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Relative shape of the bremsstrahlung-photon energy spectrum from 7.0-keV electrons on Ag and Au

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We have measured the relative shape of the bremsstrahlung-photon energy spectrum from 7.0-keV electrons incident on Ag and Au targets; the targets are thick enough to stop the incident electrons, yet thin enough to transmit a substantial fraction of the radiated photons. Our results for the ratio of double differential cross sections for the bremsstrahlung-photon emission from Ag and Au at 90° to the incident electron beam direction are found to yield excellent agreement with Pratt's theoretical prediction [Comments At. Mol. Phys. **10**, 121 (1981); *Electron Bremsstrahlung ×80: Theory and Recent Developments,* Proceedings of the International Conference on X-ray Processes and Inner Shell Ionization, Stirling, Scotland, 1980, edited by D. J. Fabian, H. Kleinpoppen, and L. M. Watson (Plenum, New York, 1981)] on the relative shape of the spectrum; however, the thick-target effect introduces a discrepancy between experiment and theory of about 20%. Also, the calculated absolute efficiency of the detector employed using the theoretical bremsstrahlung cross sections is found to agree with the normalization to the radioactive source within the uncertainty of about 20% in the target thickness.

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Extensive studies have shown that when an electron beam of a given energy, say, T keV, impinges upon a target, a continuous radiation (electron bremsstrahlung) of photons of energy k is emitted. The most prominent feature of this radiation is found to exhibit two limiting cases: a soft-photon ($k/T \approx 0$) and a hard-photon ($k/T \approx 1$) end point. The two limiting cases may be related to other atomic processes [1]. The hard-photon end ("tip" of the bremsstrahlung spectrum) is a direct consequence of the quantum nature of electromagnetic radiation; no photon can be emitted with an energy greater than that of the bombarding electrons. Investigations of the electron-bremsstrahlung spectra may be grouped into two categories: first, the targets are sufficiently thick to stop all the incident electrons, that is, the targets may be massive, as in anticathodes of conventional x-ray tubes, or they may be foils that are thin enough to transmit a substantial fraction of the x rays but nevertheless sufficiently thick to arrest all the incident electrons; second, the targets are extremely thin foils in order to allow the electrons to pass through with only a very small number of interactions and with as little loss of energy as possible.

The theory of the bremsstrahlung process has been considered by many workers over the years and has been recently reviewed by Pratt [1]. Tseng and Pratt [2] have calculated the atomic field bremsstrahlung (AFB) numerically by means of partial wave expansion using the screened, self-consistent, relativistic central potential of the target atom. These calculations are believed to be the best prediction over the entire range of atomic numbers and radiated photon energies of both the photon energy spectra or singly differential cross section $d\sigma/dk$ and the energy and angular distribution of the photons or doubly differential cross section (DDCS) $d^2\sigma/dk d\Omega$. Stimulated by these calculations, several experimental investigations were carried out recently in low- and medium-energy regions with thin solid [3] and gaseous [4] targets. Since the theory [2] is believed to be accurate in the shape of the photon energy dependence to about 5% or better, it is desirable to have experimental data of this precision. By considering the ratio of the DDCS for different targets at the same incident energy and photon-emission angle, we have obtained the relative shape of the photon energy spectrum to a precision of better than 4%. Theoretical predictions on AFB [2] have been tested by Ambrose, Altman and Quarles [3] both for absolute magnitude and for photon energy-dependent spectral shapes for the electron-impact energy range of 50–100 keV at a photon emission angle of 90° for a series of elements with atomic number Z having values between 6 and 92.

The purpose of this Brief Report is to present investigations on the validity of Pratt's calculations for low impact energies of electrons incident on thin solid targets. A monoenergetic beam of 7.0-keV electrons strikes the thin self-supported targets of Ag and Au and the resulting photons are detected at 90° to the incident beam direction. The ratio of DDCS's of bremsstrahlung spectra for two targets is obtained and compared with the theoretical predictions. What follows is a brief account of the experimental setup, data analysis, results, and discussions.

