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著者	Yamadera A., Ishii K., Sera K., Sebata M., Morita S.
journal or publication title	CYRIC annual report
volume	1980
page range	143-147
year	1980
URL	http://hdl.handle.net/10097/48592

V. 28 Quasifree Electron Bremsstrahlung Induced by Projectile Field

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Continuum x-ray emission from solid or gas targets bombarded by heavy-charged particles or heavy ions has been studied by several groups of researchers.[1-9] As the origin of these x rays, following processes have been considered: secondary-electron bremsstrahlung (SEB),[2,5-8] molecular orbital x rays (MO), radiative ionizations (RI),[3,9] radiative electron capture (REC),[1,4] nuclear bremsstrahlung[5] and γ rays from nuclear reactions. In a case of low-energy heavy-charged-particle bombardments, SEB is generally the most predominant one among these processes. However, if the velocity of projectile v_p is large enough in comparison with the velocity of orbital electron, the orbital electron can be considered as free and at rest, and in the center-of-mass frame, the electron collides with the projectile with the relative kinetic energy $T_r = \frac{1}{2} m_e v_p^2$ — m_e is the electron mass —, and the bremsstrahlung is produced by the interaction between the projectile and the orbital electron. We call this process the quasi-free-electron bremsstrahlung (QFEB). The spectrum of QFEB is therefore characterized by the relative kinetic energy T_r. These x rays were first observed by Schnopper *et al.*[1] in a case of heavy-ion collision and was called primary bremsstrahlung.[2] Theoretical calculations of this process have been achieved by Jakubatssa and Kleber,[3] and they called this process radiative ionizaitons. Experiments on QFEB have mostly been done in heavy-ion collisions, where MO x rays and REC are dominant, and QFEB by itself has not been identified.

Here, we have systematically measured the continuum x rays from Be, C and Al targets bombarded with 6-40-MeV protons from the cyclotron, and the results are discussed in connection with calculations of QFEB based on PWBA and of SEB based on BEA.

The production cross section of the QFEB based on PWBA is expressed by[11]

$$\frac{d\sigma^{QFEB}}{d\Omega d(\hbar\omega)} = \frac{N_T}{\pi} Z_p^2 \left(\frac{e^2}{\hbar c}\right)^5 a_o^2 \frac{m_e c^2}{T_r \hbar\omega}$$

$$\times \left[\{\sin^2\theta + \frac{1}{4}(1 + p^2)(3\cos^2\theta - 1)\, \ell n\left(\frac{1+p}{1-p}\right)\right.$$

$$\left. - \frac{1}{2} p(3\cos^2\theta - 1)\right], \qquad (1)$$

where $p^2 = 1 - \hbar\omega/T_1$, N_T is the number of electrons of the target atom, Z_p is the atomic number of the projectile, a_o is the Bohr radius, $\hbar\omega$ is the energy of emitted photon, and θ is the angle between directions of the projectile and the photon emission. The formula of QFEB for the case where the velocity of an orbital electron is not negilible in comparison with the projectile velocity has been given by Jakubatssa and Kleber[3] on the basis of PWBA. In conformity with their calculation, which takes account of the velocity distribuiton of orbital electrons, the angular distribution and the spectrum of the emitted photons are expressed by

$$\frac{d\sigma^{QFEB}}{d\Omega d(\hbar\omega)} = \sum_i N_i \frac{2}{\pi} z_p^2 \left(\frac{e^2}{\hbar c}\right)^5 a_o^2 \frac{m_e c^2}{T_r \hbar\omega}$$

$$\times \int_0^\infty dk_f \int_0^\infty dT \, \rho_i(k_z^2 + T) \, G(k_f, T, \theta), \qquad (2)$$

where

$$G(k_r, T, \theta) = \left(\frac{1}{2}\sin^2\theta' + \mathrm{con}^2\theta'\right) \frac{k_f^4}{B^2-4C^2}$$

$$+ \left(\frac{1}{2}\sin^2\theta' - \cos^2\theta'\right) \frac{k_f^4}{4C^2} \left\{1 + \frac{B^2}{B^2-4C^2} + \frac{B}{C} \ln \left|\frac{C-k_f^2}{C+k_f^2}\right|\right\}$$

$$- 2\sin^2\theta' \, D k_f^2 \left\{\frac{B}{B^2-4C^2} + \frac{1}{4C} \ln \left|\frac{C-k_f^2}{C+k_f^2}\right|\right\}$$

$$+ \sin^2\theta' \frac{D^2C^2}{B^2-4C^2} ,$$

with

$$B = (k_o + k_z)^2 + T + k_f,$$

$$C = k_f \sqrt{(k_o + k_z)^2 + T} ,$$

$$D = \hbar\omega\left[\hbar\omega + U_i + \frac{\hbar^2}{2m_e}(k_z^2 + T)\right],$$

