Radiation by Electrons in Passing Through Thin Metallic Films

F. R. Arutyunyan, A. Kh. Mkhitaryan, R. O. Ovsepyan, R. A. Oganesyan, and B. O. Rostomyan
Physics Research Institute, Academy of Sciences, Armenian SSR
Submitted July 3, 1971
Zh. Eksp. Teor. Fiz. 62, 1263–1271 (April, 1972)

Results are discussed of an experimental study of radiation in the visible and ultraviolet portions of the spectrum arising in passage of electrons with energies up to 100 keV through thin metallic films (Al, Ag, Au, Cu). Studies have been made of the spectral and angular distributions of the radiation, and also of the dependence of intensity on electron energy, film thickness, angle of entry of the electron into the film, and the optical constants of the materials. Analysis of the data shows that they are in complete agreement with the Ginzburg-Frank theory of transition radiation.

In bombardment of the surface of metals by nonrelativistic electrons, the main contribution to the optical portion of the spectrum of the observed radiation is from the transition radiation predicted by Ginzburg and Frank.[1] A review of early experiments on these problems is contained in an article by Frank.[2] Experiments [2–6] have been devoted mainly to the radiation of electrons moving in a direction normal to the metal surface, and the data are in agreement with the theory of transition radiation. However, unpolarized radiation whose nature is not understood is also observed in the experiments. In this connection it is of considerable interest to study the radiation in thin metallic films produced by charged particles having various directions with respect to the surface. A distinctive feature of the radiation in films is a characteristic dependence of the radiation intensity on film thickness. This shows up more distinctly for transparent plates, in which interference of the radiation from the boundaries occurs. In this case we consider the plates thin if their thickness a is much smaller than the wavelength of the emitted radiation (a ≈ 100–1000 Å). In the first place, effects associated with multiple scattering of the electrons are less important in such films. In the second place, the surface of thin films is much closer to an ideal surface than is true in massive samples. In this way it is possible to avoid radiation arising as the result of surface nonuniformities. Finally, it is well known that the optical constants of thin films of metals differ from the optical constants of the same metals in massive samples and, furthermore, that they depend substantially on the thickness of the film and the conditions under which it was made. This provides the possibility of throwing light on the sensitivity of transition radiation to the optical constants of the material, which in the last analysis can serve as the basis for solution of the inverse problem—bringing out the possibilities of measuring the optical constants of thin films by means of transition radiation.

In the present work we report the results of an experimental study of radiation arising in passage of electrons with energies up to 100 keV through thin metallic films ($a \ll \lambda$). Studies have been made of the polarization, spectral composition (λ = 2800–5800 Å), and angular distribution of the radiation, and the dependence of the intensity on electron energy, beam current, target thickness, bombardment time, electron entry angle into the film, and the optical constants of the material. The films were obtained by vacuum evaporation of metals onto a collodion base. The well known optical methods [7,8] were used to measure the optical constants and the film thickness. The latter are necessary for the theoretical calculations with which the experimental data are compared. The target is placed in the center of a vacuum chamber, inside which a pressure of 5×10^{-5} mm Hg is maintained. It was possible in the experiment to change the angle of incidence of the electrons on the target by rotation of the target. The diameter of the electron beam focused on the target surface did not exceed 0.4 mm. After traversing the film the electrons hit a Faraday cup with which the electron beam current is determined. During the measurements the current was maintained at 2–2.5 μA.

The radiation produced by the electron in the film passes through a vacuum window and falls onto a detecting system. The latter consists of an objective, a Glan polarizing prism (for study of the polarization of the radiation), a DMR-4 double monochromator (for analysis of the spectral composition of the radiation), and a FÉU-18A photomultiplier. By means of a rotating table it was possible to set the detecting system at various angles to the direction of motion of the initial electron (7.5–142.5°) and in that way to investigate the angular distribution of the radiation. The measurements were made for a fixed direction of the electron beam. Radiation in the horizontal plane was recorded both from the side of the target at which the electron entered (backward radiation) and from the electron exit side (forward radiation).

