RIXS-hXES @ XFELs

MARTINA DELL'ANGELA

CNR-IOM, TRIESTE

Outline

RIXS-hXES@ XFELs

I. Techniques
   1. X-ray absorption (XAS)
   2. X-ray emission (XES) /High resolution X-ray Emission (hXES)
   3. Resonant Inelastic X-ray Scattering (RIXS)

II. Instruments

III. Selected RIXS-hXES applications @ XFELs
   I. RIXS @FLASH: Phase Transitions
   II. RIXS@LCLS: Femtochemistry
   III. RIXS@LCLS: Liquids
   IV. RIXS@SACLA: Magnetism
   V. RIXS@FERMI: dd excitations

I. Exp. Techniques

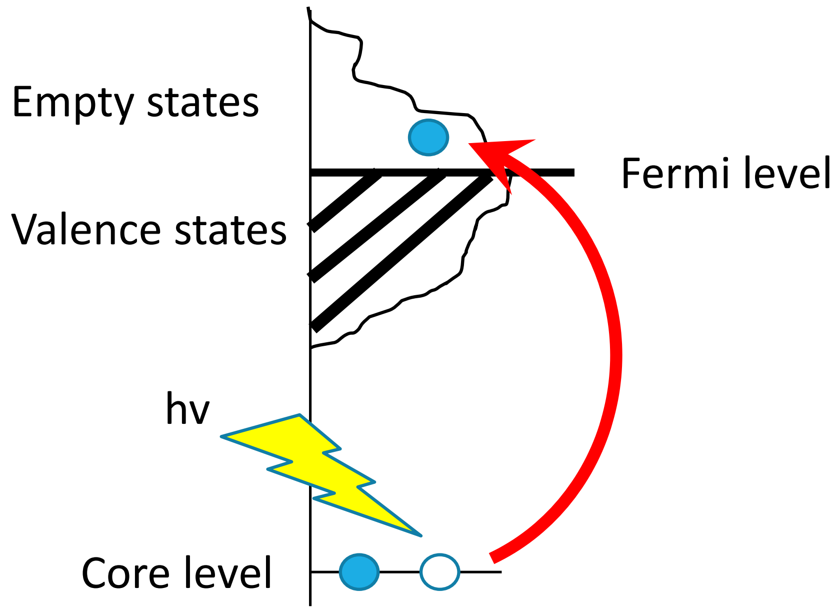
hXES

RIXS

Core level spectroscopies

Photon-in/Photon-out

X-ray absorption spectroscopy (XAS)



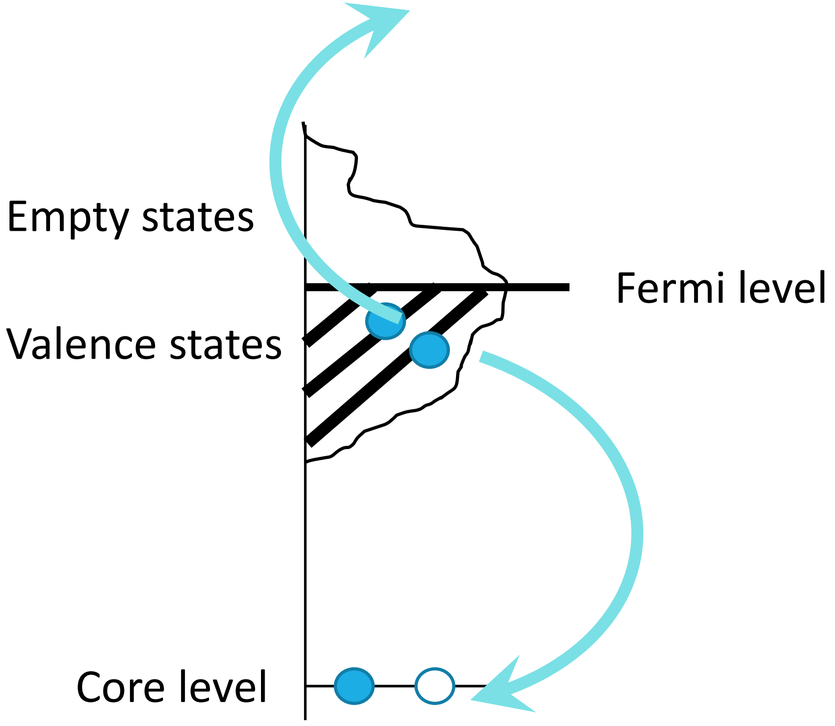
A photon is absorbed and a core electron is excited to an unoccupied state

$$P_{i\to f} \propto |< f|H'|i > |^2 \varrho_f$$

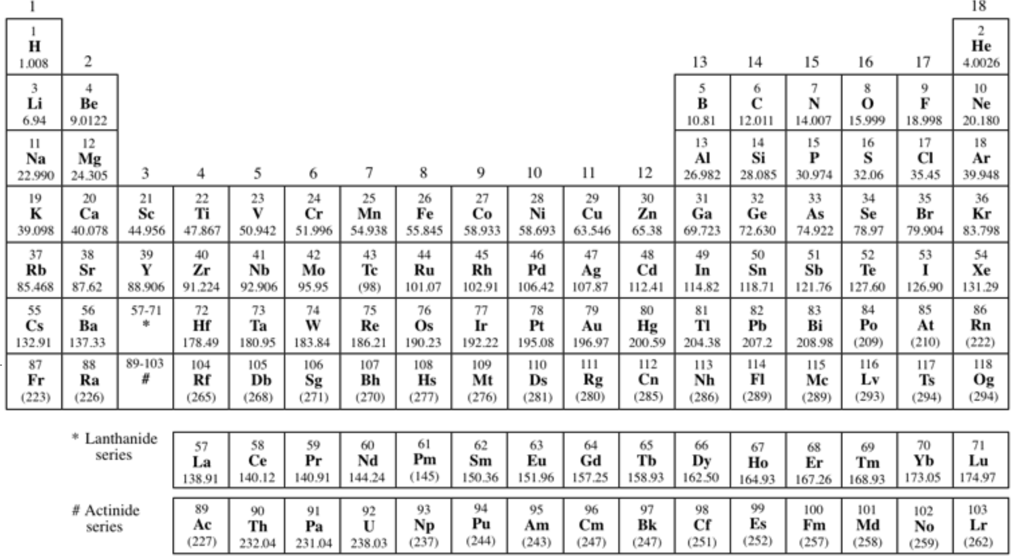
$$H' = \boldsymbol{p} \cdot \boldsymbol{e} \exp(i\boldsymbol{kr}) \quad \textit{dipole approximation}$$

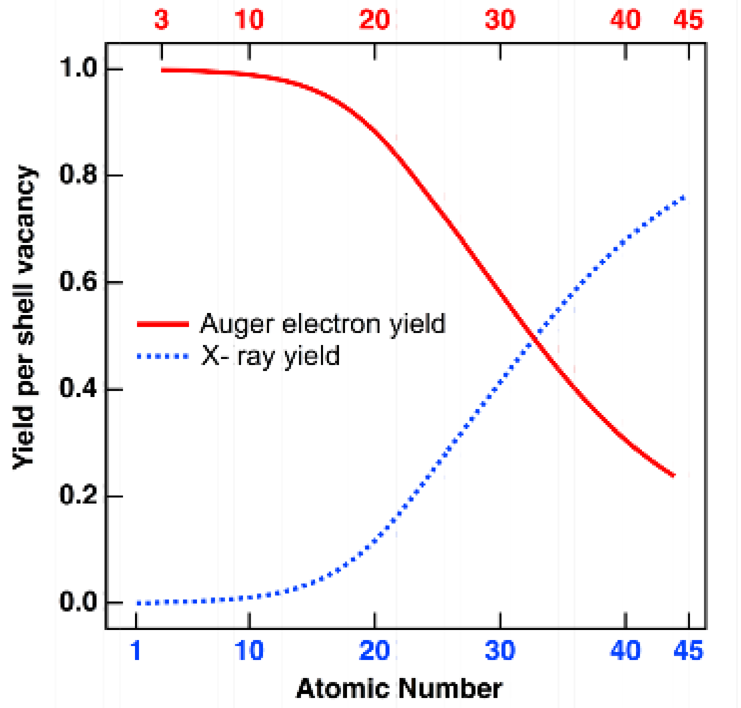
XAS is element-specific

Decay of core holes

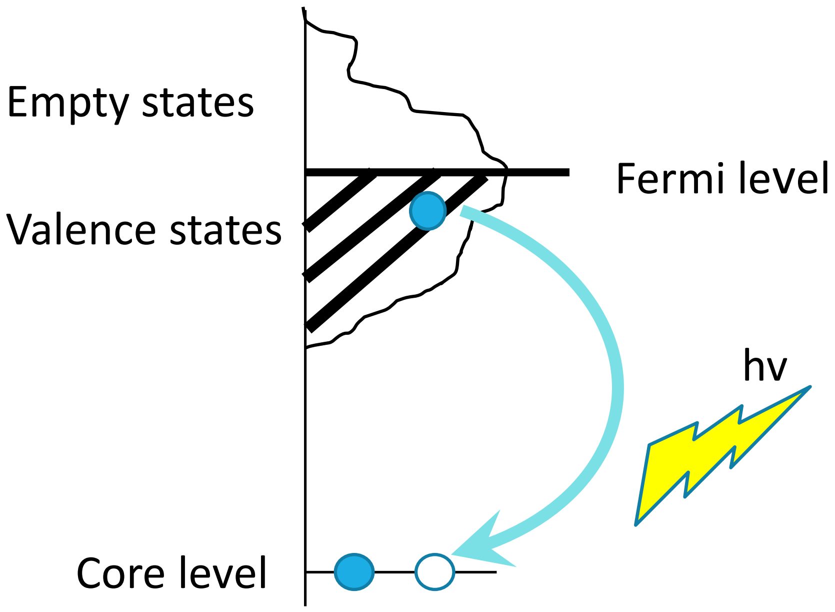


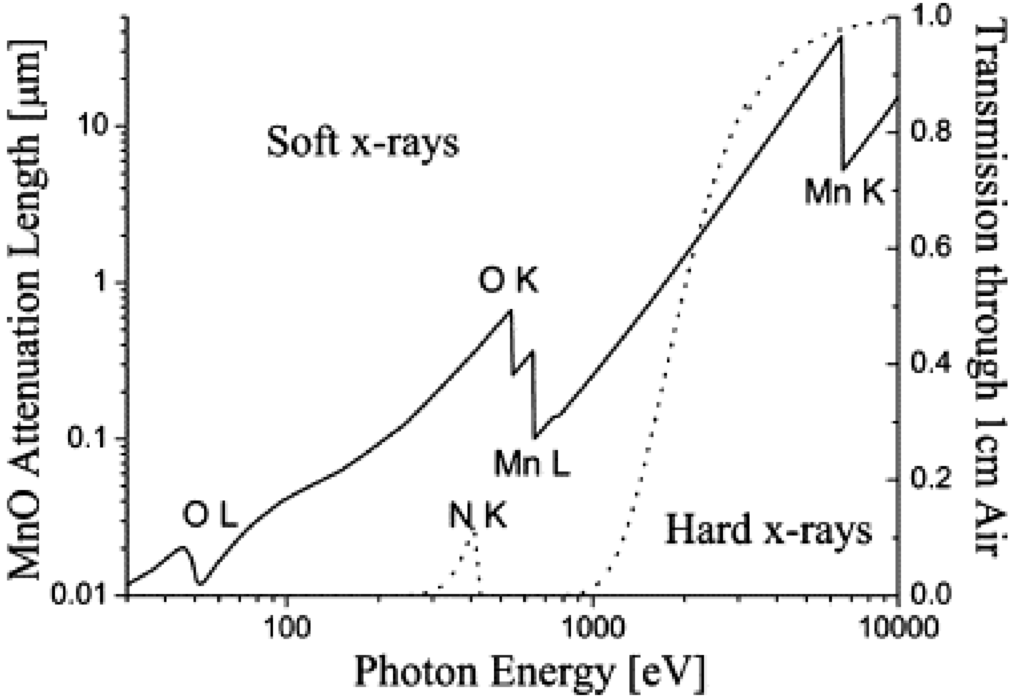
Auger Electron Emission





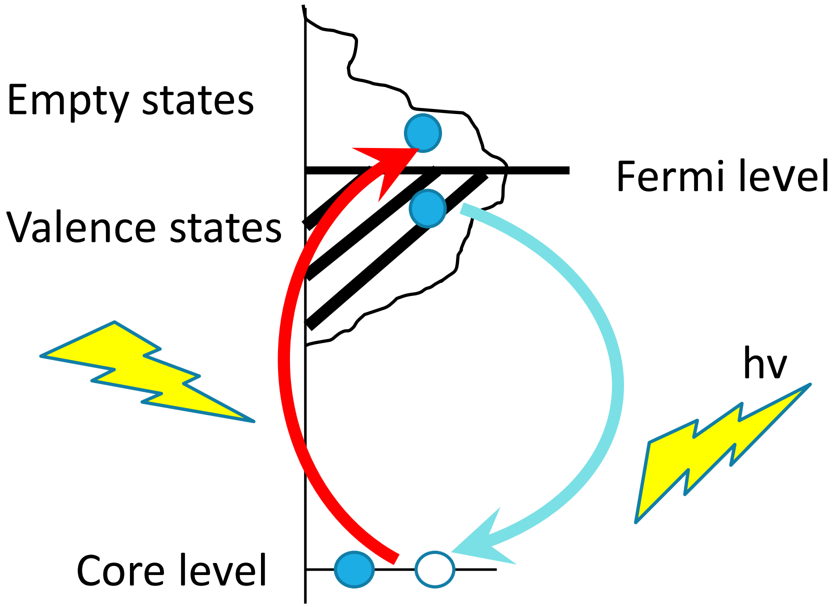
X-ray emission spectroscopy (XES)





P. Glatzel, bergmann U., Coord. Chem. Rev. 249 (2005) 65

Resonant Inelastic X-ray Scattering (RIXS)



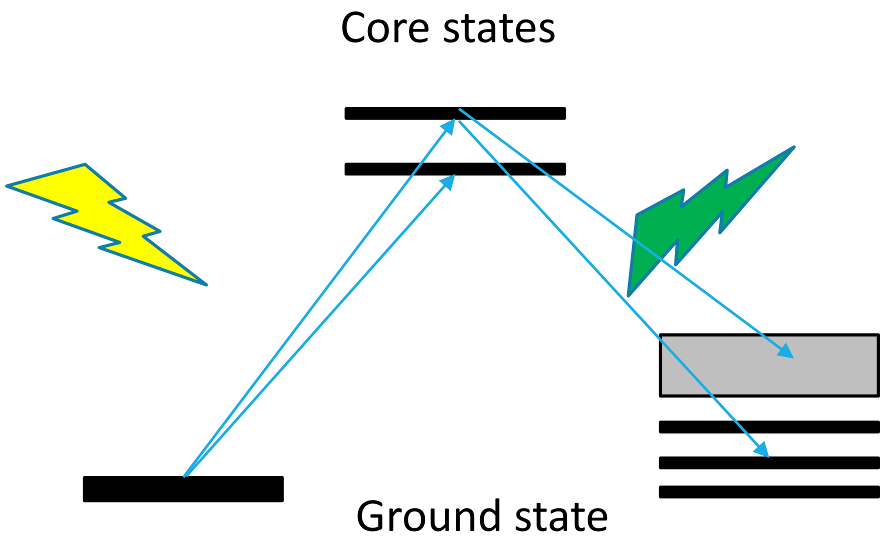
J. Nordgren et al., in Handbook of Solid State Spectroscopy, Springer 2006, Ed. W.R. Wij

