This dispersion relation has been given by Stern.[6] For nonrelativistic incident particle energies, the average decrease of the surface plasmon frequency below the value $\omega_p/2$ is small. Stern and Ferrell[6] show that the fractional decrease is $\sim(v_i/2c)^2$ in this region. At relativistic energies, however, the effect should be noticeable.

For the case $a\neq\infty$, the dispersion relation for surface-plasmon creation is given by the solution of

$$(\nu\epsilon+\nu')=(\nu\epsilon-\nu')e^{-\nu' a}.$$

The nonrelativistic form of this equation has been considered previously.[3,6]

Radiative surface excitation occur when either ν or ν' in Eq. (A1) are imaginary. This happens whenever $\omega>Kc$ for plasma, and corresponds to charged particle transitions accompanied by photon emission into the far zone. One may derive the expression for the photon energy-angle distribution given in Sec. II by considering the general expression for losses to the finite foil.

Energy loss by photon emission is quite small compared with loss in the creation of surface plasmons at nonrelativistic energies. However, in the relativistic range, they are of comparable magnitude, and it is conceivable that a characteristic loss experiment could be performed which would show the existence of both of these excitation modes.

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Optical Emission from Irradiated Foils. II

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The spectra from silver foils irradiated by electron beams from an accelerator consist of weak maxima at 3500 Å and broad continua at longer wavelengths. The intensity of the maxima do not exhibit as strong a dependence on foil thickness as predicted by Ferrell and reported by Steinmann. The intensities of both maxima and the continua were found to be directly proportional to beam energy over the range from 40 kev to 115 kev in agreement with the experiments of Goldsmith and Jelley, and of Boersch *et al.*, and the theory of Ginsburg and Frank for transition radiation. The intensity of similar continua found for Al, Au, and Mg also increased linearly with beam energy. Light from Ag and Al foils was found to be polarized in the plane containing the foil normal and the photon direction as predicted theoretically. The intensity of the light from silver was found to be small near the foil normal and at angles approaching 90°, and to achieve a maximum at an intermediate angle in agreement with the theories of Ferrell, and of Ritchie and Eldridge. The absolute light yield from foils of Al and Ag revealed substantial agreement with the predictions of Ritchie and Eldridge from the transition theory of Frank and Ginsburg.

I. INTRODUCTION

THE possibility that studies of the emission of light from thin metal films may prove or disprove the existence of a conduction electron plasma in certain metals has recently led several groups of experimenters to examine the emission spectra of foils irradiated by electron beams. While the electron plasma is thought to play its most significant role in the absorption of energy from high-energy electrons in foils of Al, Mg, Be, and the alkali metals, the rapid oxidation of these metals even as films evaporated and maintained in vacua of the order of 10^{-6} mm Hg has increased the experimental difficulties already severe because the most interesting spectral region lies in the vacuum ultraviolet. Thus, at the suggestion of R. A. Ferrell, considerable work has been initiated and reported recently on the emission of light from Ag where the spectrum has been known for some time to achieve a maximum at about 3400 Å, and oxidation problems are much reduced. Using 25-kev electrons from an accelerator and a quartz spectrograph which looked at the foil on the side of beam incidence, Steinmann[1] found a maximum in the emission spectrum at 3300 Å for a foil 450 Å thick. A thicker foil (850 Å) showed no such maximum; but after a further increase to 1500 Å thickness, the maximum was again apparent. Such a strong dependence on foil thickness was one of the predictions of the Ferrell[2] theory which is based on a simple model of plasma decay involving emission of a single spectral component at a wavelength corresponding to the plasma frequency. Accordingly, Steinmann interpreted his observations as being strong evidence for the existence of an electron plasma in Ag having an energy of 3.75 ev. Additional correlation with the Ferrell theory was obtained by Brown, Wessel, and Trounson[3] who showed that the intensity at the peak was low near the normal and tangent to a 500-Å foil but became quite

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

[1] W. Steinmann, Phys. Rev. Letters **5**, 470 (1960); Z. Physik **163**, 92 (1961).
[2] R. A. Ferrell, Phys. Rev. **111**, 1214 (1958).
[3] R. W. Brown, P. Wessel, and E. P. Trounson, Phys. Rev. Letters **5**, 472 (1960).

