REF ID: A111111
100-100000-100

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October, 1993

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*This work supported by the U.S. Department of Energy, BES-Materials Sciences, under contract no. W-31-109-ENG-38

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Germanium X-Ray Phase Plates for the Production of Circularly Polarized X-Rays

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We have constructed an x-ray phase plate to produce both linearly and circularly polarized x-rays at discrete energies between 20 keV and 88 keV. The plate is a monolithic two-crystal design, constructed from germanium, which increases the resultant degree of circular polarization of the output beam. We have measured the degree of circular polarization at 65 keV to be $90\% \pm 4\%$, significantly better than that produced by silicon phase plates. This radiation was used to measure the magnetic Compton profile for Fe, which was found to be in good agreement with theory and previous work. The underlying x-ray optics and the characterization of the device between 62 keV and 93 keV at the Cornell High Energy Synchrotron Source are presented.

1. Introduction

Increases in the available flux of circularly polarized x-rays from synchrotron radiation sources have renewed interest in their use as a tool with which to probe condensed matter. Many experiments of this nature require sources with both a high photon flux and a high degree of circular polarization. Such sources include off-axis bending magnet radiation, specialized insertion devices, and x-ray crystal optics. We have built an x-ray optical element, made of single crystal germanium, to produce circularly polarized photons with emphasis in the 50 keV to 100 keV energy range.

Previous attempts at the use of x-ray phase plates for the production of circularly polarized x-rays by Golovchenko et al. [1] and Mills [2] focused on the use of silicon perfect crystals as the diffracting element. Their experiments, performed at energies between 10 keV and 55 keV, demonstrated that a degree of circular polarization (P_c) between 30% and 75% could be achieved. At increasing energies, a higher degree of P_c can be obtained by using a germanium perfect crystal as the diffracting element rather than silicon. Improvement in the degree of circular polarization is, in our case, motivated by magnetic x-ray scattering experiments that are sensitive to the degree of circular polarization of the incident beam [3,4]. Additionally, because the cross section for such scattering experiments increases linearly with the incident photon energy [5], the phase plate was designed to operate at energies up to 88 keV.

2. Theory of Operation

It is well established that a perfect crystal operating in Laue (transmission) geometry is four-refrinct at energies that satisfy Bragg's condition [6]. In such instances, there will be four wave fields present in the crystal, each propagating with a distinct wave vector and, therefore, phase velocity. In addition, if one considers that there are both a diffracted ("H") beam and a transmitted ("O") beam, then there are actually eight wavefields propagating in the crystal at Bragg's condition. In the following, only the "H" beam will be used. Therefore, the discussion is limited to the four different wave fields associated with the diffracted beam.

The four wave fields are characterized by both the location of their nodes within the crystal and also the orientation of the incident polarization with respect to the diffracting planes. Those

wave fields with their nodes located at the atomic sites of the crystal lattice are referred to as α branches, while those with their antinodes at these same sites are referred to as β branches. In addition, those wave fields with polarization parallel to the diffracting planes are referred to as having π polarization, while those wave fields with polarization perpendicular to the diffracting planes are referred to as having σ polarization. Thus, the four electric field vectors in the crystal can be written E^{α}_0 , E^{α}_π , E^{β}_0 , E^{β}_π .

The interaction of the wave fields within the crystal is well described by Golovchenko et al. [1] and Hart [7]. As already noted, the wave vectors propagating through the crystal each propagate with their own distinct phase velocity, and hence there is a phase difference between any two given wave vectors at the exit face of the crystal. In the symmetric Laue geometry, this phase difference can be expressed as:

$$\begin{aligned} \varphi &= 2\pi(\bar{\mathbf{K}}^{\alpha}_{H0} - \bar{\mathbf{K}}^{\pi}_{H\alpha}) \\ &= \frac{t_0 |\Gamma_H| r_e \lambda}{\cos \Theta_B a_0^3} \left(\left((\eta_\sigma^2 + 1)^{1/2} - \eta_\sigma \right) - \left[\cos 2\Theta_B \left((\eta_\pi^2 + 1)^{1/2} - \eta_\pi \right) \right] \right), \end{aligned} \quad (1)$$

where t_0 is the thickness of the crystal, Γ_H is the structure factor for the reflection, Θ_B is the Bragg angle, r_e is the classical electron radius, λ is the incident wavelength, a_0 the lattice spacing, and $\eta_{\sigma,\pi}$ is a dimensionless quantity proportional to the deviation from the perfect Bragg condition as shown below:

$$\eta_{\sigma,\pi} = \frac{\pi a_0^3 \Delta \Theta \sin 2\Theta_B}{r_e \lambda^2 P |\Gamma_H|}. \quad (2)$$

Here, $\Delta \Theta$ is the deviation of the incident x-ray from the Bragg condition, and $P=1$ for η_σ and $\cos 2\Theta_B$ for η_π .