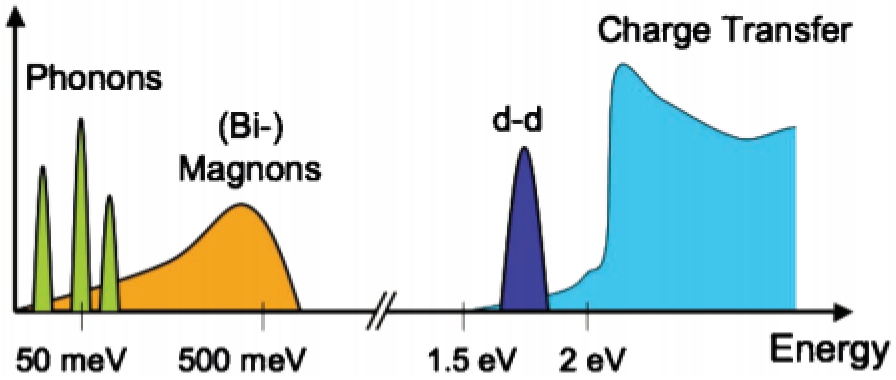
Inelastic scattering cross section (Kramers-Heisenberg formula):

$$F(\omega, \omega^{i}) = \sum_f \left| \sum_m \frac{<f|D|m><m|D|g>}{E_g + \hbar\omega - E_m - i\Gamma_m} \right|^2 \delta(E_g + \hbar\omega - E_f - \hbar\omega')$$

i. **Site selectivity**
ii. **Simmetry selectivity**
iii. **Probe low energy excitations**
iv. **Sub-natural width spectra**
v. **Ultrafast dynamics**
vi. **Bulk and buried structures**
vii. **Band dispersion**

Low energy excitations in materials





L.J.P. Ament, et al., Rev. Mod. Phys., 83, No.2 (2011)

Outline

RIXS-hXES@ XFELs

Requirements

1. Photon Detection System (energy resolution)

2. Tunable and brilliant photon source (VUV and X-ray)

Monochromatic synchrotron beamlines

Photon hungry

X-ray Spectrometers …history

VG Scienta, XES 350 *Grace*

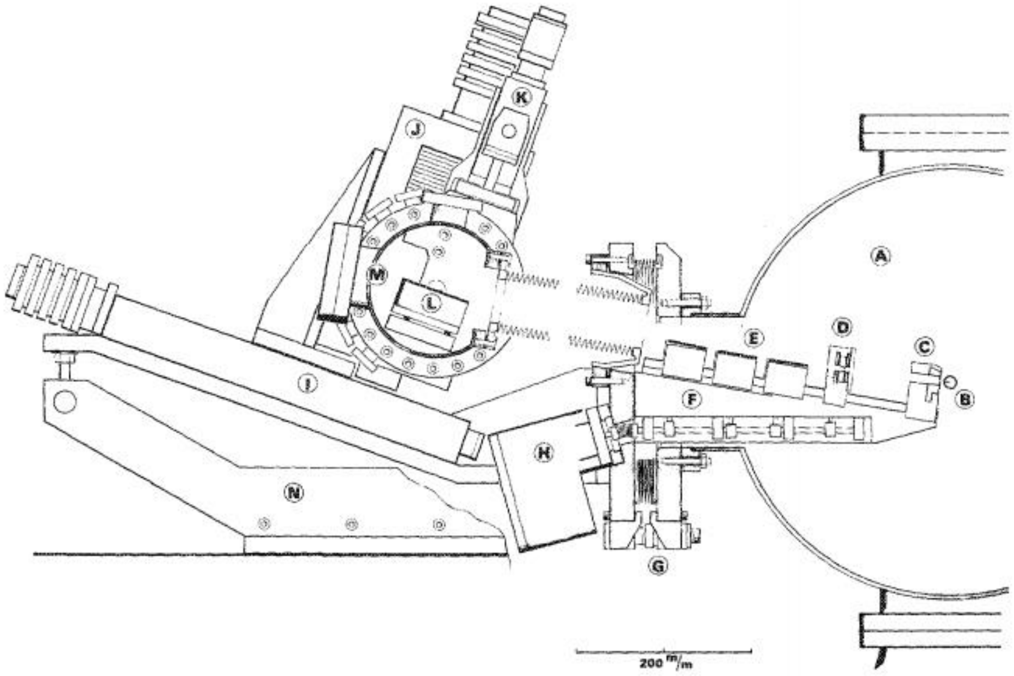
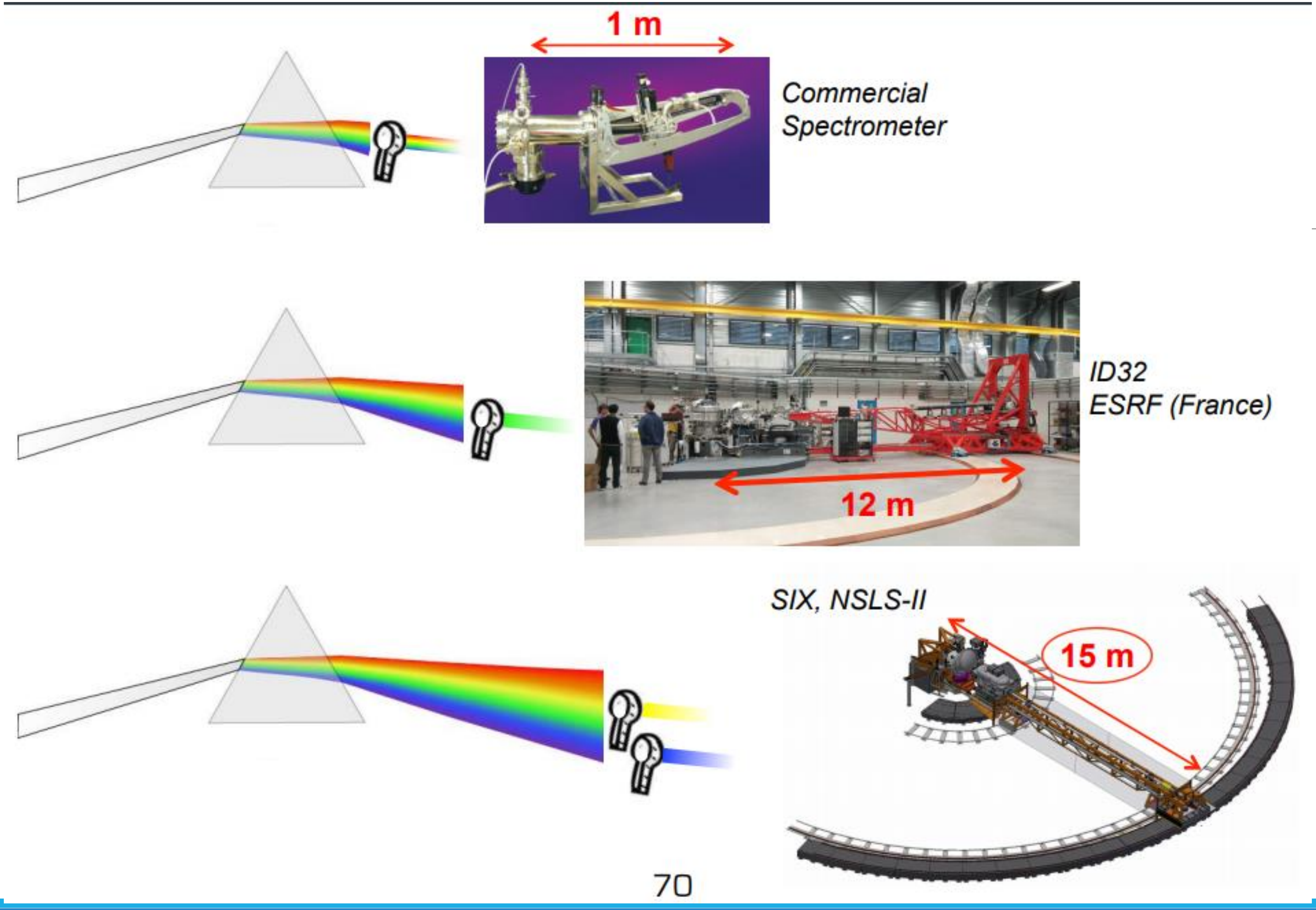


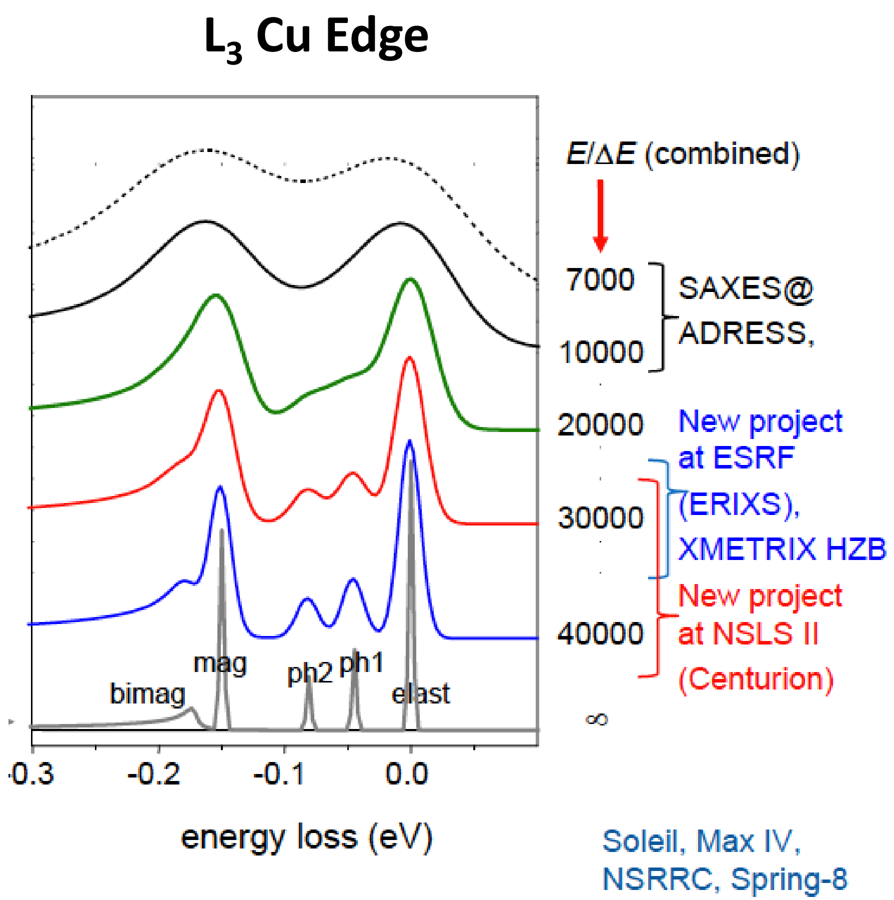
FIG. 1. Outline of the fixed-grating grazing incidence instrument. A; experiment chamber, B; sample, C; entrance slit, D; grating selector aperture, E; gratings, F; reference slab, G; optical axis adjustment, H; mechanical feedthroughs, I,J,K; coordinate tables, L; detector, M; detector house, and N; support structure.

Nordgren, J., Bray, G., Cramm, S., Nyholm, R., Rubensson, J.-E. & Wassdahl, N. (1989). *Rev. Sci. Instrum.* **60**, 1690–1696.



I. Jarrige, BNL

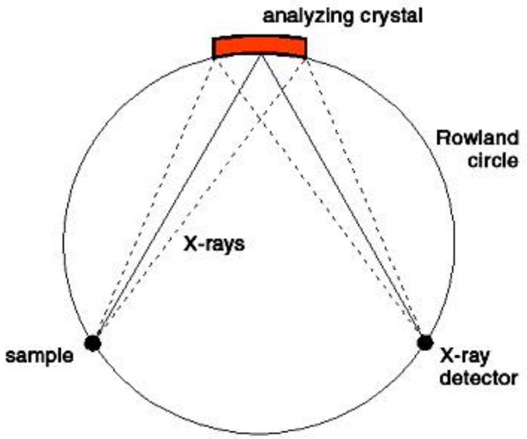
RIXS resolution



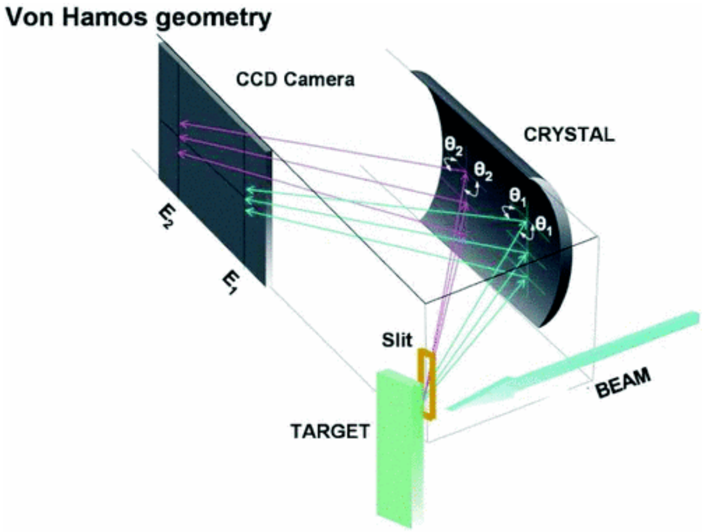
A. Fohlisch, XFEL hRIXS

Examples of X-ray spectrometers

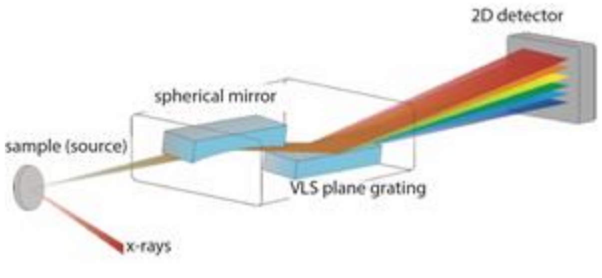
Rowland geometry (Monochromatic; spherical mirror)



von Hamos (Dispersive)



Hettrick-Underwood (qRIXS, MERLIN(ALS))



M. Czarnota et al., Phys. Rev. A 88, 052505 (2013)

Lab based RIXS/XES ….future developments

PHYSICAL REVIEW X **6,** 031047 (2016)

Ultrafast Time-Resolved Hard X-Ray Emission Spectroscopy on a Tabletop

Luis Miaja-Avila,[1,*] Galen C. O'Neil,[1] Young I. Joe,[1] Bradley K. Alpert,[1] Niels H. Damrauer,[2] William B. Doriese,[1] Steven M. Fatur,[2] Joseph W. Fowler,[1] Gene C. Hilton,[1] Ralph Jimenez,[2,3] Carl D. Reintsema,[1] Daniel R. Schmidt,[1] Kevin L. Silverman,[1] Daniel S. Swetz,[1] Hideyuki Tatsuno,[1] and Joel N. Ullom[1,4,†]

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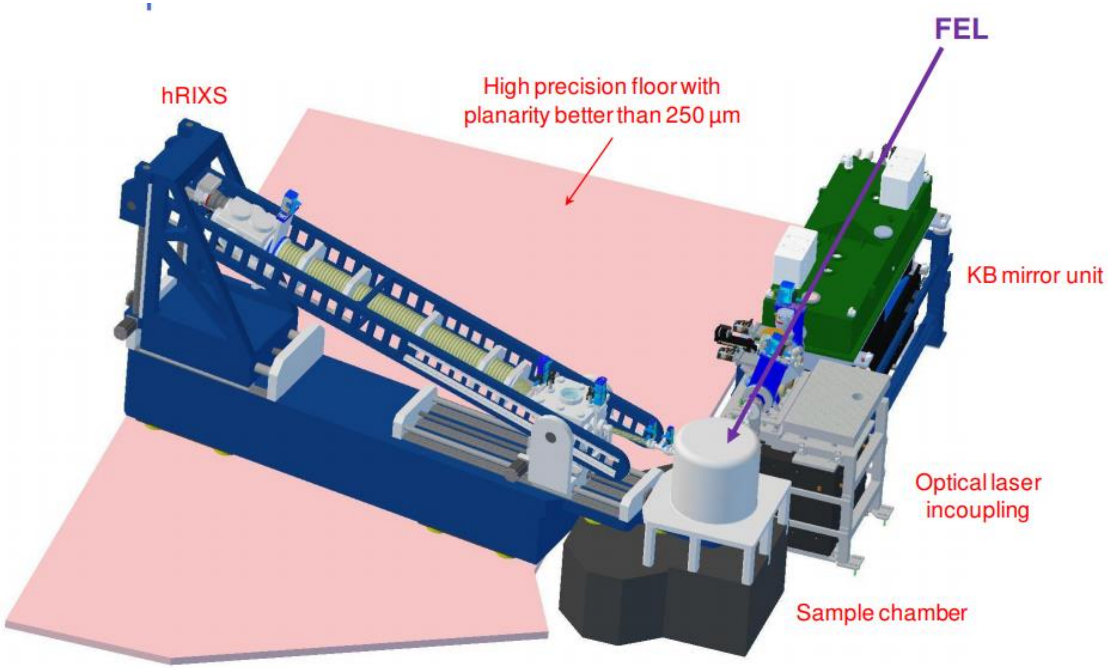
(Received 28 March 2016; revised manuscript received 20 June 2016; published 27 September 2016)

Experimental tools capable of monitoring both atomic and electronic structure on ultrafast (femtosecond to picosecond) time scales are needed for investigating photophysical processes fundamental to light harvesting, photocatalysis, energy and data storage, and optical display technologies. Time-resolved hard x-ray (>3 keV) spectroscopies have proven valuable for these measurements due to their elemental specificity and sensitivity to geometric and electronic structures. Here, we present the first tabletop apparatus capable of performing time-resolved x-ray emission spectroscopy. The time resolution of the apparatus is better than 6 ps. By combining a compact laser-driven plasma source with a highly efficient array of microcalorimeter x-ray detectors, we are able to observe photoinduced spin changes in an archetypal polypyridyl iron complex $[Fe(2,2'\text{-bipyridine})_3]^{2+}$ and accurately measure the lifetime of the quintet spin state. Our results demonstrate that ultrafast hard x-ray emission spectroscopy is no longer confined to large facilities and now can be performed in conventional laboratories with 10 times better time resolution than at synchrotrons. Our results are enabled, in part, by a 100- to 1000-fold increase in x-ray collection efficiency compared to current techniques.

