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THE ANGULAR AND SPECTRAL DISTRIBUTIONS OF LIGHT EMITTED FROM ELECTRON-BOMBARDED SILVER FOILS

(Thesis)

Norma O. Davis
E. T. Arakawa
L. C. Emerson
R. D. Birkhoff

OAK RIDGE NATIONAL LABORATORY
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(Submitted as a thesis to the Faculty of the Graduate School of Vanderbilt University in partial fulfillment of the requirements for the degree of Master of Science in Physics).

MARCH 1964

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ABSTRACT

The spectral distribution of photons emitted by Ag foils 660 Å and 1980 Å in thickness bombarded by 40-keV electrons has been determined experimentally in the wavelength region from 2500 Å to 5600 Å. The spectra were determined for photons emitted at 0° to 150° from the foil normal using an angular distribution chamber which permitted the spectrometer to be rotated around the foil in a continuous fashion without breaking the vacuum. A Glan prism analyzer was used to separate the light into a component polarized parallel to the plane of the electron and photon and another component perpendicular to it. Transition radiation, as was shown by Frank and Ginzburg, is polarized in the parallel plane, whereas bremsstrahlung has both a parallel and perpendicular component. The photon in the perpendicular plane was found to be about 10% of that in the parallel plane. The spectrum in the parallel plane showed a sharp peak at 3300 Å, this value being an average over photon directions from 10° to 50° from the foil normal. This agrees with the theoretical predictions and is within the limits of error of previous determinations at 30°. In addition to the peak, the spectrum showed a continuum which decreased slowly with increasing wavelength, and was characterized by a deep minimum at 3200 Å and a rise in the short wavelength region. All features of the observed spectrum are accurately predicted by Ritchie's generalized transition radiation theory. The angular distribution of photons emitted at the wavelength of the peak showed a maximum intensity at 30° from the foil normal with zero intensity at 0° and near 90°, whereas the photon

intensity at other wavelengths in the continuum, e.g., 2700 Å and 4500 Å, was a maximum at 50° from the foil normal. The long wavelength continuum for the Ag foil 660 Å thick was more intense in the forward than in the backward direction, in agreement with theory. The photon yield was found to agree with the theoretical prediction in all respects at all wavelengths except at that of the sharp peak for photon directions from 10° to 40° where the experimental values were about 30% lower. On the basis of the agreement between the absolute measurements of the photon intensity and theoretically predicted intensities it is concluded that the light observed is due almost entirely to transition radiation.

I. INTRODUCTION

When a uniformly moving electron passes through a metallic foil, various processes may occur which give rise to photon emission in the form of transition radiation, bremsstrahlung, plasma radiation, Cherenkov radiation, and radiation due to heating of the foil. The latter two processes can be dismissed from consideration in this investigation. Cherenkov radiation is not emitted in the region investigated, because the threshold velocity is not reached using 40-keV electrons. A simple calculation of the heating produced in a thin foil shows that the temperature rise is at most a few degrees using 2 microamps of 40-keV electrons with 1% being stopped in the foil.

In 1945 Frank and Ginzburg[1] predicted that radiation would be emitted when an electron of constant velocity passed from one medium into another. This radiation they named transition radiation. To explain the nature of the phenomenon, they considered an electron passing from a vacuum into a conductor. While the electron is moving in the vacuum, the electromagnetic field in the vacuum is equal to the field of the electron and of its image moving toward it. The electron and its image cease to exist once the electron enters the conductor and their field undergoes a rapid collapse. The radiation

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[1] I. M. Frank and V. L. Ginzburg, J. Phys. (USSR) 9, 353 (1945).

emitted would be the same as that which is due to the sudden annihilation of the electron and its image at the interface.

Ferrell[2] in 1958 predicted radiation from the decay of electron plasma oscillations in metal films. The plasma decay should radiate a single spectral component at the plasma wavelength. Ferrell's theory for the angular distribution predicts that the spectrum exhibits a cosine distribution modified by a damping due to interband transitions.

A generalization of the Frank and Ginzburg treatment was presented by Ritchie and Eldridge.[3] They showed that photon emission can be expected from a solid not only at the plasmon energy but also around the interband transition energy where single-particle excitation occurs. Ritchie's expression is shown to reduce to Ferrell's when the charged particle is nonrelativistic and the dielectric constant is that of a free electron gas.

Transition radiation is polarized with the E vector in the plane defined by the incident electron beam and the photon direction. This plane is hereafter called the parallel plane, and the plane perpendicular to this plane is called the perpendicular plane.

Calculations for isolated atoms by Gluckstern and Hull[4] show that

---

[2] R. A. Ferrell, Phys. Rev. 111, 1214 (1958).

[3] R. H. Ritchie and H. B. Eldridge, Phys. Rev. 126, 1935 (1962).

[4] R. L. Gluckstern and M. H. Hull, Jr., Phys. Rev. 90, 1030 (1953).

bremsstrahlung is partially polarized in the perpendicular plane. The ratio of photons polarized in the parallel plane to those polarized in the perpendicular plane is $\left[\frac{\cos\theta-\beta}{1-\beta\cos\theta}\right] = 0.7055$ for $\theta = 30$ and $E = 40$ keV. However the experimental work reported by Arakawa, Emerson, Hammer, and Birkhoff[5] showed good agreement with the transition radiation theory only if the bremsstrahlung was assumed to be unpolarized. Their experiment was preformed with gold foils 340 Å and 530 Å in thickness with observations at 30 degrees from the foil normal on the emergent-beam side of the foil.

The element which has been investigated in greatest detail is silver which emits a sharp peak at 3300 Å in addition to a continuum at longer wavelengths. The relative intensity of the silver peak for angles of 10, 20, 30, 40, 50, 60, 70, and 80 degrees from the normal on the emergent-beam side of foils 500 Å thick has been reported by Brown Wessel, and Trounson.[6] They used 20-keV electrons normally incident on the foil. The angular distribution showed fair agreement with the Ferrell theory. The complete spectral distributions are reported only for 30 and 72 degrees. Wessel[7] later showed that the light at the peak was predominately polarized in the parallel plane.

---

[5] E. T. Arakawa, L. C. Emerson, D. C. Hammer, and R. D. Birkhoff, "Transition Radiation and Optical Bremsstrahlung from Electron-Bombarded Thin Gold Foils," Phys. Rev. 131, 719 (1963).

[6] R. W. Brown, P. Wessel, and E. P. Trounson, Phys. Rev. Letters 5, 472 (1960).

[7] P. Wessel, Bull. Am. Phys. Soc. 6, 310 (1961).

Frank, Arakawa, and Birkhoff[8] reported the complete spectra for angles 2, 4, 30, and 72 degrees from the normal on the emergent-beam side of silver foils 800 Å thick. The comparison of the intensity at these angles showed good agreement with theoretical predictions. Their data showed a stronger dependence on the angle of observation than did the data of Brown, Wessel, and Trounson.

The normalized intensity from electron-bombarded, thick tungsten targets was reported by Boersch, Radeloff, and Sauerbrey[9] for angles of 10, 20, 30, 45, 60, and 75 degrees from the target normal on the incident-beam side of the target. Their distribution showed agreement with theory to 70 degrees. The higher intensity observed at the larger angles was attributed to the roughness of the surface of their targets.

All previous experiments have shown the silver peak to be broader and lower in intensity than is expected theoretically and that there is more emission on the long wavelength side of the peak than predicted. No angular distribution of the complete spectra for both sides of the foil has been reported.

The primary purpose of this work was to obtain a complete spectral distribution for photons emitted on both sides of silver

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[8] A. L. Frank, E. T. Arakawa, and R. D. Birkhoff, Phys. Rev. 126, 1947 (1962).

[9] H. Boersch, C. Radeloff, and G. Sauerbrey, Z. Physic 165, 464 (1961).

foils bombarded by electrons. A new irradiation chamber[10] was used to observe the light emitted at all the angles between 0 and 150 degrees from the normal on the emergent-beam side of the foil by a continuous rotation of the spectrometer around the irradiation chamber. The light polarized in the parallel plane consisted of transition radiation and bremsstrahlung, while the perpendicular plane contained only bremsstrahlung. The transition radiation emitted from silver was compared with the theory of Ritchie and Eldridge. The complete spectral distributions, variation of the photon intensity as a function of angle at specific wavelengths, and the spectra at corresponding angles on the front and back sides of the foils were compared with theory. The angular distribution of bremsstrahlung radiation was also investigated.

In addition, observations were made on the effect of substrate material, heat treatment, and the crystal structure of the silver foils.

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[10] The principles used in designing this angular distribution chamber had originated with Verba and Hawrylak at the University of Rochester who had built a similar device to be used as a scattering chamber in nuclear research. J. Verba and R. Hawrylak, Rev. Sci. Instr. 32, 1037(1961).

II. THEORY

Ferrell has explained one source of optical emission from metallic foils bombarded by electrons as the reradiating of photons by excited plasma oscillations. The angular dependence of photon emission is given by:

$$I(\theta) = \cos\theta \left[1 + \frac{\lambda_p \cos\theta}{\gamma_d \omega_p \pi \gamma \sin^2\theta}\right]^{-1}$$

where $\gamma_d^{-1} = 2\frac{\omega}{nk}$ is the rate of damping by interband transition and θ is the angle between the photon direction and the foil normal on the emergent-beam side. This angular distribution is valid only at the plasma frequency, ω_p.

Ritchie and Eldridge have described the optical emission from foils bombarded by charged particles in terms of the dielectric properties of the foils. Their general equation for the number of photons emitted per unit solid angle in the direction specified by the angle θ and per unit frequency interval at the frequency ω per incident particle is

$$n(\mu,\omega,a,\beta) = \sum_{p_f} \frac{d^2n}{d\omega d\Omega} = \frac{Z^2e^2\beta^2}{\pi^2 hc\omega} \mu^2(1-\mu^2) \left|\frac{\gamma}{\Delta}\right|^2 \qquad (1)$$

where

$$\gamma = \left[\frac{\beta\sigma + \varepsilon}{1-\mu^2\beta^2} - \frac{1}{1-\beta\sigma}\right](\mu e + \sigma)e^{-it\sigma}$$

$$+ \left[\frac{\beta\sigma - \varepsilon}{1-\mu^2\beta^2} + \frac{1}{1+\beta\sigma}\right](\mu\varepsilon - \sigma)\, e^{it\sigma}$$

$$-2\sigma \left[\frac{\epsilon}{1 - \mu\beta} - \frac{1 + \beta\epsilon\mu}{1 - \beta^2\sigma^2} \right] e^{-it/\beta},$$

$$\Delta = (\mu\epsilon - \sigma)^2 e^{it\sigma} - (\mu\epsilon + \sigma)^2 e^{-it\sigma},$$

$$\epsilon = \epsilon_1 + i\epsilon_2, \ \beta = v/c, \ \mu = \cos\theta, \ t = a\omega/c,$$

$$\sigma = Re^{i\Phi}, \ \Phi = 1/2 \tan^{-1} \left[\frac{\epsilon_2}{\epsilon_1 - 1 + \mu^2} \right],$$

and

$$R = \left[(\epsilon_1 - 1 + \mu^2)^2 + \epsilon_2^2 \right]^{1/4}$$

where ϵ_1 and ϵ_2 are the real and imaginary parts of the dielectric constant and a is the foil thickness. This expression which is relativistically correct, has been shown by Ritchie and Eldridge to reduce to Ferrell's when the dielectric constant ϵ is that of a free electron gas and $\beta \ll 1$. The comparison between the angular distribution at the Ag peak, as derived by Ritchie and Eldridge and by Ferrell, is shown in Fig. 1. From zero to 13 degrees, Ferrell's theory agrees closely with the Ritchie and Eldridge theory, but Ferrell's theory for the angular distribution reaches its maximum around $\theta = 20^\circ$ while the Ritchie and Eldridge theory peaks at $\theta = 30^\circ$. Both theories predict zero intensity at 90°.

From a microscopic point of view the optical emission results from the coherent addition of the radiation due to the changing dipole moments from the atoms in the foil polarized by the field of the incident charge. Thus, it would be expected that the familiar peaking in the forward direction of the radiation from accelerated charges in relativistic motion would also be observed in the case of transition

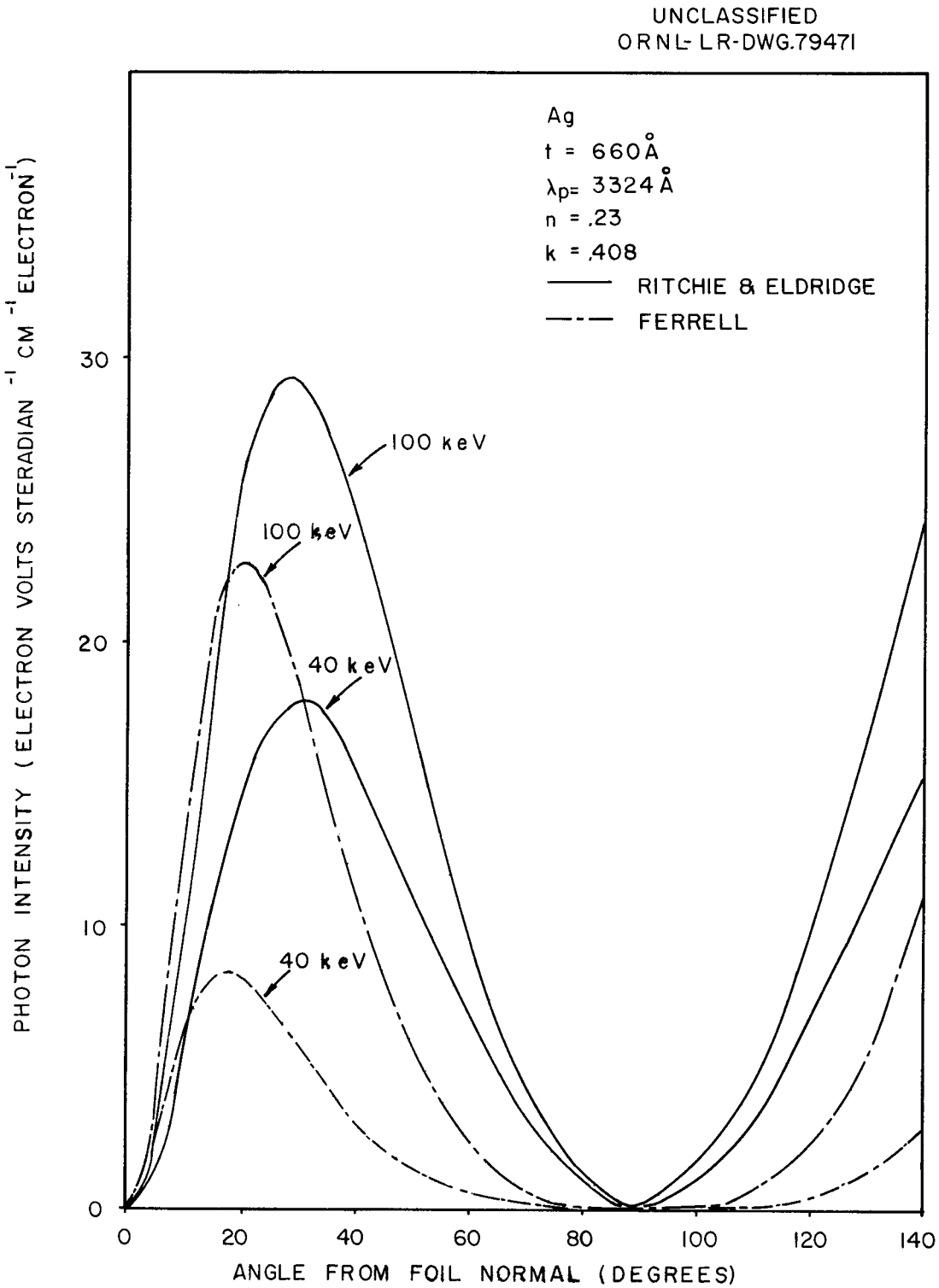

Fig. 1. Comparison of Angular Distributions of the Ferrell Theory and the Ritchie-Eldridge Theory for the Peak Wavelength of Ag.

radiation. This effect is well known and has been described in standard texts.[11]

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[11] L. Landau, and E. Lifshitz, The Classical Theory of Fields (Reading, Massachusetts, Addison-Wesley Publishing Co., 1951) Chapter 9; W.K.H. Panofsky, and M. Phillips, Classical Electricity and Magnetism 2nd Ed. (Reading, Massachusetts, Addison-Wesley Publishing Co., 1962) Chapter 20.

III. APPARATUS

The equipment consisted of an electron accelerator, angular distribution irradiation chamber, vacuum ultraviolet spectrometer, and photomultiplier (see Fig. 2).

Electrons emitted from the gun are accelerated and after traveling through a field-free region approach the entrance of the angular distribution chamber. An insulated collimator with a 1.5-mm diameter hole is located at the entrance and connected to a micro-microammeter. The beam can be directed through this collimator by varying the current in two mutually perpendicular degaussing coils.

The electron beam then passes through the foil and is collected by the inner cylinder. This current is read by another micro-microammeter. The light emitted by the foil within a small solid angle is focused by the spectrometer grating onto the exit slit of the spectrometer where the photomultiplier tube is located. The photomultiplier current is amplified by a Keithley-model-410 micro-microammeter and recorded on a Brown recorder.

A. Electron Gun

The electron gun is the same as that described by Frank, Arakawa, Birkhoff, Ritchie, and Eldridge.[12] The gun is designed for easy

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[12] A. L. Frank, E. T. Arakawa, R. D. Birkhoff, R. H. Ritchie, and H. B. Eldridge, "Optical Emission from Irradiated Thin Metallic Foils," Oak Ridge National Laboratory Report ORNL-3114 (July 2, 1962).