The present work was carried out on a recently developed experimental setup in our laboratory, the details of which will be given elsewhere. Briefly, the setup consists of a stainless-steel scattering chamber of 40.0 mm inner diameter and a homebuilt electron gun. The gun is mounted horizontally to the chamber and renders a beam of electrons with a 3.0-mm spot size on the target. The scattering chamber and the enclosure of the electron gun are evacuated by separate oil diffusion pumps (300 and 100 l/s) to provide a base pressure of the system of about 1×10^{-6} mbar. The chamber is equipped with a movable, aluminum target holder in the vertical plane at

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its center, which facilitates the positioning of targets in front of the beam without cycling the vacuum of the system. The photons emitted from the beam-target interaction zone pass through a 6-μm hostaphan vacuum window of 8.0 mm height in the horizontal plane and finally strike the detector. A Canberra Si(Li) x-ray detector (with a full width at half maximum of 250 eV at 5.9 keV) sits outside the chamber at a distance of 57.0 mm from the collision center. An aluminum aperture of 3.0 mm diameter is mounted in front of the Be window (25 μm) to minimize the background radiation. The detector can be placed at any angle θ_k between 30° and 150° with respect to the incident beam direction. The photon signals generated by the Si(Li) detector are amplified, shaped, and digitized by the standard nuclear instrument modules. The pulse height spectrum of the signals is collected in an IBM PC/XT-based 4 K multichannel analyzer, the histogram of which produces the bremsstrahlung-photon energy spectrum of the chosen target. The incident electron beam is monitored on the insulated target and is finally integrated by a current integrator (ORTEC 439). A schematic diagram of the experimental setup is shown in Fig. 1.

High-purity thin foils of Ag and Au having thicknesses of 150 and 200 μg/cm^2, respectively, were purchased commercially. In the present work, the precise knowledge of the target thickness was not important for an accurate measurement of the photon energy dependence of the spectral shape, as discussed below. However, uncertainty in the target thickness is the major contribution to the error in the absolute cross-section determination. Since foils were thick enough to arrest all impinging electrons but thin enough to transmit a substantial fraction of x rays, the beam monitoring was made on the target itself. Again, the solid-state effects, for example, electron diffusion, straggling, backscattering, and absorption of x rays in the target, do not affect the results in this investigation as their effects are combined and contained in a simple scale factor (see below). The beam current used to record the DDCS spectra was kept low enough in order to avoid the pulse pileup and was typically in the range of 1–3 nA. For a 3% counting statistics, about 20–30-min data collection times were required. The background was determined by making a long data run with a blank target frame in the presence of the beam. The contribution of the background was found to be less than 2% per channel. This was confirmed by comparing data runs with and without the empty frame in place. The calibration of the detector efficiency and that of the photon energy spectra was made by using a ^{55}Fe radioactive source of a known activity.

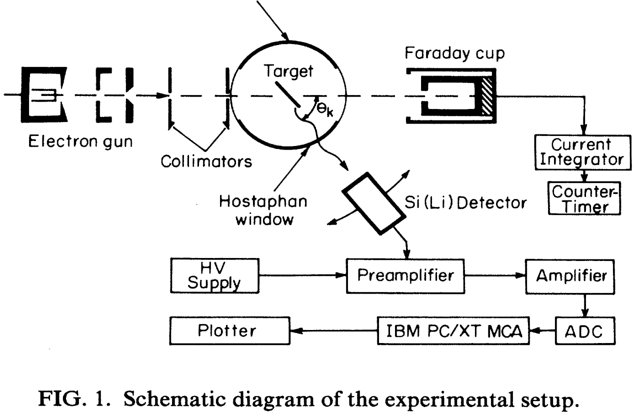

FIG. 1. Schematic diagram of the experimental setup.