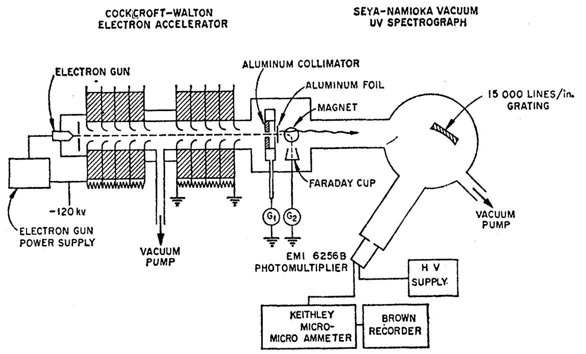

FIG. 1. Schematic diagram of accelerator, irradiation chamber, and monochromator.

high at about 40° to the normal. Wessel[4] showed that the light at the peak was polarized predominately in the plane containing the foil normal and the direction of observation as predicted also by Ferrell. It should be noted that Gluckstern, Hull, and Breit[5] have shown that bremsstrahlung is polarized primarily in the direction perpendicular to the above.

Recently, still another paper has appeared by Boersch, Radeloff, and Sauerbrey[6] in which the spectra from thick irradiated slabs of W, Ta, Mo, Ti, Pt, Al, Cu, Ag, and Cs have been obtained. Comparison is made with the theory of transition radiation by Ginsburg and Frank.[7] This application had previously been studied by Ritchie and Eldridge.[8] Boersch *et al.* report, in agreement with the transition radiation theory, that the intensity is proportional to beam energy from 6 to 30 kev, and that the radiation is almost completely polarized in the plane containing the foil normal and the direction of observation. Agreement is found also for the spectral

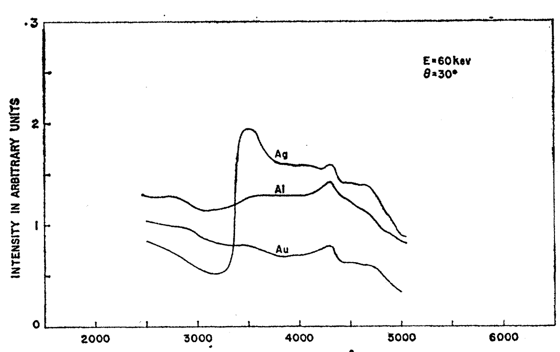

FIG. 2. Spectral distribution from Ag, Al, and Au ($\theta=30°$; $E=60$ kev).

[4] P. Wessel, Bull. Am. Phys. Soc. **6**, 310 (1961).
[5] R. L. Gluckstern, M. H. Hull, Jr., and G. Breit, Phys. Rev. **90**, 1026 (1953); R. L. Gluckstern and M. H. Hull, Jr., *ibid.* **90**, 1030 (1953).
[6] H. Boersch, C. Radeloff, and G. Sauerbrey, Phys. Rev. Letters **7**, 52 (1961).
[7] W. Ginsburg and I. Frank, J. Exptl. Theoret. Phys. (U.S.S.R.) **16**, 15 (1946).
[8] R. H. Ritchie and H. B. Eldridge, Bull. Am. Phys. Soc. **4**, 384 (1959).

and angular distributions. These results seem rather surprising when one considers that thick targets were employed which might be expected to contribute a large bremsstrahlung component to the observed radiation.

Observations of polarization, spectra, angular distribution, and dependence on beam energy have been reported by the present authors[9] for both Ag and Al and form the basis for this paper. Good agreement was found with the transition radiation theory as applied by Ritchie and Eldridge as set forth in Part I.

