Condensed Matter Physics Research At Extreme Conditions: High Pressure and Pulsed Magnetic Fields

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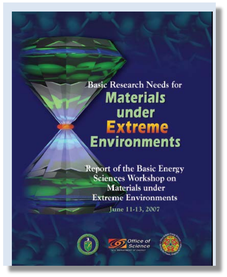
Abstract

The brilliance and penetration power of high-energy x-ray beams at the Advanced Photon Source enable studies of condensed matter at extreme conditions of high pressure and high magnetic field. We describe recent developments in x-ray scattering and spectroscopic probes of structure, electronic structure, and electronic/magnetic ordering and excitations in the diamond anvil cell and under pulsed magnetic fields at selected XSD beamlines.

Motivation



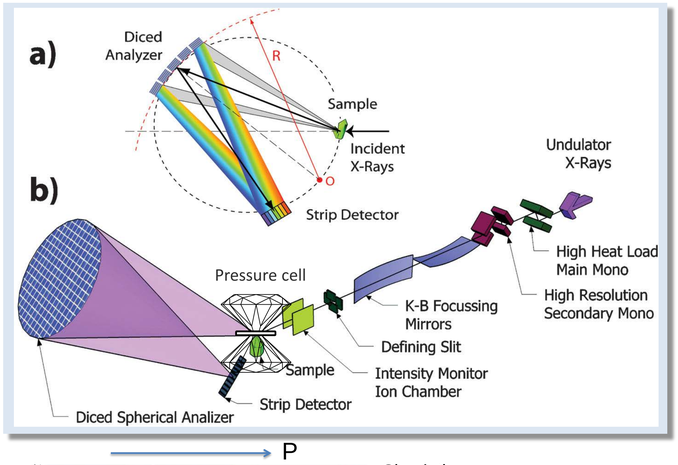
Extreme pressures and magnetic fields can be used to affect the state of outer valence electrons hence controlling a material's transport and magnetic properties. They do so by altering electronic bandwidth and electron density, exerting torques on magnetic (orbital and spin) moments and raising/lowering energy levels via changes in crystal electric fields and Zeeman splittings.

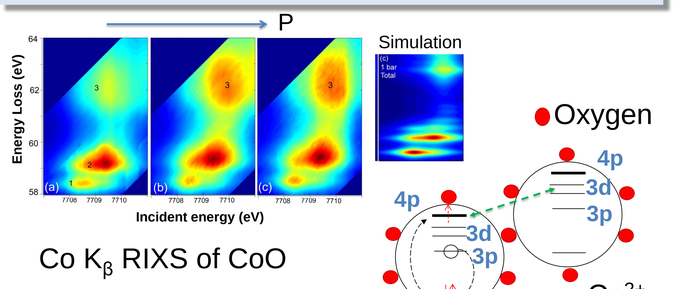
Resultant changes in electron-electron correlations give rise to a plethora of novel phenomena including insulator-metal, metal-superconducting, high-spin to low-spin, valence, volume collapse and quantum phase transitions. We exploit the high flux, collimation, penetration power, energy and polarization tunability of APS x-ray beams to develop a broad suite of probes that allow exploration of phase diagrams at the extremes providing a route to transformational studies of materials.

Techniques	Extremes	Beamline
RIXS/IXS	Mbar, 6 K	3-ID, 9-ID, 30-ID
Nuclear res. scat.	Mbar, 6 K	3-ID
XMCD	Mbar, 1.4 K, 6.5 T	4-ID
Magnetic diffraction	0.2 Mbar, 4 K	4-ID
Diffraction (pulsed field)	30 T, 6 K	6-ID
XAFS	Mbar (room temp)	20-BM

Resonant Inelastic X-ray Scattering

RIXS probes low energy electronic and magnetic excitations (charge transfer, crystal field, spin waves, plasmons) via measurements of energy and momentum transfers in the 50 meV- few eV range spanning the entire BZ. The ability of RIXS to measure dispersion of excitations over such wide E,Q range is unique. High-pressure RIXS leverages the highly collimated x-ray beams by using a Be-gasket geometry thus avoiding the absorbing diamond anvils at the relatively low resonant energies.

