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Absolute total cross section measurements for intermediate energy electron scattering I. He†

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Abstract. Total absolute cross section measurements have been performed on the e^-–He system in the energy range 100–1400 eV. A modified Ramsauer-type apparatus was used; the angular resolution was increased by means of a new original design of the interaction chamber. An analysis of the experimental accuracy is given. The systematic uncertainty is 2%; the random uncertainty is 1·5%. The measurements are compared with those of other experimental and theoretical groups. Good agreement is found with the latest experimental results.

1. Introduction

As a consequence of the renewed interest in atomic physics, a growing number of theoretical and experimental papers on electron–atom and electron–molecule total cross section are now being published aiming at a deeper insight into the subject.

In our laboratories in Trento, as an extension of our previous work on electron scattering at low energies (0·5–100 eV), we decided to extend the energy range of our experiments. We have built a Ramsauer-type apparatus suitable for both e^-–molecule and H^+-molecule scattering from 100 to 2000 eV and 5 to 50 eV respectively.

To test the performance of the new machine we have chosen to measure the e^-–He total cross section for two reasons. Firstly, helium has been studied in other laboratories so that some comparisons are possible, and secondly, because the e^-–He is a simple system where the chances of building reliable theoretical models are highest. Moreover, because of the rather large spread in both the experimental and theoretical cross sections determined previously, it appears that a series of new measurements could be quite useful to improve our knowledge of such an important system.

The latest absolute measurements on e^-–He total cross sections above 100 eV were performed up to 750 eV by de Heer's group at the FOM laboratories in Amsterdam during the last few years (Blaauw *et al* 1977, Wagenaar 1978). Recent theoretical work has been extensive but not necessarily conclusive because of the lack of experimental data in the higher energy range.

In the present paper we describe the new Ramsauer-type apparatus (with an improved scattering geometry that allows for a better angular resolution) and present absolute total cross sections for the e^-–He system obtained using it over the range 100–1400 eV.

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2. Experimental apparatus

The basic scheme of the apparatus is shown in figure 1. The configuration is of the Ramsauer type (Bederson and Kieffer 1971). The orbital radius is 200 mm.

The main difference in comparison with previous Ramsauer-type apparatuses lies in the interaction chamber. In the present apparatus the interaction chamber was split into two electrically connected parts. The first one (called the 'gas chamber' from now on) limits the gas region (from slit S_5 to S_6). The second part (S_6 to S_7) is a pumped section in which the pressure is held constant at less than the gas chamber pressure by means of a diverter valve (Basta *et al* 1976). If this pressure stays constant, it is easily shown that no correction need be made to the gas chamber length to allow for the presence of gas in the second part of the interaction chamber.

In addition, measurements at energies higher than 600–700 eV would not have been possible without the diverter valve, due to the gas–beam and gas–cathode interactions.

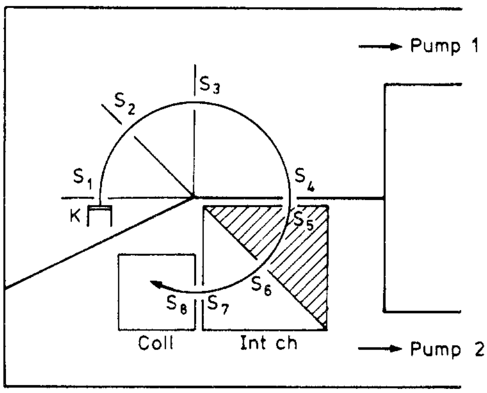

Figure 1. Basic scheme of the apparatus. K: cathode; Int ch: interaction chamber (hatched: the 'gas chamber'); Coll: collector.

2.1. Angular resolution

The main purpose of splitting the interaction chamber was to improve the angular resolution of the Ramsauer configuration. Referring to figure 2(a), one can see that electrons which enter the interaction chamber in a collimated beam and are scattered are not counted as scattering events (i.e. they reach the collector) if their scattering angle is such that their trajectory is not intercepted by the exit aperture (see trajectory A–A'). Electrons can be scattered at large angles and reach the collector anyway if the scattering happened in the vicinity of the output aperture (see trajectory *B–B'*).

