Continuum X-ray Background in the Collisions of Protons with Thick Targets of Ge, Ho, and Au at 50-300 keV

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An extensive study of cross sections for the production of characteristic x-rays has been carried out for proton bombardment of a wide variety of targets in the energy range of 50-300 keV [1]. In the work reported here, we have focused on the x-ray spectra obtained with a select set of targets (Ge, Ho, Au) in order to study the underlying continuum background. Two possible mechanisms are being considered. First is the bremsstrahlung from secondary electrons ejected from the target atoms in binary collisions with the projectile (SEB). The predominant contribution to this process comes from ejection of the nearly free valence electrons. However, the bremsstrahlung from these electrons has a kinematic cutoff below 0.65 keV for protons with energy under 300 keV, while the observed continuum background extends to much higher energies. On the other hand, inner-shell electrons of the target atoms can be ejected with high energy due to their large momentum component in the direction of the projectile velocity. Therefore, they are expected to contribute significantly to the bremsstrahlung above the quasi-free electron cutoff.

A second process that may contribute is polarization bremsstrahlung (PB), i.e. radiation by the target atom electron cloud while being polarized by the projectile charge. The kinematic endpoint for this process also extends to energies well above the quasi-free electron cutoff mentioned above [2]. For example, for 300 keV protons, the endpoint is at 33.5 keV for Ho and at 38.0 keV for Au. Calculations of PB for 1 MeV protons on Cu have been reported by Korol, Solovyov, Obolenski, and Lyalin [3]. They have also provided calculations for Ge [4] for comparison with the data considered here. Their calculations suggest that the contribution to the continuum x-ray spectrum from PB may be important, especially for heavy projectiles at low energies.

The data were taken using the University of Nebraska 350 kV Cockcroft-Walton accelerator. A current integrator connected to the target ladder was used to determine the number of protons hitting a target. X rays were measured with a Si(Li) detector equipped with an ultra-thin boron-nitride window. To minimize dead-time effects from detection of very soft x rays, one or two layers of 6 :m thick doubly-aluminized Mylar absorber were placed in front of the detector. The relative efficiency of the detector was determined using the model equation described in [5]. Its absolute efficiency was determined using radioactive standards for photon energies above the Si K edge (1.84 keV) and using thick-target analysis along with ECPSSR K x-ray production cross sections for photon energies below the Si K edge.

The SEB calculations presented here are based on the following scenario. The projectile travels inside the target (positioned at 90° relative to the beam direction), gradually losing its energy with negligible angular straggling. (a) At some depth *z* inside the target the projectile collides with a target-atom electron. The electron emerges from the collision as a binary encounter (BE) electron with a kinetic energy E_e, traveling in the direction defined by the polar angle θ and the azimuthal angle ϕ. The positive y direction is chosen to be upward. It is assumed that the range of the BE electron is small compared with the diameter of the target and the target-to-detector distance, but not necessarily small compared with the target thickness. (b) The BE electron emits bremsstrahlung photons while inside the target. (c) The emitted photons propagate through the target material on their way to the detector (positioned at 135° relative to the beam direction).

The number of detected photons with energy from the interval (k, $k+\Delta k$) per beam particle, $\Delta N_{det}^{BS} / N_p$, is then equal to

$$\frac{\Delta N_{det}^{BS}}{N_p} = \int dz\, P_c(z) \int dE_e \int d(\cos\theta) \times \int d\phi\, P_b(z, E_e, \theta, \phi)\, P_a(z, E_e, \theta, \phi) \;, \quad (1)$$

where P_a, P_b and P_c, respectively, are the (differential) probabilities for the events (a), (b), and (c) described above.

The probability P_a is given by the following expression:

$$P_a(z,E_e,\theta,\phi) = \frac{N_A\, \rho_2}{A_2} \frac{d^2\sigma_{BE}(z,E_e,\theta,\phi)}{dE_e d\Omega} \;, \quad (2)$$

where $d^2\sigma_{BE} / (dE_e\, d\Omega)$ is the doubly differential cross section for the production of BE electrons in the collisions between projectile nuclei and target-atom electrons in the laboratory frame [6]. It was derived by transforming the corresponding expression (calculated in the impulse approximation) [7] from the center-of-mass frame.

In the equation above, $d\Omega = d(\cos\theta)d\phi$ is the differential emission solid angle, while N_A is Avogadro's number, ρ_2 is the target density, and A_2 is the target-atom molar mass. The dependence of projectile velocity on depth inside the target was calculated using the method of Ziegler [8].