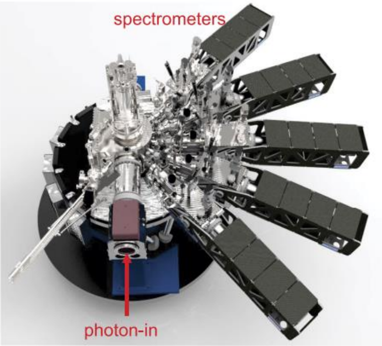
RIXS projects @FELs ...(soft X-rays)

XFEL Heisenberg RIXS (A. Fohlisch)



https://www.xfel.eu/sites/sites_custom/site_xfel/content/e51499/e60513/e63567/e63600/9_XFUM2017-SASE3_Satellite_Neppl_hRIXS_eng.pdf

LCLS qRIXS



Yi de Chuang et al. Review of Scientific Instruments **88**, 013110 (2017); https://doi.org/10.1063/1.4974356

PAL-XFEL, ...

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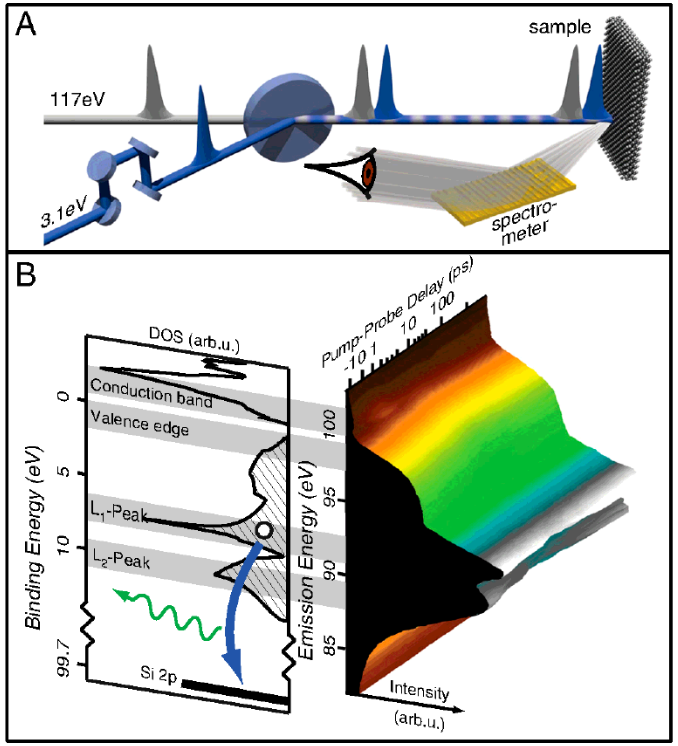
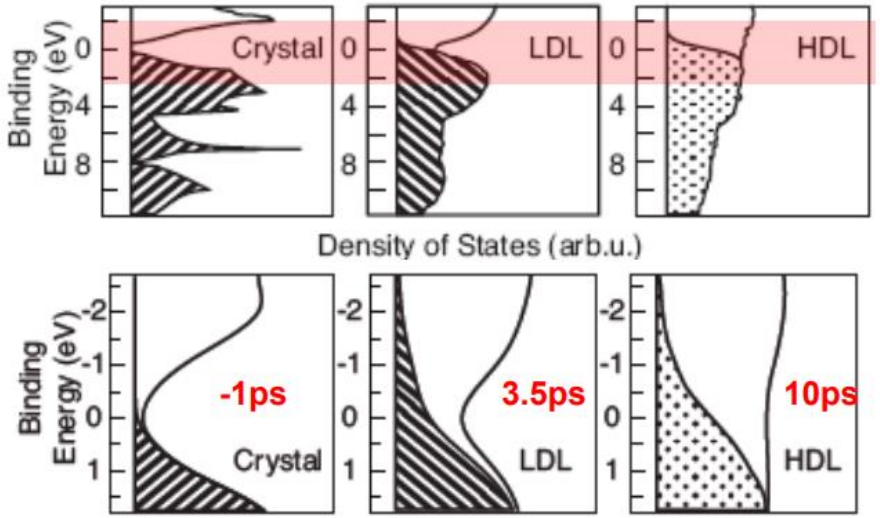
Tr-XES on Silicon



M. Beye *et al*., **PNAS** 107, 16772 (2010)

Liquid-liquid transition in silicon



Transient ''low density ''state accessible at short timescales

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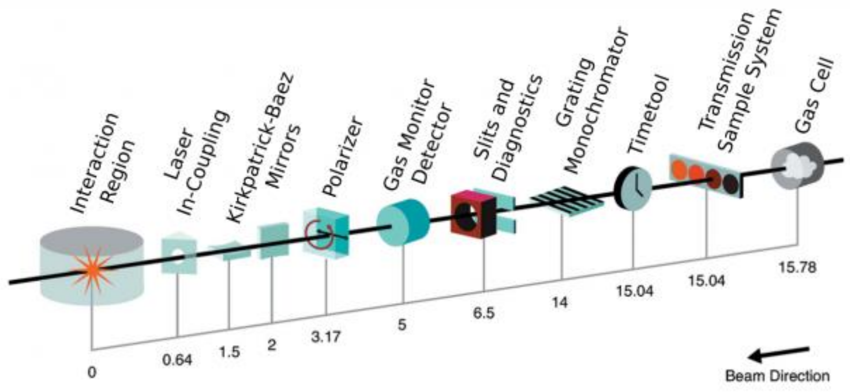
II. RIXS@LCLS: Femtochemistry

LCLS (Stanford)

https://lcls.slac.stanford.edu/overview

SXR Instrument

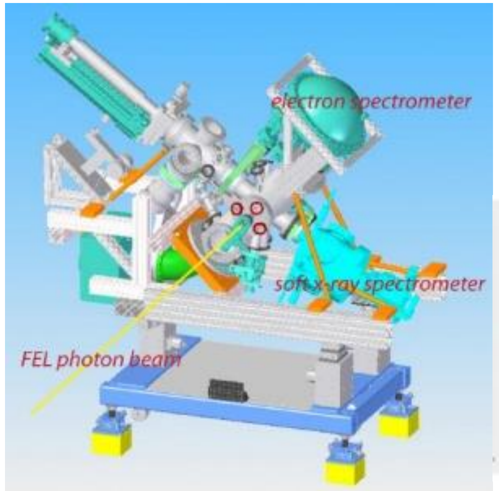


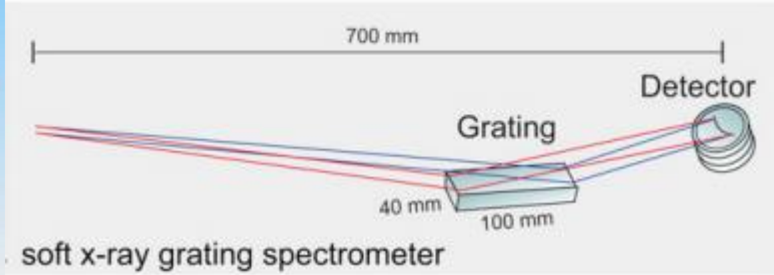
X-ray Spectrometer

Photon Beam Properties

Sample Configurations	Pre-Mono Transmission Sample Chamber, white beam	Endstation, white beam	Endstation, mono
Focusing Capability (Kirkpatrick-Baez)	1 x 1 mm (unfocused at sample)	≈ 2 x 2 µm	≈ 2 x 2 µm
Energy Range	280-2000 eV		grating 1 (100 lines/mm): 500-1500 eV
			grating 2 (200 lines/mm): 800-2000 eV
Energy Resolution	~0.1 eV (500 eV)	~0.5 eV (500 eV)	~0.1 eV (500 eV)
	~0.2 eV (1000 eV)	~1.0 eV (1000 eV)	~0.5 eV (1000 eV)
	~0.6 eV (2000 eV)	~2.0 eV (2000 eV)	~0.6 eV (2000 eV)
Flux (ph/pulse) @ resolution limit	1 x 10^{12} (500 eV)	1 x 10^{11} (500 eV)	1 x 10^{10} (500 eV)
	1 x 10^{13} (1000 eV)	1 x 10^{12} (1000 eV)	3 x 10^{12} (1000 eV)
	1 x 10^{13} (2000 eV)	1 x 10^{12} (2000 eV)	2 x 10^{12} (2000 eV)

https://lcls.slac.stanford.edu/instruments/sxr/specifications





T. Katayama, et al. J. Elect. Spec. Rel Phen 187 (2013) 9

Surface Science Endstation (prof. A. Nilsson)

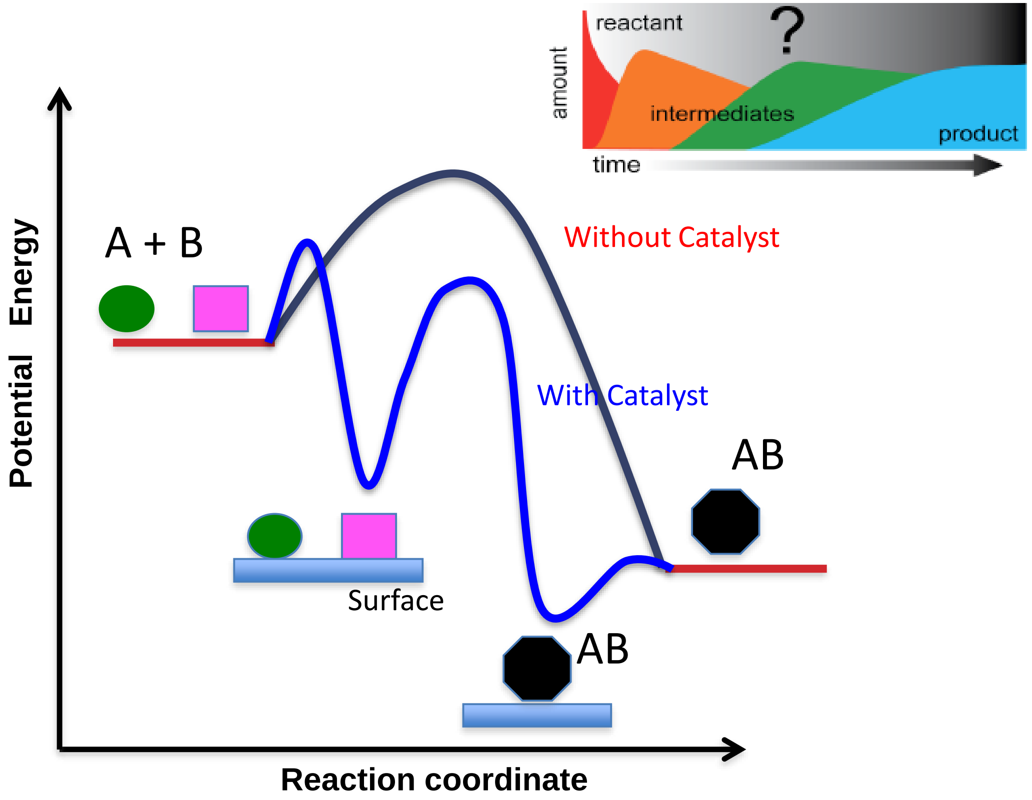
Spectrometer (Rowland type):

Elliptical grating (Ni coated)

Negative Diffraction Order

No entrance slit

Femtochemistry

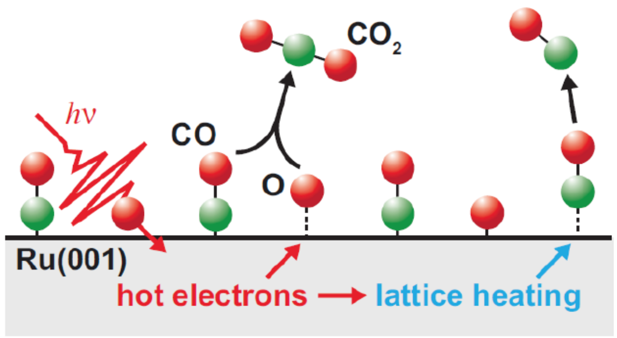


Challenge:

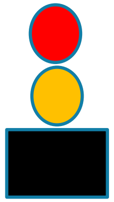
Understand **reaction mechanism**

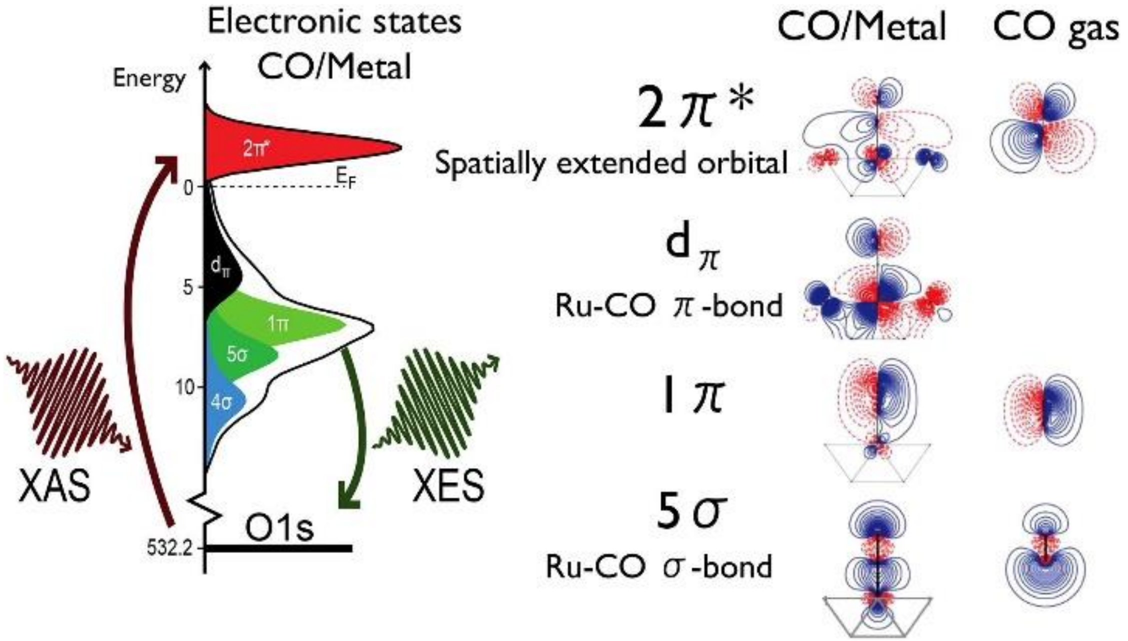
and **dynamics**

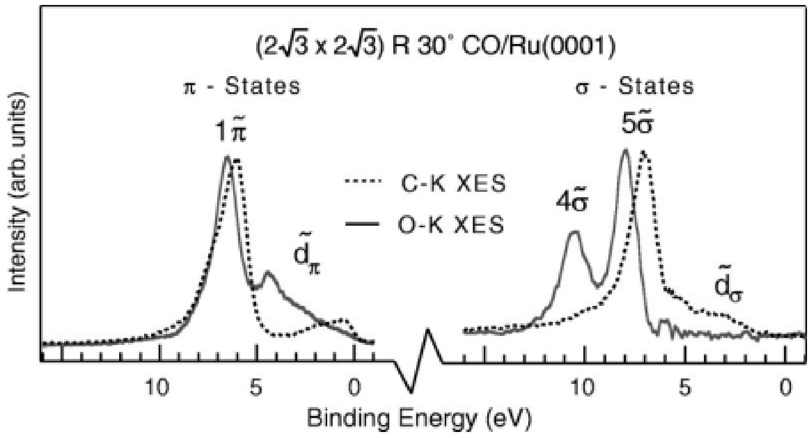
Case study:



