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The role of elastic electron scattering in coincidence spectroscopy of W(100) in back-reflection geometry

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Abstract

The correlated emission of two electrons from a surface excited by a low energy primary electron (coincidence spectroscopy) involves elastic back scattering of the primary electron in the sample. In the present experiments we also used an internal electron source: photoelectrons from the valence band created by synchrotron radiation. Within the experimental error we found the same threshold energy as with an external electron source. We studied the angular dependence of the number of coincidence events following 25–45 eV primary electron scattering on W(100). The most probable angle between two scattered electrons was found to be about 60–75°, regardless of the primary electron incidence angle. The best agreement between calculated (in the kinematic approximation) and measured angular distributions of the coincidence events was achieved when the effective mass of the valence electrons was taken to be 2–3 times that of the free electron mass. This may be due to the predominant scattering on the d-electrons of the tungsten valence band.

In the past few years a series of papers has appeared, dealing with measurements of the spectral momentum density of electrons in solid films in the transmission geometry using high energy primary electrons [1–3]. Such measurements can give rich information about the energy and momentum spectra of electron states in solids. Similar experiments in the low energy region are attractive as they may give information about the momentum density distribution of electrons in the surface region of solids.

In our previous work [4] we reported on the first successful two-electron coincidence experiment of the (e,2e) type at solid surfaces in the back-reflection geometry and found that coincident two-electron emission events required a certain threshold energy of the primary electron. We

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showed that the threshold energy depends on the work function of the surface. In the case of a clean tungsten surface the threshold energy was about 18 eV relative to the Fermi level when the angles of both detectors relative to the normal to the surface are equal to 60°. The aim of the present work is to estimate the role played by elastic back scattering of the exciting electrons in the process of formation of the pair of electrons detected outside the sample.

Since the mechanism of formation of a correlated electron pair resulting from a single event of a primary electron scattering on a valence electron includes elastic electron backscattering [4], we used, for comparison, an internal source of electrons: photoelectrons excited from the valence band by synchrotron radiation. In the latter case emission of an electron pair formed in a single event of photoelectron scattering on a valence electron is possible without additional elastic scattering. Besides we measured the angular distributions of true coincidence events (TCE) for various primary electron incidence angles and compared them to a kinematic model of scattering.

The experimental set-up was briefly described in Ref. [4]. Two detectors (channeltrons or multichannel plates) of scattered electrons and the normal to the sample surface were placed in the same plane and it was possible to change the angles of the detectors relative to the surface normal in the range from 0° to ±90°. The minimum angle between the detectors was about 15°. The entrance apertures of both detectors were about 0.02 srad for channeltrons and about 0.07 srad for multichannel plates. An electron gun was placed in the same plane or in the plane perpendicular to the scattering plane, and the angle of incidence was varied in the range from 0° to ±90°. One of the detectors starts a time-to-amplitude converter (TAC), while the other stops the TAC. The TAC output is analyzed by a multichannel analyser (MCA). In the case of photoelectron scattering a beam of monochromatized synchrotron radiation from BESSY entered the chamber through a system of collimating diaphragms and was directed along the normal to the W(100) sample surface. Measurements were

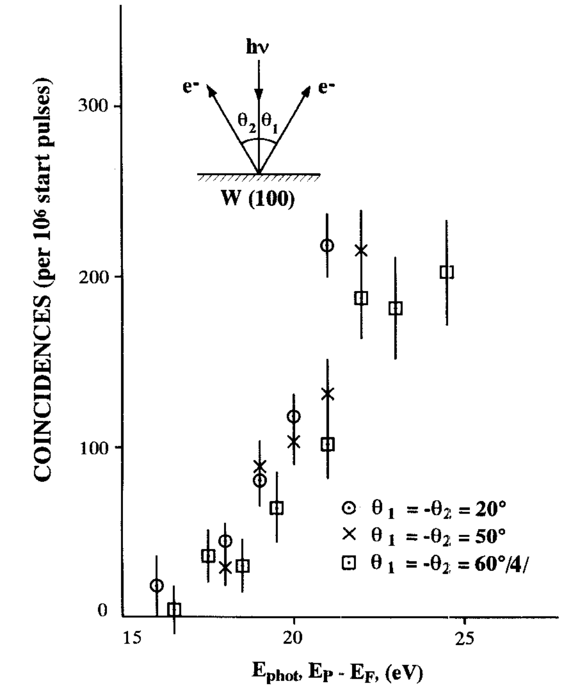

Fig. 1. The number of true coincidence events (TCE) as a function of the primary electron energy relative to the Fermi level ($E_p - E_F$) and of the exciting photon energy E_{phot} for W(100). θ_1 and θ_2 are the detector positions relative to the surface normal. Open circles and crosses are for photon excitation, open boxes are for primary electron excitation. Vertical bars indicate the 1σ statistical error.

carried out in vacuum of the order of 10^{-11} Torr. The cleaning of the W(100) surface is checked by LEED monitoring. The magnetic field of the earth near the specimen was compensated to 5% of the earth field approximately.