With the modification introduced (figure 2(b)), events of the B–B' type are intercepted by the second baffle of the interaction chamber (S_7) and therefore they are correctly counted as scattering events. Note that also part of the events of the A–A' type are correctly counted.

The resolution of the apparatus, as defined by Kusch (1964), was evaluated at 0·7°. Alternatively, the angular acceptance of the detector can be given as 5×10^{-4} sr.

These figures refer to the slit dimensions given in table 1. With these dimensions, the energy resolution was $E/\Delta E \simeq 100$.

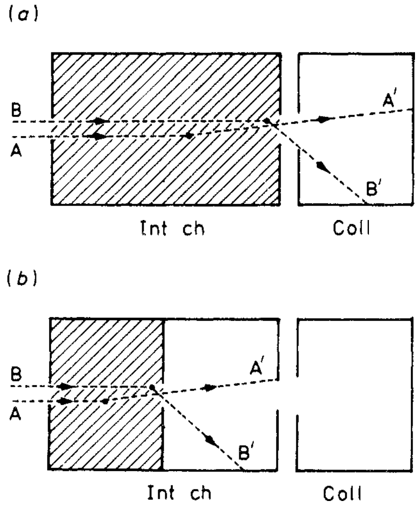

Figure 2. Interaction chamber and collector. (*a*) Standard set-up; (*b*) present set-up. (The dimensions are not to scale.) (Hatched: the 'gas chamber'.)

Table 1. Slit dimensions (mm)

Slit number	Width	Height
1	1·0	3·0
2	2·5	3·2
3	2·0	3·2
4	1·0	3·0
5	1·3	3·3
6	3·5	4·7
7	4·5	6·3
8	5·0	6·5

2.2. Magnetic field

The bending magnetic field was generated by a pair of ironless Helmholtz coils. The distance between the coils was computer optimised in order to achieve the best field uniformity in the region occupied by the electron beam. With a mean radius of the coils of 688 mm and a mean distance of 635 mm, the non-uniformity on the beam section was computed at less than 1 part over 10^4.

The Earth's magnetic field was compensated by means of additional coils.

2.3. Pumping system

The apparatus was supplied with a differential pumping system reaching the ultimate pressure of 1×10^{-8} Torr.

The first pump was connected to the cathode and selection region, the second one to the interaction chamber and collector region. Differential pumping enables the cathode and selection region pressure to be kept constant, smaller than the gas chamber pressure by a factor of at least 1000.

3. Experimental procedure

A single measurement run, at a fixed energy, consisted in measuring seven to eleven different values of gas pressure, and the corresponding pairs of currents: I_c (current reaching the collector), I_s (current intercepted by the interaction chamber).

The experimental cross section σ was evaluated from the formula

$$I_{ci}/(I_{ci}+I_{si}) = I_{cj}/(I_{cj}+I_{sj})\exp[-\sigma l(N_i - N_j)] \tag{1}$$

where l is the gas chamber length, N is the gas density, obtained from the pressure and temperature measurements, the indexes i, j label the values corresponding to two contiguous pressures.

With n pressures, $n-1$ values of the cross section were computed for a single run. The average of these $n-1$ values was assumed to be the best determination of the cross section for that run.

A computer program gave the best fit of $\ln[I_c/(I_c+I_s)]$ versus p on a straight line. The linearity of this relation is known to be a necessary condition for reliable measurements and for the applicability of equation (1).

Typical values of the linear correlation coefficient ranged between $R = 0{\cdot}9999$ and $R = 0{\cdot}99999$.

The pressure in the gas chamber was changed by a factor of 10 to 15 in a single run. Typical values ranging from 1×10^{-3} to 1×10^{-1} Torr were used in different runs. The maximum pressure was chosen to maintain the beam attenuation ratio $(I_{c,max}/I_{c,min})$ below 2·5, in order to keep the probability of double scattering events very low. The independence of the measured cross sections for attenuation ratios up to 3 was checked.