CO RIXS @synchrotron



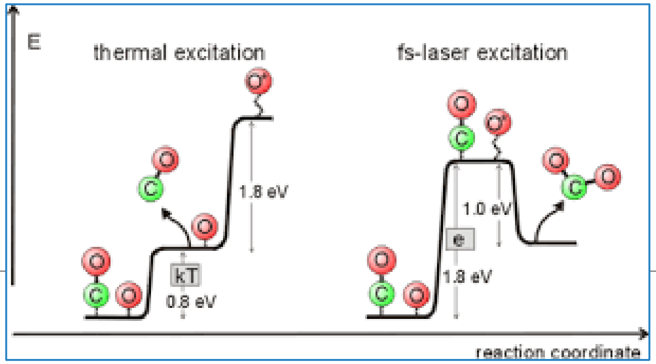




A. Nilsson et al., Chem Phys Lett, 675 (2017) 145

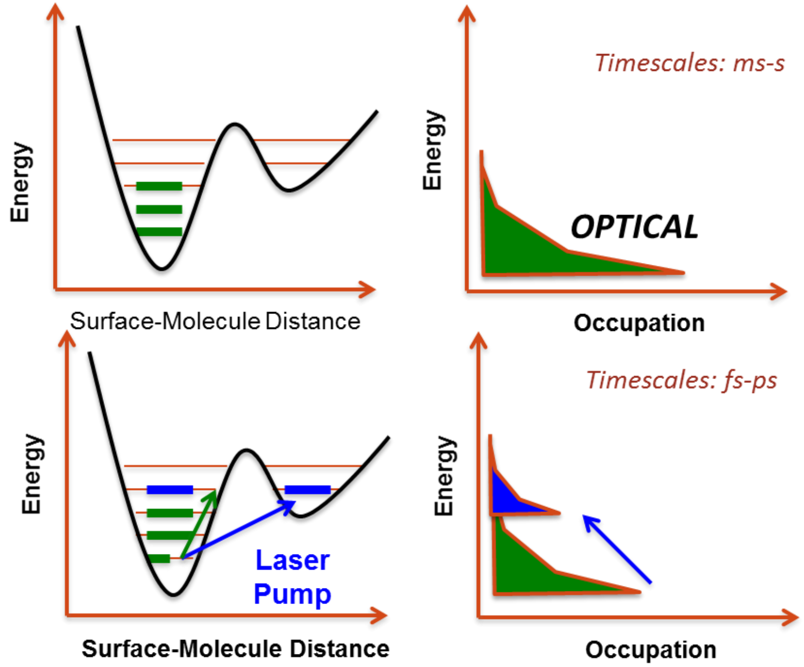
A. Föhlisch et al., J. Chem Phys, 121 (2004) 4848

Tr-RIXS in catalysis



M. Bonn et al, Science 285, 1042 (1999)

Create HOT ELECTRONS that trigger reactions

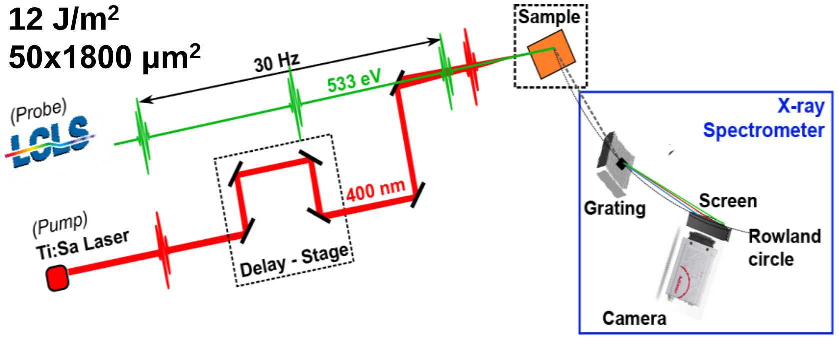


THERMAL vs **ULTRAFAST**
laser induced heating

LCLS set up

60 Hz
533eV
(100 l/mm grating)
100fs
12 J/m^2
50x1800 μm^2

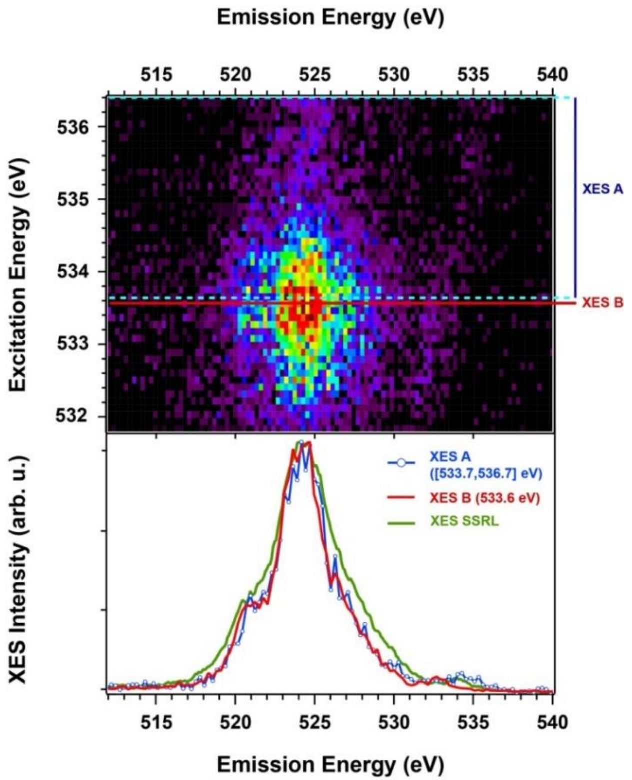
Scienta R3000
Electron
Spectrometer



FEL vs Synchrotron "static" data

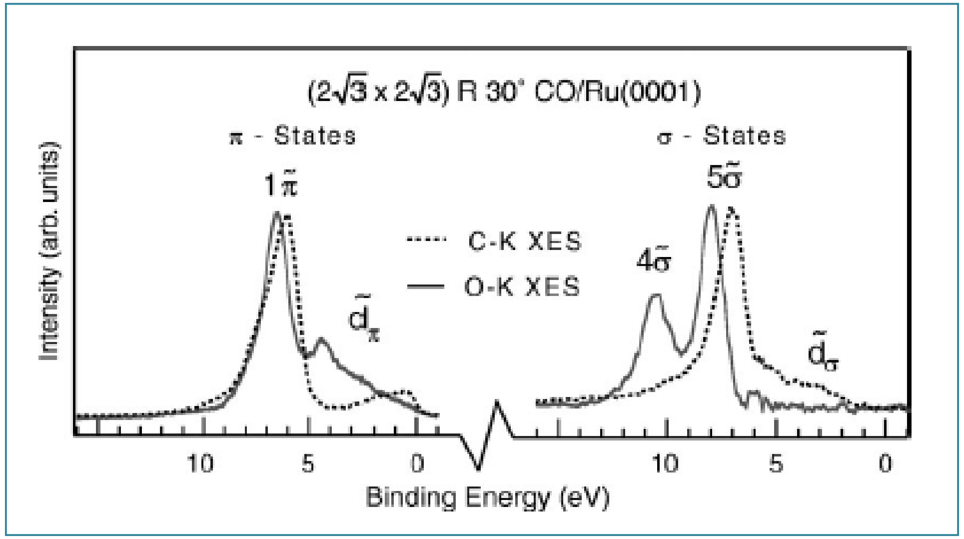
RIXS MAP

FEL Bandwidth



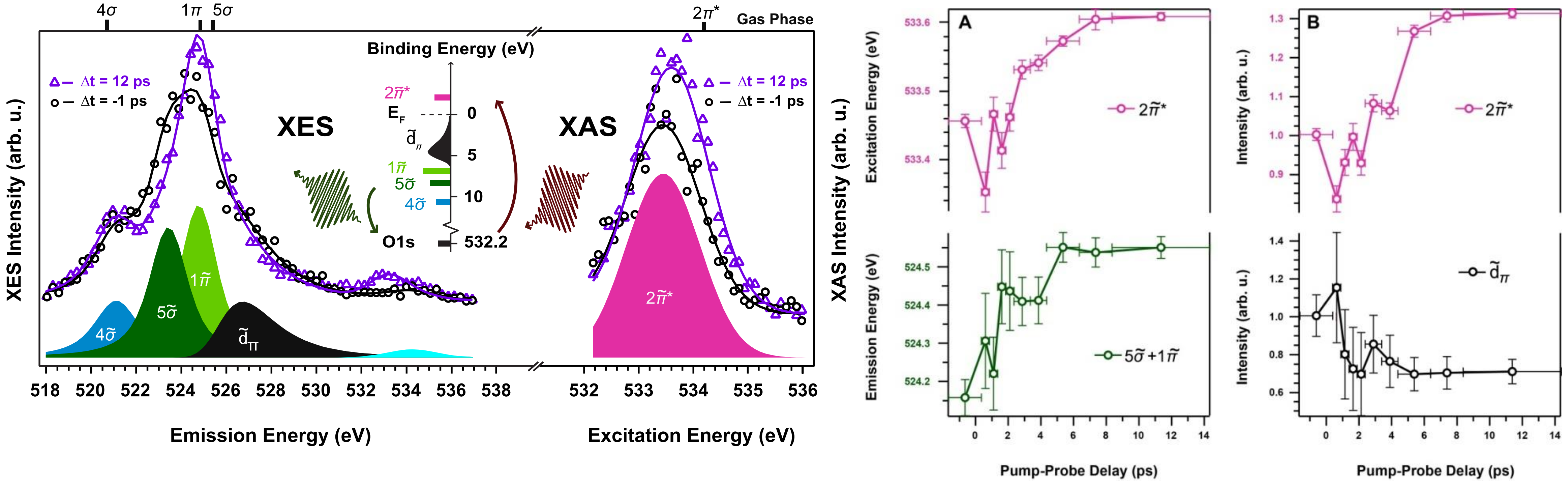
M. Dell'Angela, et al. Science 339, 1302 (2013)

CO/Ru(0001)



A. Fohlisch et al., J. Chem Phys 121 (2004) 4848

Co desoprtion from Ru(0001)

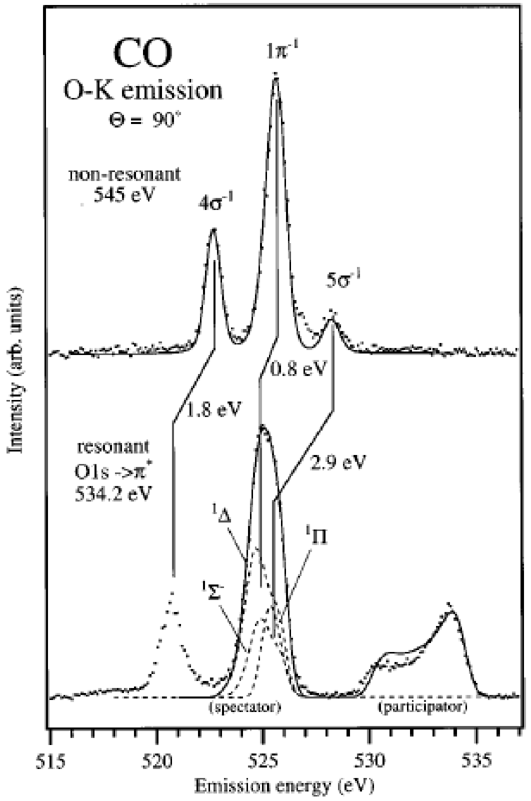


M. Dell'Angela, et al. Science 339, 1302 (2013)

Bond Weakening towards gas phase

Are the molecules in the gas phase?

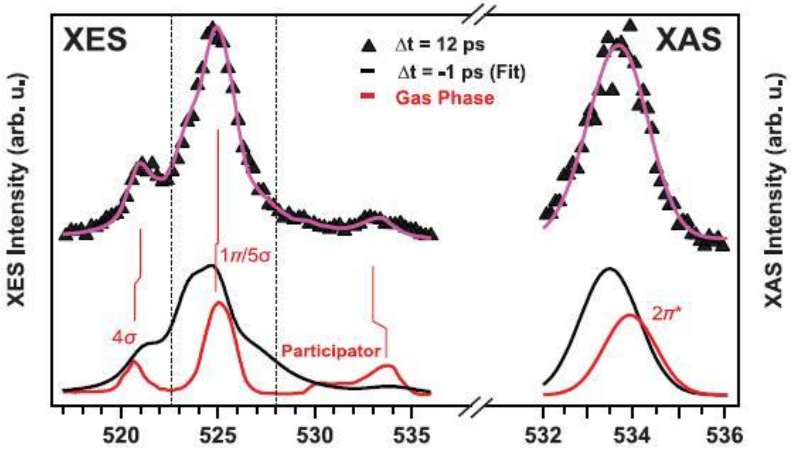
Literature



P. Skytt et al, PRA 55 (1997) 134

Spectator shifts due to 2π*

Our data



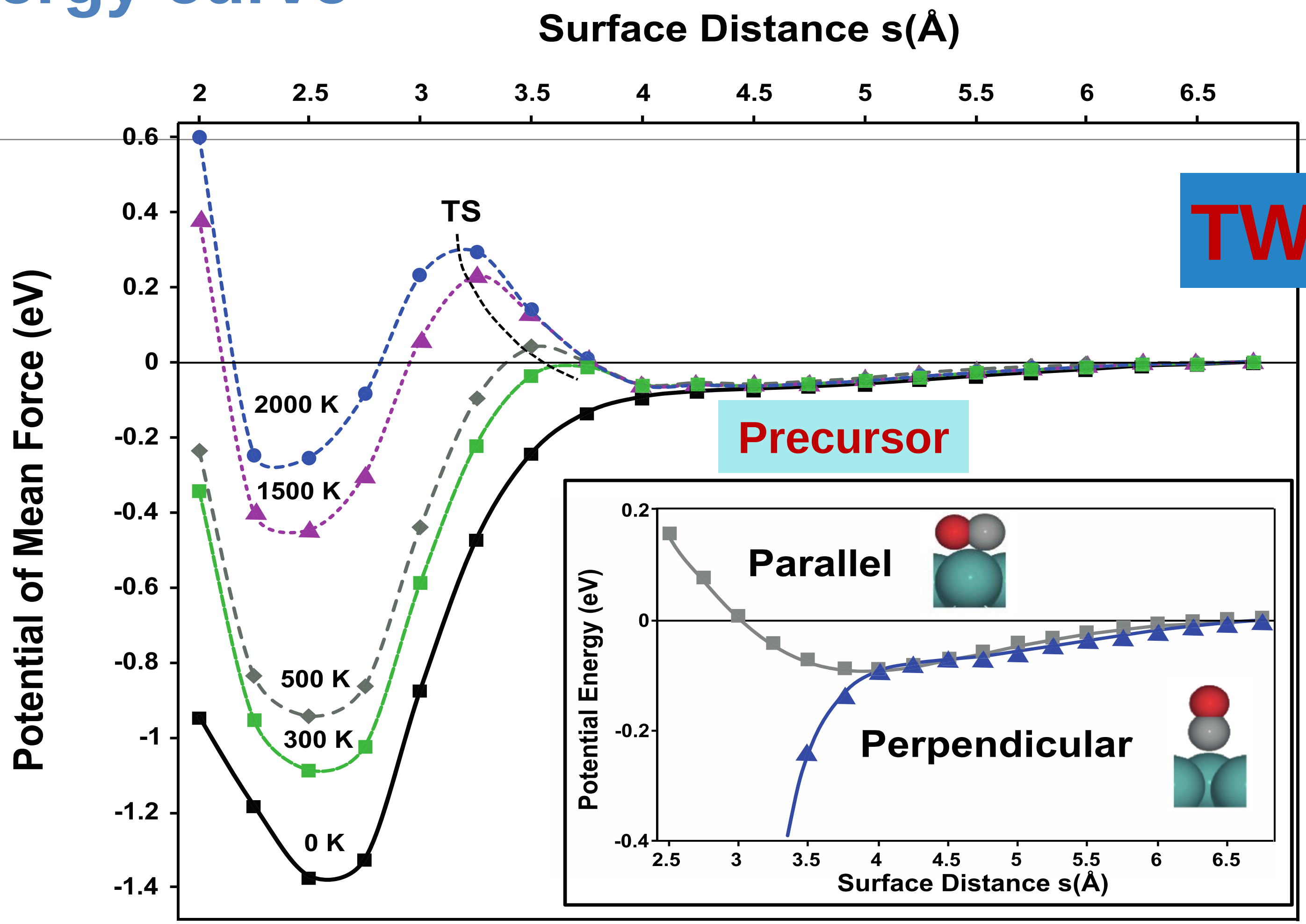
FIT = Chemisorbed + Gas Phase Resonant

70% Unpumped + 30 % “Gas phase”

Spectator shifts: 1π 0.1eV less
4σ 0.3eV less
Participator: -0.5eV and x0.5

Not really! …PRECURSOR?

