Aust. J. Phys., 1982, **35**, 513–19

Large Momentum Transfer Excitation of He(3^1P) by Electron Impact at 81·2 eV Incident Energy

R. McAdams and J. F. Williams

Department of Physics, University of Western Australia,
Nedlands, W.A. 6009.

Abstract

This paper reports measurements of helium λ and χ parameters for electron impact excitation of the 3^1P state of helium at an incident energy of 81·2 eV and at large momentum transfers. Comparison is made with previous 2^1P results and both sets of results show very similar trends. The data are also compared with a number of theoretical calculations but the agreement is not good.

1. Introduction

In the past decade the use of coincidence techniques in atomic collision experiments has given rise to a generation of experiments which allow the scattering dynamics to be probed at the most fundamental level. For the electron impact excitation of atomic states where the transition is optically allowed, coincidence methods are used to measure the angular correlation between the inelastically scattered electrons and the photons emitted in the decay of the state. This removes any of the implicit averages over either the direction of the scattered electron or that of the photon which are present in single particle or photon counting experiments. In particular we shall deal with the specific case of the excitation of the 2^1P and 3^1P states of helium. Both these states decay to the 1^1S ground state with the emission of photons with wavelengths of 58·4 and 53·7 nm respectively.

The target atom is in the ground state and it receives one unit of angular momentum from the incident electron. Because the excited atom is in a P state, the possible values of magnetic quantum number are $M_L = +1, 0, -1$ depending on the direction of the angular momentum vector.

From the measured angular correlations one can derive two parameters λ and χ, which are directly related to the magnitudes and phases of the excitation amplitudes of the magnetic sublevels, or alternatively to the orientation and alignment of the atomic state. In this paper we shall present results for the excitation of the 3^1P state at large momentum transfers using incident electrons of 81·2 eV energy.

The present data will be combined with previous He(3^1P) small angle data due to Eminyan *et al.* (1975) at 80 eV and Crowe *et al.* (1981) at 75·6 eV and compared with the He(2^1P) results of Hollywood *et al.* (1979) at 81·2 eV. Comparison will also be made with a number of calculations based on various theoretical approximations.

2. Angular Correlations from ^{1}P States

The theory of electron–photon coincidence experiments has been discussed previously by Macek and Jaecks (1971), Fano and Macek (1973) and Blum and Kleinpoppen (1979) and only a brief description of its application to the excitation of the ^{1}P states will be given.

One defines the z-axis to be the direction of the incident electron beam and together with the scattered electron detector these form the x–z or scattering plane. The wavefunction of the excited atomic state is given by the coherent superposition

$$|\psi\rangle = \sum_{M_L=-1}^{+1} a_{M_L} |L, M_L\rangle, \tag{1}$$

where a_{M_L} is the excitation amplitude of the M_Lth magnetic sublevel and $|L, M_L\rangle$ is an orbital angular momentum vector. Reflection symmetry in the scattering plane gives rise to the relationship

$$a_1 = -a_{-1}, \tag{2}$$

hence reducing the number of parameters required to specify the wavefunction. Because $|a_{M_L}|^2$ is the probability of excitation to a particular sublevel, we make the normalization $|a_{M_L}|^2 = \sigma_{M_L}$, where σ_{M_L} is the differential cross section for that sublevel. Now we define the λ and χ parameters as

$$\lambda = |a_0|^2/(|a_0|^2 + 2|a_1|^2) = \sigma_0/\sigma, \tag{3}$$

$$\chi = \arg a_1/a_0, \tag{4}$$

where σ is the differential cross section of the ^{1}P state as a whole. The λ parameter is then just the contribution of the $M_L = 0$ sublevel to the total differential cross section and χ is the quantum mechanical phase difference between the $M_L = 0$ and 1 sublevels. Knowledge of λ, χ and σ represents a complete determination of the scattering amplitudes. It should be noticed that the excitation of ^{1}P states by electron impact is in fact spin independent. Only a single spin channel exists and therefore no average over initial states and sum over final states need be made.

