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EXPERIMENTAL STUDIES OF TRANSITION RADIATION AND OPTICAL BREMSSTRAHLUNG*

E. T. Arakawa
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

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This report summarizes research on the optical emission from thin films and bulk metals bombarded by 25-120 keV electrons carried out at Oak Ridge National Laboratory. Details concerning the experimental apparatus and theoretical calculations may be found in the references listed in this paper. Measurements have been carried out on the dependence of the emitted spectra on angle of observation, polarization, sample thickness, surface roughness, surface contamination, and incident electron energy.

The photon intensities from an electron entering a metal surface from vacuum is given by Eq. (1) in Fig. 1, where θ is the angle of observation from the foil normal, β is the electron velocity relative to light in vacuum, and ε is the frequency dependent, complex dielectric constant of the metal[1]. Note that according to Eq. (1), transition radiation (TR) is expected at all frequencies. However, when the dielectric constant takes on the values $\varepsilon_2 \approx 0$, and $\varepsilon_1 = 0$, a resonance occurs in both the transition radiation and the electron energy loss. In the case of a nearly-free-electron metal, as shown by the equations in Fig. 1, the above condition implies that the phase velocity v of the electromagnetic wave in the medium is infinite. This means that the whole medium responds

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to the electromagnetic wave completely in phase (i.e., a collective resonance). Therefore, the collective resonance, or plasma resonance radiation at $\omega = \omega_p$, is a special case of the more general transition radiation.

The experimental apparatus used in these studies[2] is shown in Fig. 2. The angle of observation θ could be varied continuously from 0° to 153°, and the target chamber contained evaporation terminals such that fresh Al and other metals could be vacuum-evaporated in-situ. The target chamber was also surrounded by a liquid nitrogen shroud to provide a cleaner environment than the diffusion-pumped vacuum system operating at $\sim 10^{-6}$ Torr would allow. For the vacuum UV spectral region the glan prism polarizer was removed, and the photomultiplier tube (EMI 9256S) was coated with sodium salicylate.

The optical emission from a 330 Å thick, self-supported gold foil bombarded by 40-100 keV electrons[3] is shown in Fig. 3. The calculated transition radiation spectra agree well both in shape and in absolute intensity with the experimental ($\parallel - \perp$) spectra for all electron energies. Transition radiation is expected only in the $\parallel$ plane (defined by the electron beam direction and angle of observation) since transition radiation is like dipole radiation. The observed $\perp$ component is due to optical bremsstrahlung, and the expected inverse electron energy dependence is seen in the data. The experimental $\perp$ intensities are compared in Fig. 4 with calculations of bremsstrahlung by Gluckstern, Hull, and Breit[4] for isolated atoms. The energy dependence agrees well, although the absolute intensities cannot be compared due to the difference expected between condensed matter and isolated atoms.

The photon emission from a Ag film 713 Å in thickness bombarded by 25 keV electrons[2] is show in Fig. 5. The spectra for Ag shows not only the transition radiation continuum, but also a resonance feature (plasmon emission) at 3300 Å. Again the agreement between transition radiation theory and the experimental ($\parallel - \perp$) spectra agree very well.

Figures 6 and 7 show how the Ag spectrum changes as the angle of observation is varied from 5° to 87°, and the comparison between the forward (50°) and backward (130°) emission[2] is shown in Fig. 8. The experimental spectra again agree well with the theoretical spectra. The difference in intensity at the peak wavelength between theory and experiment is due to the use of the optical constants of bulk Ag[5] instead of vacuum evaporated Ag.[6]

Figure 9 shows that the agreement between theory and experiment becomes very good when the proper optical constants (ORNL) are used in the transition radiation calculations.[7]

The photon intensity at the peak wavelength (3300 Å) is given as a function of film thickness for electron energies of 25, 40, and 60 keV[7] in Fig. 10. The oscillatory dependence of the yield arises from the constructive and destructive interference of the photons created when the high-energy electron first enters and then exits the thin foil.

The vacuum ultraviolet photon emission at various observation angles from an Al foil 320 Å in thickness bombarded by 80 keV electrons (Fig. 11) is compared with the transition radiation calculations (Fig. 12) using the optical constants of Al reported by Hunter.[9]

The emission from a 220 Å thick Mg foil bombarded by nearly normal incidence 80 keV electrons[10] for various observation angles θ is shown in Fig. 13. From these data, we may determine, using the equations given in Fig. 14, the plasmon energy E_p from the y intercept of the graph of peak energy versus $\tan^2 \theta$, and the film thickness from the slope. From a graph of the resonance width at half maximum $\Delta\lambda$ versus $\sin \theta \tan \theta$, the intrinsic lifetime can be obtained from the y intercept, and, again, the film thickness from the slope.

Similar data as illustrated here have been obtained for Be,[11] Cd, Zn, In, Th,[12] and Ni.[13] The effects of surface contaminations and surface structure have also been studied.

References

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13. E. T. Arakawa, unpublished.

TRANSITION RADIATION - THICK FOIL

$$I(\mu,\omega) = \frac{\mu^2(1-\mu^2)|\epsilon-1|^2}{|\mu\epsilon + (\epsilon-1+\mu^2)^{\frac{1}{2}}|^2} \qquad (1)$$

where $\mu = \cos\theta$, $\beta = \frac{v}{c} < 1$

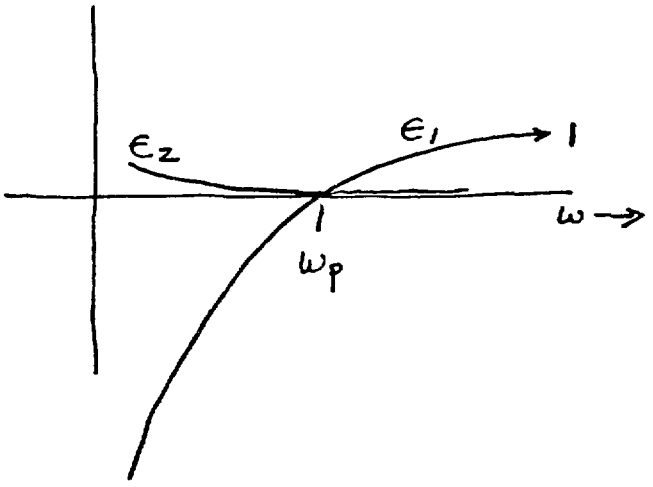
and $\epsilon = \epsilon_1 + i\epsilon_2$

Electron Energy Loss $\propto Im\frac{1}{\epsilon} = \frac{\epsilon_2}{\epsilon_1+\epsilon_2}$