The e^-–He total absolute cross section values given in the first column of table 3 are average values over a minimum of three runs for each point. The standard deviation of these averages was about 1·5%. This figure was then taken as the random uncertainty of our measurements (the error on relative measurements). More attention was paid to some points (e.g. 200, 400, 500, 600, 700, 800, 1000, 1400 eV): for these energies the cross sections were averaged over 10 to 15 measurement runs. The total number of runs was 195 distributed over 29 points.

4. Accuracy evaluation

4.1. *Current measurements*

The electron current reaching the collector and the one intercepted by the interaction chamber were alternatively measured by means of the same amplifier (Keythley mod 417) and three digits DVM, both used on a single range. Typical values of I_c were around 10^{-7} A.

The error in the $I_c/(I_c+I_s)$ ratio is due only to the non-linearity of the electrometer: this was checked to be less than 0·1% for our instrument, which corresponds to an error on the cross section varying from 0·3 to 0·6% over all the energy range.

4.2. *Pressure measurements*

4.2.1. Instrument calibration. The gas pressure was read by means of an MKS Baratron capacitance meter (type 94 AH–1). The instrument was calibrated at the factory to a stated accuracy of 0·15% at 10^{-3} Torr and higher pressures. In view of calibrations of capacitance meters against a McLeod gauge achieved by several authors (e.g. Bromberg 1969), we will assume a (pessimistic) 1% figure for the intrinsic accuracy of our manometer in the pressure range from 1×10^{-3} to 1×10^{-1} Torr.

4.2.2. Reference pressure. The reference pressure of the capacitance head was the pressure in the cathode region of the apparatus. This was not zero but it was kept constant by means of the diverter valve. The systematic error introduced did not propagate to the cross section value, which was computed, following equation (1), from pressure differences.

4.2.3. Thermal transpiration. The thermal transpiration between the manometer and the gas chamber was reduced by having the capacitance head temperature tracking the gas chamber temperature. All measurements were made with a temperature difference smaller than 1 °C. This should limit the error on the cross section to less than ±0·2% (Hobson 1973).

4.2.4. Temperature compensation. The manometer reading was compensated for the temperature coefficient of the head with the manufacturer's compensation unit. The operating temperatures were always between 13 and 20 °C. The correction introduced by the compensation unit was 0·8% in the worst case.

4.3. Temperature measurement

The gas temperature was monitored by means of two thermocouples, the first one near the entrance slit, the second one at the midpoint of the gas chamber. The two thermocouples gave the same reading within 1 °C. By using their mean value, the error on the cross section was at most 0·3%.

4.4. Sample gas purity

Standard precautions were taken in order to avoid sample gas contamination. The helium gas had a certified purity of 99·9996%. The impurities were: $O_2 < 1$ ppm, $N_2 < 2$ ppm, $H_2O < 2$ ppm, $CH_4 < 0{\cdot}2$ ppm. In view of the sufficiently low ultimate pressure of the vacuum system (1×10^{-8} Torr), the error due to the background gas was considered negligible.

4.5. Energy measurements

The entire apparatus, from the anode to the collector, was equipotential. The error due to field penetration in the gas chamber was therefore negligible. The error associated with the energy measurements was estimated to be less than ±0·2%. The contact potential from the cathode to the remaining apparatus, measured with a retarding potential at the anode, was found to be (1·5 ± 0·2) volts. This value was then subtracted from the accelerating voltage reading in order to correct the energy scale. The resulting correction on the cross section amounted to −0·8% in the worst case (100 eV).

4.6. Interaction length determination

4.6.1. Geometrical length. The mean geometrical length of the gas chamber was 147·7 ± 0·3 mm. The ±0·2% uncertainty propagates directly to the cross section.

4.6.2. Trajectories spread. The maximum deviation of the electron trajectories from the mean geometrical length was computed to be ±0·4%.