A detector placed at an angle θ_k with respect to the incident beam direction and subtending a solid angle $\Delta\Omega$ detects the bremsstrahlung photons $N_B(k)$ within an energy width of Δk given by

$$N_B(k)=N_e N_t(d^2\sigma/dk d\Omega)\Delta k \Delta\Omega \epsilon(k) , \tag{1}$$

where N_e is the total number of electrons incident on the target, N_t is number of target atoms per cm^2, and $\epsilon(k)$ is the detector's efficiency at photon energy k. A typical plot of the photon energy spectrum at $\theta_k=90°$ for 7.0-keV electrons on silver is shown in Fig. 2. The energy spectrum shows a well-pronounced characteristic Ag L peak around $k\approx3.0$ keV over a continuous bremsstrahlung background of a well-defined high-energy "tip." The Ag L line could not be resolved into its constituent components due to insufficient resolution of the Si(Li) detector. The cutoff of low-energy photons below about 2.0 keV arises due to poor efficiency of the detector and to a partial absorption of x rays in the target. However, no data below $k=4.0$ keV have been included in the analysis due to presence of Ag L ($k\simeq2.9$–3.5 keV) and Au M ($k\simeq2.1$–2.3 keV) lines.

Theoretical calculations [2] predict slowly varying changes in the bremsstrahlung energy spectrum as a function of incident energy β (β is the velocity of incident electron in units of the speed of light) and of photon energy k, in addition to a strong dependence of Z^2. Measurements of absolute DDCS's often bear large uncertainty, because of which they are not very sensitive to the above-mentioned variations. However, the experimental uncertainties can be reduced to a considerable extent if the ratio of the DDCS for two targets is measured as discussed below.

The ratio of theoretical bremsstrahlung DDCS's for

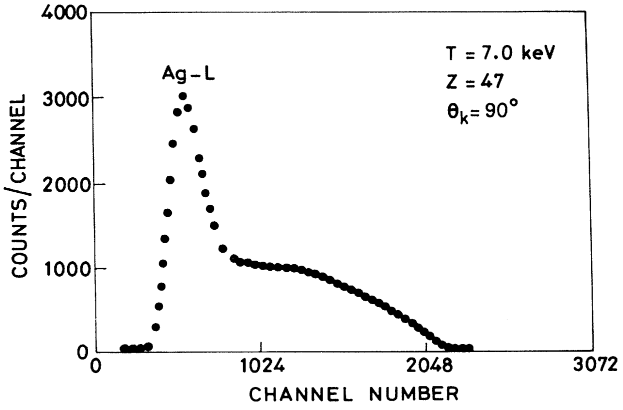

FIG. 2. Bremsstrahlung-photon energy spectrum from 7.0-keV electrons incident on a thin Ag target. The angle of photon emission $\theta_k=90°$.

two elements X and Y with respective atomic numbers Z_X and Z_Y for the same values of T, k, and θ_k can be written as

$$\left[\frac{\beta^2}{Z_X^2}\right]k\frac{d^2\sigma_X}{dk\,d\Omega}\Big/\left[\frac{\beta^2}{Z_Y^2}\right]k\frac{d^2\sigma_Y}{dk\,d\Omega}=R_1 \tag{2}$$

or

$$\frac{d^2\sigma_X}{dk\,d\Omega}\Big/\frac{d^2\sigma_Y}{dk\,d\Omega}=R_1R_0\,, \tag{3}$$

where

$$R_0=\left[\frac{Z_X^2}{Z_Y^2}\right].$$

The experimental ratio of DDCS's for the above elements can be calculated using Eq. (1) with respective photon counts $N_B^X(k)$ and $N_B^Y(k)$ accumulated within the energy window Δk as

$$\left[\frac{d^2\sigma_X}{dk\,d\Omega}\right]\Big/\left[\frac{d^2\sigma_Y}{dk\,d\Omega}\right]=R_2\frac{N_B^X(k)}{N_B^Y(k)}\,, \tag{4}$$

where $R_2=(N_eN_t)_Y/(N_eN_t)_X$. In this ratio, the solid angle $\Delta\Omega$, the detector efficiency $\epsilon(k)$, and the chosen energy width Δk are canceled. Hence a comparison of experimental and theoretical ratios of DDCS's yields

$$R_1=\frac{R_2}{R_0}\frac{N_B^X(k)}{N_B^Y(k)}=R_3\frac{N_B^X(k)}{N_B^Y(k)}\,. \tag{5}$$

R_3 is a simple scale factor that depends on the target thickness, the total of incident electrons, and the atomic numbers (densities) of X and Y. The individual uncertainties in these quantities have no effect on the photon energy dependence of the cross-section ratios. The total uncertainty is thus reduced to a much smaller value that originates basically from the uncertainties in variation of incident electron energy and in counting statistics.

