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Momentum-transfer cross section for electron-helium collisions in the range 4–12 eV

H. B. Milloy and R. W. Crompton

Electron and Ion Diffusion Unit, Research School of Physical Sciences, Australian National University, Canberra, Australia 2600

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Drift velocities of electrons in helium at 293 K have been measured in the range $2.5 \leq E/N \leq 7.0$ Td ($1\ \mathrm{Td} = 10^{-17}\ \mathrm{V/cm^2}$), and analyzed to determine the momentum-transfer cross section between 4 and 12 eV. The estimated error bounds on the cross section are $\pm 3\%$ in the range $4 \leq \epsilon \leq 7$ eV and $\pm 5\%$ in the range $7 < \epsilon \leq 12$ eV. The implications of the new result to the problem of determining standard cross sections for electron-helium scattering below the first excitation threshold are discussed.

I. INTRODUCTION

In recent years there has been considerable theoretical and experimental effort to derive reliable elastic-scattering data at low energies which, apart from their fundamental importance, can be used to normalize electron-beam data.[1] Much of the effort has been concentrated on electron-helium scattering because, below the first excitation threshold, helium is one of the simplest targets to study both experimentally and theoretically.

In their 1971 review of low-energy elastic scattering, Bederson and Kieffer[1] concluded that the total cross section for helium had not been determined experimentally "to better than perhaps 10–15%" and that further work remained to be done before the helium cross section could be accepted as a suitable cross-section standard. A higher accuracy had been claimed by Crompton *et al.*[2] for the momentum-transfer cross section over a more limited energy range, but several factors were against the unqualified acceptance of this cross section. First, for energies less than 3 eV, where the maximum accuracy was claimed for the experimental cross section, there were considerable discrepancies between the results of alternative theoretical approaches[3,4]; second, since a comparison of the momentum-transfer cross section and the total cross sections measured in transmission experiments rests on a knowledge of angular scattering data, a comparison of the total cross section calculated from the swarm-derived momentum-transfer cross section with the results of transmission experiments was open to question at the time of the review; third, the limited range of the swarm-derived cross section itself posed some problems in making comparisons with the results of beam experiments since there was limited overlap of the energies at which the beam and swarm techniques might be expected to yield their most reliable results.

Two new factors have prompted a reexamination of this problem. Since 1971 there have been several new theoretical attacks[5-8] on e-He scattering in this energy range all of which are in good agreement above 4 eV, although the agreement at lower energies is still unsatisfactory. In addition, the recent experimental work of Andrick and Bitsch[9] has provided for the first time the possibility of a *direct* comparison between the results of beam and swarm experiments since their phase-shift analysis of the angular scattering data from their crossed-beam experiment provides absolute data for the momentum-transfer cross section as well as the total and differential cross sections. However, for a significant comparison to be made between swarm data and these new theoretical and experimental data it is necessary to have data for the swarm-derived momentum-transfer cross section of higher accuracy than was previously available for energies greater than 3 eV.[10] This in turn requires more accurate mobility data for $E/N > 3.5$ Td (E/N is the ratio of electric field strength to gas number density; 1 townsend $= 10^{-17}\ \mathrm{V/cm^2}$).

We have therefore extended measurements of the drift velocity W of electrons in helium up to E/N values of 7 Td and analyzed the data to determine the momentum-transfer cross section $q_m(\epsilon)$ for energies up to 12 eV. The cross section so obtained is compared in Sec. IV with Andrick and Bitsch's results and with theoretical results that have been published since the 1971 review.

II. EXPERIMENTAL TECHNIQUE AND RESULTS

A full description of the design and mode of operation of the drift tube and associated equipment used in this work has already appeared in the literature.[11,12] The overall accuracy of the apparatus was checked by repeating some earlier measurements of the drift velocity of electrons in helium at 293 K by Crompton *et al.*[13] The largest discrepancy between the present and previous results was 0.2%, which compares favorably with the

TABLE I. Drift velocity of electrons in helium at 293 K.

E/N (Td)	W (10^5 cm/sec)
2.5	7.68
3.0	8.49
3.5	9.26
4.0	10.01
5.0	11.52
6.0	13.13
7.0	15.03

TABLE II. Momentum-transfer cross section for electron-helium collisions.

ϵ (eV)	$q_m(\epsilon)$ (Å^2)
4.00	6.62
5.00	6.31
6.00	6.00
7.00	5.68
8.00	5.35
9.00	5.03
10.00	4.72
11.00	4.44
12.00	4.15

error limits of ±1% quoted by these authors.

