Inelastic scattering of 100-keV electrons in thin polycrystalline copper films

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The angular and energy distributions of electrons scattered in thin polycrystalline copper films have been investigated experimentally. The results cannot be explained by the existing theory of inelastic electron scattering by atoms. The theory must apparently be modified to take into account the scattering of the electron in the Coulomb field of the nucleus of the atom being ionized.

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It is well known that the angular distribution of fast charged particles scattered by a Coulomb potential is described by the Rutherford formula or, in the case in which the scattered particles are electrons and relativistic and spin corrections must be taken into account, by the Mott formula.[1] Morse[2] showed that scattering accompanied by excitation of the scattering atom is also described approximately by the Rutherford formula. A number of authors have treated the scattering of fast electrons with ionization of the scattering atom (see the monograph by Mott and Massey[3]). If the energy E_0 of the incident electron is substantially higher than the binding energy of the electron in the atom, the scattering can be treated in the first approximation as scattering by a free electron. This case was treated theoretically by Møller[4,5] who showed that the angular distributions and energy spectra of the scattering electrons have peaks at scattering angles θ_e and scattered-electron energies E_e determined by the kinematics of the electron-electron scattering process.

Even at fairly high energies (E_0 of the order of hundreds of KeV), however, significant differences from the simplified Møller picture are found in the angular and energy distributions of the scattered electrons. The most detailed measurements in this energy range were made by Missoni *et al.*[6] These authors showed that the energy spectra of the scattered electrons exhibit not only the previously known broadening of the electron-electron scattering peak (the Møller peak), but also a rise in the low-energy region.

The results of Missoni *et al.*[6] were analyzed theoretically by Cooper and Kolbenstvedt,[7] who calculated the differential cross section for elastic scattering of fast electrons by an atom in the first Born approximation with allowance for relativistic and spin effects. The ionization was treated as a two-body process, the incident, scattered, and ejected electrons being described by plane waves. A nonrelativistic hydrogenlike wave function was used to describe the bound state of the electron in the atom. Satisfactory agreement with the experimental results[6] was obtained, but with one exception: in the case of the smallest incident-electron energy used in the experiments[6] ($E_0 = 100$ keV), the measured intensity of the electrons scattered at small angles ($\theta < 20°$) with energies exceeding E_e was much higher than its calculated value. Cooper and Kolbenstvedt attributed this discrepancy to multiple scattering due to the finite thickness of the target and to the use of approximate wave functions in the calculation.

The results of the present work show that the theory of Cooper and Kolbenstvedt requires qualitative corrections; in particular, it is apparently necessary to take into account the scattering of the incident electron in the field of the nucleus of the atom being ionized. Such scattering could probably account for the increase in the scattering intensity observed in the present work at scattered-electron energies above E_e, and in particular, near the elastic scattering peak at E_0 (this part of the scattered-electron energy spectrum was not investigated in Ref. 6). The same correction could also apparently account for the shape of the angular distribution of the electrons scattered inelastically at angles greater than θ_e, which turns out to be close to the shape given by the Mott formula.

We measured the angular and energy distributions of the scattered electrons, using the apparatus diagrammed schematically in Fig. 1a. The electron beam was formed by the illuminating system *1* of a type of EG-100M electron diffraction camera and, after passing the magnetic deflection coils *2* and through the opening in the integrator collector *3*, struck the target *4*, which was mounted at the center of the scattering chamber *5*. The scattering chamber was cylindrical in shape, 540 mm in diameter, and 240 mm high. The magnetic

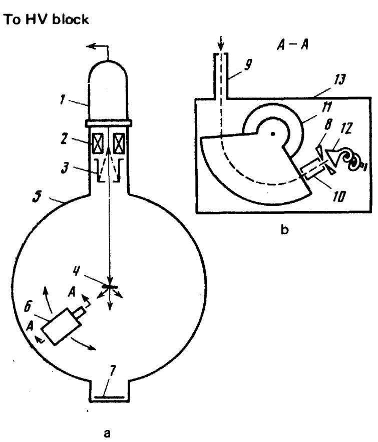

FIG. 1. Diagram of the apparatus.

