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Electron Impact Excitation–Autoionisation of the $(2s^2)^1S$, $(2p^2)^1D$ and $(2s2p)^1P$ Autoionising States of Helium

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Abstract

The electron impact excitation of the $(2s^2)^1S$, $(2p^2)^1D$ and $(2s2p)^1P$ autoionising states of helium and their subsequent radiationless decay was studied by observation of the ejected electrons. The present work was carried out at an incident energy of 94·6 eV and for ejected electron scattering angles in the range 25–135°. This study was conducted simultaneously with an (e, 2e) investigation into these same autoionising states with the results of this latter work being discussed elsewhere. The lineshapes observed in the present ejected electron spectra are analysed using the Shore–Balashov parametrisation. As part of the analysis procedure we determine numerically rigorous confidence limits for the derived parameters. We believe this is the first time that such error limits are presented in the literature for the derived parameters. No previous experimental or theoretical work has been undertaken at the incident energy of the present investigation but, where possible, the resulting parameters are qualitatively compared against the 80 eV results of other experiments and theory.

1. Introduction

The autoionisation of helium atoms excited by electron impact involves, in general, the interference between the direct-ionisation amplitude and the resonance or autoionisation amplitude. The respective ionisation amplitudes for these two processes interfere since the final states for both processes are indistinguishable. This interference results in the observed asymmetric profiles in the vicinity of the doubly excited states. The nature of the interference and hence the resonance lineshape, or Fano profile, depends on both the magnitudes and relative phases of the competing processes and these in turn depend on both the ejected electron momenta and the resonant state symmetry. The ejected electron is by convention taken to be the electron whose energy corresponds to the difference between the energy of the autoionising state and that of the residual ion.

The early work in this area established the positions and widths of the dominant autoionising states of helium. Examples of these studies include the photoabsorption work of Madden and Codling (1965) and the electron spectroscopy investigations of Lassettre and Silverman (1964) and Hicks and Comer (1975). More recent experimental work has concentrated on the determination and characterisation of the lineshapes. These studies include the work of Mitchell *et al.* (1980) for inelastic electron scattering, Gelebart *et al.* (1974, 1976),

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Oda *et al.* (1977), Tweed *et al.* (1976), van den Brink *et al.* (1989, 1990) and McDonald and Crowe (1992*a*, 1992*b*) for ejected electron spectroscopy and Weigold *et al.* (1975), Pochat *et al.* (1982), Lower and Weigold (1990) and McDonald and Crowe (1992*c*, 1993) for coincidence (e, 2e) spectra.

From a theoretical perspective the angular variation of the shape of the ejected electron spectra in the region of the $(2s^2)^1S$ and $(2s2p)^1P$ states has been calculated by Pochat *et al.* (1982) at an incident electron energy of 100 eV and by Tweed and Langlois (1986*a*) at 70 and 80 eV. Both calculations used a first-order model of autoionisation including exchange. The wavefunctions of the incident, scattered and ejected electrons were calculated using the polarised orbital approximation (Tweed 1973), whilst those for the autoionising state have been discussed in detail by Tweed and Langlois (1986*b*). However, their predictions of the angular variation of the ejected electron spectra are *a priori* not expected to be good, because of the poorly represented small-angle scattering in this model. No theoretical predictions have been made for the $(2p^2)^1D$ state. For completeness, even though they are not strictly relevant to the present study, we note the very recent triple differential cross section calculations for helium autoionisation by electron impact of McCarthy and Shang (1993) and Kheifets (1993).

Shore (1967) and Balashov *et al.* (1973) have shown that the double differential cross section for the production of ejected electrons can be written (for separable resonances) in the form:

$$\frac{d^2\sigma}{d\Omega_e dE_e} = f_r(\mathbf{k}_e) + \sum_\mu \frac{a_\mu(\mathbf{k}_{e\mu})\mathcal{E}_\mu + b_\mu(\mathbf{k}_{e\mu})}{1+\mathcal{E}_\mu^2}\,, \tag{1}$$

where

$$k_{e\mu}^2 = 2\bar{E}_\mu\,, \tag{2}$$

$$\mathcal{E}_\mu = 2(E_e - \bar{E}_\mu)\Gamma_\mu^{-1} \tag{3}$$

and $\bar{E}_\mu$ and E_e are respectively the energies of the rth autoionising resonance and the energy of the ejected electron with total angular momentum and spin quantum numbers denoted by $\mu = \{r; L, M, S\}$. The energy full width at half maximum of the resonance is given by Γ_μ. Here $\bar{E}_\mu$ and Γ_μ are dictated by the configuration interaction of the discrete doubly excited and continuum states and are well known for the states studied [see Table 1 of Lower and Weigold (1990), although note that the ejected electron energy for the ^1D state is given incorrectly there—it should read $E_e = 35\cdot32$ eV]. In this parametrisation $f_r(\mathbf{k}_e)$ is the direct ionisation cross section in the vicinity of the rth resonance and $a_\mu(\mathbf{k}_{e\mu})$ and $b_\mu(\mathbf{k}_{e\mu})$ are the momentum-dependent Shore parameters. These parameters have the units of a cross section and are assumed to be constant in the energy region of the resonance. The parameter $a_\mu(\mathbf{k}_{e\mu})$ characterises the asymmetry of the resonance profile and is composed of an interference term between the direct and resonant ionisation amplitudes, while $b_\mu(\mathbf{k}_{e\mu})$ also contains an interference term and an additional term which yields the resonant cross section in the absence of any direct ionisation cross section (Lower and Weigold 1990). Separable

autoionisation resonances may also be parametrised in the equivalent Fano (1961) representation:

$$\frac{d^2\sigma}{d\Omega_e dE_e} = \sigma'_\mu(\mathbf{k}_{e\mu}) + \sum_\mu \sigma_\mu(\mathbf{k}_{e\mu}) \frac{[q^s_\mu(\mathbf{k}_{e\mu}) + \mathcal{E}_\mu]^2}{1 + \mathcal{E}^2_\mu}, \tag{4}$$

where q^s_μ is the dimensionless Fano shape parameter, and σ_μ is the interacting and σ'_μ the non-interacting continuum cross section. McDonald and Crowe (1992*b*) have shown that the Fano shape parameter is related to the Shore parameters via

$$q^s = \frac{b \pm (a^2 + b^2)^{\frac{1}{2}}}{a}, \tag{5}$$

where the sign of q^s is equivalent to the sign of a.