In order for the x-rays at the exit face of the crystal to be circularly polarized, two conditions must be satisfied. First, there must be a 90° (or 270° , 450° , etc.) phase shift between the two orthogonal polarization states σ and π . Second, the amplitude of each of these states must be equal. If these conditions are not satisfied, the resultant beam is elliptically polarized.

By choosing the phase difference in equation (1) to be $(2n+1)\pi/2$ ($n=0,1,2,\dots$), the first of the two conditions necessary for circular polarization is satisfied. This condition determines the set

of discrete thicknesses of the crystal that yield the necessary phase shift as given below:

$$t_0 = \frac{(2n+1)\pi a_0^3 \cos(\Theta_0)}{2|F_H| r_e \lambda (1 - |\cos 2\Theta_0|)} \quad (\text{for } \varphi = (2n+1)\frac{\pi}{2}). \quad (3)$$

To satisfy the second condition necessary for circular polarization, the crystal is rotated by 45° about the incident beam so that its diffracting planes make a 45° angle with the linearly polarized incident beam from the storage ring. In actuality, the rotation angle is greater than 45° because, in some cases, the difference in the absorption coefficients between the σ and π states of the α branch leads to significantly different amplitudes at the exit face of the crystal. This is particularly true for lower energies and higher order diffractions.

In Figure 1, a comparison is shown between the performance (at 65 keV) of a silicon phase plate to one constructed of germanium. From this figure, we can see that, particularly for larger beam divergences, germanium clearly outperforms silicon in its ability to polarize the incident x-rays. This increased performance is connected to the fact that germanium absorbs more of the β branch wave fields than does silicon. These β branch wave fields produce circularly polarized x-rays of opposite helicity to those produced by the α branch as they are 180° out of phase with the α branch wave fields. Thus, when combined with the α branch photons in the output beam, the β branch photons reduce its degree of circular polarization.

3. Construction and Characterization of the Device

The phase plate is a monolithic, two-crystal design similar to that used by Mills [2] and is shown in Figure 2. The first crystal was cut to the symmetric Bragg geometry, while the second crystal (the phase plate) was cut to the symmetric Laue geometry. The advantages of this combined geometry are the following: first, the doubly diffracted, circularly polarized beam will be parallel to the incident beam. This greatly simplifies the experimental task of tracking the exit beam as the incident energy is changed. In fact, if the energy is changed by rotating the crystal about its corner (where the Laue crystal and the Bragg crystal meet), the exit beam will remain fixed in space. Second, the incident beam will have its power distributed over a larger area on the Bragg crystal than would be possible if it were incident upon the Laue crystal. This will reduce the heat

load upon the crystal. The third advantage is the inherent mechanical stability of such a device compared to a separated two crystal device. This advantage is magnified by the fact that the Darwin width at these energies is much less than an arc second. A “weak link,” which allows the Bragg crystal to be rotated relative to the phase plate, was included to compensate for the slight difference in the Bragg angle between the Laue and Bragg geometry due to index of refraction corrections. Although this difference is energy dependent, it was of the order of a fraction of an arc second in the energy range of our interest. The rotation is performed by an electrostrictive actuator (similar to a piezoelectric transducer) with a resolution of 0.05 arcseconds in our particular geometry.

The (440) diffraction planes were chosen for two reasons. The first reason is practical as the $\langle 110 \rangle$ direction is perpendicular to the $\langle 111 \rangle$ direction, the most readily available boule growth direction. The second reason is that the Bragg angle for the (440) reflection at the highest possible energies at which the phase plate was designed to work (88 keV), is large enough to permit the corresponding beam footprint to fit on the Bragg crystal.

The step cut in the phase plate allows two different energy ranges to be studied (as shown in Table 1). The thickness of each plate was determined from equation (3).

The height of the phase plate and the length of the Bragg crystal are determined solely from the geometrical considerations arising from the angle of incidence, and to a lesser extent, the size of the incident beam.