The TCE number, normalised to 10^6 start pulses, as a function of the exciting photon energy is presented in Fig. 1 (open circles and crosses). For comparison, in the same Fig. 1 the TCE number as a function of the exciting electron energy is shown [4]. In the latter case, the ordinates have been multiplied by a factor corresponding to the relative change of the detector acceptance angle. It can be seen from Fig. 1 that the threshold of the TCE appearance in photoexcited electron scattering on a valence electron for two different detector positions (at ±20° and ±50° to the normal of the surface) is the same

(E_{th} = 17–18 eV). Within the limit of the experimental accuracy it agrees with the TCE appearance threshold when using an external primary electron source. Let us note, that the maximum possible energy of a photoexcited electron relative to the Fermi level is equal to the exciting radiation energy. In our case, the minimum primary electron energy relative to the Fermi level necessary for a correlated electron pair appearance corresponds to the minimum photon energy necessary for the same process. This is an evidence in favour of the previous suggestion [4] of the elastic or quasi-elastic primary electron scattering into the back hemisphere.

We measured the angular distributions of true coincidence events (TCE) for primary electron energies E_p = 20–45 eV at various primary electron incidence angles to the W(100) single crystal surface. We found that the variation of the primary electron incidence angle had little effect on the TCE angular distributions both for the electron gun in the detectors plane and in the plane perpendicular to the detectors plane.

Let us consider the following results concerning the TCE angular dependence with regard to the following simple model. We assume that as a result of the elastic scattering, the primary electron is distributed isotropically over all possible states on the sphere corresponding to the energy E_p in momentum space. The valence electrons are also assumed to be distributed isotropically in the volume corresponding to valence states. Applying Fermi's golden rule, the probability of the primary electron scattering on a valence electron is proportional to the volume of available final electron states of the system after the scattering. As a rather crude approximation we assume the matrix element of the transition to be constant. The volume of the final states of the system is determined by the product of the solid angles of the detectors with the energy intervals of the electrons belonging to the pair. The refraction of the electron trajectories at the surface potential barrier leads to changes of the solid angles in which the electrons are detected depending on the electron energy and average emission angle. Then we integrate over all possible energies of the electron pair and over the valence band.

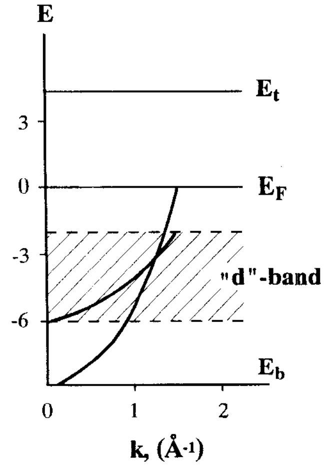

Fig. 2. A free-electron-gas approximation to the valence band of tungsten. The d-band is shown by shading. The effective mass values of the s- and d-band electrons are $m_s^* = 1$, $m_d^* = 1.5$. The top and the bottom of the potential barrier relative to the Fermi level are E_t = 4.5 eV, E_b = −9 eV.

We chose the free-electron-gas model with the effective electron mass as a parameter for description of the tungsten valence band electron structure. In this model the electron structure of valence states is characterised by the positions of the bottom and the top of the valence band relative to the Fermi level (E_F) and by the effective mass value (m^*) of valence electrons. The valence electron configuration of tungsten is $6s^2 5d^4$, and so we may roughly describe its valence band by two bands schematically presented in Fig. 2. Two s-band valence electrons with the effective mass $m_s^* = 1$ occupy the energy interval from −9 to 0 eV relative to the Fermi level. Four d-band valence electrons with a variable effective mass m_d^* are in the energy interval from −6 to −2 eV relative to the Fermi level. A quadratic dispersion is assumed in both cases according to the free-electron-gas model. The potential barrier at the vacuum–solid interface is determined by the positions of the potential barrier top (E_t) and its bottom (E_b) relative to the Fermi level (the work function is $e\phi = E_t - E_F$). We used the following parameters: E_t = 4.5 eV, E_b = −9 eV relative to the Fermi level.

It is well known that in the case of scattering of two particles of equal mass with one of them at rest, the angle between the flight directions of the particles after the scattering (i.e. the scattering angle) is equal to 90°. In the considered case valence electrons have finite velocities, so the scattering angle may be less than 90°. An increase of the effective mass of the valence electrons also leads to a decrease of the scattering angle. The general trend shown by the TCE distributions at $E_p = 35$ eV with the increase of the valence electron effective mass is to widen the distribution and to decrease the average scattering angle. Variations of potential barrier parameters E_t and E_b had little effect on the angular distribution in the case of $E_p = 35$ eV.

Fig. 3 shows the experimental angular dependence of the TCE number for a fixed position of the start-pulse detector at $\theta_2 = 75°$ relative to the surface normal. The primary electron beam is in the detector plane at the angle $\alpha = 60°$ to the surface normal. The TCE number as a function of the scattering angle has a maximum in the direction close to the normal, which corresponds to a most probable scattering angle of about 75° when the refraction at the potential step at the surface is taken into account. The angular distribution of the secondary electrons (full dots curve in Fig. 3) exhibit a maximum in the mirror reflection direction of the primary electrons but is relatively flat in a wide range of detection angles. Fig. 3 also shows angular distributions of the TCE probability calculated for the chosen geometry. The valence electron effective mass $m_d^* = 3$ gives reasonable agreement with the experimental results.

