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Electron Scattering from Copper*

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Abstract

A measurement of the total cross section for the excitation of the 4^2P state in copper by 60 eV electrons is described. These relative measurements are converted into absolute values by a generalised oscillator strength formalism which is also described. The result agrees very favourably with that predicted by a four state close coupling calculation, but is about a factor of three smaller than the previous measurement of Trajmar *et al.* (1977).

1. Introduction

It could be argued that it is inappropriate to discuss the problems of scattering electrons from copper atoms in conjunction with I.E. McCarthy's sixtieth birthday celebrations because Ian has not yet devoted any effort to the theory of electron scattering from copper. Nevertheless, it is an interesting problem which not only is worth studying for its own sake, but also raises the concept of the generalised oscillator strength about which Professor McCarthy and I have had lengthy tutorials over the past twenty years.

The excitation of the 4^2P state in copper lies at the heart of the operation of the copper vapour laser because population of this state by electron impact immediately establishes a population inversion between this state and the lower lying 3^2D state. Thus lasing action is established between the $4^2P_{\frac{3}{2}} \rightarrow 3^2D_{\frac{5}{2}}$ and $4^2P_{\frac{1}{2}} \rightarrow 3^2D_{\frac{3}{2}}$ states. The cross sections for the excitation of the P states are clearly important parameters for the development of models for the operation of copper vapour lasers.

Williams and Trajmar (1974) reported total cross sections for the excitation of the ^{2}P and ^{2}D states in copper at several energies between 6 and 100 eV. Subsequently these cross sections were renormalised by Trajmar *et al.* (1977) which lead to the cross sections being reduced by about a factor of two. The basis of this renormalisation was the calculated 40° differential cross section for elastic scattering at 100 eV of Winter (1977) who had used a static exchange approximation.

Msezane and Henry (1986) have reviewed further work in the field. This review includes Born calculations by Winter (1977) and by Peterkop and Liepinsh

* Dedicated to Professor Ian McCarthy on the occasion of his sixtieth birthday.

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(1979) and an unpublished report of an impact parameter approximation by Winter and Hazi (1982). Msezane and Henry have used a four state close coupling calculation in the energy range from 6 to 100 eV and they find a difference of about a factor of three between the predictions of the theory and the renormalised data of Trajmar *et al.* (1977). Clearly there is scope for another measurement of the total cross section.

We have measured the total cross section for the excitation of the 4^2P state at an energy of 60 eV. The total cross section was derived by converting an angular distribution into a set of generalised oscillator strengths and doing the appropriate integral. It is now well established (see e.g. Brunger *et al.* 1988) that this technique can be used with confidence for the study of inelastic transitions where the differential cross sections are sharply peaked in the forward direction. In some sense this technique is equivalent to the assumption that the first Born approximation is valid in this kinematic range. Yet this assumption could not be tested in our case because the cross sections derived from two Born calculations differ by a factor of about two at 60 eV.

The experimental technique is described in Section 2; in section 3 we present the generalised oscillator strength formalism and our results are discussed in Section 4.

2. Experimental Technique

A modulated crossed beam technique has been used to measure the angular distribution of scattered electrons after they had excited the 4^2P state of copper. The major part of the apparatus has been described in detail previously (see Brunger *et al.* 1988). The most significant addition to the equipment is the oven which is used to produce the copper atoms and details of this will be given elsewhere (Ismail *et al.* 1991). Briefly, a beam of copper atoms was produced in an oven which was heated to a temperature of 1500 K by electron bombardment. The copper beam was collimated before it passed through a rotating toothed wheel which modulated the beam at 240 Hz. The beam was further collimated before it passed into the interaction region where it intersected a beam of electrons. A cylindrical mirror electron spectrometer viewed the interaction region and analysed the energy of electrons which had been scattered through a particular angle θ. The overall energy resolution of the apparatus was 0·8 eV (FWHM). This was sufficient to resolve the energy loss of electrons which had excited the P state from either the D state or higher states.

The angular distribution $I(\theta)$ of electrons which had lost 3·83 eV of energy and had been scattered at an angle of θ was measured by counting the number of electrons scattered from the beam at the appropriate angle in a fixed time. This was achieved with two gated counters which were enabled by a reference signal derived from the rotating toothed wheel.

