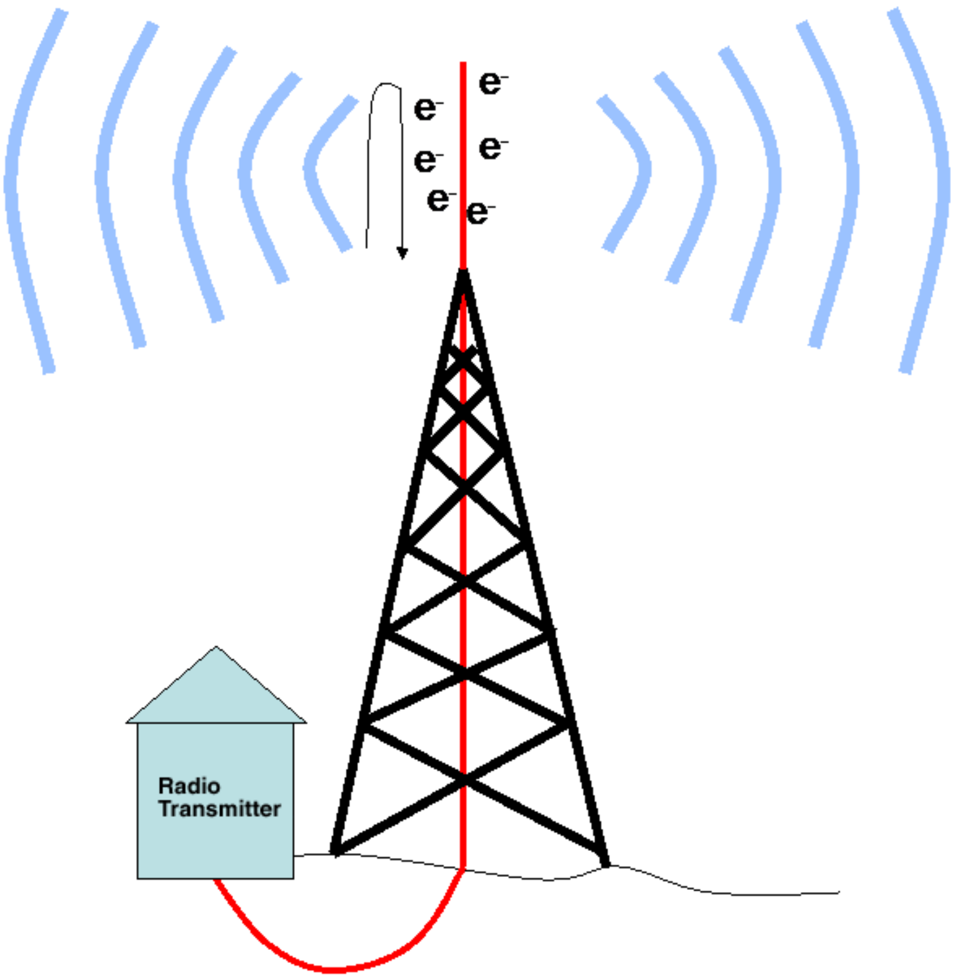
Synchrotron Radiation

How is synchrotron light made?

by accelerating electrons

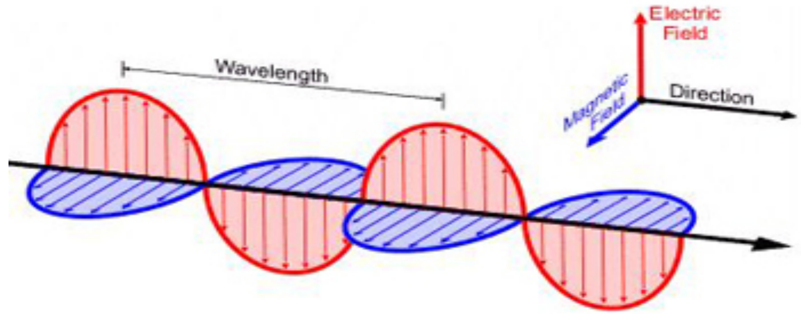
Electromagnetic Radiation

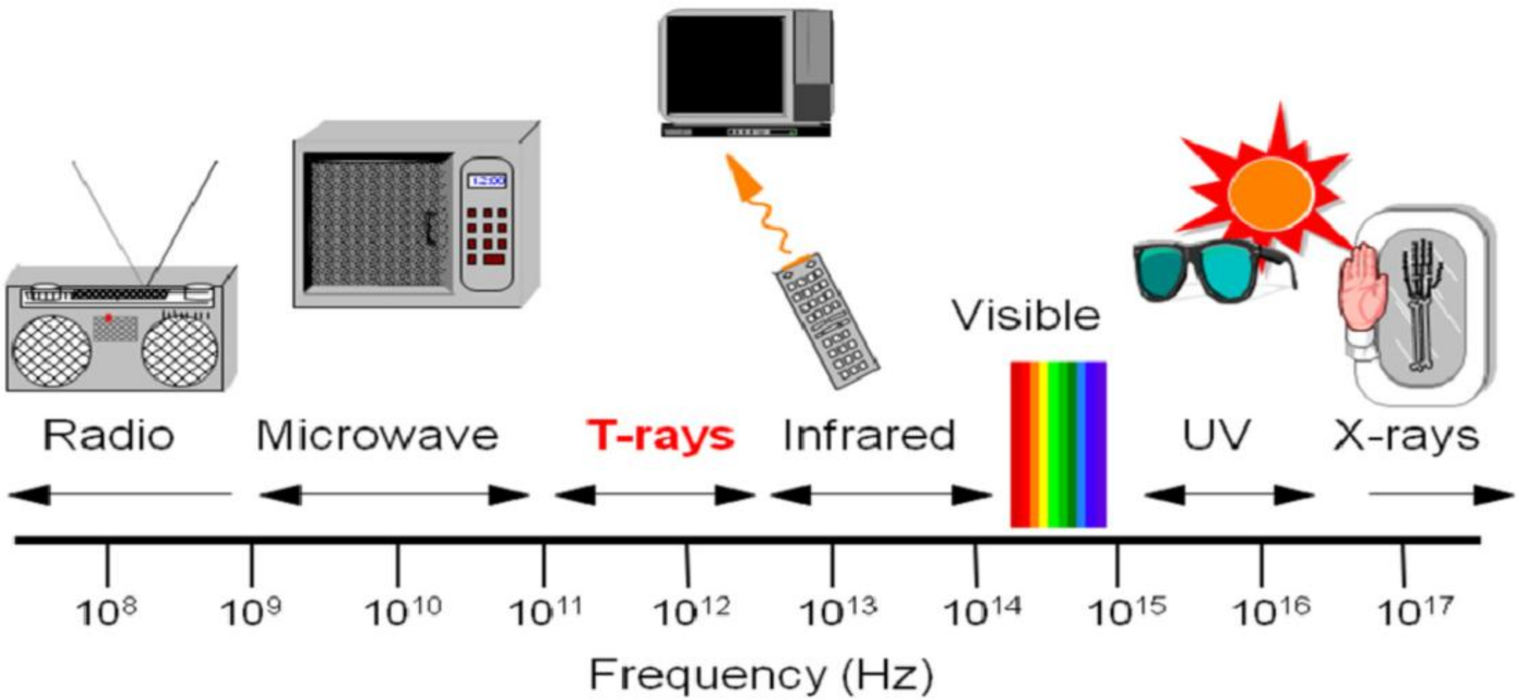


Electrons *accelerating* by running up and down in a radio antenna emit radio waves

Radio waves are nothing more than Long Wavelength Light

Electromagnetic Spectrum

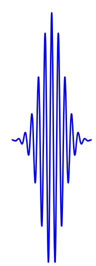




How far does light travel in 1 second? 1 femtosecond?