The drift-velocity results are listed in Table I. There are two main sources of error in the measurements. The larger of these is due to uncertainty in the magnitude of the correction applied to account for diffusive effects.[12,14] We applied the formula for the correction factor derived empirically by Crompton *et al.*[13] from measurements made at lower E/N values. In order to ensure that we have not underestimated the errors in our drift-velocity data from the assumption that the same formula can be applied at higher E/N, we assumed that the corrections may be in error by a factor of 2. Since the corrections applied to the data were everywhere less than 1%, we have included an uncertainty of 1% to allow for this contingency. The other main source of error was in the measurement of the transit time of the electrons between the shutters. At high values of E/N the peaks in the current-frequency spectra were very broad making accurate transit-time measurements difficult. The breadth of the peaks was a result of the low pressure (2.69 kPa) required to attain high E/N values without electrical breakdown and the high values of D_L/μ, the ratio of the longitudinal diffusion coefficient to mobility. In addition there was a background current due to the inability of the shutters to stop the electrons in the high-energy tail of the energy distribution even when the maximum gating voltage was applied to the shutters. These two factors combined to introduce an uncertainty of <0.3% in the transit-time measurements. When other sources of error such as uncertainties in the pressure and temperature measurements were considered, we concluded that the total estimated error in the W data was <1.5%.

III. MOMENTUM-TRANSFER CROSS SECTION

The momentum-transfer cross section was determined by adjusting trial cross sections until the measured drift velocities agreed to within 0.2% with the calculated values of all E/N.[15] In the fitting procedure Crompton, Elford, and Robertson's cross section[2] was used without modification at energies in the range 0–3 eV. The cross section derived at higher energies is listed in Table II. Using the method of assessment developed previously,[2] it was concluded that the present cross section is in error by < ± 3% at energies in the range 4–7 eV and by < ± 5% in the range 8–12 eV.

IV. DISCUSSION

The momentum-transfer cross section derived in this work can be compared directly with the results of single-collision experiments only when such experiments provide angular distribution data which may be subsequently analyzed to give sets of phase shifts as in the work of Andrick and Bitsch.[9] Provided the relative errors in the primary angular scattering data are small, it is possible to derive unique values for the phase shifts at each energy and hence the absolute differential, momentum transfer, and total cross sections. The momentum-transfer cross section derived in this way by Andrick and Bitsch is compared with the present result in Fig. 1. The error limits claimed by Andrick and Bitsch are ±11% at 5 eV decreasing to ±3% at 12 eV. There is thus no significant disagreement between their determination and ours within the common energy range, while at the upper end where the error limits claimed for both are better than 5% the agreement is to within 2%. The agreement between the results of these fundamentally different experiments can be taken as confirming the estimates of error for each and the validity of the cross section at least to within 5% between 9 and 12 eV.

In this energy range the agreement with theory is equally satisfactory. The results of Duxler *et al.*'s full polarized orbital treatment,[5] Sinfailam and Nesbet's variational calculation,[6] and Yarla-

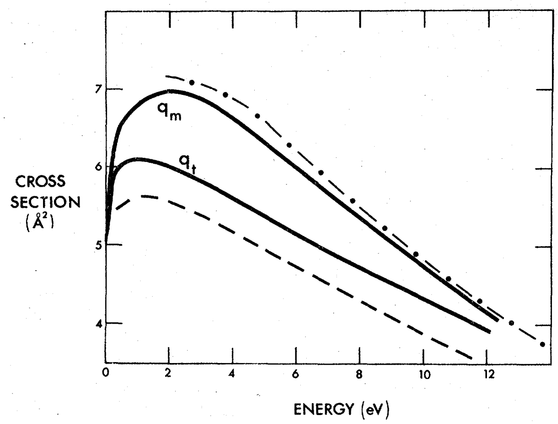

FIG. 1. The momentum-transfer cross section (q_M) derived in this work is compared with that derived by Andrick and Bitsch (— • —). Also plotted are the total cross sections (q_T) derived in this work and measured by Golden and Bandel (---).

gadda *et al.*'s calculation based on the use of Green's functions in a many-body perturbation treatment[7] all agree with the present result to within 2.5%. The agreement with Wichmann and Heiss's variational calculation[8] is to within 4%.

