Postcollision interaction in the excitation of a gold 4*d* vacancy by fast electrons

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A comparative study has been made of the energy spectra of the Auger electrons emitted as a result of excitation of a gold 4*d* vacancy by x rays and high-energy electrons. In the case of electron collision, a change is observed in the kinetic energy of an Auger electron as the result of a postcollision interaction of this electron with an electron knocked out of an inner shell. A theoretical model is proposed. Equations are proposed for describing the postcollision interaction for isolated atoms (in a gas) and also for atoms at a metal surface. The change in the energy of an Auger electron due to the postcollision interaction is calculated to be 0.6 eV. This figure is comparable to the experimental value of 0.25 ± 0.15 eV. It is concluded that the classical Barker–Berry postcollision interaction does not occur at a metal surface, in contrast with the case involving an isolated atom.

The emission and scattering of electrons by a substance cannot be described correctly without consideration of the Coulomb interaction after the collision, which leads to a redistribution of energy among the emitted and scattered particles.[1] The overwhelming majority of studies of this topic have been devoted to various versions of the classic Barker–Berry postcollision effect[2] at an isolated atom (an atom in the gas phase). This effect is manifested at the threshold for inelastic collisions, where the velocity of the scattered particle and the cross section for collisions processes are small. An anisotropic postcollision effect has come under study comparatively recently. This effect is significant under the unconventional conditions of large absolute velocities but small relative velocities of the scattered and emitted particles.[1,3] The anisotropic postcollision effect differs from the classical one in being large at velocities characterized by cross sections close to the maximum values. It may thus be of considerable practical interest. This effect has received little experimental study. Almost nothing is known about the role played by the postcollision effect in a solid or at its surface.

Our purposes in the present study were to search for and study the postcollision effect at the surface of a solid during the scattering of fast electrons. We assumed that the anisotropic postcollision effect would play a particularly large role in this case.

The experiments were carried out on a Leybold AG LHS-11 electron spectrometer in high vacuum (10^{-7} Pa). An atomically clean surface of a gold sample was prepared by ion etching. Spectra of the Auger electrons (e_3) emitted in the direction perpendicular to the sample surface during excitation of a 4*d* vacancy of gold atoms

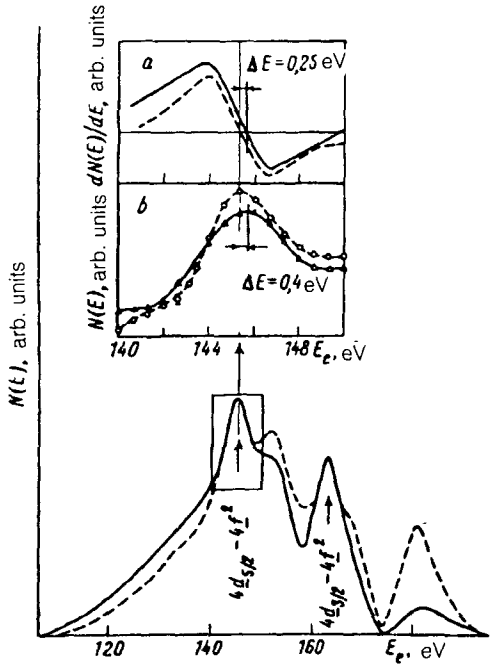

FIG. 1. *N–NN* energy spectra of Auger electrons emitted during the bombardment of a gold surface by Al $K\alpha$ x rays (solid curve) and during the scattering of fast electrons ($E_0=3000$ eV) by this surface (dashed curves). The insets show spectra measured in separated experiments. a—The differential spectrum $dN(E)/dE$; b—the actual spectrum $N(E)$.

(binding energy $I_{4d}=336$ eV) by x rays ($h\nu=1486.6$ eV) were measured in a counting regime:

$$h\nu+\mathrm{Au}\rightarrow e_1+\mathrm{Au}^{+*}(\underline{4d})\rightarrow e_1+\mathrm{Au}^{2+}+e_3. \tag{1}$$

We also carried out corresponding measurements during excitation by fast electrons (e_0) with an energy $E_0=3000$ eV:

$$e_0+\mathrm{Au}\rightarrow e_1+\mathrm{Au}^{+*}(\underline{4d})+e_2\rightarrow e_1+\mathrm{Au}^{2+}+e_3+e_2, \tag{2}$$

where e_1 is the scattered electron or photoelectron, and e_2 is an electron which has been ejected (Fig. 1a).

The photon energy in (1) was chosen large enough that we could ignore the interaction of the photoelectron (e_1) with the decay products of the $4d$ vacancy. Accordingly, the kinetic energy of the Auger electron in (1) is not perturbed by the postcollision interaction; the corresponding line in the electron spectrum was used as a reference for studying the postcollision interaction in process (2). The unknown change in the kinetic energy of the Auger electron in (2) is equal to the difference in the positions of the Auger lines for processes (1) and (2).