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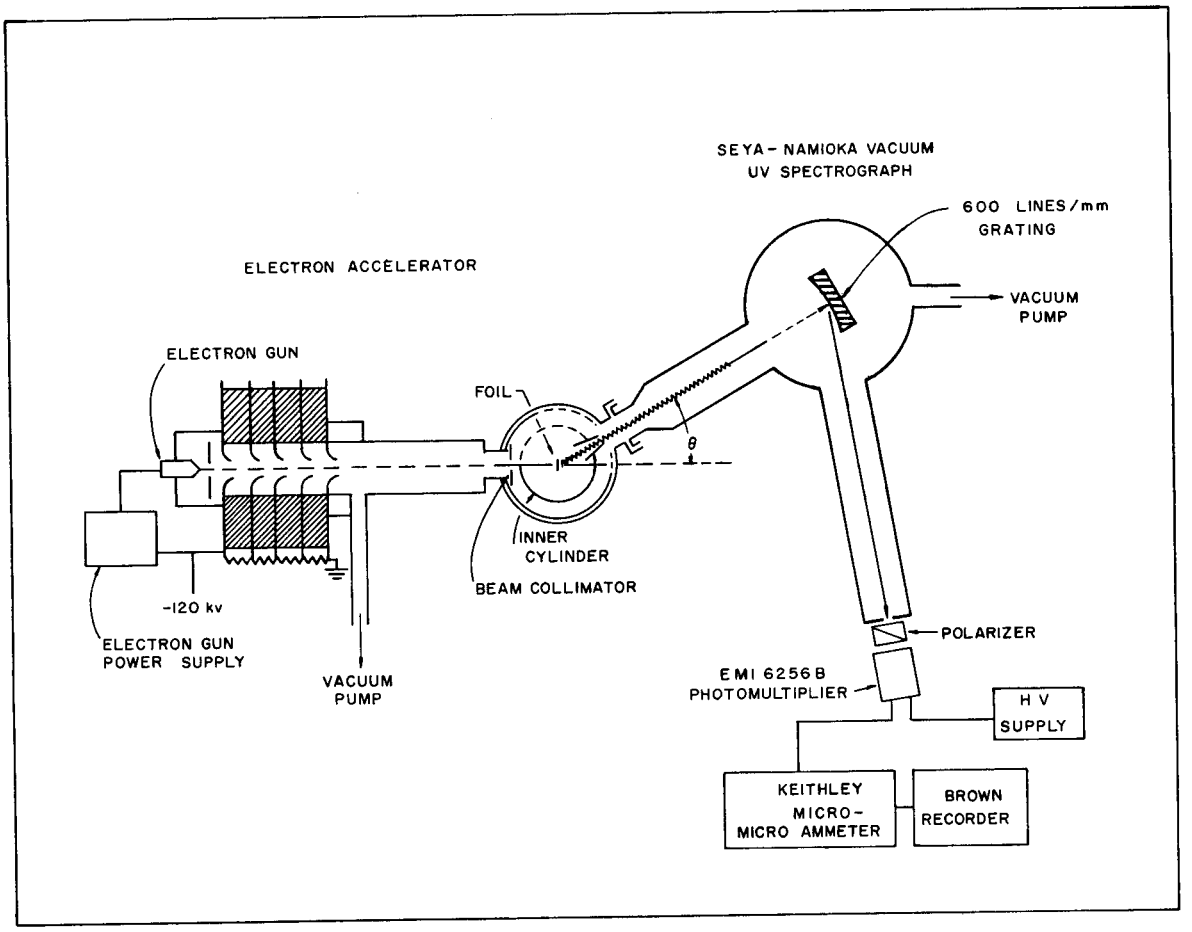

Fig. 2. Schematic Diagram of Accelerator, Angular Distribution Irradiation Chamber, and Spectrometer.

alignment of the filament with respect to the gun electrodes. The filament used was a 5-volt Westinghouse-1709 light bulb from which the glass envelope had been removed. The filament is coated with a special emission coating manufactured by Kulite Tungsten Company, Ridgefield, New Jersey. The filament, still on its base, is inserted from the side of the brass tube and can be viewed through a window over the face of the gun to obtain proper alignment. The electron gun was taken from a General-Electric-3MP1 cathode ray tube with its base and filament removed. The deflection plates were connected to the second anode. The second anode was connected to the end plate of the accelerator, and thus the final potential difference through which the electrons have been accelerated is the sum of the potential difference across the accelerator electrodes and the potential difference between the second anode and the filament. The potential difference across the accelerator may be varied from 100 KV to 25 KV. The potential difference between the filament and second anode varies from 500 to 2500 volts as the electron gun is focused. The power supply for the electron gun was described in detail by Zeimer, Johnson, and Birkhoff.[13]

B. Accelerator

The accelerator consists of alternate ceramic insulators and electrodes in a vacuum-tight arrangement. The electrodes are

---

[13] P. L. Zeimer, R. M. Johnson, and R. D. Birkhoff, "Measurement of Stopping Power of Copper by Calorimetric Methods," Oak Ridge National Laboratory Report ORNL-2775 (December 17, 1959).

separated electrically by six 50-megohm resistors. The high voltage is applied from a Beta-Electric Corp. 5-ma, 120-KV power supply with a meter accuracy of 2% and ripple voltage of 0.01%. The accelerator is contained within a wire enclosure with double safety interlocks at both entrances. The accelerator vacuum system includes a liquid-nitrogen trap, an oil diffusion pump, and a fore-pump.

C. Seya-Namioka Vacuum Scanning Spectrometer

The light emitted by the foil was analyzed with a Jarrell-Ash-model-78-650, Seya-Namioka Vacuum Scanning Spectrometer. Seya[14] and Namioka[15] developed the theory and constructed, respectively, a new mounting for the concave diffraction grating in which the entrance and exit slits are stationary while the grating is rotated. The theory and construction of the spectrometer have been described by Frank et al.[16]

D. Angular Distribution Irradiation Chamber

The angular distribution chamber is composed of three coaxial cylinders (see Figs. 3 and 4). The electron beam enters the chamber through the entrance tube which is connected to the middle cylinder.

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[14] M. Seya, Science of Light 2, No. 1, 8 (1952).

[15] T. Namioka, Science of Light 3, No. 1, 15 (1954).

[16] A. L. Frank, E. T. Arakawa, R. D. Birkhoff, R. H. Ritchie, and H. B. Eldridge, "Optical Emission from Irradiated Thin Metallic Foils," Oak Ridge National Laboratory Report ORNL-3114 (July 2, 1962).

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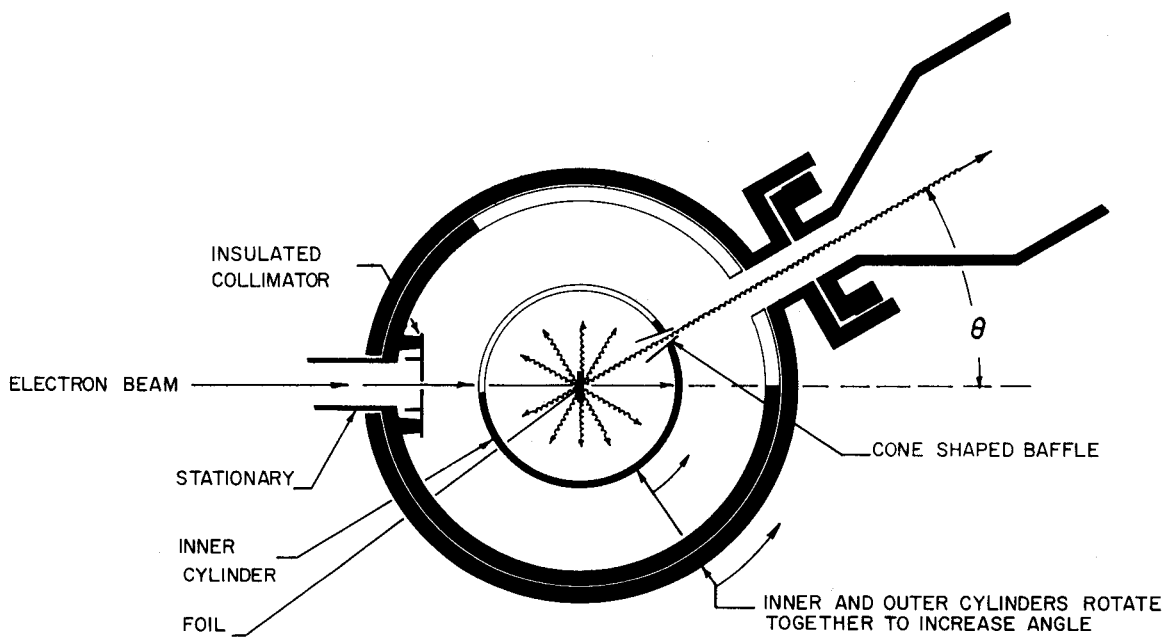

Fig. 3. Angular Distribution Irradiation Chamber (horizontal cross section).

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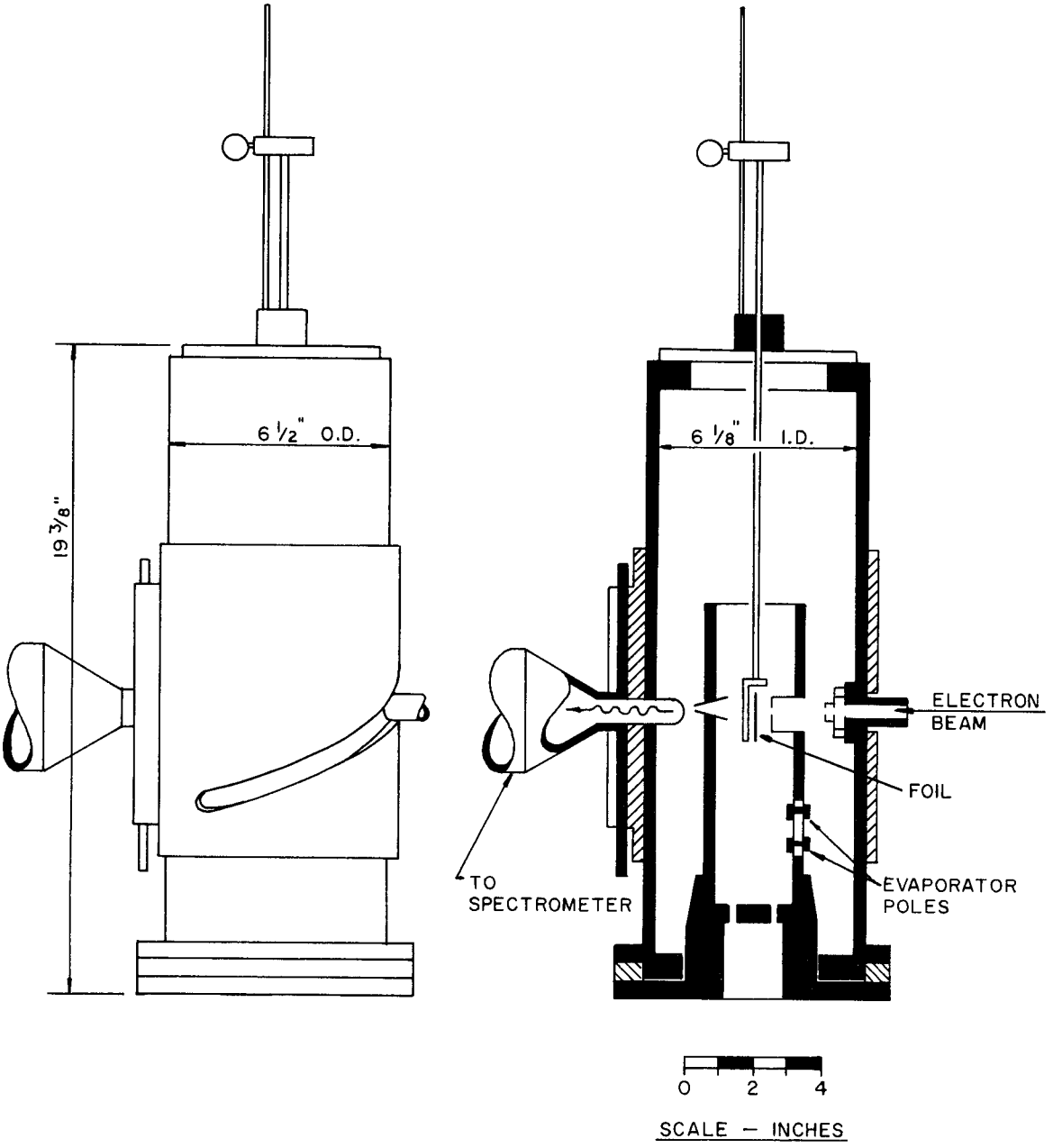

Fig. 4. Angular Distribution Irradiation Chamber (vertical cross section).

The outer cylinder, which has a helical slot, rotates and moves vertically so that the entrance tube lies within the helical slot. The light emitted from the foil passes through a cone-shaped baffle (Fig. 3) in the inner cylinder which is at the same height as the horizontal slot in the middle cylinder which in turn crosses a vertical slot in the outer cylinder. The light passes through the opening formed by the intersection of these slots and enters the spectrometer. The inner cylinder revolves with the outer cylinder, while the middle cylinder is stationary. The chamber is made vacuum tight with O-ring seals around the top and bottom of the outer cylinder, the vertical slot, and the helical slot of the outer cylinder.

The inner cylinder is insulated from the rest of the chamber and used as a collector for the beam current. The inner cylinder also contains facilities for evaporation of those metals which oxidize rapidly if exposed to air subsequent to their preparation. The emitted light can be viewed at an angle of 0 to 150 degrees from the direction of the electron beam. A magnet, located in the entrance arm of the spectrometer, deflects scattered electrons vertically so that they cannot enter the spectrometer where they may produce extraneous light. The cone-shaped baffle shields the spectrometer from light produced by stray electrons hitting the baffle.

The top of the middle cylinder is sealed with a lucite window which permits visual observation of the foils. The rod on which the foils are mounted can be moved vertically to bring the desired foil area to the horizontal level of the electron beam. Foils are

3/16-inch wide and 3/4-inch long as compared with an electron beam diameter of 1.5mm. The electron beam is focused and the foil is positioned so that the electron beam hits only the foil and no part of the foil holder.

IV. CALIBRATION AND TECHNIQUE

A. Preparation of Thin Silver Foils

Silver foils were needed with a thickness of about 700 Å since previous data indicated that the sharp peak in the emission spectrum would occur at about that thickness. The desired foil properties also included unwrinkled surfaces, constant thickness, and small crystal size. The foils were made by vacuum evaporating silver onto glass substrates.

The evaporation system consisted of a bell jar sealed to a base plate which contained a pumping port and three electrical terminals. A fore pump and an oil diffusion pump with a liquid nitrogen cold trap reduced the pressure to 5 to 10 x 10^{-6} mm Hg. An external evaporation facility could be used since silver does not oxidize too quickly. The silver (99.9% pure) was contained in a molybdenum boat heated by alternating current. The mass of silver needed for the desired thickness, t, was approximately $M = 2\pi r^2 \rho t k$ where k is an experimentally determined constant equal to approximately 1/4 for the type of boat used, r is the distance from the silver segment to the glass slide, and ρ is the density of Ag.[17]

A very small amount of a wetting agent, Victawet,[18] was placed on a second Mo boat. With a pressure of 7 to 9 x 10^{-6} mm Hg in the bell

---

[17] L. Holland, Vacuum Deposition of Thin Films (John Wiley and Sons Inc., New York, 1960).

[18] Victawet 35B marketed by Victor Chemical Company, Chicago, Illinois.

jar, the Victawet was heated slowly until a pressure of 1 to 2 x 10^{-4} mm Hg was observed and then kept at this pressure for around 30 seconds. The pressure was then allowed to return to 7 x 10^{-6} mm Hg by turning off the heat on the Victawet and the Ag was slowly heated until it melted into a ball which was then evaporated as quickly as possible. The time elapsed during evaporation was usually less than 10 sec. This time depended to some extent upon the amount of Ag being evaporated. For thicker foils, a larger mass of Ag and a longer time were required.

Kodak lantern slides cut to 8 x 2.5 cm were placed 15 to 20 cm above the boat depending on the thickness desired. Points on the surface of the slide were from 0° to 20° from the normal to the plane of the boat. The foil was cut into strips while on the slide and then gently immersed in a water bath. As the Victawet dissolved the under the foil the latter floated off onto the water surface. The foil holder was then placed under the foil in the water vertically so that when it was raised, its long flat edge would come in contact with the edge of the foil, and the foil would remain on one side of the holder.

A preliminary experiment had revealed that the intensity of light emitted decreases according to the period of time the beam has been on the foil (see Figure 5). This is probably due to the deposition of foreign material such as carbonized pump oil. Because of the change in the intensity of the spectrum with time, a foil holder was made that would support a long foil (3/16" x 3/4") which could

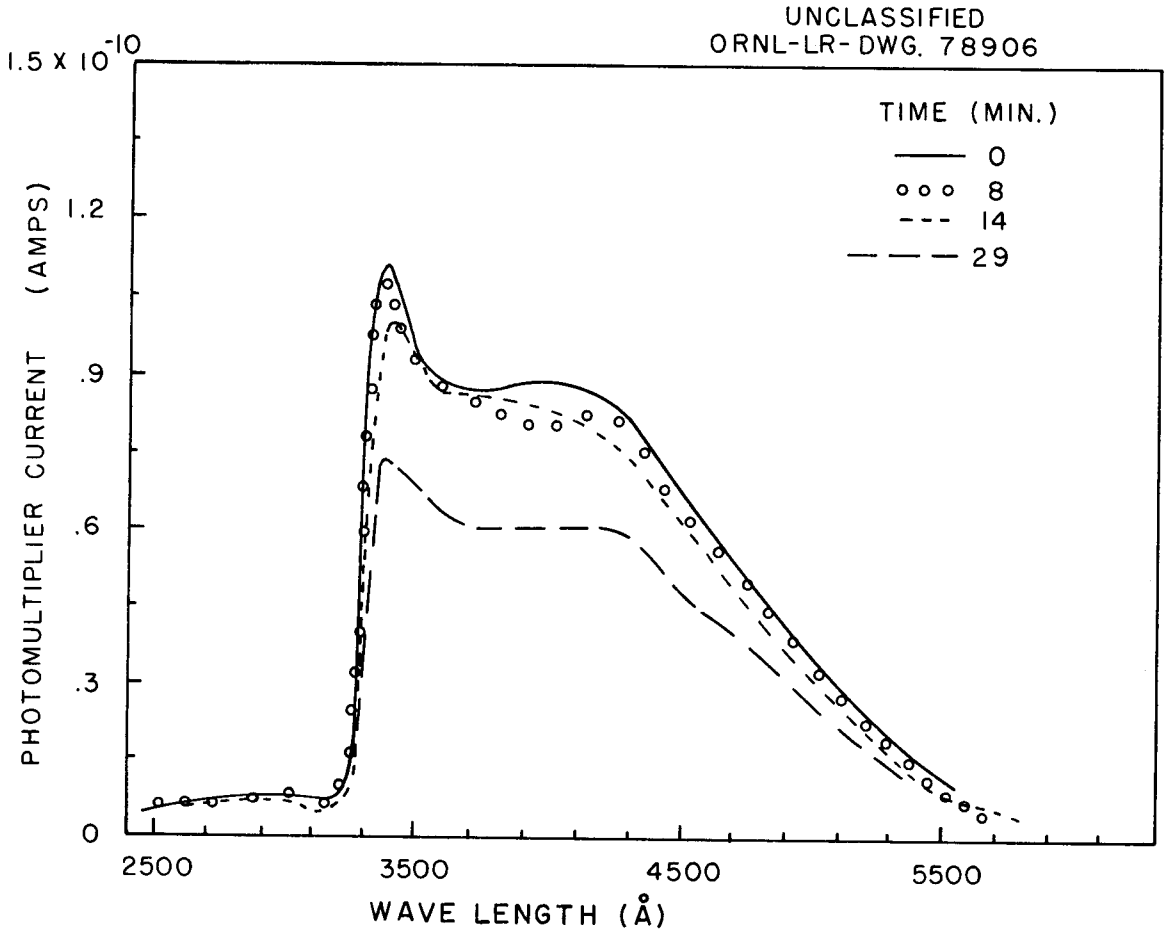

Fig. 5. Effect of Irradiation Time on Ag Emission.

be moved vertically to a new foil position for each angle of observation.