NFE

$\epsilon_2 \approx 0$

$\epsilon_1 = 1 - \frac{\omega_p^2}{\omega^2}$



At $\omega = \omega_p$

$\epsilon_1 = n^2 - k^2 = 0$

$\epsilon_2 = 2nk = 0$

$\therefore n, k = 0$

$n = \frac{c}{v} = 0 \rightarrow \boxed{v = \infty}$

$\therefore$ Collective

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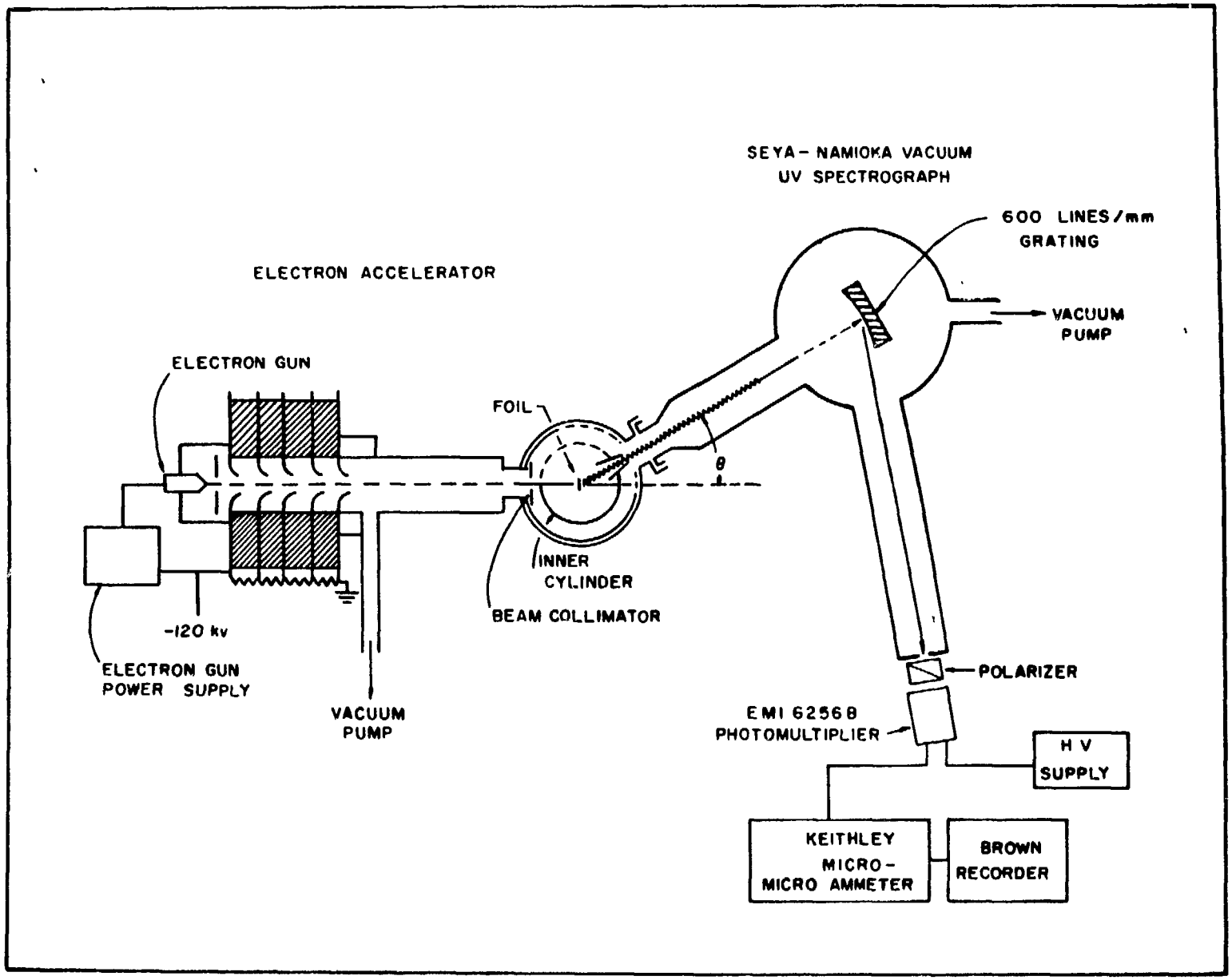
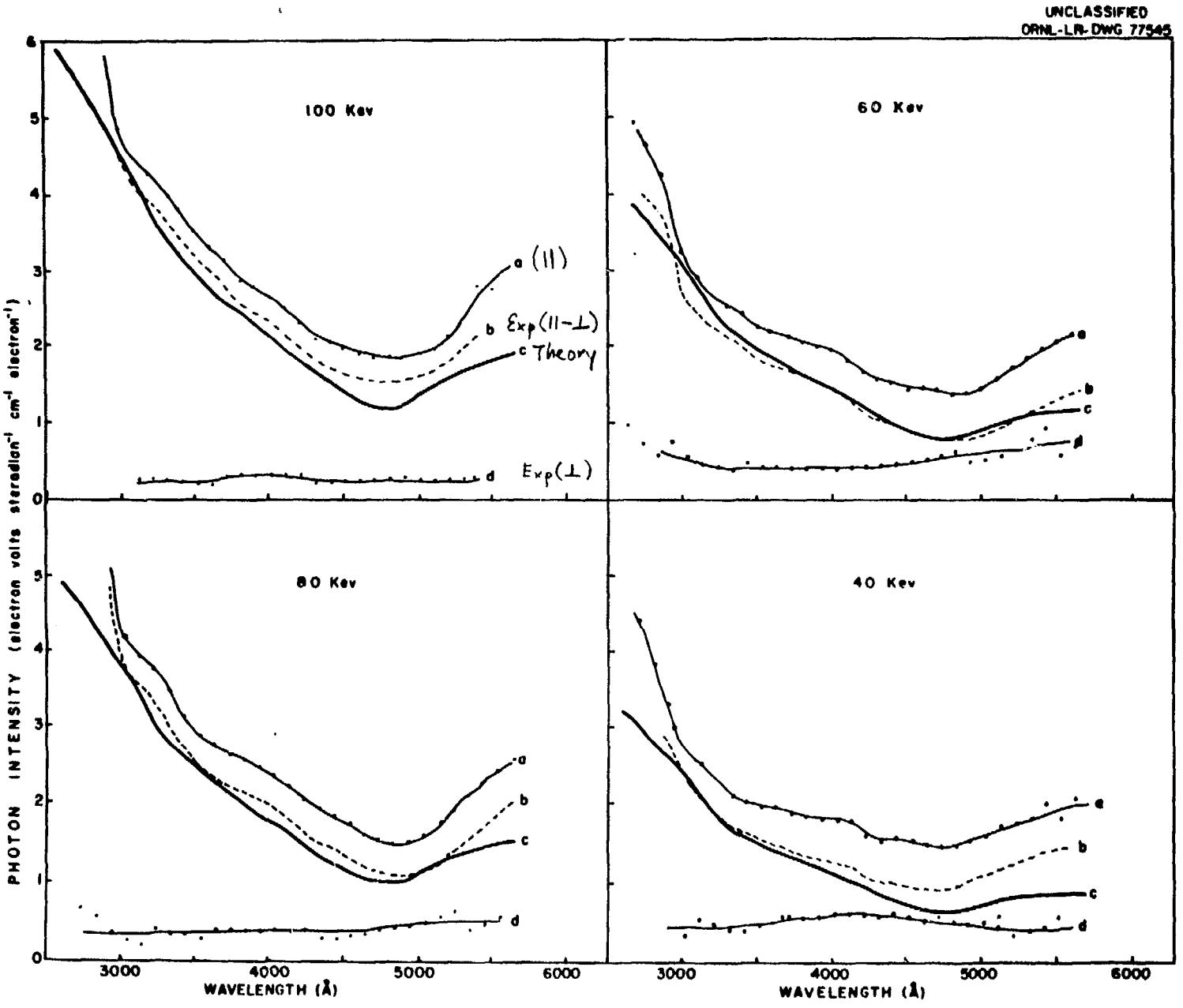
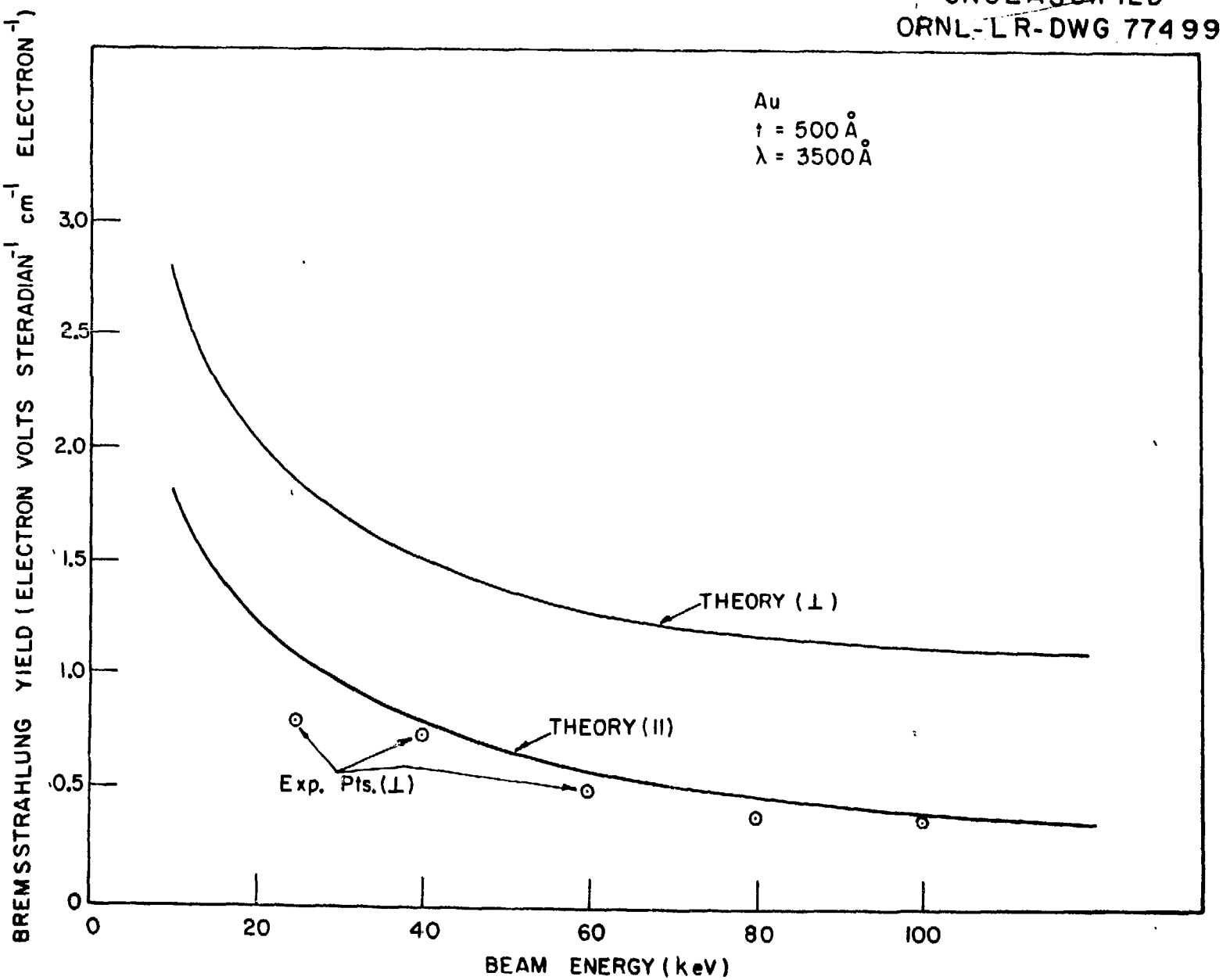
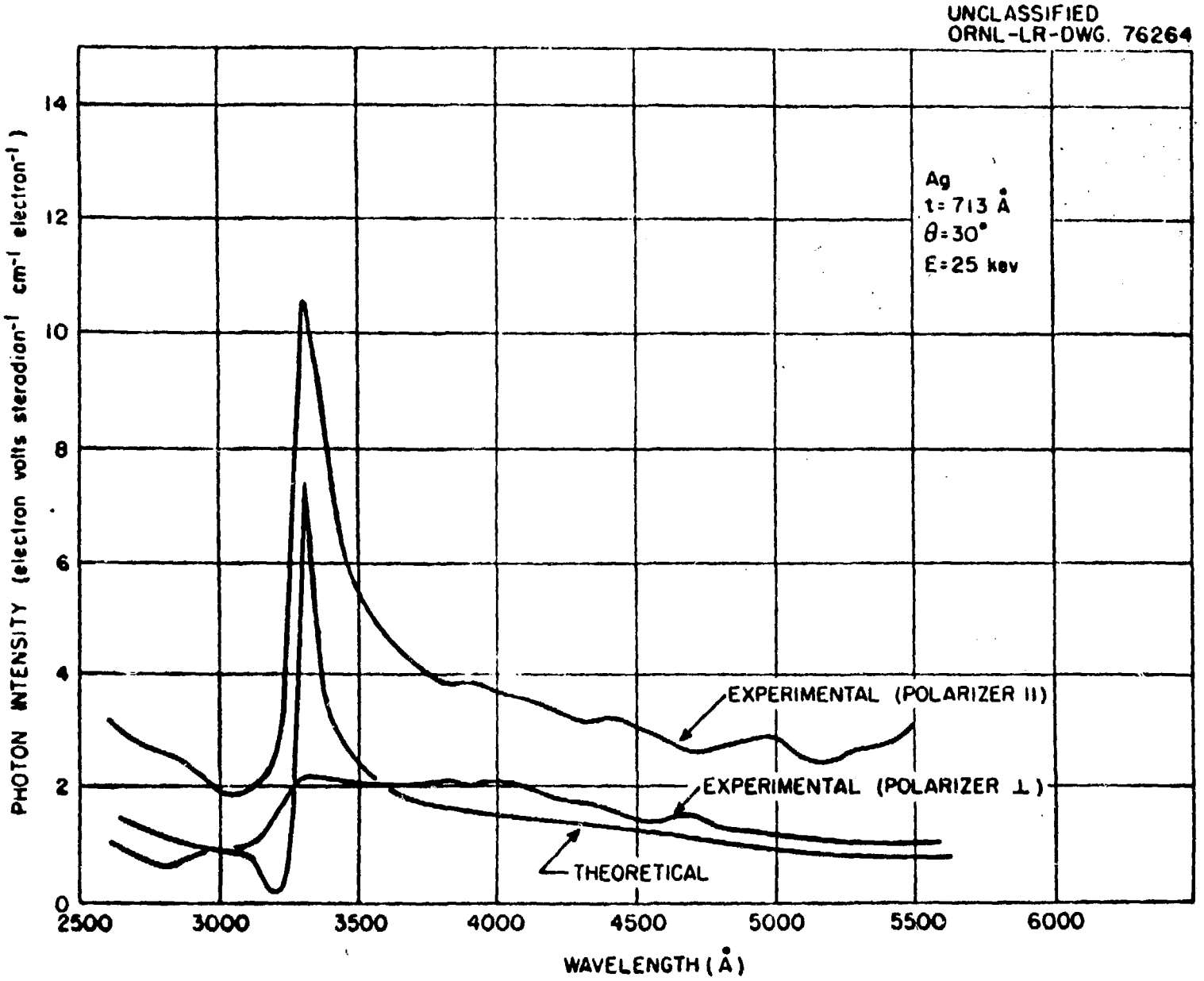
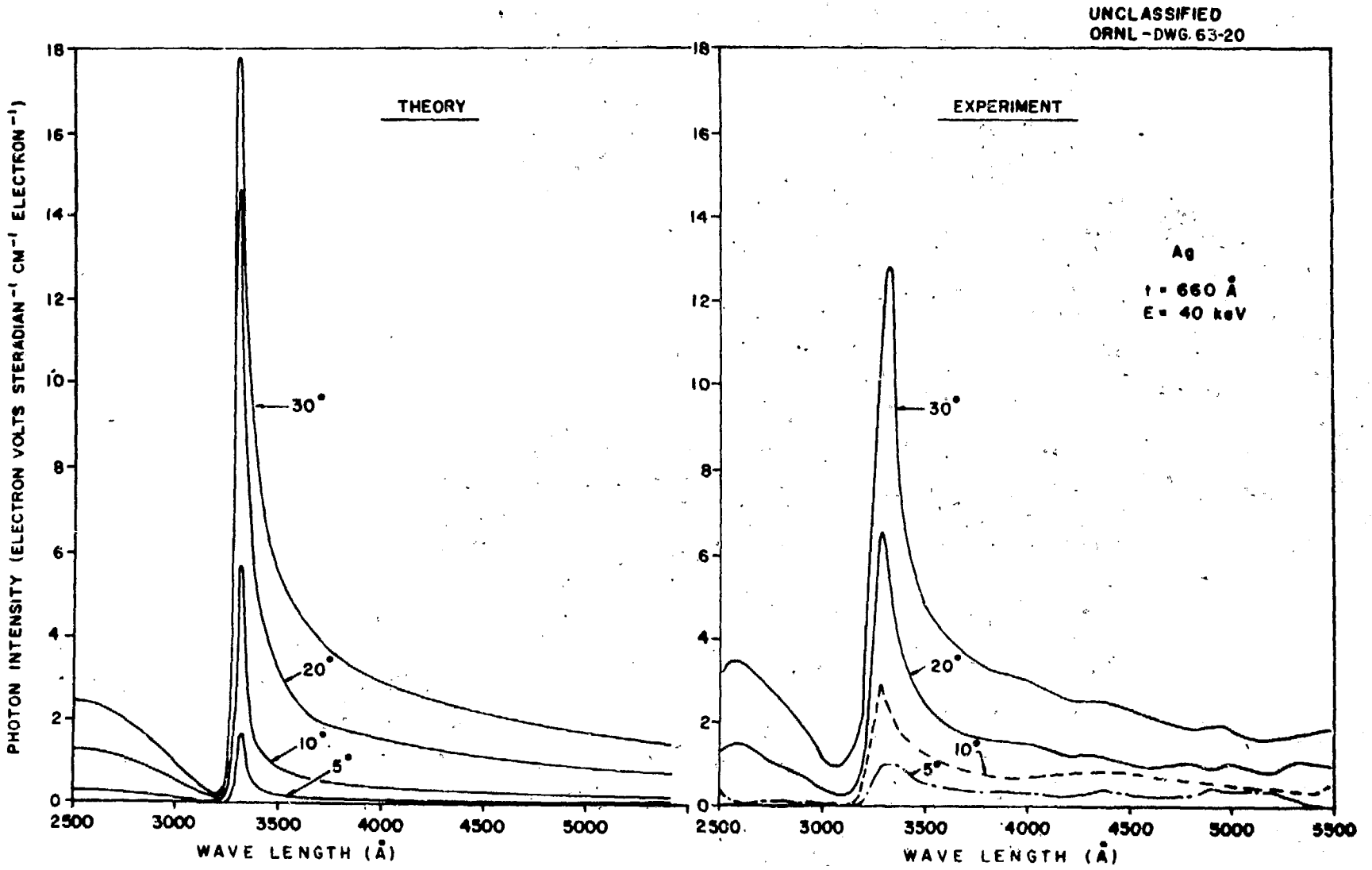
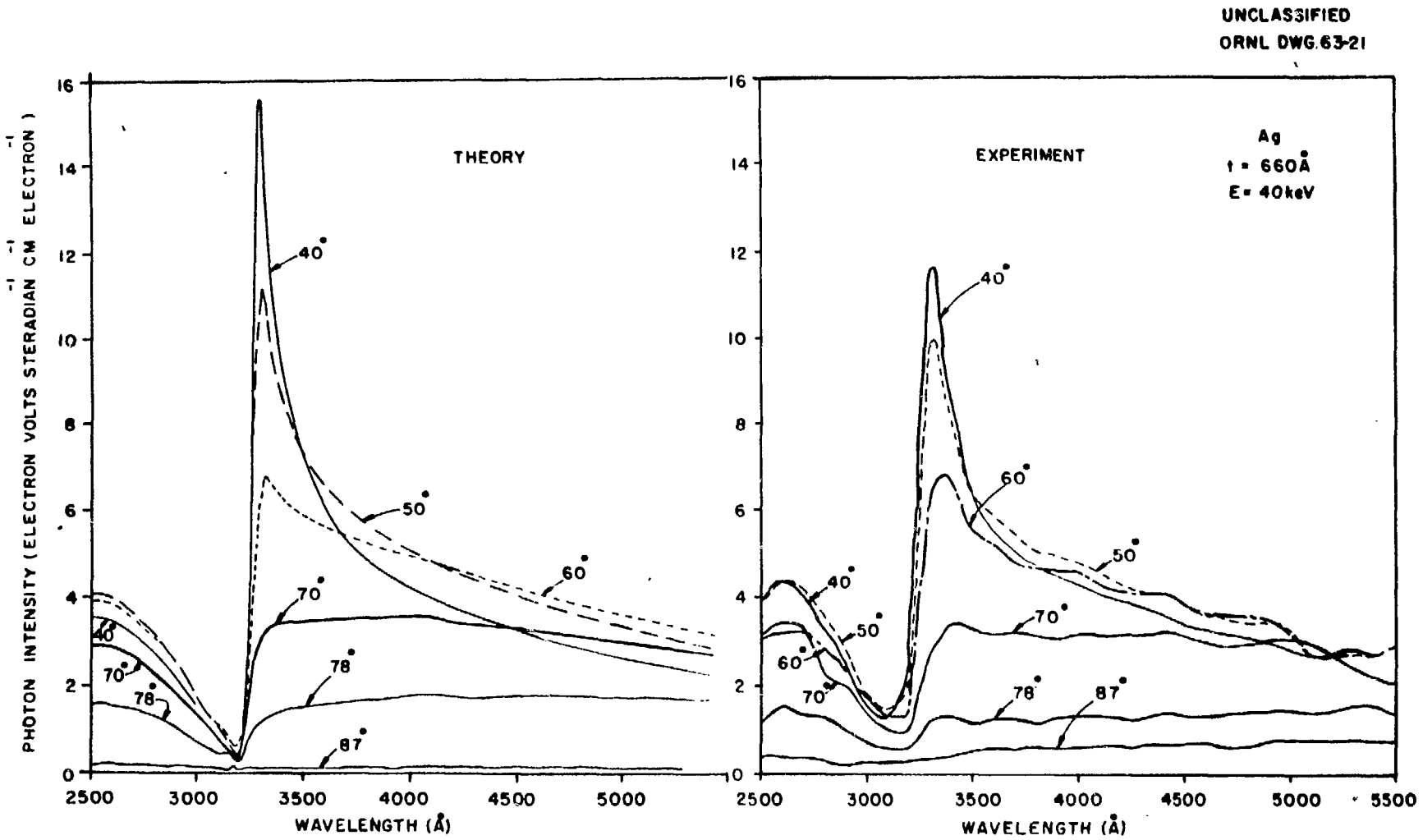