1 sec

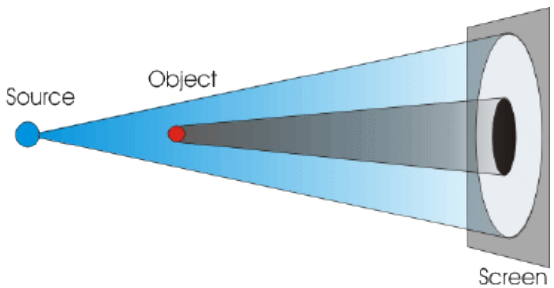
1 fs



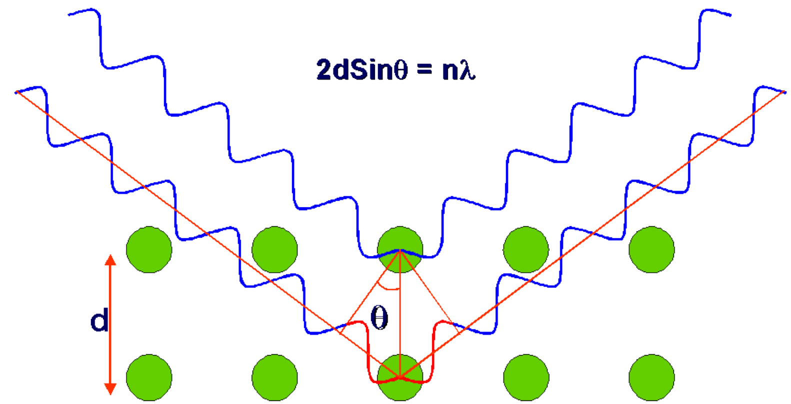
3,000 nm

(1/10 of a hair)

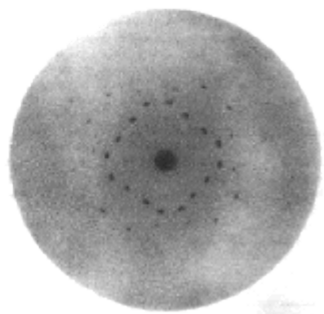
Interaction of photons with matter



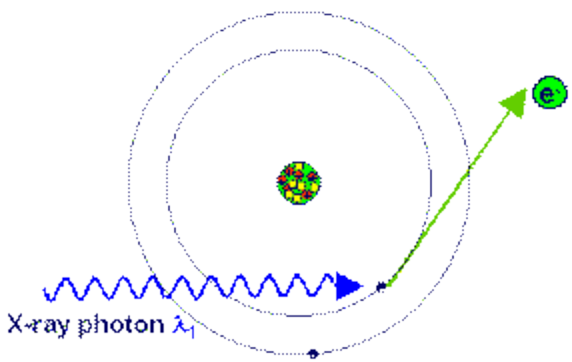
Radiagraphy



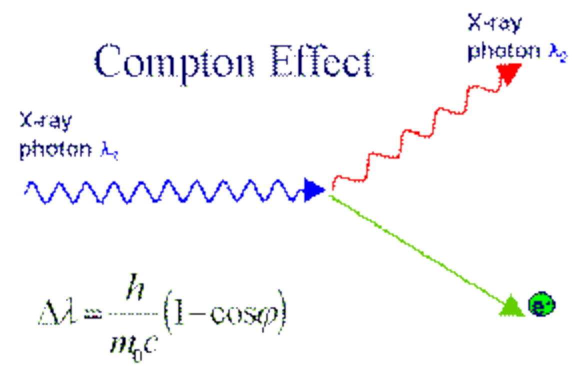
Bragg Diffraction



Laue Diffraction



Photoelectric Effect



Compton Scattering

X-rays have enabled seminal scientific discoveries

18 Nobel Prizes Based on X-ray Work

Chemistry

1936: Peter Debye

1962: Max Purutz and Sir John Kendrew

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

2003 Peter Agre and Roderick Mackinnon

Physics

1901 Wilhem Rontgen

1914 Max von Laue

1915 Sir William Bragg and son

1917 Charles Barkla

1924 Karl Siegbahm

1927 Arthur Compton

1981 Kai Siegbahn

Medicine

1946 Hermann Muller

1962 Frances Crick, James Watson and Maurice Wilkins

1979 Alan Cormack and Godrey Hounsfield

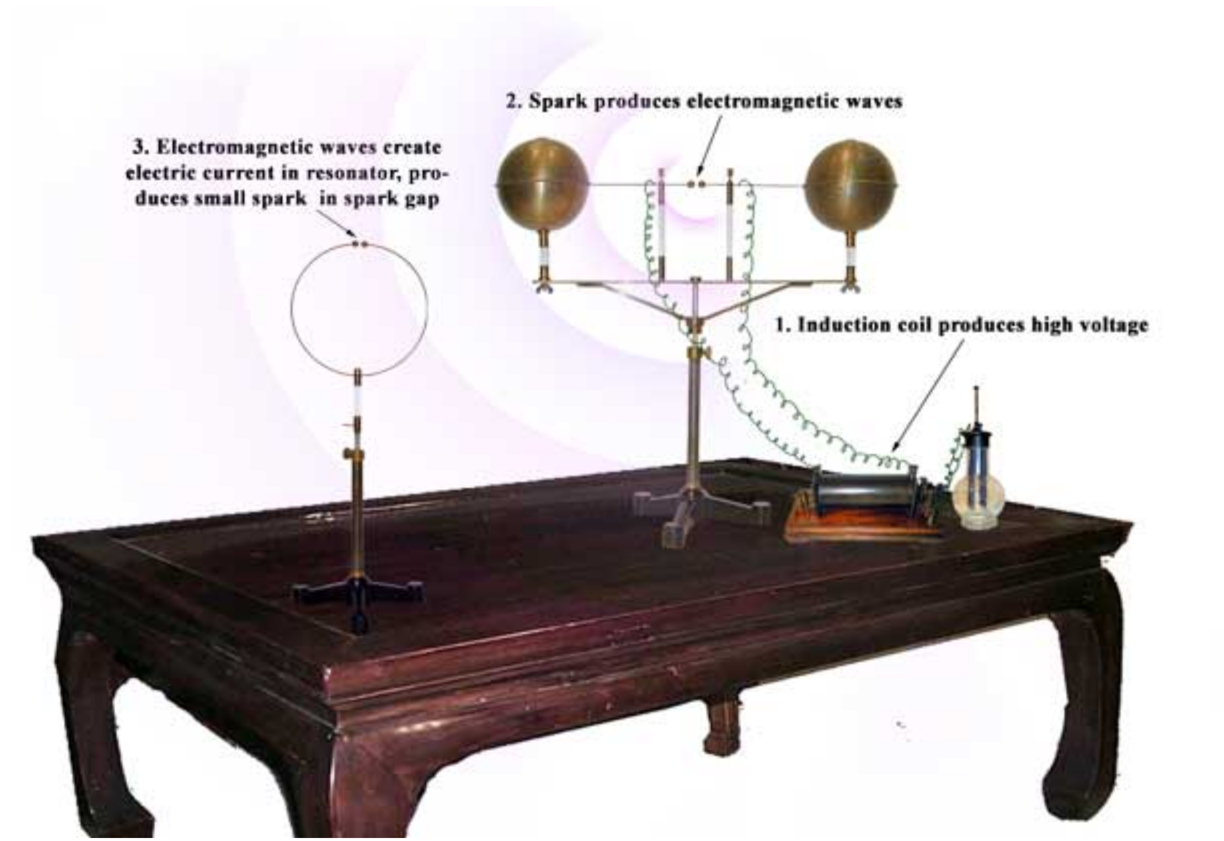
Early History

1873 Maxwell’s Equations

- **Made evident that changing charge densities would result in electric fields that would radiate outward**

1887 Hertz demonstrated such waves

Discovery of Radio Waves



Heinrich Rudolf Hertz
(1847-1894)