The time elapsed after foils were made and placed in the chamber had no effect on the spectrum when the period was no longer than a few days.

Electron micrographs were made of the silver foils prepared in the described manner. Figures 6 and 7 are micrographs of the same area of the 660-Å Ag foil that was used in the experiment before and after the foil was bombarded by electrons. The foil had a few wrinkles on the areas that had been bombarded and appeared to transmit light somewhat better than non-irradiated areas. The electron micrographs of the bombarded areas show the same crystal structure as those areas that were not bombarded. The electron beam covered an area approximately 300 times the area shown in Figure 7. The crystal sizes varie from a diameter of 1 μ to .05 μ. Their emission spectra when bombarded by 40-keV electrons agree well with the theory as will be shown later.

The foil thickness measurements were made by the multiple beam interferometric method as described by Tolansky.[19]

B. Wavelength Calibration

Since the monochromator dial was calibrated to read the wavelength for a 1200- lines/mm grating, whereas the grating used had 600 lines/mm, the dial reading was multiplied by two after the

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[19] S. Tolansky, An Introduction to Interferometry (Longman, Green and Co., London, 1955).

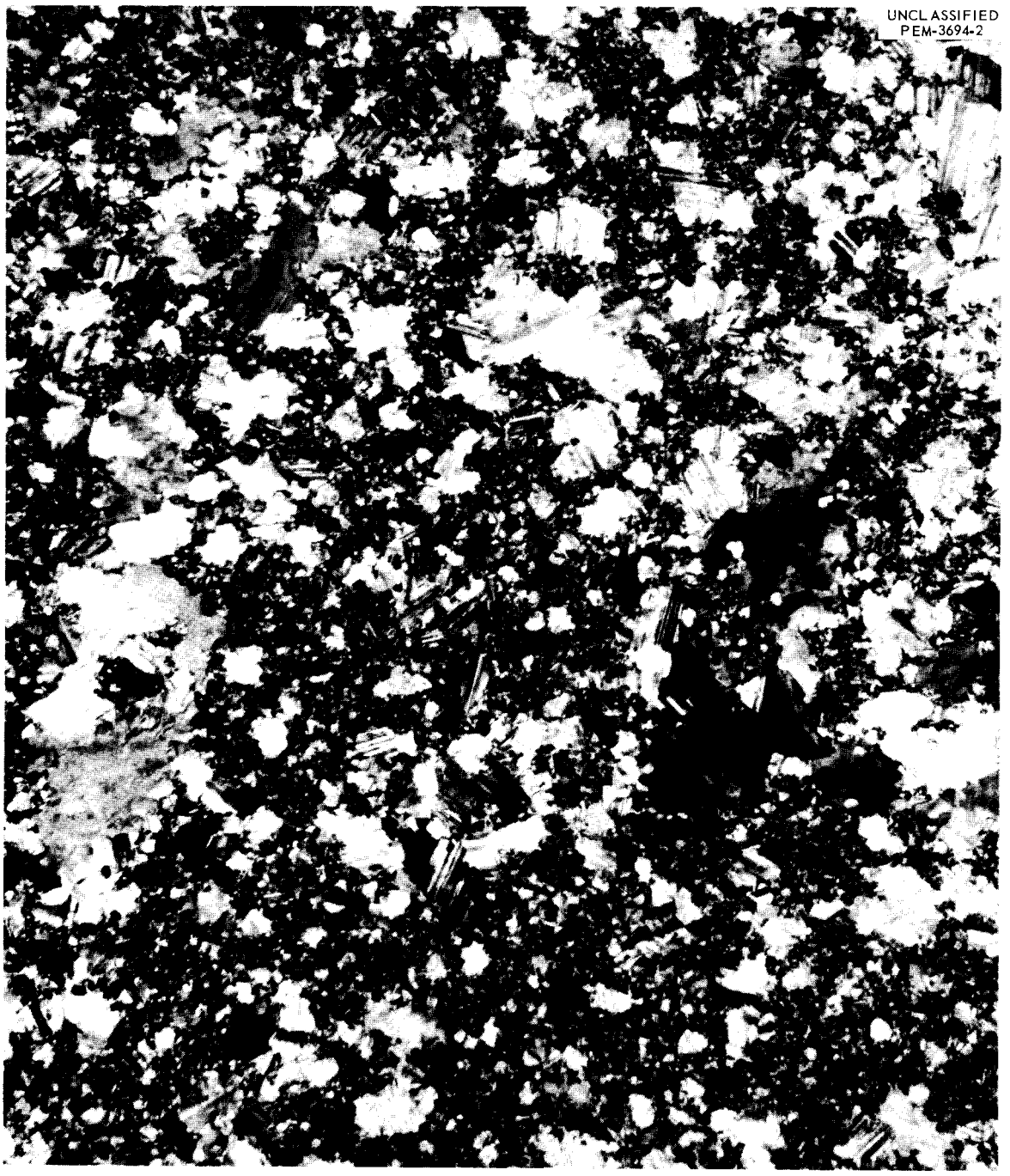

Fig. 6. Electron Micrograph of a Ag Foil 660 Å Thick Before Irradiation. 34,000X. Reduced 15%.

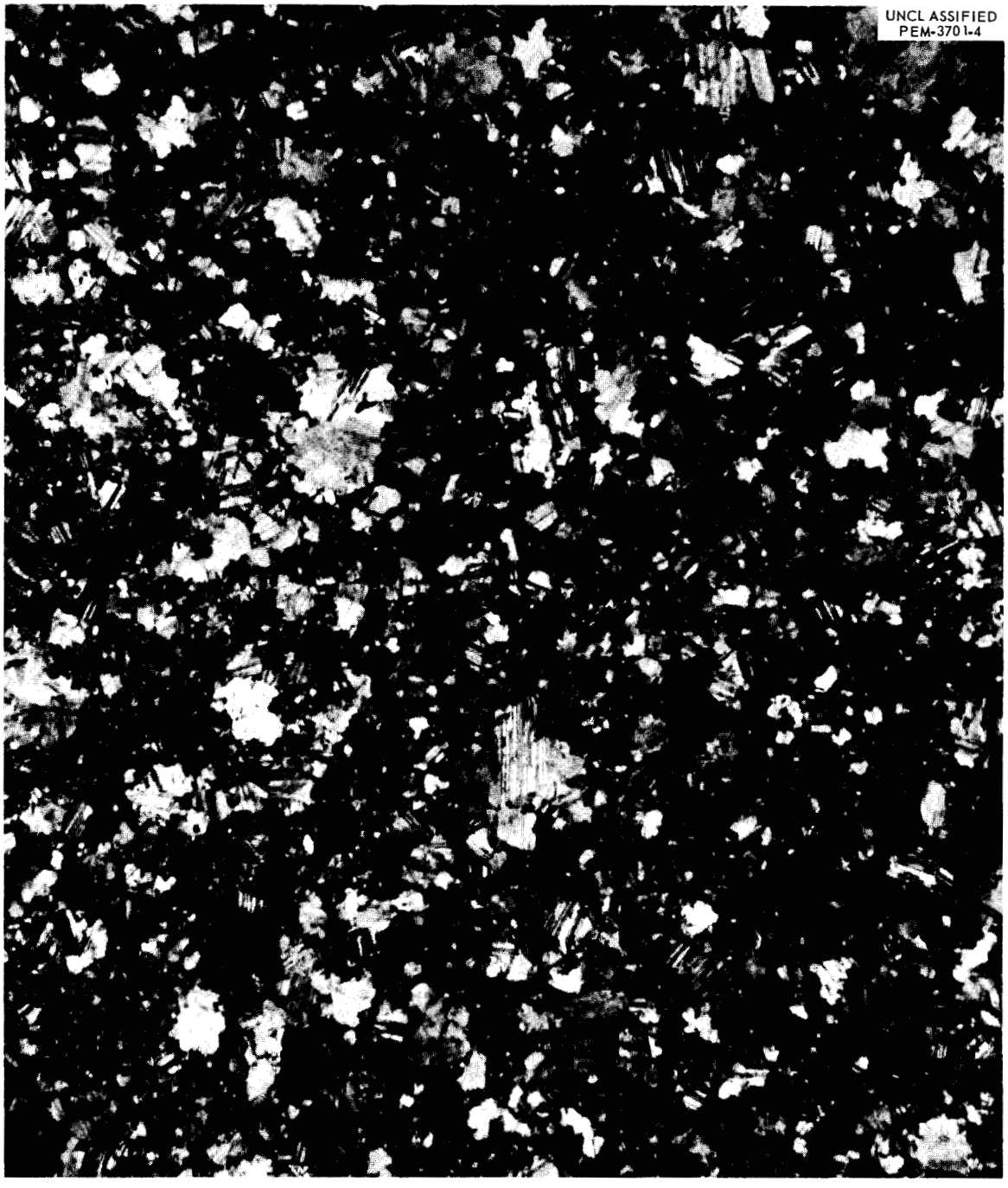

Fig. 7. Electron Micrograph of a Ag Foil 660 Å Thick After Irradiation. 34,000X. Reduced 15%.

central image dial reading was subtracted. The wavelength calibration was checked several times during the investigation using a low pressure mercury arc lamp as a source of monochromatic lines of known wavelength.

Recordings of the central image were made at 300 Å per min after each spectral distribution scan taken at 1000 Å per min. Because of this relatively high scanning rate, the accuracy of the wavelength was approximately ± 10 Å for the recorded spectral distribution.

C. Data Correction

To determine the absolute response of the spectrometer, two separate calibrations were made, one with the polarizer transmitting light in the parallel plane, and another with the polarizer transmitting light in the parpendicular plane. A GE-AT/24/3 (NBS-U123) tungsten filament lamp calibrated by the National Bureau of Standards was used as a source of known spectral radiance. A concave mirror was used to focus the filament at the foil position with a magnification of unity (see Figure 8). A 1.98-mm diameter collimator was placed at the foil position and an EMI-6256B photomultiplier tube was used to detect the light from the grating. Both mirrors used were front surface mirrors coated with aluminum. The radius of curvature for the grating blank used as a concave mirror was 50 cm.

The standard lamp had been calibrated with 35 amps passing through its filament, and this same current was employed here with the current being monitored during each run and kept constant

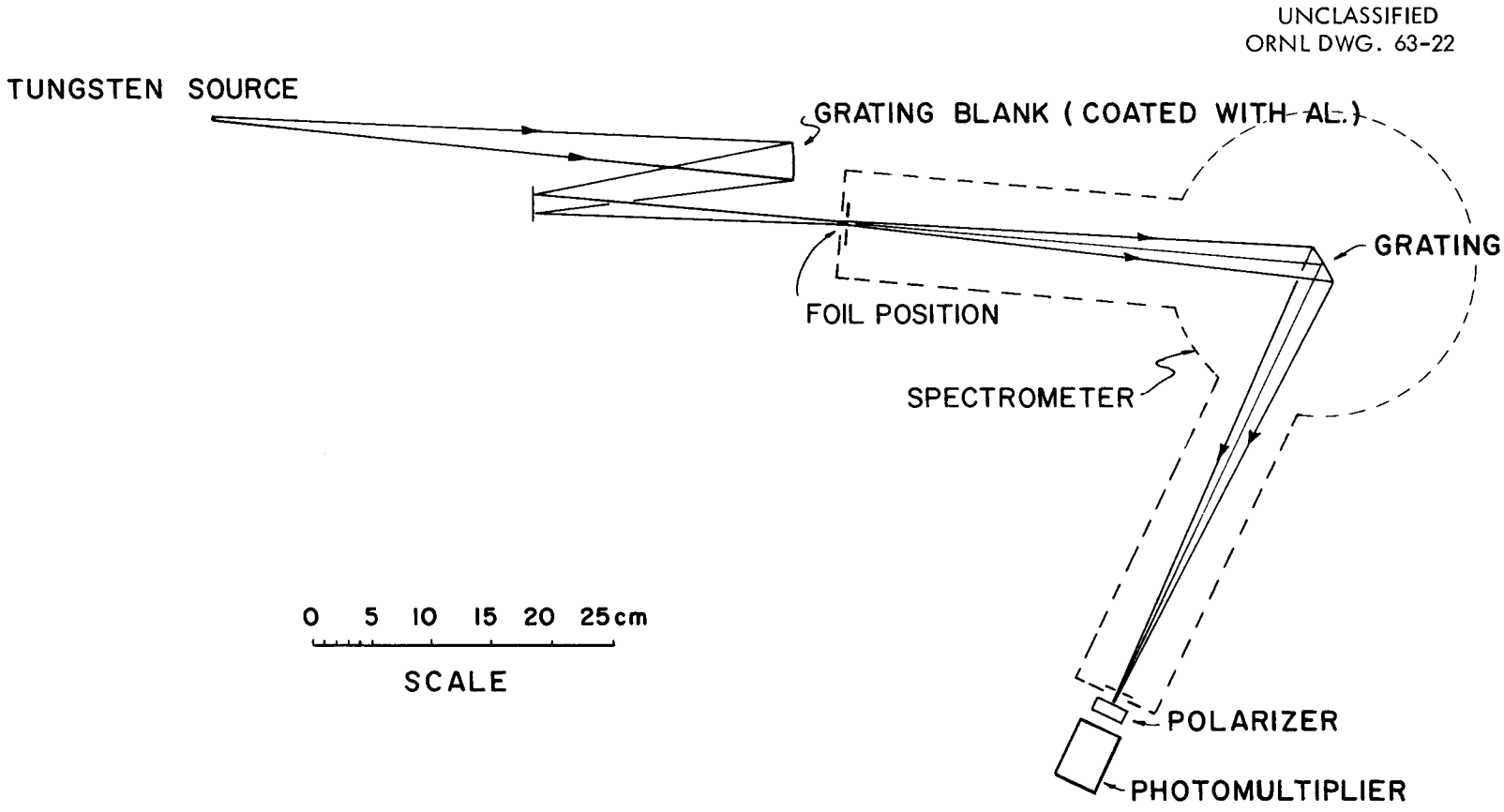

Fig. 8. Arrangement of Optical Apparatus for Calibration of Spectrometer.

to less than $\pm$ 0.1 amp. The photomultiplier voltage was reduced to one-half its normal operating voltage to reduce the gain during the time the high-intensity lamp was in use. The ratio of gain of the photomultiplier at 1000 volts to 500 volts was determined to be 1170 $\pm$ 20.

Because of the much higher intensity emitted by the tungsten lamp at 4400 to 6000 Å than at 2200 to 3000 Å and because the grating was blazed so as to have very little second order diffraction, there was not a sufficient amount of the second order contribution present to necessitate correction.

A correction was made for the scattered light present at the short wavelengths. When a glass plate which would not transmit those wavelengths less than 3000 Å was inserted between the foil position and the grating, a small amount of light was still recorded from 2200 Å to 3000 Å and increased, as expected, on the longer wavelength side of 3000 Å. The curve from 2200 Å to 3000 Å was extrapolated to approximately 4200 Å and this amount was subtracted from the spectrum without the glass plate. The intensity of scattered light beyond 4200 Å was negligible compared to the direct light.

The correction curve (see Figure 9) was calculated in the following manner for both the parallel and perpendicular positions of the polarizer.

$$C_E(\lambda) = \frac{(\text{lamp output})\ (\text{area of collimator})\ (\text{mirror reflectivity})^2}{(I_{\text{lamp}})\ \ 1170}$$

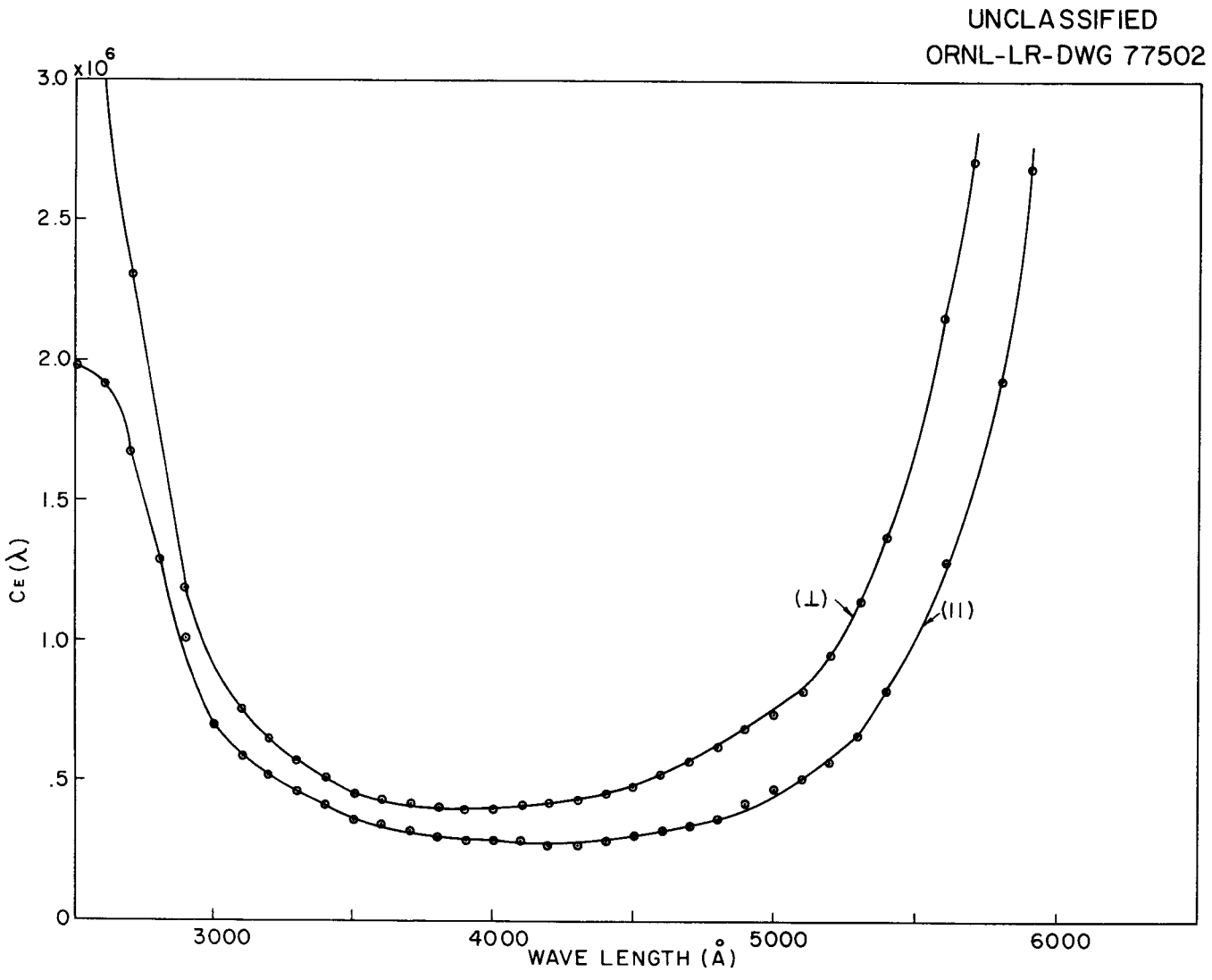

Fig. 9. Correction Curves for Spectral Response of the Spectrometer.

where I_{lamp} is the photomultiplier current with the lamp in operation and 1170 is the ratio of the photomultiplier gain at 1000 volts to that at 500 volts. The photon intensity $E(\lambda)$ from the electron bombarded foils was determined by the following equation:

$$E(\lambda) = C_E(\lambda) \frac{I_{foil}}{I_{beam}} \qquad (2)$$

where I_{beam} is the electron beam current collected by the inner cylinder, and I_{foil} is the photomultiplier current. An uncorrected spectrum for parallel polarized light is shown in Figure 10 and when corrected according to Equation (2), the spectrum in Figure 11 is obtained. All figures shown hereafter have been corrected in this manner, and all comparisons are made on an absolute intensity scale.

