New Developments in Inelastic X-ray Scattering at the Advanced Photon Source

THOMAS GOG
On behalf of the Inelastic X-ray and Nuclear Resonant Scattering Group
@ APS @ Argonne Nat'l Laboratory

IXS 2019
June 28th, 2019
The Elephant’s Nightmare
(Garry Larson)
Introduction

**Progress in IXS Instrumentation, Theory, ...**
(Spectrometers, Analyzer Systems, Detectors, Sample Environments, ...)

**Upgrade of Synchrotron Radiation Sources**
(Conversion to Low-Emittance MBA Machines)

**New Opportunities for IXS Experimentation, Science at Synchrotrons**
RIXS at the APS

9-ID

1999
RIXS at the APS

9-ID

2004
RIXS at the APS

30-ID

2007
“MERIX”
RIXS at the APS

27-ID

2020
Introduction

Progress in IXS Instrumentation, Theory, ...
(Spectrometers, Analyzer Systems, Detectors, Sample Environments, ...)

Upgrade of Synchrotron Radiation Sources
(Conversion to Low-Emittance MBA Machines)

New Opportunities for IXS Experimentation, Science at Synchrotrons
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments
- ...
Introduction

Progress in IXS Instrumentation, Theory, ...
(Spectrometers, Analyzer Systems, Detectors, Sample Environments, ...)

Upgrade of Synchrotron Radiation Sources
(Conversion to Low-Emittance MBA Machines)

New Opportunities for IXS Experimentation, Science at Synchrotrons
World-wide MBA Low-Emittance Synchrotron Sources

**HEPS (China)** – Greenfield accelerator facility to be built near Beijing; planned completion in early 2020s

**ESRF (France)** – MBA Source upgrade 2019 resume operation in 2020

**SIRIUS (Brazil)** – Construction underway Commissioning to start 2019

**MAX-IV (Sweden)**
Inauguration June 2016
in operation

**SPring-8 (Japan)** – Upgrading in 2027 timeframe

**APS-U** – Upgrade 2022 Resume operation in 2023

Many other projects are planned (ALS-U, Swiss Light Source, Soleil, etc.)
APS - Upgrade

- Dramatically improved Brilliance (Flux / (Area × Solid Angle) )
  (... mostly through reduction of horizontal emittance)

Electron Beam at APS

- Double the Ring Current to 200 mA
- Improved Focusing, Smaller (sub-µm-, nm-) beams
- Improved Coherence (IXS?)

\[ \varepsilon_x = 3100 \text{ pm-rad} \]
\[ \sigma_x = 275 \mu m \]
\[ \sigma'_x = 11 \mu \text{rad} \]
\[ \varepsilon_x = 42 \text{ pm-rad} \]
\[ \sigma_x = 14.5 \mu m \]
\[ \sigma'_x = 2.9 \mu \text{rad} \]
New Opportunities for IXS

- Polarization Analysis
- Imaging (of)
- Time-Resolved Me
- Improved Energy
- Novel In situ

polarization largely ignored in the past
(... hard to do experimentally)

Sources of (variable) Polarization
- Phase Plates (low efficiency, low polarization purity)
- Special Insertion Devices (availability)
New Undulator Concepts: SCAPE  (Yuri Ivanyushenkov, APS)  
(Superconducting Arbitrarily Polarizing Emitter)

• Would like Undulator capable of generating linear and circular polarized photons
• Electromagnetic, superconducting undulator with four planar, magnetic cores, assembled around a cylindrical beam vacuum chamber
• APS Upgrade MBA-lattice enables cylindrical vacuum chambers with 6 mm ID
• Prototype successfully tested

Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.
**SCAPE PROTOTYPE TEST**

- SCAPE 0.5-m long prototype magnet is built:
  - period length – 30 mm
  - magnetic gap – 10 mm

- The prototype has been successfully tested in a LHe bath cryostat equipped with a movable Hall probe.
Why Polarization?

