X-ray Imaging Following Synchrotron Beam Excitation

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First Hard X-ray Laser in the world:
Linac Coherent Light Source
Outline

• introduction to synchrotron radiation (SR)
• x-ray transmission imaging
• x-ray fluorescence (XRF) imaging
• examples of SR based XRF imaging
• details and numbers
• proposed plan
SR Facilities Around the World

- 54 operational light source rings in 19 countries
- 8 rings in construction
- 11 in advanced stages of design/planning

For a list of SR facilities around the world see:
http://ssrl.slac.stanford.edu/SR_SOURCES.HTML
Four Largest US Synchrotron Sources

Stanford Synchrotron Radiation Laboratory (SSRL)
Stanford Linear Accelerator Center (1974)

National Synchrotron Light Source (NSLS)
Brookhaven National Laboratory (1982)

Advanced Light Source (ALS),
Lawrence Berkeley National Laboratory (1993)

Advanced Photon Source (APS),
Argonne National Laboratory (1996)
Different Types of Synchrotron Sources

schematics of a synchrotron lab

Bend-Magnet Radiation

\[ E_e = \gamma m c^2 \]

\[ \theta_x = \frac{1}{\gamma} \]

Beamline optics acceptance angle

Undulator Radiation

\[ \lambda_u = \frac{\lambda_0}{2N} \left( 1 + \frac{K^2}{2} + \frac{\gamma^2}{2} \right) \]

In the central radiation cone:

\[ \frac{\Delta \omega}{\omega} = \frac{1}{N} \]

\[ \theta_{cen} = \frac{1}{\gamma / N} \]

Photon flux

Photon energy

\[ \frac{\lambda}{\Delta \lambda} = N \]
Properties of Synchrotron Sources?

- very intense
- tunable
- polarization
- short pulses
Concept of contrast enhanced X-ray Transmission Imaging

- every element has a characteristic edge
- measure transmission at two energies: below and above absorption edge of element of interest
- take difference to enhance contrast
- chemical dependence

plus:
- line sources: faster imaging

minus:
- large ink concentration necessary
- sample has to be sufficiently transparent to x-rays
1) incident x-ray photon knocks out inner-shell electron
2) hole is immediately filled from electron in outer shell
3) fluorescence photon is emitted, predominantly Ka radiation
4) fluorescence is detected for imaging

plus: greatly enhanced sensitivity compared to transmission imaging
Choice of X-ray Energy

CaFeZn, 2µm

Transmission

Energy [keV]

Ca Ka
Fe Ka
Zn Ka
Investigation of calcifications in breast tissue using EXAFS and XRF

Sayers et al

Figure 2: Photograph of one of the tissue samples. The dashed lines enclose the region of the calcification.
X-Ray Fluorescence Studies of Elements in Human Lung Tissue

Figure 1. a) Photomicrograph of lung tissue sample from a worker at the radiochemistry factory in Chelyabinsk. b) Elemental distribution maps of P, S, Ca, and Zn.
Detection of Trace Impurities

sensitivity to extremely low concentrations
much less than millionth of a mono layer!
Schematic Experimental Setup

Detector

Fluorescence from element in ink

X-ray beam from synchrotron

Scanning directions

X

Z
Schematic Experimental Setup

- continuous x-scans
- steps in z-direction

example:

10 * 10 cm² scanning area,
30 µm ~ 800 dpi resolution
5 msec illumination per data point

17 seconds/line, 3300 lines
~ 16 hours total scanning time

intense x-ray beam and polarization might be crucial for best imaging
Some Details

- scans are performed with high precision
  computer-controlled translation stages (Huber)
- fast scan ability *
- large area Ge detector for fluorescence detection available
- incident/transmitted intensity is recorded for normalization
- automated system that closes beam shutter
  if scanning gets interrupted
- tests on sample texts for best x-ray parameters
  and potential radiation damage (see list from Abigail)
- build airtight frame to mount and transport palimpsest
- data reduction/analysis programs are available (e.g. Matlab)

blue = available now green = still to be done
Proposed Plan

• assemble and test all the scanning/imaging hardware

• study a test object of composition similar to the original text

• identify one or several elements for imaging (e.g. Fe)

• test for appropriate sample protection, X-ray energy, beam size and exposure times (radiation damage)

• study the original text
End of Show
Support Slides
Electrons in circular motion are also undergoing acceleration (centripetal).

When electrons are moving slowly, the radiation comes out in all directions.

When the electron speed gets close to the speed of light, the radiation comes out only in a narrow forward cone.
Selective X-ray Excitation

(a)

Energy (eV)

Normalized Absorption

Fe$_2$O$_3$
Fe (acac)$_3$
FeCp$_2$
FePO$_4$

Fe$^{2+}$
Fe$^{3+}$

Energy (eV)
X-ray Fluorescence Spectroscopy

chemical sensitivity of K fluorescence

level diagram

valence levels

3p

Kβ₂,₅, Kβ''

Kβ₁,₃, Kβ'

2p

Kα₁,₂

1s