The light in the parallel plane is thought to be composed of transition radiation and bremsstrahlung, whereas the light in the perpendicular plane is assumed to be only bremsstrahlung. Since a previous investigation[20] on gold foils had shown that the observed bremsstrahlung is unpolarized, the light in the perpendicular plane was subtracted from the light in the parallel plane (see Figure 12), and the difference spectrum is assumed to be only transition radiation. It should be noted that the ratio of light in the perpendicular plane to that in the parallel plane is usually very small, and therefore the

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[20]Arakawa, loc. cit.

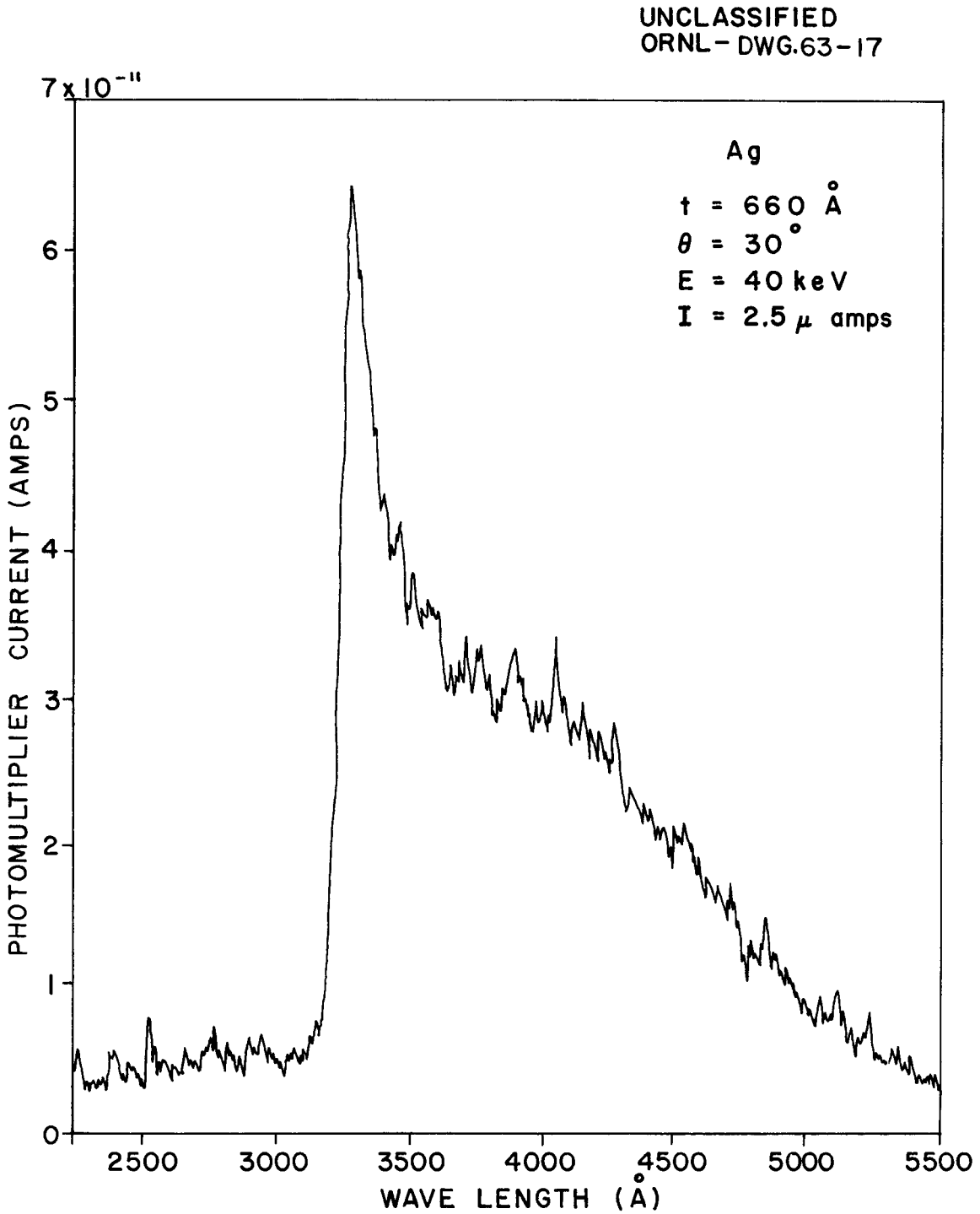

Fig. 10. Uncorrected Spectrum of a Ag Foil 660 Å Thick Bombarded by 40-keV Electrons.

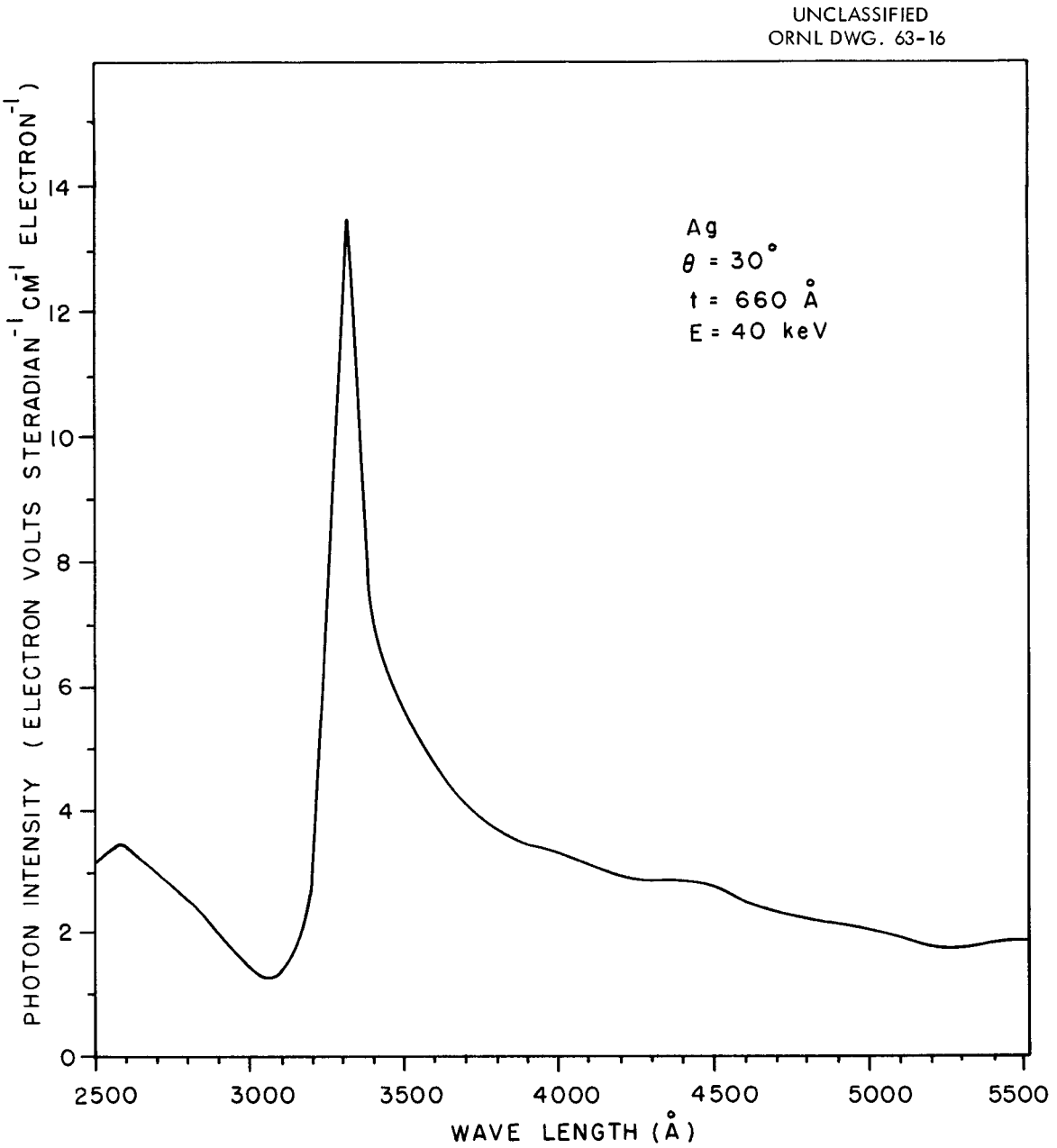

Fig. 11. Corrected Spectrum of a Ag Foil 660 Å Thick Bombarded by 40-keV Electron.

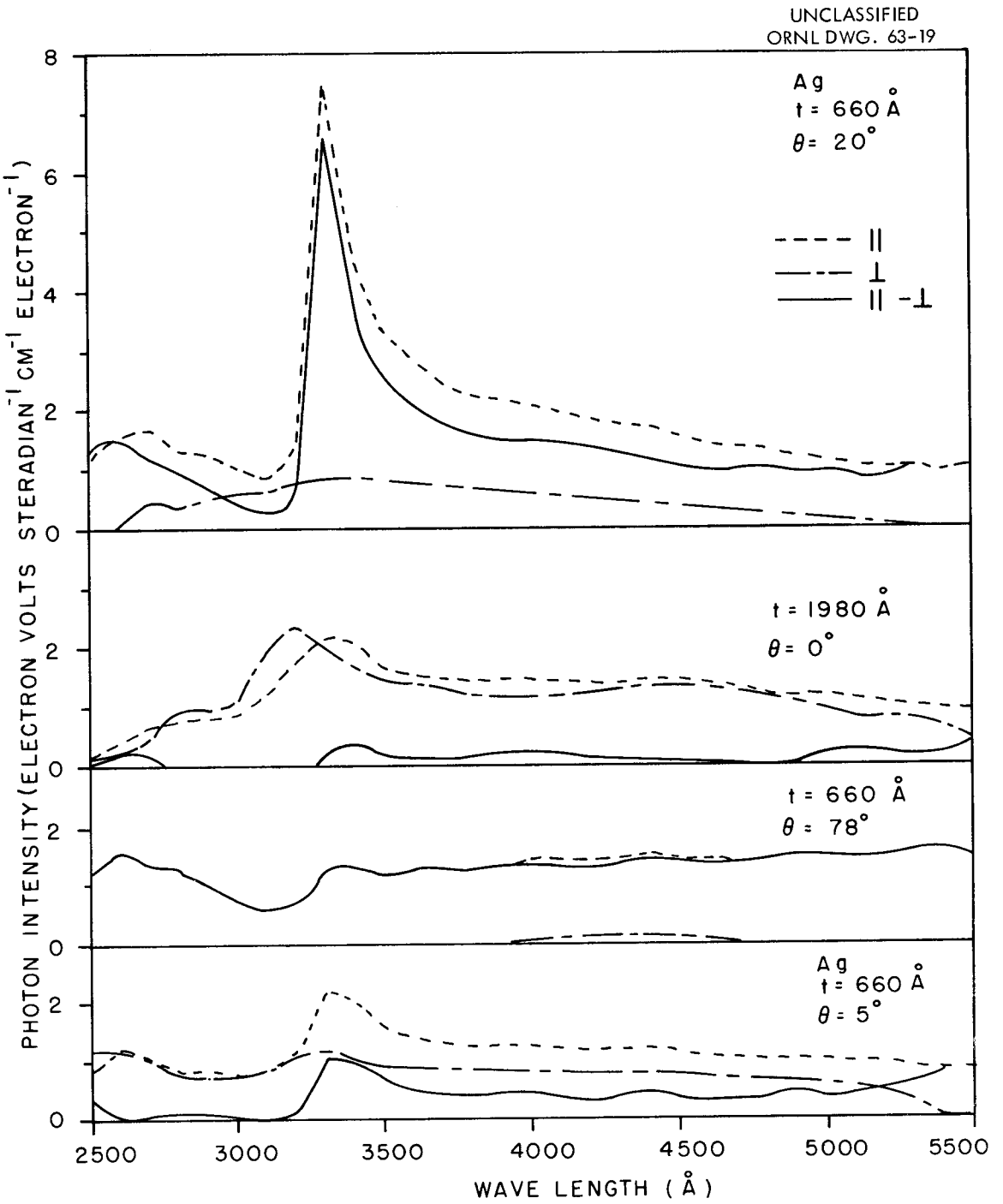

Fig. 12. Typical Spectra of Light Polarized in the Parallel Plane, the Perpendicular Plane, and the Difference Between the Two.

uncertainty in this correction usually introduces only a small error. All experimental distributions shown hereafter for transition radiation are the parallel component minus the perpendicular component.

V. PROCEDURE

The silver foil was mounted on the foil rod so that the foil would be in the center of the irradiation chamber. The irradiation chamber was isolated by three valves from the accelerator vacuum system and the two oil diffusion pumps. The foil was raised to the top of the irradiation chamber so that it would not be ruptured by the flow of air when the system is first opened to the pump. The valve between the fore pump and the oil diffusion pump of the spectrometer was closed, and this fore pump was used to evacuate the spectrometer slowly. When the vacuum in the spectrometer and irradiation chamber was 200 to 100 μ Hg, the oil diffusion pump was opened to the system. An air-cooled oil diffusion pump was also opened to the irradiation chamber at this time. After ten minutes the valve that separated the accelerating system from the irradiation chamber was opened. The current to the degaussing coils was turned on and allowed to stabilize for approximately thirty minutes.

After thirty to forty minutes the vacuum in the electron accelerator reached 0.5 to 2 x 10^{-6} mm Hg. The accelerating voltage was turned on and raised to the desired operating potential of 40 keV. The electron gun was turned on and the filament temperature raised until a sufficient electron emission was obtained as indicated by the beam current collected by the collimator. The filament was either dull red or orange in color. The inner cylinder current was maximized while the collimator current was minimized by adjusting the first and second anode voltages on the gun and the

current through the degaussing coils. The electron gun filament current was then raised until the inner cylinder current was 2.5 μa. This current was monitored during each run and kept constant to ± 0.1 μa. The foil current was also observed and was usually 0.1 μa of positive current because more secondary electrons were being emitted by the foil than primaries that were being absorbed.

The spectrum from 2500 Å to 5600 Å was scanned at 1000 Å per min for three runs with the polarizer accepting light polarized in the parallel plane. The photomultiplier current was amplified and recorded by a Brown recorder. Then the central image was scanned at 300 Å per min. The spectrum was also recorded with the polarizer in the perpendicular plane. The foil was then raised to the top of the chamber, and the valves isolating the irradiation chamber and spectrometer were closed while the spectrometer was rotated around the irradiation chamber to a new angle. The valves were closed as a precautionary measure against an accidental leak into the angular distribution chamber during rotation. The valves were then opened again, and there was usually no rise in pressure. The degaussing coils were re-adjusted with the foil still at the top of the chamber. The foil was then lowered to a new foil position and the spectrum was measured. This procedure was repeated for each new angle.

The foil holder was always positioned such that the foil was between the holder and the spectrometer. This was very important because the spectrum showed an increased intensity in the 4000-Å region when the foil was on the accelerator side of the foil holder.

Previous experiments had shown that light in the 4000-Å region was produced when the beam was allowed to strike the foil holders. With the holder reversed, light caused by electrons scattering in the foil and hitting the edge of the holder is shielded from the spectrometer by the foil itself.

VI. RESULTS

The experimental results are compared with the transition radiation theory of Ritchie and Eldridge on an absolute scale for emission from both the front and back sides of the silver foils. The theoretical curves were obtained from Equation (1) using the dielectric constants of Ehrenreich and Philipp[21]. The equation was programmed for solution on a CDC-1604 A digital computer.

A comparison of the experiment with theory of the complete spectral distribution for transition radiation for the silver foil 660 Å in thickness at 40 keV is shown for the angles on the front side of the foil in Figure 13 and 14. For the small angles ($\theta = 5^{\circ}$ to 40°), the sharp peak at $\lambda = 3300$ Å is less intense than the theoretical peak. The continua for the experiment on both sides of the peak agree closely with the theory. The spectral distributions found experimentally at the larger angles ($\theta = 50^{\circ}$ to 87°) show good agreement with the theory for all wavelengths.

The experimental spectral distributions for the angles on the back side of the foil which is 660 Å thick are compared with the theory in Figures 15 and 16. Very close agreement was observed for the complete spectral distributions at these angles. Also in the same figures the spectral distributions on the back side are

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[21] H. Ehrenreich and H. R. Philipp, Phys. Rev. 128, 1622 (1962).