We note here that Lhagva *et al.* (1991) have addressed the extent to which the unconvoluted ^{1}D and ^{1}P resonances can be treated separately, considering their proximity. They concluded that for a range of kinematics there is no appreciable interference between ejected electrons from these two states, even though for some kinematical conditions there is appreciable overlap of the profiles. If such interference was present, an additional term would be necessary in the Shore–Balashov parametrisation and thus the resonance profiles could not be satisfactorily represented by equation (1) or, for that matter, equation (4). McDonald and Crowe (1992*a*, 1992*b*) also found that for their kinematics, E_0 = 70–200 eV and ejected electron angles θ_{ej} in the range 40–130°, such interference effects are not important. An additional complexity can arise due to post-collision interaction (PCI). However, in the present double differential cross section experiments, where one is essentially integrating over the momenta of the undetected (in this case scattered) electrons, such effects are only important near threshold, where the scattered electron has such a small excess energy that it may still be very near the atom at the instant it autoionises. Under these circumstances a three-body Coulomb interaction in the final state can thus occur, i.e. PCI (Heideman *et al.* 1974). On the other hand, for the (e, 2e) experiments we conducted simultaneously with the ejected electron spectra measurements, where all the kinematics of the process are completely determined, PCI effects can still in principle be observed (Kuchiev and Sheinerman 1989) away from threshold. This can occur in the present (e, 2e) case due to energy being exchanged between the scattered and ejected electrons after collision. Indeed PCI is quite possible in the current (e, 2e) investigation as the kinematics had $E_{sc} = E_{ej} = 35$ eV. A full discussion of our (e, 2e) results and any observed PCI effects are given elsewhere (Samardzic *et al.* 1994). For the E_0 of the current ejected electron spectra we simply reiterate that PCI can be neglected.

The situation, however, can in principle also be complicated by coherences between autoionising states of different excitation energies. These arise when the excitation and subsequent autoionisation of the different states give rise to final states (residual ion + scattered + ejected electron), where the roles of the scattered and ejected electrons are interchanged, but which are indistinguishable in the experiment (van den Brink *et al.* 1989). An interesting near-threshold study of this effect was given by van den Brink *et al.* (1989), who presented

a theoretical description of the observed coherence effects and, from this, then derived an alternative parametrisation for the ejected electron spectra [compared to that given in our equations (1)–(3)] which they fitted to their experimental data and which clearly appeared to describe the observed state–state interference very well. We cannot, in the present study, completely rule out such an effect although, given the quality of the fits to the present data by a function of the form of equations (1)–(3) (see Fig. 1 below), it does appear that such effects are not significant for the present kinematical conditions.

In the present study we have observed the ejected electron spectra, at $E_0 = 94{\cdot}6$ eV, in the region of the $(2s^2)^1S$, $(2p^2)^1D$ and $(2s2p)^1P$ lower-lying autoionising states of helium, following electron impact excitation. Data for the $(2s2p)^3P$ state were also collected. We do not, however, report results for these data simply because in our companion (e, 2e) study (Samardzic *et al.* 1994) its excitation cross section was too small to allow the extraction of reliable data and thus a study of PCI for that state. The first ejected electron spectra for these states to be analysed in terms of the resonance shape were presented by Gelebart *et al.* (1976) for the incident electron energies 70, 80 and 100 eV and $\theta_{ej} = 10$–$100°$. We note, however, that the later work of Tweed and Langlois (1986*a*) found that the data of Gelebart *et al.* were only reliable at $\theta_{ej} \geq 40°$, a conclusion supported by McDonald and Crowe (1992*a*, 1992*b*) in their subsequent studies. Further work by the Bretagne group (Pochat *et al.* 1982) disagreed with the results of their original study in that the previously measured angular variations in the a and b parameters were no longer observed. Theoretical support for this latter result came from their own calculations (Pochat *et al.* 1982) and those of Tweed and Langlois (1986*a*). The recent extensive study of the ^1S, ^3P, ^1D and ^1P autoionising states at $E_0 = 70, 80, 100$ and 200 eV and for $\theta_{ej} = 40$–$130°$ by McDonald and Crowe (1992*a*, 1992*b*) found, for each state, significant oscillatory behaviour of the a and b parameters as a function of θ_{ej}, particularly at the lower incident electron energies, in fair qualitative agreement with the study of Gelebart *et al.* (1976).

Clearly there is a need for a further, independent, study of the angular variation of the autoionising lineshapes observed in the ejected electron spectra. In this regard we report data for the $(2s^2)^1S$, $(2p^2)^1D$ and $(2s2p)^1P$ states of helium at an incident electron energy of $94{\cdot}6$ eV and for an ejected electron angular range 25–135°. Whilst the present incident electron energy does not coincide with those of the earlier studies (Gelebart *et al.* 1976; McDonald and Crowe 1992*a*, 1992*b*) we can and have made a detailed qualitative comparison with the 80 eV results of the earlier work. Furthermore, we have modified (Bevington and Robinson 1990) the fitting program of Lower and Weigold (1990) so that it now provides numerically valid estimates for the uncertainties in the fitted parameters. We believe that this represents the first time that true confidence intervals will have been reported in the literature, for the lineshape parameters as obtained in a multiparameter fit. This is an important development in relation to drawing quantitative conclusions with respect to the level of agreement between the various sets of experimental data and between experiment and theory. We note that observations of interference effects have been shown to provide highly sensitive tests of theoretical models for scattering processes. It is hoped that the present data, and the measurements of McDonald and Crowe (1992*a*, 1992*b*)

and Gelebart *et al.* (1976), will stimulate a much greater theoretical interest in the autoionisation process. In this regard we note the recent triple differential cross section calculations of McCarthy and Shang (1993) and Kheifets (1993).

2. Experiment and Data Analysis

The present apparatus and data collection techniques have been described in detail previously by Lower and Weigold (1989, 1990) and so only a cursory description is given here. The ejected electron spectrometer consists of an electron gun providing an electrostatically focused electron beam of typically 10 μA, with an energy spread of $\sim$0·5 eV due to the thermal spread in the thoriated tungsten hairpin filament source. This beam is monitored and focused into a small Faraday cup, which can be lowered out of the way if required. The electron beam is crossed at right angles by the target beam (helium atoms of ultrahigh purity) thereby defining the interaction region. The helium atoms effuse through a 15 mm long molybdenum tube of internal diameter 0·7 mm, before proceeding through a collimating aperture. Buckman *et al.* (1993) have recently investigated the spatial profiles of target beams for both single and multicapillary sources. For a source comparable to that used in this work and for helium driving pressures consistent with that employed in the present study, they found that the spatial profile of the helium beam was well collimated (full width at half maximum FWHM = 1·3 mm). As our incident electron beam is also highly focused we are confident that the interaction volume is similarly well defined and entirely viewed by the ejected electron analyser for all ejected electron scattering angles. Consequently we are also confident that the collision volume seen by the ejected electron analyser is independent of angle, although this can easily be checked by comparing (albeit at a lower E_0) the differential cross section for elastic scattering from helium with the data of Brunger *et al.* (1992).