Free-energy curve



TWO MINIMA!

Chemisorbed

DFT+BEEF-vdW Wellendorff L. et al PRB 85, 235149 (2012)

Conclusion II

We have been able to measure for the first time molecules in the precursor state upon desorption.

Review of FEL femtochemistry experiments:

Chemical Physics Letters 675 (2017) 145–173

Contents lists available at ScienceDirect

Chemical Physics Letters

journal homepage: www.elsevier.com/locate/cplett

ELSEVIER

CPL FRONTIERS

Frontiers article

Catalysis in real time using X-ray lasers

CrossMark

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Ultrafast Surface Chemistry and Catalysis Collaboration

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Alexander Foehlisch (4)
Jorgen Gladh (3)
Florian Hieke (2)
Markus Hantschmann (5)
Tetsuo Katayama (1)
Sarp Kaya (1)
Oleg Krupin (1)
Jerry LaRue (1)
Giuseppe Mercurio (2)
Ankush Mitra (1)
Stefan Moeller (1)
Andreas Moegelhoej (1)
Anders R. Nilsson (1)
May Ling Ng (1)
Dennis Nordlund (1)

Jens Norskov (1)
Henrik Oberg (3)
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Mats Persson (6)
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(4) Methods and Instrumentation in Synchrotron Radiation, Helmholtz-Zentrum Berlin, Berlin, Germany;
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(6) Surface Science Research Centre, Department of Chemistry, University of Liverpool, United Kingdom

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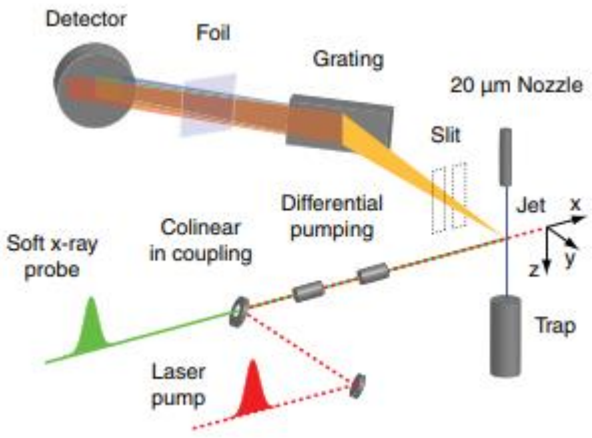
III. RIXS@LCLS: Liquids (next lecture by Ph. Wernet)



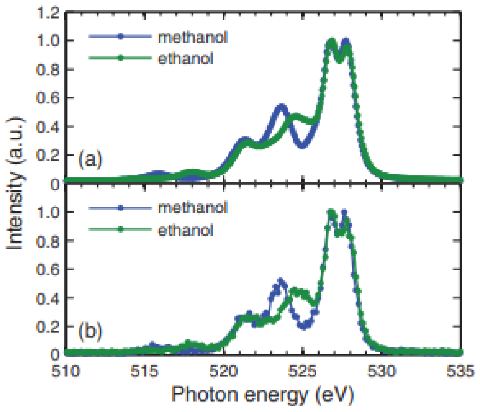


FIG. 6. Comparison of liquid methanol and ethanol RIXS spectra taken at an incident photon energy of 540 eV and measured (a) at the BESSYII U41-PGM beamline and (b) at the LCLS SXR beamline. For details on the experimental parameters see Table II.

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 123109 (2012)

A setup for resonant inelastic soft x-ray scattering on liquids at free electron laser light sources

Kristjan Kunnus,[1,2,a)] Ivan Rajkovic,[3] Simon Schreck,[1,2] Wilson Quevedo,[3,b)] Sebastian Eckert,[1] Martin Beye,[1] Edlira Suljoti,[1] Christian Weniger,[1] Christian Kalus,[4] Sebastian Grübel,[3,c)] Mirko Scholz,[3] Dennis Nordlund,[5] Wenkai Zhang,[6] Robert W. Hartsock,[6] Kelly J. Gaffney,[6] William F. Schlotter,[7] Joshua J. Turner,[7] Brian Kennedy,[8] Franz Hennies,[8] Simone Techert,[3,9,d)] Philippe Wernet,[1,e)] and Alexander Föhlisch[1,2,f)]
[1]*Institute for Methods and Instrumentation for Synchrotron Radiation Research, Helmholtz-Zentrum Berlin GmbH, Albert-Einstein-Straße 15, 12489 Berlin, Germany*
[2]*Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Straße 24/25, 14476 Potsdam, Germany*
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[4]*Abteilung Betrieb Beschleuniger BESSYII, Helmholtz-Zentrum Berlin GmbH, Albert-Einstein-Straße 15, 12489 Berlin, Germany*
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[6]*PULSE Institute, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[7]*Linac Coherent Light Source, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[8]*MAX-lab, PO Box 118, 221 00 Lund, Sweden*
[9]*Advanced Study Group of the MPG, CFEL, Notkestraße 85, 22853 Hamburg, Germany*

Outline

RIXS-hXES@ XFELs

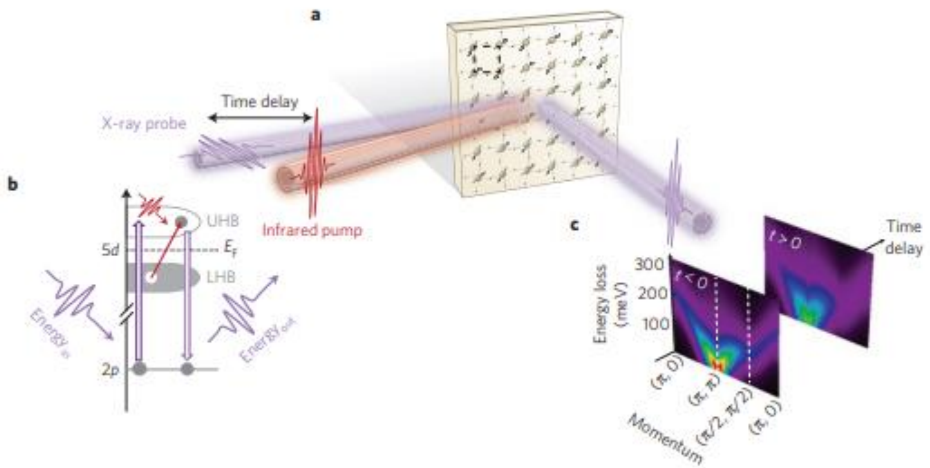
I. Techniques
   1. X-ray absorption (XAS)
   2. X-ray emission (XES) /High resolution X-ray Emission (hXES)
   3. Resonant Inelastic X-ray Scattering (RIXS)

II. Instruments

III. Selected RIXS-hXES applications @ XFELs
   I. Phase Transitions
   II. RIXS@LCLS: Femtochemistry
   III. RIXS@LCLS: Liquids
   IV. RIXS@SACLA: Magnetism
   V. RIXS@FERMI: dd excitations

Tr-RIXS on Sr_2IO_4

Strongly correlated system



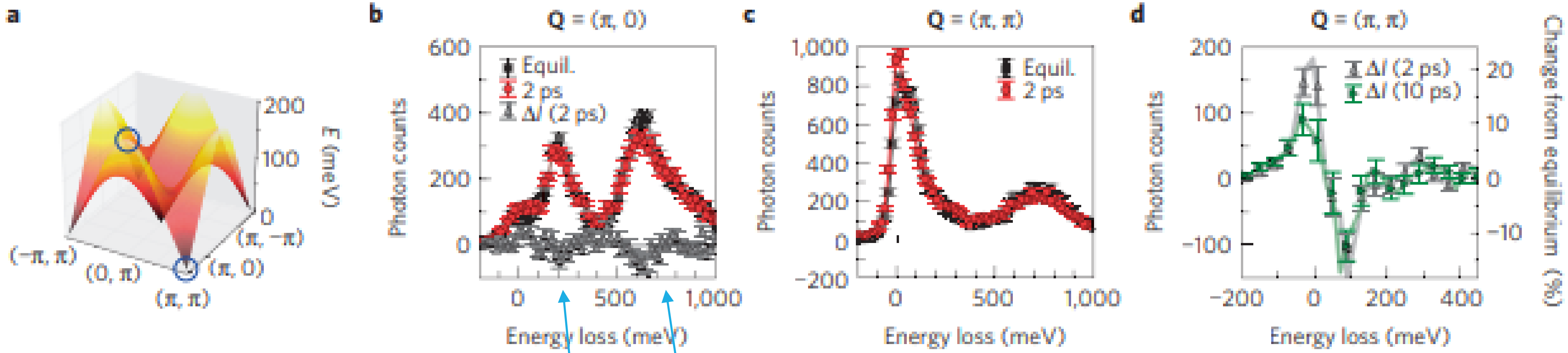
nature materials
LETTERS
PUBLISHED ONLINE: 9 MAY 2016 | DOI: 10.1038/NMAT4641

Ultrafast energy- and momentum-resolved dynamics of magnetic correlations in the photo-doped Mott insulator Sr_2IrO_4

M. P. M. Dean[1*†], Y. Cao[1*†], X. Liu[2,3*], S. Wall[4], D. Zhu[5], R. Mankowsky[6,7], V. Thampy[1], X. M. Chen[1], J. G. Vale[8], D. Casa[9], Jungho Kim[9], A. H. Said[9], P. Juhas[1], R. Alonso-Mori[5], J. M. Glownia[5], A. Robert[5], J. Robinson[5], M. Sikorski[5], S. Song[5], M. Kozina[5], H. Lemke[5], L. Patthey[10], S. Owada[11], T. Katayama[12], M. Yabashi[11], Yoshikazu Tanaka[11], T. Togashi[12], J. Liu[13], C. Rayan Serrao[14], B. J. Kim[15], L. Huber[16], C.-L. Chang[17], D. F. McMorrow[8], M. Först[6,7] and J. P. Hill[1]

hv = 11.22 keV (L_3 Ir)

Tr-RIXS on Sr_2IO_4

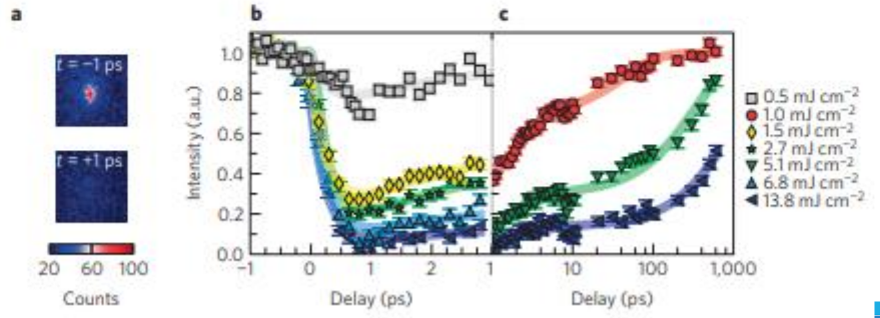


Magnons or spin waves

orbital

magnetic

Bragg peak



Outline

RIXS-hXES@ XFELs

I. Techniques
   1. X-ray absorption (XAS)
   2. X-ray emission (XES) /High resolution X-ray Emission (hXES)
   3. Resonant Inelastic X-ray Scattering (RIXS)

II. Instruments

III. Selected RIXS-hXES applications @ XFELs
   I. RIXS@FLASH: Phase Transitions
   II. RIXS@LCLS: Femtochemistry
   III. RIXS@LCLS: Liquids
   IV. RIXS@SACLA: Magnetism
   V. RIXS@FERMI: dd excitations

V. RIXS@FERMI: dd excitations

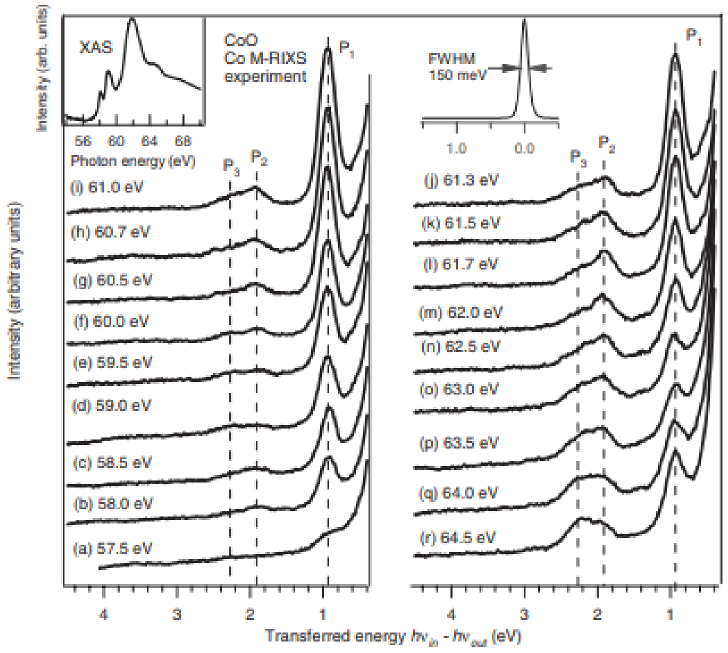
Photon Beam Parameters	FEL-1 *	FEL-2 *
Photon Energy (eV)	12.4-65	65-310
Average pulse energy [μJ]	200-25 **	100-10 **
Pulse duration [fs] (FWHM)	100-50	60-20
Peak power [GW]	3-0.4	2.5-0.4
Repetition rate [Hz]	10-50	10-50
FEL mode	SEEDED, TEM_00	SEEDED, TEM_00
Photon energy fluctuations [meV][rms]	1-2	4-15
FEL bandwidth ΔE/E [rms]	2.5-5 (x10sup-4)	2-7 (x10sup-4)
FEL bandwidth fluctuations [%][rms]	3-5	3-40
Polarization	Linear Horizontal Linear Vertical Circular Left Circular Right	Linear Horizontal Lineal Vertical Circular Left Circular Right

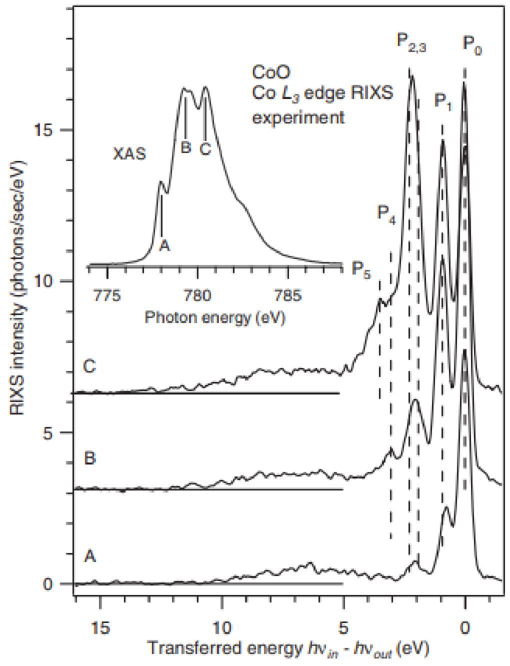
FERMI (Elettra Sincrotrone Trieste)