$$\cos^2\theta' = \{(k_o+k_z)^2 \mathrm{cons}^2\theta + \frac{1}{2} T \sin^2\theta\}/\{(k_o+k_z)^2+T\},$$

$$k_z = \frac{m_e}{\hbar^2 k_o}\left(\hbar\omega + U_1 + \frac{\hbar^2 k_f^2}{2m_e} - T_r\right),$$

$$k_o^2 \equiv \frac{2m_e}{\hbar^2} T_r .$$

and N_i is the number of electrons in the i-shell, U_i is the ionization energy of the i-shell, $\rho_i(k^2)$ is the velocity distribution of the i-shell electrons and is normalized by

$$\int_0^\infty k^2 dk \rho_1(k^2) = 1. \qquad (3)$$

The QFEB spectra calculated from Eqs. (1) and (2) for 20-MeV proton bombardments of Be and Al targets are illustrated in Figs. 1(a) and (b), where no difference in the spectrum is found between Eq. (1) and Eq. (2) for Be, while a difference is seen for Al. This fact reveals that the QFEB spectrum becomes dependent on the velocity distribution of orbital electrons with increase in the atomic number and the steep rise of the spectrum near the high-energy limit $\hbar\omega = T_r$ is smoothed out for higher atomic number. Electrons ejected from a target atom by the projectile interact with other atoms in the target and produce the bremsstrahlung. This SEB was analysed first by Folkmann[5] and then in more detail by Ishii *et al.*[7,8] This continuum x-ray spectrum is characterized by the maximum energy $T_m = 2m_e v_p^2$ that can be transferred from the projectile to a free electron.

In the continuum x-ray spectra from Be target shown in Fig. 2, contribution from QFEB and the Doppler shift are clearly observed at all the proton energies. The cross sections of QFEB and SEB for Be are compared with experimental results in Fig. 3. Agreement between the theory and the experiment is quite satisfactory. Since the Be target used is very thick — 46 mg/cm^2, escape probability of the secondary electron from the target is expected to be negligible and the SEB calculated must be a good approximation. The projectile-energy loss in the Be target amounts to about 2 MeV and 0.6 MeV, respectively, for 9- and 40-MeV protons. On the other hand, the cross sections for QFEB and SEB gradually increase with increase in the projectile energy. Hence, the theoretical calculation neglecting the effect of projectile-energy loss can well be compared with the experiment as in Fig. 3.

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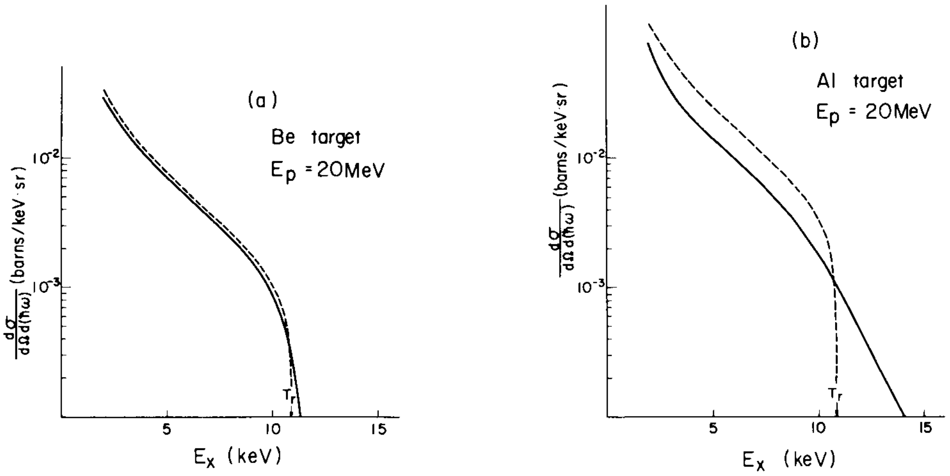

Fig. 1. Comparisons between the QFEB spectra calculated from Eq. (1) and from Eq. (2) for Be (a) and Al (b) targets.