The approach of Fano and Macek (1973) avoided the use of excitation amplitudes to describe the excited state. In their formalism an orientation vector $\boldsymbol{O}$ and alignment tensor $\mathbf{A}$ are used to describe the anisotropy of the sublevel populations. The orientation and alignment depend on the expectation values of the orbital angular momentum of the atom and its Cartesian components, and on λ and χ, through the relations

$$O_{1-}^{\text{col}} = \tfrac{1}{2}\langle L_y\rangle = -\{\lambda(1-\lambda)\}^{\frac{1}{2}}\sin\chi, \tag{5a}$$

$$A_{0+}^{\text{col}} = \tfrac{1}{2}\langle 3L_z^2 - L^2\rangle = \tfrac{1}{2}(1-3\lambda), \tag{5b}$$

$$A_{1+}^{\text{col}} = \tfrac{1}{2}\langle L_x L_z + L_z L_x\rangle = \{\lambda(1-\lambda)\}^{\frac{1}{2}}\cos\chi, \tag{5c}$$

$$A_{2+}^{\text{col}} = \tfrac{1}{2}\langle L_x^2 - L_y^2\rangle = \tfrac{1}{2}(\lambda-1). \tag{5d}$$

Experimentally, the electron detector is set at some scattering angle θ_e and the number of coincidences between the electrons which have lost the excitation energy of the state of interest and the photons emitted in the subsequent decay of the state is recorded as a function of the polar coordinates θ and ϕ of the photon detector.

For the particular case of coplanar geometry, i.e. $\phi = 180°$, the normalized angular correlation function is given by

$$N = \lambda \sin^2\theta + (1-\lambda)\cos^2\theta - \{\lambda(1-\lambda)\}^{\frac{1}{2}} \cos\chi \sin 2\theta , \qquad (6)$$

which is a sinusoid of period π with maximum amplitude of unity.

By carrying out a least squares fit of the data to equation (6) one determines values of λ and $|\chi|$.

3. Experimental Apparatus

A crossed electron–atom beam apparatus was used to carry out the experiment. It has already been described by Hollywood *et al.* (1979) and McAdams *et al.* (1980). Briefly, an electron beam produced from a gun passes through an atomic beam produced by effusing gas through a single capillary tube placed at right angles to the electron beam. This source has now been inclined at 45° to the scattering plane.

The inelastically scattered electrons which have lost the excitation energy of the $n = 3$ states are selected out by a hemispherical electrostatic analyser and detected by a channeltron placed at the exit slit of the analyser. The overall resolution of the gun and analyser is about 0·9 eV.

A channeltron is used to detect the ultraviolet photons emitted in the scattering plane. Ions and electrons are prevented from reaching the channeltron by placing biased grids in front of it.

The pulses from both detectors are amplified and then discriminators reject any low level noise. In order to record the coincidences use is made of the fact that electrons and photons from the same excitation event have a fixed time difference in their arrival at the detectors. Pulses from the electron detector are used to start a time-to-amplitude converter (TAC) and the delayed photon pulses are used to stop the ramp. The output from the TAC is then a pulse whose height is proportional to the time difference of arrival of the two pulses. These pulses are then fed to a pulse height analyser giving rise to a time spectrum which consists of a coincidence peak representing electrons and photons from the same collision superimposed on a level of random coincidences due to uncorrelated pairs of electrons and photons. The number of true coincidences can be readily found by subtracting the background.

Because the resolution of the electron spectrometer is low enough to allow detection of electrons which have excited the 3^1D and 3^1S states, there is a possible cascade contribution to the time spectrum due to the decay of these states to the 2^1P and then to the ground state. However, no such contribution was observed. The experiment of van Linden van den Heuvell *et al.* (1981) did produce this effect at an incident energy of 32·9 eV and a scattering angle of 22°. At 81·2 eV incident energy and at large scattering angles the 3^1P differential cross section is larger than that of the other two states. Even the work of Crowe *et al.* (1981) at 34·6 eV and at small scattering angles did not show any cascade contribution.

