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LETTER TO THE EDITOR

Total scattering cross sections for low-energy electrons in helium and argon

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Abstract. A time-of-flight system developed to study positron scattering has been adapted for electrons. Total scattering cross sections have been measured for helium and argon in the energy range 2–50 eV to absolute accuracies of better than 4%.

The scattering of low-energy electrons by the inert gases has been studied for many years. More recently the development of monoenergetic slow positron beams has enabled similar measurements to be performed for positrons, and several research groups have measured total scattering cross sections covering the range of positron energies between 0·4 and 1000 eV. The low intensity of the positron beams has necessitated the use of single particle counting techniques, the most convenient type of detector used for this purpose being a channel electron multiplier. This detector is equally suitable for positrons and electrons and Stein *et al* (1978) and Kauppila *et al* (1977) have recently measured total cross sections for both particles using the same apparatus with only slight modifications of the experimental conditions. The accuracy of these and other recent measurements (Kennerly and Bonham 1978, Wagenaar 1978, Blaauw *et al* 1980) obtained using more conventional electron scattering apparatus and techniques have raised some doubts about the reliability of the earlier electron scattering measurements of Golden and Bandel (1965, 1966), Ramsauer (1921a, b) and Bruche *et al* (1927). The importance attached to resolving these discrepancies has been emphasised by Steph *et al* (1979) and the time-of-flight system developed by Coleman *et al* (1973) for positron cross section measurements offers a new approach to the problem.

The recent version of the positron time-of-flight system using a channel electron multiplier, described by Griffith *et al* (1979a), has been adapted for electron scattering. With this apparatus total cross sections for electrons in helium and argon were measured over the energy range 2–50 eV, thereby bridging the energies covered by the other recent experiments. The positron source was replaced by a 20 μCi ^{137}Cs beta source followed by a thin aluminium foil as moderator and then an earthed grid. Secondary electrons emitted by the aluminium foil in the transmission mode were accelerated by applying a negative potential directly to the foil. The electrons, confined to the axis of the system by axial magnetic fields, were detected at the end of the flight

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tube by a channel electron multiplier with a 20 mm diameter aperture. The electrons were scattered in the localised gas cell described by Griffith *et al* (1979b) and absolute cross sections were established using similar normalisation procedures to determine the gas cell 'normalisation constant' as was used for that e^+–inert-gas work.

It was shown by Griffith *et al* (1978) that the relative strengths of the axial magnetic fields in the source, scattering cell and flight tube detector regions are of crucial importance in minimising the errors due to the detection of particles scattered at small angles to the forward direction. In the three regions cited the field strengths for the present investigation were in the ratio of 6 : 1 : 8 respectively. For slowly varying fields the pitch angle, α_1, of a charged particle in an axial field B_1 is changed, in a region where the field intensity is B_2, to α_2 according to

$$\sin \alpha_2 = \sqrt{(B_2/B_1)} \sin \alpha_1 . \tag{1}$$

The large decrease in the magnetic field between the source and gas cell ensures that the electron beam is essentially axial before entering the scattering region. The large increase in the magnetic field on approaching the detector causes an increase in the pitch angle of *all* the scattered electrons. Electrons scattered through angles greater than 20° (corresponding to $\alpha_2 = 90°$) are totally reflected and cannot reach the detector. Those electrons which scatter at angles less than 20° can be distinguished on a time-of-flight spectrum due to their delayed arrival at the detector.

It should be noted that the yield of low-energy electrons is only 0·01% of the number of source disintegrations. This ensures that the measured cross sections are not in error due to the simultaneous emission from the moderator of more than one slow electron per incident fast electron. The low slow-electron yield is probably due to a combination of the high incident electron energy and the use of the moderator in the transmission mode. In contrast to the slow positron spectrum with its narrow peak representing an energy spread of about 1 eV the secondary emission spectrum for the electrons has a pronounced peak corresponding to the applied potential followed by a high-energy tail extending for several electron volts. Since the electrons are constrained to the axis for the major part of their flight path, independent of the accelerating potential, the time-of-flight spectrum is a direct measure of the energy spectrum of the incident beam. With a slow-electron beam strength of about 20 electrons per second it was possible to measure cross sections at several energies simultaneously over a range extending for about 2 eV above the setting of the applied accelerating voltage.