Although experimental derivations of the momentum-transfer cross section $q_m(\epsilon)$ cannot be compared directly with results for the total cross section $q_t(\epsilon)$, a comparison can be made by using the ratio of $q_t(\epsilon)/q_m(\epsilon)$ computed from phase-shift or angular scattering data.[1] Modified effective-range theory[16,17] cannot be used in this energy range since the range of its application must be restricted to energies below about 1 eV if the accuracy is to be better than 5%.[18] It has been argued[1] that the error in $q_t(\epsilon)/q_m(\epsilon)$ is likely to be smaller than the error in either $q_t(\epsilon)$ or $q_m(\epsilon)$. To effect the comparison we have calculated the $q_t(\epsilon)/q_m(\epsilon)$ ratios from the experimentally determined phase shifts of Andrick and Bitsch and from the data of the four theoretical analyses[5-8] referred to above. At all energies the values of the ratio lay within ±1% of the mean values confirming that the accuracy of the ratio is higher than the accuracy of the individual cross sections. The actual values of $q_t(\epsilon)/q_m(\epsilon)$ used to convert our values of $q_m(\epsilon)$ were those of Sinfailam and Nesbet; the resultant $q_t(\epsilon)$ is plotted in Fig. 1. When the 1% uncertainty in the ratio $q_t(\epsilon)/q_m(\epsilon)$ and the errors in $q_m(\epsilon)$ are taken into account, it is estimated that the total cross section derived in this way is in error by $< \pm 4\%$ for energies between 4 and 7 eV and $< \pm 6\%$ from 8 to 12 eV.

The agreement between the total cross section derived by Andrick and Bitsch and the cross section calculated from our momentum-transfer cross section is of the same order as the agreement between the two momentum-transfer cross sections, that is, a worst discrepancy of 4% and agreement to within 2% at higher energies where there is a marked improvement in the accuracy of the beam experiment. A comparison with the cross section measured by Golden and Bandel,[19] which is shown as a dashed line on the figure, shows good agreement with respect to the energy dependence in the energy range under discussion but a difference in normalization amounting to about 9%, just outside the error limit of 7% obtained by summing the individual errors discussed by Golden and Bandel. Because the 9% discrepancy is maintained into the energy region below 3 eV where error limits of ± 3% might reasonably be assigned to the total cross section derived from the swarm measurements, and because of the excellent agreement between theory and the present results at higher energies, we believe there is strong evidence in favor of Andrick and Bitsch's conclusion that Golden and Bandel's cross section is subject to a systematic error of about 10%.

V. CONCLUSION

The new results have a bearing on the problem of determining standard cross sections (or phase shifts) for electron-helium scattering below the first excitation threshold which will be discussed in more detail elsewhere. The present situation may be summarized as follows:

(1) Above about 9 eV, where the error limits for Andrick and Bitsch's momentum-transfer cross section become less than about 4%, the agreement between three of the four theoretically derived cross sections cited above and Andrick and Bitsch's cross section is to within 3%, while between 7 and 12 eV there is agreement between theory and our momentum-transfer cross section to within 2% even though the error limits for the latter are ± 5%.

(2) The agreement of our momentum-transfer cross section with theory remains to within ± 2% down to 4 eV. When it is noted that the claimed accuracy of the experimental result is ± 3% between 4 and 7 eV, *the overall agreement between the theory, our results, and those of Andrick and Bitsch provides strong evidence that the cross sections derived from theoretically derived phase shifts are accurate to within 2 or 3% above 4 eV.*

(3) Below 4 eV the discrepancy between theory and the swarm-derived momentum-transfer cross section increases, but the theoretical cross sections themselves no longer agree. For example, the cross sections of Sinfailam and Nesbet[6] and

of Duxler *et al.*[5] differ by about 7% at 0.1 eV. The worst disagreement between the swarm-derived cross section[2] and the cross section of Sinfailam and Nesbet is 4%.

(4) There are a number of points in favor of the experimental result rather than the theoretical result(s) at low energies. These are (a) that smaller error limits (± 2%) can be assigned to the experimental cross section below 3 eV because of the increased accuracy with which mobility measurements have been made at lower E/N; (b) that the cross section and/or its normalization have been checked through an analysis of the results of other types of swarm experiment[13,20,21]; (c) that the validity of the transport theory on which the analysis depends has been checked[15,22] over the entire range of E/N covered by this and earlier investigations; (d) the independent check of the accuracy of the swarm-derived cross section at higher energies as reported in this paper where there is convergence between all the theoretical results, our results and those of Andrick and Bitsch. *Thus it seems reasonable to claim an accuracy of ± 2% for the momentum-transfer cross section below 4 eV even though there is less supporting evidence from single-collision experiments and theory in this energy range.*

(5) Because the ratios of $q_t(\epsilon)/q_m(\epsilon)$ found from theory[5-8] agree to within ±1% at all energies, *it also seems reasonable to claim an error limit of 3 or 4% for the total cross section in the low-energy region found by multiplying the swarm-derived momentum-transfer cross section by the theoretically derived ratio of* $q_t(\epsilon)/q_m(\epsilon)$.

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