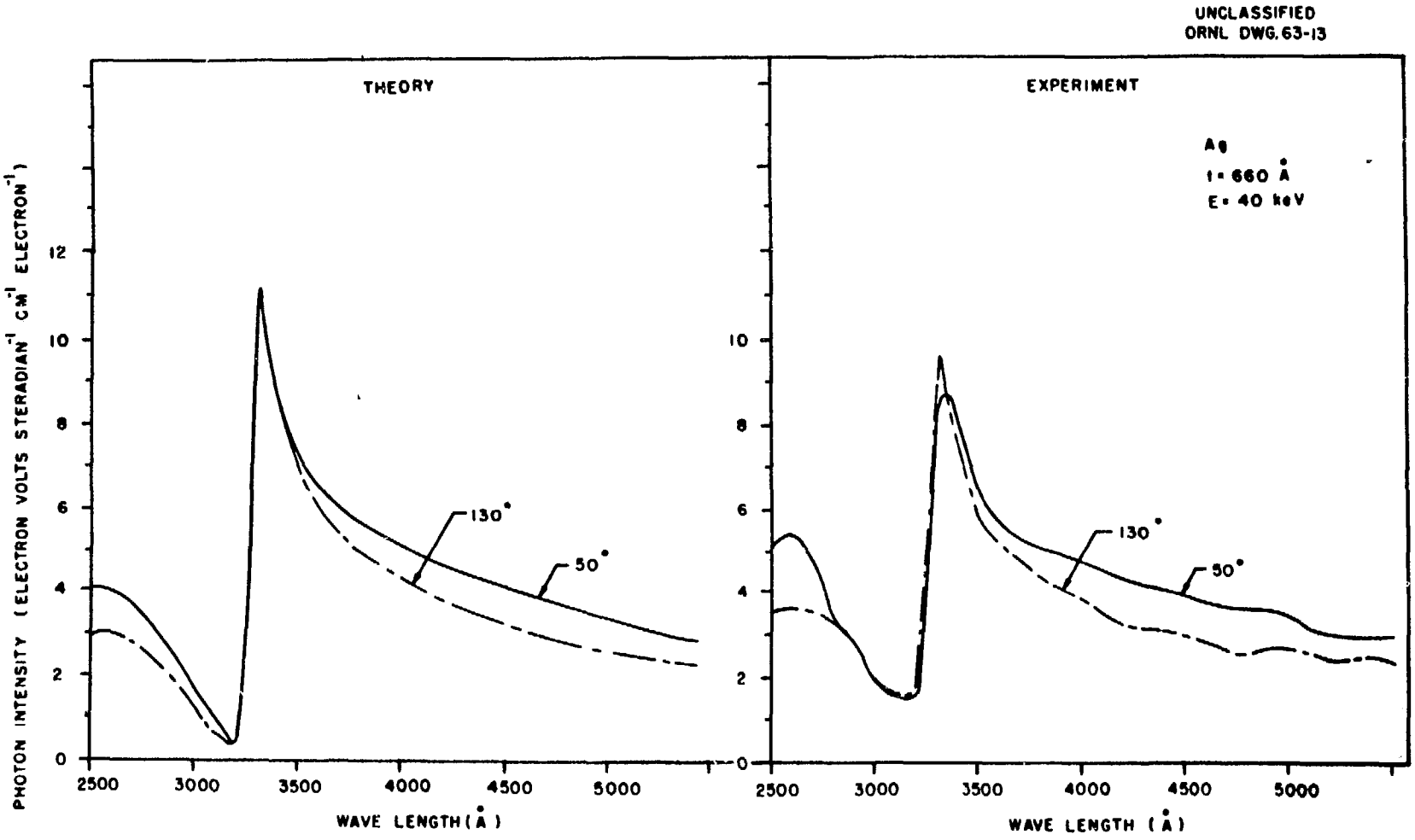

UNCLASSIFIED
ORNL-LR-DWG 77545
100 Kev
60 Kev
80 Kev
40 Kev
a (||)
b Exp(||-⊥)
c Theory
d Exp(⊥)
PHOTON INTENSITY (electron volts steradian⁻¹ cm⁻¹ electron⁻¹)
WAVELENGTH (Å)
WAVELENGTH (Å)




UNCLASSIFIED
ORNL-LR-DWG. 76264
Ag
t = 713 Å
θ = 30°
E = 25 kev
EXPERIMENTAL (POLARIZER II)
EXPERIMENTAL (POLARIZER ⊥)
THEORETICAL
PHOTON INTENSITY (electron volts sterodian⁻¹ cm⁻¹ electron⁻¹)
WAVELENGTH (Å)
0
2
4
6
8
10
12
14
2500
3000
3500
4000
4500
5000
5500
6000


UNCLASSIFIED
ORNL - DWG. 63-20
THEORY
EXPERIMENT
Ag
t = 660 Å
E = 40 keV
30°
20°
10°
5°
PHOTON INTENSITY (ELECTRON VOLTS STERADIAN⁻¹ CM⁻¹ ELECTRON⁻¹)
WAVE LENGTH (Å)
0
2
4
6
8
10
12
14
16
18
2500
3000
3500
4000
4500
5000
5500


