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ABSTRACT

We have observed up to eight orders (n) in the spectra of parametric x-radiation, in the range 5-40 keV, produced by the interaction of a 90 Mev electron beam with mosaic graphite and 90 and 35 Mev beams with single silicon crystals. The measured yields and intensity ratios, I(n≥2)/I(n=1), in graphite are not in agreement with the theory of PXR for mosaic crystals. In comparison, the yield and ratios of intensities in silicon are close to the predictions of PXR theory for perfect crystals. The bandwidths of spectral lines measured in both silicon and graphite are in good agreement with theoretical predictions, and are determined by the angular field of view of the detector.

INTRODUCTION

The phenomenon of parametric x-radiation (PXR) produced by a charged particle interacts with a crystal was first predicted in the early 1970's[1-3]. Since then, a number of classical and quantum electrodynamical theorical treatments of PXR have been developed, based on kinematical approximation[4], and on the dynamical theory of x-ray diffraction[5-8]. These theories predict PXR to be highly directed, quasi-monochromatic, tuneable, polarized, spectrally intense[6-10] and, at small Bragg angles, a particularly efficient, bright source of hard x-rays[8]. Such properties make it potentially useful for a wide variety of applications [10,11]. Experimental studies of PXR from beams with energies from 25 to 900 MeV interacting with several types of single crystals have generally verified the predicted angular distribution, bandwidth and polarization of PXR[12-18]. However, we have recently reported the first measurements of PXR spectra in Bragg from a mosaic crystal[19], compression annealed pyrolytic graphite, in which the measured yields for higher order spectra do not agree with theoretical predictions of the single crystal theory. In contrast, the ratio of intensities in single crystal silicon do follow theoretical predictions. The measured bandwidths of PXR spectral lines, in both types of crystals are shown to be determined by aperture of the detector.

THEORY

The spectral-angular distribution of PXR from a perfect crystal has been given in Ref. 5,6 and 19. The spectral distribution is obtained by integreting this expression is integreted over the solid angle subtended by the detector, $d\Omega=\Delta\theta_x\Delta\theta_y$, where $\Delta\theta_x$ and $\Delta\theta_y$ are the angular fields of view in and out of the plane of observation, respectively. When $\Delta\theta_x >> \rho_s$,

$$\frac{\partial N}{\partial \omega} = \frac{e^2}{\hbar c}\frac{|\chi_{10}|^2 \cdot e^{-2M}}{(4\sin\theta_B\cos\theta_B)}\frac{L_a(1-e^{-L/L_a})}{\pi c\theta_p} J_2(\alpha_y, u) \cdot S(\alpha_x-|u|), \qquad (1)$$

where

$$J_2(u) = \cos^2(2\theta_b)\, u^2 \left[\frac{\alpha_y}{1+u^2}\cdot\frac{1}{\alpha_y^2+1+u^2} + \tan^{-1}\left(\frac{\alpha_y}{(1+u^2)^{1/2}}\right)\cdot\frac{1}{(1+u^2)^{3/2}}\right] + \left[\tan^{-1}\left(\frac{\alpha_y}{(1+u^2)^{1/2}}\cdot\right)\frac{1}{(1+u^2)^{1/2}} - \frac{\alpha_y}{(\alpha_y^2+1+u^2)}\right] \quad (2)$$

$u \equiv [(\omega-\omega_B)/\omega_B](\tan\theta_B)/\theta_p = \theta_x/\theta_p$, $S(\alpha_x - |u|)$ is the step function which is unity when its argument is positive and is zero otherwise. $\alpha_{x,y} = \Delta\theta_{x,y}/2\theta_p$, where $\theta_p = (\gamma^{-2} + |\chi_0| + \theta_s^2)^{1/2}$, and $\theta_s^2 = \theta_d^2 + \theta_{scat}^2 + \theta_{mos}^2$ is included, ad hoc, to approximate the effects of beam divergence, multiple scattering and mosaicity[11]. θ_B is the Bragg angle, θ_x, θ_y are the angular displacements away from θ_B, in and out of the incidence plane respectively, χ_0 is the mean dielectric susceptibility, χ_{10} is the structure factor, $\rho_s = \lambda/2\pi L_a(\omega)$, $L_a(\omega)$, L are the absorption and path lengths respectively, and e^{-2M} is the Debye-Waller (DW) factor. $\omega_B(n)=n\pi c/d\sin\theta_B$, where d is the interplanar spacing of the set of crystal reflecting planes, and n is the spectral order. In deriving Eq.(1) we use a δ function approximation which correlates θ_x and $\omega-\omega_B$, and also connects the finite aperture of the detector $\Delta\theta_x$ with the observed spectral bandwidth, $\Delta\omega$. This use of the δ function is essentially a kinematic approximation which has been shown[4] to be adequate for comparison with experiments when $\gamma^{-1} >> |\chi_{10}|$, which is the case for our experiments. In the case of a very narrow detector aperture ($\Delta\theta_x \sim \rho_s$), the δ function approximation cannot be used, and the spectral distribution will be a Lorentian function with a full width $\sim \rho_s$. To date no experimental measurements have been reported for this natural or narrow line width regime. When $\Delta\theta_{x,y} \to \infty$, Eq.(1) reduces to Eq. (8) of Ref. (6).

For most experimental situations, $\infty > \Delta\theta_x > \rho_s$. Then, if $\Delta\theta_x/\theta_p < \Gamma_2$, the FWHM of J_2, S limits the bandwidth in Eq. (1), i.e. $\Delta\omega \propto \Delta\theta_x$, otherwise, $\Delta\omega \propto \Gamma_2$. We shall refer to these situations as the *far case* and *near case*, respectively. Far case conditions apply to all the experiments previously reported. These two regimes are illustrated in Figure 1, which shows spectral function J_2 and the aperture function, $S(\alpha_x - |u|)$ superimposed for both far and near cases.