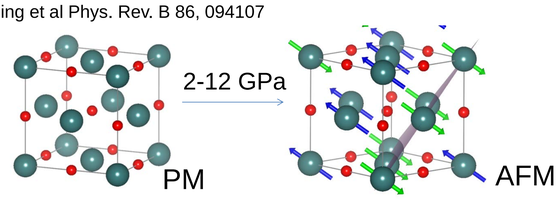




Co K_β RIXS of CoO

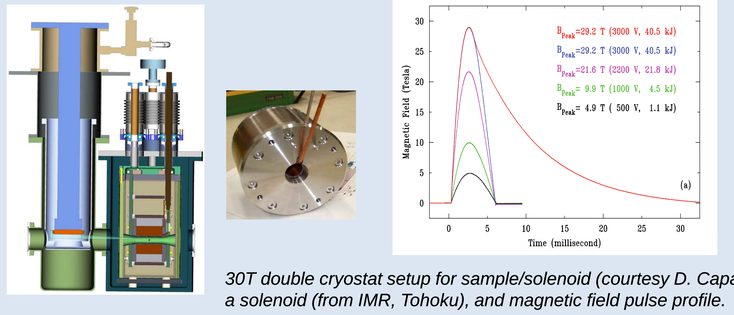
Non-local excitation corresponds to inter-site hopping between 4p and 3d states; correlates with onset of AFM order

Ding et al Phys. Rev. B 86, 094107

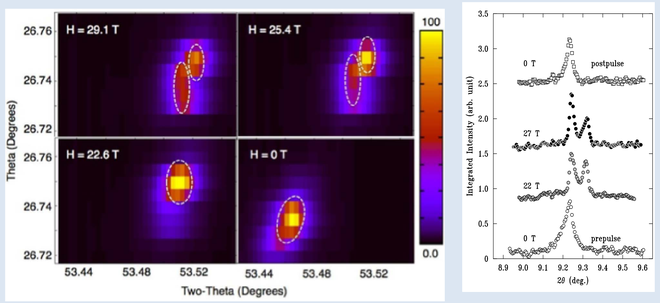


Diffraction studies in Pulsed magnetic fields

X-ray diffraction in magnetic fields allows exploration of field-driven electronic phenomena in quantum matter and their coupling to lattice structure. Intensity of a crystal Bragg peak is collected in the time domain during a field pulse with a rise time of ~3 msec. Structural effects may be observed in single-shot measurements. A pulse repetition rate of ~8 min at 30 T is achievable, while in split-pair magnet (not shown) it is > 20 min.



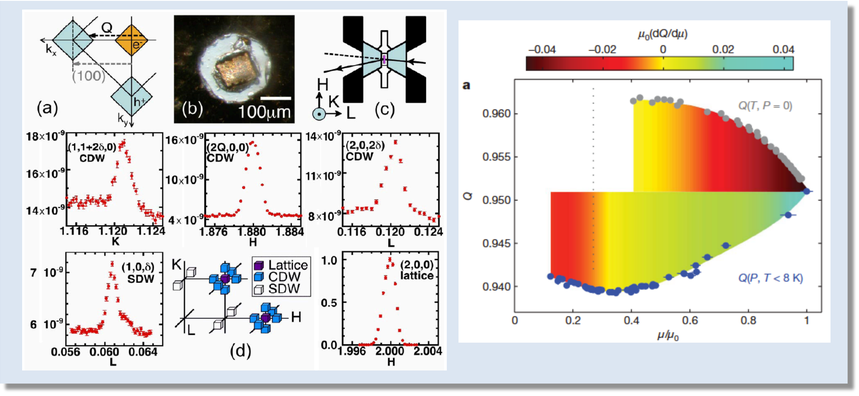
30T double cryostat setup for sample/solenoid (courtesy D. Capatina), a solenoid (from IMR, Tohoku), and magnetic field pulse profile.