Early History

1873 Maxwell's Equations

- **Made evident that changing charge densities would result in electric fields that would radiate outward**

1887 Hertz demonstrated such waves

1895 Röntgen discovered X-Rays

Discovery of X-rays:

Maybe the most important discovery for medicine

Wilhelm Conrad Röntgen (1845-1923)

Crooke' s Tube

Bertha Röntgen' s Hand 8 Nov, 1895

Modern radiograph of a hand

Early History

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- **Made evident that changing charge densities would result in electric fields that would radiate outward**

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1897 Larmor derived an expression for the instantaneous total power radiated by an accelerated charged particle

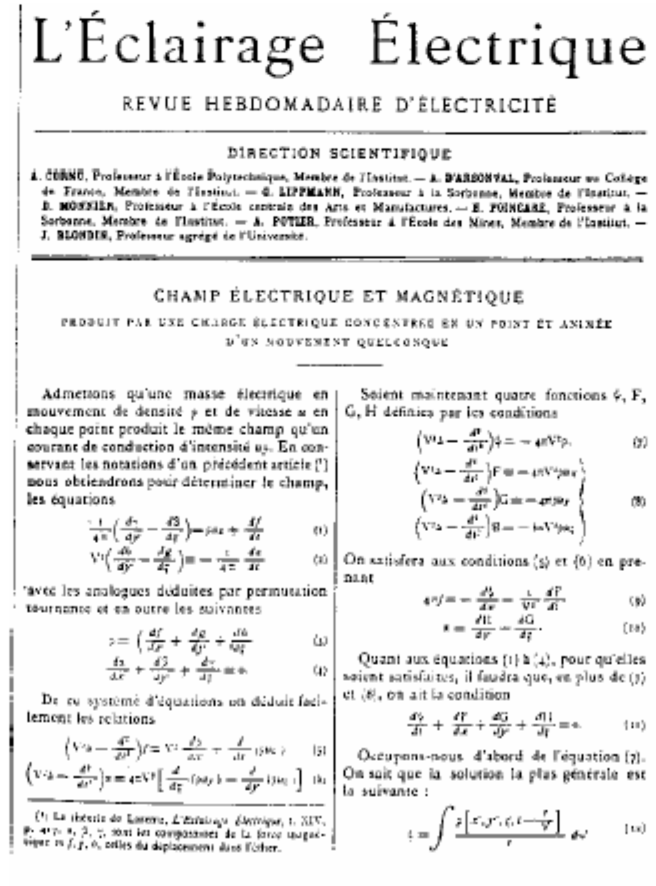
1898 Lienard's extended Larmor's result to the case of a relativistic particle undergoing centripetal acceleration in a circular trajectory

Lienard’ s Equations

1898 Liénard:

ELECTRIC AND MAGNETIC FIELDS PRODUCED BY A POINT CHARGE MOVING ON AN ARBITRARY PATH

(by means of retarded potentials)



L'Éclairage Électrique

REVUE HEBDOMADAIRE D'ÉLECTRICITÉ

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

PRODUIT PAR UNE CHARGE ÉLECTRIQUE CONCENTRÉE EN UN POINT ET ANIMÉE D'UN MOUVEMENT QUELCONQUE

Admettons qu'une masse électrique en mouvement de densité ρ et de vitesse u en chaque point produit le même champ qu'un courant de conduction d'intensité $u\rho$. En conservant les notations d'un précédent article (¹) nous obtiendrons pour déterminer le champ, les équations

$$\frac{1}{4\pi}\left(\frac{d\gamma}{dy}-\frac{d\beta}{dz}\right)=\rho u_x+\frac{df}{dt} \qquad (1)$$

$$V^2\left(\frac{dh}{dy}-\frac{dg}{dz}\right)=-\frac{1}{4\pi}\frac{d\alpha}{dt} \qquad (2)$$

avec les analogues déduites par permutation tournante et en outre les suivantes

$$\rho=\left(\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}\right) \qquad (3)$$

$$\frac{d\alpha}{dx}+\frac{d\beta}{dy}+\frac{d\gamma}{dz}=0 \qquad (4)$$

De ce système d'équations on déduit facilement les relations

$$\left(V^2\Delta-\frac{d^2}{dt^2}\right)f=V^2\frac{d\rho}{dx}+\frac{d}{dt}(\rho u_x) \qquad (5)$$

$$\left(V^2\Delta-\frac{d^2}{dt^2}\right)\alpha=4\pi V^2\left[\frac{d}{dz}(\rho u_y)-\frac{d}{dy}(\rho u_z)\right] \qquad (6)$$

(¹) La théorie de Lorentz, *L'Éclairage Électrique*, t. XIV, p. 417; α, β, γ, sont les composantes de la force magnétique; f, g, h, celles du déplacement dans l'éther.

Soient maintenant quatre fonctions ψ, F, G, H définies par les conditions

$$\left(V^2\Delta-\frac{d^2}{dt^2}\right)\psi=-4\pi V^2\rho \qquad (7)$$

$$\left.\begin{aligned}\left(V^2\Delta-\frac{d^2}{dt^2}\right)F&=-4\pi V^2\rho u_x\\ \left(V^2\Delta-\frac{d^2}{dt^2}\right)G&=-4\pi V^2\rho u_y\\ \left(V^2\Delta-\frac{d^2}{dt^2}\right)H&=-4\pi V^2\rho u_z\end{aligned}\right\} \qquad (8)$$

On satisfera aux conditions (5) et (6) en prenant

$$4\pi f=-\frac{d\psi}{dx}-\frac{1}{V^2}\frac{dF}{dt} \qquad (9)$$

$$\alpha=\frac{dH}{dy}-\frac{dG}{dz}. \qquad (10)$$

Quant aux équations (1) à (4), pour qu'elles soient satisfaites, il faudra que, en plus de (7) et (8), on ait la condition

$$\frac{d\psi}{dt}+\frac{dF}{dx}+\frac{dG}{dy}+\frac{dH}{dz}=0. \qquad (11)$$

Occupons-nous d'abord de l'équation (7). On sait que la solution la plus générale est la suivante :

$$\psi=\int\frac{\rho\left[x',y',z',t-\frac{r}{V}\right]}{r}\,d\omega' \qquad (12)$$

Fig. 1. First page of Liénard's 1898 paper.

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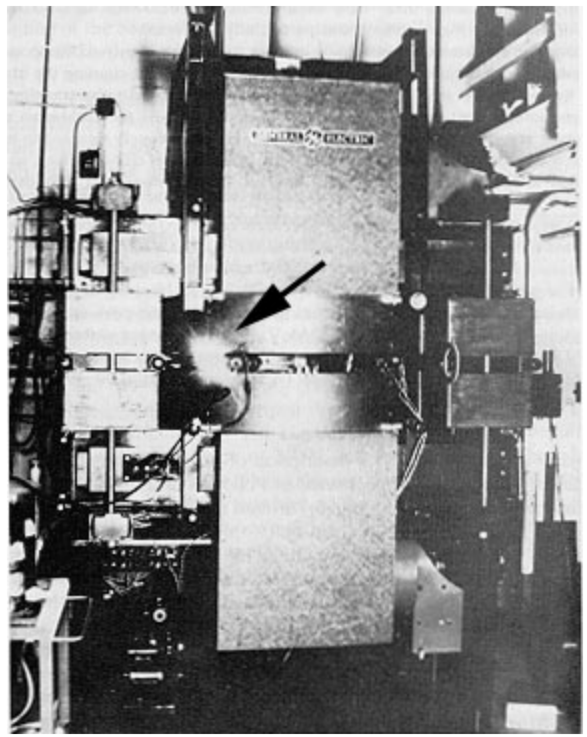
1947 GE's 70-MeV synchrotron : First observation of Synchrotron Light in an accelerator