Care was taken to ensure that the incident electron flux was constant during the measurements. It proved to be difficult to keep the source temperature of the copper atoms constant during each run to better than 2 K. Thus it was necessary to correct the data at each angle to a constant target density. Care was taken to measure the scattering angle. We estimate that this was known to better than 0·2°. The angular distribution was converted into a set of differential cross sections by the generalised oscillator strength technique which is explained below.

3. Generalised Oscillator Strength

The generalised oscillator strength $f(K)$ is related to the differential cross section $\sigma(\theta)$ by (Mott and Massey 1965)

$$\sigma(\theta) = \frac{2}{W}\frac{k_n}{k_0}\frac{f(K)}{K^2}, \tag{1}$$

where W is the excitation energy of the bound state and K is the momentum transfer between the initial momentum $\mathbf{k}_0$ and the final momentum $\mathbf{k}_n$, i.e.

$$\mathbf{K} = \mathbf{k}_0 - \mathbf{k}_n . \tag{2}$$

Atomic units have been used in equation (1). The generalised oscillator strength is given by

$$f(K) = \frac{W}{K^2} \mid \epsilon_{0n}(K) \mid^2 , \tag{3}$$

where ϵ_{0n} is

$$\epsilon(K) = \langle 0 \mid e^{i\mathbf{K.r}} \mid n \rangle \tag{4}$$

$$= iK\epsilon_1 - K^2\epsilon_2 - iK^3\epsilon_3 + \dots , \tag{5}$$

where the z axis is chosen parallel to the direction of the momentum transfer vector and

$$\epsilon_m = \frac{1}{m!}\langle 0 \mid z^m \mid n \rangle. \tag{6}$$

For optically allowed transitions, the parity between the states 0 and n changes, so

$$\epsilon_m = 0 \qquad \text{for } m \text{ even} \tag{7}$$

and thus

$$\mid \epsilon_{0n}(K) \mid^2 = K^2[\epsilon_1^2 - 2K^2\epsilon_1\epsilon_3 + \epsilon_3^2 K^4] + O(K^6) .$$

Substitution of equation (6) into (3) yields

$$f(K) = W[\epsilon_1^2 - 2K^2\epsilon_1\epsilon_3 + \epsilon_3^2 K^4] + O(K^6) . \tag{8}$$

As $K^2 \to 0, f(K) \to W\epsilon_1^2$ which is the optical oscillator strength f_{OPT}.

The generalised oscillator strength can be determined from the angular distribution $I(\theta)$ by noting that $I(\theta)$ is related to $\sigma(\theta)$ by

$$I(\theta) = C\sigma(\theta) , \tag{9}$$

where $C = I_0\, n_a(\ell d\Omega)\epsilon\tau$ and I_0 is the incident beam current, n_a the density of copper atoms in the beam, ℓ the scattering length, $d\Omega$ the solid angle of the detector, ϵ the efficiency of the detector and τ the transmission of the electron spectrometer. At each energy these parameters are constant with respect to the scattering angle θ, i.e.

$$I(\theta) = C\frac{2}{W}\frac{k_n}{k_0}\frac{f(K)}{K^2}\,. \tag{10}$$

At each incident momentum, k_0, k_n, W and C are fixed. Thus equation (9) can be expressed as

$$I(\theta)K^2 = Gf(K) \tag{11}$$

$$= f_{rel}(K)\,. \tag{12}$$

For small values of K^2, the function $f_{rel}(K)$ can be written as

$$f_{rel}(K) = A - BK^2 + DK^4\,. \tag{13}$$

The coefficients A, B and D can be found by fitting a function of the form (13) to the experimental data $I(\theta)K^2$. The constant G is given by

$$G = \frac{A}{f_{OPT}}\,.$$

In the case of the 4^2P state in copper we use the measured value of Hannaford and McDonald (1978) of 0·645 which is in excellent agreement with that obtained by Msezane and Henry (1986). The determination of the constant G from the measured data then determines $f(K)$ which can be used in equation (1) to calculate $\sigma(\theta)$ at a particular angle. Thus C can be determined from equation (8) and consequently the differential cross section at all angles is then known.

The total cross section Q is given by

$$Q = 2\pi\int_0^{\pi}\sigma(\theta)\sin\theta d\theta\,. \tag{14}$$

Given $\sigma(\theta)$, the total cross section can be determined by Simpson's rule.

