# Transition Radiation and Optical Bremsstrahlung from Electron-Bombarded Thin Gold Foils

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Unbacked gold foils 340- and 530-Å thick were bombarded by a 1.5-μA electron beam of energy 25 to 100 keV. The light emitted at 30° from the foil normal on the beam exit side was analyzed between 2500 and 5500 Å with a vacuum ultraviolet spectrometer and a glan prism polarizer. The spectral distribution and absolute photon yield in the plane containing the electron beam and photon direction agree well with the transition radiation theory if the bremsstrahlung contribution is assumed to be unpolarized. The photon intensity perpendicular to the plane (of incidence) has the dependence on primary energy indicated by the bremsstrahlung theory of Gluckstern, Hull, and Breit, but only 40% of the expected absolute value. The discrepancy is thought to be due to neglect of optical absorption and refraction in the calculation.

## INTRODUCTION

THE prediction in 1958 by Ferrell[1] that plasma oscillations induced by charged particle excitation should decay by the emission of monochromatic photons at the plasma frequency has led many investigators to search for this radiation.[2–4] Many observations of electron-irradiated silver have revealed a sharp peak. In addition to this peak at 3300 Å, a continuum has been found in the longer wavelength region. A description of the complete emission spectrum has been given by Ritchie and Eldridge[5] and others[6] in terms of the transition radiation theory of Frank and Ginzburg. It is apparent from recent experiments[3,4] that radiation is emitted by many elements and that many careful investigations of these elements will be required before the various sources of light are identified, distinguished, and understood.

This paper presents the results obtained experimentally for gold foils bombarded by an electron beam and compares the results with the theories of transition radiation and bremsstrahlung. Gold was chosen for this study for several reasons. First, gold presents the best possibility for obtaining the emission from a clean, unoxidized foil because of its stable chemical character; second, the optical constants of gold which are required for the theoretical calculations are available; and third, the high atomic number of gold introduces an appreciable bremsstrahlung component in the observed emission which may be compared with theory.

## EXPERIMENTAL

The experimental techniques employed in measuring the optical emission from electron bombarded thin foils have been described in a previous paper.[4] Briefly, the thin foils were prepared by evaporating gold onto microscope slides which had previously been coated with a wetting agent, "Victawet."[7] The evaporations were carried out in a vacuum evaporator at pressures of $1-2\times10^{-5}$ mm Hg. The foils were scratched into 1-cm squares, floated off on water, and mounted on foil holders as circular foils $\frac{1}{4}$ in. in diameter. Two foils, which measured 340 and 530 Å thick interferometrically, were bombarded by a 1.5-μA electron beam whose energy was varied from 25 to 100 keV. The size of the beam striking the foil was determined by a 1.5-mm-diam collimator placed in front of the foil. The light emitted at 30° from the foil normal on the beam exit side was analyzed with a 50-cm Seya-Namioka vacuum ultraviolet spectrometer using an EMI 6256B quartz window photomultiplier as a detector. The grating was a Bausch & Lomb aluminized replica grating blazed at 3500 Å. A glan prism polarizer was placed between the spectrometer exit slit and the photomultiplier and used in two positions such that the light transmitted was either polarized parallel to or perpendicular to the plane formed by the electron beam and photon direction. The parallel plane is the plane in which transition radiation has been predicted to appear, whereas bremsstrahlung may contribute light to both planes of polarization.