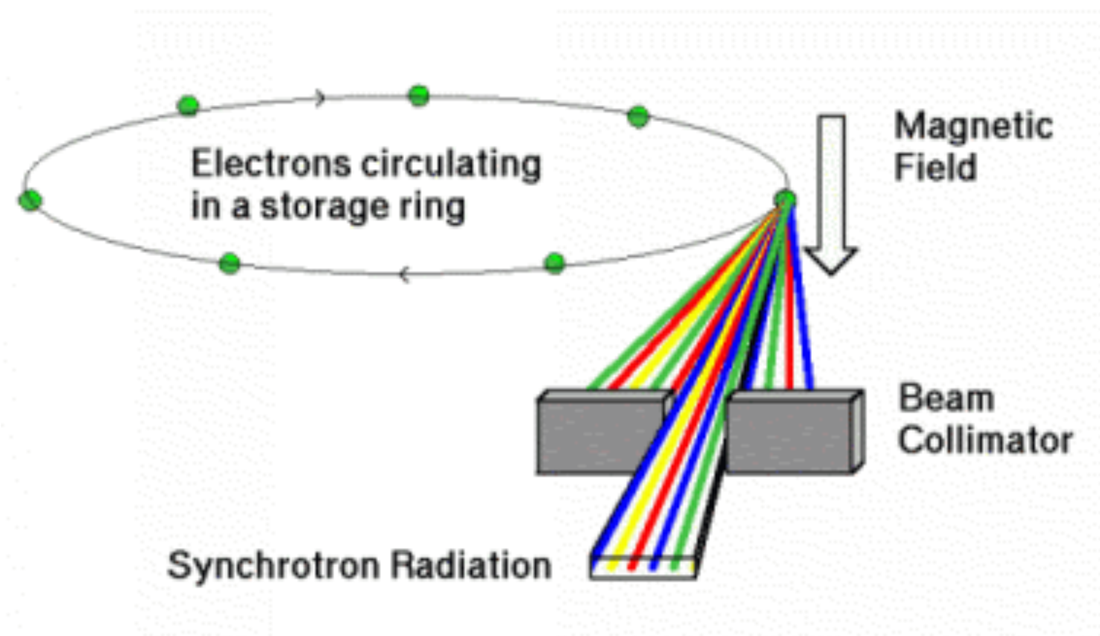
First observation of synchrotron radiation

GE Synchrotron
New York State



First light observed
1947

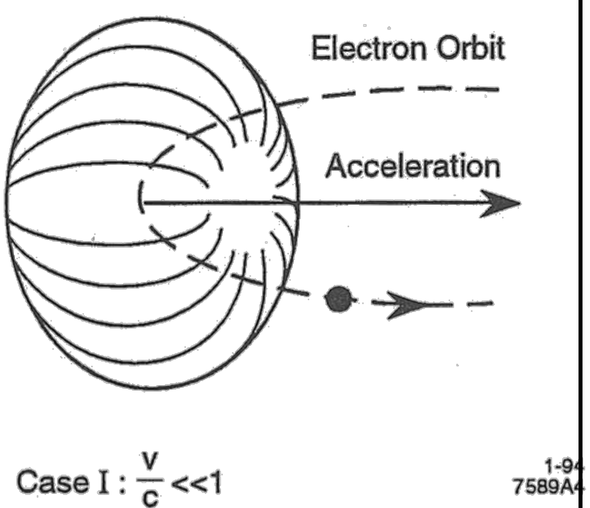
Why we need synchrotron radiation



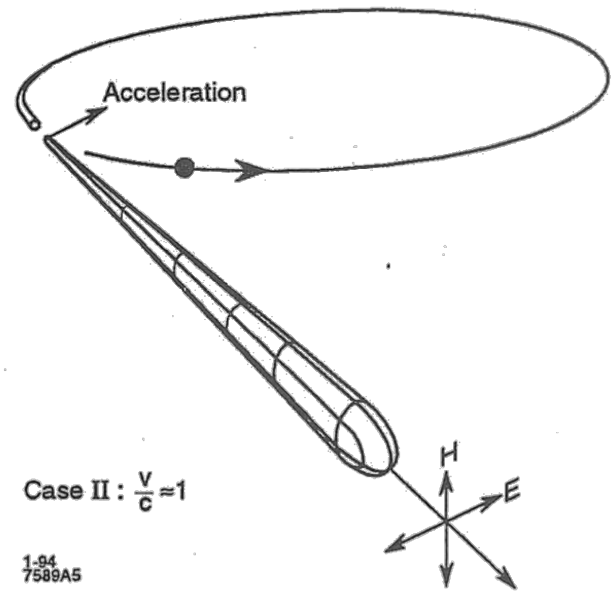
Synchrotron radiation is electromagnetic radiation emitted when charged particles are radially accelerated (move on a curved path).

Synchrotron Radiation

- Radiated power increases at higher velocities
- Radiation becomes more focused at higher velocities

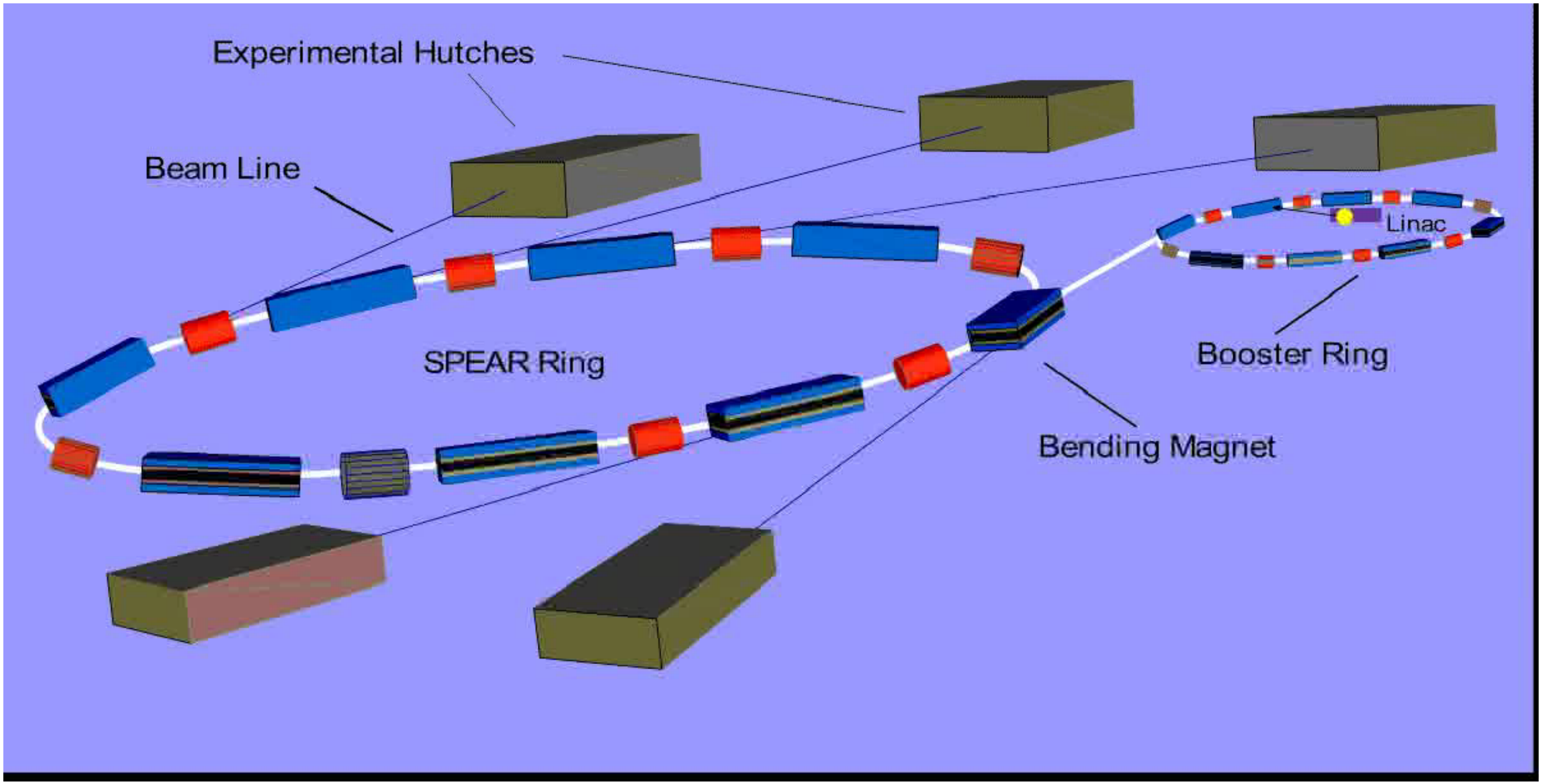


At low electron velocity (non -relativistic case) the radiation is emitted in a non-directional pattern