Phonons can carry angular momentum:

**CHIRAL PHONONS**

(in materials with broken inversion Symmetry)

Chiral Phonon in Mono-layer of WSe$_2$
PROBING PHONONS WITH ANGULAR MOMENTUM BY IXS (HERIX@30-ID, Chen Li, UCR)

- WC lacks space inversion symmetry
  - may exhibit chiral phonons

Scientific questions:
- Is it possible to identify chiral phonons by meV-IXS, using circular- or linear-polarized X-ray?
- Are the rules governing the scattering different?
- How do such chiral phonons contribute to the thermal and transport properties in materials with broken inversion symmetry?
  - Phonon-phonon scattering and phonon lifetime
  - Spin-phonon and electron-phonon interactions
Polarization Analysis of Scattered Beam

Typical IXS Set-up

Polarizer Set-up
Polarization Analysis of Scattered Beam

Polarization-analyzed resonant inelastic x-ray scattering of the orbital excitations in KCuF$_3$

K. Ishii,1 S. Ishihara,2,3 Y. Murakami,1,2,4 K. Ikeuchi,1,4 K. Kuzushita,1 T. Inami,1 K. Ohwada,1 M. Yoshida,1 I. Jarrige,1 N. Tatami,3 S. Niioka,2 D. Bizen,2 Y. Ando,2 J. Mizuki,1 S. Maekawa,3,5 and Y. Endoh1,6

1Spring-8, Japan Atomic Energy Agency, Hyogo 679-5148, Japan
2Department of Physics, Tohoku University, Sendai 980-8578, Japan
3CREST, Japan Science and Technology Agency (JST), Tokyo 102-0075, Japan
4Photon Factory / Condensed Matter Research Center, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
5Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan
6International Institute for Advanced Studies, Kizu, Kyoto 619-0025, Japan

(Received 18 May 2011; published 16 June 2011)

Spherical Analyzer + Flat HOPG crystal
HOPG reflectivity ~ 2%
Energy Resolution: 400...600 meV
Could distinguish orbital excitations between $e_g \Rightarrow e_g$ and $t_2g \Rightarrow e_g$

Spherical Analyzer + Sculptured HOPG crystal
HOPG reflectivity ~ 6%
Energy Resolution: ~200 meV
Preliminary measurements on CuGeO$_3$

Development of a graphite polarization analyzer for resonant inelastic x-ray scattering

Cite as: Rev. Sci. Instrum. 82, 113108 (2011); https://doi.org/10.1063/1.3662472
Submitted: 07 September 2011. Accepted: 30 October 2011. Published Online: 23 November 2011

Xuan Gao, Clement Burns, Diego Casa, Mary Upton, Thomas Gog, Jungho Kim, and Chengyang Li
Polarization Analysis of Scattered Beam (soft x-ray)

The simultaneous measurement of energy and linear polarization of the scattered radiation in resonant inelastic soft x-ray scattering

Cite as: Rev. Sci. Instrum. 85, 115104 (2014); https://doi.org/10.1063/1.4900959
Submitted: 09 September 2014 . Accepted: 22 October 2014 . Published Online: 11 November 2014


Graded, parabolic W/B₄C multilayer mirror as polarizer
underdoped YBa₂Cu₃O₆.₆
Energy Resolution: ~200 meV
Interlude: Flat Crystal Optics

• Striving for greatly improved energy resolution ($\approx 5\text{meV}$)
• Flat crystal optics:
  • Additional variable: crystal asymmetry, no figure errors
  • Opportunity for polarization analysis

BUT: Very little Solid-Angle Acceptance

$\varnothing 25\text{mm Sph. Analyzer at 2m: } \Omega \approx 100 \text{ } \mu\text{srad}$

Flat X-tal 20 $\times$100 $\mu$rad$^2$: $\Omega \approx 0.002 \text{ } \mu\text{srad}$

→ Need Collimator to bridge the gap
Interlude: Flat Crystal Optics

Parabolic, laterally graded multi-layer mirror

Multi-layer: Ruthenium / Carbon
Substrate: Si(100)
Dimension 150×7×7 mm³
Focal distance: 200 mm
Reflectivity: > 80 %

Angular Acceptance: 10×10 mrad²
⇒ $W \approx 100 \, \mu\text{srad}$
Angular Emittance: 100×100 μrad²
Manufacturer: Incoatec GmbH

Honnicke et al., J. Synchr. Rad. 18, 862 (2011)
Mundboth et al., J. Synchr. Rad. 21, 16 (2014)
Flat Crystal Analyzer with Polarizer

Asymmetric Collimator Crystal:
Si(111), b=-0.064
Angular Acceptance: 95 $\mu$rad
Angular Emission: 6 $\mu$rad