4. Results and Discussion

The angular distribution for electrons which have excited the 4^2P state in copper at an incident energy of 60 eV is shown in Fig. 1. The present data cover the angular range from 3° to 20°. The lower limit is set by the width of the incident electron beam, whilst at the upper limit the integrand is essentially zero. Fig. 2 shows the relative generalised oscillator strength at 60 eV plotted as a function of K^2. The fitted function is of the form (13).

In order to calculate the total cross section from equation (14) it is necessary to extrapolate the angular distribution into a scattering angle of 0°. The extrapolation was carried out using equation (13) and the integral then

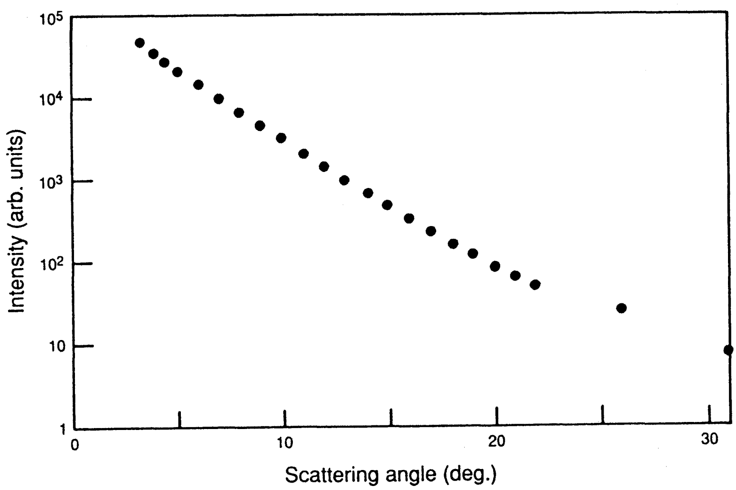

Fig. 1. Angular distribution of 60 eV electrons which have excited the 4^2P state of copper and been scattered through forward angles.

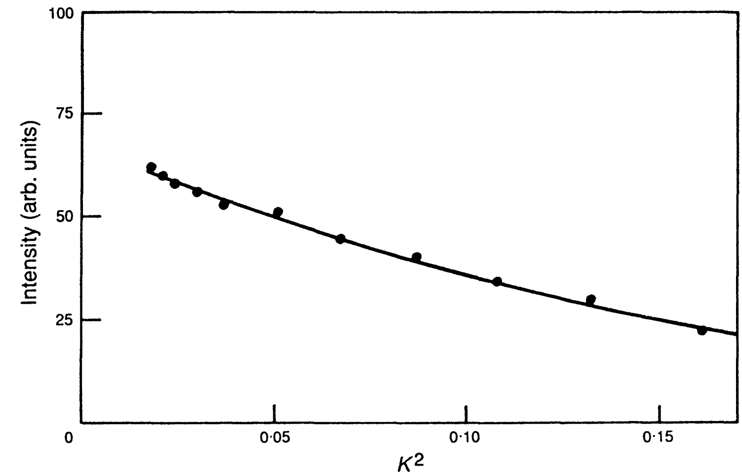

Fig. 2. A relative generalised oscillator strength of 60 eV electrons fitted to a function of the form $A+BK^2+D^4$.

performed. We find that the total cross section for the excitation of the 4^2P state in copper is $6\cdot0\pm0\cdot6$ πa_0^2. This is in excellent agreement with the value of $6\cdot44$ πa_0^2 reported by Msezane and Henry (1986) from their close coupling calculation. It also agrees favourably with the value of $6\cdot9$ πa_0^2 of Winter and Hazi but it is significantly less than that predicted by either of the Born calculations.

The total cross section reported by Trajmar *et al.* (1977) at 60 eV is $20\cdot1$ πa_0^2. This value was deduced by renormalising the data reported by Williams and Trajmar (1974) who measured a value of $41 \cdot 5\ \pi a_0^2$ for the cross section at 60 eV. The present result is about a factor of three less than the preferred result of the JPL group. A similar factor has been inferred by Msezane and Henry (1986) who compared the measured generalised oscillator strengths with those calculated from a four state close coupling approximation.

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