UNCLASSIFIED
ORNL DWG.63-21
THEORY
EXPERIMENT
Ag
t = 660Å
E = 40keV
PHOTON INTENSITY (ELECTRON VOLTS STERADIAN CM ELECTRON)
WAVELENGTH (Å)
WAVELENGTH (Å)
40°
50°
60°
70°
78°
87°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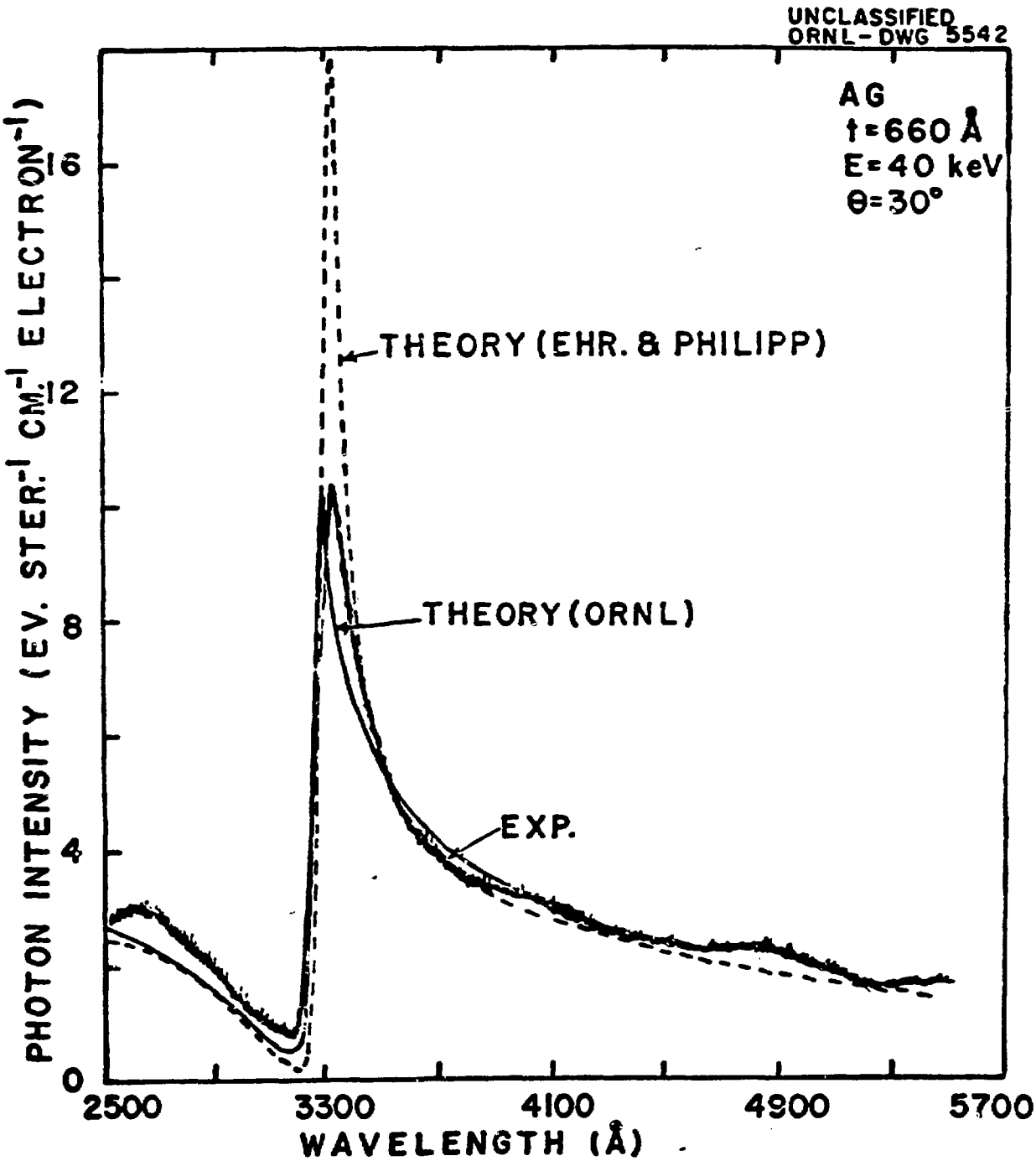
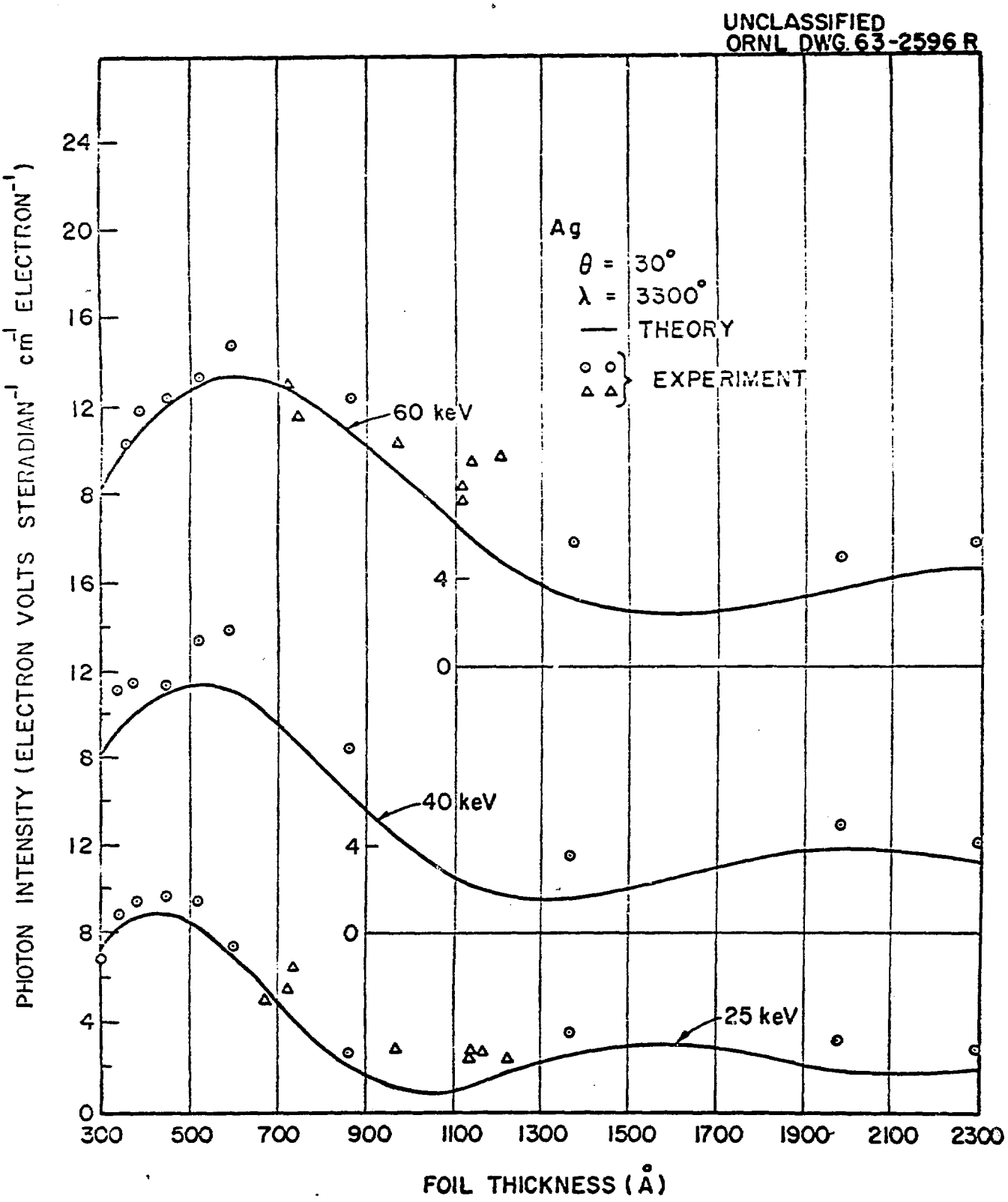