Symmetric Analyzer Crystal:
Quartz(309)
Angular Acceptance: 12 $\mu$rad

Polarizer Crystal:
Si(444)
Angular Acceptance: 6 $\mu$rad

Strip Detector (Mythen)
Flat Crystal Analyzer with Polarizer

Elastic spectra w/ and w/o polarizer:
- No loss in resolution
- ~50 % throughput
- ~80 % w/ asymmetric polarizer crystal
Polarization Analysis of Scattered Beam

Probing the elusive fractionalized Majorana excitations

→ Polarization analysis is required to distinguish the SC from the NSC (magnon).
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments

... for hard x-rays, now possible efficiently and without loss of resolution, using
- new insertion devices
- flat crystal optics
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments
- …
Imaging (of heterogeneous materials)

- XRS-based Direct Tomography
- Energy / Spatial Resolution: 1 to 3 eV / 50 to 150 µm

Direct Tomography with Chemical-bond Contrast
Simo Houtari et al., Nature Mat 10, 489 (2011)
Sahle et al., J. Synchrotron Rad 24, 476 (2017)
Imaging (of heterogeneous materials)

- RIXS
- Improved Energy Resolution using multi-layer collimator

\[ \Delta E \approx \sqrt{\Delta E_o^2 + \Delta E_i^2 + (E_o \cot(\theta_B) \Delta \theta)^2} \]

\[ E_o = 11.215 \text{ keV}, \text{ Si}(844): \Delta E \approx 125 \text{ meV} \]

- Mapping electronic / magnetic excitations
- Batteries, Catalysts
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Res
- Novel In situ Sample

First RIXS study to probe the dynamic response of magnetic and orbital excitations

Ultrafast energy- and momentum-resolved dynamics of magnetic correlations in the photo-doped Mott insulator $\text{Sr}_2\text{IrO}_4$
Dean et al., Nature Mat 15, 601 (2016)
Time-Resolved Measurements

- Exploit unique time structure at APS (152 ns)
- MEMS (micro-electro-mechanical-system)

Study the electron-hole recombination dynamics response of two Iridium oxide catalysts, \(\text{IrO}_x\) and \(\text{IrBL}\), by time- and energy resolved RIXS imaging.

New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments
- ...
Improved Energy Resolution

\[ \Delta E_{tot} = \sqrt{\Delta E_{inc}^2 + \Delta E_{ana}^2 + \Delta E_{det}^2 + \Delta E_{spot}^2} \]

Spherical, Near-backscattering Analyzer

High Resolution Monochromator

Undulator source

High Heatload Monochromator

Sample

Focusing Mirrors

Monochromatic (Bandpass \( \Delta E \)), Micro-focused Incident Beam

\( E \approx 5\text{-}23 \text{ KeV} \)
Improved Energy Resolution

\[ \Delta E_{tot} = \sqrt{\Delta E_{inc}^2 + \Delta E_{ana}^2 + \Delta E_{det}^2 + \Delta E_{spot}^2} \]

\( \Delta E_{inc} \): Bandpass determined by High-Resolution Monochromator

suitable \( \Delta E_{inc} < 5 \text{ meV} \) achievable

\( \Delta E_{det} \): Detector Pitch < 50 \( \mu \text{m} \)

\( \Delta E_{spot} \): Micro-focusing < 10 \( \mu \text{m} \)
\( \Delta E_{\text{ana}} \): **Diced, spherical analyzers**

- large solid angle coverage
- energy resolution: \( \Delta E = E \cot \theta_B \Delta \theta \) => need near-backscattering
- resonant character of RIXS => need to find suitable material/reflection for \( E \)
- material: typically Si or Ge (large, perfect crystals)
- but: lower symmetry materials offer more choices of reflections
- Quartz, Sapphire, Lithium Niobate, ... available as near perfect crystals
- compiled “Analyzer Atlas” to aid choice of analyzer
- recently, using Q(309) => \( \Delta E_{\text{tot}} = 10.5 \) meV  

**New Record!**
Improved Energy Resolution
A prototype spherical quartz (309) analyzer has been made and tested at 27-ID at the APS.

A record energy resolution was achieved (10.5 meV).