FERMI = $M_{2,3}$ Edges of Cu, Ni, Co

M-edge vs L-edge

	M-edge	L-edge
Energy	50 eV -100 eV	500 eV -1 keV
Resolving Power	100 eV/10 meV = 10^4	1 keV/ 10 meV = 10^5





PHYSICAL REVIEW B **78**, 245102 (2008)

Combining *M*- and *L*-edge resonant inelastic x-ray scattering for studies of 3*d* transition metal compounds

S. G. Chiuzbăian,[1,*] T. Schmitt,[2] M. Matsubara,[3] A. Kotani,[4,5] G. Ghiringhelli,[6] C. Dallera,[7] A. Tagliaferri,[8] L. Braicovich,[8] V. Scagnoli,[9] N. B. Brookes,[9] U. Staub,[2] and L. Patthey[2]

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[2]*Swiss Light Source, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[3]*Laboratoire des Colloïdes, Verres et Nanomatériaux (UMR 5587), Université Montpellier II, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France*
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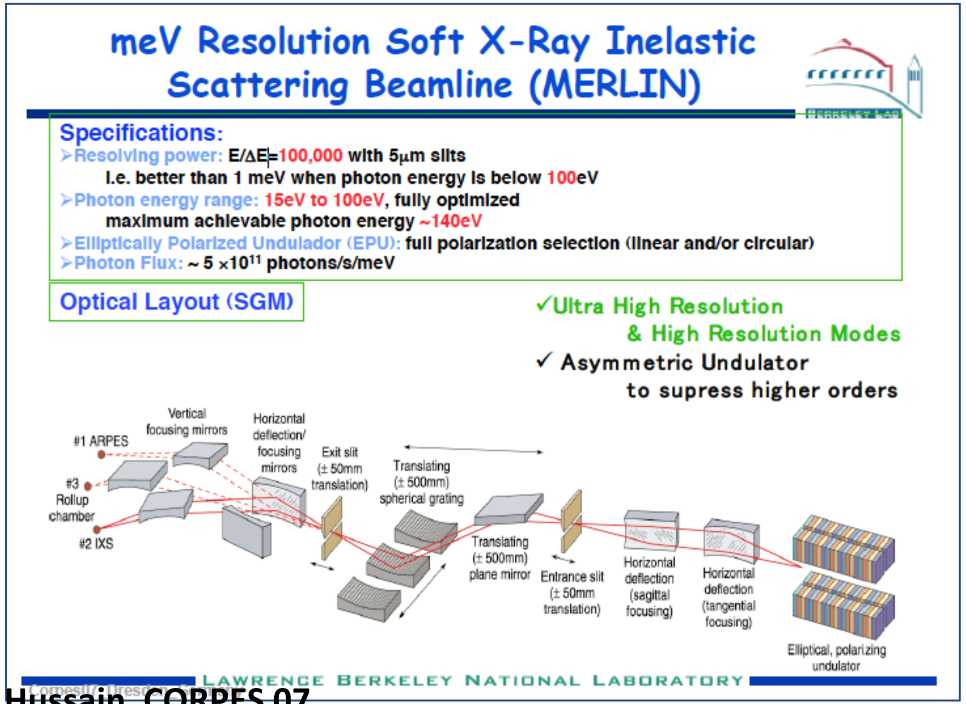
(Received 15 July 2008; revised manuscript received 16 October 2008; published 2 December 2008)

Small machine
Larger throughput
but
Strong elastic peak
More branching

M-edge RIXS

Nordgren Spectrometer @ SLS



Z. Hussain, CORPES 07

PRL 95, 197402 (2005) PHYSICAL REVIEW LETTERS week ending 4 NOVEMBER 2005

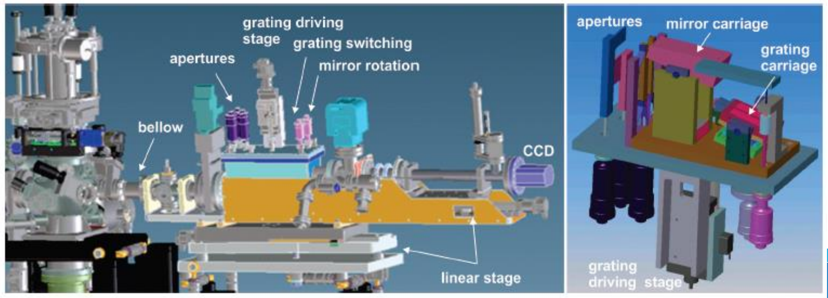
Localized Electronic Excitations in NiO Studied with Resonant Inelastic X-Ray Scattering at the Ni *M* Threshold: Evidence of Spin Flip

S. G. Chiuzbăian,[1,*] G. Ghiringhelli,[2] C. Dallera,[2] M. Grioni,[3] P. Amann,[1,†] X. Wang,[3] L. Braicovich,[2] and L. Patthey[1]
[1]*Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[2]*INFM-Dipartimento di Fisica, Politecnico di Milano, p. Leonardo da Vinci 32, 20133 Milano, Italy*
[3]*IPN, Ecole Polytechnique Fédérale, CH-1015 Lausanne, Switzerland*
(Received 24 February 2005; published 31 October 2005)

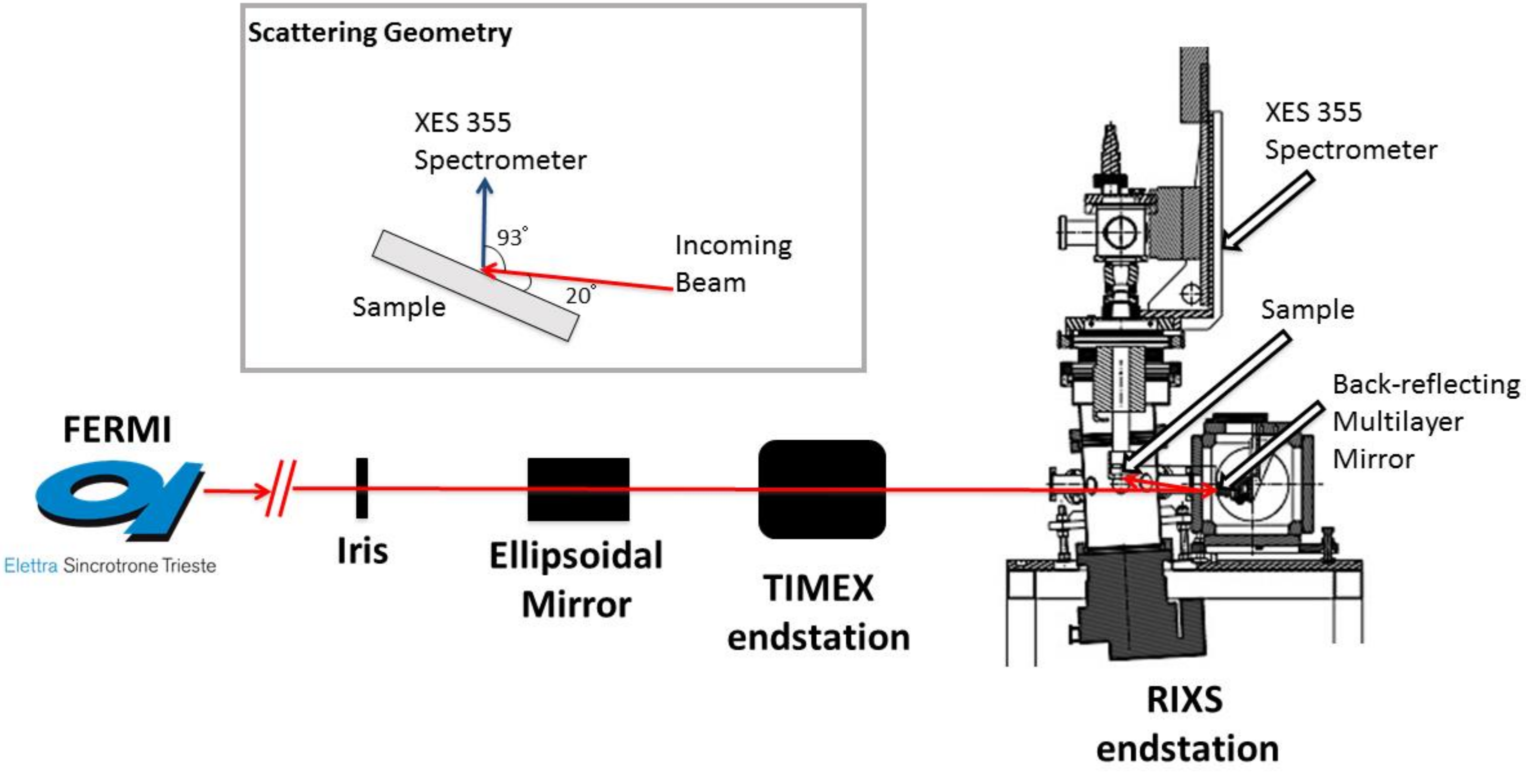
We studied the neutral electronic excitations of NiO localized at the Ni sites by measuring the resonant inelastic x-ray scattering (RIXS) spectra at the Ni $M_{2,3}$ edges. The good energy resolution allows an unambiguous identification of several spectral features due to *dd* excitations. The dependence of the RIXS spectra on the excitation energy gives evidence of local spin flip and yields a value of 125 ± 15 meV for the antiferromagnetic exchange interaction. Accurate crystal field parameters are also obtained.

MERIXS/MERLIN @ ALS
(Worlwide Record)

Y.D. Chuang, **Synchrotron Radiation News,** 25 (4), 22 (2012)



Set-up for RIXS @FERMI



First experiment: $KCoF_3$

MERIXS Beamline @ALS

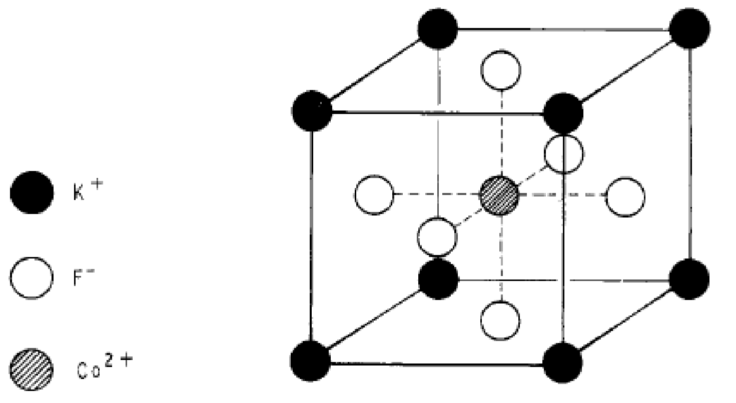
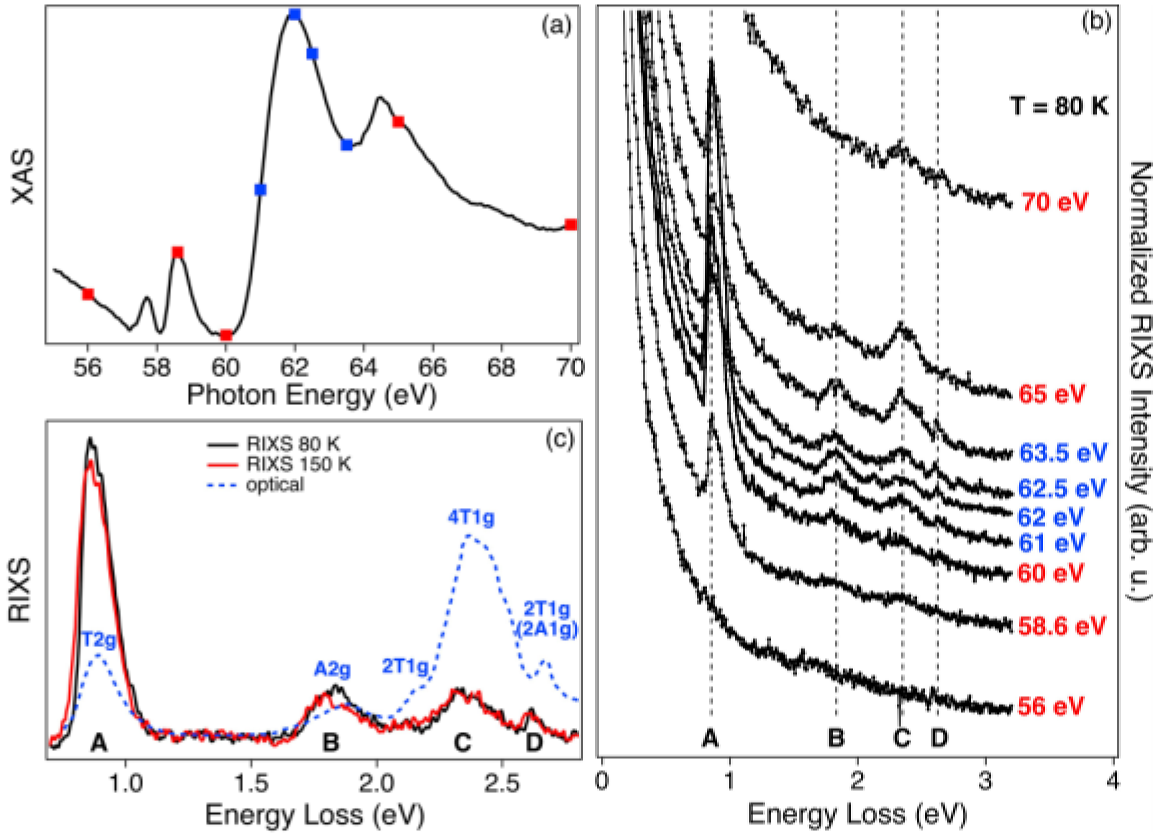


Figure 1. The crystal structure of $KCoF_3$.