II. EXPERIMENT

The experimental arrangement is shown in Fig. 1. Thin foils of Al, Ag, Mg, and Au were irradiated with 40- to 115-kev electrons from an electron accelerator. The light emitted by these foils was analyzed with a Jarrell-Ash 50 cm vacuum UV monochromator. The de-

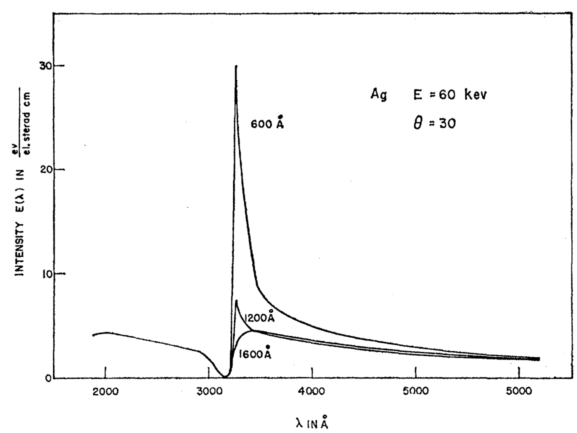

FIG. 3. Theoretical spectral distribution from Ag ($t=600$, 1200, 1600 Å; $\theta=30°$; $E=60$ kev).

tector was an EMI 6256 B quartz window photomultiplier whose output was amplified with a Keithley D.C. micromicroammeter and recorded on a Brown recorder.

Since the foils were located at the entrance slit position of the spectrometer, the resolution was limited by the width of the electron beam. The beam was collimated to a 2-mm diam circle by an aluminum plate 7 mm in front of the foil. The resolution was, therefore, 2 mm×24 Å/mm or 48 Å for a 15 000 line-per-in. grating. Provisions were made for metals to be evaporated directly onto thin Formvar backings in the irradiation chamber so that foils could be investigated without exposure to the atmosphere. Several spectral distributions were started within a minute after preparation of the foils. Mg and Al foils were made in this manner. Most of the Ag foils, however, were made in an external vacuum system. These were unbacked foils made by evaporating Ag onto microscope slides which had previously been coated with a wetting agent. The thin foil

[9] E. T. Arakawa, A. L. Frank, R. D. Birkhoff, and R. H. Ritchie, Bull. Am. Phys. Soc. **6**, 266 (1961).

on the slide was then floated off on water and mounted on an aluminum ring which was placed in the target position. No difference in spectra was observed between unbacked foils and foils backed with Formvar. Several runs were also made on thin Formvar foils. A feeble light was observed several orders of magnitude less intense than the light emitted by the metallic foils.

An attempt was made to survey the spectra of irradiated Al and Mg foils between 500 Å and 2500 Å with a sodium salicylate coated photomultiplier. The high background in this region, due to bremsstrahlung or scattered electrons, obscured any signal which may have been present. Therefore all data presented in this report were taken without sodium salicylate. This consequently limited the data to the spectral region between 1600 and 6000 Å. However, the results are presented only between 2500 and 5500 Å, due to the uncertainty in determining relative response of the spectrometer and detector system outside of this region.

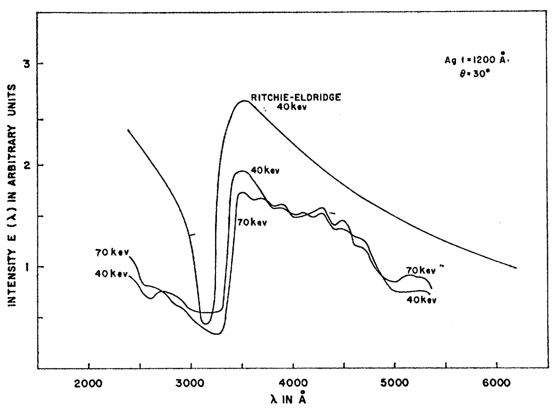

FIG. 4. Spectral distribution from Ag and the calculations of Ritchie-Eldridge (t=1200 Å; θ=30°; E=40, 70 kev).

