Intensity of Electron Channeling Radiation and Occupation Lengths in Diamond Crystals

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The intensity of channeling radiation from natural diamonds of thicknesses of 13 to 55 μm has been investigated at electron energies of 5.2 and 9.0 MeV. The intensities scale with electron energy according to $\gamma^{5/2}$ and vary with the crystal thickness d as $(1-e^{-\lambda d})$, from which the occupation length λ^{-1} of the electronic states in the crystal could be deduced. It amounts to 18 and 29 μm for 5.2 and 9.0 MeV electrons, respectively. The strongest transition has an intensity of 0.1 photon per e^- per sr.

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Channeling radiation is emitted by relativistic electrons or positrons passing through single crystals along a direction of high symmetry, i.e., a plane or an axis. The general properties of this process have been investigated intensively during recent years [1-3]. With the advent of a new generation of electron accelerators, like, e.g., the superconducting Darmstadt electron linear accelerator S-DALINAC [4], providing cw electron beams with a normalized emittance as low as $\epsilon \sim 1\pi$ mm mrad, the details of the interaction between the incoming electrons and the constituents of the crystal can be studied more qualitatively due to a selective preparation of crystal states with sufficiently large intensities.

Here the intensity of the channeling radiation, which depends on various aspects such as the electron beam divergence, the electron crystal interaction, and the population of and transitions between electronic states, is investigated with high quality beams from the S-DALINAC and various thin crystals of natural diamonds. Such investigations are of importance not only for a better understanding of the channeling process itself, but also for possible applications of channeling radiation as a monochromatic, bright, and tunable x-ray source [5-13].

The radiation intensity is determined by the product of the dipole transition probability times the population probability $P_n(z)$ of the intitial state integrated over the crystal thickness d according to

$$\frac{d^2N_{\text{if}}}{dE_{\text{ch}}d\Omega}=\frac{d^3N_{\text{if}}}{dE_{\text{ch}}d\Omega dz}\int_0^d P_n(z)dz\,, \tag{1}$$

where N_{if} denotes the number of transitions with energy E_{ch} between initial and final states emitted into a solid angle $d\Omega$, and the integration proceeds along the electron path z through the crystal. The population of an electronic state depends on the initial population, which is a function of the electron beam divergence and the entrance angle of the beam onto the crystal, and on various scattering processes that might feed or depopulate the state under consideration. With electron beams of low beam divergence ($\varphi < 2$ mrad) the initial population is different for each state.

At the S-DALINAC where the beam divergence amounts to about 0.3 mrad, channeling radiation studies with a noteworthy difference in the initial population, especially also between odd and even states, become possible as in [14], but for the first time with electron beams interacting with the crystal without having passed any apertures before. Because of scattering processes the population of state changes along the electron path z through the crystal, resulting in a decreasing population of the even states and an increasing population of the odd states at the beginning of the path. The feeding of odd states is finally compensated by losses, and beyond a characteristic length, called the equipopulation length l_{eq}, each state exhibits the behavior of a decreasing population only. It should be noted, however, that the precise value of this length will depend on the incidence conditions of the beam as angle and divergence. Hence l_{eq} is most useful as a qualitative concept. The so-called occupation length $l_{\text{occ}}=\lambda^{-1}$ describes the distance over which the population decreases by a factor of $1/e$. Here we wish to relate the measured intensity of a transition to the quantity l_{occ} of the initial state [8] under the condition of an electron beam of very small divergence.

In this Letter we report on intensity measurements of various channeling radiation lines obtained by bombarding diamond crystals with electrons of 5.2 and 9.0 MeV. The experiments were performed at the low energy channeling site [9,10] behind the 10 MeV injector of the S-DALINAC. The beam divergence was selected to be 0.3 mrad, and the current was kept at a few nA in order to keep the counting rate at a level the detector can still process. Photons were recorded with a Si(Li) detector, which subtended a solid angle of 2.6×10^{-6} sr and which was placed in the vacuum directly under zero degree with respect to the beam axis. Four thin natural diamond crystals of type *Ia* were prepared by grinding down thicker samples. A precise determination of their thickness (13 ± 2, 20 ± 2, 30 ± 2, and 55 ± 2 μm) was accom-