The uncertainty in the incident beam energy is of the order of 1% and that in counting statistics is less than 3% in the present measurements. Hence the total uncertainty, when combined in quadrature, amounts to less than 4%. It should also be noted further that by considering the ratio of the DDCS's for two targets, the contribution of the thick-target bremsstrahlung produced, if any, in the hostaphan vacuum window by elastically scattered electrons is almost canceled out [3]. We thus obtain the relative shape of the photon energy spectrum to a precision of about 4% or better, which is comparable to the theoretical uncertainty of 5%.

The bremsstrahlung data for Ag and Au targets are presented in Fig. 3 for 7.0-keV electrons wherein the plotted quantities on the Y axis are the DDCS ratios for Ag and Au, (R_1R_0) and $\{R_2[N_B^X(k)/N_B^Y(k)]\}$ [see Eqs. (3) and (4)], and on the X axis are the fractions of photon energy radiated (k/T). Experimental data are found to overestimate the theory by about 20%; however, the relative shape of the photon energy spectrum remains unchanged at all photon energies between 4.0 and 7.0 keV.

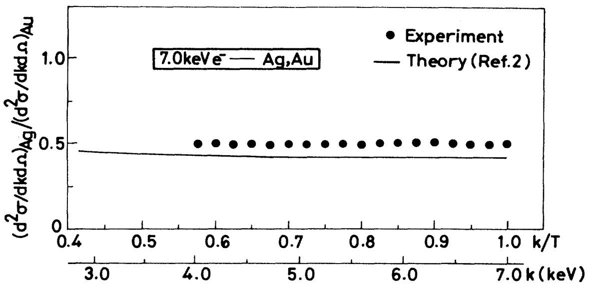

FIG. 3. Ratio of the DDCS of bremsstrahlung photons for 7.0-keV electrons on Ag and Au vs the fraction of photon energy radiated k/T.

The above discrepancy between experiment and theory is expected to be due largely to the thick-target effect in the present measurements caused by energy loss and backscattering of incident electrons and by x ray absorption in the target. The corresponding losses of x ray photons are expected to be larger for Au than for Ag due to the higher values of Z and the thickness of the former. To this effect [5], we have cross-checked the experimental DDCS ratio for Ag and Au, e.g., at $k/T=0.8$; the corresponding value is found to scale within 19% for (Z_{Ag}/Z_{Au}) and within 42% for $(Z_{Ag}/Z_{Au})^2$. This analysis tends to suggest that the data are influenced by the thick-target effect, which follows a Z dependence, in contrast to a Z^2 dependence in the case of very thin targets. The actual value of the simple scale factor R_3 is obtained to be 1.4. As mentioned earlier, its absolute magnitude has no effect on the relative shape of the photon energy spectrum. In Fig. 3, the filled circles represent our data and the solid line gives the theoretical prediction [2]. We have plotted the data for $k>4.0$ keV; the data for $k<4.0$ keV contain the characteristic Ag L and Au M x-ray lines and they have been omitted in the plot. The agreement between experiment and theory on the relative shape of the photon energy spectrum is found to be excellent within an experimental uncertainty of less than 4%. We have also calculated the absolute efficiency of our photon detector in the photon energy range of $k=2.0-7.0$ keV using Eq. (1) and following the procedure given in Ref. [6] and compared the values with those determined by a calibrated radioactive source. The calculated absolute efficiency is found to agree with the normalization to the radioactive source within the uncertainty in the target thickness of about 20%.

In summary, we have measured the ratio of the DDCS of the bremsstrahlung spectrum from 7.0-keV electrons incident on thin Ag and Au targets. Agreement between experiment and theory for the relative shape of the photon energy spectrum is found to be excellent, within the estimated 5% uncertainty in the theory; however, the thick-target effect introduces a discrepancy between experiment and theory by about 20%. The efficiency values calculated using theoretical bremsstrahlung cross sections and using a calibrated radioactive source are found to be in agreement within 20% error. The study of angular distributions of the bremsstrahlung spectra from keV electrons with gaseous targets is in progress.

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