Analysis of the data followed the method described by Griffith *et al* (1979b). The time-of-flight spectra were accumulated in the multichannel analyser for vacuum and gas runs of durations up to 60 000 s. The data were first subjected to the signal restoration procedure of Coleman *et al* (1974) and the attenuation $A_i = (n_i)_v/(n_i)_g$ calculated for each channel i, where $(n_i)_v$ and $(n_i)_g$ are the corrected counts in channel i for vacuum and gas runs normalised for equal time duration. A cross section $(\sigma_T)_i$ was then assigned to each channel according to

$$(\sigma_T)_i = \ln A_i/\rho_s . \tag{2}$$

where $\rho_s = \int_0^L n(l)\, dl$ is the surface density integral of the gas number density $n(l)$ over the whole flight path L. ρ_s was assumed to be proportional to the gas density n_0 determined at the centre of the gas cell of geometric length l_0 given by

$$\rho_s = n_0 l_0/k. \tag{3}$$

The cell constant k was taken to be $1{\cdot}275 \pm 0{\cdot}02$ for the argon data. This was the value of k used by Griffith *et al* (1979b) and, since the measurements ranged over similar gas densities, was considered applicable to the present work. The gas densities used for the electron–helium data were, however, an order of magnitude lower than those required for the corresponding positron–helium measurements. It was found that the cell constant k, for helium, was density dependent and has to be increased to $1{\cdot}393 \pm 0{\cdot}030$ at the lowest density employed. The density dependence was investigated by renormalising the present data to the e^-–He total cross section of $1{\cdot}91\ \pi a_0^2$ at 50 eV where the measurements by Blaauw *et al* (1980) and by Kennerly and Bonham (1978) are in agreement to better than 1%. The gas pressure at the centre of the gas cell was continuously recorded using an absolute capacitance manometer.

Cross sections for a sequence of energies obtained in argon from runs centred on 5 and 7 eV are shown in figure 1. Each point on the graph represents the mean cross section, compounded over a group of five channels on the multichannel analyser spectrum, obtained from gas and vacuum runs by the application of equation (2).

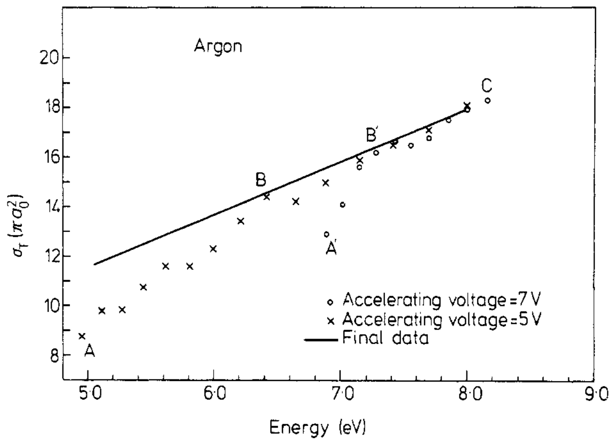

Figure 1. Two sets of overlapping data taken for argon to illustrate the method used to deduce the true cross sections.

Corrections for forward scattering would not be necessary if there were no contributions from scattered electrons to any part of the gas spectrum. The occurrence of small-angle forward scattering would result in an underestimation of the true cross section on approaching the low-energy side of the spectrum. This corresponds to a distortion of the gas spectrum by the detection of delayed scattered electrons and it can be seen in figure 1 that the measured cross sections fall more rapidly for the low-energy regions AB and A′B′ than for the high-energy regions BC and B′C. The envelope of these overlapping sets of data was used to deduce the true cross section. This procedure was applied to a series of overlapping runs taken with the applied accelerating potential increasing in steps of 1 eV from 2 to 8 eV. Between 8 and 50 eV the true cross sections were determined by applying a moderator voltage of typically 2 V less than the required energy, ensuring that the measurement was free from forward scattering errors. Tests were made to confirm that the true cross sections were being deduced. It was noted, for example, that there was no change in the measured cross sections in the high-energy regions when the magnetic field in the gas cell region was halved in value. This was interpreted as showing that the contribution from scattered electrons in this region of the spectrum was negligible. Another check involved varying the length of the flight path. At $L = 1{\cdot}5$ m there was no evidence for a contribution from scattered electrons in the regions BC and B′C etc at any energy. With $L = 0{\cdot}4$ m and values of the applied voltage greater than 8 V there was definite evidence that scattered electrons were being included over the whole of the gas spectrum. The failure of the method above 8 V using the shorter flight path meant that the delay experienced by the scattered electrons was not sufficient to distinguish them from the unscattered ones. In general, the observed behaviour in the regions AB and A′B′ etc was less pronounced in helium than argon and in both cases less pronounced at the lower energies.

