High-resolution monochromators for nuclear resonant scattering of ^{119}Sn

M. Y. Hu, T. S. Toellner, W. Sturhahn, P. L. Lee, P. M. Hession, J. P. Sutter, E. E. Alp
Advanced Photon Source, Argonne National Laboratory,Argonne, IL 60439

Nuclear resonant scattering with synchrotron radiation has been an active research field recently [1, 2]. A key component in implementing the experiments with a synchrotron source is high-resolution monochromator. It is used to reduce the energy bandwidth of the incident X-ray beam in nuclear forward scattering to improve signal-to-noise ratio. For inelastic nuclear resonant scattering, a unique way to study vibrational properties, a high-resolution monochromator provides the spectral resolution needed. In the following paragraphs, we will briefly describe two monochromators made primarily for inelastic nuclear resonant scattering experiments with ^{119}Sn whose nulcear resonant energy is 23.880 keV.

The development of high-resolution monochromators above 20 keV is difficult due to the narrow angular acceptances of suitable crystal reflections. This fact has two adverse effects. One is that the crystal may not accept the full beam and results in a low efficiency optic. The narrow angular acceptance also puts stringent requirements on mechanical control and temperature stability. A nested channel-cut monochromator for ^{119}Sn was reported [3] using Si(3 3 3) and Si(5 5 5) reflections. It had an energy resolution of 23 meV, an angular acceptance of 7 μrad, and was used in the first observation of the ^{119}Sn nuclear resonance at a synchrotron source [4]. To achieve higher resolution, the highest order of reflection possible should be employed. In silicon, for 23.880-keV x-rays, the (12 12 12) reflection is one of the highest order reflections. However, its intrinsic angular acceptance is only 0.3 μrad. Recently, a nested channel-cut monochromator using this reflection was reported to have achieved 0.97 meV energy resolution [5].

To transmit as much spectral flux as possible, the angular acceptance of the monochromator needs to be comparable to the beam divergence. At the APS undulator beamline 3-ID, where this experiment was performed, the vertical divergence of the x-ray beam is initially estimated to be about 15 μrad. Here we can employ the principle of asymmetric diffraction to overcome this severe mismatch between the incident beam divergence and the angular acceptance of the high-order reflection. A second, asymmetrically cut crystal is placed before the high-order reflection crystal to "funnel" the more divergent incident beam into a smaller angular range.

Table 1: The design parameters for the monochromator with energy resolution of 3.6 meV. Listed are the Bragg angle θ_B, the asymmetry angle α and the asymmetry factor b, the angular acceptance ω_o, and the angular divergence ω_h of the two reflections used. Both ω_o and ω_h are in μrads.

reflection	θ_B	α	b	ω_o	ω_h
(4 0 0)	11.02°	8.9°	0.108	13.9	1.50
(12 12 12)	83.46°	-70.53°	1.96	0.20	0.39

For the first attempt [6], we have chosen Si(4 0 0) as the first reflection. With a modest asymmetry angle, it matches the assumed incident beam divergence fairly well but does not quite match the acceptance of (12 12 12). The parameters of this two-crystal monochromator are listed in Table 1. Its schematic is shown in Fig. 1. The final exiting beam has a vertical size five times that of the incident beam and is going backwards with an angle of 9° from the horizontal plane. In comparison to a channel-cut design [3, 5], which preserves the beam direction and size, this might cause inconvenience in sample and detector positioning. However, this two-crystal design avoids the losses from two more reflections in the channel-cut design and does not suffer from the adverse effect of temperature differences between the reflecting surfaces of channel-cut crystals.

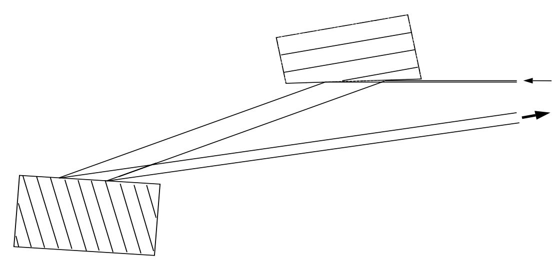

Figure 1: The monochromator Si(4 0 0) – (12 12 12).

The energy resolution of monochromators can be measured by nuclear forward scattering [6]. Result of the measurement for this monochromator is presented in Fig. 2 along with a simulation. The energy resolution is determined as the FWHM of the measured energy response function, which is 3.6 meV. The simulation is done using results from the dynamical diffraction theory. The resolution function strongly depends on the profile of the incident beam in λ–θ space. An incident beam with a Gaussian vertical angular profile of 15 μrad FWHM is assumed in the simulation.

While the incident flux was measured as 8.3×10^{12} photons per second per 100 mA storage ring current in an energy bandwidth of 2.6 eV, for the monochromatic beam, we obtained $9.0 \times 10^8\, ph/s/100\, mA$ ring current in the energy bandwidth of 3.6 meV.