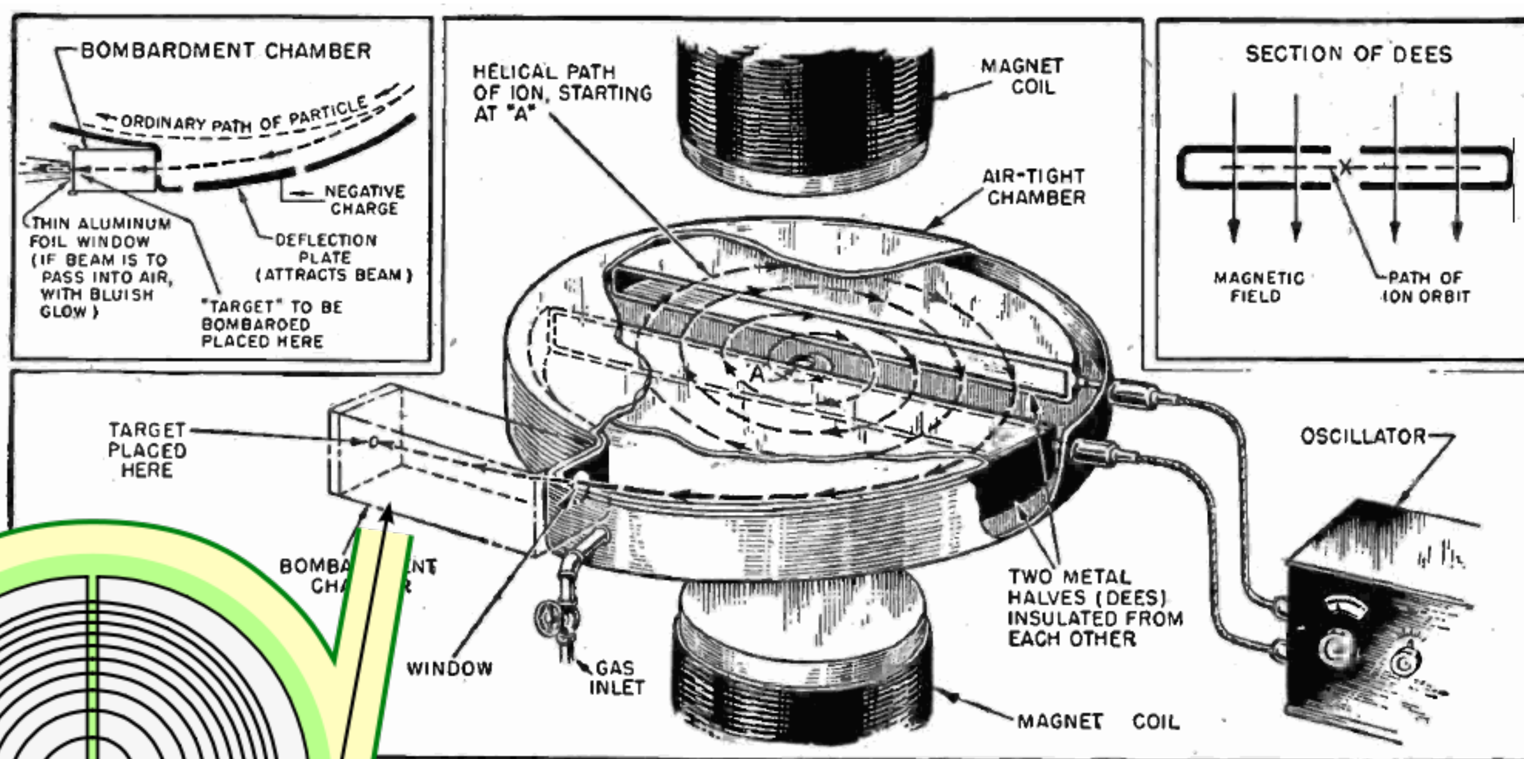


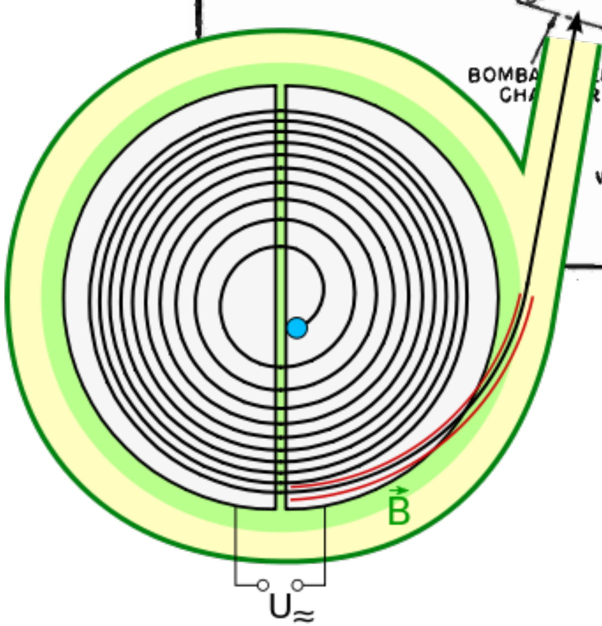
When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward. Also the radiated power goes up dramatically

