**Optical Design and Performance of the Inelastic Scattering Beamline
at the National Synchrotron Light Source**

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Phase I of the X21 beamline at the National Synchrotron Light Source was commissioned during 1993. The research program at the X21 beamline is focused on the study of electronic excitations in condensed matter with total energy resolution of 0.1 eV to 1.0 eV. The source is a 27 pole hybrid wiggler. A water-cooled horizontal focusing Si(220) monochromator and a spherically bent Si(444) analyzer were installed and commissioned. At 8 keV the energy resolution of the monochromator is about 0.7 eV, and the energy resolution of the analyzer is about 0.1 eV. Results from several selected experiments are also discussed.

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Introduction

The research program at the X21 beamline at the National Synchrotron Light Source (NSLS) is high energy resolution inelastic x-ray scattering. It is focused on the study of electronic excitations in condensed matter with total energy resolution of 0.1 eV to 1.0 eV. The phase I beamline consists of a focusing Rowland circle monochromator, and a high resolution backscattering spectrometer. It is designed to allow initial experiments to be performed with total energy resolution of 1 eV, and to provide a facility for the testing of new optics. At 8 keV, the energy resolution of the monochromator is about 0.7 eV, the line focused beam size is about 0.2 mm (H) x 10 mm (V). The photon flux delivered onto the sample is about 2×10^{11} per second at 100 mA ring current. The energy resolution of the analyzer is about 0.1 eV. Initial experiments ranging from high resolution Compton scattering, x-ray resonant Raman scattering, as well as non-resonant Raman scattering have been conducted. Results from a few selected experiments are included here to demonstrate the capability of the beamline. Various types of analyzer benders, developed at the NSLS, APS, and ESRF were also tested.

Source

The radiation source is a 27 pole hybrid wiggler located at one of the straight sections of the 2.5 GeV x-ray storage ring. The device is constructed of samarium-cobalt magnet blocks sandwiched between vanadium-permendur pole pieces, in a hybrid configuration [1]. The peak field of the device is 1.1 T with a 22 mm gap and the length of the magnet period is 12 cm, which give the deflection parameter K a value of 12.33, and the horizontal opening angle of 2.5 mrad for a 2.5 GeV storage ring energy. The full vertical opening is about 0.25 mrad. The critical energy at the center of the horizontal fan is 4.6 keV. At a current of 230 mA, the wiggler produces 1.8 kW of total power with a central

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power density of 450 W/mrad [2].

Beamline

The front end of the beamline consists of a water-cooled copper mask, a fast vacuum valve, a twin-blade x-ray beam position monitor, a set of glancing-incidence adjustable apertures, and a water-cooled x-ray shutter [2,3]. The beamline is separated from the storage ring by a 0.25 mm thick beryllium window. A set of seven pyrolytic graphite filters, of 0.17 mm total thickness, is positioned immediately upstream of the beryllium window to protect the window from absorbing excessive power. The central power density after the beryllium window is reduced to about 200 W/mrad at 230 mA ring current [2].

The phase I beamline optics consists of a focusing Rowland circle monochromator and a high resolution backscattering spectrometer. A schematic of the beamline is shown in figure 1. The monochromator, located at 37 m from the source, consists of a single cylindrically bent Si(220) crystal. The monochromator crystal accepts the full vertical opening of the source, and only 0.5 mrad in the horizontal direction due to source size contribution to the energy resolution. Also, in order to achieve high energy resolution, the crystal is cut with an asymmetry angle of 19° (the incident angle larger than the Bragg angle), which gives an asymmetry factor of about 8 at 8 keV. The cylindrical shape is achieved by mounting the triangle-shaped crystal as a cantilever, with the base of the triangle clamped to a water-cooled copper block, and applying force to the free end [4]. At 8 keV, the bending radius of the crystal is about 50 m, and the focus of the monochromatized beam is about 4 m from the crystal. The demagnification of the source is about 8 to 10 between 8 keV and 8.5 keV. The theoretical energy resolution of the monochromator is calculated to be about 0.4 eV. Finally, the thermal load on the crystal

is removed by a water-cooled copper block, which is coupled to the crystal through a thin layer of He.

At 8 keV, the energy resolution of the monochromator is measured to be about 0.7 eV by using a Si(333) analyzer. The line focused beam size is about 0.2 mm (H) x 10 mm (V). The photon flux, measured by an ion chamber filled with air, delivered onto the sample is about 2×10^{11} per second at 100 mA ring current. The discrepancy between the measured energy resolution and the calculated energy resolution is most likely due to imperfection in the crystal bending and thermal distortion of the crystal.