For clarity we will list certain definitions and designations adopted. The plane (**p**, **k**) containing the directions of the electron and the detected photon always coincides with the horizontal plane and is called the plane of observation. The plane (**k**, **n**) containing the direction of propagation of the photon and the normal to the target surface is called the plane of radiation, and the plane (**p**, **n**) is called the plane of incidence. The acute angle ψ between **p** and **n** is the angle of incidence (or entry) of the electron on the target. In the experiment it was varied between 0 and 45° in the case of observing forward radiation, and from 0 to 75° in the case of observing backward radiation. The target could be rotated in such a way that the plane of incidence coincided either with the plane of observation or with the plane perpendicular to it (the vertical plane). In the first case the planes of incidence, observation, and radiation coincide, and the data corresponding to this case are designated by Γ_-, Γ'_-, Γ_+, Γ'_+. In the second case the planes of incidence and observation are mutually perpendicular, and the plane of radiation forms some angle with the plane of observation. The value of this angle depends on the angle of observation θ and the angle of incidence (or entry) of the electron on the target. The data corresponding to this variant are designated by B_- and B_+. The indices + or − correspond to radiation forward or backward. The angle at which the radiation is studied in the variant Γ is designated by θ' ($-90° \le \theta' \le 90°$) and is measured from the normal to the target. It is considered positive if the electron direction and the photon propagation direction are on the same side of the normal (in the figures these cases are designated by Γ'_- and Γ'_+), and negative if they are on different sides (these cases are designated by Γ_- and Γ_+). In the B variant the observation angle θ ($0 \le \theta \le 180°$) is measured from the positive direction of electron motion.

The dependence of the spectral density of radiation on the angle φ, where φ is the angle between the plane of transmission of the polarization filter and the plane of observation, is shown in Fig. 1. The data were obtained from measurements for variants B and Γ and for various electron entrance angles ψ. The radiation turns out to be linearly polarized, the degree of polarization being rather high and reaching 95–98%. If the plane of radiation coincides with the plane of observation (variant Γ), then, independently of the direction of entry of the electron into the film, the electric vector of the radiation always lies in the plane $\varphi = 0$. If these planes do not coincide (variant B), then the plane in which the electric vector lies is displaced relative to the plane $\varphi = 0$. With increasing entry angle this displacement increases. Thus, the radiation is always polarized in the plane of radiation, which follows also from the theory of transition radiation. Therefore in analysis of other characteristics of the radiation we measured the spectral density of radiation both of waves polarized in the plane of

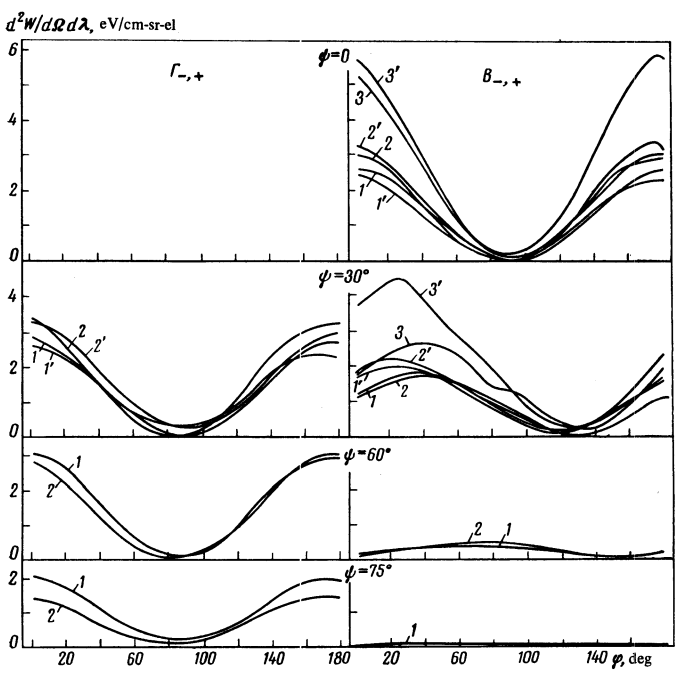

FIG. 1. Spectral density of radiation as a function of the angle φ. E = 80 keV, λ = 5000Å. Backward radiation: 1–Au, a = 400Å; 2–Cu, a = 674Å; 3–Al, a = 272Å; B_-–θ = 127.5°, Γ'_-–θ' = −52.5°. Forward radiation: 1′–Au, a = 400Å; 2′–Cu, a = 674Å; 3′–Al, a = 272Å; B_+–θ = 52.5°; Γ_+–θ' = −52.5°.

radiation ($W_{\parallel}$—the parallel component) and of waves polarized in the plane perpendicular to it ($W_{\perp}$—the perpendicular component).