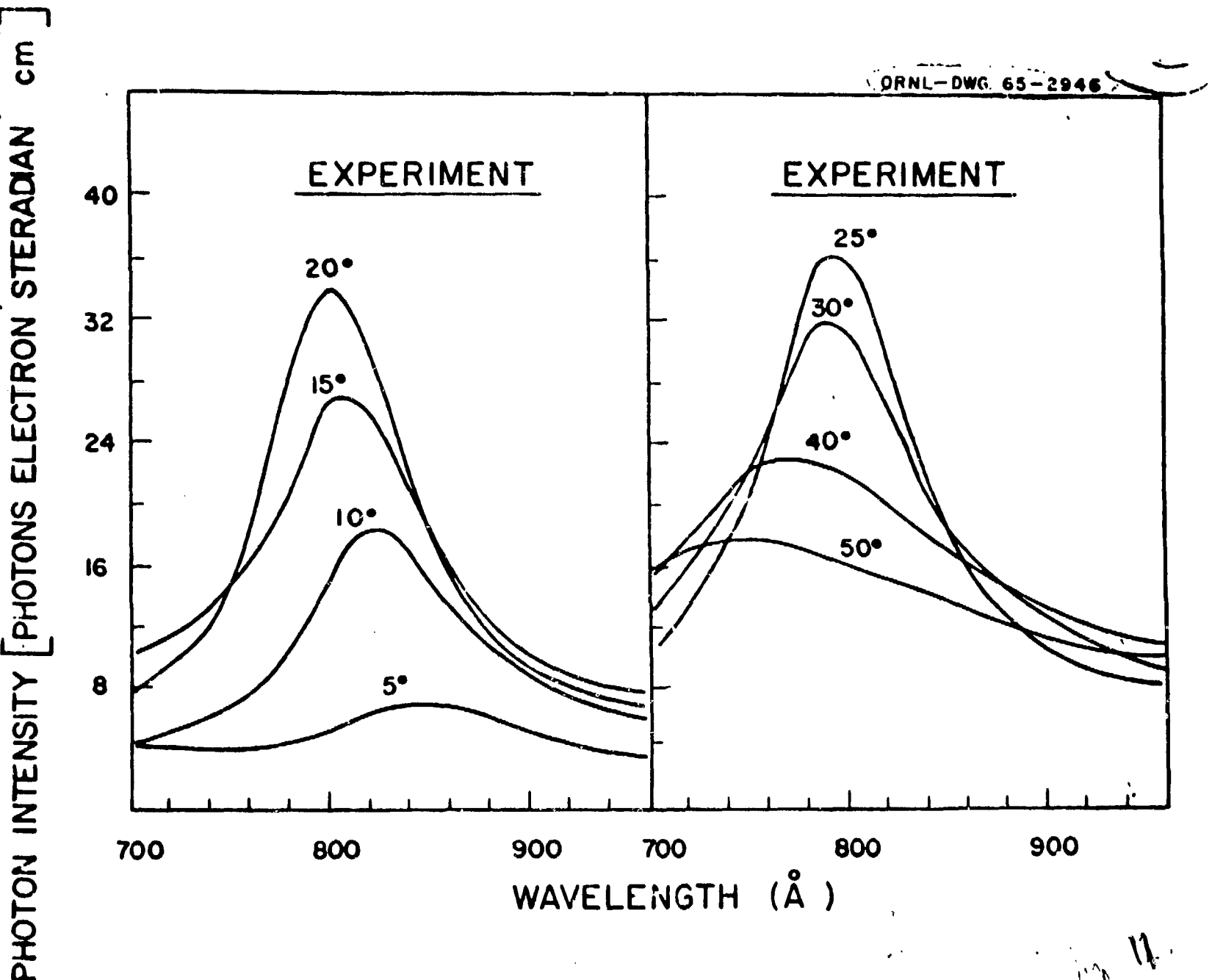
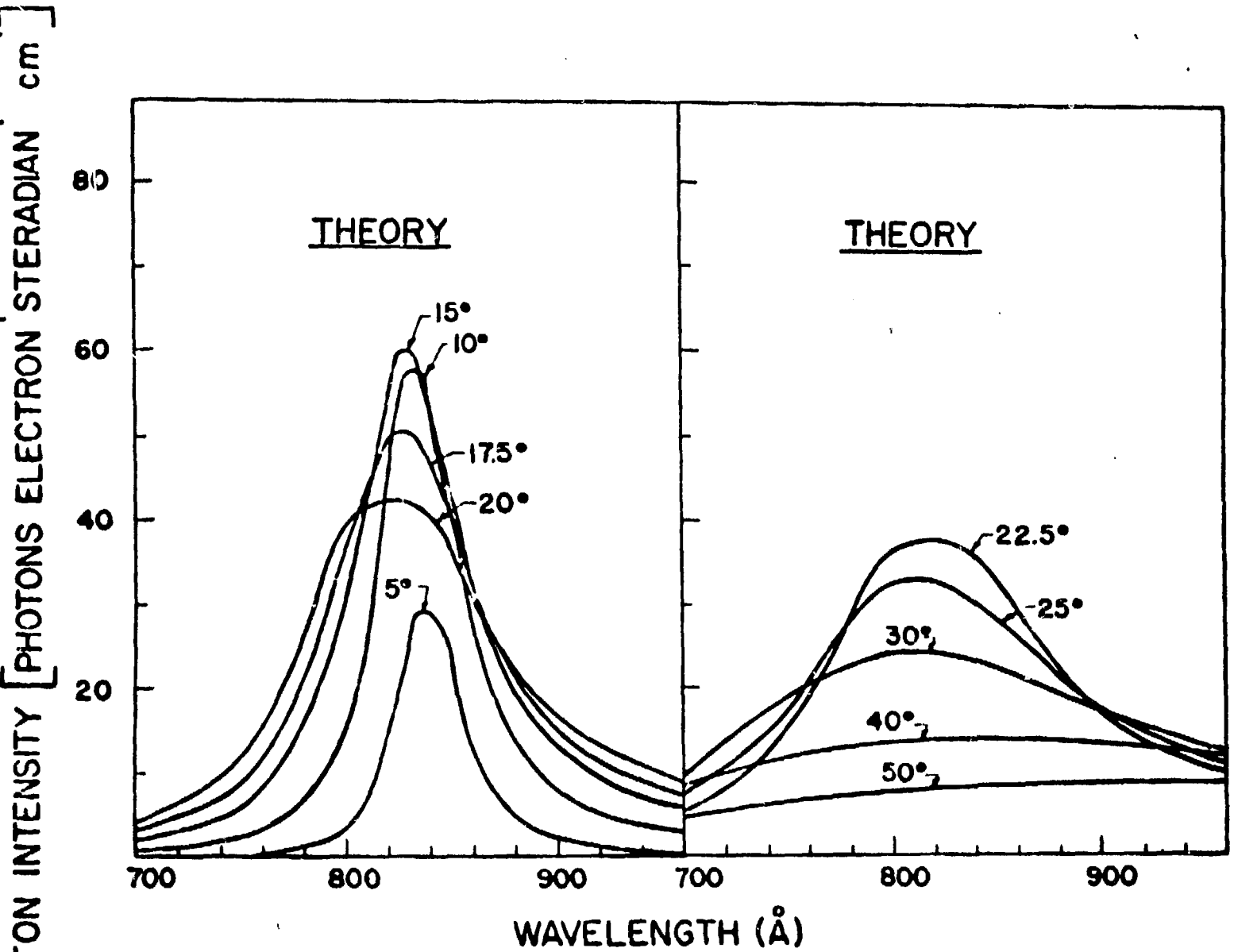
ORNL DWG. 63-13
THEORY
EXPERIMENT
Ag
t = 660 Å
E = 40 keV
130°
50°
PHOTON INTENSITY (ELECTRON VOLTS STERADIAN^{-1} CM^{-1} ELECTRON^{-1})
WAVE LENGTH (Å)
0
2
4
6
8
10
12
2500
3000
3500
4000
4500
5000