4. Results and Discussion

In Fig. 1*a* we have plotted the present measurements of λ (solid circles) together with previous values for 3^1P excitation at small scattering angles from Eminyan *et al.* (1975) at 80 eV (open circles) and the results of Hollywood *et al.* (1979) for 2^1P

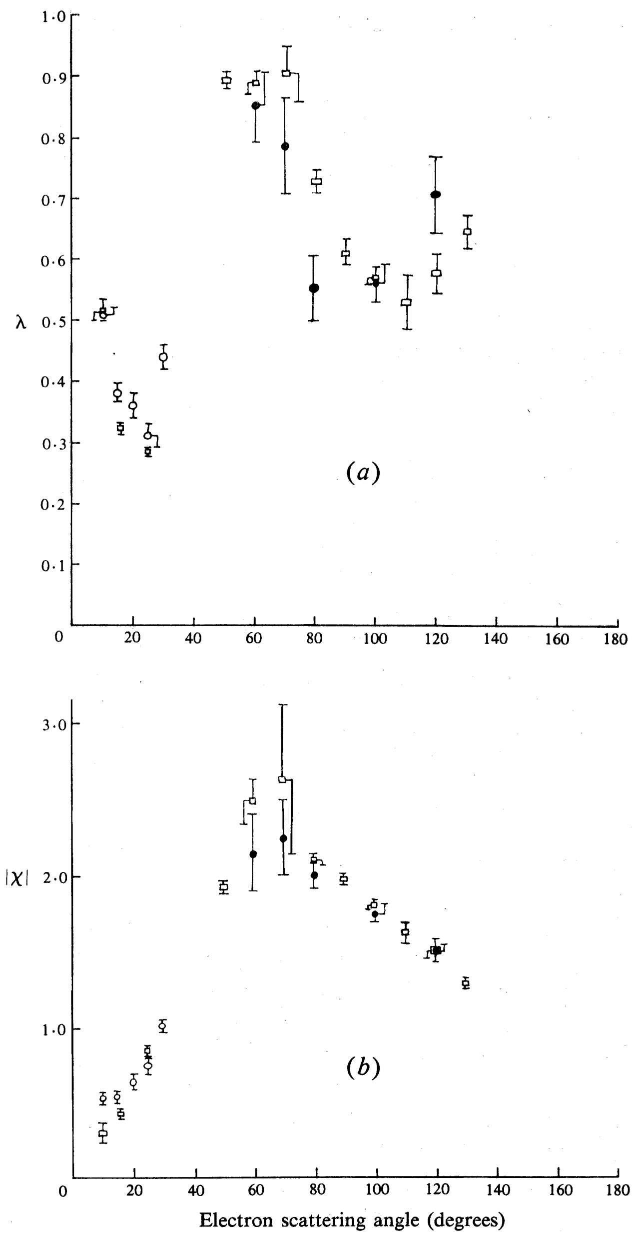

Fig. 1. Comparison of the values of (*a*) λ and (*b*) $|\chi|$ for 2^1P and 3^1P excitation: solid circles, present results at 81·2 eV; open circles, Eminyan *et al.* (1975) at 80 eV; and squares, Hollywood *et al.* (1979) at 81·2 eV.

excitation at 81·2 eV (squares). As can be seen, the angular trends for both the 2^1P and 3^1P results are very similar which is not altogether surprising. The depth of both the small and large momentum transfer minima are almost equal for the two states. As can be seen in Fig. 1*b*, there is also a marked similarity between the results for both states in the case of the phase parameter $|\chi|$.