The ejected electron analyser is rotated about the collision centre in a plane perpendicular to the helium beam. This analyser is a 180° hemispherical electrostatic analyser, preceded by a series of electrostatic lenses of cylindrical symmetry (Kevan 1983) which focus the ejected electrons emitted in a particular direction onto the input plane of the hemispherical analyser. Those ejected electrons transmitted by the analyser are detected by a position-sensitive multidetector placed at the exit plane of the hemispheres. This detector consists of two microchannel plates (MCP) and a resistive anode (RA) placed a few millimetres behind the MCPs. The arrival position of the charge cloud is usually deduced by the charge division method (McCarthy and Weigold 1991). This is achieved through the position decoding electronics (PDE), which in the present experiments are Surface Science (now QUANTAR)* units. These units produce a DC level output proportional to the position and hence energy of the detected electrons and a strobe pulse on the occasion that a true position has been determined. The DC output from the PDE unit is used to drive a linear gate which is gated by the PDE strobe pulse. The output of this linear gate is then fed into a mixer/router and analogue-to-digital converter, the output of which is accumulated in a CAMAC wordstore. These data are then read, stored and displayed by a PDP LSI-11 computer. The entire experiment is conducted under

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computer control. This also includes setting the preset to determine the dwelltime at each angular position and the rotation of the ejected electron analyser (Lower and Weigold 1990). Each measurement involved repeated scans through the angular range of the ejected electron analyser, to average over beam and target density fluctuations and long-term instrumental drifts.

Care was taken to avoid other possible sources of corruption of the data. Magnetic fields in the apparatus were reduced to ≤ 1 mG using a combination of a mu-metal shield and two sets of mutually perpendicular Helmholtz coils. Furthermore, great care was taken with electrical shielding to ensure that no stray electric fields could penetrate into the interaction region. During some of the measurements, however, long-term energy drifts were observed. These were, however, easily corrected for by adjustment of the energy scales of individual scans over the whole angular range, which together make up each measurement. After adjustment, the many individual scans were again summed to give the final spectrum at each respective θ_{ej}.

Non-uniform detection efficiencies across the face of the MCP/RA detector were observed and the measured spectra were corrected for this. The procedure by which this response function was measured is well described in Lower and Weigold (1990) and so we do not repeat it here. Similarly, a second correction to compensate for the effects of dead time in the position decoding electronics was made. This correction was also discussed in detail in Lower and Weigold (1990) and so again we do not go into detail here.

Having applied the appropriate corrections, the double differential cross section spectra were ready for analysis. Each spectrum shows a series of resonance profiles superimposed upon a background of direct ionisation events. According to equation (1), we can describe each resonance profile for the respective states by the parametric form $f+(a_r\mathcal{E}_r+b_r)/(1+\mathcal{E}_r^2)$, convoluted with the instrumental response function.

The instrumental response function was determined in a separate experiment (see Lower and Weigold 1990) and is well described by a gaussian of 180 meV (FWHM). In contrast to the resonant behaviour, the direct ionisation cross section f varies smoothly with energy and may be represented by a first-order polynomial. Using these functions, a root-mean-square (RMS) fit to each ejected electron spectrum was performed. The a_r and b_r parameters were separately extracted for each resonant state and the polynomial coefficients describing the background shape were determined. Thus in each experiment, the angular behaviour of a_r and b_r was determined, along with that of the direct ionisation cross section f_r, which is the value of the direct ionisation cross section f extracted at the position of the resonance $\bar{E}_r$. In all cases it was verified that the parameters were independent of the initial estimates supplied. The present experiments, however, did not determine cross sections on an absolute scale (although relative normalisations between the states are maintained) and hence the results require normalisation before comparison with the results of the other experiments (Gelebart *et al.* 1976; McDonald and Crowe 1992*a*, 1992*b*) and theory (Tweed and Langlois 1986*a*). Both Gelebart *et al.* (1976) and, by normalising to Gelebart *et al.* at an arbitrary angle, McDonald and Crowe (1992*a*, 1992*b*) reported their results on an absolute scale by normalising to the singles cross sections for excitation of the $n = 2$ states of helium. The original data used by Gelebart *et al.* in their normalisation are

no longer considered to be reliable (Cartwright *et al.* 1992; Trajmar *et al.* 1992) and so in the present work, for $\theta_{ej} = 25°$, we have normalised the data so that $f_{1S}(\theta_{ej}{=}25°) = 1$. For the purposes of comparison the 80 eV data of Gelebart *et al.* (1976) and McDonald and Crowe (1992*a*, 1992*b*) and the calculation of Tweed and Langlois (1986*a*) have been renormalised to the present scale (via the b parameter).

As with any least-squares minimisation fit to the experimental data, it is desirable to minimise the number of free variables in an attempt to keep the fitted function reasonably well behaved. This is especially true in regions of marginal statistical accuracy. Consequently we have used the energies and natural widths for each of the resonant states that were previously determined with high accuracy by other workers (Gelebart *et al.* 1976; van den Brink *et al.* 1989), who used both electrons and photons to excite the states. Furthermore we have modified the fitting program of Lower and Weigold (1990) to obtain statistically valid confidence levels for the respective variables in the current multiparameter fits. A full description of the basis and validity of this procedure can be found in Bevington and Robinson (1990) and so we do not discuss it at length here. Briefly, however, the technique requires a true reduced χ^2 value, χ^2_{red}, to be calculated as a measure of the quality of the fit to the data. This is defined by

$$\chi^2_{red} = \frac{1}{M_{pts} - M_{free}} \sum_{i=1}^{M_{pts}} \frac{(\text{residual}_i)^2}{\Delta\sigma_i^2}, \tag{6}$$

where M_{pts} is the number of data points in the spectrum, M_{free} the number of variable parameters in the fit, $\Delta\sigma_i$ the statistical uncertainty in the ith data point, and residual_i is the experimental value of the double differential cross section minus the fitted value of the double differential cross section, for the ith data point.

Having obtained χ^2_{red}, the one standard deviation or 68·3% probability of finding the true values of the variable parameters from the fit is simply found by, in turn, holding $M_{free} - 1$ of the original parameters at their optimised values (RMS) and allowing the remaining one to further vary until the value of χ^2_{red} changes by 1, i.e. $\Delta\chi^2_{red} = 1$. The one standard deviation error in this parameter is then defined by the amount needed to cause the value of χ^2_{red} to increase by 1. This procedure is subsequently repeated for each of the original variables in the fit.

McDonald and Crowe (1992*a*) previously made a thorough investigation of the effect of the experimental energy resolution on the ability to extract unique values of the parameters, in particular for the ^{1}D and ^{1}P states, from an analysis procedure similar to that which we described earlier. They concluded that this was not possible unless the energy resolution was better than approximately 80 meV. The present error analysis clearly indicates that this criterion is too harsh. McDonald and Crowe (1992*a*, 1992*b*, 1992*c*, 1993) did not describe how they determined the errors in their derived parameters but we believe that the resolution dependence of these parameters for $\Delta E(\text{FWHM}) > 80$ meV, which they saw, was probably an artefact of their not employing a numerically rigorous procedure for determining the true errors on the values of the a, b and f parameters derived in their fits. What can be said, however, is that for two spectra collected under

identical kinematical conditions and of equal statistical accuracy, the parameters derived from the spectrum with superior energy resolution will have smaller errors than those correspondingly derived from the data with the poorer energy resolution. Furthermore the present analysis indicates that, provided the energy resolution is not so poor as to largely smear out the structure in the spectra, these values of the a, b and f parameters would be consistent, to within their respective determined uncertainties.