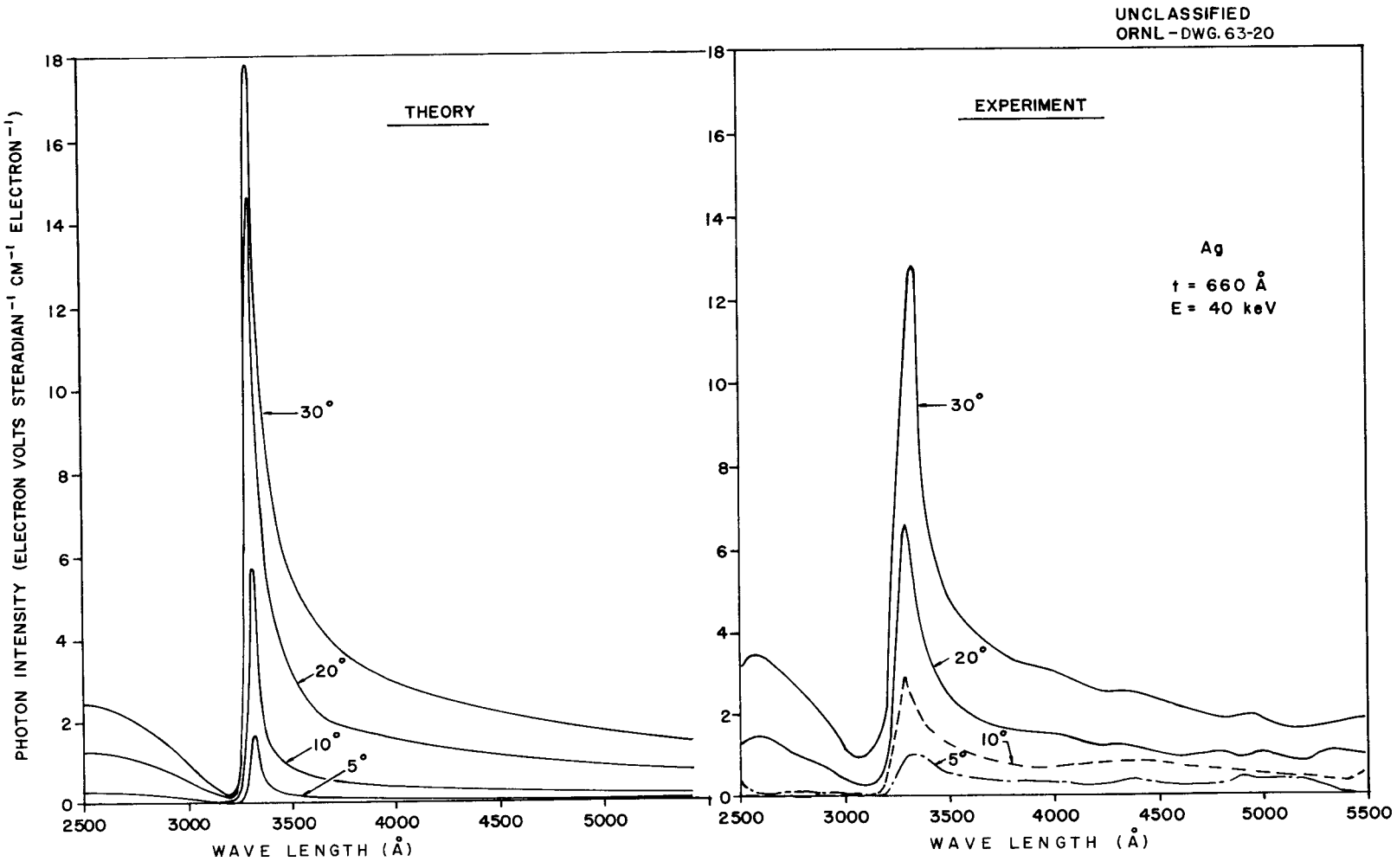

Fig. 13. Theoretical and Experimental Spectra from a Ag Foil 660 Å Thick (θ = 5° – 30°, E = 40 keV).

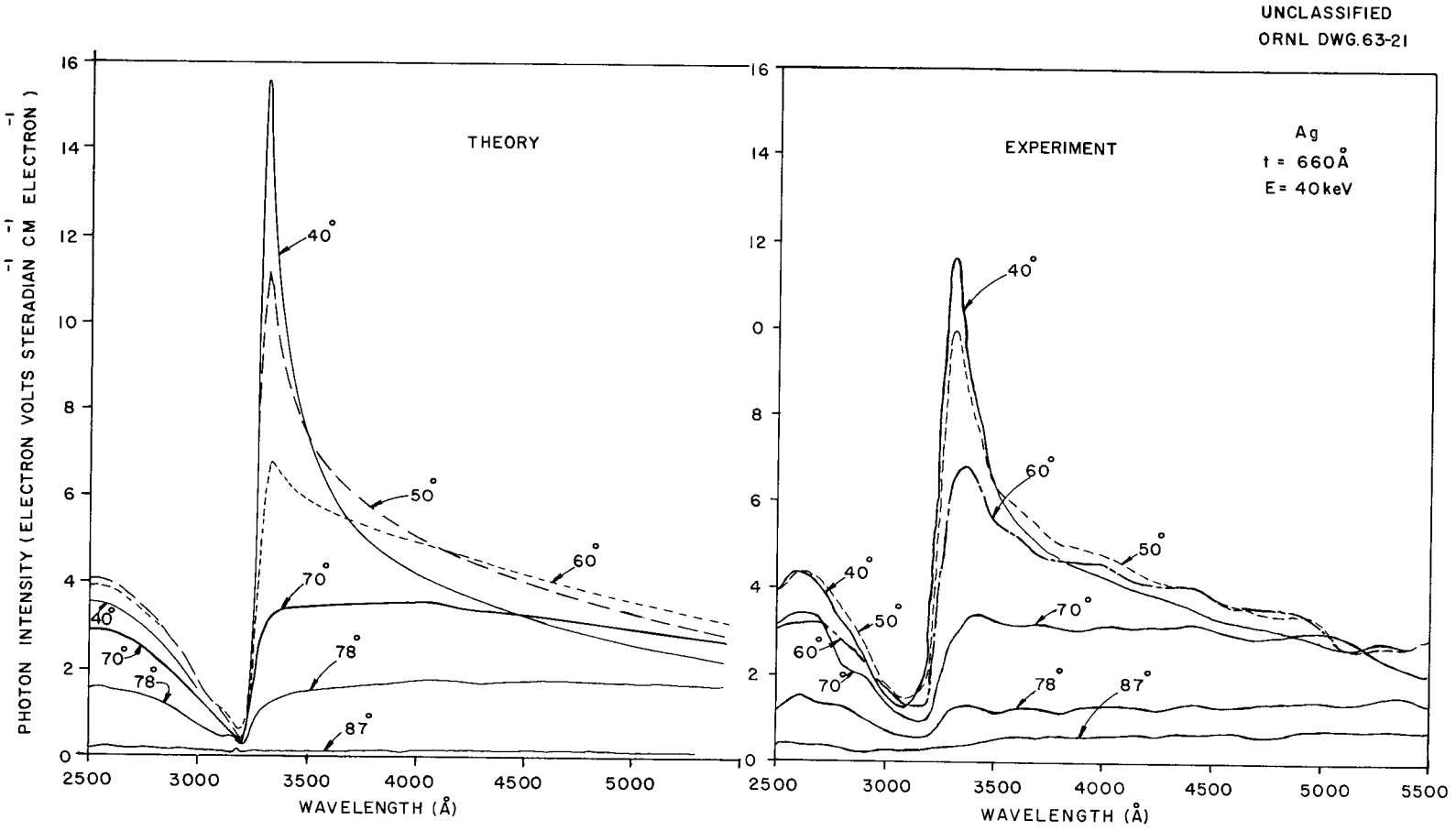

Fig. 14. Theoretical and Experimental Spectra from a Ag Foil 660 Å Thick (θ = 40° – 87°, E = 40 keV).

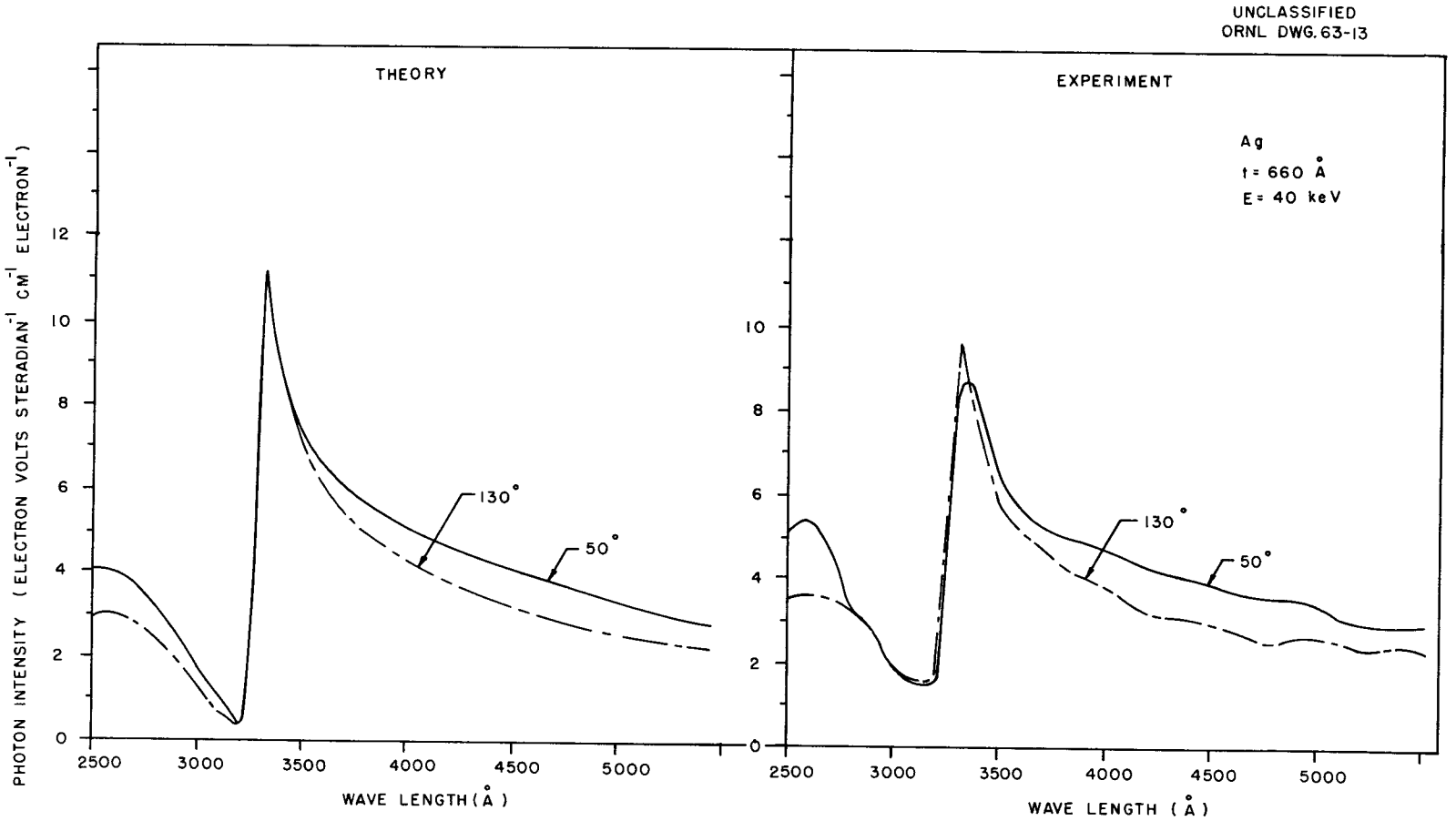

Fig. 15. Theoretical and Experimental Spectra for Corresponding Angles on Front and Back Sides of a Ag Foil 660 Å Thick (θ = 50° and 130°).

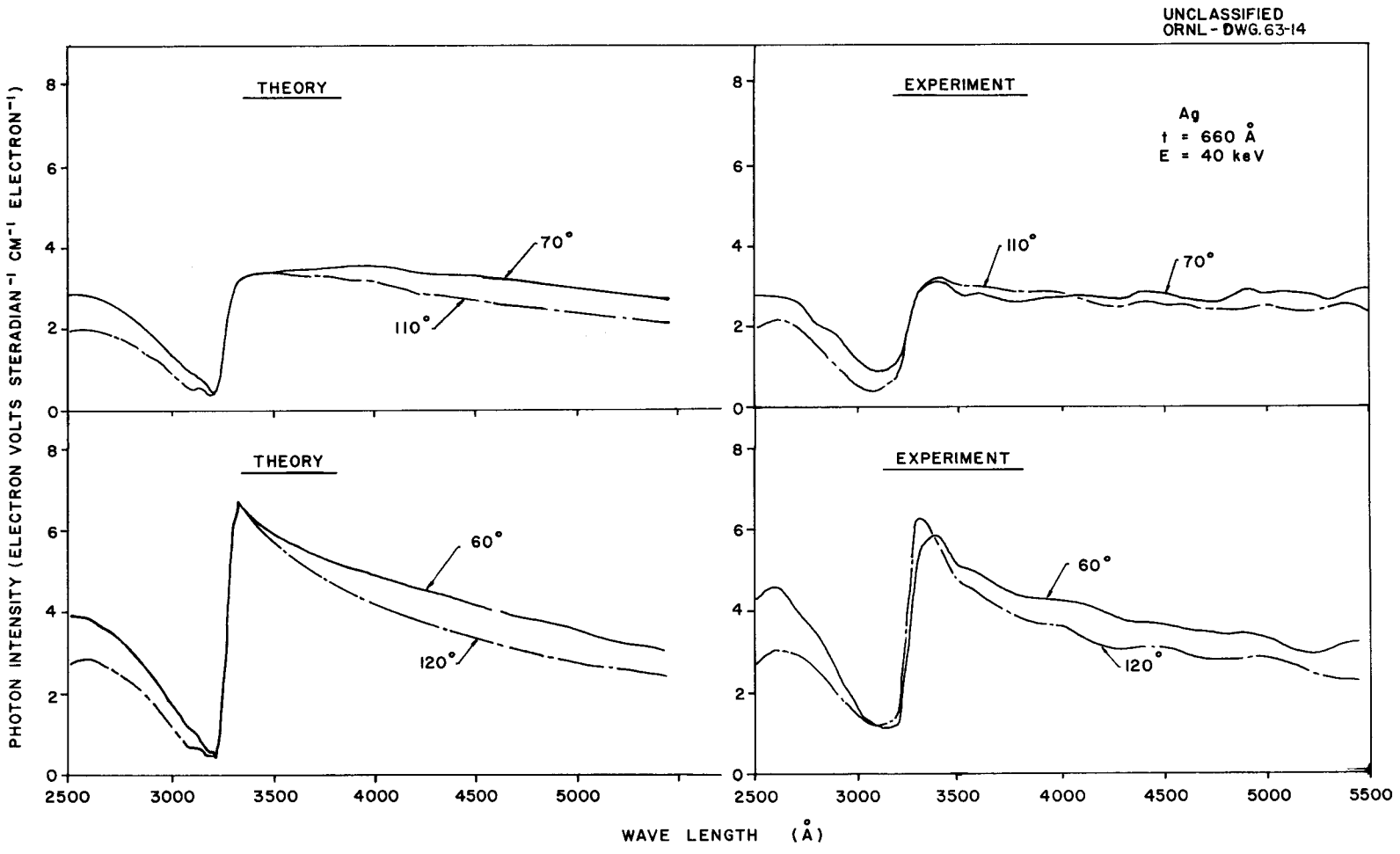

Fig. 16. Theoretical and Experimental Spectra for Corresponding Angles on Front and Back Sides of a Ag Foil 660 Å Thick (θ = 60° and 70° vs 120° and 110°; E = 40 keV).

compared with those on the front side at corresponding angles. As was shown earlier the theoretical spectrum is higher in the forward direction because of the relativistic velocity of the electron. The experiment shows the same difference in the intensity as does the theory for the front and back sides.

In Figure 17 the complete spectral distribution observed experimentally for a silver foil 1980 Å in thickness is compared with theory for the small angles. The experimental peak is broader and lower in intensity than the theoretical peak at $\theta = 10^{\circ}$, 20°, and 30°. The experimental spectral distributions on the back side of the same foil are shown in Figure 18. Close agreement of experiment with theory is observed except for $\theta = 150^{\circ}$ where the peak in the experimental data is broader and the continuum on the short wavelength side is higher than predicted by theory. Also, in this figure, the spectral distributions on the back side are compared with their corresponding angles on the front side for both experiment and theory. The theoretical spectra for the foil 1980 Å in thickness show no difference for the corresponding back and front angles in contrast to the experimental results for the foil 660 Å in thickness where the intensity of the continuum was greater in the forward direction. The experimental spectrum for the foil 1980 Å in thickness is more intense for the back angles than for the front angles. This slight discrepancy in the thick foil is not completely understood but may be due to multiple electron scattering which has been neglected in the theory.

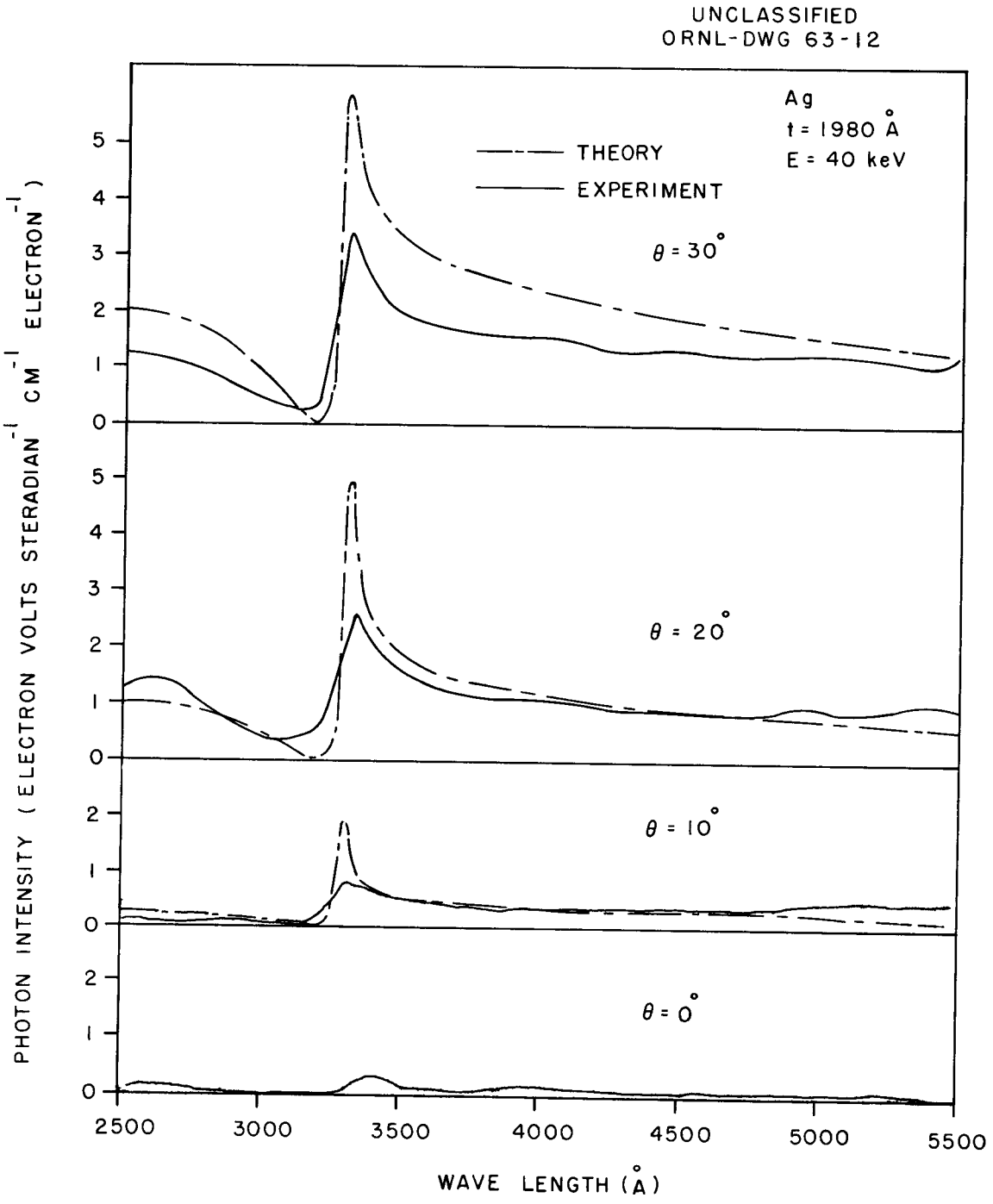

Fig. 17. Theoretical and Experimental Spectra for a Ag Foil 1980 Å Thick (θ = 0° to 30°).