Structural phase transition in $Tb_2Ti_2O_7$ spin-liquid (Ruff et al, PRL 105, 077203 (2010) and $TbVO_4$ (Islam et al., RSI 83, 035101 (2012)).

Single crystal diffraction at high pressures and low T

Pressure is used to tune electron density altering electron-electron correlations responsible for AFM and CDW order. Single crystal charge and magnetic diffraction is used to probe electronic ordering driven by a variety of mechanisms including Fermi-surface nesting, elecron-phonon coupling, spin-Peierls, Mott, and RKKY interactions. Emphasis is on quantum phase transitions at zero temperature and many observables (T= 2K) can be traced to quantum fluctuations.

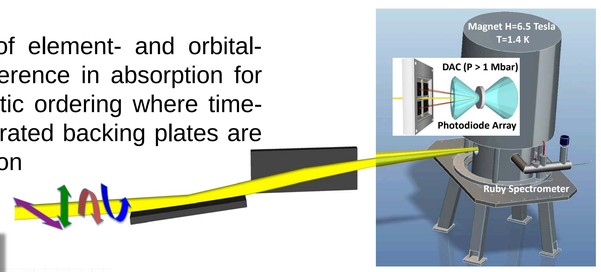


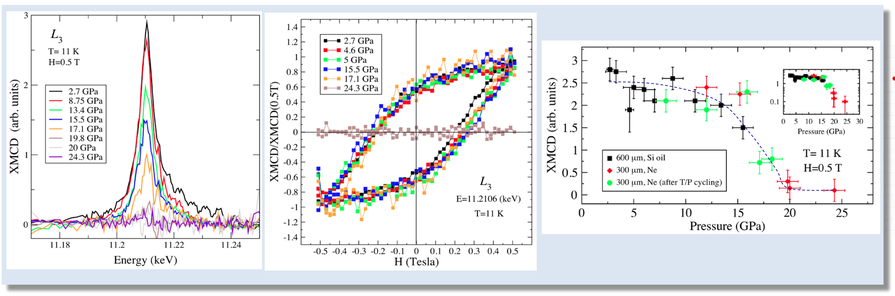
*(Left) Schematic of Fermi-surface nesting in AFM/CDW itinerant Cr metal, Cr single crystal in DAC sample chamber, sample chamber, schematic of scattering geometry. Incommensurate CDW and SDW Bragg peaks are 10^{-8}- 10^{-9} weaker than lattice peaks [Feng et al, PRL **99**, 137201 (2007)]. (Right) Different temperature- and pressure-dependence of incommensurate CDW wavevector is indicative of the presence of quantum fluctuations in the continous,pressure-induced order-disorder transition [Jaramillo et al,, Nature **459**, 405 (2009)].*

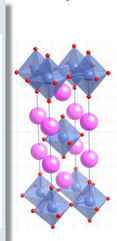
X-ray Magnetic Circular Dichroism at high pressures

Polarization-dependent x-ray absorption spectroscopy allows measurements of element- and orbital-specific magnetic ordering at high pressures. XMCD, which measures the difference in absorption for opposite x-ray helicity, probes Ferro, Ferri, Para, and canted anti-Ferro magnetic ordering where time-reversal symmetry is broken. Partially-perforated anvils and mini-anvils on perforated backing plates are used to reduce x-ray attenuation at the relatively low resonant energies of transition

Metals (3d and 5d systems), rare-earths (4f systems) and actinides (5f systems).







Collpase of canted AFM order under pressure in layered Sr_2IrO_4. Frustration in interlayer coupling is responsible for the loss of 3D magnetic order at low temperature above 20 GPa. The material remains insulator indicating that long-range magnetic correlations are not responsible for the insulating gap (Haskel et al., PRL 109, 027204 (2012)].

Upgrade to MBA lattice

The high-brilliance/coherence of x-ray beams from an MBA lattice will enable studies of spatiotemporal correlations with 10 nm, 70 ps resolution at high pressure and high magnetic fields using imaging and coherent scattering techniques opening new frontiers for studies of correlated electron systems.

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