The relative response was determined using a tungsten ribbon filament as a blackbody source. The intensity of the light from a blackbody decreases rapidly in the short-wavelength region. It was found that the intensity was too weak below 2500 Å to permit an accurate determination in this region. The efficiency of the photocathode was very low in the long-wavelength region between 5500 and 6000 Å. Therefore any correction made into an experimental spectrum with such a low response was subject to large errors. The spectral distribution used in the determination was corrected for the emissivity of tungsten as reported DeVos.[10]

The ordinates used in the presentation of the spectral distribution curves (Figs. 2, 4, 6, 8–11) are in arbitrary units. These units are actually the photomultiplier current divided by the relative response of the system and are therefore consistent from one curve to the next.

Polarization of the radiation emitted was determined with a Glan prism mounted in the entrance arm of the

[10] J. C. DeVos, Physica **20**, 690 (1954).

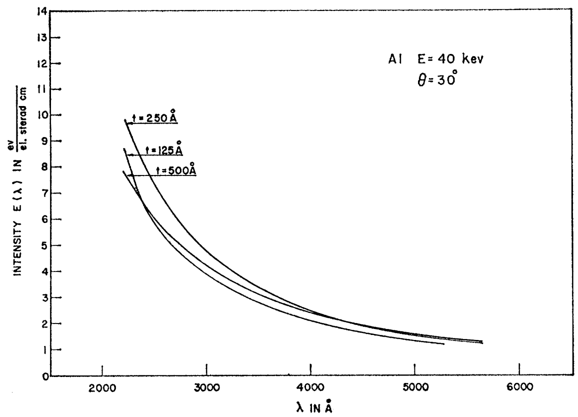

FIG. 5. Theoretical spectral distribution from Al (t=125, 250, 500 Å; θ=30°; E=40 kev).

spectrometer. This was connected to a rotatable shaft through the walls of the vacuum chamber by an O-ring seal. All data taken with the polarizer were corrected for the elliptical polarization introduced into the system by the reflecting surface of the grating. This correction factor was determined by sending unpolarized monochromatic light from a Beckman DU spectrometer through the system and noting the output as a function of polarizer orientation.

III. RESULTS

The spectral distribution of radiation between 2500 to 5500 Å emitted by Au, Ag, and Al foils is shown in Fig. 2. It is seen that the photon intensities for Au and Al foils tend to decrease with increasing wavelength whereas Ag shows a pronounced minimum at 3200 Å and a very sharp rise which peaks at 3500 Å. A theoretical spectrum calculated by Ritchie and Eldridge using the optical data of Taft and Phillip[11] shows a very sharp peak at 3265 Å for foils of Ag having thickness less than ~1200 Å (Fig. 3). The region between 3200 and

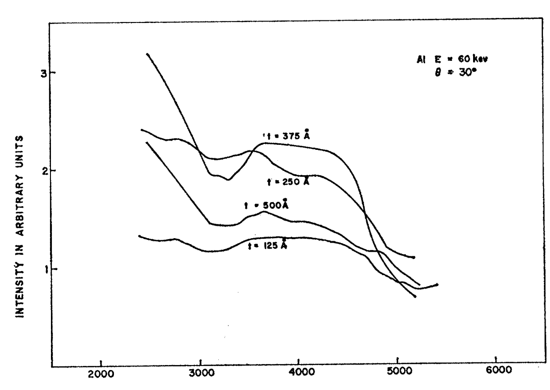

FIG. 6. Spectral distribution from Al (t=125, 250, 375, 500 Å; E=60 kev).

[11] E. A. Taft and H. R. Phillip, Phys. Rev. **121**, 1100 (1961).