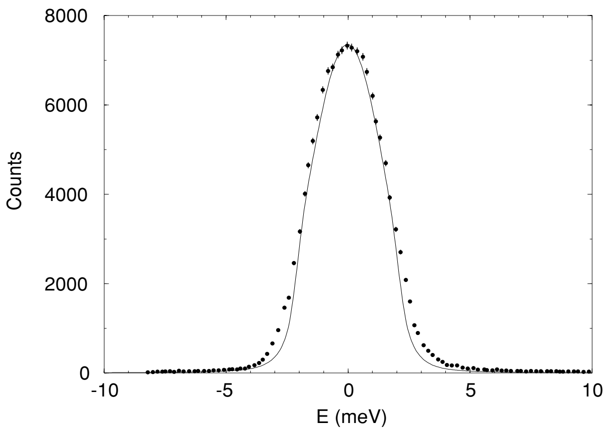

Figure 2: The measured energy response function (dots, FWHM = 3.6 meV) of the Si(4 0 0) – (12 12 12) monochromator, compared with a simulation (solid line, the vertical scale is arbitrary).

In light of the fact that the actual beam divergence is only about 12 μrad (vertical) and may become even smaller as the high-heat-load monochromator is improved, the design for the high-resolution monochromator can be improved by using a higher order reflection for the first crystal. Table 2 lists the parameters for a new monochromator, which is shown in Fig 4. A third reflection is used asymmetrically to reverse the significant blowup of vertical beam size by the first two reflections. Its large angular acceptance and high reflectivity ensure that it has only minute effects on the transmission function of the monochromator and thus leaves its energy resolution and spectral transmission basically unchanged. The resolution is measured to be 0.98 meV, as shown in Fig. 3. We obtain a monochromatic beam flux of about $3 \times 10^8 ph/s/100mA$, which is adequate for conducting inelastic nuclear resonant scattering experiments.

Table 2: The parameters for the 1-meV monochromator with a "beam contractor." For meaning of the symbols see Table 1.

reflection	θ_B	α	b	ω_o	ω_h
(4 4 4)	19.34°	18.47°	0.0248	10.3	0.25
(12 12 12)	83.48°	-70.53°	1.96	0.20	0.39
(1 1 1)	4.75°	-4.12°	14.02	2.89	40.6

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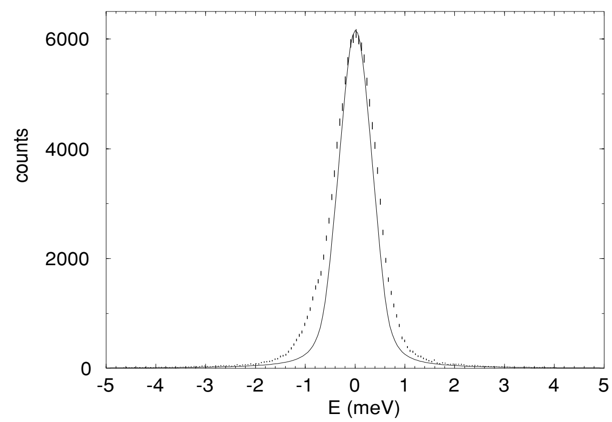

Figure 3: The measured energy response function (vertical bars, FWHM = 0.98 meV) of the monochromator Si(4 4 4) – (12 12 12) compared with a simulation (solid line, with FWHM of 0.80 meV).

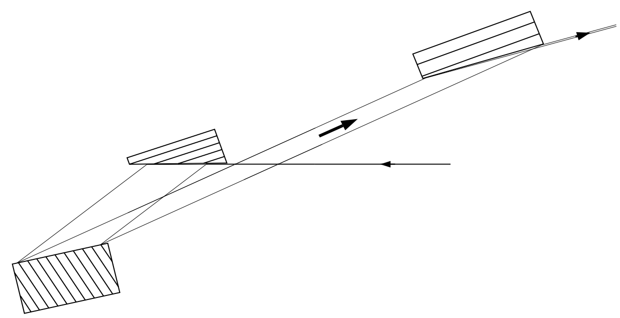

Figure 4: The 1 meV monochromator in a 3-crystal setup.

References

[1] see, for example, a review paper by G. V. Smirnov, *Hyperfine Interactions* **97-8**, 551 (1996).

[2] E. Gerdau and H. de Waard, ed., *Nuclear Resonant Scattering of Synchrotron Radiation*, Baltzer Science Publishers, Oxford, UK, 2000.

[3] T. M. Mooney, T. S. Toellner, W. Sturhahn, E. E. Alp, S. D. Shastri, *Nucl. Instrum. Methods A* **347**, 348 (1994).

[4] E. E. Alp, T. M. Mooney, T. S. Toellner, W. Sturhahn, E. Witthoff, R. Röhlsberger, E. Gerdau, H. Homma, M. Kentjana, *Phys. Rev. Lett.* **70**, 3351 (1993).

[5] A. I. Chumakov, A. Barla, R. Rüffer, J. Metge, H. F. Grünsteudel, H. Grünsteudel, J. Plessel, H. Winkelmann, M. M. Abd-Elmeguid, *Phys. Rev.* **B58**, 254 (1998).

[6] M. Y. Hu, T. S. Toellner, W. Sturhahn, P. M. Hession, J. P. Sutter, and E. E. Alp. *Nucl. Instrum. Methods A*, **430**, 271 (1999).