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spectrometer *6* was mounted within the scattering chamber; it could be moved so as to cover the scattering-angle range from 0 to 160° without breaking the vacuum. The target holder was so designed as to permit the target to be arbitrarily moved and oriented. The scattering chamber also contained a fluorescent screen *7* for use in adjusting the apparatus. The electron source 1 from the diffraction camera provided electron beams for electron energies from 10 to 100 keV; the beam had a convergence angle $\lesssim 10^{-3}$ rad and, when focused on the target, covered a circular spot $\sim 100\ \mu m$ in diameter.

The design of the double focusing magnetic spectrometer[8] that we used is illustrated schematically in Fig. 1b. The vertex angle of the spectrometer sector was made 120° so that when one of the foci of the system was put at the point of intersection of the electron beam with the target, its conjugate focus would lie in the plane of the slit *8*, which is outside the magnetic field and defines the energy resolution of the spectrometer. The surfaces of the spectrometer pole pieces were so tapered as to ensure a field decrement index close to 0.5 (within a percent or so) in the vicinity of the equilibrium orbit (radius 40 mm). To reduce the background of electrons scattered by parts of the chamber and spectrometer, the spectrometer pole pieces were covered with beryllium foil and the beam was carefully collimated at the spectrometer entrance and exit with the aid of the collimators *9* and *10*.

During the course of the work it was necessary to alter the energy resolution of the spectrometer without breaking the vacuum. To make this possible the jaws of the slit *8* that determines the resolution were fastened to bimetallic plates in such a manner that the width of the slit could be altered by heating the plates. This made it possible to vary the energy resolution of the spectrometer from 0.05 to 0.5%.

A one-to-one relation between the current in the winding *11* and the field strength in the spectrometer can be achieved only be eliminating hysteresis effects. We therefore demagnetized the spectrometer before each run, using a device that automatically reduced the current in the spectrometer windings in discrete steps and changed its direction at each step. The electron detector *12* was a type VEU-6 channel electron multiplier mounted at the spectrometer exit. The spectrometer was enclosed in the case *13* for shielding.

The measured angular and energy distributions of the scattered electrons should be reduced to a constant primary-beam intensity for presentation. Such normalization can be effected either by stabilizing the primary-beam intensity or by monitoring that intensity. In our case, in which the inelastic scattering differential cross section was being measured, the scattered-electron intensity varied by up to nine orders of magnitude, depending on the scattering angle and the energy of the scattered electron, and in order to accumulate the necessary statistics in the available time it was necessary also to change the intensity of the primary beam by the same amount. We therefore chose the second method of relating the measured results to the primary-beam intensity. The electron beam was periodically directed into the collector of an integrator by means of the deflecting magnets *2* (Fig. 1a) and the charge reaching the collector was measured by a current integrator. A measuring cycle was initiated by the starting of the integrator. When a specified charge had accumulated the integrator sent a control pulse to the scaling circuit to stop the recording of signals. The gate pulse, entering the signal-transmission circuit simultaneously with the deflection of the beam, ensured that no signals from the detector would be recorded while the beam was deflected. Our monitoring system enabled us to make measurements at all scattering angles, including zero scattering angle.

The targets were free copper films ~300Å thick obtained by vacuum deposition of copper onto a polished cleavage face of a rocksalt crystal. The film was removed from the crystal by immersing the latter in distilled water.

In the work reported here we were measuring absolute values of the electron inelastic scattering differential cross section. This made it necessary to measure as accurately as possible the target thickness, the detector efficiency for electrons of various energies, the energy width of the spectrometer slit, and a number of other parameters. The target thickness was measured during deposition with an error no greater than 5%, using a quartz thickness gauge. The efficiency of the channel electron multiplier for electrons of various energies was determined with an error of about 10% (the method used for this measurement is described in detail elsewhere[9]). The errors in measuring the other quantities were smaller. We estimate the over-all error in measuring the absolute cross sections as 15%. The methods used in testing the apparatus, making the measurements, and processing the data are described in more detail elsewhere.[10]

In presenting the experimental results we shall begin with the angular dependences of the electron inelastic scattering differential cross sections. First let us justify our earlier assertion that the inelastic scattering of electrons cannot be described over the entire range of scattering angles within the limitations of the model used by Cooper and Kolbenstvedt.[7] Figure 2 shows the experimental (1) and theoretical (2) angular distributions of electrons with initial energy $E_0 = 98.6$ keV after being scattered by copper atoms with the energy loss $\Delta E = 24.8$ keV. The theoretical differential cross section (curve 2) was calculated by us using a formula taken from the theory employed in Ref. 7. The figure reveals a large discrepancy between the theoretical and experimental curves, which reaches several orders of magnitude in the scattering-angle region to the right of the Møller peak (the calculated position of the peak is marked by an arrow above the curve).