## RESULTS AND DISCUSSION

The results obtained for the 340-Å foil are shown in Fig. 1 and for the 530-Å foil in Fig. 2, each experimental curve being an average of three separate runs. All spectral distribution curves are on an absolute intensity scale obtained by correcting for the spectral response of the spectrometer, photomultiplier, and polarizer in both the parallel and perpendicular planes. The corrections curves were computed from spectral measurements of light from a tungsten strip filament lamp calibrated by the National Bureau of Standards.[8] The

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.
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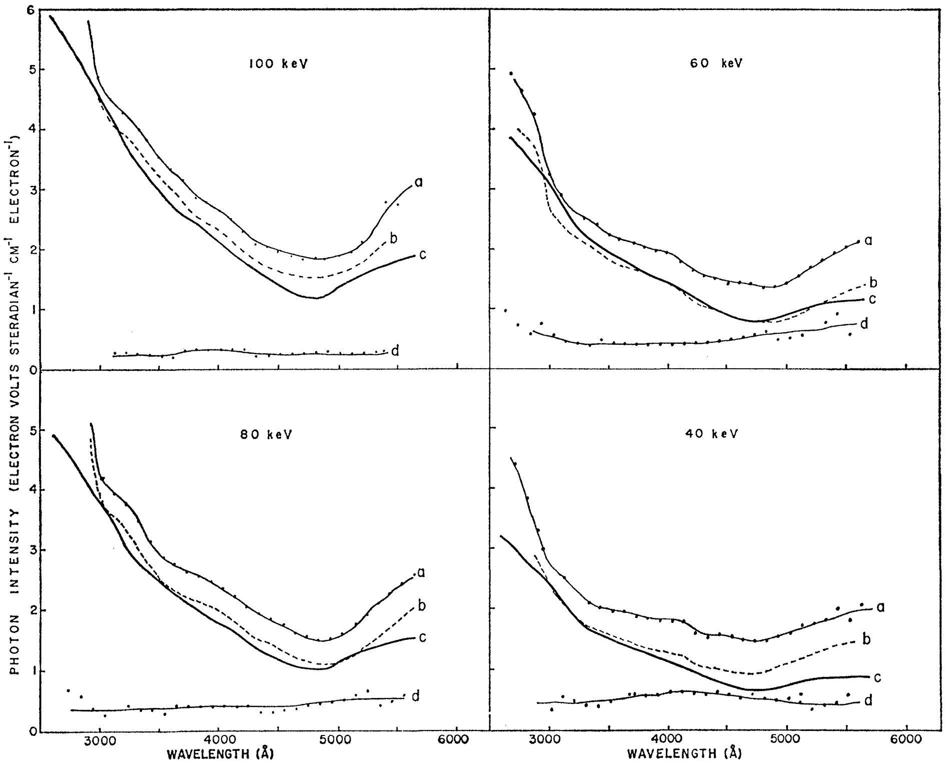


FIG. 1. Spectral distribution of radiation from 340 Å gold foil. a = experimental intensity in the parallel plane ($I_{\parallel}$); d = experimental intensity in the perpendicular plane ($I_{\perp}$); b = curve a − curve d ($I_{\parallel} - I_{\perp}$); c = transition radiation theory.

