High-Resolution Inverse-Cauchois Scanning Analyzer for High-Energy X-Rays

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Analyzer Geometry

A bent Laue crystal analyzer for high-energy x-rays is described, intended for use in fluorescence spectroscopy and Compton scattering. Operating in the *inverse-Cauchois geometry* (Fig. 1), a perfect, 1.5-mm-thick, slightly asymmetrically cut Si(422) Laue crystal, oriented to minimize multiple reflections and mechanical twisting, is cylindrically bent to a Rowland circle going through the source (i.e., the analyzed sample). Since only one energy at a time is selected by diffraction into a photon counter, angular scanning of the crystal while preserving the Rowland condition is required to acquire a spectral profile. By keeping the sample scattering plane horizontal but the analyzer scattering plane vertical, one achieves the desirable consequence of an effective source size (as viewed by the analyzer) that is fixed to be equal to the primary exciting beam's vertical size. For spectroscopy purposes, the combined energy resolution from all contributing effects varies from 15 eV at 20 keV to 120 eV at 70 keV. From a Compton scattering application viewpoint, wherein additional resolution contributions enter, the electron momentum resolution changes from .08 au to .15 au as the Compton-scattered photon energy (after a 150°-angle scattering) varies from 20 keV to 70 keV.

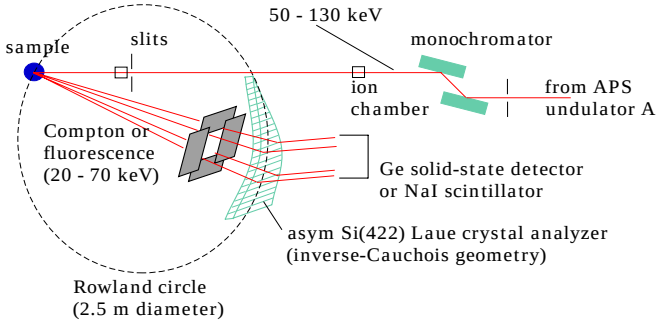

Figure 1: Illustration of crystal analyzer setup. While the sample scatters horizontally, the analyzer diffracts vertically. An aperture defines an analyzer active area of a few square centimeters.

Resolution

The analyzer was characterized over the 20–70 keV range by scanning through the Kα_1 fluorescence lines of Ag, Sb, Sm, Ho, Hf, and Pt. The measured profile of the Ho Kα_1 line is shown in Fig. 2. From the measured width of 75 eV and the known intrinsic linewidth of 31 eV, one can infer an instrumental resolution of 68 eV at this energy, i.e., ∼48 keV. Similarly, other fluorescence line profiles yielded resolutions at other energies. Table 1 gives the full energy resolution of the instrument as relevant from a photon energy spectroscopy viewpoint (as opposed to a Compton scattering viewpoint to be addressed below), as well as its breakdown into the two contributing influences, assumed to add in quadrature. One, labeled "source size", arises from the small vertical angle subtended by the illuminated spot on the sample as seen by any given point on the analyzer crystal. In this case the vertical beam size incident on the sample was 200 μm at a 2.5 m distance from the analyzer. The other contribution is the intrinsic energy acceptance of the crystal reflection, which is dependent on energy, reflection order, asymmetry, thickness, and bend radius.

For Compton scattering applications where one analyzes the profile of the Compton peak to get information on the electron momentum distribution in the sample, the spectrometer resolution performance should be assessed

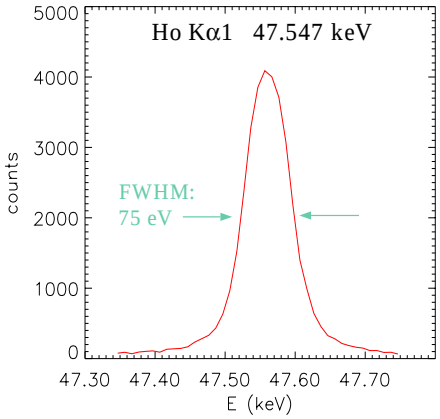

Figure 2: Scanning measurement of the Ho Kα_1 line having intrinsic width $\Gamma_K + \Gamma_{L3} = 31$ eV.