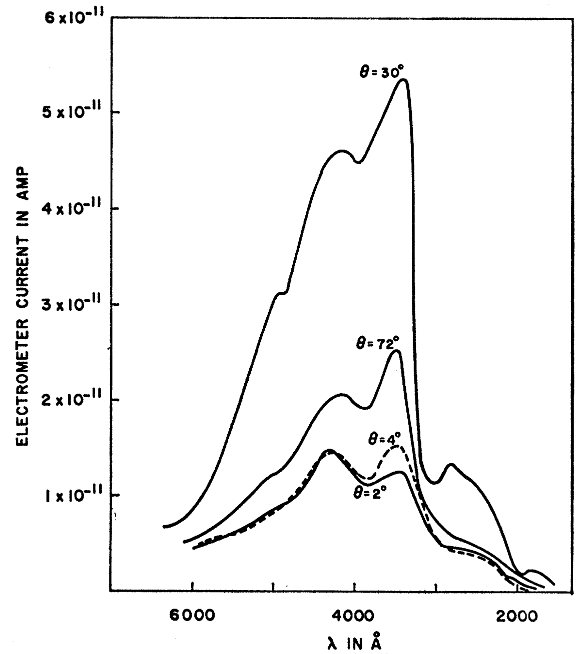

FIG. 7. Uncorrected spectral distributions from Ag ($\theta = 2°, 4°, 30°, 72°$).

3600 Å was therefore scanned very carefully. No sharp peak was found with the foils investigated whose thicknesses ranged from 800 to 2400 Å. However, the experimental spectra showed excellent agreement with the theoretical predictions for thick foils (>1600 Å) shown in Fig. 4. The sharp peak at 3265 Å has presumably been damped out for thick folis. Experiments are being continued to search for this sharp peak with thin foils of Ag.

The spectral distribution of Al predicted theoretically by Ritchie on the basis of optical data by Haas and Waylonis[12] and Berning, Haas, and Madden[13] shows a monotonic decrease in intensity with increasing wavelength (Fig. 5). Experimental data exhibit this general trend but show in addition a broad band in the visible, peaked at around 4400 Å (Fig. 6). Foils of Au and Mg were also found to emit radiation in this same wavelength region.

The radiation emitted by a silver foil at 2°, 4°, 30°, and 72° from the foil normal is shown in Fig. 7. These spectral distribution curves have not been corrected for the response of the spectrometer system in order to illustrate the type of data obtained. The intensities at the peak wavelength ($\lambda = 3500$ Å) have been compared with the theoretical angular distribution in Fig. 8. Good agreement is found between experiment and the theoretical predictions of both Ferrell and Ritchie-Eldridge. The present data show a stronger angular dependence than the results of Brown, Wessel, and Trounson.

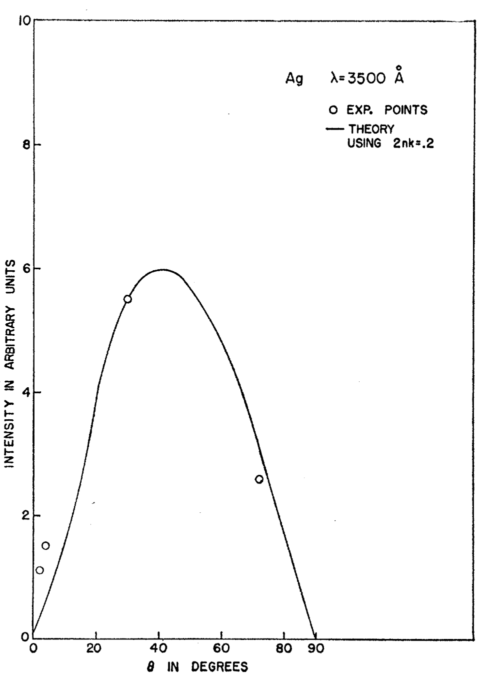

FIG. 8. Theory and experimental points on the angular distribution from Ag ($\lambda = 3600$ Å; $t = 800$ Å).