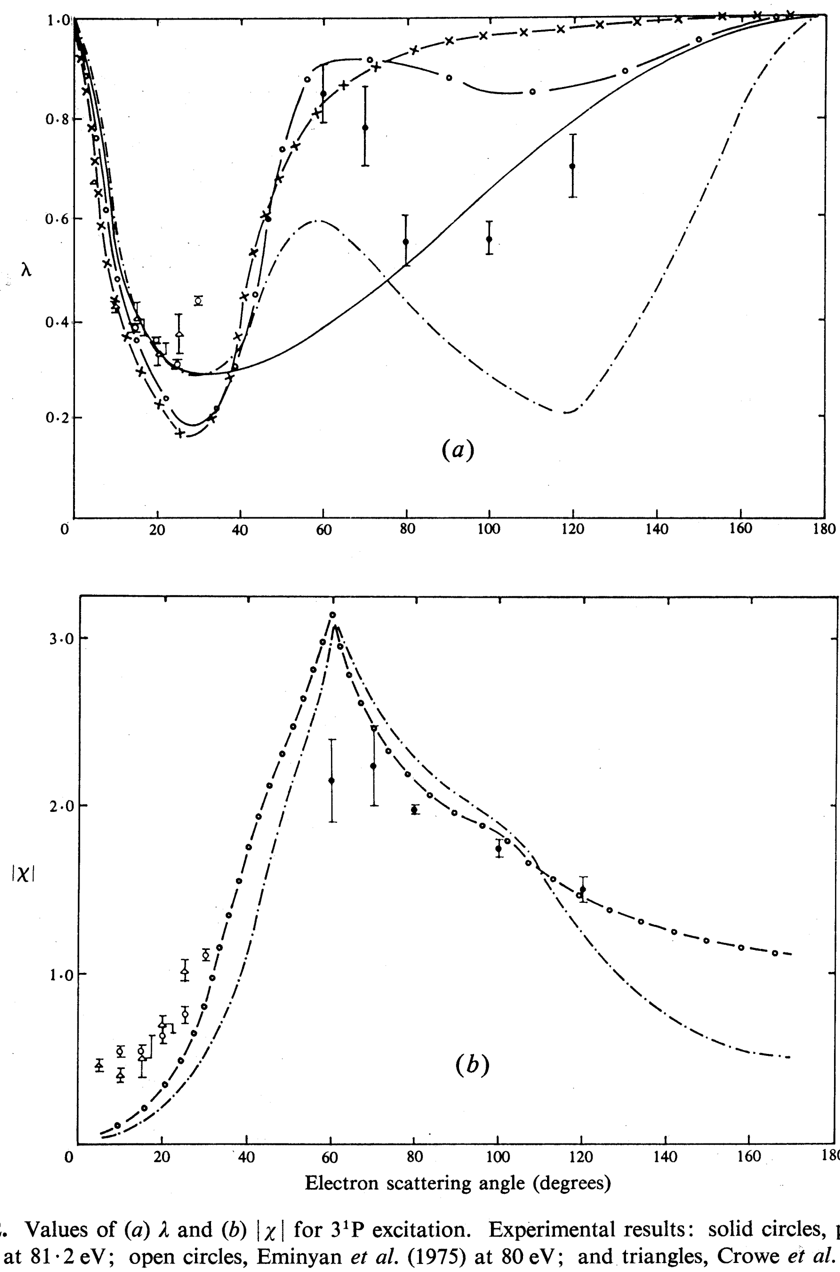

Fig. 2. Values of (*a*) λ and (*b*) $|\chi|$ for 3^1P excitation. Experimental results: solid circles, present work at 81·2 eV; open circles, Eminyan *et al.* (1975) at 80 eV; and triangles, Crowe *et al.* (1981) at 75·6 eV. Theoretical calculations: solid curve, first Born approximation; curve with crosses, multi-channel eikonal theory; curve with circles, first order many body theory; and dot–dash curve, distorted wave polarized orbital calculation.

The usefulness of the λ and χ parameters lies in the fact that they are the real test of any inelastic electron–atom scattering theory because they are so closely linked to the magnitude and phase of the scattering amplitude. Fig. 2*a* shows the present data together with that of Eminyan *et al.* (1975) and Crowe *et al.* (1981) and with the predictions of a number of theoretical calculations. The first Born approximation (solid curve) shows no large angle minimum, as is also the case with the multi-channel eikonal calculation (curve with crosses) of Flannery and McCann (1976). The first order many body theory (curve with circles) of Meneses and Csanak (1980) does predict a shallow minimum at large scattering angles, whereas the results of the distorted wave polarized orbital calculation (dot–dash curve) of Scott and McDowell (1976) show a deep large momentum transfer minimum. None of the theories agrees with our measurements. It is interesting to note that those theories which do show the structure at large scattering angles include exchange scattering in their approximations, whereas the first Born approximation and multi-channel eikonal theory do not.