UNCLASSIFIED
ORNL-DWG 5542
AG
t=660 Å
E=40 keV
θ=30°
THEORY (EHR. & PHILIPP)
THEORY (ORNL)
EXP.
PHOTON INTENSITY (EV. STER.⁻¹ CM.⁻¹ ELECTRON⁻¹)
0
4
8
12
16
2500
3300
4100
4900
5700
WAVELENGTH (Å)


UNCLASSIFIED
ORNL DWG 63-2596 R
PHOTON INTENSITY (ELECTRON VOLTS STERADIAN^{-1} cm^{-1} ELECTRON^{-1})
FOIL THICKNESS (Å)
Ag
θ = 30°
λ = 3300°
THEORY
EXPERIMENT
60 keV
40 keV
25 keV
0
4
8
12
16
20
24
300
500
700
900
1100
1300
1500
1700
1900
2100
2300


ORNL-DWG. 65-2946
EXPERIMENT
EXPERIMENT
20°
15°
10°
5°
25°
30°
40°
50°
40
32
24
16
8
700
800
900
700
800
900
WAVELENGTH (Å)
PHOTON INTENSITY [PHOTONS ELECTRON^{-1} STERADIAN^{-1} cm^{-1}]


PHOTON INTENSITY [PHOTONS ELECTRON^{-1} STERADIAN^{-1} cm^{-1}]
80
60
40
20
THEORY
THEORY
15°
10°
17.5°
20°
5°
22.5°
25°
30°
40°
50°
700
800
900
700
800
900
WAVELENGTH (Å)