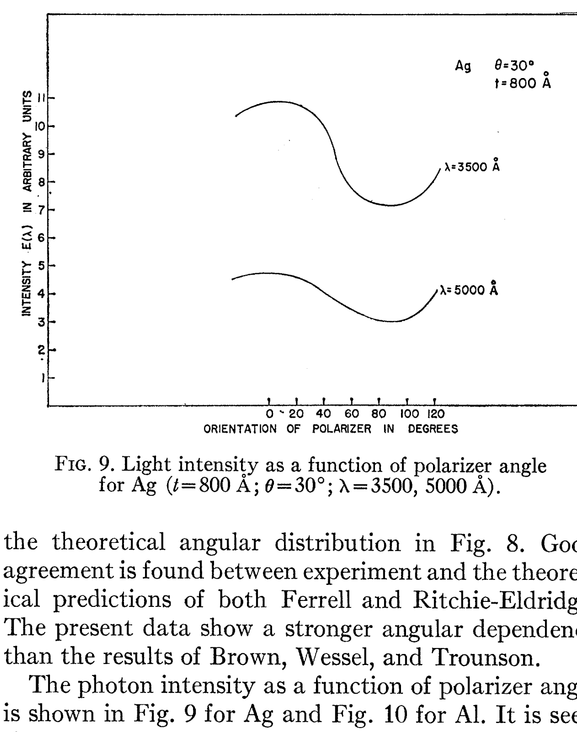

FIG. 9. Light intensity as a function of polarizer angle for Ag ($t = 800$ Å; $\theta = 30°$; $\lambda = 3500$, 5000 Å).

The photon intensity as a function of polarizer angle is shown in Fig. 9 for Ag and Fig. 10 for Al. It is seen that maximum intensity is observed when the electric vector is in the plane of incidence to the grating in agreement with transition radiation which arises from vibrations normal to the plane of the foil. The plane of incidence is defined by the normal to the grating and the photon direction. It is also observed that the minimum is much deeper for Al than for Ag. This is believed to be due to the fact that bremsstrahlung, which is partially polarized perpendicular to the plane of incidence, is more intense in Ag than in Al.

[12] G. Haas and J. E. Waylonis, J. Opt. Soc. Am. **51**, 719 (1961).
[13] P. H. Berning, G. Haas, and R. P. Madden, J. Opt. Soc. Am. **50**, 586 (1960).

Ferrell[2] predicted that the photon yield for plasma radiation should vary in an oscillating manner with incident electron energy. The photon intensity as a function of electron energies is shown in Fig. 11 for Ag and in Fig. 12 for Al. It is seen that in both cases photon intensity is nearly proportional to incident electron energy. The data taken on Al with a polarizer is linear with energy and goes through the origin of the coordinate system in agreement with theory, whereas data taken without a polarizer show a smaller slope. It is believed that bremmsstrahlung contributes to the intensity at lower energies since bremsstrahlung intensity varies inversely with energy. Bremsstrahlung is polarized primarily perpendicular to transition radiation and has thus been discriminated against in the data taken with the polarizer. The fact that radiation observed at various wavelengths for both Ag and Al shows this linear dependence with electron energy leads to the conclusion that the radiation observed is not due to plasma oscillation but to transition radiation.