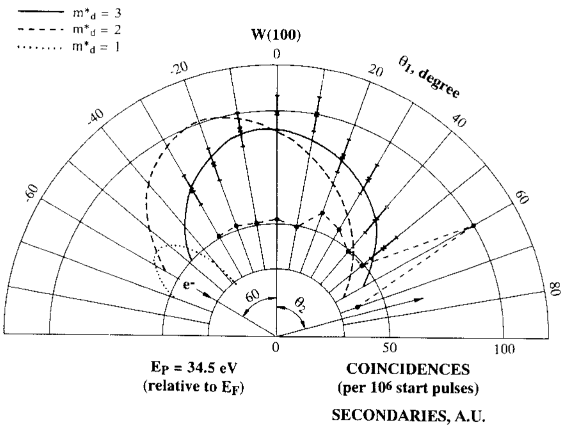

Fig. 3. The number of true coincidence events as a function of the scattering angle for W(100). The primary electron energy is $E_p = 34.4$ eV relative to the Fermi level. θ_1 and θ_2 are the angles of the detector positions relative to the surface normal. The "start" detector is fixed at $\theta_2 = 75°$. The primary electron beam is in the same plane as the detectors at an angle of incidence $\alpha = 60°$. Crosses with bars are experimental data of the number of true coincidence events. The full dots connected by the dotted line represent the angular dependence of the measured electron flux from the sample in arbitrary units. Full, dashed and dotted lines show the calculated dependence of true coincidence events following the primary electron scattering on the valence electrons with various effective mass, $m_d^* = 1,2,3$ m_e as indicated.

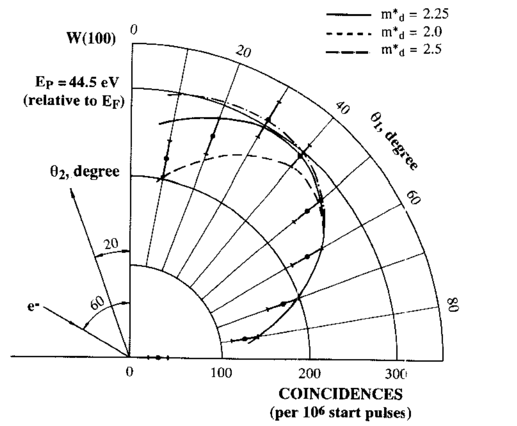

Fig. 4. The number of true coincidence events as a function of the scattering angle for W(100). The primary electron energy is $E_p = 44.4$ eV relative to the Fermi level. θ_1 and θ_2 are angles of the detector positions relative to the normal to the surface, $\theta_2 = 20°$. The primary electron beam is in the same plane as the detectors (angle of incidence $\alpha = 60°$). Full dots with bars are experimental data of the number of true coincidence events. Full line, dashed and dashed–dotted curves show the calculated dependence for scattering of the primary electron on a valence electron with various effective masses.

Fig. 4 shows experimental and calculated dependencies of the TCE number for another geometry of the positions of the detectors. The start-pulse detector is at $\theta_2 = -20°$, the primary electron beam with the energy of $E_p = 44.5$ eV relative to the Fermi level falls at the angle of about 60° to the normal to the surface and is situated in the same plane as the detectors. A reasonable agreement was achieved with the experiment when the effective mass was chosen to be $m_d^* = 2.25$.

In all cases considered above we detected all electrons without any energy selection. Because different fractions of the primary electron energy may be transferred to the secondary electron in the scattering event, the angles between the electrons can also be different. Besides, at the surface potential barrier, electrons with different energies are refracted at different angles. It means, that our data on the coincidence events represents some value averaged over all available energies of the scattered electrons.

The results suggest that the elastic backscattering of primary electrons plays an important role in the observation of coincidence events in the back-reflection geometry. At the same time, the threshold of the TCE detection, within the limits of the experimental accuracy, does not depend on whether we use the external primary electron source and take into account the elastic scattering in the solid, or an internal source of electrons excited directly in the solid by synchrotron radiation.

The TCE angular distribution exhibits a wide maximum, the most probable scattering angle between both electrons being in the region of 60–75°. Comparison of the experimental dependencies and those calculated in the kinematic approximation shows that the main characteristics of the angular distributions (the full width at half-maximum and average scattering angle) qualitatively agree if we assume that the primary electron has had an additional elastic scattering event after which it is scattered from a valence electron with the effective mass in the interval $m_d^* = 2$–3 depending on the geometry. It may be supposed that the main contribution to the creation of the correlated electron pairs is given by the primary electron scattering on "heavy" d-electrons of the valence band.

Still unclear is the role played by the cascade electron–electron scattering, the probability of which increases with the increase of the primary electron energy. This problem may be solved by measuring the energy distributions of electrons belonging to the correlated pair.

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