# Photon Energy Dependence of Phase-contrast Synchrotron-light Imaging

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## Introduction

We observed and analyzed the photon energy dependence of diffraction and refraction features in phase-contrast x-ray images of sharp edges in several different systems. This issue is very interesting, since the photon energy dependence in proximity of specific ranges can selectively identify the corresponding elements in the features. Preliminary theoretical analysis explains some of experimental results.

Phase-contrast imaging exploits the real part of the refractive index to obtain good images with a low radiation dose. The imaginary part $\beta$ of the refractive index $n = 1 - \delta - i\beta$ of low-electronic-density materials is very close to zero for high-energy x-rays and varies only slightly with the atomic number Z [1]. Thus, absorption contrast is weak in x-ray images.

On the other hand, the real part $\delta$, although it is also very small, can be up to 1000 times greater than $\beta$ in the spectral range of 15-25 keV. Thus, contrast based on $\delta$ (phase contrast) can be more effective than absorption contrast. Several different techniques of exploiting phase information as a source of image contrast were developed [2-14]. In particular, phase-contrast radiology can achieve very high lateral and time resolution, but it requires collimated and coherent x-rays.

Phase-contrast imaging has been extensively investigated. However, one important aspect has not yet been sufficiently explored: photon energy dependence. By investigating this point, we can enhance the flexibility of the phase-contrast radiology. Specifically, the image modifications near an absorption edge can label the features because of the corresponding element. This would be the second application ever of the spectral tunability of synchrotron radiation to radiology — after coronary angiography near the iodine K edge.

## Methods and Materials

The experiments were performed on the 2-BM-B bending magnet beamline of APS. The photon energy could be selected by a double-crystal monochromator with an energy resolution of $10^{-4}$ in the range of 2.5-33 keV. The specimens were located 50 m from the source. The images were detected with a 12-bit, 1280 × 1024-pixel charge-coupled device (CCD) camera. The x-rays were converted into visible light by a thin (5-μm) scintillator and then magnified (32 times) by an optical microscope, giving an effective pixel size of 0.22 μm at the camera.

## Results and Discussion

A sketch of the experimental setup is shown in Fig. 1. A nearly parallel monochromatic beam illuminates the object. At the edge, there is a deviation of the x-ray beam due to refraction because of the edge slope. This causes a characteristic sequence of one dark pseudofringe and one white pseudofringe. Furthermore, the interference of x-rays traveling through the specimen with those traveling through vacuum causes a series of fringes. The relative role of the two effects depends on the geometry and on the edge shape.

Several different specimens consisting of pure elements (Cu, Ta, Au, and Ga) were investigated. However, we concentrate our attention here on copper specimens and the Cu K edge.

The Kramers-Kronig relations link the real and imaginary parts of the refractive index. An absorption edge corresponds to a rapid variation of $\beta$ as a function of the photon energy. In the same spectral region, rapid variations should occur for $\delta$. The expected contrast

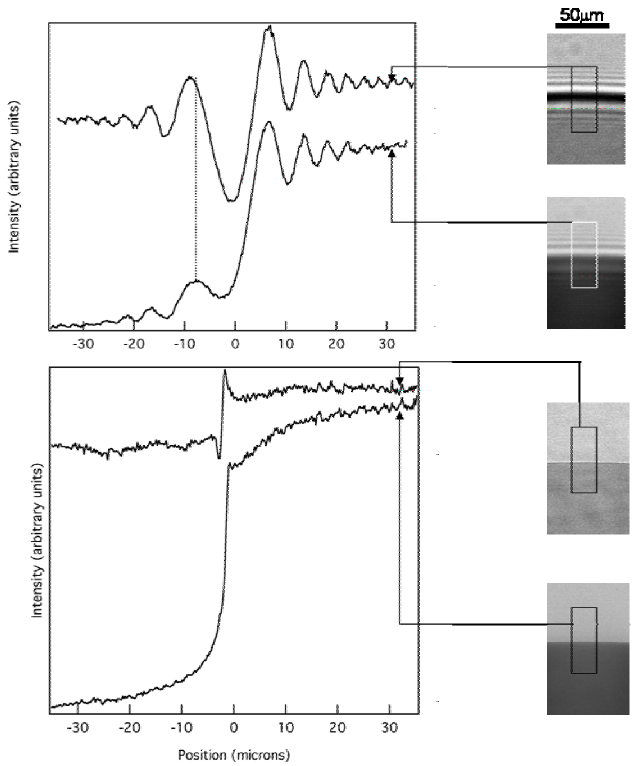


*FIG. 2. Top: Intensity profiles (left) and corresponding images (right) for the edge of a 9-μm-thick Cu wire in a mesh. The results were obtained for two different energies: 8970 and 9010 eV (below and above Cu K absorption edge) with a 60-cm object-detector distance. This geometry emphasizes the diffraction effects, so that diffraction fringes are visible on both sides of the wire edge. Note the differences between the results for the two photon energies, including a small but detectable shift in diffraction fringe positions (e.g., the dashed line). Bottom: Similar results for a short (1-cm) object-detector distance. With this geometry, only dark bright "refraction" fringes are visible, and they disappear for strong absorption (9010 eV).*

changes as a function of the photon energy are a result of the interplay of these two correlated phenomena.

The first objective of our study was to detect edge contrast changes as a function of the photon energy. This objective was achieved. The typical results of Fig. 2 refer to the edge of a 9-μm-thick Cu wire in a mesh. The spectral range in which images were taken was 8970-9010 eV, including the Cu K edge at 8978.9 eV.

The top right part of Fig. 2 shows images taken at 8970 and 9010 eV (below and above the absorption edge) with a 60-cm object-detector distance. The top left part of the