^1S \rightarrow 2^3P$ differential cross section at (*a*) 81·63 eV; (*b*) 100 and 150 eV; (*c*) 200 eV. Theory: ——, present *R*-matrix five-state calculation; · · · ·, Thomas *et al* (1974); – –, Scott and McDowell (1976). Experiment: ●, Yagishita *et al* (1976); ○, Chutjian and Srivastava (1975).

The values of these parameters obtained using the five-state *R*-matrix calculations are tabulated in tables 4 and 5.

4. Conclusions

We have presented our five-state *R*-matrix results for total and differential cross sections for the $1^1S \rightarrow 2^3S$ and $1^1S \rightarrow 2^3P$ transitions. Above about 100 eV our results are in good agreement with experiment and are a considerable improvement on earlier calculations. In addition at low energies, below the $n = 3$ threshold, our earlier

Table 4. Parameter λ for the excitation of the 2^3P state of helium.

Angle (deg)	Energy of incident electron E (eV) 26·5	29·6	81·63	100	120	150	200
0	1·000	1·000	1·000	1·000	1·000	1·000	1·000
10	0·943	0·959	0·792	0·668	0·570	0·468	0·352
20	0·812	0·864	0·623	0·503	0·432	0·372	0·314
30	0·690	0·778	0·629	0·538	0·492	0·456	0·422
40	0·618	0·739	0·722	0·654	0·623	0·603	0·588
50	0·589	0·743	0·824	0·776	0·758	0·755	0·774
60	0·582	0·770	0·884	0·849	0·841	0·854	0·900
70	0·598	0·811	0·871	0·826	0·810	0·819	0·860
80	0·654	0·862	0·782	0·703	0·677	0·686	0·720
90	0·740	0·892	0·646	0·570	0·563	0·585	0·632
100	0·798	0·859	0·493	0·476	0·511	0·554	0·611
110	0·788	0·755	0·334	0·414	0·497	0·565	0·630
120	0·720	0·611	0·188	0·375	0·504	0·596	0·670
140	0·525	0·311	0·048	0·399	0·598	0·719	0·794
160	0·515	0·208	0·460	0·717	0·843	0·902	0·936
180	1·000	1·000	1·000	1·000	1·000	1·000	1·000

Table 5. Parameter χ (in radians) for the excitation of the 2^3P state of helium.

Angle (deg)	Energy of incident electron E (eV) 26·5	29·6	81·63	100	120	150	200
0	−1·430	−1·562	−1·195	−1·055	−0·944	−0·832	−0·706
10	−1·364	−1·497	−1·123	−0·960	−0·849	−0·734	−0·616
20	−1·189	−1·322	−0·988	−0·822	−0·723	−0·628	−0·546
30	−0·952	−1·087	−0·923	−0·790	−0·721	−0·660	−0·611
40	−0·720	−0·855	−0·979	−0·884	−0·845	−0·811	−0·788
50	−0·551	−0·679	−1·193	−1·143	−1·141	−1·148	−1·155
60	−0·494	−0·603	−1·656	−1·680	−1·751	−1·846	−2·001
70	−0·590	−0·682	−2·279	−2·415	−2·584	−2·805	3·090
80	−0·854	−0·990	−2·729	−2·998	3·036	2·774	2·391
90	−1·256	−1·592	−3·006	2·856	2·549	2·291	1·961
100	−1·775	−2·279	3·097	2·531	2·193	1·941	1·656
110	−2·297	−2·731	2·956	2·277	1·943	1·702	1·451
120	−2·700	−3·001	2·781	2·048	1·741	1·520	1·295
140	3·035	2·861	1·358	1·493	1·358	1·243	1·054
160	2·457	1·985	0·437	1·044	1·066	1·046	0·846
180	2·09	1·35	0·352	0·88	0·94	0·86	0·64

calculations (Fon *et al* 1978) were satisfactory. However at intermediate energies our cross sections are too high. This intermediate energy region is also complicated by the presence of many pseudo-resonances in our approximation which make the determination of the differential cross section difficult. In conclusion therefore we have shown that accurate spin exchange cross sections can be obtained at low energies and at high energies but that there is still an energy gap where further theoretical work is necessary.

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