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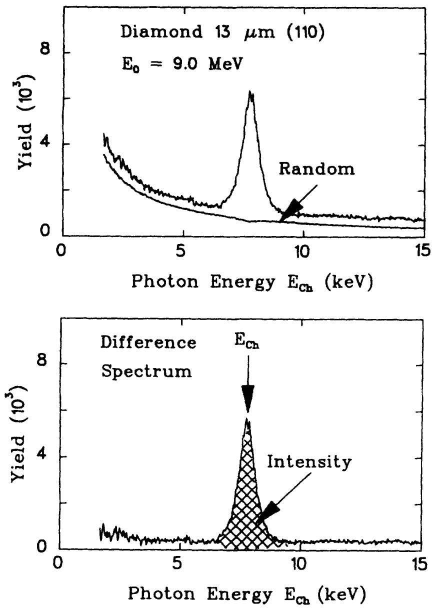

FIG. 1. Channeling radiation spectrum obtained with the crystal aligned in the (110) plane and at random position (upper part). The lower part exhibits the difference spectrum.

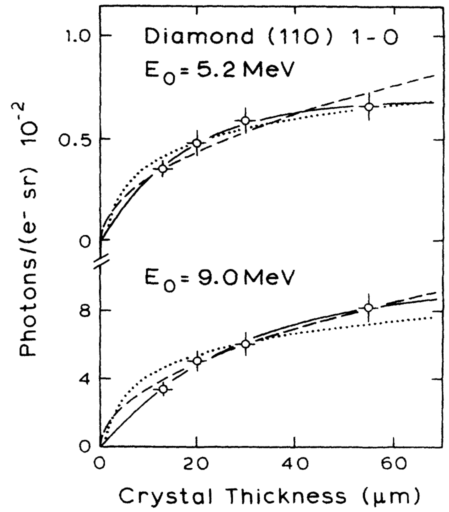

FIG. 2. Intensity of channeling radiation from diamond crystals of various thicknesses z at two bombarding energies. Theoretical predictions based on different approximate solutions of Eq. (2) yield, according to [17], intensities proportional to $(1-e^{-\lambda z})$, $\sqrt{z}$, and from [18] to $\log(z)$ shown as solid, dashed, and dotted lines, respectively.

plished by applying the following independent methods: fast Fourier infrared spectroscopy, energy loss of α particles, bremsstrahlung production, and photon absorption.

A typical channeling radiation spectrum is shown in Fig. 1. The upper part displays a spectrum for electrons channeled along the (110) plane with the peak corresponding to the 1-0 transition. The photon yield for a random orientation is also shown. The difference spectrum in the lower part exhibits for this electron energy and plane a single line at 7.91 keV with a width of 460 eV (FWHM). The ratio of the channeling radiation intensity to the bremsstrahlung background is of the order of 10:1. To our knowledge it is the strongest line ever observed in channeling radiation at low electron energies. Its intensity exceeds the one emitted from other transitions at various crystal planes, and the most intense transition known so far in the ⟨110⟩ axis [9,10] even by a factor of about 2.5.

Fitting a Voigt function, i.e., a convolution of a Gaussian and a Lorentzian in the parametrization of [15], to the lines, a Gaussian that describes contributions from free-to-bound and free-to-free transitions and a function for the increased bremsstrahlung background observed under channeling condition, a unique way to extract the intensity became possible. The intensity is displayed in Fig. 2 for the 1-0 transition as a function of the crystal thickness z for two electron energies. It is evident that it varies smoothly with thickness and about 0.1 photon per e^- per sr can be produced. This makes the 1-0 transition in the (110) plane of diamond an excellent candidate for a bright and tunable photon source of reasonably small bandwidth. From comparison with data from Refs. [12,13] the predicted $\gamma^{5/2}$ dependence ($\gamma = E/mc^2$ with E being the total energy) of the intensity could be confirmed (Fig. 3).

