MEASUREMENT OF X-RAY INDUCED ELECTRON EMISSION

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SUMMARY

The development and use of a magnetic spectrograph for the measurement of X-ray induced electron emission is described. Results are presented for metal and dielectric targets ranging in atomic number from $Z=82$ to $Z=6$. Materials studied were lead, tantalum, copper, aluminum, magnesium, solar cell cover glass, silica cloth, thermal control paint (A surface coating with specific thermal absorption and emissivity properties), Kevlar, Mylar and conducting and non-conducting epoxy. Direct measurement was made of the quantum yield and energy distribution of electrons emitted at angles of 0° , 30° , 45° and 60° with respect to the surface normal of targets exposed to normal incidence unfiltered and filtered (0.12 cm Al) 50kV bremsstrahlung x rays. The range of electron energies analyzed was 0.1 keV to ≈ 50 keV. Experimental results are compared with previous measurements^{1,2} and with QUICKE 2M³ predictions where predictive capability matches the measurement range.

Experimental Approach

The experimental technique is based on magnetic analysis of the energy of the emitted electrons. The analysis is done in an evacuated semicircular magnetic spectrograph, configured to define specific emission angles relative to the direction of the incident photon beam and surface normal of the target. Target materials are placed in the beam to obtain the emission characteristics at normal incidence. Emission yields are measured in terms of the number of electrons of energy E at selected emission angles θ_k for known conditions of X-ray intensity and energy distribution. The target surfaces were cleaned by acetone or alcohol rinse prior to exposure.

The X rays are generated by a constant potential industrial radiographic unit employing a tube rated at 2.5 kW at 100 kV potential. The tube contains a tungsten anode and X rays exit through a beryllium window. X-ray flux and energy spectrum are measured by a NaI scintillation detector in conjunction with a multi-channel analyzer. X-ray spectra used in the experiment are shown in Fig. 1. The materials to be investigated are placed in the spectrograph with the collimated X-ray beam entering through a thin Mylar window. Vacuum conditions are maintained by a mechanical roughing pump and a gas absorption pump. The variable magnetic field required for energy analysis of the emitted electrons is established by an electromagnet enclosing the spectrograph body. Windowless helical channel electron multipliers (channeltrons or CEM) are used in the pulse saturation mode as electron counters. The output of these detectors is fed through amplifiers to scalars. This experimental setup is shown schematically in Fig. 2.

Instrument calibration permits a reliable detection of electrons in the energy range 100 eV to a few hundred keV. Data are obtained by counting for a predetermined period at a given magnetic field strength for a number of field intensities. The electron energy spectrum is constructed in a stepwise fashion. The

targets were thick compared to the range of the most energetic electrons created by the X-ray interactions. Investigation of backward emission under these conditions maximizes the effect on the yield due to multiple scattering events. Detailed calibration of the spectrograph was performed using an electron gun to simultaneously measure the energy resolution of each detector. These measurements directly confirmed the resolution calculated from the target, aperture and detector geometrical relationships.

Instrument Design

The instrument used in these measurements is an adaptation of a semicircular magnetic spectrograph. The coordinate system used to describe the trajectories of the electrons within the spectrograph is shown in Fig. 3. The target is represented by the rectangle in the X,Z plane at the origin of the coordinate system with $\hat{n}$ defining the surface normal. Electrons are emitted with a velocity vector $\vec{v}_e$ forming angle ψ with respect to the plane of the spectrograph (X,Y plane) and whose component in the spectrograph plane forms angle θ with respect to $\hat{n}$. Electron trajectories with radius of curvature ρ_0 are described in the plane of the spectrograph as determined by $|\vec{v}_p|$ and the magnitude of the magnetic field $|\vec{B}_z|$ perpendicular to the plane of the spectrograph. The fundamental adaptation to the basic design was to define four separate channels viewing different emission angles relative to the target normal. This was done by positioning defining slits (primary and secondary) and detectors for each emission angle θ_k . The geometry of the instrument was established to measure electrons traversing paths of 10 cm radius of curvature with a momentum resolution of 5%. The internal arrangement of the spectrograph is shown in Fig. 4.