Initial characterization of the phase plate was done by measuring the rocking curve of the crystal, which is the Darwin-Prins curve of the Bragg crystal convoluted with a Laue rocking curve. The experiment was done in-house using the $K\alpha$ characteristic line ($E=17.479$ keV) from a sealed molybdenum (Mo) tube operating at 40 kV and 30 mA. Because the width of the perfect Laue curve at this energy for the (440) planes is 0.41 arc seconds, which is smaller than the Darwin-Prins curve ($w_{D,P}=1.68$ arc seconds) of the Bragg geometry, the measured rocking curve should trace the Darwin-Prins curve. Indeed as shown in Figure 3, the experimental data were in good agreement with the theoretical curve, which, in turn, indicated the crystal boule was of a good quality and that mounting of the phase plate was relatively strain free.

4. Description of the Experimental Setup

The phase plate was tested on the F2 wiggler beamline at the Cornell High Energy Synchrotron Source (CHESS). The critical energy of the wiggler is 22.4 keV, which is well suited to our interest in high-energy, magnetic Compton scattering experiments.

A top view of the layout of the components in our experiment is shown in Figure 4. A 15-mm-thick carbon filter and a 0.5-mm-thick copper filter were used to remove the lower energy (220) harmonic reflection from the phase plate and also to reduce the effects of heating from the wiggler white beam. This brought the normal incidence power density at 80 mA beam current from 15.4 W/mm² down to 0.8 W/mm². Upon exit from the crystal, the beam passed through a sealed Xe ion chamber, which acted as a beam monitor, before its polarization was measured by means of a Compton polarimeter similar to that used by Smend et al. [8] and Schildkamp [9]. While this type of polarimeter can measure the intensity of the orthogonal electric fields, it cannot measure the relative phase difference between the two components. Thus, the polarimeter can measure the degree of *linear* polarization, but not the degree of *circular* polarization. This measurement is used to determine the energies for which the circular polarization is a *maximum* by identifying the energies for which the linear polarization is a *minimum* ($P_L=0$). The degree of circular polarization (P_C) at these energies is then measured by a magnetic Compton-scattering experiment.

The magnetic Compton-scattering experiment required the removal of the polarimeter and the installation of an electromagnet with an Fe target placed between the poles. The Compton scattered photons were collected using a Ge solid-state detector, and their energies were resolved using a multichannel analyzer.

5. Linear Polarization Measurement

The polarimeter used NaI scintillation counters placed at 90° relative both to each other and the direction of the incident beam to measure the Compton scattered radiation from a 1-cm-thick aluminum target. This design differed from that of Smend and Schildkamp in two ways. First, the target was aluminum, not kapton or beryllium, to provide a significant amount of scattering at high photon energies. Second, both detectors viewed the sample in a reflection-reflection geometry rather than in a transmission-reflection geometry. This insures that each detector sees an

equal amount of scattering. The output from each detector was connected to separate multichannel analyzers. The inelastic or Compton peak corresponding to the correct energy was integrated over the region of interest (ROI) for each detector. The ROI was centered upon the peak of the Compton profile and was defined to include the ± 10 a.u. of momentum. This gave two quantities: one that was proportional to the degree of linear polarization parallel ($I_{\parallel}$) to the storage ring plane of orbit (defined to be the horizontal plane) and another that was proportional to the degree of linear polarization perpendicular to this plane ($I_{\perp}$). The degree to which the beam was linearly polarized (P_L) was calculated as follows:

$$P_L = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}. \quad (4)$$

From this definition, it follows that $P_L = -1$ ($+1$) corresponds to 100% polarization in the vertical (horizontal) plane. To reduce contamination in the NaI detectors from fluorescence, 1/8"-thick lead disks with a 1.5-mm pinhole were placed in front of each detector. To minimize systematic errors that could have arisen from the slight difference in the size of the pinholes, two sets of data were collected for each energy by rotating the Compton polarimeter by 90° about the exit beam from the phase plate.

The above procedure yields P_L for a particular energy. Equation 1 shows that, as the incident Bragg angle is changed (and hence the incident energy upon the phase plate), the phase between $E_{\parallel}$ and $E_{\perp}$ changes as well. This will, in turn, affect the degree of linear and circular polarization. Thus, P_L was measured as a function of energy over the range 62 keV to 93 keV. The result is shown in Figure 5. From this figure, one can see the linear polarization change from horizontal linear ($E > 88$ keV) to vertical linear (at 75 keV) and back to horizontal linear ($E < 65$ keV), where this cycle will continue to repeat itself as the energy is decreased. The energies for which $P_L = 0$ are either 45° linearly polarized, circularly polarized, or unpolarized. To eliminate the possibility of 45° linear polarization, P_L was measured after the Compton polarimeter was rotated by 45° about the incident beam. No change in P_L was measured, so the beam could not have been 45° linearly polarized.