How a storage ring light source works



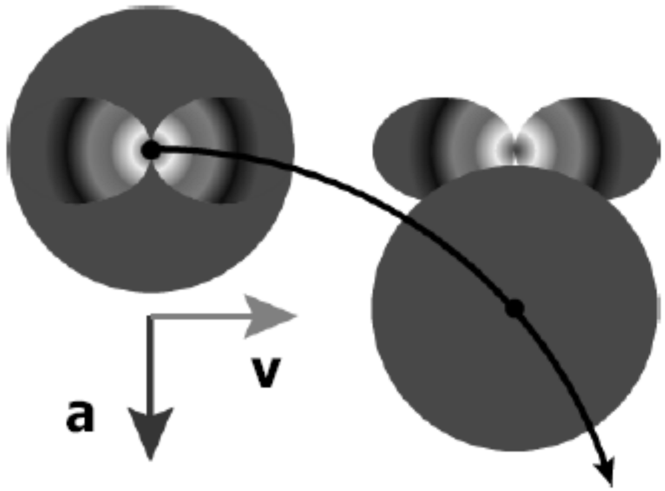
Cyclotron



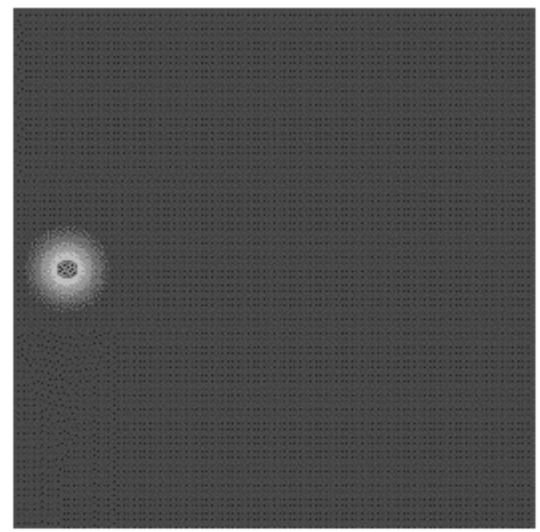


$$f = \frac{qB}{2\pi m}$$

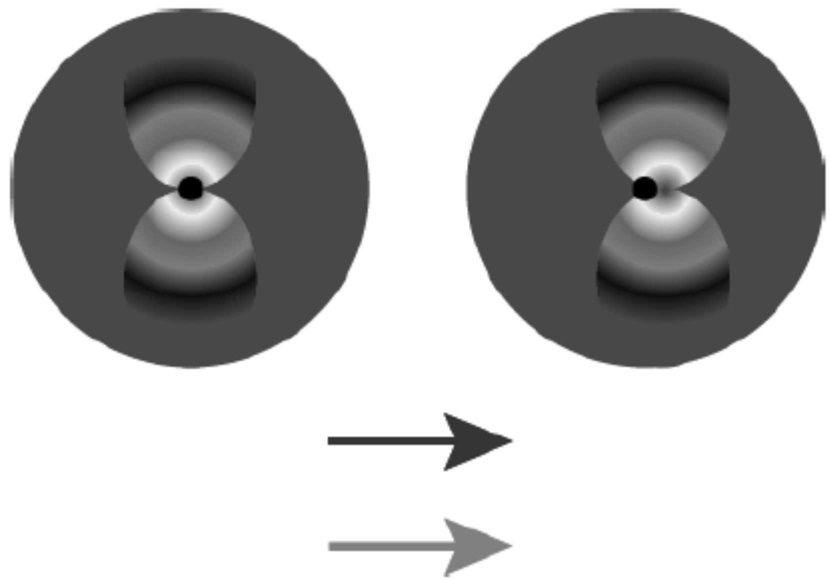
Transverse acceleration



Radiation field quickly separates itself from the Coulomb field



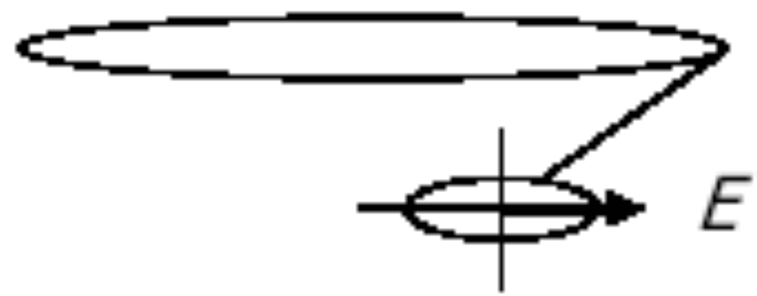
Longitudinal acceleration



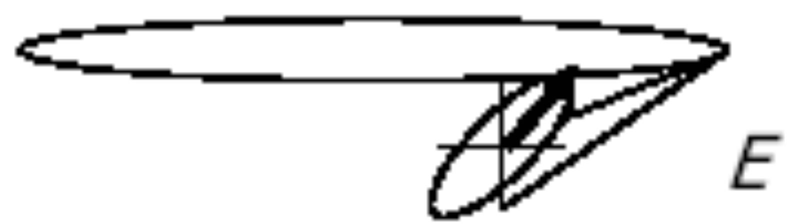
Radiation field cannot separate itself from the Coulomb field

Polarisation

Synchrotron radiation observed in the plane of the particle orbit is horizontally polarized, i.e. the electric field vector is horizontal



Observed out of the horizontal plane, the radiation is elliptically polarized



Basic Properties of Synchrotron Radiation

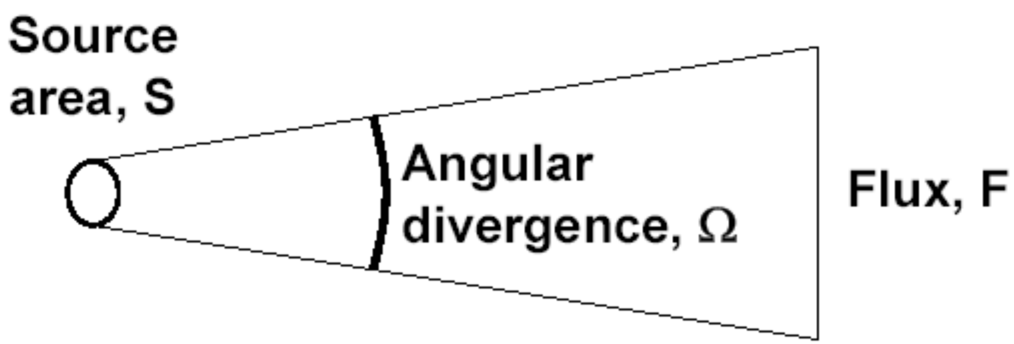
1. **HIGH FLUX, BRIGHTNESS, STABILITY**
2. **BROAD SPECTRAL RANGE - Tunability**
3. **POLARIZATION (linear, elliptical, circular)**
4. **PULSED TIME STRUCTURE (0.01 - 1 nsec)**
5. **SMALL SOURCE SIZE ($\leq$ mm)**
6. **PARTIAL COHERENCE**

The brightness of a light source

$$\textbf{Flux} = \frac{\#\text{ of photons in given }\Delta\lambda/\lambda}{\text{sec}}$$

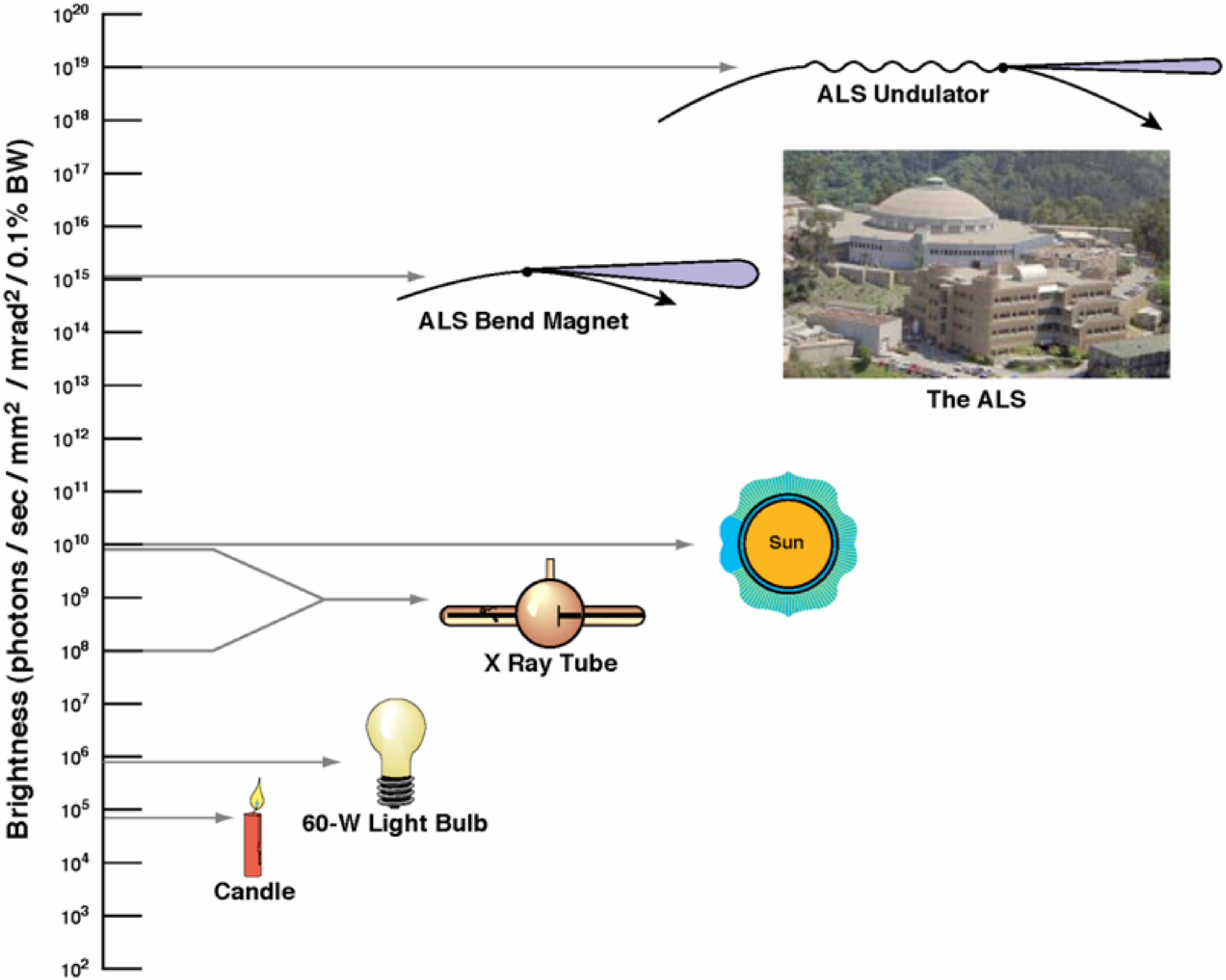
$$\textbf{Brightness} = \frac{\#\text{ of photons in given }\Delta\lambda/\lambda}{\text{sec, mrad }\theta\text{, mrad }\varphi\text{, mm}^2}$$