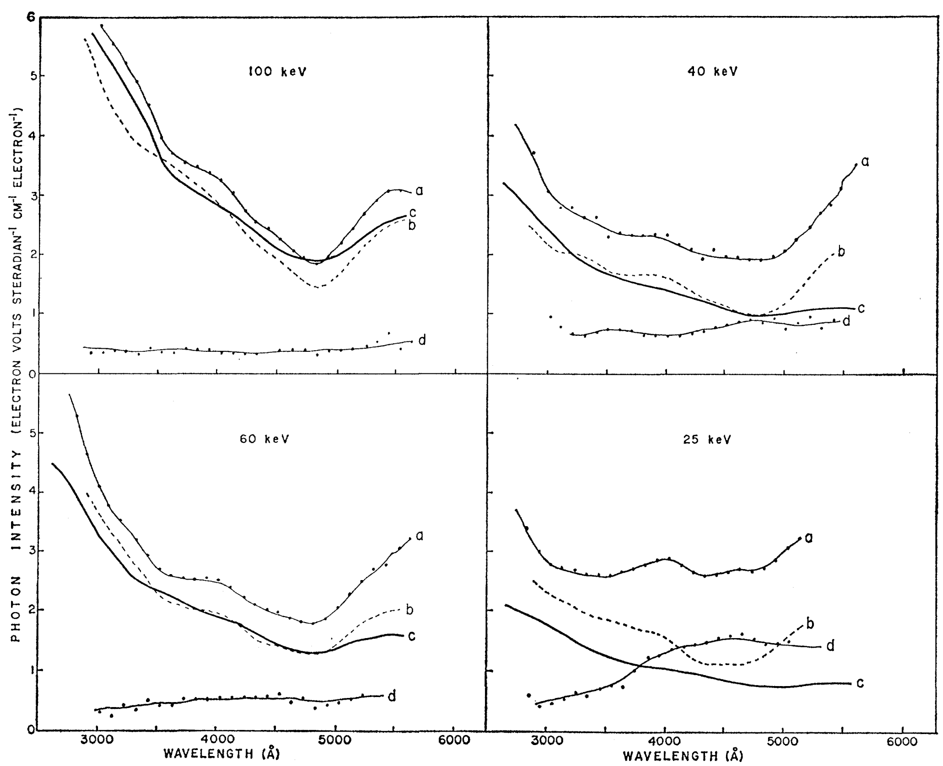


FIG. 2. Spectral distribution of radiation from 530 Å gold foil. a = experimental intensity in the parallel plane ($I_{\parallel}$); d = experimental intensity in the perpendicular plane ($I_{\perp}$); b = curve a − curve d ($I_{\parallel} - I_{\perp}$); c = transition radiation theory.

theoretical curves, plotted on the same absolute scale, were calculated using an equation derived by Ritchie and Eldridge from an extension of the Frank and Ginzburg transition radiation theory.[5] The optical constants required in the calculations were taken from the results of Philip.[9]

Good agreement is seen between the theoretical predictions and the experimental results in the parallel plane for both foils at the higher electron energies. At lower energies, agreement on the absolute yield is poorer with experimentally determined yields higher than theoretical values. However, it is also apparent from the results that the perpendicular component increases with decreasing beam energies. This perpendicular component is ascribed to long wavelength bremsstrahlung emission. Although bremsstrahlung emission from isolated atoms has been investigated theoretically, calculations on bremsstrahlung production in solids have not yet been reported. For isolated atoms, Gluckstern, Hull, and Breit[10] give the distribution of photons averaged over all possible deflections of the electron. The differential cross section for bremsstrahlung production for photon energies small compared to the electron energy is

$$d\sigma_{\parallel}=Z^2\left[\frac{e^2}{\hbar c}\right]\left[\frac{e^2}{m_0c^2}\right]^2\frac{(1-\beta^2)}{\beta^2}\frac{dk}{k}\frac{(\cos\theta_0-\beta)^2}{(1-\beta\cos\theta_0)^4}\sin\theta_0 d\theta_0 \times\left\{\ln\frac{(m_0c^2)^2\beta^2}{(1-\beta^2)\{k^2[(1-\beta\cos\theta_0)/\beta]^2+Z^{2/3}(m_0c^2)^2/(108)^2\}}+O_{\parallel}(1)\right\},\quad(1)$$

for photons polarized in the plane of the electron and photon, and

$$d\sigma_{\perp}=Z^2\left[\frac{e}{\hbar c}\right]\left[\frac{e^2}{m_0c^2}\right]^2\frac{(1-\beta^2)}{\beta^2}\frac{dk}{k}\frac{1}{(1-\beta\cos\theta_0)^2}\sin\theta_0 d\theta_0 \times\left\{\ln\frac{(m_0c^2)^2\beta^2}{(1-\beta^2)\{k^2[(1-\beta\cos\theta_0)/\beta]^2+Z^{2/3}(m_0c^2)^2/(108)^2\}}+O_{\perp}(1)\right\},\quad(2)$$