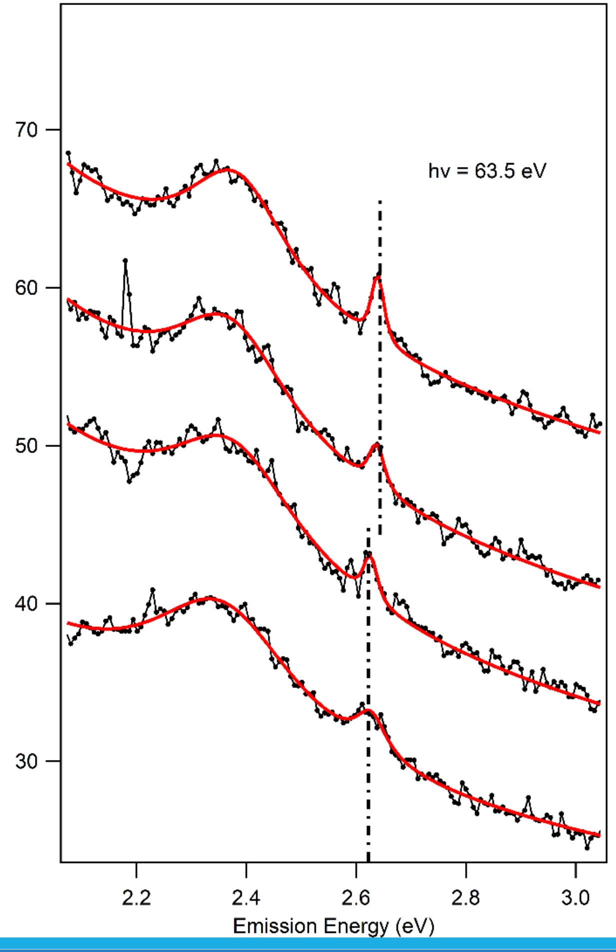
-Perovskite

-114K Neel Temperature
(small thetragonal distortion)



A. Caretta et al., PRB 96, 184420 (2017)

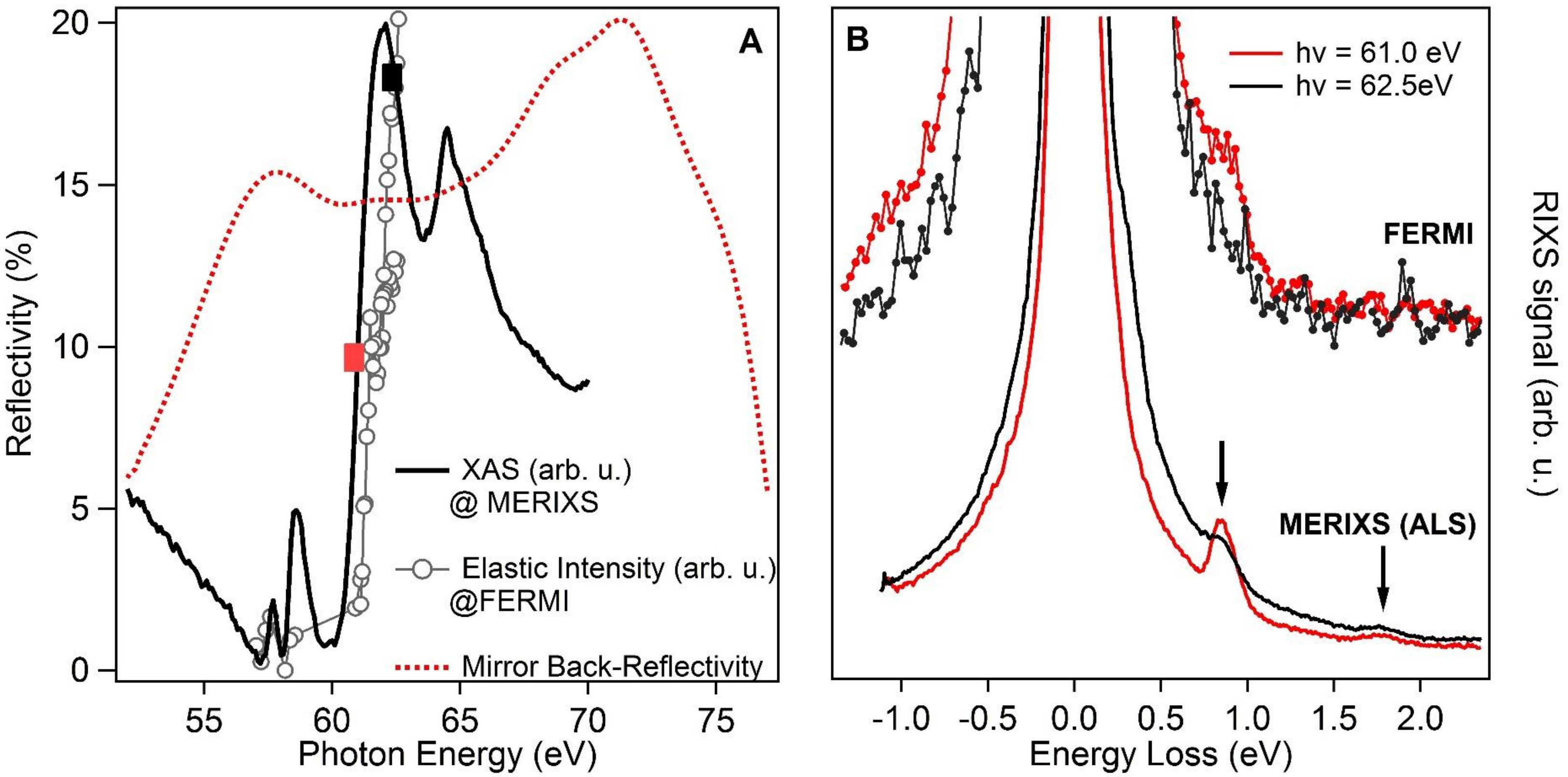
$KCoF_3$ M-edge RIXS



The onset of magnetic ordering, which quenches the spin-flip excitation channel, affects the overall energy of dd excitations.