(a measure of concentration of the radiation)

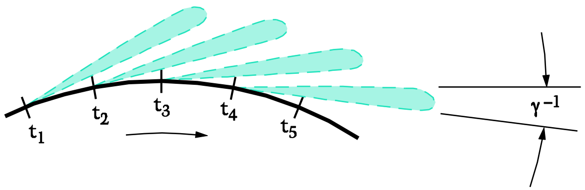


$$\textbf{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

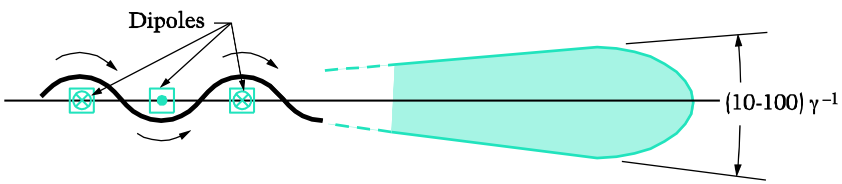
How Bright Is the Advanced Light Source?



Bending Magnets and Insertion Devices on Storage Rings



bending magnet - a "sweeping searchlight"

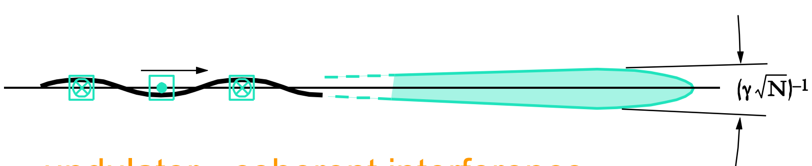


wiggler - incoherent superposition

Continuous spectrum characterized by ε_c = critical energy

$\varepsilon_c(\text{keV}) = 0.665\ B(\text{T})E^2(\text{GeV})$

eg: for B = 1.35T E = 2GeV
ε_c = 3.6keV



undulator - coherent interference

Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_U}{\gamma_2} \text{ (fundamental)}$$

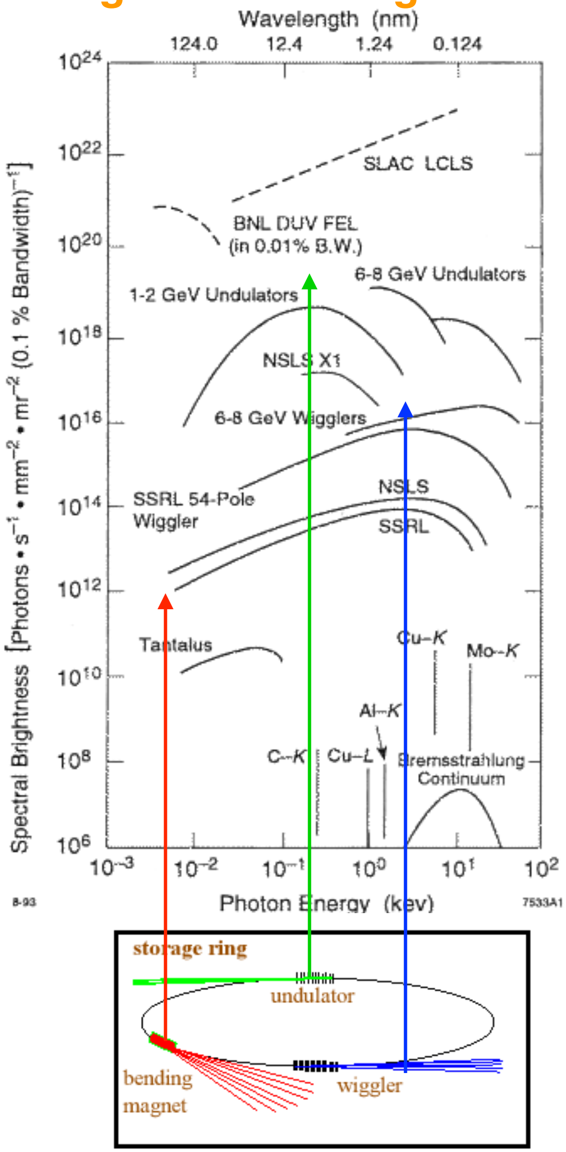
+ harmonics at higher energy

$$\varepsilon_1\ (\text{keV}) = \frac{0.95\ E^2\ (\text{GeV})}{\lambda_u{}^{(\text{cm})}\left(1 + \frac{K^2}{2}\right)}$$

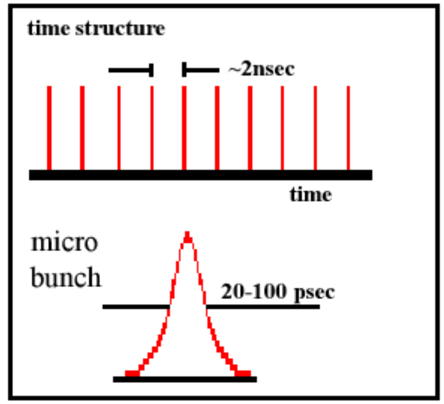
K = γθ where θ is the angle in each pole

Synchrotron Radiation - Basic Properties

High flux and brightness



Pulsed time structure



Broad spectral range

Polarized (linear, elliptical, circular)

Small source size

Partial coherence

High stability

Flux = $\dfrac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec}}$

Brightness = $\dfrac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$

(a measure of concentration of the radiation)

Synchrotron Radiation Facilities Around the World

- **54 in operation in 19 countries used by more than 20,000 scientists**

  (Brazil, China, India, Korea, Taiwan, Thailand)