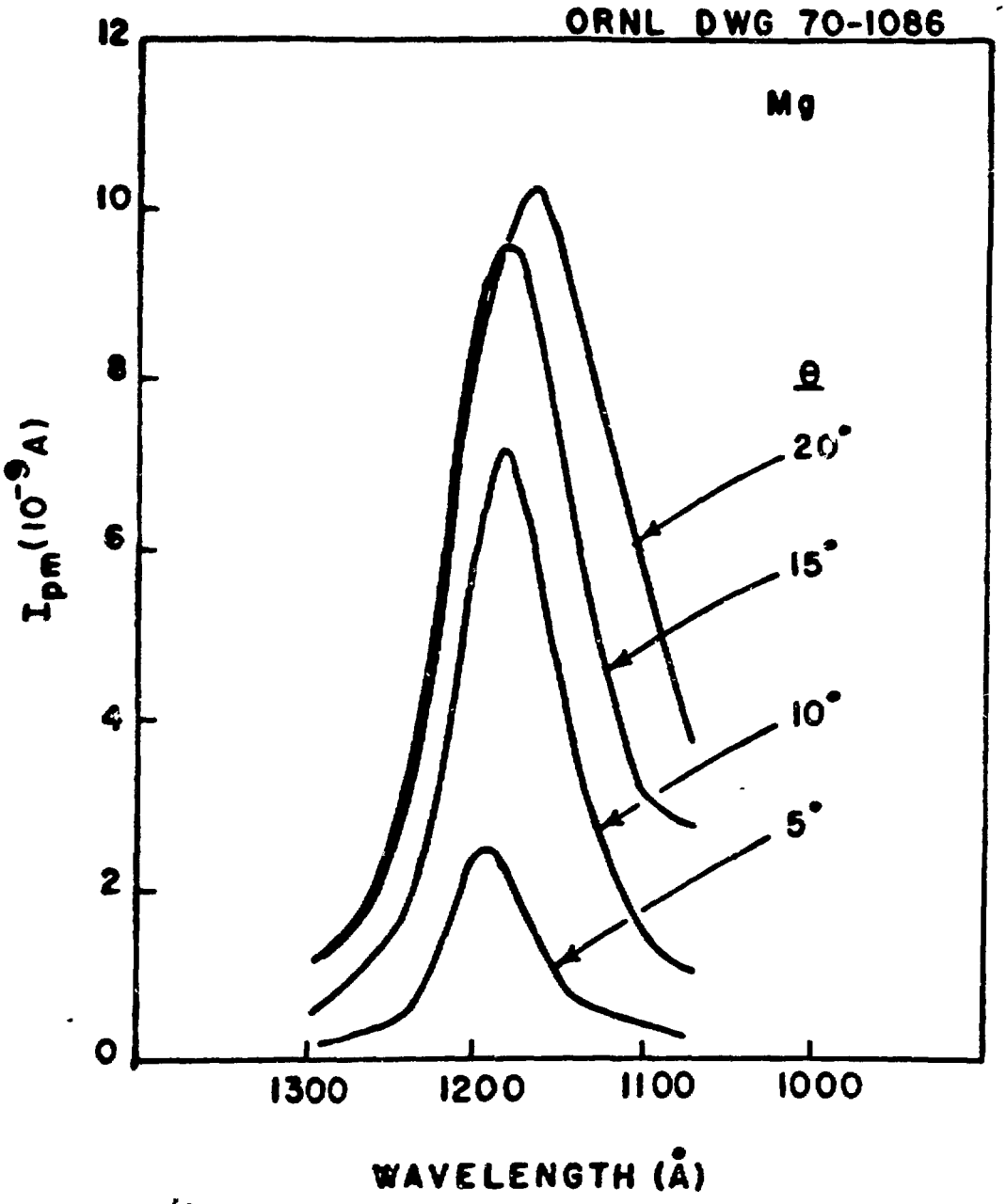
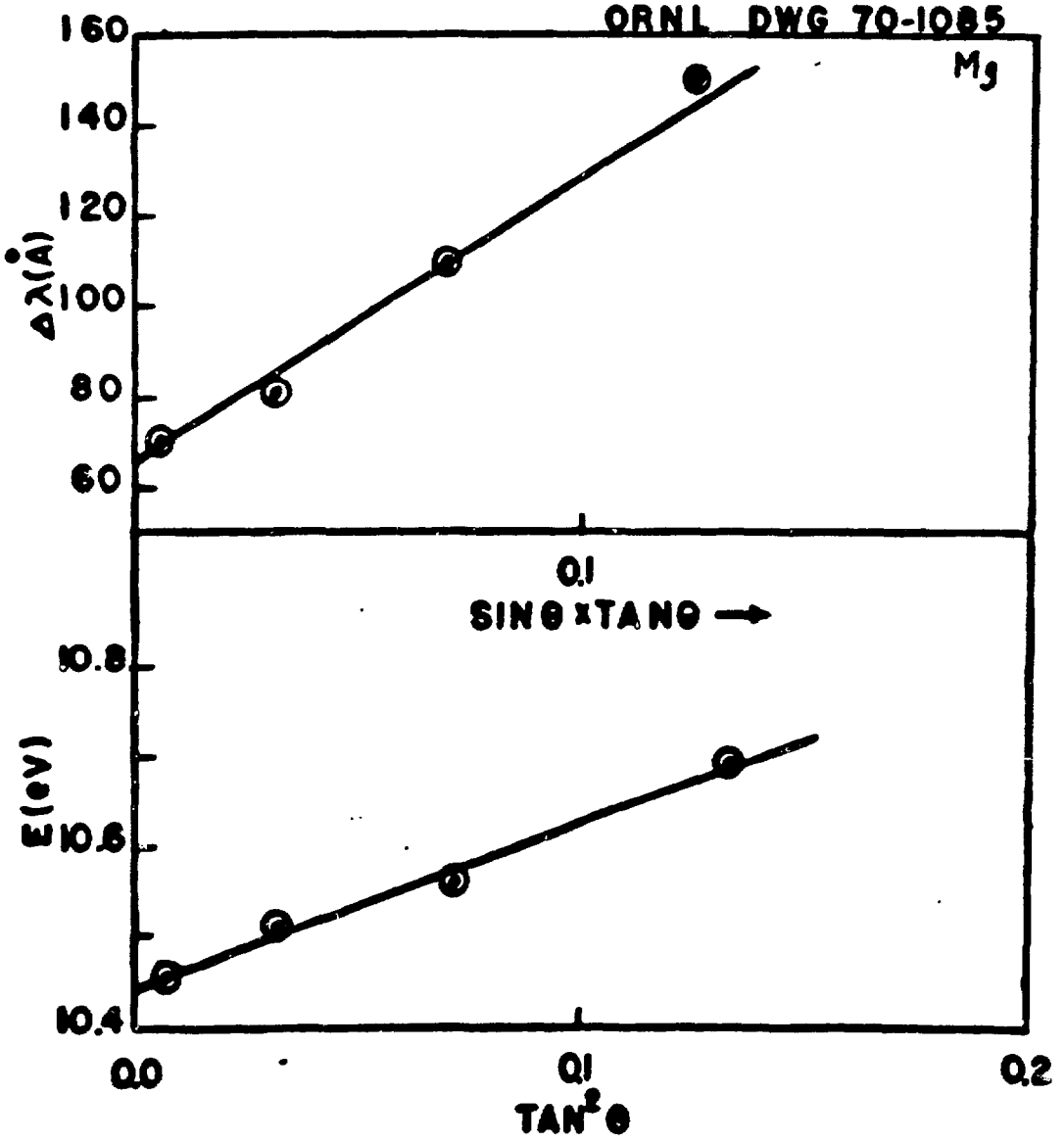


Figure 13. Spectra of radiation emitted from a 220 Å thick Mg film bombarded by nearly-normal 80 keV electrons for various observation angles.



For NFE, $E = E_p\left[1 + \frac{\omega_p^2 t^2}{8c^2}\tan^2\theta\right]$

$E_p = 10.43 \pm .03$ eV ; $t = 225$ Å

Resonance Width $\Delta\lambda = \underbrace{\frac{\lambda_p}{\tau_d \omega_p}}_{\text{intrinsic}} + \underbrace{\pi t \sin\theta \tan\theta}_{\text{radiative}}$

$\tau_d = (1.14 \pm 0.11) \times 10^{-15}$ sec ; $t = 217$ Å

Fig 14