Data Reduction Method

Data accumulated for determination of the electron emission from various targets consisted of the number of electrons counted in each detector over a measured time interval as a function of magnetic field strength. During this interval the fluence of X rays incident on the target was also measured with the normalization counter. Processing of the raw data (counts versus magnetic field strength) into differential emission yield (electrons/photon keV sr) involved the use of the following equation:

$$G(\alpha, \theta_k) = \frac{N_k F(\alpha)}{\epsilon \phi \Omega} \quad (1)$$

$G(\alpha, \theta_k)$ is the differential yield of electrons of energy E emitted at angle θ_k from the target. N_k is the electron count in each detector and ϕ is the incident X-ray fluence. ϵ is a detector efficiency factor which includes energy dependence (obtained from manu-

facturer's data) and magnetic field sensitivity (obtained by separate measurements in the spectrograph), and Ω is the effective solid angle defined by the target, aperture and detector geometry. $F(\alpha)$ is a momentum to energy conversion factor where $\alpha = E/m_0 c^2$.

Reproducibility, Errors and Accuracy

Data from Mylar, aluminum, copper and lead were used to determine the reproducibility of the measurements and estimate the random errors influencing the precision of the experiment ($\pm 15\%$). Corrections for background and detector "dark count" were made and statistical errors treated in processing the raw data. The dominant source of uncertainty contributing to the accuracy of the results is the lack of exact data on the energy dependence of the detector response. Over the energy range employed in these measurements the variation in the detector efficiency, according to manufacturer's data is no larger than approximately $\pm 15\%$. Other systematic errors associated with the geometry of the spectrograph (target, aperture and detector positions, target area, aperture dimensions, etc.) are negligibly smaller. The combined estimated accuracy and measured precision of the measurements is $\pm 30\%$, assuming the systematic and random errors are additive.

Results and Comparisons

Examples of the differential emission yields obtained are shown in Figs. 5 through 8. Comparison of Figs. 5 and 6 show the influence of filtered vs unfiltered X-ray spectra in a single target while Figs. 6 through 8 show the variations in emission characteristics in high Z to low Z targets with the unfiltered spectrum. Fig. 9 shows the energy integrated yields as a function of θ_k for all targets examined. Total reverse emission yield into 2π steradians is obtained from the equation

$$Y = G(\theta_1) \int_0^{2\pi} \int_0^{\pi/2} f(\theta) \sin\theta d\theta d\phi \quad (2)$$

where $\theta_1 = 0^\circ$ and $f(\theta)$ is the yield angular dependence. Table 1 gives yield values obtained from equation 2 with the indicated $f(\theta)$ from Fig. 9.

Comparisons

Comparisons among present results (EXPTL), previous measurements (Bradford, Dolan) and QUICKE 2M calculations are shown in Fig. 10 for the filtered spectrum, copper target. Table 2 gives a summary comparison with QUICKE 2M yields for aluminum, copper, tantalum and lead targets with the unfiltered spectrum. Note that for the filtered spectrum the experimental results are generally lower than QUICKE 2M predictions. For the unfiltered spectrum the experimental results are generally higher than the predictions. Closest agreement for the filtered spectrum over equal energy ranges occurs for copper. Total yield agreement with Dolan's results is within experimental error. For tantalum, present results are $\sim 30\%$ below those reported in reference 1. QUICKE 2M code predictions are 17% and 74% higher than experimental results for copper and tantalum. The ratio of experimental results to QUICKE 2M predictions for the unfiltered spectrum are 1.7, 1.0, 1.3 and 1.3 for aluminum, copper, tantalum and lead, respectively. No experimental data exist for comparisons with the unfiltered spectrum results.