Joel Bertinshaw talk on Sr$_2$IrO$_4$ / Sr$_3$Ir$_2$O$_7$ super lattices.

**Issues:**
- Small area (lower efficiency)
- We saw degradation of the glue used to hold the quartz pixels.
Current Challenge
Finding a glue or other bonding method which can survive more than 10 hours of HF etching and keep its integrity over time.

Overcame Challenge
Dicing (cracking during dicing)
Improved Energy Resolution

Angular Acceptance: $10 \times 10 \text{ mrad}^2 \approx 100 \mu\text{srad}$

Angular Emittance: $100 \times 100 \mu\text{rad}^2$

- Si(440) sph.
- Quartz(309) sph.
- Q(309) flat 8.9 meV
- Q(309) flat 4 meV

Intensity [a.u.]

Energy Loss [meV]

- ~25 meV
- 9.7 meV
- 10.5 meV
- 5.5 meV
MONTEL-CDW ANALYZER (FROM: YONG CAI)

10-ID @ NSLS II

Detector

200mm

1-2 mm

~0.1 mrad

~20 µm

1.2 m

Multilayer Mirror

~10 mrad

Acceptance

200mm

~10 meV

Detector

W

Si (220)

C

η ~ 5 µr

Dispersing crystal

90° φ

Dispersion tan

Sample

200mm

~100 meV

eV

°
Summary

- X-ray echo spectroscopy relies on imaging IXS spectra and does not require x-ray monochromatization, ensuring strong signals along with a very high spectral resolution.

- The hard x-ray optical components (large-dispersion-rate “diffraction gratings”, truly imaging optics, etc.) required for the realization of the x-ray echo spectrometers are feasible.

- X-ray echo spectrometers will either enable up to \( \sim 1000 \)-fold reduction in measurement time for experiments at presently available \( \sim 1 \text{ meV/1 nm}^{-1} \) resolution, or make practical experiments with a \( \sim 0.1 \text{ meV/0.1 nm}^{-1} \) resolution.

- X-ray echo spectrometers (XES) will bridge the gap between the high- and low-frequency inelastic probes and enter the uncharted domain.
X-ray Echo
Yu. Shvyd’ko

Improved Energy Resolution

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution
- Novel In situ Sample Environments

- Spherical analyzers: ~10 meV might be the limit due to strain and figure errors
- Flat crystals: everything’s possible, but flux will become the limit
- Complexity, stability, ease-of-use will be the issues
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- **Meaningful In situ Sample Environments**
  - High-Pressure
  - Magnetic Fields
  - Uniaxial Strain
High Pressure

- Confined metal at 59.5 GPa: metallicity in ab-Plane, insulating along c axis
- No collapse of spin-orbit coupling, rather: first-order structural change
- Intricate interplay between structural and electronic properties in Sr$_3$Ir$_2$O$_7$

Pressure-Induced Confined Metal from the Mott Insulator Sr$_3$Ir$_2$O$_7$
Ding et al., PRL 116, 216402 (2016)
High Pressure

Post sample collimating resonant inelastic x-ray scattering spectrometers for studying low-energy excitation spectrum under high pressure Jin-Kwang Kim et al., in preparation

Field of view at focal point of Montel mirror is small enough to see sample but discriminate scattering from surrounding environment
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Meaningful In situ Sample Environments
  - High-Pressure
  - Magnetic Fields
  - Uniaxial Strain
Magnetic Fields

- Unconventional magnetism in 5d materials with strong SOC
- Honeycomb-Li$_2$IrO$_3$ promising Kitaev material -> QSL ground state (?)
- Ext. magnetic field -> degeneracy of magnetic ground states: incommensurate spiral, commensurate zig-zag phase
- Dispersing magnon identified for both spiral and zigzag
- First results with $B \neq 0$ ($\leq 2$T): softening of zigzag, hardening of spiral

From: Alejandro Ruiz, Alex Frañó, et al., UCSD
Magnetic Fields

• Small magnet assemblies for use in closed-cycle cryostats
• 1.5 ... 2 ... 3 T(?)