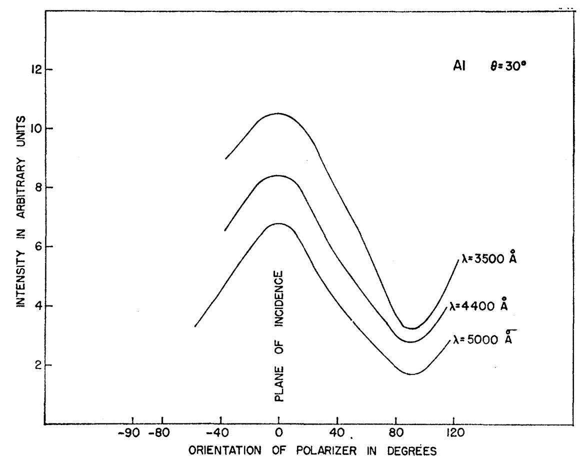

FIG. 10. Light intensity as a function of polarizer angle for Al ($\theta=30°$; $\lambda=3500$, 4400, 5000 Å).

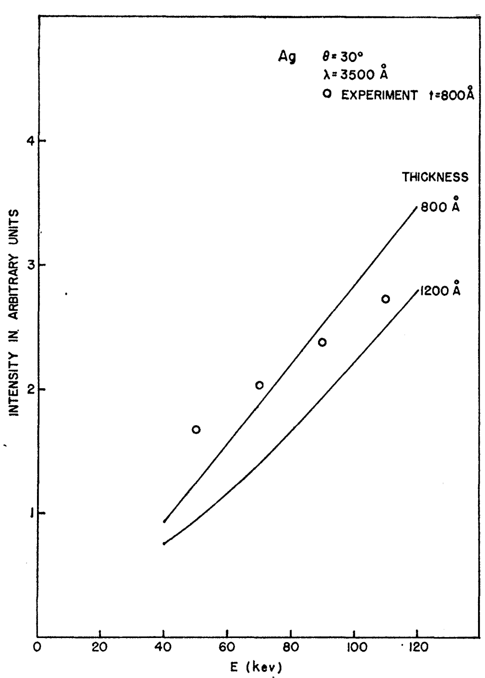

FIG. 11. Light intensity from Ag as a function of beam energy and the Ritchie-Eldridge theory ($t=800$, 1200 Å; $\theta=30°$; $\lambda=3500$ Å).

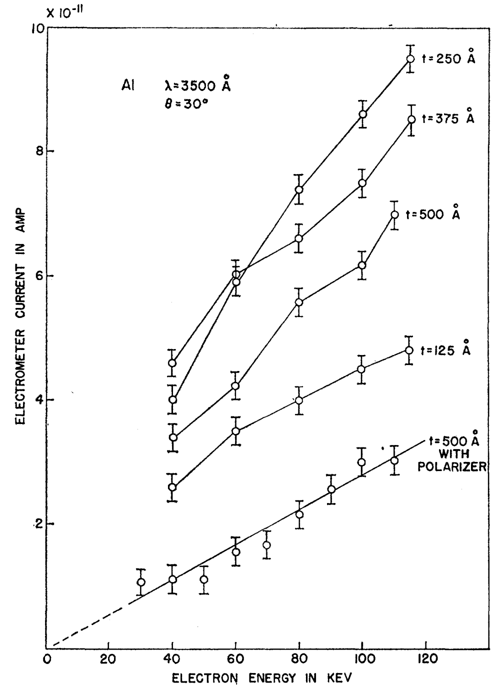

FIG. 12. Photomultiplier current as a function of beam energy for Al ($t=125$, 250, 375, 500 Å; $\lambda=3500$ Å).

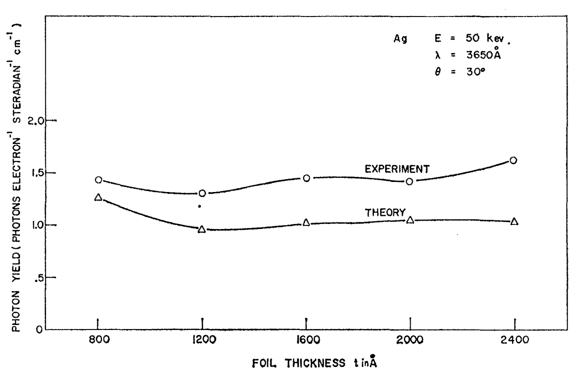

FIG. 13. Photon yield as a function of foil thickness for Ag ($E=50$ kev; $\lambda=3650$ Å; $\theta=30°$) and the transition radiation theory.