4.6.3. End effects. It still constitutes a controversial problem whether the corrections to the interaction length due to the gas flow out of the beam entrance and exit apertures of the gas chamber are negligible or not (Toburen *et al* 1968, Mathur *et al* 1975, Blaauw *et al* 1977). The problem was resolved, for the present apparatus, by direct measurement. The cross section measurements were repeated with a different gas chamber for a few energy values. The length of the new gas chamber was 235·6 ± 0·3 mm. The cross sections measured with the two gas chambers were identical within the statistical spread of the measurements (±1·5%).

4.7. Overall accuracy

The error evaluation accomplished in this section is summarised in table 2. By quadratic sum we obtained an overall error of ±2% (error on absolute measurement).

As far as the error due to the apparatus finite angular resolution is concerned, an evaluation was possible only for the total elastic part of the cross section. The small-angle elastic cross section results of Byron and Joachain (1977a, b and private communications) were used. These calculations extend up to 5 keV and are in agreement with the measurements of Bromberg (1974) and Jansen *et al* (1976) in the overlap range. The systematic error due to the apparatus finite angular resolution evaluated from these data ranges from 0·2% at 100 eV to less than 1% at 1400 eV.

The lack of angular inelastic data at sufficiently small angles prevented us from a complete evaluation of the error. The data presented in this paper were thus not corrected for the angular resolution error.

Table 2. Error evaluation in absolute total cross section measurements.

Current measurements	±0·6%
Pressure measurements	
—instrument calibration	±1·0%
—thermal transpiration	±0·2%
Temperature measurement	±0·3%
Interaction length determination	
—geometrical measurement	±0·2%
—trajectories spread	±0·4%
—end effects	±1·5%
Energy measurement	±0·2%
Overall error (quadratic sum)	±2%

5. Discussion

Table 3 and figures 3 and 4 show a comparison of our results with previous experiments and theories. The semiempirical data of de Heer and Jansen (1977) are also quoted. The data of Wagenaar (1978) are a refinement of the data reported by Blaauw *et al* (1977). The measurements of Normand (1930), reported in figure 3, and the calculations of Winters *et al* (1974), reported in figure 4, are not quoted in table 3.

Table 3. e^-–He total scattering cross section (units a_0^2).

	Experimental				Semiempirical	Theoretical				
E(eV)	Present exp	Wagenaar (1978)	Jost and Möllenkamp (1977)	Brode (1925)	de Heer *et al* (1977)	1st Born	EBS[a]	2nd Born[b]	DWSB[c]	OM[d]
100	4·154	3·90		3·94	4·069	3·71	4·68	5·31	5·47	6·16
125	3·628									
150	3·296	3·03	3·22	3·08	3·149	3·15	3·54	3·93		
175	2·928									
200	2·732	2·53	2·69	2·63	2·626	2·67	2·92	3·13	3·20	3·37
250	2·303	2·18								
300	2·021	1·93	1·98	1·90	1·977	2·04	2·15	2·26	2·32	2·38
350	1·839	1·74								
400	1·611	1·57	1·61		1·606	1·65	1·71	1·79	1·83	1·86
450	1·500	1·43								
500	1·346	1·32	1·33		1·358	1·39	1·43	1·49	1·52	1·54
550	1·271	1·24								
600	1·161	1·17				1·21				
650	1·100	1·10								
700	1·011	1·04			1·038	1·07	1·09	1·12	1·15	1·16
750	0·957	0·97								
800	0·914					0·962		1·01		
850	0·864									
900	0·811					0·874				
950	0·775									
1000	0·739				0·763	0·802			0·855	
1050	0·706									
1100	0·689					0·741				
1150	0·665									
1200	0·633					0·690				
1250	0·608									
1300	0·575					0·645				
1350	0·560									
1400	0·527					0·607				

[a] Byron and Joachain (1977b). [b] Buckley and Walters (1974). [c] Dewangan and Walters (1977). [d] Byron and Joachain (1977).