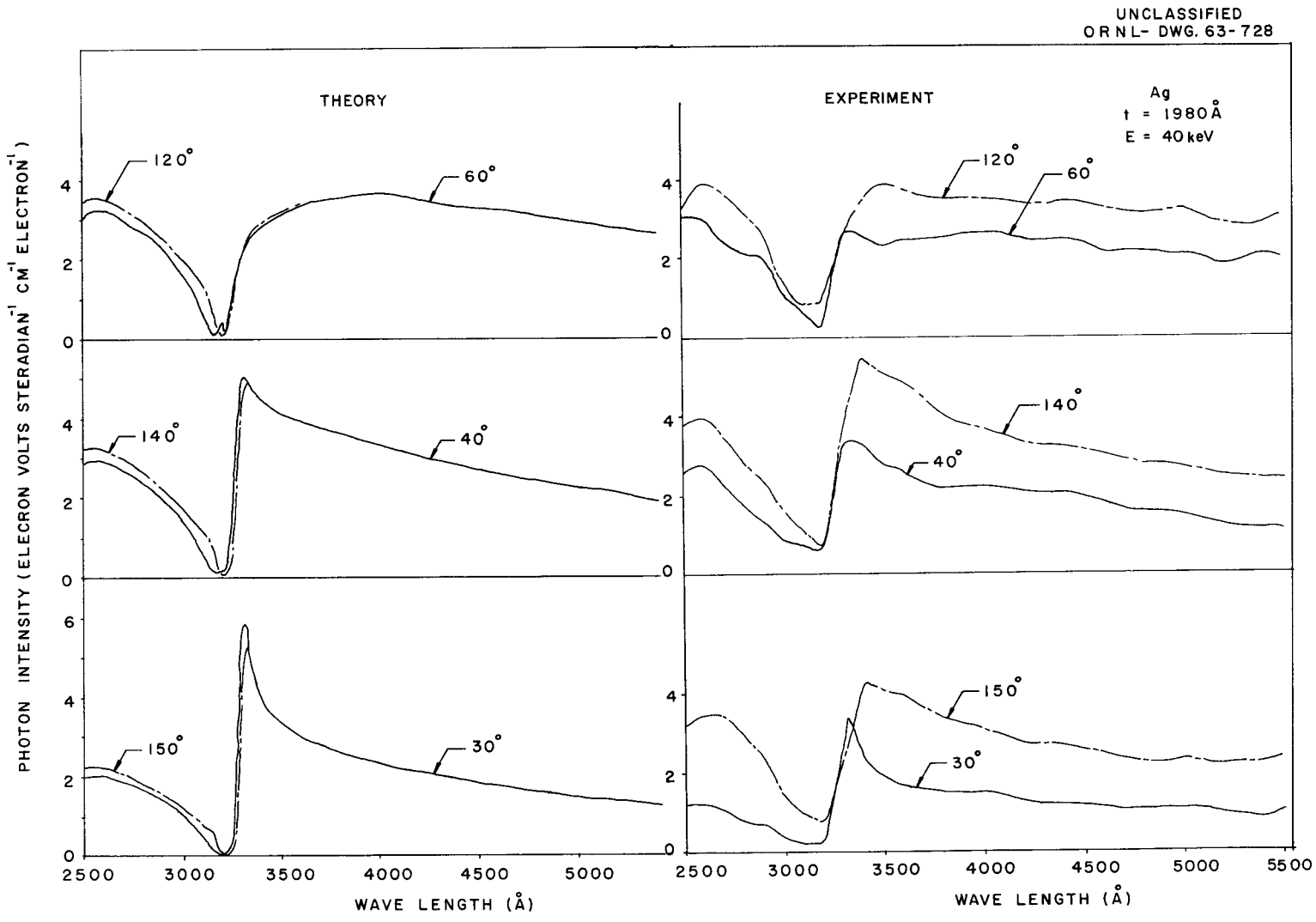

Fig. 18. Theoretical and Experimental Spectra for Corresponding Angles on the Front and Back Sides of a Ag Foil 1980 Å Thick (θ = 30°, 40°, and 60° vs 150°, 140°, and 120°).

The intensity at the silver peak as a function of angle for the foil 660 Å in thickness is shown in Figure 19. The solid line represents the theory while the + and o represent experimental runs with two foils of the same thickness. The experiment indicates a maximum intensity at 30° from the foil normal in agreement with theory. A comparison of the experiment with theory of the photon intensity at $\lambda = 4500$ Å and 2700 Å is also made in the same figure. Good agreement is observed for these two wavelengths for the foil 660 Å in thickness. The maximum intensities for the continua occur at $\theta = 50^{\circ}$, whereas the maximum intensity for the peak occurs at 30°.

The intensity as a function of angle for the silver foil 1980 Å in thickness is shown in Figure 20. The maximum intensity at $\lambda = 3300$ Å again occurs at $\theta = 30^{\circ}$, while for $\lambda = 2700$ Å and $\lambda = 4500$ Å the maximum intensity occurs at $\theta = 50^{\circ}$. The experimental intensity for $\lambda = 4500$ Å and for the angles between $\theta = 0^{\circ}$ and 70° also appears to be slightly lower than the theoretical value.

In Figure 21 the wavelengths of the silver peak determined experimentally for foils 660 Å in thickness are compared with the theoretical values as a function of the angle. The x, o, and + represent three separate experimental runs. The wavelength of the peak as determined experimentally shows a definite tendency to increase with increasing angle, whereas theory predicts a constant value of 3324 Å. The wavelength of the peak increased linearly from $\lambda = 3280$ Å at $\theta = 10^{\circ}$ to 3316 Å at $\theta = 50^{\circ}$. The average of all the peak wavelengths determined experimentally was 3300 Å $\pm$ 12 Å.

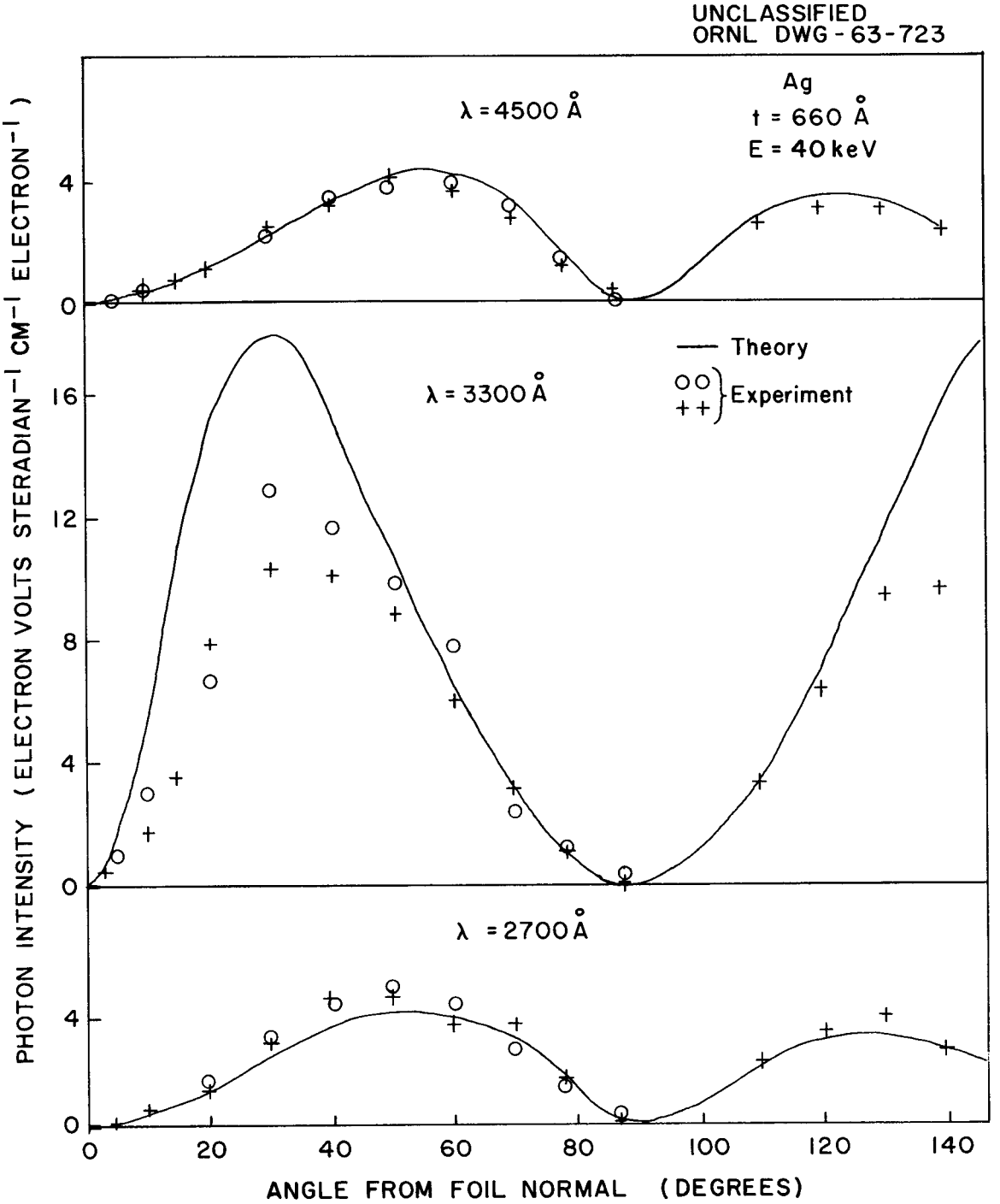

Fig. 19. Comparison Between Theory and Experiment of the Angular Distribution at λ = 2700 Å, 3300 Å, and 4500 Å for a Ag Foil 1980 Å Thick (E = 40 keV).

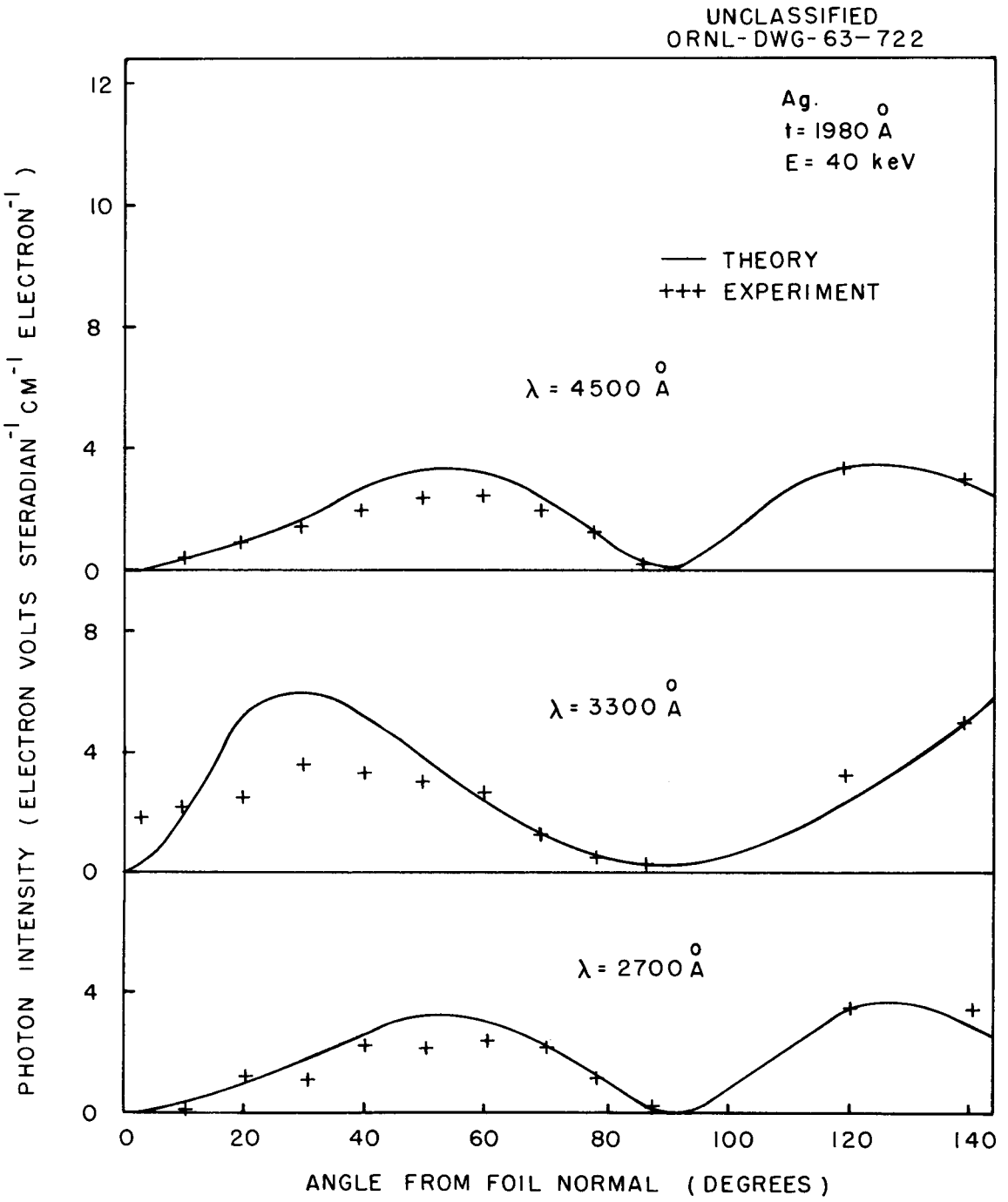

Fig. 20. Comparison Between Theory and Experiment of the Angular Distribution at λ = 2700 Å, 3300 Å, and 4500 Å for a Ag Foil 1980 Å Thick (E = 40 keV).

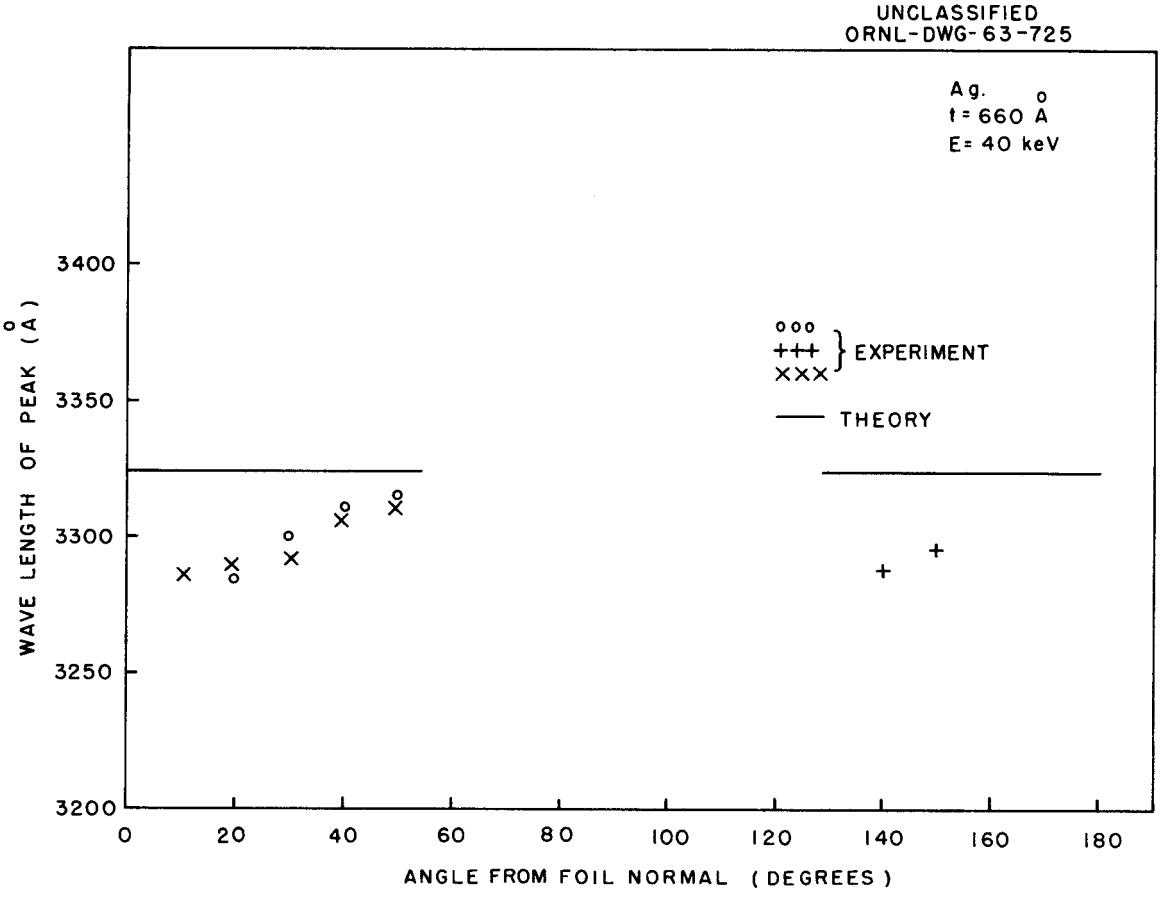

Fig. 21. Wavelength of Ag Peak Determined Experimentally for a Ag Foil 660 Å Thick as a Function of Angle of Observation.