From Figure 5, we can clearly see the points at which the linear polarization is a minimum,

and the agreement with theory is good in this region. At these points (88 keV and 65 keV), the degree of circular polarization is at a maximum. In the regions for which the exit beam is highly linearly polarized (75 keV), multiple scattering effects within the target account for the discrepancy between the data and theory. No corrections for multiple scattering have been made though as our interest in the precise value of P_L is only for $P_L \approx 0$.

6. Circular Polarization Measurement

In order to confirm that the exit beam at 65 keV and 88 keV was indeed circularly polarized (and not unpolarized), a magnetic Compton-scattering experiment was performed using a polycrystalline iron target. Two sets of data were separately collected for opposite directions of the applied magnetic field in an ABBA sequence using a multichannel analyzer. One A or B step was approximately 5 min. long. Data were collected at a rate of 262 counts/s (in the Compton peak) for four hours. The profiles for opposite directions of the magnetic field were subtracted and these results were then summed for all of the sequences to produce a single magnetic Compton profile (MCP). The integral of the profile from -10 a.u. to +10 a.u. is normalized to the number of magnetic electrons/atom (2.2 for Fe) to yield the profile shown in Figure 6. These data are in good agreement with that obtained by Mills [4] and Cooper et al. [3] and the theory calculated by Wakoh and Kubo [10]. From this profile in Figure 6, the degree of circular polarization P_c at 65 keV was calculated to be $90\% \pm 4\%$. The exact value of P_c at 88 keV could not be calculated due to contamination of the Compton profile by lead fluorescence ($K\alpha_1$, $K\alpha_2$, and $K\beta$).

7. Summary of Results

We have shown that a germanium phase plate can be used to convert linearly polarized radiation to circularly polarized radiation at high x-ray energies (65 keV and 88 keV). The degree of this circular polarization has been shown to be $90\% \pm 4\%$, significantly better than that produced by silicon phase plates. This radiation was used to measure the magnetic Compton

profile of Fe, which was found to be in good agreement with theory and previous work.

Acknowledgements

The authors would like to thank Prof. N. Sakai and the staff members of both the CHSS and Experimental Facilities Division at the APS for valuable discussions. This work is supported by the U.S. DOE-BES under Contract No. W-31-109-ENG-38.

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Table 1. Designed energies for a circularly polarized exit beam.

Phase (°)	Energy for thin part (keV)	Energy for thick part (keV)
90	40.880	88.457
270	27.536	65.427
450	22.829	55.217
630	20.147	49.385

Figure 1. Comparison of the total degree of circular polarization for both germanium (solid line) and silicon (broken line) as a function of input beam divergence. Note that, even for large beam divergences, the germanium still has a polarization of approximately 86%-nearly twice that of silicon.

Figure 2. Photograph of the phase plate. The length, height, and width of the crystal are 120 mm, 35 mm and 35 mm respectively.

Figure 3. Comparison of the rocking curve data (open circles) taken at 17.479 keV (Mo $K\alpha$) with theory (solid line). The theory was determined by convoluting a Laue rocking curve (0.41 arc seconds) with the Darwin-Prins curve ($W_{D-P} = 1.68$ arc seconds). The Darwin width of this convoluted curve is 1.98 arc seconds.

Figure 4. Schematic top view of setup used. The incident white beam is linearly polarized in the plane of this page. The crystal is rotated by 45° about the *incident* beam to produce a monochromatic, circularly polarized exit beam. The Compton polarimeter is removed when the magnetic Compton scattering experiment is performed.

Figure 5. Comparison of the measured degree of linear polarization (%) with theory. No corrections for multiple scattering were made. The data are shown for two different positions of the Compton polarimeter. Position 2 (open diamond) is that in which the polarimeter is rotated by 90° from position 1 (open circle) about the exit beam from the phase plate.

Figure 6. Magnetic Compton profile (MCP) for Fe at 65 keV incident photon energy. The agreement between the data (solid circle) and theory (broken line) [10] are good. Data from both Mills (open square) [4] and Cooper et al. (open triangle) [3] are presented for comparison. The lack of a null result indicates that the incident radiation is circularly polarized. The integral of this profile determines the degree of circular polarization.

Degree of Linear Polarization (%)