Neodymium Block Magnet

Pole Piece

Cu Heat Transfer Housing

~2mm
Magnetic Fields

- Pulsed, DC magnets on 6-ID @ APS
- Trapped-field magnets
  (Z. Islam, APS)
New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- **Meaningful In situ Sample Environments**
  - High-Pressure
  - Magnetic Fields
  - Uniaxial Strain
Uniaxial Strain

Uniaxial pressure control of competing orders in a high-temperature superconductor

• Ground states of TMOs (High Tc, CDW, ...) can be tuned by doping, external fields
• Tuning might introduce disorder
• Application of strain can distinguish between competing orders

In-Plane Resistivity Anisotropy in an Underdoped Iron Arsenide Superconductor

• Application of strain can remove twinning
Uniaxial Strain

- W. Jin et al.: RIXS in Sr$_2$IrO$_4$
- Suppression of structural phase transition in STO

High T / Low T

from: Wentao Jin, U Toronto
Conclusions

• IXS has come a long way as a practical, efficient probe of elementary excitations in complex materials
• => Novel materials discovery, characterization
• Efficient polarization analysis possible and will further enhance IXS
• Imaging and time-resolved (ps,ns) measurements at Synchrotrons possible
• As probe of magnetic excitations, RIXS energy resolution has been greatly improved (~ 10 meV)
• ... but needs to improve even further (~< 1 meV) to be on “equal” footing with Inelastic Neutron Scattering
• Novel flat crystals optics and special spherical analyzers provide path to ultra-high resolution
Conclusions

• New multilayer optics / flat-crystal on the horizon / being implemented
• Meaningful in-situ sample environments
People

Diego Casa (dcasa@anl.gov)
Mary Upton (mhupton@anl.gov)

Jungho Kim (jhkim@anl.gov)
Ahmet Alatas, XianRong Huang, Jinkwang Kim

Wenli Bi (wbi@anl.gov)
(High Pressure, Diamond Anvil Cells)

Ayman Said (said@anl.gov)
(Spherical Analyzers)

Rick Krakora
Emily Aran
(Scientific Assc.)

Tom Toellner (toellner@anl.gov)
(High-Resolution Monochromators)
# People

<table>
<thead>
<tr>
<th>XSD-IXN group</th>
<th>XSD-OPT</th>
<th>CNM</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Alatas</td>
<td>X. Huang</td>
<td>R. Divan</td>
</tr>
<tr>
<td>E. Alp</td>
<td>E. Kasman</td>
<td>S. Miller</td>
</tr>
<tr>
<td>E. Aran</td>
<td>J. Qian</td>
<td></td>
</tr>
<tr>
<td>W. Bi</td>
<td>B. Shi</td>
<td></td>
</tr>
<tr>
<td>D. Casa</td>
<td>M. Wieczorek</td>
<td></td>
</tr>
<tr>
<td>T. Gog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M. Hu</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Kim</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T. Toellner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M. Upton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J. Zhao</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thank you
Path to Ultra-High Energy Resolution

Compilation of viable Reflections in Si, Ge, Sapphire, Lithium Niobate, Quartz

www.aps.anl.gov/Analyzer-Atlas/Analyzer-Atlas

Point to an element for available absorption edges / emission lines

contact: Thomas Gog, last updated: 16 Feb 2012
Path to Ultra-High Energy Resolution