The following characteristics of the radiation were measured: spectral composition (Figs. 2–4), angular distribution (Fig. 5), and the dependence of the spectral density of the radiation on the electron energy, film thickness, and electron entry angle into the target (Fig. 6). In the inserts of Figs. 2–4 we have shown the dependence of the optical constants of the corresponding material. Silver was studied in more detail. This is due to the fact that for inclined (more exactly, almost grazing) incidence of the electron on the surface of silver in the wavelength region near 3500 Å, high-intensity radiation was observed which cannot be explained by the theory of transition radiation.[9–11] Some authors[9,10] associate this radiation with excitation of surface plasma waves, while other authors[11] consider that it has the nature of bremsstrahlung.

The experimental data are compared with the theory of transition radiation for a plate of material.[12–14] The formulas obtained by these authors are in complete agreement. In all the figures the dashed curves represent the theory of transition radiation calculated on the basis of the measured optical constants, and the solid curves—on the basis of the optical constants taken from [15–19]. The calculated perpendicular component of the transition radiation ($W_{\perp}$), which should appear only in variant B, is small in value and, except for specific cases, is not shown in the figures.

The measured value of the perpendicular component of the radiation turns out in most cases to be at the level of the experimental background and only sometimes exceeds it (mainly at large entry angles). Appearance of an appreciable value of $W_{\perp}$ can be due to bremsstrahlung, luminescence, electron multiple-scattering effects, and nonuniformities in the target surface.

The formulas for bremsstrahlung for the case of an isolated atom are inapplicable for comparison with the experimental data, since the effect of the medium should lead to a substantial suppression of the radiation. The theory of bremsstrahlung for the optical portion of the spectrum, taking into account the dielectric properties of the medium,[12] exists, unfortunately, only for the case of normal entry of the particle into the target. Nevertheless, calculations according to the formulas given by Pafamov[12] show that the intensity of bremsstrahlung under the conditions of the present experiment are on the average an order of magnitude smaller than the experimental background, which amounts to $\lesssim 0.1$ eV/cm-sr-el. We note also that in those cases in which $W_{\perp}$ is appreciable, an increase in its magnitude is observed with increasing electron energy. This in turn indicates the absence of contributions from bremsstrahlung and luminescence to $W_{\perp}$.

If the electron undergoes substantial multiple scattering, then it will hit the second boundary at an angle. As a result of this the experimental geometry is changed and transition radiation can contribute to $W_{\perp}$. This should be most clearly evident in variant Γ. In this case the variant B geometry corresponds to electrons scattered in the vertical plane, and for φ = 90° (Fig. 1) a fraction of the transition radiation can be detected.

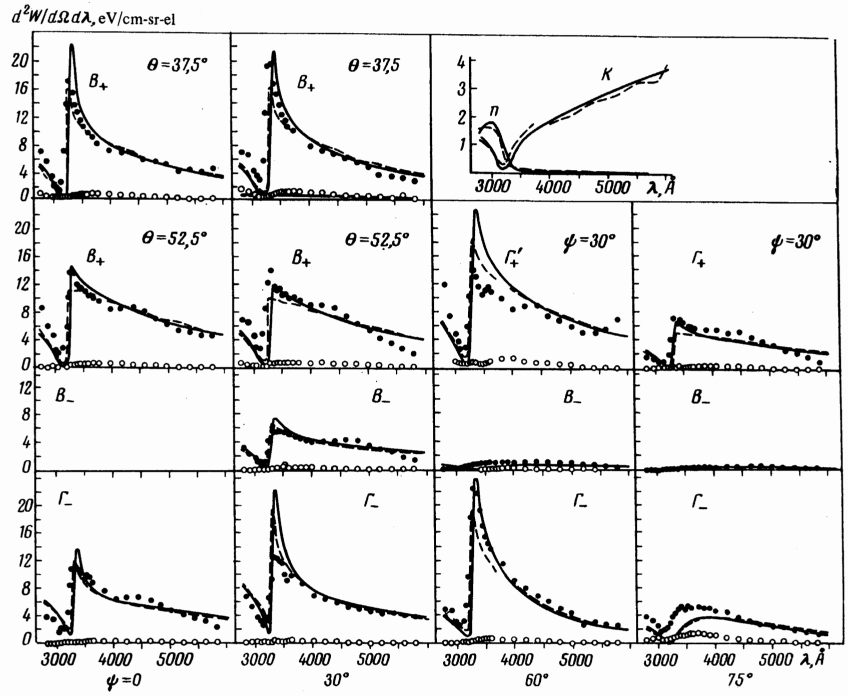

FIG. 2. Spectral distribution of radiation density for Ag (a = 633Å for E = 80 keV): ●—$W_{||}$, O—$W_{\perp}$. Backward radiation: B₋—θ = 127.5°; Γ₋—θ' = −52.5°. Forward radiation: Γ₊—θ' = −52.5°; Γ′₊—θ' = 52.5°.