EXPERIMENTAL RESULTS

We have reported[19] the PXR spectra from the <111> and <022> planes of silicon (Si) in a Laue geometry for the far case condition, and the <002> planes of mosaic graphite in a Bragg geometry for both far and near cases. Si crystals 20, 44 and 320 μm thick, and a 1.39 mm thick mosaic graphite crystal (0.4° mosaic spread) were used. In these experiments $\theta_B = 22.5°$. The Si crystals were cut so that the <022> planes are oriented at 90 degrees relative to the crystal face, whose normal is in the <200> direction. For the graphite, the <002> reflection planes are parallel to the face of the crystal. The experimental setup is described in Refs.(17) and (19). We use Si(Li) detectors to detect the x-rays and a gated multichannel analyzer is used to obtain the x-ray energy spectra. The methods used for energy calibration, measurement of the resolution of the detector and determination of the absolute PXR yield (photons/electron), η for graphite, is described in the accompanying paper presented by X.K.Maruyama et. al.[20]

The PX spectrum from the <002> planes of graphite, for the far case exhibits 8 spectral lines. This result can be qualitatively explained by considering the energy dependence of the terms containing L_a and χ_{10} in Eq.(1). As the energy of the order increases, L_a increases so that for n>2 the production becomes proportional to the path length L, since $L_a(\omega) > L$ for E > 10 keV. The term $|\chi_{10}|^2$ decreases with increasing energy, but not as fast as L_a increases.

However, as shown in Table I, the measured higher order yields are higher than calculated using Eq.(1). Similar results are obtained for the near case. The values of θ_s^2 used to calculate the theoretical yields in Table I. include θ^2_{mos} and θ^2_{scat}, which is obtained from the Bethe-Ashkin multiple scattering formula in which we use $\langle x\rangle \equiv \int x e^{-x/La}dx / \int e^{-x/La}dx$, the effective crystal thickness, to account for absorption in the crystal. The theoretical values and ratios have been corrected from those of ref. 19, in which FWHM instead of RMS values for θ^2_{mos} and θ^2_{scat} were incorrectly used. We have previously measured the beam divergence, θ_d^2 of the Naval Postgraduate School linac at 90 MeV using optical

transition radiation interferometry[21] to be $\approx 10^{-6}$ which is much less than θ^2_{mos}, θ^2_{scat} for all energies considered, and is thus negligible. In view of the large discrepancies between theory and experiment in mosaic graphite we are pursuing several possible approaches to improve the theory for mosaic crystals. These are discussed in the accompanying paper by D.Rule, A. Pak and R.B.Fiorito[22]. In addition, experiments using graphite crystals with larger mosaic spreads are currently in progress.

Figure 2 of ref. 19 shows a comparison of the PXR spectra from the <111> planes of single crystal Si for three different thicknesses: 20, 44 and 320 μm. The spectra of the 44 and 320 μm crystals show the n=3 and n=4 spectral lines but as seen in x-ray scattering, the selection rule for normal x-ray scattering for diamond-like, face centered cubic crystals such as silicon forbid the n=2 reflection. This effect has also been observed by Asano et. al.[23] The appearence of the <333> line at ~15 keV, and the <444> line at ~21 keV, in the these crystals is due to the fact that $\eta \propto L$, since $L_a >> L$ at these energies. The 20 μm spectrum exhibits a single line and dramatically shows how one can produce a single photon energy PXR spectrum by chosing the path length L appropriately. A comparison of measured and theoretical ratios of integrated intensities for each order is also given in ref. 19, which shows the measured ratios in Si to be much closer to the theoretical predictions than in mosaic graphite. For single crystal Si, $\theta^2_{mos}=0$, and θ^2_s contains only the θ^2_{scat} contribution which has only a small effect on the calculated values.

More recently we have measured the absolute yield of PXR from the <111> planes of 1 mm thick Si in a Bragg geometry, at an electron beam energy of 35 Mev at the Naval Research Laboratory. The electron beam current is measured by observing the fluorescence of the Si Kα line at 1.72 keV. For this experiment we use a special Si(Li) detector with a 0.5μ Boron Nitride window. The detector is in the vacuum system. In these experiments $\theta_B=45$ degs. Spectra similar to those taken in the Laue geometry are observed. The measured yield of the first order PXR spectral line at 2.79 keV is 4.1±1 x 10^{-8}, which is in agreement with the single crystal theoretical value of 3.6 x 10^{-8} .

Our measurements of the percent bandwidths of spectral lines observed, averaged over the energy range of observation: $\Delta\omega/\omega_B$ = 3.2±1.5% (graphite) and 4±1.8% (Si) for the far case, and 6.1±3.2% (graphite) for the near case. These values are in excellent agreement with the predictions of Eq.(2): 3.8% and 7% for the far and near cases, respectively, and explicitly show how the PXR bandwidth is directly correlated and prescribed by the angular aperture $\Delta\theta_x$ for far case conditions for crystals with small mosaic spread.

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TABLE I. PXR YIELDS IN GRAPHITE

n	E (kev)	η_{meas} (N/elec) x 10^{-6}	η_{meas}/η_{thy} $\theta_s^2>0$	η_{meas}/η_{thy} $\theta_s^2=0$
1	4.88	1.67	0.25	0.13
2	9.53	1.72	1.8	0.36
3	14.29	0.85	4.6	0.79
4	19.08	0.42	10.2	1.54
5	23.88	0.23	20.4	3.04
6	28.68	0.13	42.8	6.18
7	33.56	0.07	89.4	12.3
8	38.44	0.03	160.0	260.0