The weighted mean of the cross sections obtained from several runs have been compared with the results of other recent experiments in figures 2 and 3. Numerical values of the present results in helium and argon are given in tables 1 and 2 respectively. The errors cited have been compounded from the errors in the normalisation constant,

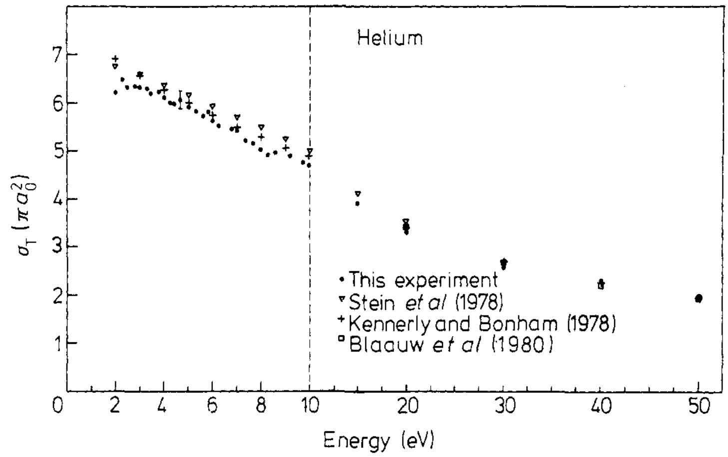

Figure 2. The present results in helium are compared with the values obtained in other recent experiments. The vertical broken line indicates a change of scale.

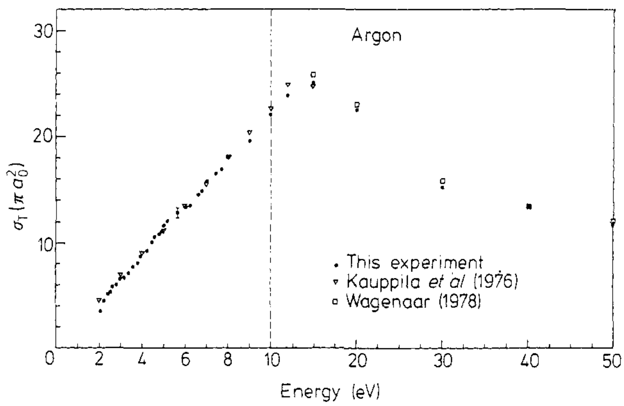

Figure 3. The present results in argon are compared with the values obtained in other recent experiments. The vertical broken line indicates a change of scale.

Table 1.

Energy (eV)	$\sigma_T(\pi a_0^2)$†	Energy (eV)	$\sigma_T(\pi a_0^2)$†
2·00	6·21	6·24	5·52
2·26	6·49	6·83	5·45
2·47	6·36	7·08	5·45
2·80	6·33	7·35	5·21
3·00	6·31	7·63	5·17
3·30	6·29	7·93	5·02
3·40	6·14	8·24	4·89
3·78	6·23	8·58	4·96
4·00	6·12	9·31	4·92
4·23	6·00	9·71	4·76
4·35	5·97	10·0	4·71
4·60	6·07	15·0	3·90
5·00	5·94	20·0	3·34
5·37	5·83	30·0	2·62
5·60	5·73	40·0	2·28
5·83	5·82	50·0	1·91
6·02	5·65		

† Errors on all values of σ_T are ±3%.

Table 2.

Energy (eV)	$\sigma_T(\pi a_0^2)$†	Energy (eV)	$\sigma_T(\pi a_0^2)$†
2·01	3·50	5·15	12·09
2·20	4·43	5·67	12·85
2·39	5·12	6·00	13·19
2·50	5·32	6·21	13·50
2·61	5·84	6·60	14·59
2·79	5·91	6·75	14·83
2·99	6·57	7·00	15·89
3·15	6·67	8·00	18·01
3·39	7·18	9·02	19·60
3·52	7·78	10·0	22·06
3·76	8·16	12·0	23·74
3·97	8·80	15·0	25·09
4·20	9·31	20·0	22·53
4·45	10·14	30·0	15·17
4·57	10·63	40·0	13·47
4·71	10·94	50·0	11·52
5·00	11·70		

† Errors on values in energy range 2·01–3·15 eV are ±3·5%. All other values are ±3%.

in the pressure measurement and in the calculated attenuation for each channel in the spectra.

In argon the present results are in excellent agreement with those of Kauppila *et al* (1976) and of Wagenaar (1978) but are substantially higher than the earlier work of Golden and Bandel (1966). The helium results for the present work are approximately 2·5% lower than those of Kennerly and Bonham (1978) in the energy range 2–10 eV and approximately 5·5% lower than those of Stein *et al* (1978) in the same range but agree with these results within the combined experimental errors. Above 15 eV there is excellent agreement between the present work and that of Blaauw *et al* (1980) and of Kennerly and Bonham (1978). Since the work of Golden and Bandel (1965, 1966), the present experiment is the first to cover the full energy range of 2–50 eV in one set of measurements taken with the same apparatus for both helium and argon.

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