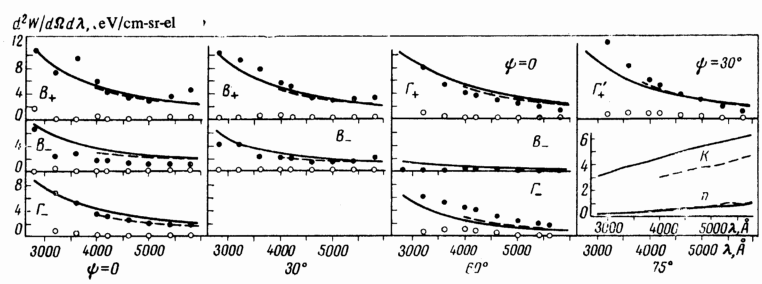

FIG. 3. Spectral distribution of radiation density for Al (Γ—a = 384Å, B—a = 272Å) for E = 40 keV: ●—$W_{||}$, O—$W_{\perp}$. Backward radiation: B₋—θ = 127.5°; Γ₊—θ' = −52.5°; Γ′₊—θ = 52.5°.

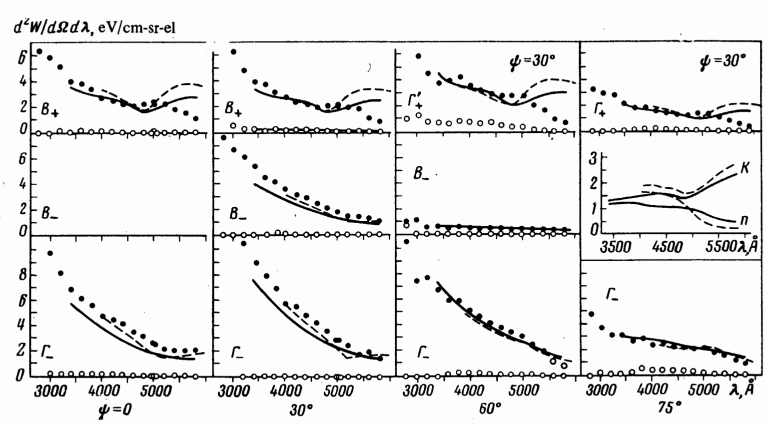

FIG. 4. Spectral distribution of radiation density for Au (a = 400Å) for E = 80 keV: ●—$W_{||}$, O—$W_{\perp}$. Backward radiation: B₋—θ = 127.5°; Γ₋—θ' = −52.5°. Forward radiation: B₊ - θ = 52.5°; Γ₊—θ' = −52.5°; Γ′₊—θ' = 52.5°.

Nonuniformity of the target surface can also lead to appearance of $W_{\perp}$. This is due in the first place to the fact that the theory of transition radiation is constructed on the assumption of an ideally smooth boundary separating the media. However, the surfaces of the targets studied naturally depart from the ideal, which can lead to depolarization of the radiation. In the second place, as the result of roughness of the target surface, radiation can be generated which is due to excitation of surface waves[9,10] and to the passage of electrons over such a surface.[20] These factors should have the greatest effect at large angles of electron entry into the target. However, it should be noted that $W_{\perp}$ comprises an insignificant part of the total radiation, and the latter consists primarily of photons polarized in the plane of radiation and is identified as transition radiation.