Conclusions

An experimental technique has been developed and successfully used in the measurement of X-ray induced electron emission from a variety of materials including a group of significance to satellite applications⁴. A data base has been established which extends measured emission characteristics to an order of magnitude lower energies than previously available. Direct measurement of the angular dependence of differential yield distributions has been made. For the unfiltered 50 kV spectrum, a $\cos^2\theta$ is exhibited by the mid to high Z targets while the low Z ($Z < 10$) materials show a $\cos\theta$ to isotropic distribution. The filtered spectrum in copper and tantalum targets gives a $\cos\theta$ dependence. The quantum yield of electrons of energy between 0.1 and 1.0 keV has been shown to be less than 10% of the total yield for all materials investigated with the X-ray spectra used in this experiment. Total yields based on these measurements have been compared with previous measurements and QUICKE 2M predictions where possible. Agreement with data from previous measurements and code predictions using a filtered X-ray spectrum is generally good with exceptions noted. Comparison with experimental results obtained using the unfiltered X-ray spectrum with calculations from QUICKE 2M highlight a deficiency in the code's ability to predict emission yield at X-ray energies below 10 keV. The acknowledged deficiencies in the analytical model (i.e., ignoring secondary photon interactions (Compton scattered photons, X-ray fluorescence) and generation of energetic secondary electrons) could contribute to a decrease in predicted yield at these lower X-ray energies.

References

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3. ROGERS, S., and Wood, A.J., Multiple-Plate Modification of QUICKE 2 Analytical Electron Emission Code, Defense Nuclear Agency, DNA 4062T, July 1976.
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FIG 9
EXPERIMENTS AND CODE COMPARISONS
COPPER, FILTERED SPECTRUM

FIG 10
ENERGY INTEGRATED YIELD VS EMISSION ANGLE

SUMMARY TABLES

Table 1. Total Reverse Emission Yield Summary.
 $E_e > 0.1$ keV; Filtered and Unfiltered Spectra

Target Material	$G_i \times 10^3$ $\left(\frac{\text{electrons}}{\text{Y sr}}\right)$	$Y \times 10^3$ $\left(\frac{\text{electrons}}{\text{Y}}\right)$	$f(\theta)$
Pb	7.96	16.68	$\cos^2 \theta$
Ta (Filtered)	1.17	3.68	$\cos \theta$
Ta	7.08	14.83	$\cos^2 \theta$
Cu (Filtered)	0.58	1.82	$\cos \theta$
Cu	2.19	4.58	$\cos^2 \theta$
Al	0.78	1.53	$\cos \theta$
Mg	0.56	1.17	$\cos \theta$
Cover Glass	0.55	1.15	$\cos \theta$
Silica Cloth	0.34	1.07	$\cos \theta$
Thermal Control Paint	0.17	0.53	$\cos \theta$
Kevlar	0.11	0.35	$\cos \theta$
Mylar	0.10	0.31	$\cos \theta$
Non Conducting Epoxy	0.07	0.22	$\cos \theta$
Conducting Epoxy	0.06	0.19	$\cos \theta$

TABLE 2. Experimental Reverse Emission Yield Comparisons with QUICKE 2M Calculations, Unfiltered Spectrum, for Aluminum, Copper, Tantalum and Lead

Ee	$G_i \times 10^3 \left(\frac{\text{electrons}}{\text{Y sr}}\right)$					$Y \times 10^3 \left(\frac{\text{electrons}}{\text{Y}}\right)$		
	>0.1 keV		>1.0 keV		>5.0 keV	>1.0 keV		
	EXPTL	EXPTL	CALC	EXPTL	CALC	$\cos^2 \theta$	$\cos \theta$	CALC
Al	0.78	0.73	0.25	0.33	0.13	1.53	2.30	0.88
Cu	2.19	2.08	1.46	0.94	0.82	4.37	6.55	4.40
Ta	7.08	6.63	2.81	3.50	1.27	13.88	20.82	10.26
Pb	7.96	7.30	3.01	3.55	1.34	15.29	22.93	11.82