3. Results and Discussion

The variation in the Shore parameters has been determined over the ejected electron angular range 25–135°, from the ejected electron spectra of the $(2s^2)^1S$, $(2p^2)^1D$ and $(2s2p)^1P$ states of helium, for an incident electron energy of 94·6 eV. The Fano shape parameter q^s, calculated from the Shore a and b parameters, has also been derived. As discussed previously, the measured parameters are qualitatively compared with other experimental and theoretical data at an incident electron energy of 80 eV.

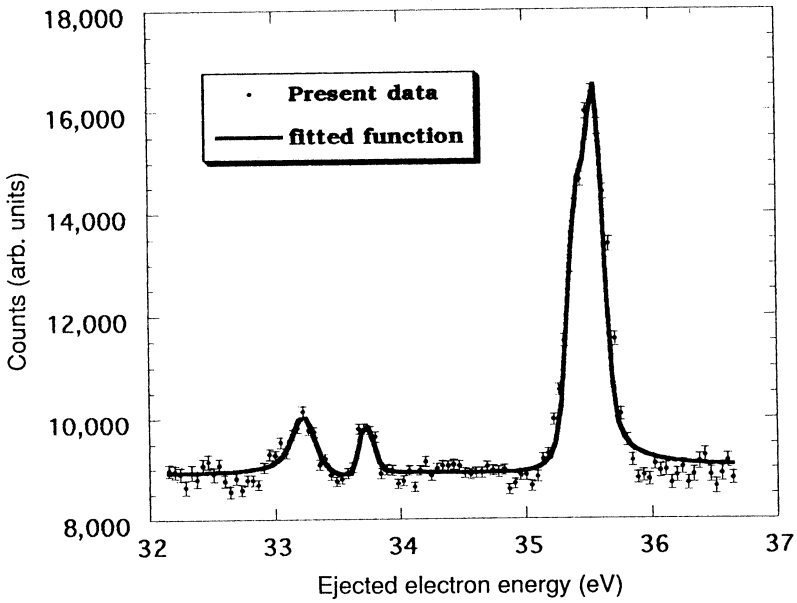


Fig. 1. Measured ejected electron spectra at $E_0 = 94{\cdot}6$ eV and $\theta_{ej} = 135°$. The present data (•) and the fit to the data (—) are illustrated.

An example of the current measured ejected electron spectra, for $\theta_{ej} = 135°$, is given in Fig. 1. The $(2s^2)^1S$ and $(2p^2)^1D$ lines exhibited a marked asymmetric profile in most cases. On the other hand the $(2s2p)^1P$ line, in general, retained a more symmetric peak shape for most of the spectra. Also shown in Fig. 1 is the fit to the data as obtained using the functional form of equation (1), convoluted with a gaussian instrumental function. In all cases the statistical errors in the data were of the order of 1% or better.

For the $(2s^2)^1S$ state the a, b, f and q^s parameters are given in Figs 2a–2d, respectively. Also shown in these figures are the respective errors in the Shore

and Fano parameters as obtained by the method we described in detail earlier. Where no error bar is shown, the error is less than the datum point size. The a parameter has quite a strong angular asymmetry over all θ_{ej} (see Fig. 2a) with a deep minimum at $\theta_{ej} = 120°$. Consistent with the 80 eV results of McDonald and Crowe (1992*b*) and Gelebart *et al.* (1976), the a parameter demonstrates an oscillatory behaviour as a function of θ_{ej}. This is, however, contrary to the prediction of Tweed and Langlois (1986*a*), thereby indicating that there are deficiencies in the approximations they employed in their model.

The angular variation of the b parameter for the ^{1}S state was also found to be anisotropic (Fig. 2b), again qualitatively consistent with the earlier data. In this case, however, we find a somewhat shallower minimum that also occurs at a larger θ_{ej} than that observed in the earlier data, although we note that McDonald and Crowe (1992*b*) found that as the incident electron energy increased, the angle of the minimum increased. Furthermore, unlike the results of McDonald and Crowe (1992*b*) and, to a lesser extent, Gelebart *et al.* (1976), who found at all the energies they investigated that the b parameter was negative at its minimum, the present data are positive at all θ_{ej}. In this respect the present data is largely consistent with what was predicted by the first-order model calculation of Tweed and Langlois (1986*a*).

For the f parameter we would *a priori* expect the data to be symmetric about $\theta_{ej} = 90°$. In Fig. 2c we plot the present results for the direct ionisation cross section at the ^{1}S resonance energy and indeed we confirm that it is basically symmetric about 90°, within the current measured ejected electron angular range, to better than 10%.

The Fano parameter q^s, obtained from a and b using the relationship of equation (5), is much less sensitive to variations in the line profile with ejected electron angle. Indeed, as indicated in Fig. 2d, at the present incident energy it retains near zero values over the angular range. Note that there is a discontinuity in the value of q^s at about $\theta_{ej} = 90°$ where the value of the a parameter changes sign.

The salient feature of the angular variation in the a and b parameters for the ^{1}D state (Figs 3a and 3b respectively) is the probable presence of oscillations in the parameters over the entire angular range. Further, consistent with the results of McDonald and Crowe (1992*a*) and Gelebart *et al.* (1976) it appears that these oscillations vary quite sharply with the ejected electron angle.

In the present experiment we found the a parameter (Fig. 3a) to be somewhat more isotropic than the 80 eV ^{1}D state data of either McDonald and Crowe (1992*a*) or Gelebart *et al.* (1976). However, McDonald and Crowe noted that as the incident beam energy was increased the a parameter became more positive and the oscillations became smaller, an observation that sits well with the current result. On the other hand for the current b parameter (Fig. 3b), the size and phase of the oscillations are in good qualitative agreement with those found by McDonald and Crowe (1992*a*) and Gelebart *et al.* (1976). All three data sets found that b is positive at all values of θ_{ej}, and that there is a primary minimum at $\theta_{ej} = 40°$ and a secondary minimum at $\theta_{ej} \sim 90$–$100°$, before the value of b starts to increase rapidly at the more backward ejected electron angles. Indeed it is worthy of note that for the ^{1}D state at $\theta_{ej} = 135°$ the value of b is comparable

