What are X-Rays, anyway?

ELECTROMAGNETIC WAVES

Wavelength

Radio Waves
Microwaves
Infrared
Ultraviolet
X-Rays
17 Nobel Prizes based on X-Ray Work

**Physics:**

1901: WILHELM RÖNTGEN

1914: MAX VON LAUE

1915: SIR WILLIAM HENRY BRAGG  
and SIR WILLIAM LAWRENCE BRAGG

1917: CHARLES BARKLA

1924: KARL MANNE SIEGBAHN

1927: ARTHUR COMPTON

1981: KAI SIEGBAHN

**Chemistry:**

1936: PETER DEBYE

1962: MAX PERUTZ and SIR JOHN KENDREW

1964: DOROTHY HODGKIN

1976: WILLIAM LIPSCOMB

1985: HERBERT HAUPTMAN and JEROME KARLE

1988: JOHANN DEISENHOFER,  
ROBERT HUBER and HARTMUT MICHEL

1997: PAUL D. BOYER and JOHN E. WALKER

**Medicine:**

1946: HERMANN JOSEPH MULLER

1962: FRANCIS CRICK, JAMES WATSON  
and MAURICE WILKINS

1979: ALAN M. CORMACK and  
SIR GODFREY N. HOUNSFIELD
Why are X-Rays so Useful?

Imaging - Seeing the Invisible
- 1901

Atomic and Molecular Structure - where are the atoms -
- 1993

Electronic Structure and Bonding - where are the electrons -

Magnetic Structure and Properties - where are the spins -
Modern X-Ray Techniques:

Photoemission:

X-Ray Absorption:

\[ I_t = I_0 e^{-\mu t} \]

Sample

Absorbance

X-Ray Diffraction:

Direct Imaging:

Zone Plate

Focusing Lens

Scanning Sample Stage

X-Ray Detector
How is Synchrotron Radiation Produced?

- Electron gun produces electrons
- Storage ring circulates electrons
- Synchrotron radiation produced where electron path is bent
- Three types of source points: bending magnets, wigglers, undulators

Brightness of x-rays increases:
- bends ➔ wigglers ➔ undulators
From Undulators to Free Electron Lasers

SASE gives $10^6$ intensity gain over spontaneous emission

FELs can produce ultrafast pulses (of order 100 fs)
How bright are different light sources?

- Candle
- 60-W Light Bulb
- X Ray Tube
- Sun
- Bending Magnets
- Undulators
- LCLS
- FELs

Graph showing the increase in log beam brilliance over years.
X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds

**Ultra-Small**

<table>
<thead>
<tr>
<th>Nature</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flea</td>
<td>Head of a pin ~ 1 mm</td>
</tr>
<tr>
<td>Human hair ~ 30 μm wide</td>
<td>Micro gears 10 -100 μm diameter</td>
</tr>
<tr>
<td>Red blood cells &amp; white cell ~ 5 μm</td>
<td>DVD track</td>
</tr>
<tr>
<td>Virus ~ 200 nm</td>
<td>1 μm Electrodes connected with nanotubes</td>
</tr>
<tr>
<td>DNA helix ~ 3 nm width</td>
<td>Carbon nanotube ~ 2 nm diameter</td>
</tr>
<tr>
<td>Water molecule</td>
<td>Atomic corral ~ 14 nm diameter</td>
</tr>
</tbody>
</table>

**Ultra-Fast**

<table>
<thead>
<tr>
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<th>Technology</th>
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<tbody>
<tr>
<td>Hydrogen transfer time in molecules is ~ 1 ns</td>
<td>Computing time per bit is ~ 1 ns</td>
</tr>
<tr>
<td>Spin precesses in 1 Tesla field is 10 ps</td>
<td>Magnetic recording time per bit is ~ 2 ns</td>
</tr>
<tr>
<td>Shock wave propagates by 1 atom in ~ 100 fs</td>
<td>Optical network switching time per bit is ~ 100 ps</td>
</tr>
<tr>
<td>Water dissociates in ~10 fs</td>
<td>Laser pulsed current switch ~ 1 ps</td>
</tr>
<tr>
<td>Light travels 1 μm in 3 fs</td>
<td>Shortest laser pulse is ~ 1 fs</td>
</tr>
<tr>
<td>Bohr period of valence electron is ~ 1 fs</td>
<td>Oscillation period of visible light is ~ 1 fs</td>
</tr>
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