for photons polarized perpendicular to this plane. $\theta_0$ is the direction of emergence of the photon with respect to the foil normal, $\beta=v/c$, $k$=photon energy, and $O_{\parallel}(1)$ and $O_{\perp}(1)$ are quantities of the order of unity. For the conditions encountered in the present experiment (photon energy $k<20$ eV, $\beta>0.2$, $Z>4$), the first term in the denominator of the logarithm is very small compared to the second term and the argument of the logarithm reduces to

$$\frac{(108^2)\beta^2}{Z^{2/3}(1-\beta)^2}.$$

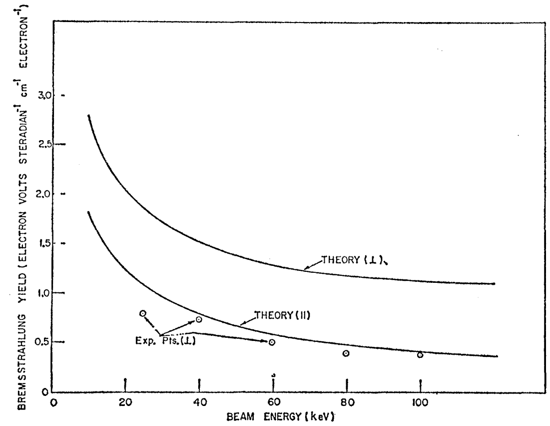


FIG. 3. Bremsstrahlung yield calculated by Gluckstern, Hull, and Breit for 500-Å-thick gold foil at $\lambda=3500$ Å. Points represent experimentally determined yields for photons polarized in the perpendicular plane.

Of greater interest here is the cross section per unit wavelength per unit solid angle which is obtained by rewriting Eq. (1) for photons polarized parallel

$$\frac{d^2\sigma_{\parallel}}{d\Omega\, d\lambda}=\frac{Z^2}{2\pi}\left[\frac{e^2}{\hbar c}\right]\left[\frac{e^2}{m_0c^2}\right]^2\frac{(1-\beta^2)}{\beta^2}\frac{1}{\lambda}\frac{(\cos\theta_0-\beta)^2}{(1-\beta\cos\theta_0)^4}\times\left\{\ln\frac{(108)^2\beta^2}{Z^{2/3}(1-\beta^2)}+O_{\parallel}(1)\right\},\quad(3)$$

where $\lambda$ is the wavelength in centimeters and $d\Omega=2\pi\sin\theta_0 d\theta_0$. The cross section per unit wave length per unit solid angle for photons polarized perpendicular to the plane of incidence may be obtained by multiplying Eq. (3) by the ratio of the perpendicular bremsstrahlung component to the parallel bremsstrahlung component,

$$\frac{d\sigma_{\perp}}{d\sigma_{\parallel}}=\left[\frac{1-\beta\cos\theta_0}{\cos\theta_0-\beta}\right]^2.\quad(4)$$

Figure 3 shows the bremsstrahlung yield calculated from the quantities $d^2\sigma_{\parallel}/d\Omega d\lambda$ and $d^2\sigma_{\perp}/d\Omega d\lambda$ versus beam energy for a 500-Å-thick gold foil at $\lambda=3500$ Å.

The points plotted on Fig. 3 are the experimentally determined yields in the perpendicular plane. The dependence of the yield on energy agrees well with theory although the absolute yield is only 40% of the theoretical value. The experimental yield is expected to be lower because the theoretical value is for isolated atoms without regard for the refraction and absorption of the bremsstrahlung photons in the dielectric medium.

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[10] R. L. Gluckstern, M. H. Hull, and G. Breit, Phys. Rev. **90**, 1026 (1953). Also, R. L. Gluckstern and M. H. Hull, *ibid.* **90**, 1030 (1953).