The design of the backscattering spectrometer can be found in ref. [5]. In brief, the spectrometer is also a Rowland circle instrument, with the sample as the source and the detector as the focus. It uses the so-called Johann geometry by spherically bending the Si(444) analyzer crystal to a radius of curvature of about 1 m. At 8 keV the energy resolution of the analyzer is about 0.1 eV. Since the monochromator resolution was much worse than that of the analyzer, a second monochromator was installed to further monochromatize the incident beam to about 0.1 eV for the testing of the analyzer. The resolution of the analyzer was then determined by measuring the full width half maximum of the elastic line obtained from a 0.25 mm thick plastic sample.

Selected Examples

A Non-resonant Raman Scattering: Non-resonant Raman scattering with total energy of 1 eV has been used to study various types of valence electron excitations, including interband transitions, plasmon dispersions, and the interactions between the single particle excitations and collective excitations [6]. It has also been used to study core-level excitations, as an alternative to soft-x-ray absorption spectroscopy [7]. Since both

incident and scattered photons are high energy x-rays, sample selection and sample environment can be much more flexible. Figure 2 shows the results from BeO. At the low energy end, the spectrum is dominated by various single particle interband transitions; while at the high energy end (see inset) excitation corresponding to Be K edge can be observed.

High Momentum Resolution Compton Scattering: Compton scattering with momentum resolution between 0.1 and 0.15 atomic units (a.u.) have been achieved by several groups recently using various combination of crystal analyzers and position sensitive detectors [8-10]. Since the momentum distribution of valence electrons in condensed matter typically extends only a few a.u., momentum resolution of 0.1 to 0.15 a.u. is essential to the study of anisotropy in the directional Compton profile and the reconstruction of three-dimensional momentum distribution of the valence electrons. However, there are other features in Compton profile that may require even higher momentum resolution, for example Compton profile of low dimensional solids. At X21, momentum resolution of 0.01 a.u. is achieved. Directional Compton profiles of Be in the $\langle 00.1 \rangle$ and $\langle 11.0 \rangle$ directions were measured, and compared with existing measurements [8], see figure 3. Significant larger anisotropy in the directional profile was observed. The first derivative of Compton profile around the Fermi surface is also sharper in the new measurement [11]. These results show that many important features in Compton scattering are still resolution limited, and that high resolution data can provide more stringent test for theory on electron-electron correlation effects.

High Energy Resolution X-Ray Resonant Raman Scattering: High resolution x-ray resonant Raman scattering, with total energy resolution of 1 eV, is performed routinely at X21. A series of rare earth elements and their compounds were studied recently [12]. As an example figure 4 shows the results from erbium iron garnet. The spectra

were measured by scanning the Si(444) analyzer near the $L_{\beta 2}$ emission line of Er^{+3} as the incident energy stepped through the L_3 absorption edge of Er^{+3} . A new feature corresponding to the 2p to 4f quadrupolar transition, which cannot be resolved from the 2p to 5d dipolar transition in traditional x-ray absorption measurement due to core-hole lifetime, was revealed. These results provide new and valuable information in the understanding of the origin of x-ray magnetic circular dichroism in these materials.

Summary

In summary, the optical design and performance of the inelastic scattering beamline at the NSLS has been described. Total energy resolution of 0.7 eV at 8 keV is achieved. Results from selected initial experiments ranging from non-resonant Raman scattering, resonant Raman scattering, to high resolution Compton scattering are discussed.

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Figure Captions

Fig. 1. Schematics of the Si(220) horizontal focusing monochromator and the Si(444) backscattering analyzer.

Fig. 2. Non-resonant Raman spectrum from BeO

Fig. 3. High resolution Compton profiles from Be. Open circle is the Compton profile in the $\langle 00.1 \rangle$ direction, and filled circle is the Compton profile in the $\langle 11.0 \rangle$ direction. The incident energy is around 8 keV, and the scattering angle is 160° .

Fig. 4. High resolution resonant Raman spectra near the Er L_{III} edge from erbium iron garnet.

X21

BeO ($q = 0.92$ a.u., $E_0 = 7.95$ keV)

Be Directional Compton Profiles

Erbium LIII Edge RRS