A. Caretta et al., PRB 96, 184420 (2017)

High resolution RIXS at FERMI: $KCoF_3$

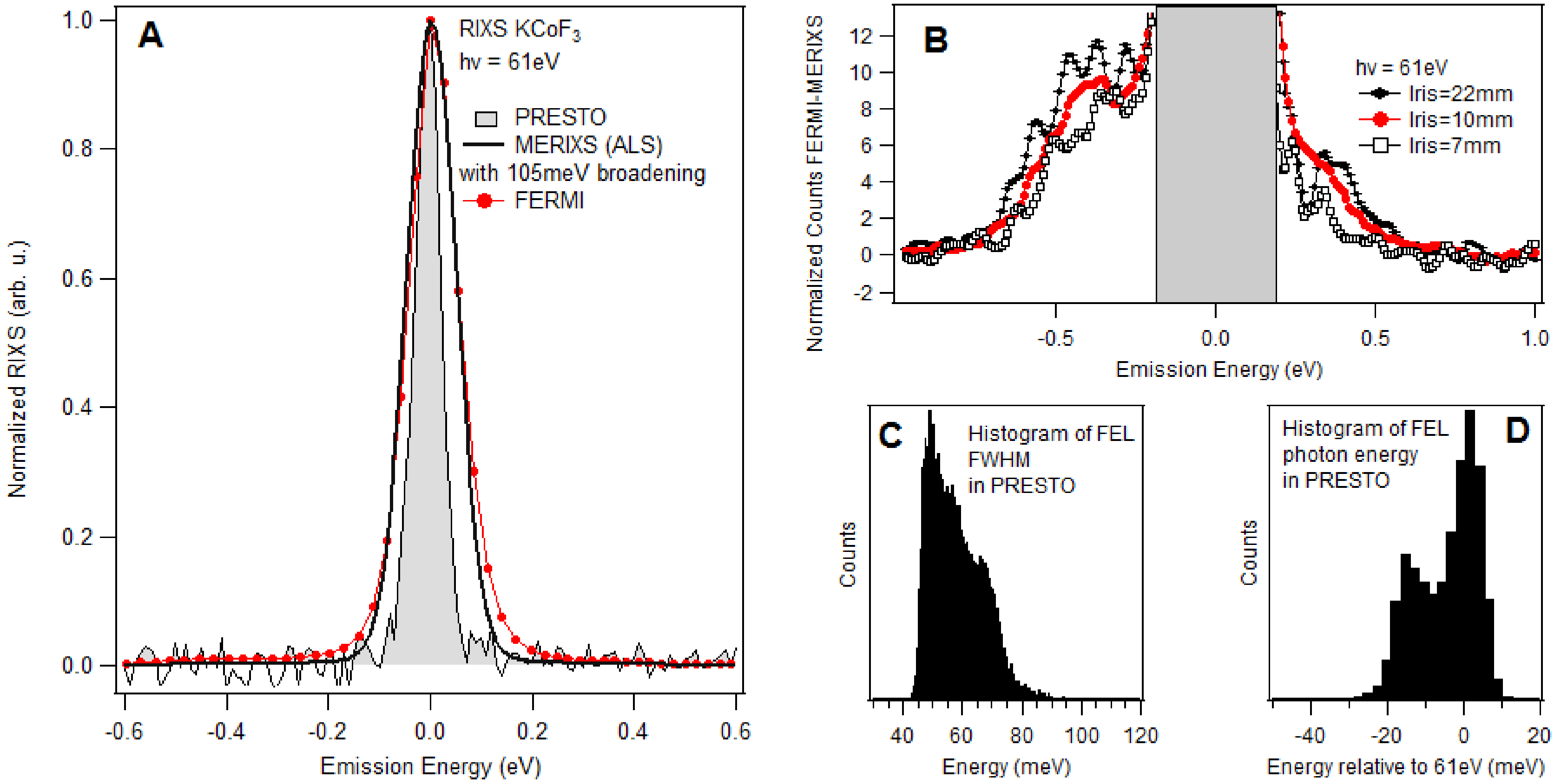


NEXAFS is feasible

RIXS is also feasible

M. Dell'Angela et al., Scientific Reports 6, 38796 (2016)

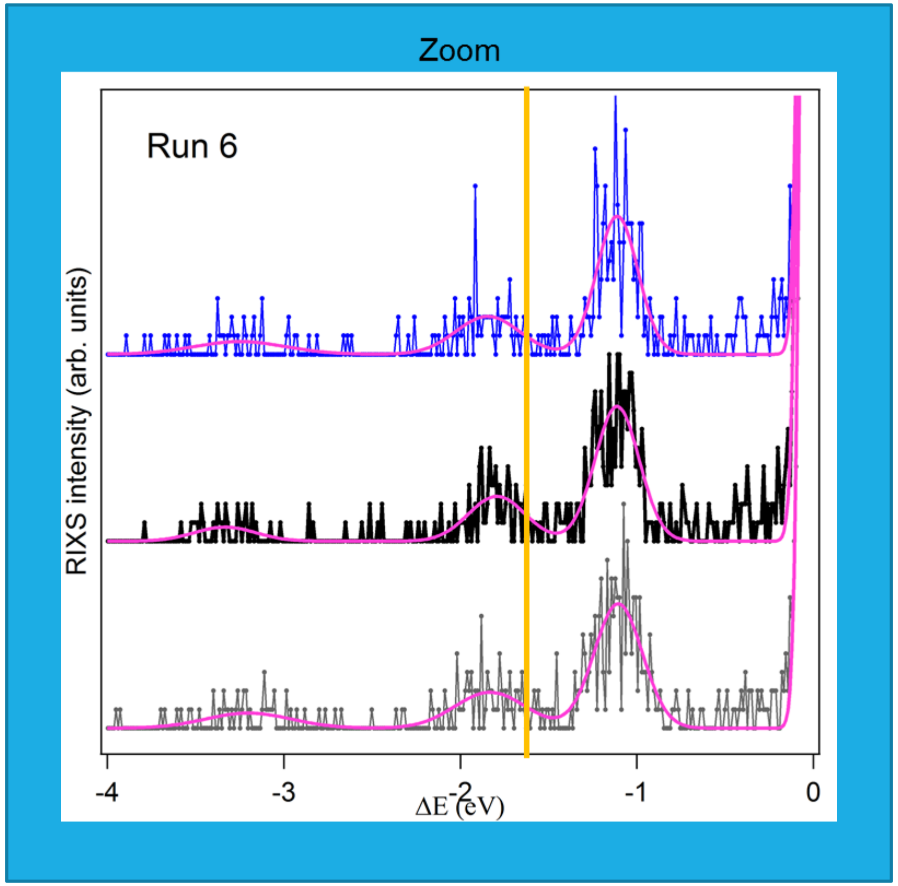
High resolution RIXS at FERMI: $KCoF_3$



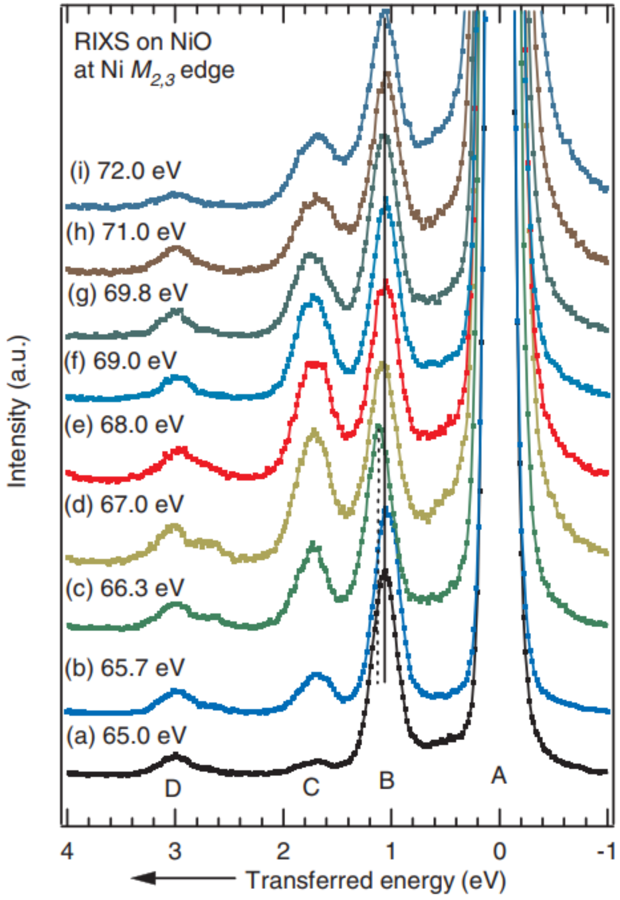
Resolution is
not limited by FERMI

M. Dell'Angela et al., Scientific Reports 6, 38796 (2016)

NiO: FEL vs Synchrotron



S. G. Chiuzbaian et al. PRL 95, 197402 (2005)

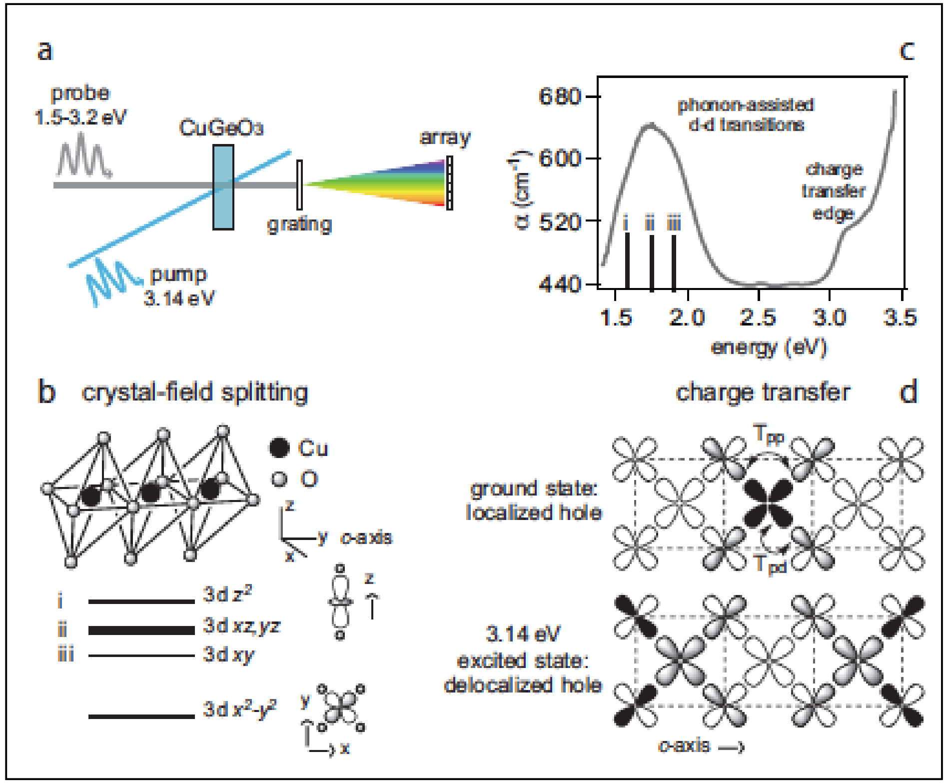


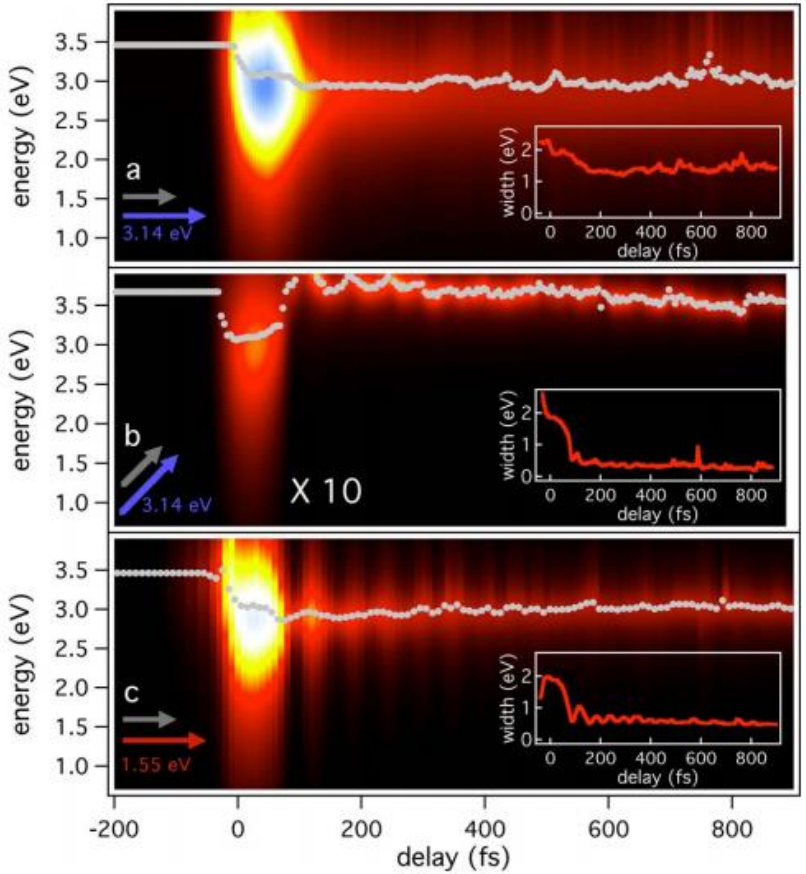
Collaboration with

G. Ghiringhelli
A. Scherz
J. Schlappa

Time resolved reflectivity of $CuGeO_3$

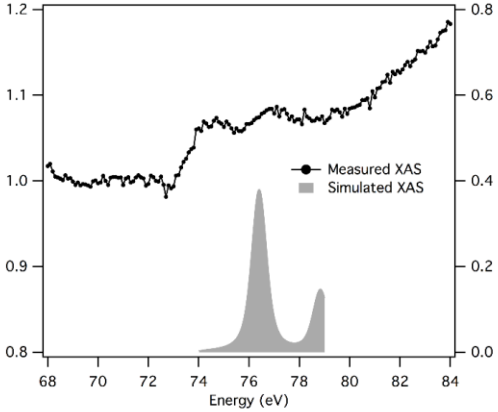
Giannetti et al. PRB 80 (2009) 235129

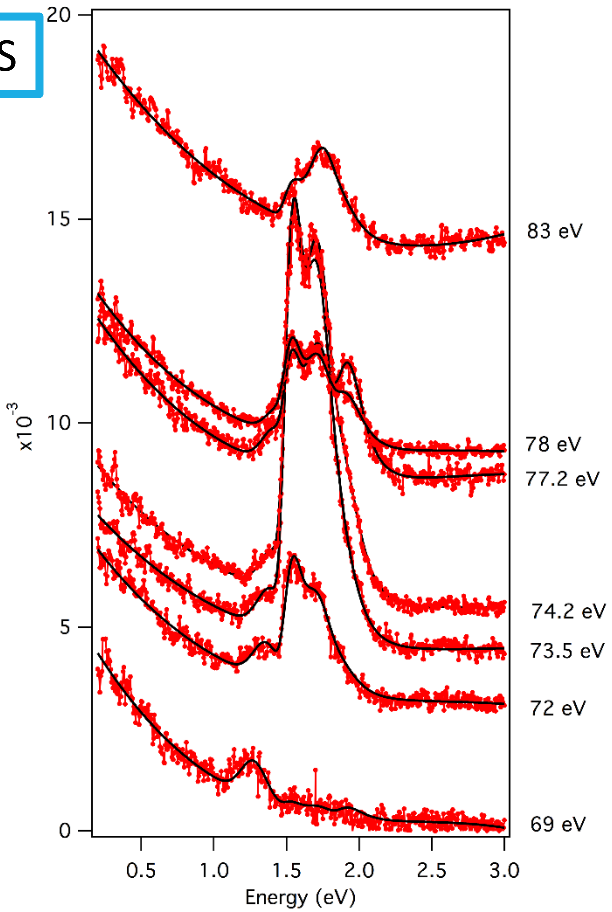




High resolution RIXS on $CuGeO_3$

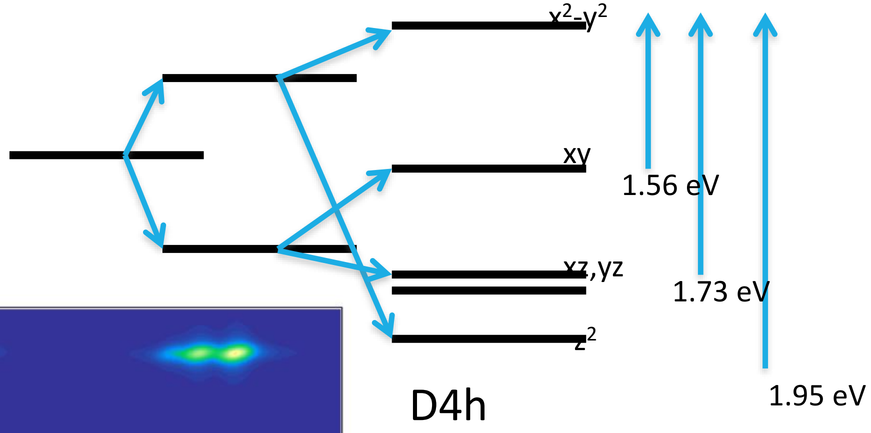
MERIXS Beamline @ALS

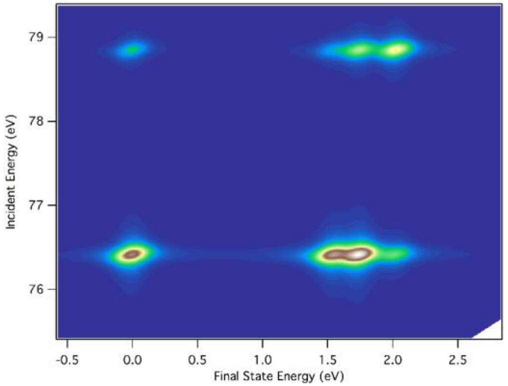




CTM4XAS, CTM4RIXS (only crystal field, no CT)

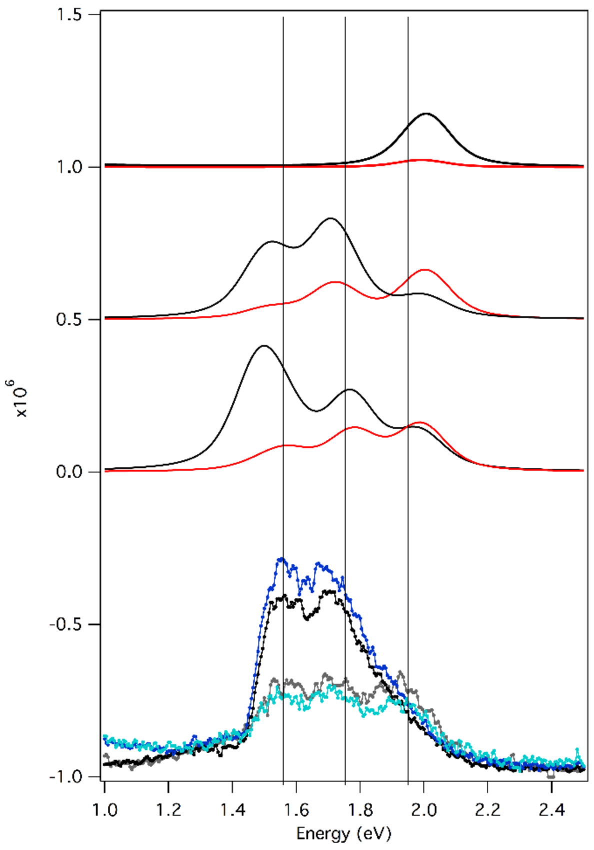
10Dq=1.56; Ds=0.306; Dt=0.145





Unpublished data

High resolution RIXS on $CuGeO_3$



Unpublished data

x^2-y^2
xy
z^2
xz,yz

Giannetti et al. PRB 80 (2009) 235129

xy
x^2-y^2
xz,yz
z^2

x^2-y^2
xy
xz,yz
z^2

De Graaf, Broer PRB 62 (2000) 705

TABLE III. CASPT2 energies (in eV) of the *d-d* transitions in a series of cuprates compared to available experimental data. The different $3d^9$ states are characterized by the character of the singly occupied orbital, i.e., the hole character.

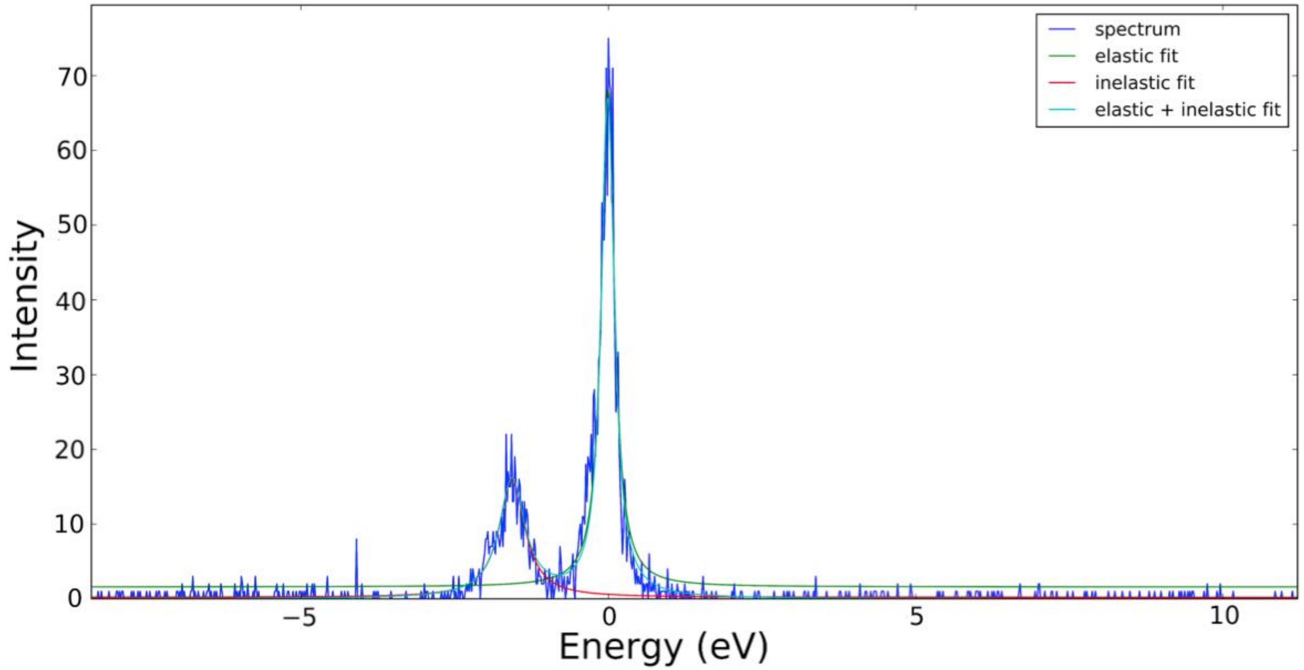
	Hole character						
	x^2-y^2	z^2	xy	xz	yz	xy (expt)	xz, yz (expt)
CuO	0.00	0.00	1.02	1.02	1.02		
La_2CuO_4	0.00	0.99	1.29	1.57	1.57	1.4, 1.7	1.6
$CuGeO_3$	0.00	1.75	1.41	1.70	1.70	1.3, 2.9	1.7
$Sr_2CuO_2Cl_2$	0.00	1.18	1.23	1.50	1.50	1.4	1.7
$YBa_2Cu_3O_6$	0.00	1.69	1.21	1.61	1.61	1.5	
Ca_2CuO_3	0.00	2.15	1.10	1.65	1.54		
Sr_2CuO_3	0.00	2.11	1.08	1.67	1.53		

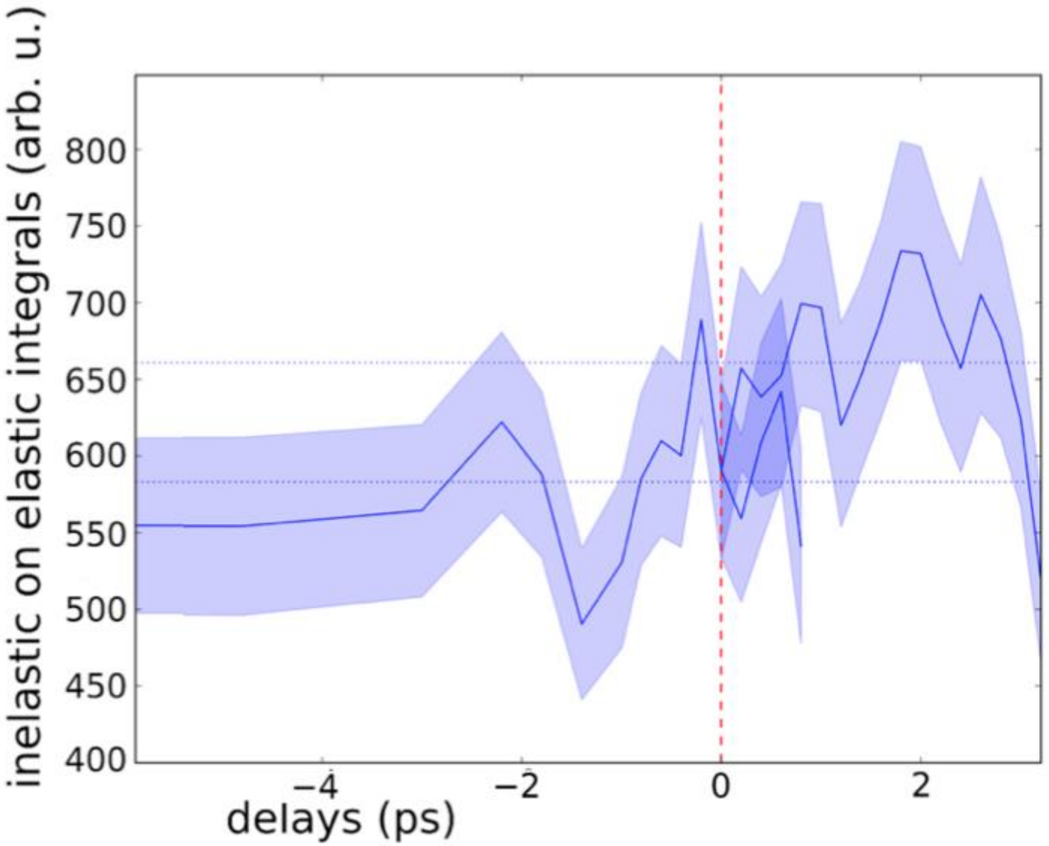
PHYSICAL REVIEW B **84**, 235125 (2011)

TABLE II. CASSCF/MRCI *d-d* excitation energies for edge-sharing chains of CuO_4 plaquettes (eV). The MRCI values include Davidson corrections.[35] The *y* axis is parallel to the CuO_2 chains, *z* is perpendicular onto the CuO_4 plaquettes, see text.

Hole orbital	$LiVCuO_4$	$CuGeO_3$	$LiCu_2O_2$	Li_2CuO_2
xy	0	0	0	0
x^2-y^2	1.08/1.28	1.19/1.41	1.13/1.43	1.20/1.52
xz	1.25/1.47	1.42/1.61	1.58/1.88	1.72/2.04
yz	1.29/1.52	1.45/1.64	1.64/1.94	1.72/2.04
z^2	0.98/1.18	1.50/1.71	1.67/1.98	1.93/2.30

Pump Probe M-edge RIXS of $CuGeO_3$





We observe dynamics in dd transitions !

Unpublished data

Conclusions IV

We measured high resolution M-edge RIXS spectra at FERMI

We measured a femtosecond dynamics in the dd-trasitions in a pump-probe RIXS experiment

Acknowlegments RIXS@FERMI

RIXS@TIMEX:

Fulvio Parmigiani
Marco Malvestuto
Antonio Caretta
Luca Sturari

Wilfried Wurth (CFEL/DESY)
Florian Hieke
Sasa Bait

TIMEX staff:

Emiliano Principi
Riccardo Mincigrucci
Laura Foglia
Alberto Simoncig

Measurements @ ALS:

Yi De Chuang
Lewis A. Wray (NYU)

NiO measurements

Giacomo Ghiringhelli (PoliMi)
Andreas Scherz (XFEL)
Justine Schlappa