Figure 1 shows experimental energy spectra of the Auger electrons emitted as the result of very fast Coster–Kronig supertransitions, $4d_{5/2,3/2}-4f^2$, for both processes. The continuous component (the pedestal) has been subtracted from the spectra. (An error in the pedestal subtraction procedure is responsible for the difference between the low-energy parts of the spectra for the photoionization and the electron scattering. The sharp increase in the high-energy peak in the second collision may be due to an

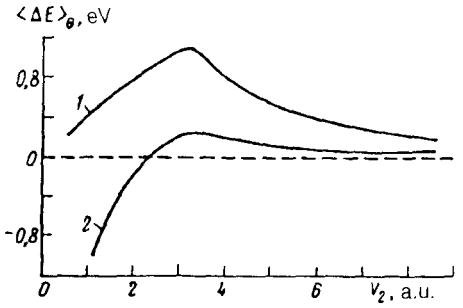

FIG. 2. Postcollision-interaction shift of the Auger line, averaged over the emission angle (θ) of the ejected electron e_2, versus the velocity of this electron, v_2.

increase in the probability for exciting the valence electron into a quasistationary state formed in the quasicontinuum by the centrifugal barrier and a subsequent Auger decay involving this electron.) The Auger peaks seen in the spectra are characterized by a large width, since they are formed by several terms (which are not resolved, because of a large intrinsic width). A detailed study of one of the peaks, $4d_{5/2}-4f^2$, was accordingly carried out in order to observe a relatively small postcollision-effect shift (integrated over angle and energy). The experiment was repeated several times in regimes in which we measured the actual spectrum $N(E)$ (Fig. 1b) and the differential spectrum $dN(E)/dE$ (Fig. 1a). Despite the large errors, the effect of interest was observed in each experiment. A comparison of the spectra of the Auger lines for processes (1) and (2) yielded an experimental value of the postcollision-interaction shift for process (2): $\Delta E_{\text{exp}}=0.25\pm0.15$ eV. (The results for one of the first experiments are reported in Ref. 4.)

The energy of the colliding electron in (2) was also chosen large enough that we could ignore the interaction of the scattered electron (e_1) with the products of the decay of the $4d$ vacancy. The postcollision effect is thus attributable to the presence of an ejected electron (e_2) in (2). For an isolated Au atom (in the gas phase) the postcollision shift can be described by an equation derived in the eikonal approximation:[1]

$$\Delta E_a^2=\xi_a\cdot\Gamma/2=(-v_2^{-1}+v_{2,3}^{-1})\cdot\Gamma/2. \tag{3}$$

Here v_2 is the velocity of the ejected electron e_2, $v_{2,3}$ is the relative velocity of the ejected electron and the Auger electron, and $\Gamma=5.5$ eV is the intrinsic width of the $4d$ level, determined in the present study from the line in the photoelectron spectrum [e_1; process (1)].

The first term in (3) is responsible for the classic Barker–Berry shift,[2] which is important at collision energies near the threshold.

Process (2) is characterized by a continuous distribution of the velocity of the emitted electron, v_2, which was found in the present study from the data of Ref. 5. Figure 2 shows the postcollision shift versus the velocity of the emitted electron for an isolated gold atom, after an averaging over the emission angle (curve 2). We see that at low velocities v_2 the postcollision interaction is determined by the first (classical) term of expression (3). However, after an average is taken over v_2, the classic postcol-

lision shift decreases substantially because of the direct interaction of the ejected and Auger electrons, which is described by the second term in expression (3).

The primary distinguishing feature of the present study is that the gold atom under study is part of a solid. The ejected electron (e_2) and the Auger electron are emitted by the metal surface. In addition to the interaction of the particles e_2, e_3, and Au^{2+}, we must therefore deal with the contribution to the postcollision interaction of these particles with the metal surface. This interaction can be dealt with effectively by introducing image charges. The postcollision shift of an Auger line can be described in this model by the formula

$$\Delta E_s^2=\xi_s^2\cdot\Gamma/2=2(v_{2,3}^{-1}-v_{2+,3}^{-1})\cdot\Gamma/2, \tag{4}$$

where $v_{2+,3}^{-1}$ is the relative velocity of the Auger electron e_3 and the induced charge e_2^+.

An important conclusion follows from (4): There is no classical Barker–Berry effect at a metal surface. The reason is a screening of the vacancies by metal electrons.

Curve 1 in Fig. 2 is dependence (4), averaged over the angle of the postcollision shift, for a metallic gold surface. An average over the energy distribution of the ejected electrons e_2 yields a theoretical value for the postcollision shift: $\Delta E_{\text{theor}}=0.60$ eV. This figure is comparable to the experimental figure.

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