This conclusion is further strengthened by the data on intensity vs foil thickness as shown in Figs. 13 and 14. It is seen that for these thick foils the intensity does not vary markedly with foil thickness but is nearly independent of this parameter as expected from theory.

The theoretical yield as calculated by Ritchie and Eldridge on the basis of the Ginsburg and Frank theory

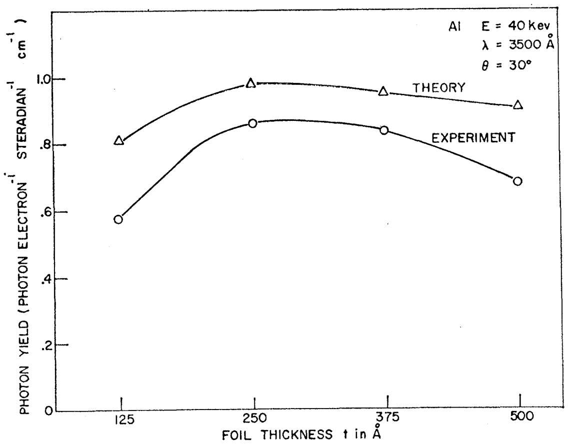

FIG. 14. Photon yield as a function of foil thickness for Al ($E=40$ kev; $\lambda=3500$ Å; $\theta=30°$) and the transition radiation theory.

was compared with an experimentally determined yield. The absolute yield was determined using photocathode efficiency and photomultiplier gain as furnished by the manufacturer, a calculated solid angle for the grating, and using a 30% grating efficiency. The agreement between theory and experiment for both Ag and Al is seen to be excellent. However, this agreement may be somewhat fortuitous due to the uncertainties involved.

Note added in proof. Since this paper was written, the spectrometer and photomultiplier response have been evaluated by comparison with a calibrated tungsten ribbon light source obtained from the National Bureau of Standards. It now appears that the agreement between theory and experiment in Figs. 13 and 14 is not as good as shown, as the ordinates on "experiment" curves should be multiplied by 1.7.

IV. CONCLUSIONS

The spectrum from silver consists of a weak maximum at 3500 Å and a broad continuum at longer wavelengths. The intensity of the maximum does not exhibit as strong a dependence on foil thickness as predicted by Ferrell and reported by Steinmann. The intensities of both the maximum and the continuum were found to be directly proportional to beam energy in agreement with the experiments of Goldsmith and Jelley[14] and Boersch *et al.* and the theoretical predictions of Ginsburg and Frank for transition radiation. Similar continua were found for Al, Au, and Mg the intensity of which increased linearly with beam energy also. Polarization measurements were made on Ag and Al foils and light was found to be polarized in the plane containing the foil normal and the photon direction as predicted theoretically. The angular distribution for the light from silver was found to be small near the foil normal and at angles approaching 90°, and to achieve a maximum at an intermediate angle in agreement with the theories of Ferrell and Ritchie. It should be noted here that the maximum intensity was predicted by Ginsburg and Frank to appear at 90° for a perfect conductor, and it was for this reason that Jelley chose to make his measurements near the tangent. A calculation based on the present data of the absolute light yield from foils of Al and Ag revealed substantial agreement with the predictions of Ritchie and Eldridge on the transition radiation from foils.

On the basis of the present results it may be concluded that the simple plasma decay model introduced by Ferrell does not adequately describe all aspects of the emission of light from irradiated metals. Present results agree better with the more complete description of a metal in terms of its dielectric properties as given by the transition radiation theory.

[14] P. Goldsmith, and J. V. Jelley, Phil. Mag. 4, 836 (1959).