Compilation of viable Reflections in Si, Ge, Sapphire, Lithium Niobate, Quartz


<table>
<thead>
<tr>
<th>Cryst</th>
<th>(h,k,l)</th>
<th>Ei (keV)</th>
<th>keV</th>
<th>ΘB (°)</th>
<th>∫IR dΘ (µrad)</th>
<th>Width (µrad)</th>
<th>Ei cot(θ)</th>
<th>∆E (meV/µrad)</th>
<th>∆Eg (meV)</th>
<th>∆Et (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>(3,3,7)</td>
<td>8.969</td>
<td>87.14</td>
<td>80.2</td>
<td>81.5</td>
<td>0.448</td>
<td>36.51</td>
<td>5.6</td>
<td>36.94</td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>(0,0,8)</td>
<td>8.766</td>
<td>77.46</td>
<td>30.3</td>
<td>28.2</td>
<td>1.998</td>
<td>56.34</td>
<td>24.97</td>
<td>61.62</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>(2,4,6)</td>
<td>8.542</td>
<td>72.02</td>
<td>13.1</td>
<td>11.5</td>
<td>2.915</td>
<td>33.48</td>
<td>36.44</td>
<td>49.48</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>(1,3,7)</td>
<td>8.768</td>
<td>77.5</td>
<td>11.8</td>
<td>10.8</td>
<td>1.991</td>
<td>21.56</td>
<td>24.89</td>
<td>32.93</td>
<td></td>
</tr>
<tr>
<td>Equiv. Refl.: (3,5,5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cryst</th>
<th>(h,k,l)</th>
<th>Ei (keV)</th>
<th>keV</th>
<th>ΘB (°)</th>
<th>∫IR dΘ (µrad)</th>
<th>Width (µrad)</th>
<th>Ei cot(θ)</th>
<th>∆E (meV/µrad)</th>
<th>∆Eg (meV)</th>
<th>∆Et (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO3</td>
<td>(1,5,-10)</td>
<td>8.941</td>
<td>84.6</td>
<td>58.1</td>
<td>55.8</td>
<td>0.85</td>
<td>47.45</td>
<td>10.62</td>
<td>48.62</td>
<td></td>
</tr>
<tr>
<td>Equiv. Refl.: (-5,-6,-10), (-6,-5,-10), (-1,-6,-10), (-5,-1,-10), (-6,1,-10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiNbO3</td>
<td>(1,-6,10)</td>
<td>8.941</td>
<td>84.6</td>
<td>56.4</td>
<td>55.8</td>
<td>0.85</td>
<td>47.45</td>
<td>10.62</td>
<td>48.62</td>
<td></td>
</tr>
<tr>
<td>Equiv. Refl.: (-5,1,-10), (-6,1,-10), (-1,-5,10), (-5,6,10), (-6,5,10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>(-4,-6,4)</td>
<td>8.972</td>
<td>87.44</td>
<td>37.5</td>
<td>34.4</td>
<td>0.401</td>
<td>13.78</td>
<td>5.01</td>
<td>14.66</td>
<td></td>
</tr>
<tr>
<td>Equiv. Refl.: (-4,-2,-4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>(6,-2,4)</td>
<td>8.972</td>
<td>87.44</td>
<td>37.4</td>
<td>34.4</td>
<td>0.401</td>
<td>13.77</td>
<td>5.01</td>
<td>14.65</td>
<td></td>
</tr>
<tr>
<td>Equiv. Refl.: (-6,4,-4), (-2,-6,4), (-2,-4,4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>(4,-6,4)</td>
<td>8.972</td>
<td>87.44</td>
<td>36.3</td>
<td>34.4</td>
<td>0.401</td>
<td>13.78</td>
<td>5.01</td>
<td>14.66</td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>(2,4,-4)</td>
<td>8.972</td>
<td>87.44</td>
<td>36.2</td>
<td>34.4</td>
<td>0.401</td>
<td>13.77</td>
<td>5.01</td>
<td>14.66</td>
<td></td>
</tr>
<tr>
<td>Equiv. Refl.: (2,-6,4), (4,2,4), (-6,2,-4), (-6,4,4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>(6,-2,4)</td>
<td>8.972</td>
<td>87.44</td>
<td>28.5</td>
<td>26.9</td>
<td>0.401</td>
<td>10.79</td>
<td>5.01</td>
<td>11.89</td>
<td></td>
</tr>
</tbody>
</table>
Introduction

Inelastic Scattering Cross Section

\[
\frac{d^2 \sigma}{d\Omega d\omega} \propto \left| \langle f | H_{\text{int}} | i \rangle + \sum_n \frac{\langle f | H_{\text{int}} | n \rangle \langle n | H_{\text{int}} | i \rangle}{E_i - E_n + i\Gamma} \right|^2
\]

Non-Resonant (weak)
Resonant Enhancement (x 50 ... 100)

RIXS Processes

direct
Indirect

Ament, van Veenendaal,
Devereaux, Hill, van den Brink,
Rev. Mod. Phys. 83, 705 (2011)
People

Diego Casa (dcasa@anl.gov)
Mary Upton (mhupton@anl.gov)

Jungho Kim (jhkim@anl.gov)

Wenli Bi (wbi@anl.gov)
(High Pressure, Diamond Anvil Cells)

Ayman Said (said@anl.gov)
(Spherical Analyzers)

Rick Krakora
(Scientific Assoc.)

Tom Toellner (toellner@anl.gov)
(High-Resolution Monochromators)