The experimental results for the light emitted in the perpendicular plane by the foil 1980 Å in thickness for the front angles are shown in Figure 22. Although detailed conclusions concerning this source of light cannot be presented because the intensity observed in this plane was only two to three times the noise level, some general trends may be seen. The intensity is maximum in the direction of the electron beam and decreases with increasing angle as is predicted theoretically for bremsstrahlung. The experimental results for the foil which was 660 Å thick are shown in Figure 23 with the same general decrease in intensity with increasing angle. The photon intensity for the foil 1980 Å in thickness is greater than for the foil which was 660 Å thick as expected for bremsstrahlung. The experimental spectra for the angles greater than 90° for the silver foils 660 Å and 1980 Å in thickness are shown in Figure 24 and show lower intensity than in the forward direction as expected.

The effect of heat treatment on the silver emission is shown in Figure 25. The spectral distribution of a silver foil 720 Å thick was taken at $\theta = 40^{\circ}$ and E = 40 keV. It was then heated at 142° C for 15 min. in an oven and then returned to the irradiation chamber. The peak at 3300 Å had disappeared and the intensity at the longer wavelengths was much greater than before the heat treatment. The heat-treated foil had a dull appearance, and it is believed that the increased emission at the longer wavelength is due to oxide formation on the silver surface. These results are in agreement

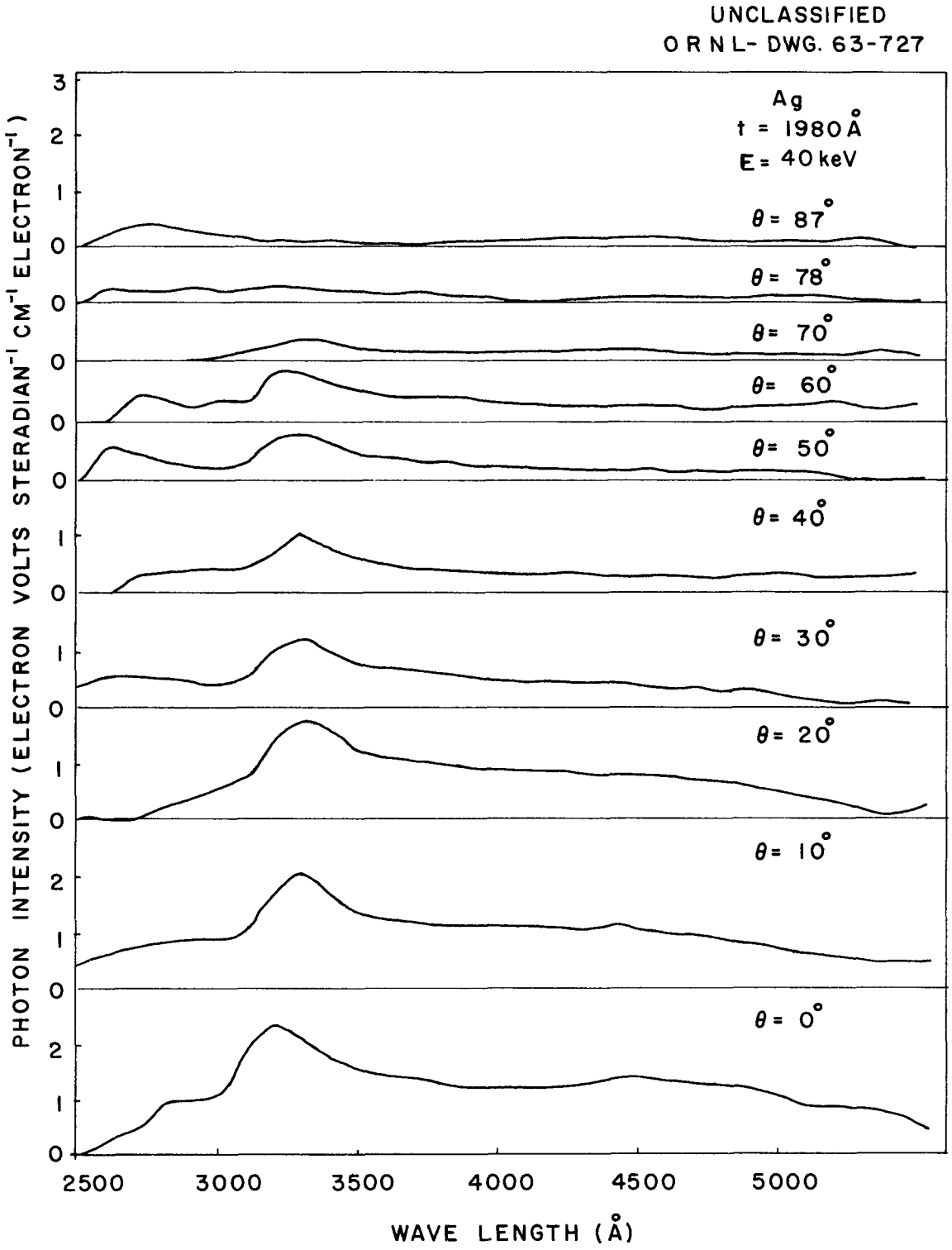

Fig. 22. Experimental Results for the Light Emitted in the Perpendicular Plane on the Front Side of a Ag Foil 1980 Å Thick (E = 40 keV).

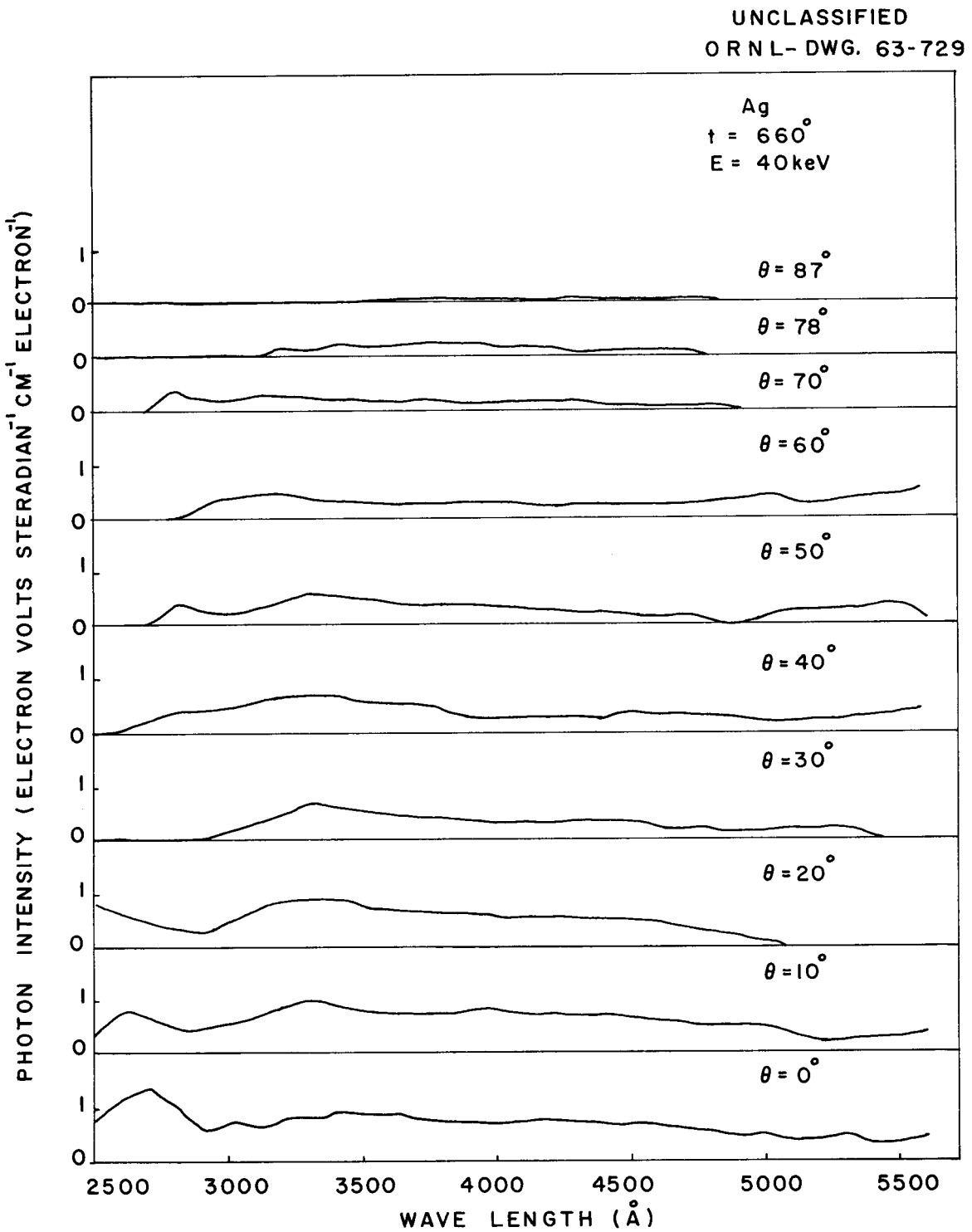

Fig. 23. Experimental Results for the Light Emitted in the Perpendicular Plane on the Front Side of a Ag Foil 660 Å Thick (E = 40 keV).

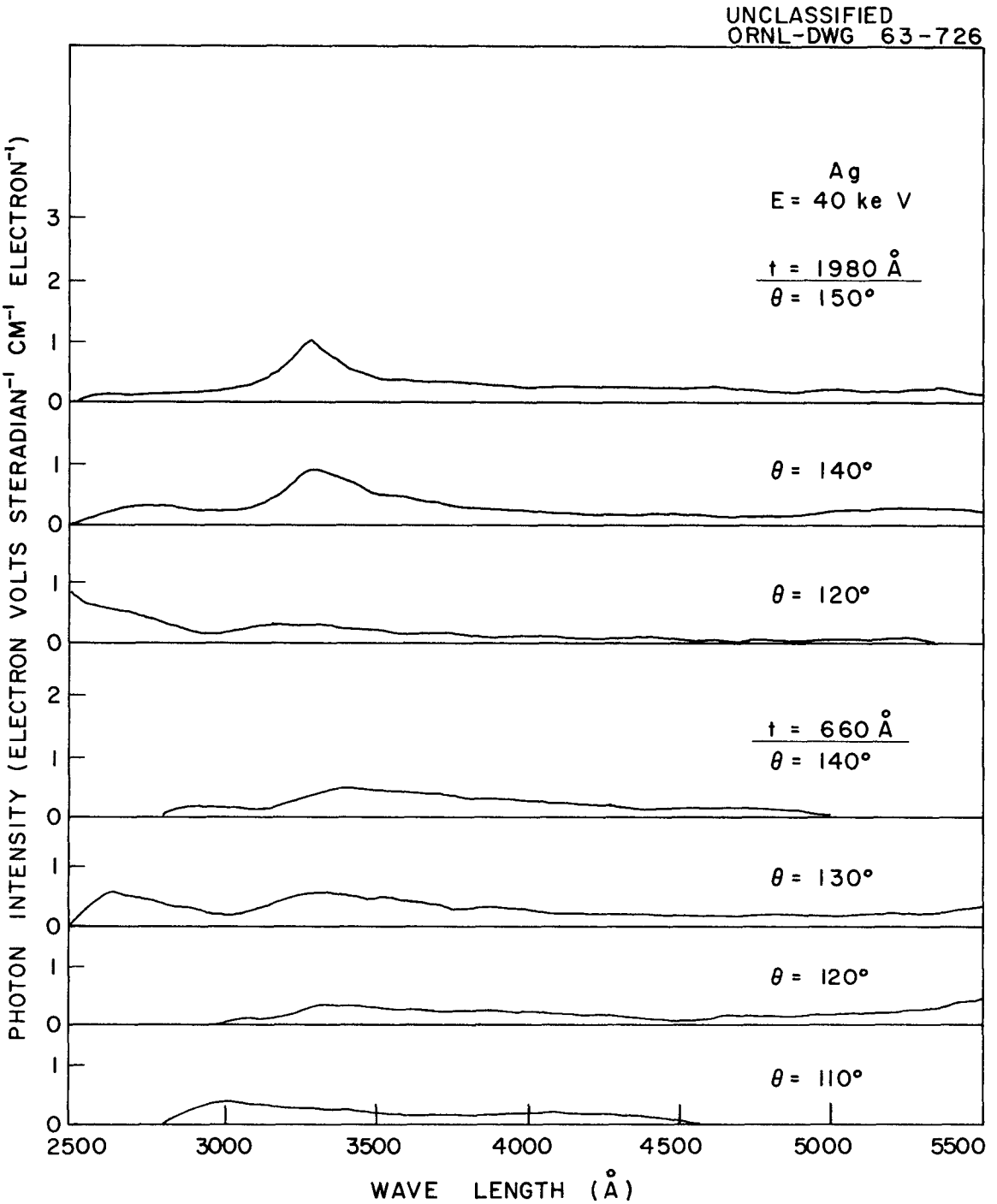

Fig. 24. Experimental Results for the Light Emitted in the Backward Direction and Polarized in the Perpendicular Plane for Ag Foils 660 Å and 1980 Å Thick (E = 40 keV).

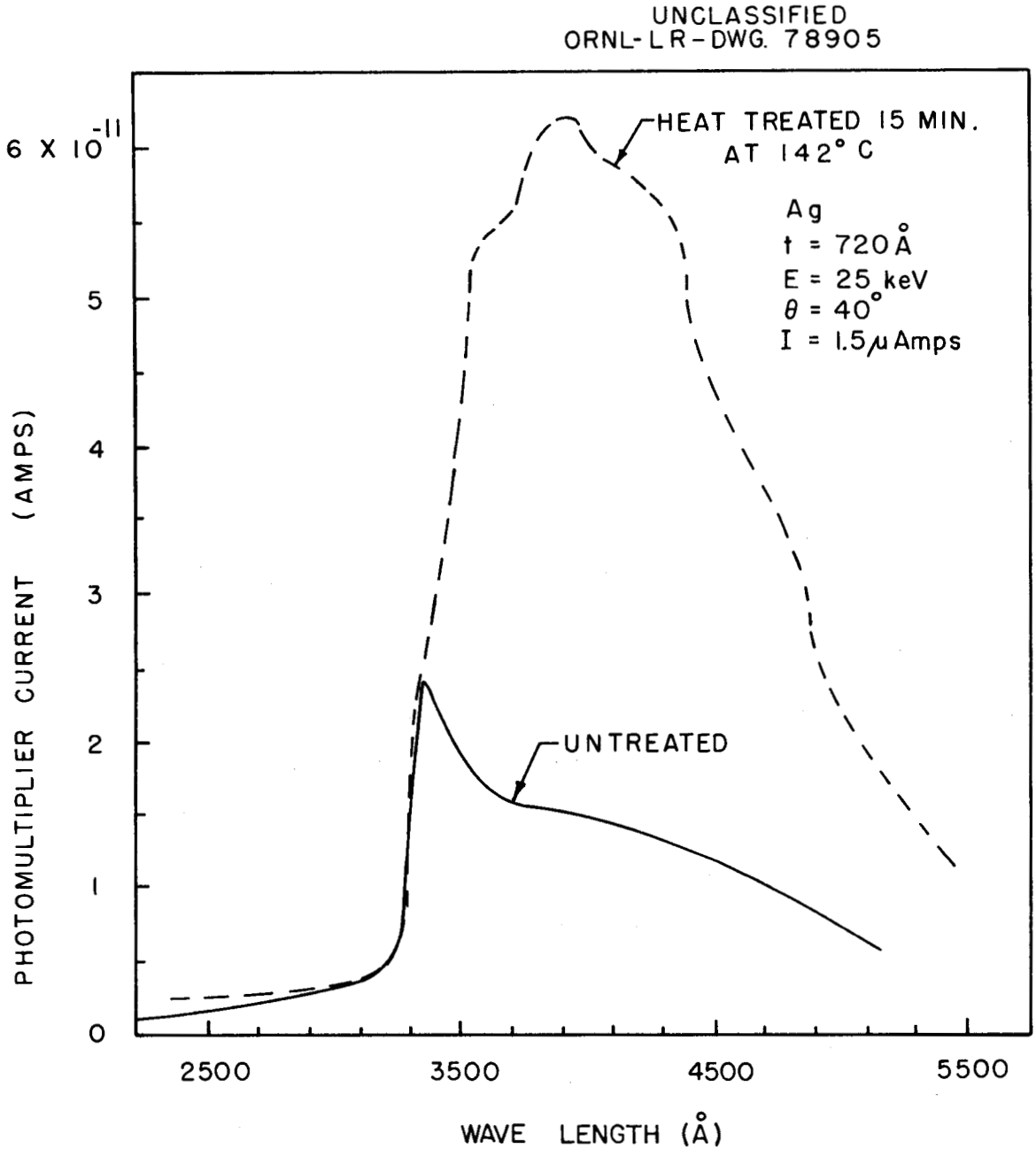

Fig. 25. Effect of Heat Treatment on Ag Emission.

with the studies of Yamaguchi[22] on the optical absorption of heat-treated silver films on fused quartz which showed a large increase in the absorption at these wavelengths by heat-treated films. (Figure 26).

A comparison of the light emitted from silver foils prepared with and without Victawet as a wetting agent on the glass substrate used for vacuum evaporation is shown in Figure 27. The spectral distribution shows no significant difference. Electron micrographs are shown of the silver foil prepared without Victawet in Figure 28 and of the foil prepared with Victawet as the wetting agent in Figure 29. Both foils seem to have a fairly uniform crystaline structure. Even with the crazing (minute cracks) on the foil prepared with Victawet, the spectrum was identical to the spectrum from the foil without the crazing. Subsequent to the preparation of this foil, the vacuum evaporation facilities were cleaned out with an attendant improvement of the vacuum from 1 to 2 x 10^{-5} mm Hg to 5 to 7 x 10^{-6} mm Hg. The crazing has not appeared on any of the recent electron micrographs prepared with Victawet (Figures 7,8, and 9). Since the foils were easier to float off when Victawet was used as the wetting agent, all the foils in this experiment were prepared using Victawet.

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[22] S. Yamaguchi, J. Phys. Soc. Japan 17, No. 7, 1172 (1962).