We examined in detail the possibility of explaining the above discrepancy as a result of multiple scattering in a target of finite thickness (300 Å) or as a result of processes associated with bremsstrahlung. In treating multiple processes we took into account only two-fold scattering (the target was thin enough) in which the

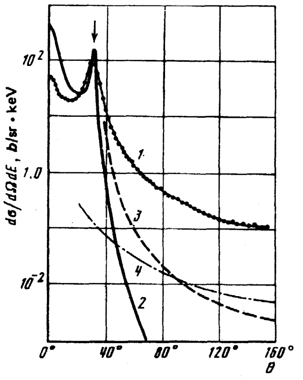

FIG. 2. Differential cross section for inelastic scattering of 98.6-keV: electrons by copper atoms with the energy loss $\Delta E = 24.8$ keV: 1—experiment, 2—calculated in accordance with allowance for multiple scattering, 4—calculated with allowance for losses by bremsstrahlung.

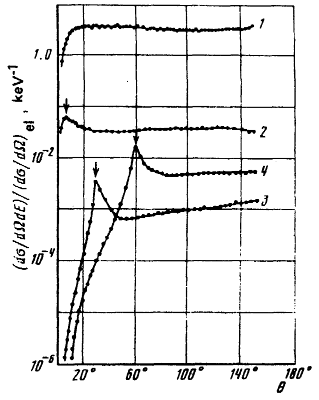

FIG. 3. Differential cross sections for inelastic scattering of electrons with $E_0 = 98.6$ keV by copper atoms with the following energy losses ΔE: 1—<100 eV, 2—1.4 keV, 3—24.8 keV, 4—75.7 keV. All the results are normalized to the elastic scattering differential cross section.

electron suffers two successive independent interactions in one (either the first or second) of which it loses energy as a result of electron-electron scattering, and in the other it is scattered elastically through some angle. The electron-electron interaction was described by the differential cross section for scattering of electrons by free electrons, and the Rutherford formula without allowance for screening was used to describe the elastic scattering (the corresponding expressions are given in Landau and Lifshitz's book[11]). Since screening was neglected, the result must be regarded as too high. The differential cross section for scattering with energy loss by bremsstrahlung emission was calculated on the basis of expressions given in Mott and Massey's book[3] [formula (22.66), p. 740]. The calculated cross sections for these two processes are shown in Fig. 2 by curves 3 and 4, respectively. In view of these results, it would not seem possible that these processes could account for the observed discrepancy between theory and experiment.

Our experimental results show that the angular distributions of electrons scattered inelastically at angles greater than θ_e are very close in shape to the angular distribution of elastically scattered electrons. The experimental angular distributions of electrons scattered with various energy losses are accordingly presented in Fig. 3 in normalized form. Curve 1 corresponds to virtually elastic scattering (energy loss less that 100 eV) and is normalized to the Mott cross section. The presence of the horizontal section in the scattering-angle region $20° \leqslant \theta \leqslant 160°$ attests to the good agreement with the theory. The sharp fall of the curve in the region $\theta < 20°$ is due to the effect of screening of the Coulomb field of the nucleus by the atomic electrons, which is not taken into account in the Mott formula. Curves 2, 3, and 4 are for scattering with various energy losses, which are given in the caption to the figure. In order to exhibit the differences between the elastic- and inelastic-scattering cross sections more clearly, we have normalized curves 2–4 to the experimental elastic scattering differential cross section (curve 1).