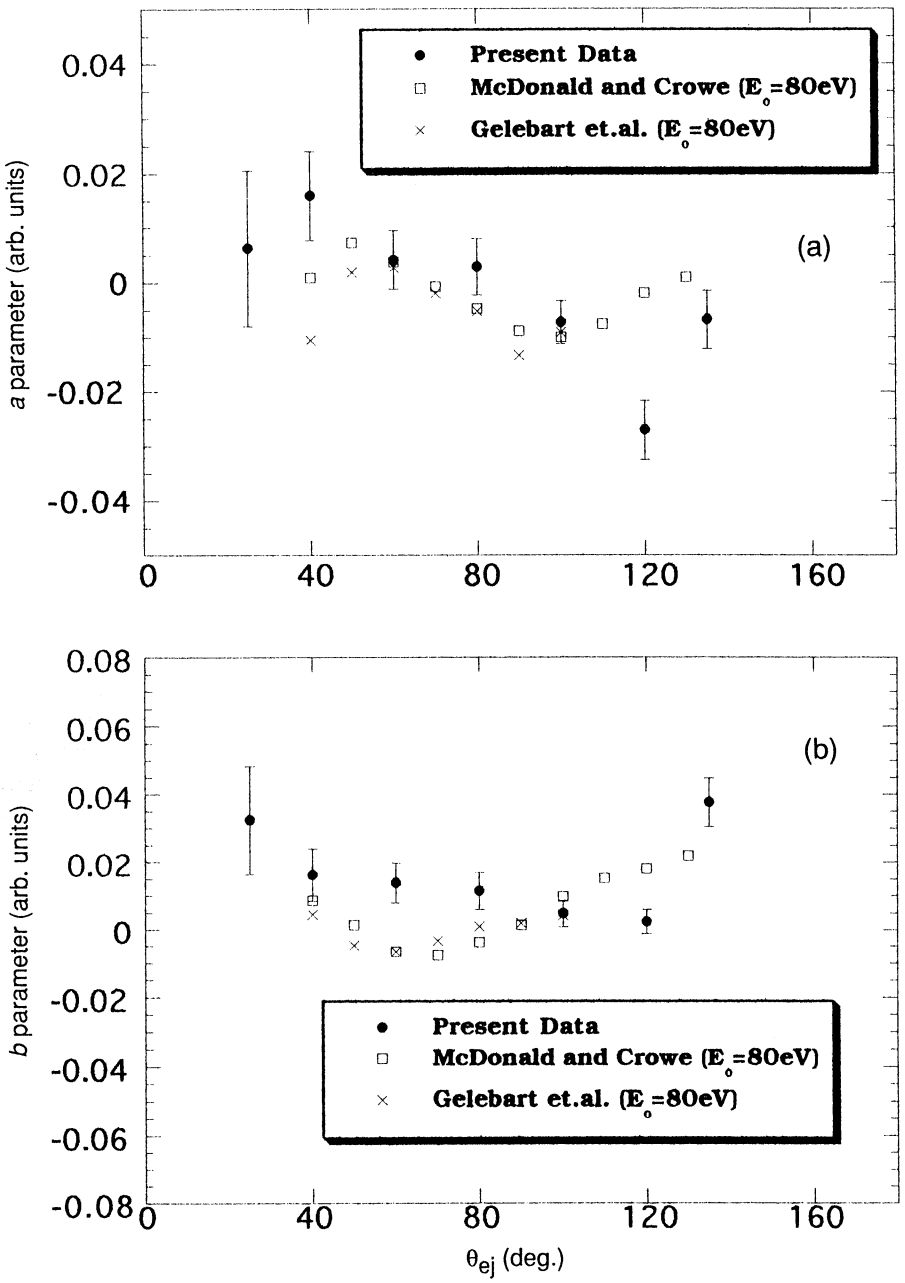
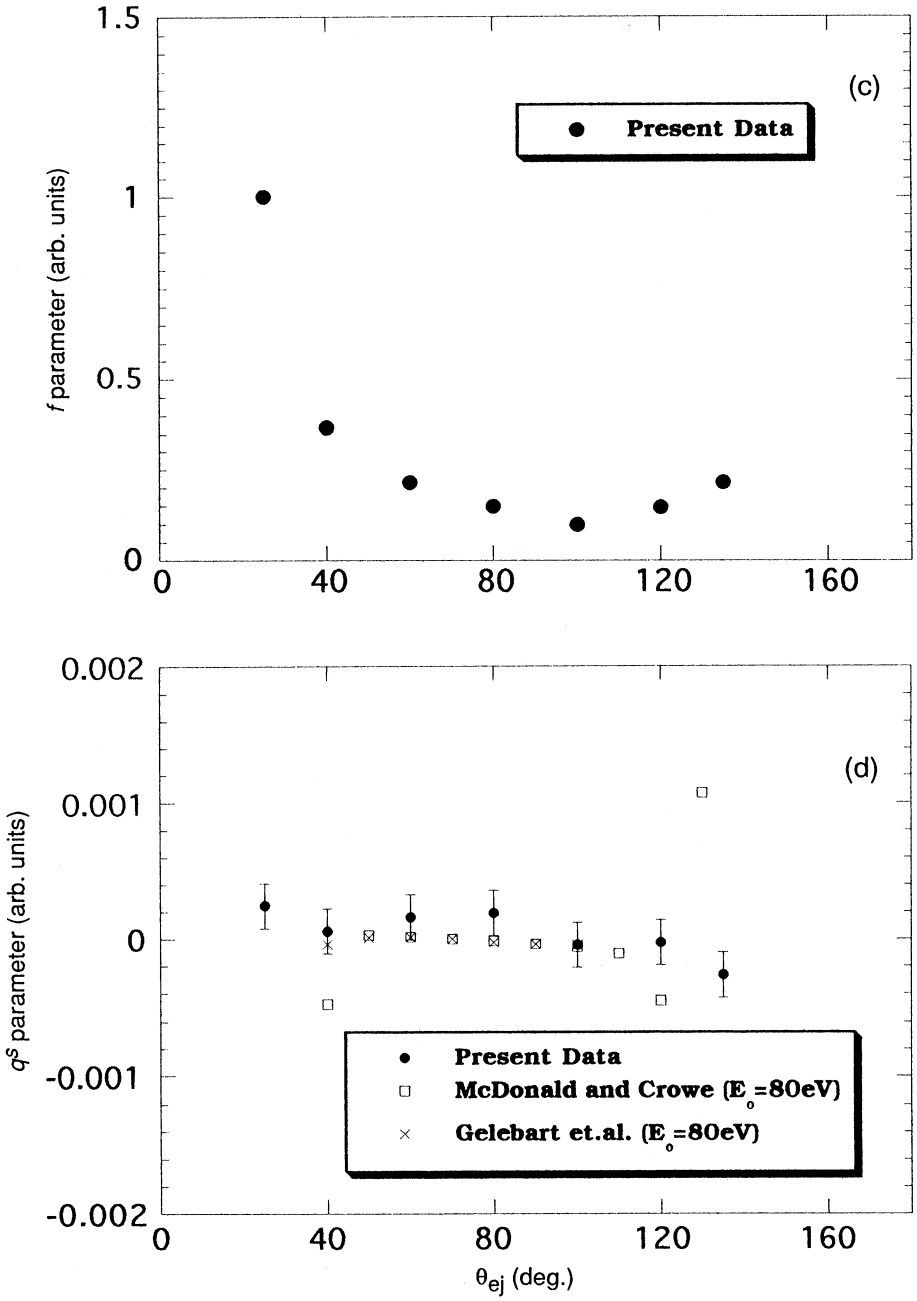


Fig. 2. Variation of the Shore parameters and the Fano parameter as a function of the ejected electron angle for the $(2s^2)^1S$ state of helium at $E_0 = 94{\cdot}6$ eV. The present data (•) for the (a) a parameter, (b) b parameter, (c) f parameter and (d) q^s parameter are compared with the corresponding 80 eV results of McDonald and Crowe (1992*b*) (□) and Gelebart *et al.* (1976) (×).