The number of bremsstrahlung photons with energy from the interval (k, $k+\Delta k$) per BE electron (the probability P_b), was derived using the energy distribution of Storm [9], so that

$$P_b(z,\, E_e,\, \theta,\, \phi) = 2.76\times10^{-6} \times Z_2[(E_e - E_e^{\prime})\, \ln(1+\frac{\Delta k}{k_o}) - \Delta k] \;, \quad (3)$$

where $k+\Delta k \leq E_e$. The quantity $E'_e(z, E_e, \theta, \phi)$ is the energy of the BE electron eventually emerging from the back surface of the target, or zero if the BE electron is stopped inside the target. The calculations of the range of BE electrons and their energy at the surface of the target were based on the relativistic Bethe formula with the Bloch correction [6] assuming a straight-line path of the BE electrons.

Finally,

$$P_c(z) = [1 - \exp(-\sqrt{2}\, \mu\, z)]\, \epsilon \;, \quad (4)$$

where μ and ϵ are the attenuation coefficient and the detection efficiency (including the detector solid angle) for the bremsstrahlung photon at energy k.

Comparison between the SEB model calculations and the measured data is illustrated in Figs. 1 and 2. In general, the SEB calculations reproduce the photon energy dependence of measured data. The two also agree within the order of magnitude at the proton energy of 75 keV

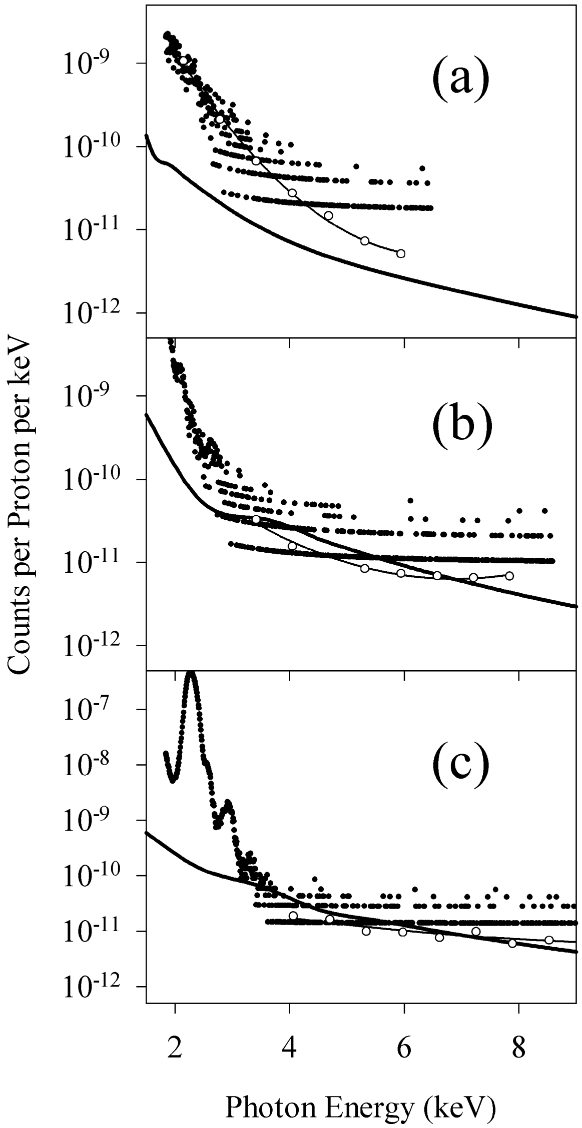

Figure 1: Measured x-ray spectra (solid circles) from the bombardment of (a) Ge, (b) Ho, and (c) Au target with protons at 75 keV. Results of the SEB calculations are shown with thick solid lines. The hollow circles represent numbers of counts in the measured spectra averaged over a large number of channels (50 to 75). The latter plot was added because the data points representing zero counts can not be shown on a log scale.