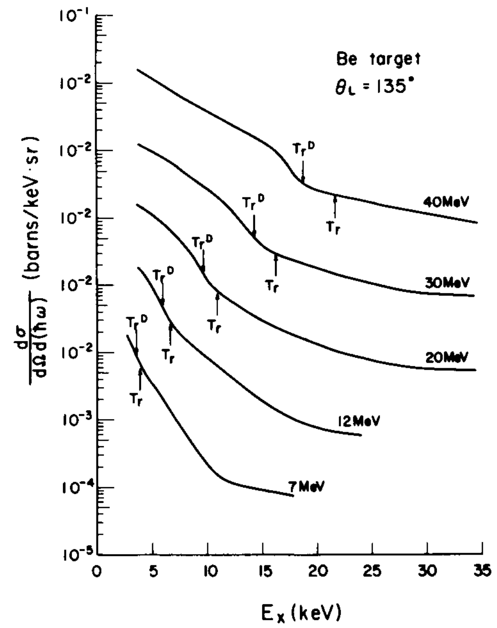

Fig. 2. Production cross sections of the continuum x rays from the Be target plotted as a function of photon energy. The notation T_r is the kinetic energy of orbital electron in the projectile frame, and T_r^D is that in the laboratory frame taking account of the Doppler shift.

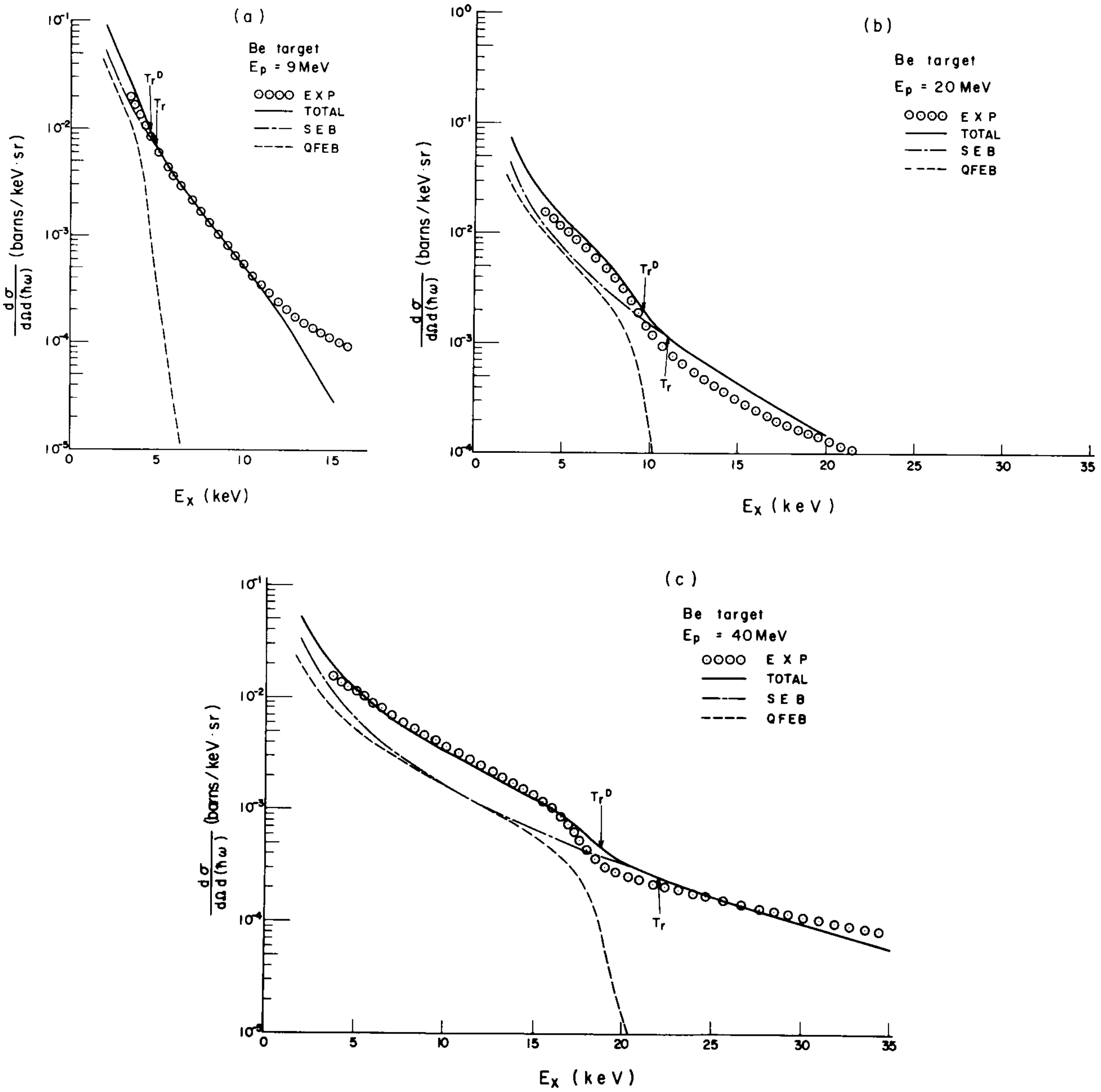

Fig. 3. Comparisons between the experimental cross sections and the theoretical ones of the QFEB and SEB for the Be target.