Figs 2c and 2d

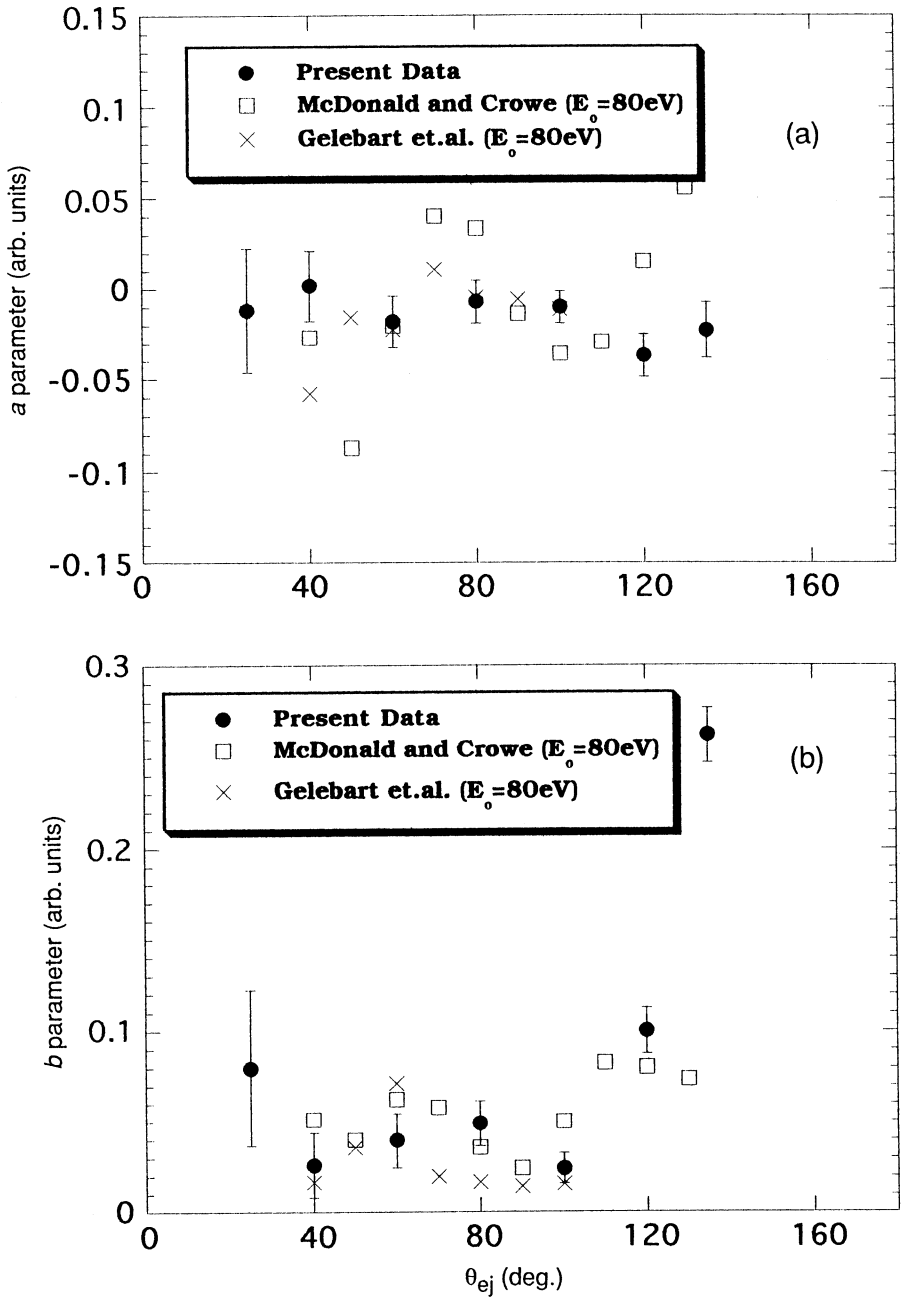
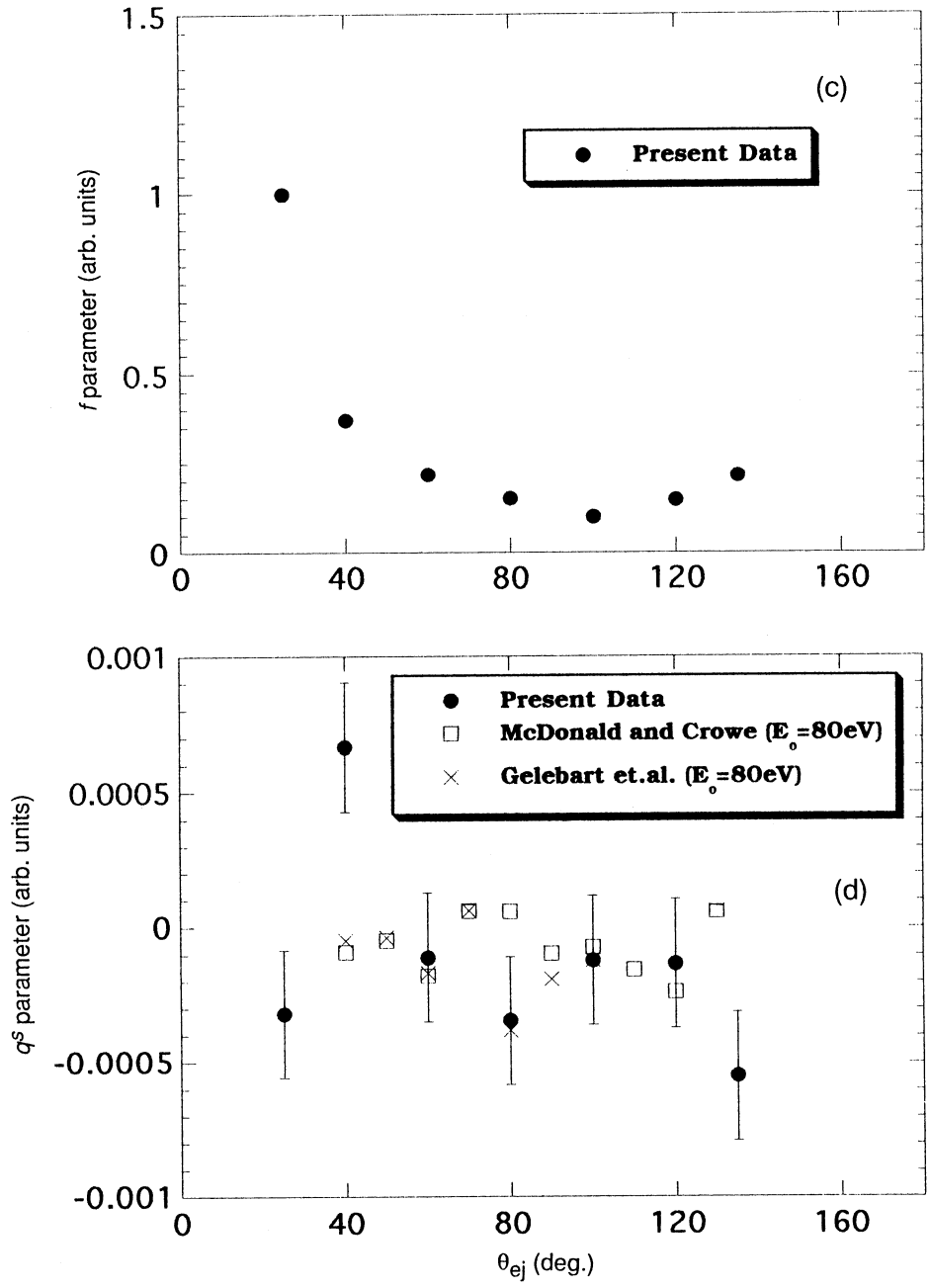