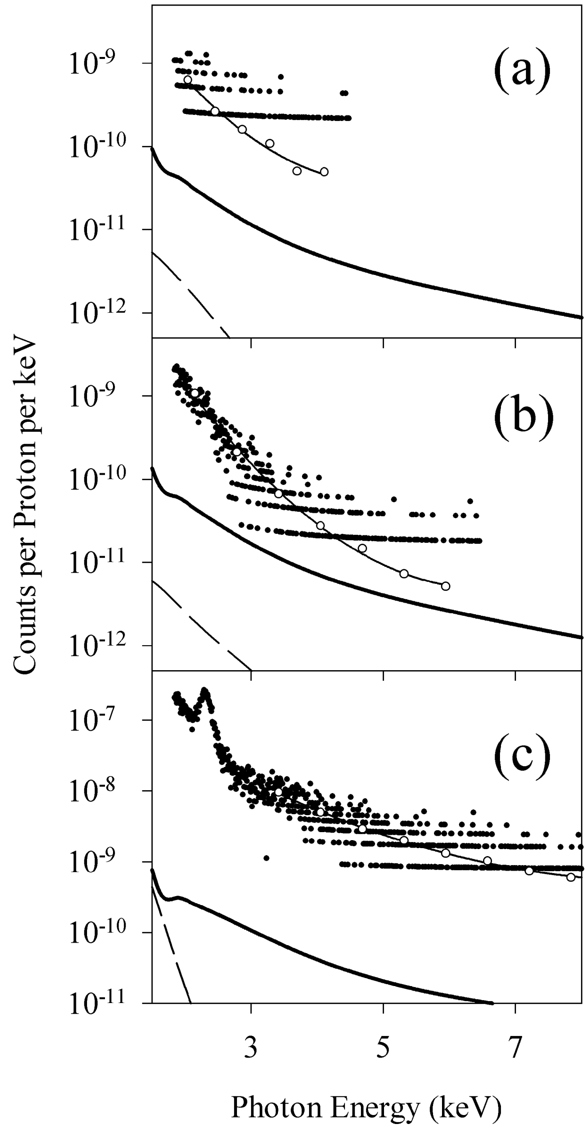

Figure 2: Measured x-ray spectra (solid circles) from the bombardment of Ge target with protons at (a) 50 keV, (b) 75 keV, and (c) 300 keV. Results of the SEB and PB calculations are shown with thick solid and thin dashed lines, respectively. The hollow circles have the same meaning as in Figure 1.

for all three targets (Fig. 1), as well as for the Ge target at the proton energy of 50 keV (Fig. 2a). At the proton energy of 300 keV the SEB calculations under predict the data by about two orders of magnitude for all three targets (as illustrated in Fig. 2c for the case of Ge target). Perhaps there is some background in the data at this higher proton energy that has not been accounted for. The calculated contribution from PB is generally negligible and it tends to fall off too quickly with proton energy to explain the overall shape of the background continuum (Fig. 2). However, the addition of PB to SEB brings the calculations somewhat closer to the measured data at lower photon energies.

This work is a preliminary effort at both the observation of the bremsstrahlung and the development of an SEB model. We have concentrated on thick targets of higher atomic number and proton projectiles at energies from 50 to 300 keV where there has been no previous data.

The SEB model can be improved by using a better approximation for the electron bremsstrahlung. New models for electron bremsstrahlung [10] could be used to provide a numerical approximation to the SEB yield as input to the SEB model. Experimental data with better statistics would also be welcome.

References

[1] S. Cipolla, Nucl. Instr. and Meth. **A422** (1999) 546; S. Cipolla, M. Dolezal, L. Casazza, AIP Conf. Proc. **392**, 113 (1997); S. Cipolla, Nucl. Instr. and Met. **B99**, 22 (1995).

[2] K. Ishii, Nucl. Instr. and Meth. **B99**, 163 (1995).

[3] A. Korol, A. Lyalin, Obolensky, and A. Solovyov, 21st ICPEAC Book of Abstracts, Sendai, Japan, p. 517 (1999).

[4] Korol, A. Lyalin, Obolensky, and A. Solovyov, private communication.

[5] S. Cipolla and S. Watson, Nucl. Instr. and Meth. B **10**/B **11**, 946 (1985).

[6] V. Horvat and R. L. Watson, J. Phys. B **34**, 777 (2001).

[7] D. H. Lee, P. Richard, T. J. M. Zouros, J. M. Sanders, J. L. Shinpaugh, and H. Hidimi, Phys. Rev. A **41**, 4816 (1990).

[8] F. Ziegler (1996), program SRIM, private communication.

[9] E. Storm, Phys. Rev. A **5**, 2328 (1972).

[10] M. Semaan and C. A. Quarles, to be published in X-ray Spectrometry (2001); C. Schiebl, "Review of Sesame Program to Calculate Bremsstrahlung and Characteristic X-Rays", presentation at CAARI 2000.