In the case of the χ parameter shown in Fig. 2*b* agreement between the measurements and both the first order many body theory and the distorted wave polarized orbital calculation is qualitatively, if not quantitatively, good even at large scattering angles.

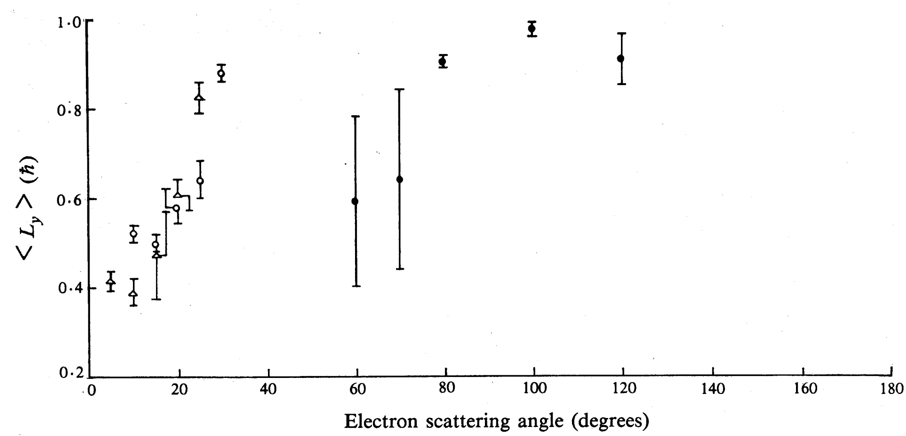

Fig. 3. Values of the atomic orbital angular momentum component $\langle L_y \rangle$: solid circles, present work at 81·2 eV; open circles, Eminyan *et al.* (1975) at 80 eV; and triangles, Crowe *et al.* (1981) at 75·6 eV.

Finally in Fig. 3 we have plotted the value of the orbital angular momentum component (in units of $\hbar$) perpendicular to the scattering plane. The excited state is fully oriented at both small and large scattering angles, although the data do not allow us to discern whether the orientation in fact goes through a value of zero which must occur if the phase difference between the excitation amplitudes is π.

Acknowledgments

This work was supported by the Australian Research Grants Committee. R. McAdams held a postgraduate research scholarship from the Northern Ireland Department of Education.

References

Blum, K., and Kleinpoppen, H. (1979). *Phys. Rep.* **52**, 203.
Crowe, A., King, T. C. F., and Williams, J. F. (1981). *J. Phys.* B **14**, 1219.
Eminyan, M., MacAdam, K. B., Slevin, J., Standage, M. C., and Kleinpoppen, H. (1975). *J. Phys.* B **8**, 2056.

Fano, U., and Macek, J. (1973). *Rev. Mod. Phys.* **45**, 554.
Flannery, M. R., and McCann, K. J. (1976). *J. Phys.* B **8**, 1716.
Hollywood, M. T., Crowe, A., and Williams, J. F. (1979). *J. Phys.* B **12**, 819.
McAdams, R., Hollywood, M. T., Crowe, A., and Williams, J. F. (1980). *J. Phys.* B **13**, 3691.
Macek, J., and Jaecks, D. H. (1971). *Phys. Rev.* A **4**, 2288.
Meneses, G. D., and Csanak, G. (1980). *In* 'Coherence and Correlation in Atomic Collisions' (Eds H. Kleinpoppen and J. F. Williams) (Plenum: New York).
Scott, T., and McDowell, M. R. C. (1976). *J. Phys.* B **9**, 2235.
van Linden van den Heuvell, H. B., Neinhuis, G., van Eck, J., and Heideman, H. G. M. (1981). *J. Phys.* B **14**, 2667.

Manuscript received 6 May, accepted 13 May 1982