Fig. 3. Variation of the Shore parameters and the Fano parameter as a function of the ejected electron angle for the $(2p^2)^1D$ state of helium at $E_0 = 94{\cdot}6$ eV. The present data (•) for the (a) a parameter, (b) b parameter, (c) f parameter and (d) q^s parameter are compared with the corresponding 80 eV results of McDonald and Crowe (1992*a*) (□) and Gelebart *et al.* (1976) (×).



Figs 3c and 3d

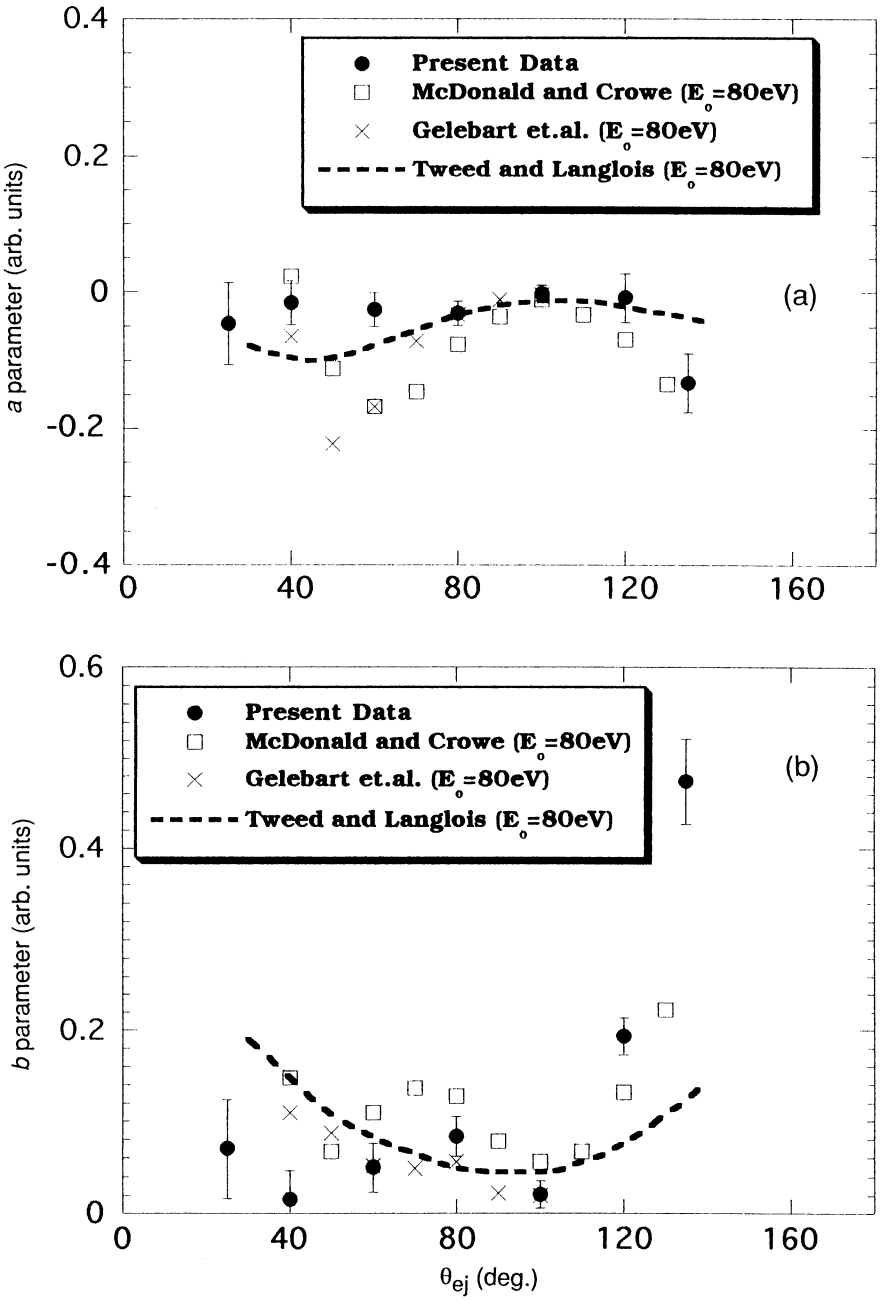
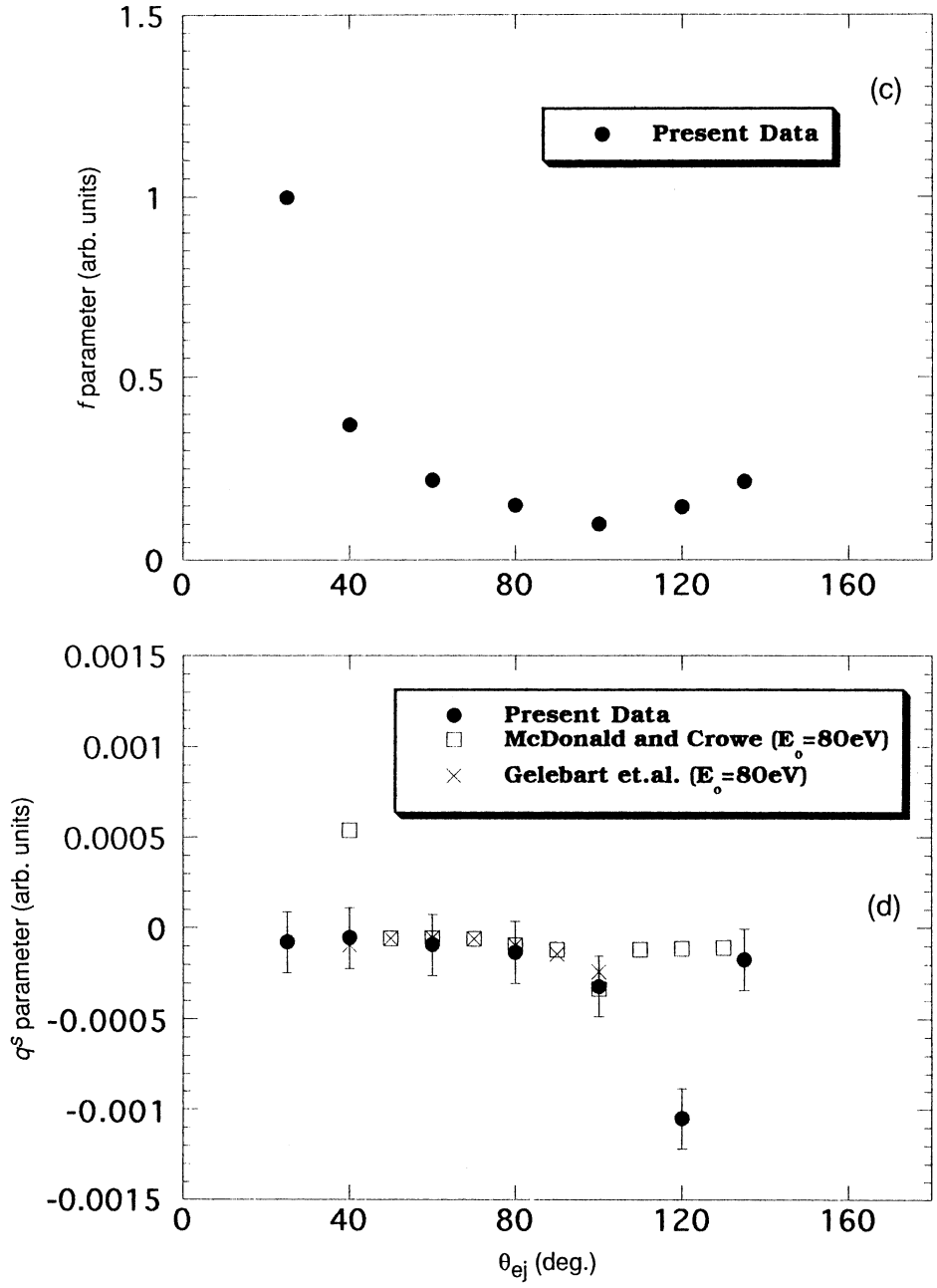