Table 1: Analyzer resolution parameters at different energies.

analyzed photon energy (keV)	resolution contribution		total resolution (eV)
	source size (eV)	analyzer energy acceptance (eV)	
22	6.8	13.9	15.5
26	9.7	20.0	22.2
40	22.8	42.3	48.1
48	32.1	60.0	68.0
56	44.3	76.7	88.6
67	63.7	105.8	123.5

Table 2: Analyzer resolution parameters for analysis of Compton scattering by 150° of various primary x-ray energies. One atomic unit (au) is the electron momentum in the ground state of hydrogen in the Bohr model.

incident photon energy (keV)	resolution contributions (au)					total resolution (au)
	incident beam energy width	incident beam divergence	source size	analyzer collection angle	analyzer energy acceptance	
24	.056	$.48\times10^{-4}$	.023	.0093	.047	.08
29	.046	$.58\times10^{-4}$	.028	.011	.058	.08
47	.028	$.90\times10^{-4}$	.044	.018	.082	.10
58	.022	1.1×10^{-4}	.053	.022	.099	.12
70	.018	1.3×10^{-4}	.063	.026	.109	.13
88	.014	1.6×10^{-4}	.077	.032	.128	.15

differently. This is because one is eventually interested in the uncertainty in the electron momentum component p_z along the the inelastic momentum transfer direction given by

$$p_z = mc\,\frac{(E-E') - EE'(1-\cos\phi)/mc^2}{\sqrt{E^2+E'^2-2EE'\cos\phi}}\quad ,$$

where E and E' are the incident and scattered energies, respectively, and ϕ is the scattering angle (typically around 150°). So in addition to the two resolution contributions mentioned in the preceding paragraph (which propagate through $\frac{\partial p_z}{\partial E'}$), the uncertainty in p_z also acquires contributions from three additional effects. These are the incident beam energy width, the incident beam horizontal divergence, and the analyzer horizontal collection angle. Of these three additional contributions, the incident energy spread propagates through $\frac{\partial p_z}{\partial E}$, and the other two, which represent sources of uncertainty in the Compton scattering angle, propagate through $\frac{\partial p_z}{\partial \phi}$. Table 2 shows all the five contributions to the electron momentum resolution assuming a primary beam energy width and horizontal divergence of 20 eV and 30 μrad, respectively, and an analyzer horizontal collection angle defined by a 15 mm aperture at 2.5 m distance from the sample.

Final Remarks

Development of the analyzer optics described here was motivated by the applications to Compton scattering and fluorescence. In fluorescence studies, the enhanced resolution and noise suppression from such a system would allow measurements of weak satellite and hypersatellite K lines of heavy elements—interesting from the standpoint of atomic physics.

Finally, one should address the relative merits of the inverse-Cauchois scheme presented here versus the more standard Johann configuration, also involving the Rowland geometry, but with a Bragg crystal instead. A Compton spectrometer of the latter type has been operational at the European Synchrotron Radiation Facility [1]. The inverse-Cauchois optics, by virtue of its roughly normal incidence operation, offers the advantage of a large collection angle in the meridional (bending) direction relative to the active length of the crystal. So, for the same meridional collection angle, a Johann analyzer demands a longer crystal, as well as a precise cylindrical figure over that distance. Furthermore, the translational motions required for the crystal and detector to preserve the Rowland condition as a function of energy are minuscule over many tens of keV for the inverse-Cauchois analyzer. This is not the case for the Johann geometry, which requires significant Rowland preserving motions during the acquisition of a Compton profile only a few keV wide. But the focusing nature of Johann optics offers the conveniences of a focal spot at the detector location, namely the adequacy of a small detector and the facilitation of shielding to suppress, for example, noise due to the crystal analyzer re-scattering radiation from the sample into the detector. However, such spurious scattering can be mitigated in the in the inverse-Cauchois instrument by inserting Soller slits after the crystal and by using an energy-discriminating photon counter, e.g., a solid-state detector.

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