The experimentally observed emission in the parallel plane contains not only transition radiation but also the parallel component of bremsstrahlung. Therefore, the spectral distribution curves were analyzed initially by subtracting from the experimental intensity in the parallel plane $I_{\parallel}$, the quantity $(d\sigma_{\parallel}/d\sigma_{\perp})I_{\perp}$ where $(d\sigma_{\parallel}/d\sigma_{\perp})$ is the ratio of the parallel to perpendicular yield calculated by Gluckstern, Hull, and Breit[10] and given by the inverse of Eq. (4), and the quantity $I_{\perp}$ is the intensity observed experimentally in the perpendicular plane. An analysis of the data in this fashion showed a little better agreement. However, better agreement still was obtained by letting the ratio $(d\sigma_{\parallel}/d\sigma_{\perp})$ be equal to 1 as shown by the dashed curves in Figs. 1 and 2. Whereas before, agreement between theory and experiment was obtained only for the higher energies, now agreement is good for all beam energies. The interpretation of the data in this fashion suggests that the observed bremsstrahlung is unpolarized. The calculations of Gluckstern, Hull, and Breit[10] for isolated atoms show that the ratio $(d\sigma_{\parallel}/d\sigma_{\perp})$ is approximately 0.5. The inclusion of optical effects will increase this ratio because light transmitted through a dielectric medium is preferentially polarized in the plane of incidence. This effect will raise the intensity in the parallel plane and, thus, the ratio $(d\sigma_{\parallel}/d\sigma_{\perp})$ will be greater than 0.5 and might easily be of the order of unity as found experimentally.

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# Fission Fragment Angular Distributions and Cross Sections for Deuteron-Induced Fission*

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Fission-fragment angular distributions and cross sections have been measured with gold surface barrier semiconductor detectors for fission induced in a group of elements from Tl to Pu by deuterons of 7- to 21-MeV energy. Apart from a pronounced dip in the radium region, the differential fission fragment cross-section ratios $W(174°)/W(90°)$ at 21 MeV show an increasing trend with decreasing $Z^2/A$, the values ranging from 1.20 for $Pu^{239}$ to 1.58 for natural Tl. Values of $K_0^2$ are calculated from the experimentally determined anisotropies for targets in which single-chance fission prevails, i.e., $Bi^{209}$ and nuclides in the plutonium region. When values of $K_0^2$ for plutonium are compared with those from available neutron fission data, there is indicated an anomalous suppression of $K_0^2$ in the low-energy region below the values extrapolated from the higher energy data by plausible temperature dependences on excitation energy. Saddle-shape calculations and semiquantitative arguments which are reviewed lend added credence to the view that the saddle shape is independent of the mode of formation. The experimentally observed change in anisotropy with the fissionability parameter $x$ is correlated with the effective moments of inertia at the saddle configuration (*vis-à-vis* scission point), indicating that thermodynamic equilibrium is first established near the saddle point in fission. Fission cross sections measured for $Th^{232}$, $U^{233}$, and $U^{238}$ are supplemented by previously determined spallation cross sections to obtain total deuteron reaction cross sections. At 21 MeV the deuteron reaction cross section of heavy elements is found to be 1800 mb. The experimental reaction cross sections are compared with theoretical values calculated with a volume-absorption optical model.

## I. INTRODUCTION

THEORETICAL formulations for the angular distribution of fission fragments from a single fissioning species have been derived, in the classical approximation, by various investigators beginning with Bohr[1] and Halpern and Strutinski.[2] Although the model neglects target and projectile spins, it approximates reasonably well the anisotropies obtained from a variety of experiments on fission induced by neutrons and by energetic charged particles (these and other developments in fission physics are discussed in various reviews).[3,4]

With excitation energies up to a few tens of MeV, fission spectra obtained in practice are usually derived from several species (distinguished by different excitation energies and $A$ values) fissioning concurrently, due to the possibility of multichance neutron evaporation prior to fission. Following the development of Bohr,[1]

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‡ On leave from the Atomic Energy Establishment, Trombay, India, under sponsorship of the International Cooperation Administration.

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[2] I. Halpern and V. M. Strutinski, in *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1959), Vol. 15, p. 408.

[3] I. Halpern, Ann. Rev. Nucl. Sci. **9**, 245 (1959).

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