Fig. 4. Variation of the Shore parameters and the Fano parameter as a function of the ejected electron angle for the $(2s2p)^1P$ state of helium at $E_0 = 94{\cdot}6$ eV. The present data (•) for the (a) a parameter, (b) b parameter, (c) f parameter and (d) q^s parameter are compared with the corresponding 80 eV results of McDonald and Crowe (1992*a*) (□), Gelebart *et al.* (1976) (×) and the calculation of Tweed and Langlois (1986*a*) (– – –).



Figs 4c and 4d

to that for the direct ionisation cross section $f_{^1D}$. Similar to the result for the ^1S state we again find the direct ionisation cross section for the ^1D state to be largely symmetric, to better than 10%, about $\theta_{ej} = 90°$ (Fig. 3c).

The Fano shape parameter (Fig. 3d) for the ^1D state is seen to be quite isotropic and is found to retain a near-zero value over the angular range. The exception to this is at $\theta_{ej} = 40°$ where a pronounced asymptotic effect is observed, corresponding to the a parameter changing sign from a negative to a positive value. These asymptotes are assumed to arise as a result of the interference effects, rather than a lack of available continua, since the Shore a and b parameters are of a similar order of magnitude and are smoothly varying. Finally we note the good qualitative agreement between the present values of q^s and those of McDonald and Crowe (1992*a*) and Gelebart *et al.* (1976) over the common angular range of the respective measurements. There is no theory for the ^1D state against which the present and earlier data can be compared.

The $(2s2p)^1P$ state parameters as a function of ejected electron angle are shown in Figs 4a–4d. Quite sharply varying angular oscillations of the a and b Shore parameters are, in general, also indicated for the ^1P state, although these differ in magnitude and period from those we have just discussed for the ^1D state. For the a parameter (Fig. 4a) the measured values are all negative, largely consistent with the results of both McDonald and Crowe (1992*a*) and Gelebart *et al.* (1976). The present a parameter does not exhibit the significant minimum around $\theta_{ej} \sim 60°$ that the earlier data does, although this may simply be due to the higher incident electron energy of the present measurement. On the other hand, the backward angle behaviour of the a parameter is in qualitatively good accord with that found by McDonald and Crowe (1992*a*). The calculation of Tweed and Langlois (1986*a*) is in relatively poor agreement with the experimental results in that it oscillates more gently with angle and its predicted maxima and minima do not correspond to the measured values.

For the b parameter of the ^1P state (Fig. 4b) the present data are in quite good qualitative agreement with the earlier data, with the observed maxima and minima largely corresponding in θ_{ej} for all three experiments. Contrary to this, however, the theoretical calculation (Tweed and Langlois 1986*a*) is found to be in rather poor agreement with the experimental results; in particular the theory does not exhibit any oscillation in this case. Similar to the ^1D case, we find the b parameter for the ^1P state to grow steeply at the more backward angles ($\theta_{ej} > 100°$). In this case, however, the value of the b parameter at $\theta_{ej} = 135°$ is almost twice that for the corresponding direct ionisation cross section, $f_{^1P}(135°)$, thereby illustrating the dominance of the autoionisation process over the direct ionisation process at this angle. We again note the symmetry of the direct ionisation cross section, in this case for the ^1P state, about $\theta_{ej} = 90°$.

The q^s parameter is again mainly isotropic and near-zero (Fig. 4d) over the ejected electron angular range. The exception to this is at $\theta_{ej} = 120°$ where we see quite a large negative value for q^s. In this case it is simply due to the fact that a is nearly zero (and negative) at that angle, although there is no evidence for a change in sign. The present data for the q^s parameter are again seen to be in qualitatively good agreement with the results of McDonald and Crowe (1992*a*) and Gelebart *et al.* (1976) over most of the angular range.

4. Conclusions

We have presented data for the Shore parameters and the Fano shape parameter, as a function of θ_{ej}, for the ^{1}S, ^{1}D and ^{1}P autoionising states of helium and at an incident electron energy of 94·6 eV. We have also provided numerically valid confidence intervals on the respective values of the derived parameters. The present data highlight the effects of interference between direct and resonant ionisation amplitudes in the autoionisation process of helium. Interference effects are manifest in the derived parameters as both partially correlated oscillations with ejected electron angle and in the magnitudes of the Shore a and b parameters. The oscillation of the a and b parameters with θ_{ej} was found to be quite rapid and extended over a large angular range. The complex nature of the interference process depends on both the magnitudes and relative phases of the competing direct and resonant ionisation amplitudes. This represents a significant challenge to the theorists with the currently available first-order theory of Tweed and Langlois (1986*a*) appearing to be inadequate in most cases. As a first step we would encourage McCarthy and Shang (1993) and Kheifets (1993) to apply their respective, quite successful, triple differential cross section models for helium autoionisation to the present kinematical case by performing the relevant (e, 2e) calculation and then integrating over all scattered electron angles. This would greatly aid us in the interpretation of the present measurements for the Shore and Fano parameters.

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