To deduce the equipopulation and occupation lengths l_{eq} and l_{occ} from the measured intensity, assumptions regarding the population probability $P_n(z)$ are necessary. According to Andersen *et al.* [14] the process of feeding and depopulating the electronic states in the crystal is described by a set of coupled differential equations

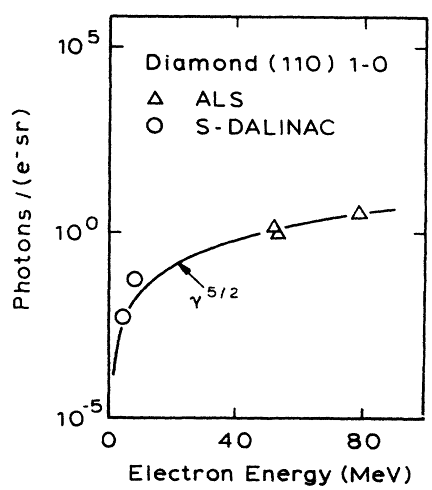

FIG. 3. Intensity of the 1-0 transition in diamond as a function of the electron impact energy. The data denoted by ALS are from Refs. [12,13]. The solid line is fitted to the data points.

$$\frac{dP_n}{dz} = \sum_{n'} W_{nn'}(P_{n'} - P_n) , \tag{2}$$

where P_n and $P_{n'}$ denote the population of states n and n', respectively, and $W_{nn'}$ is the transition rate per unit length describing the interband scattering probability between states n and n'. A complete solution of the master equation (2) requires the calculation of the transition rates $W_{nn'}$ from which the equipopulation length l_{eq} can be deduced. This somewhat elaborate procedure will be presented in a separate paper [16]. Here, we focus only on the occupation lengths. For the crystals used ($d > 10$ μm) approximate solutions [17] of Eq. (2) are $P_n(z) \sim e^{-\lambda z}$ or $P_n(z) \sim z^{-1/2}$. This implies that the radiation intensity should depend upon the crystal thickness z according to

$$I \sim 1 - e^{-\lambda z} \tag{3}$$

or

$$I \sim \sqrt{z} . \tag{4}$$

Both functions have been fitted to the data points as displayed in Fig. 2. It becomes apparent that the data are represented best (solid line) by expression (3). For a better judgment of the quality of the fits, the normalized χ^2 values have been calculated which amount to 0.2 and 0.3 at 5.2 and 9.0 MeV, respectively. Equation (4) describes the data for the lower energy (upper part) also quite well (dashed line) although there are distinct deviations at very thin or thicker crystals. The respective normalized χ^2 values are 1.0 and 0.8 at the two energies. For higher electron energies this effect is less pronounced. This may result from the fact that at 5.2 MeV single scattering dominates yielding an approximate exponential population probability $P_n(z)$ while at 9.0 MeV small angle scattering is increasing with $P_n(z) \sim z^{-1/2}$ as suggested in [17]. For completeness the results obtained from a multiple scattering model [18] yielding $I(z) \sim \log(z)$ is also displayed in Fig. 2 (dotted line), which at 5.2 MeV describes the data better ($\chi^2 = 1.3$) than $P_n(z) \sim z^{-1/2}$, at 9.0 MeV; however, the agreement is less satisfactory ($\chi^2 = 4.0$). It can thus be concluded that at the present energies the data follow an $I \sim (1 - e^{-\lambda z})$ behavior which holds also for the (111) plane of diamond [16].

The occupation lengths $l_{occ} = \lambda^{-1}$ for channeling including the individual accuracies obtained applying Eq. (3) to the (110) and the (111) planes are listed in Table I. The values are about 3 times larger than the corresponding values in Ref. [8] for Si scaled down to our electron energy by multiplying them with the ratio of the respective electron bombarding energies, i.e., by 9/17.

The present investigations thus show for the first time convincingly that diamonds having a high Debye temperature yield more channeling radiation intensity than other crystals. This is due to a lower scattering probability of electrons with the constituents of the crystal, which leads to large occupation and equipopulation lengths. This makes diamonds the ideal candidates for a bright, tunable, and monochromatic radiation source.

TABLE I. Experimental results for occupation (l_{occ}) lengths of diamond for kinetic electron energies and transitions given.

E_0 (MeV)	Plane	Transition	E_{ch} (keV)	l_{occ} (μm)	Δl_{occ} (μm)
5.2	(110)	1-0	3.45	17.5	1.5
9.0	(110)	1-0	7.91	27.6	3.4
5.2	(111)	2-1	2.40	18.9	2.4
9.0	(111)	2-1	5.94	28.8	3.9

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