A primary characteristic feature of curves 2–4 is the presence on each of them of the electron-electron scattering peak (the expected value of θ_e for scattering by free electrons is marked on each of the curves by an arrow). As is evident from the figure, each of the curves 2–4 has a prominent horizontal section in the region of scattering angles greater than θ_e; this indicates that the scattering of electrons with various energy losses is still virtually Mott scattering. In our opinion the presence of these horizontal sections can be reasonably explained by the fact that a large deflection of the electron in the field of the atomic nucleus is associated with a small impact parameter, so that ionization of one of the atomic shells with a corresponding energy loss by the scattered electron is likely. In a quantum mechanical treatment of electron inelastic scattering, this process of simultaneous ionization and deflection in the field of the nucleus of the same atom appears in the second born approximation and therefore becomes more

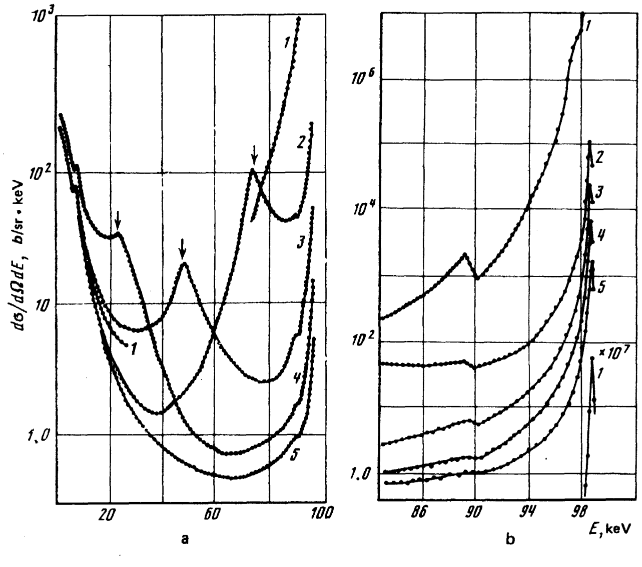

FIG. 4. Differential cross sections for inelastic scattering of electrons with $E_0 = 98.6$ keV by copper atoms at the following scattering angles θ: 1—1°, 2—30°, 3—45°, 4—60°, 5—90°.

important as the atomic number of the target material increases.

In the present work we also investigated the energy dependence of the differential cross section over the wide range of scattered-electron energies from 1 keV clear up to the initial energy. The corresponding results are presented in Fig. 4. Figure 4a shows the energy spectra of the scattered electrons over the entire range, while Fig. 4b shows the right-hand branches of the curves of Fig. 4a out to the elastic peak on an expanded scale. As is evident from Fig. 4, all the curves are of the same general type. Not only do all the curves rise sharply in the regions of low and high energy loss (the right- and left-hand branches, respectively), but the Møller peaks can be clearly seen on three of them (those for scattering angles θ of 30, 45, and 60°; the calculated positions of E_e for scattering by free electrons are marked on these curves by arrows). Of the fine details of the curves we note the presence on the right-hand branches at $\Delta E = 8.9$ keV of jumps due to K-shell ionization of copper (these jumps are clearly evident in Fig. 4b) and the presence of Auger peaks at $E \approx 8$ keV on the left-hand branches. We also note that it was difficult to obtain reliable data for the scattering angle $\theta = 1°$ (curve 1) in the range $30 < E < 70$ keV because of the relatively high background due to electrons scattered from parts of the spectrometer.

In the region $E < E_e$ and in the vicinity of E_e the observed trend of the cross section is in agreement with other studies,[6,7] but in the region $E > E_e$, which was not investigated experimentally in Ref. 6, it is in conflict with the theoretical results of Ref. 7. Specifically, the theory[7] predicts that the scattering cross section will decrease monotonically in the region to the right of the Møller peak (see curve 2 of Fig. 2), whereas actually, as is evident from Fig. 4a, the scattering intensity to the right of the Møller peak is high, and for all scattering angles it rises rapidly as the elastic scattering peak is approached (Fig. 4b). We note in passing that the scattering intensity near the elastic peak is well approximated by a $(\Delta E)^{-4}$ law for the scattering angle $\theta = 1°$ and by a $(\Delta E)^{-2}$ law for the other scattering angles.

As shown by the analysis presented above, this rise, which is due to scattering with low energy losses, cannot be attributed in our case (target thickness ≈ 300 Å, initial energy $E_0 \approx 100$ keV) to independent ionization and elastic scattering events taking place at different target atoms. At the same time, we feel that the trend of the cross section finds a consistent explanation within the framework of the hypothesis discussed above that the electron is deflected in the field of the nucleus of the atom being ionized in a single interaction event. A calculation of this process is evidently needed to supplement the existing theory of electron scattering by atoms.

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