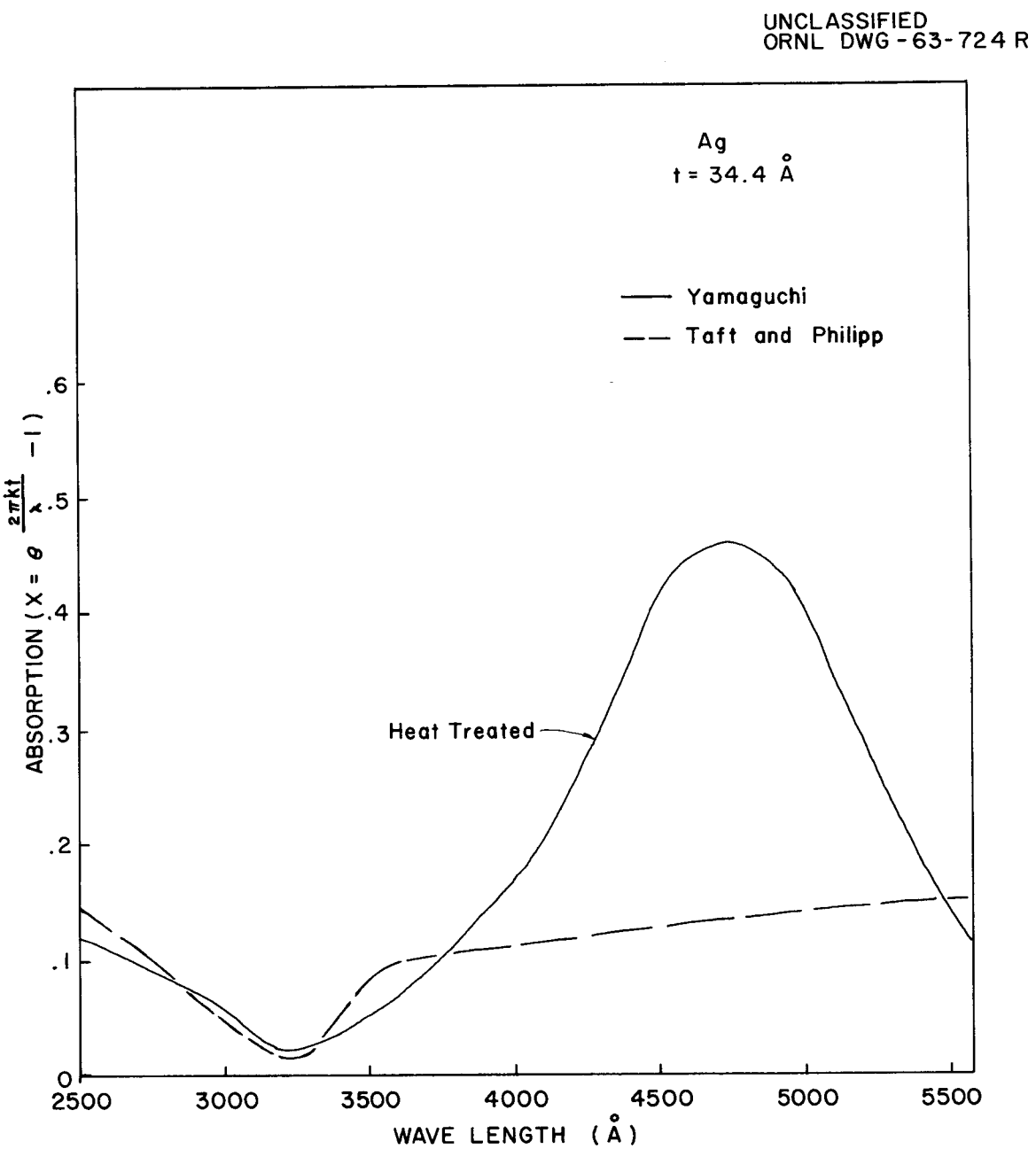

Fig. 26. Comparison of Optical Absorption of Heat-Treated Ag Films on Fused Quartz with a Non-Heat-Treated Film.

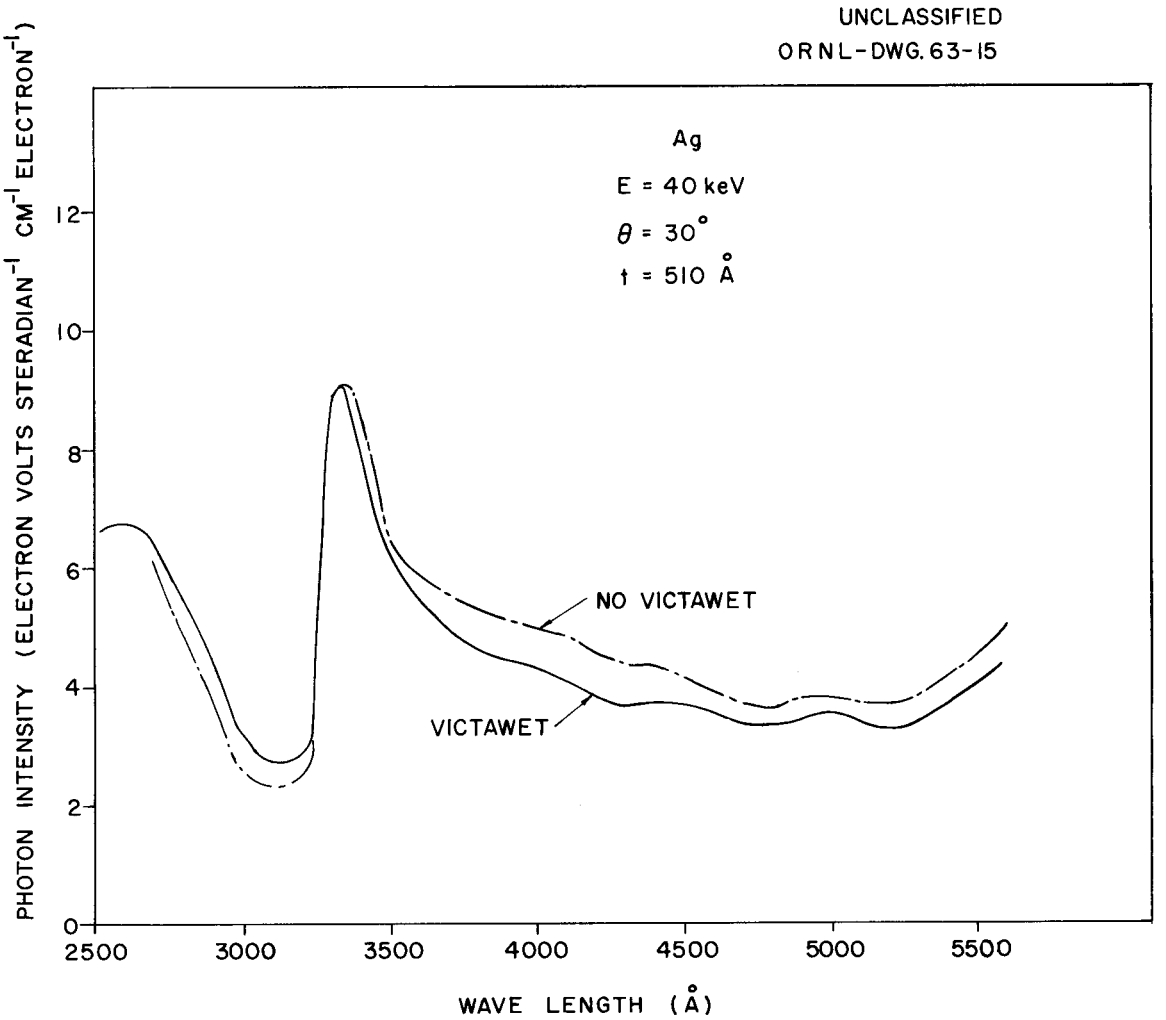

Fig. 27. Spectra from Ag Foils Prepared With and Without Victawet (E = 40 keV, θ = 30°).

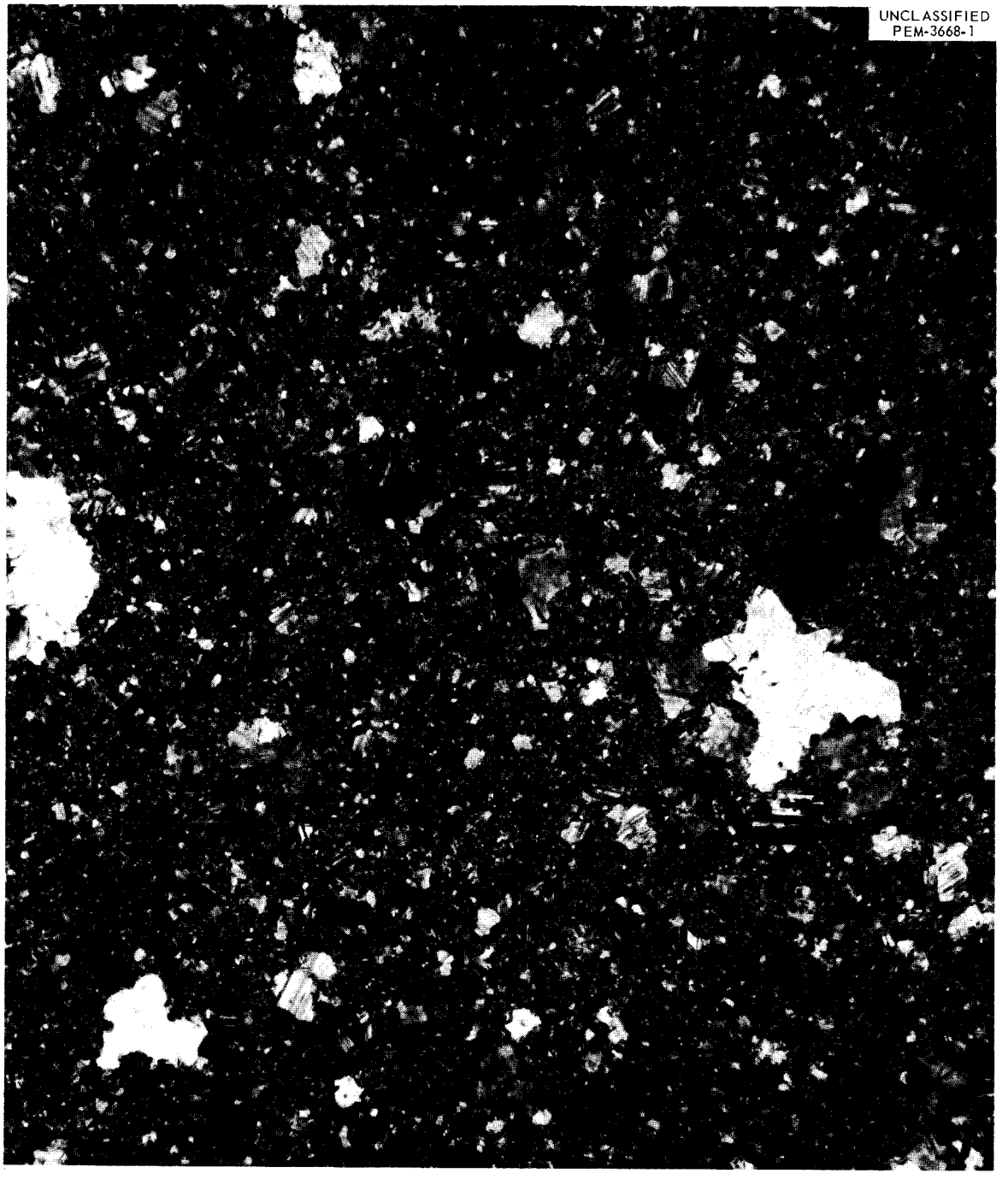

Fig. 28. Electron Micrograph of a Ag Foil 510 Å Thick Prepared Without Victawet. 34,000X. Reduced 15%.

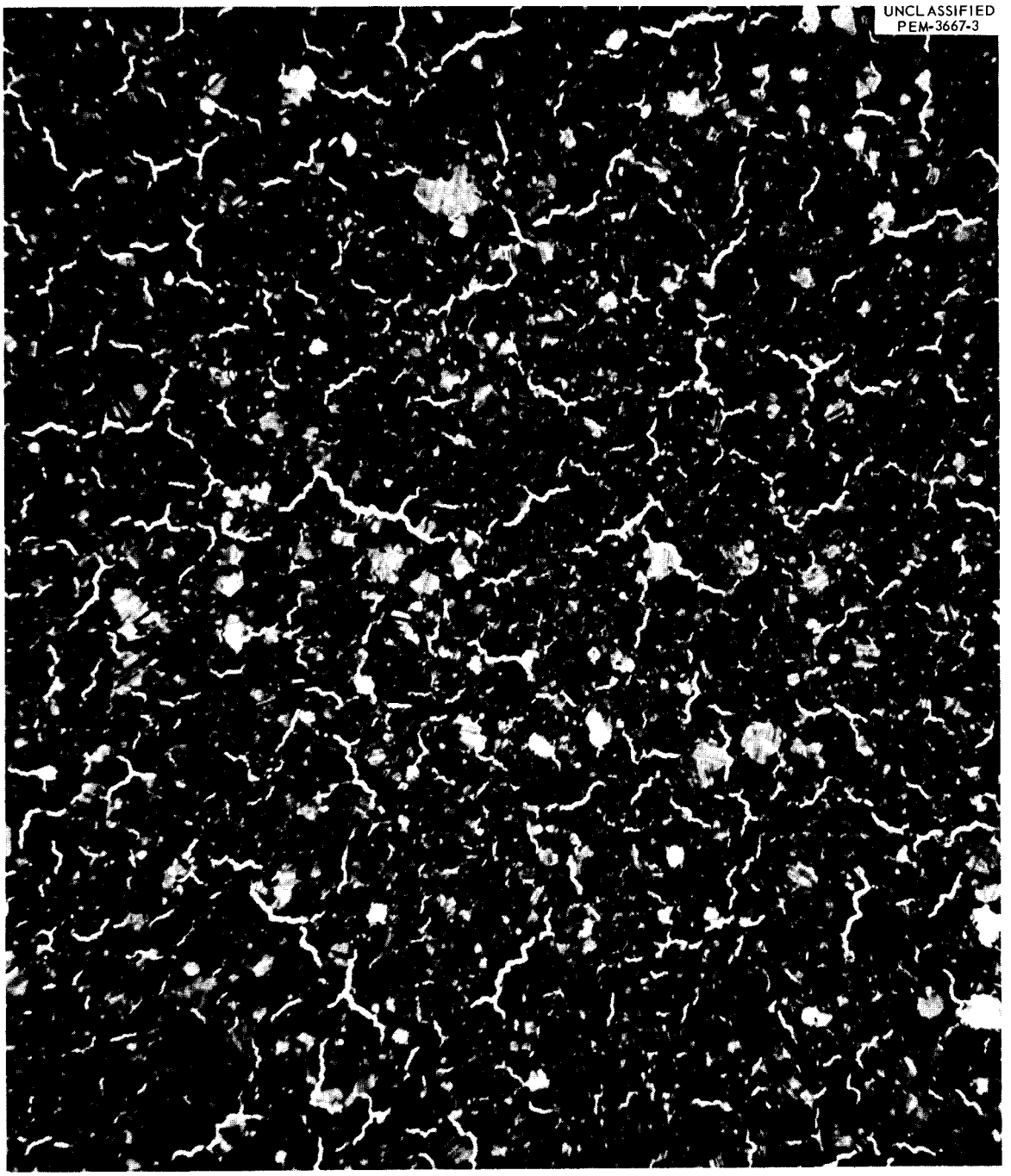

Fig. 29. Electron Micrograph of a Ag Foil 520 Å Thick Prepared with Victawet. 34,000X. Reduced 15%.

VI. CONCLUSIONS

The light emitted by silver foils, 660 Å and 1980 Å in thickness, bombarded by 40-keV electrons was investigated experimentally between λ = 2500 Å and 5500 Å and observed to be polarized primarily in the plane of the electron and photon. The light detected in the plane perpendicular to the above was assumed to originate from an unpolarized component and was subtracted from the intensity observed in the parallel plane. The experimental results obtained for the parallel minus the perpendicular components were compared with the calculations of Ritchie and Eldridge for transition radiation.

The spectral distribution for the silver foil 660 Å in thickness showed a sharp peak near 3300 Å superimposed upon a broad continuum which decreased slowly with increasing wavelength. A rise was also noted on the short wavelength side of the peak. The experimental results of the complete spectral distribution showed good agreement with theory for all angles on both sides of the silver foil 660 Å in thickness except for the small angles ($\theta = 5^{\circ}$ to 40°), where the peak is about 30% lower than predicted by theory. The photon intensity in the foward directions is higher than that at the corresponding angle on the back side of the foil for both the experiment and the theory because of relativistic effects.

The general agreement of the experimental spectra with theory for the silver foil 1980 Å in thickness was good at all angles in the front and back except for a few minor discrepancies. The experimental peak was slightly lower and broader than the theory at

$\theta = 10^{\circ}$, 20°, and 30°. The intensity of the experimental spectrum on the front side was lower than on the back, whereas theory predicted equal intensities. This slight discrepancy in the thicker foil may be due to multiple scattering which has been neglected in the theory.

The general features of the intensity of light emitted as a function of angle from the silver foils 660 Å and 1980 Å in thickness are very similar. The intensity is nearly zero at $\theta = 0^{\circ}$ and 90° with the maximum occurring at an intermediate angle which depends upon the wavelength. For both foils, the maximum intensity of the peak ($\lambda = 3300$ Å) was observed at 30° from the foil normal, whereas the intensity of the continua on both sides of the peak, e.g., at $\lambda = 2700$ Å and 4500 Å, was maximum at 50° from the foil normal. Ferrell's theory for the plasma resonance predicts that the intensity of the silver peak occurs at $\theta = 20^{\circ}$.

The experiment showed a definite increase of the wavelength of the silver peak from 3280 Å at $\theta = 10^{\circ}$ to 3316 Å at $\theta = 50^{\circ}$, whereas theroy predicts a constant value of 3324 Å. The average of all the peak wavelengths determined experimentally was 3300 Å $\pm$ 12 Å.

The maximum intensity of the light detected experimentally in the perpendicular plane was in the direction of the electron beam and was found to be greater for the thicker foil as is predicted theoretically by Gluckstern and Hull for bremsstrahlung. Detailed conclusions concerning bremsstrahlung can not be made since the intensity observed in the perpendicular plane was only two to three times the noise level.

When a silver foil was heated to 142° C for 15 min. in an oven, the peak at 3300 Å was washed out and the intensity at the long wavelengths was much greater than before the heat treatment. The heat-treated foil had a dull appearance, and it is believed that the increased emission at the longer wavelength is due to oxide formation on the silver surface. These results are in general agreement with the studies of Yamaguchi who found increased absorption at these same wavelengths for heat-treated silver films on fused quartz.

The spectral distribution from silver foils prepared with and without Victawet as a wetting agent on the glass substrate used for vacuum evaporation showed no significant difference. The electron micrographs of the foils also showed the same crystaline structure.

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