The spectral distribution of transition radiation, which for ideal conductors has the comparatively simple form $\lambda^{-2}d\lambda$, for real metals depends substantially on the optical constants and can assume a more complicated nature. This is clearly evident for silver (Fig. 2), where in the region of its transparency (λ

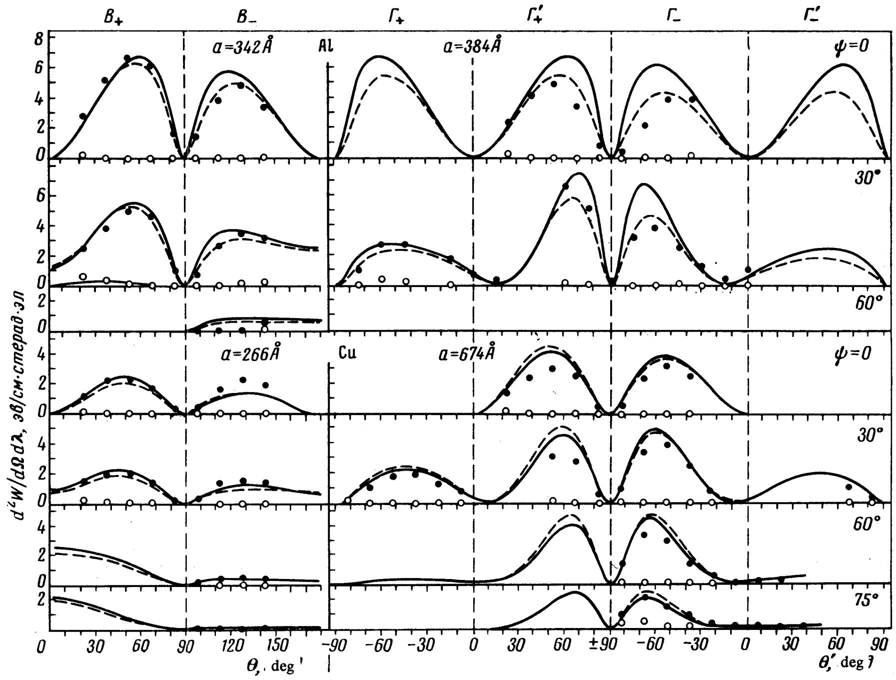

FIG. 5. Angular distribution of spectral density of radiation. E = 80 keV, λ = 5000Å: O—$W_{||}$, O—$W_{\perp}$. B_-, Γ'_-—backward radiation B_+, Γ_+, Γ'_+—forward radiation.

~ 3300 Å) there is a peak of radiation. For all metals studied (Figs. 2–4) the experimental spectra are in good agreement with the theoretical transition-radiation spectra both qualitatively and quantitatively. The difference between the theoretical transition-radiation curves calculated with the optical constants measured by us and with those taken from the literature is small and in most cases does not exceed the experimental errors. This difference is noticeable to a greater degree in the angular distributions (Fig. 5) and in the dependence of the spectral density of radiation on the entry angle ψ (Fig. 6). Where differences between these curves appear, the experimental data agree better with the theoretical transition-radiation curves calculated from the measured optical constants.

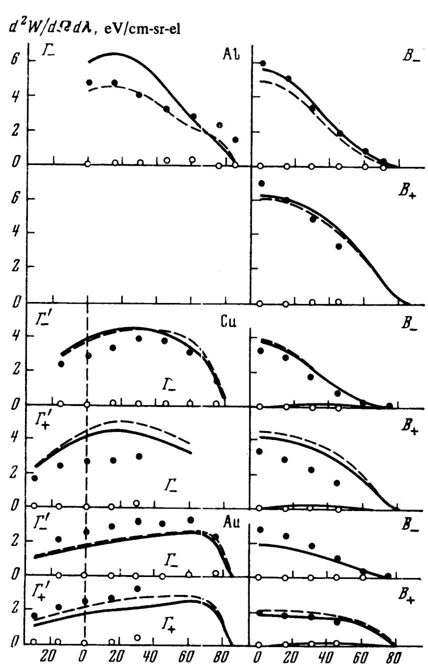

FIG. 6. Spectral density of radiation as a function of angle of incidence Ψ for Au (a = 400Å), Cu (a = 674Å), and Al (B—a = 342Å, Γ—a = 384Å). E = 80 keV, λ = 5000Å: O—$W_{||}$, O—$W_{\perp}$. Backward radiation: B_-—θ = 127.5°; Γ_-—θ' = −52.5°; Γ'_-—θ' = 52.5°. Forward radiation: B_+—θ = 52.5°; Γ_+—θ' = −52.5°; Γ'_+—θ' = 52.5°.

Thus, the results of the present experiment as a whole show that the radiation of thin films of various metals under the action of nonrelativistic electrons incident on the target surface at angles up to ψ = 75° consists practically entirely of transition radiation, and the experimental data agree with high accuracy with the values expected from transition-radiation theory.

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Translated by C. S. Robinson
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