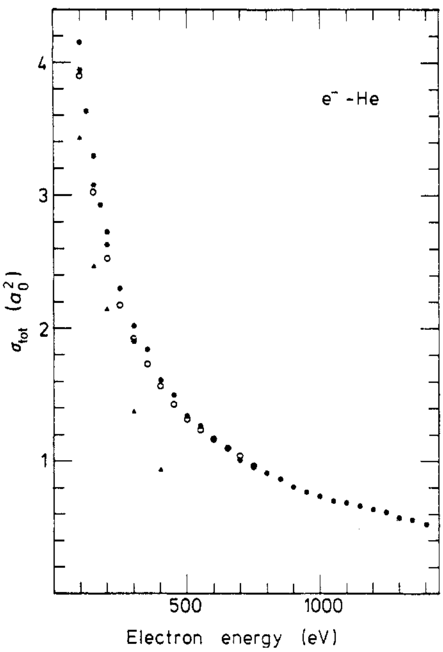

Figure 3. e$^-$–He total cross section versus electron energy. Experimental results: ●, present experiment; ○, Wagenaar (1978); △, Normand (1930); ∗, Brode (1925).

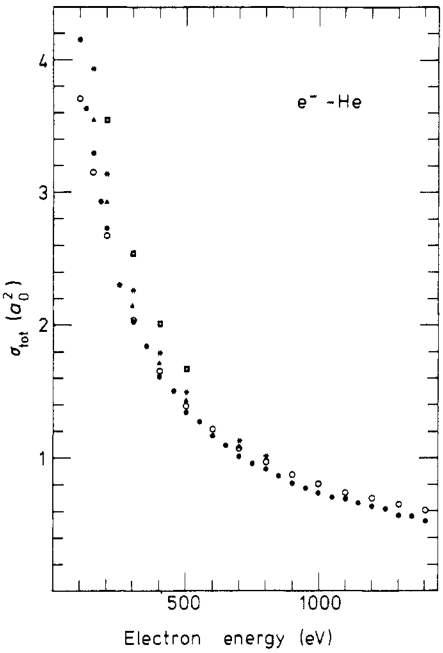

Figure 4. e$^-$–He total cross section versus electron energy. Theoretical results: ●, present experiment; ○, first Born approximation; △, EBS calculations (Byron and Joachain 1977a,b); ∗, second Born approximation (Buckley and Walters 1974); □, SOP calculations (Winters *et al* 1974).

The agreement of our measurements with the data of Jost and Möllenkamp (1977) and Wagenaar (1978) is quite satisfactory. All these measurements fall within ±6% of ours, except for a few points. The data of Jost and Möllenkamp (1977) fall within 2% of ours. The highest discrepancy is found with Wagenaar (1978), whose data are some 7% lower at low energy; the discrepancy is smaller at higher energy.

The agreement of our measurements with the semiempirical data of de Heer and Jansen (1977) is within −4·5% at 140 eV and +3% at 1000 eV. The results of Brode (1925) are near to the recent ones, whereas the results of Normand (1930) are much lower (some 15%; see figure 3).

It is evident from table 3 and figure 4 that the theoretical data are much more scattered than the recent experimental ones. The theoretical data are all higher than the experimental results, except for the first Born approximation calculations (de Heer and Jansen 1977). These results are higher than our experimental data at the highest energies, and are lower from 100 to 200 eV.

The EBS results (Byron and Joachain 1977b) are 5% higher than our data from 200 to 500 eV; they are 13% higher at 100 eV and 11% higher at 1000 eV. Table 3 thus shows, in order of increasing discrepancy from our measurements, the second Born approximation calculations of Buckley and Walters (1974), the distorted-wave second Born calculations (DWSB) of Dewangan and Walters (1977) and the optical model calculations (OM) of Byron and Joachain (1977a). In conclusion, our measurements agree fairly well with the latest experimental data. Of all the theories, the Born approximation is closest to our data. At low energies this agreement may be fortuitous. Towards higher energies, considering more sophisticated theoretical calculations, closest agreement is present with EBS, in particular between 200 and 500 eV within 5% (slightly beyond our error limit). At energies above 500 eV, the agreement between experiment, Born and EBS unexpectedly becomes less good and the difference becomes as great as 15% between Born and present experiment at 1400 eV. This discrepancy might be connected with the 'incompleteness' of our total cross section due to inelastic small-angle scattering into the collector. Theoretical estimates made about this effect would be important.

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