- **8 in construction**

  Armenia, Australia, China, France, Jordan, Russia, Spain, UK

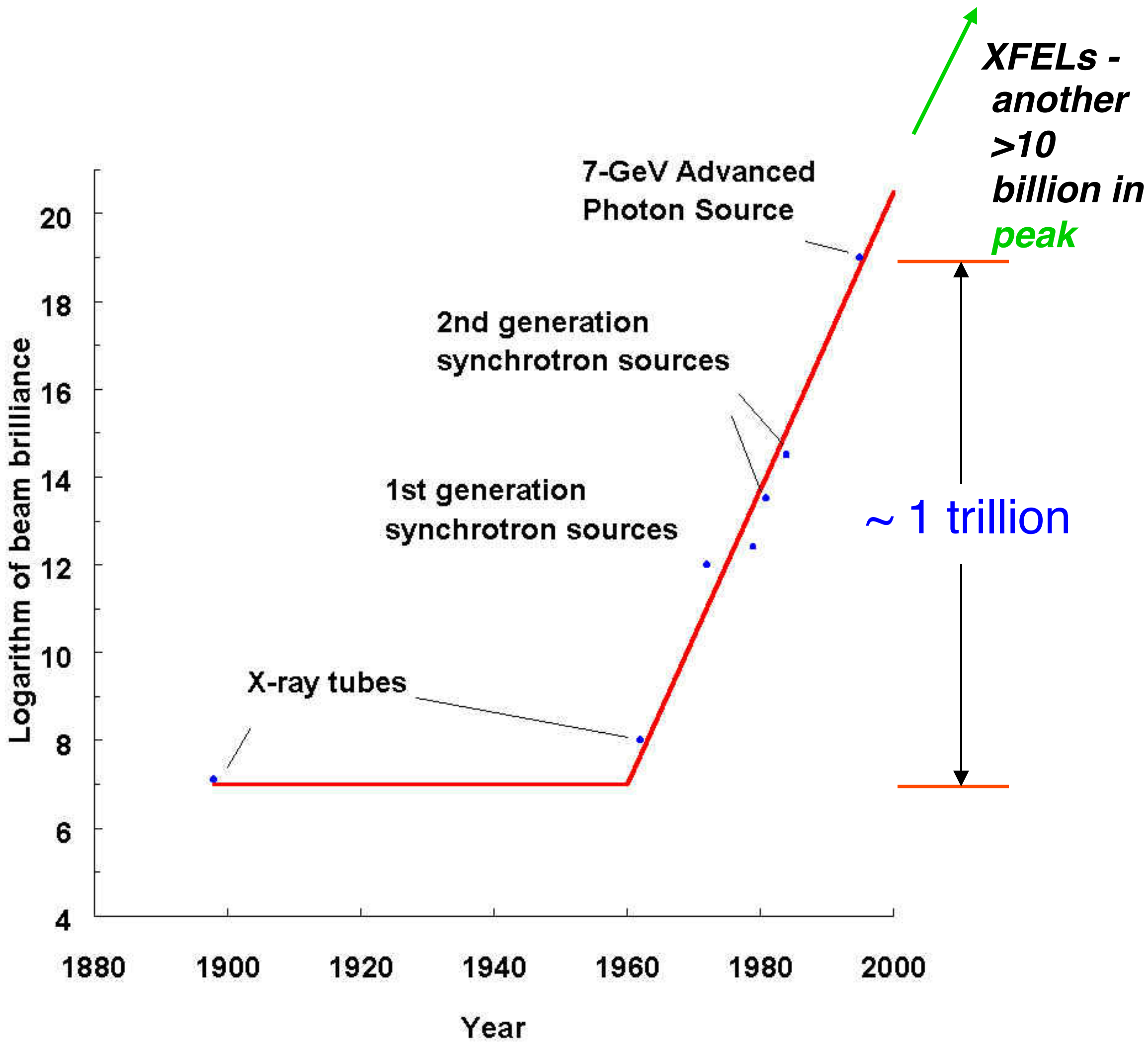
- **11 in design/planning**

For a list of SR facilities around the world see

http://ssrl.slac.stanford.edu/SR_SOURCES.HTML

www.sesame.org.jo

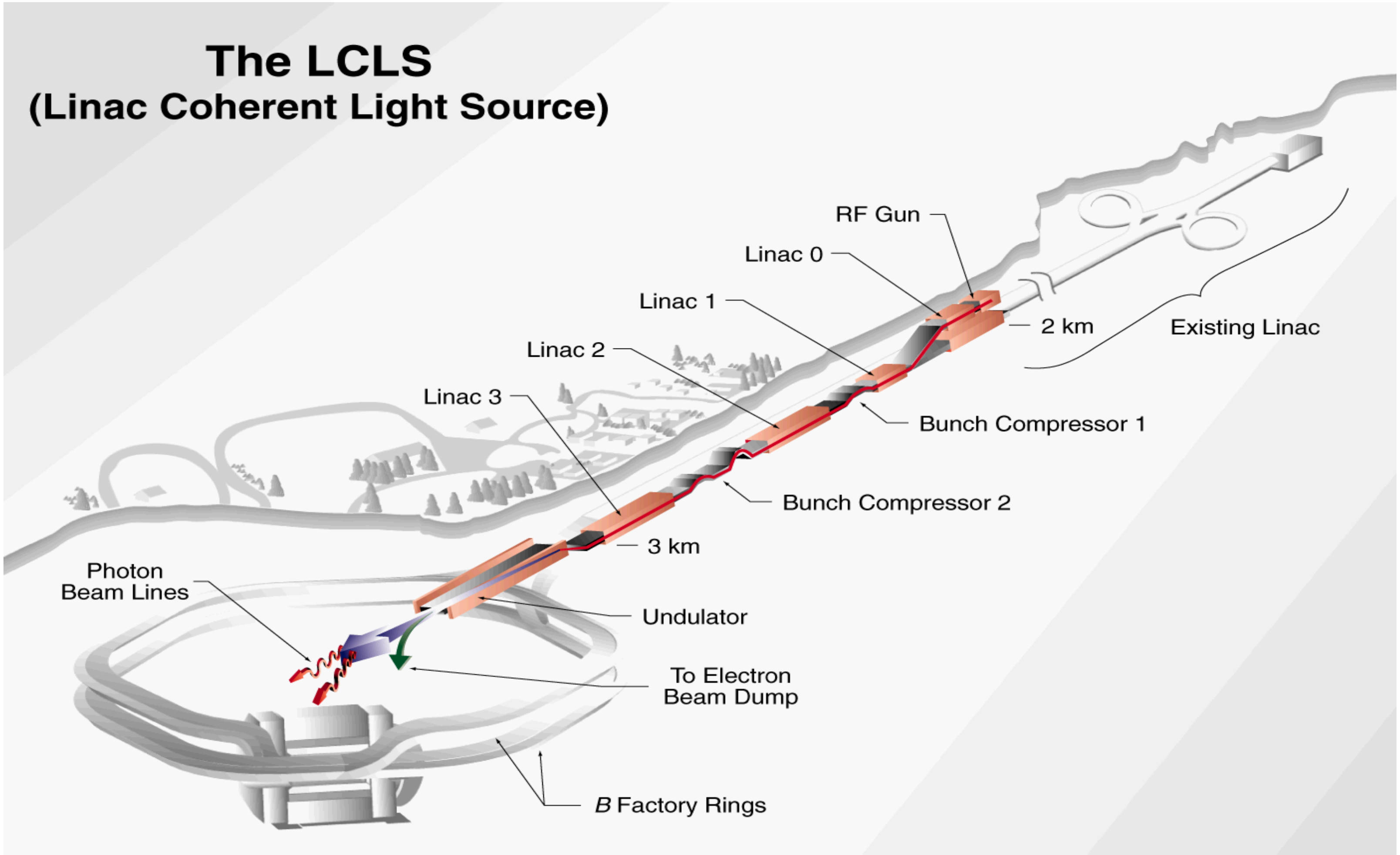
Steep growth in brightness



Future of Synchrotron Radiation

- Higher Brightness
  - Free Electron Lasers
- Shorter Pulse Lengths
  - Femto (10^{-12}) and Attosecond (10^{-15})
- Terahertz (T-rays)
  - Coherent Synchrotron Radiation

Linac-driven Light Sources - Toward the 4th Generation (operation in 2008)



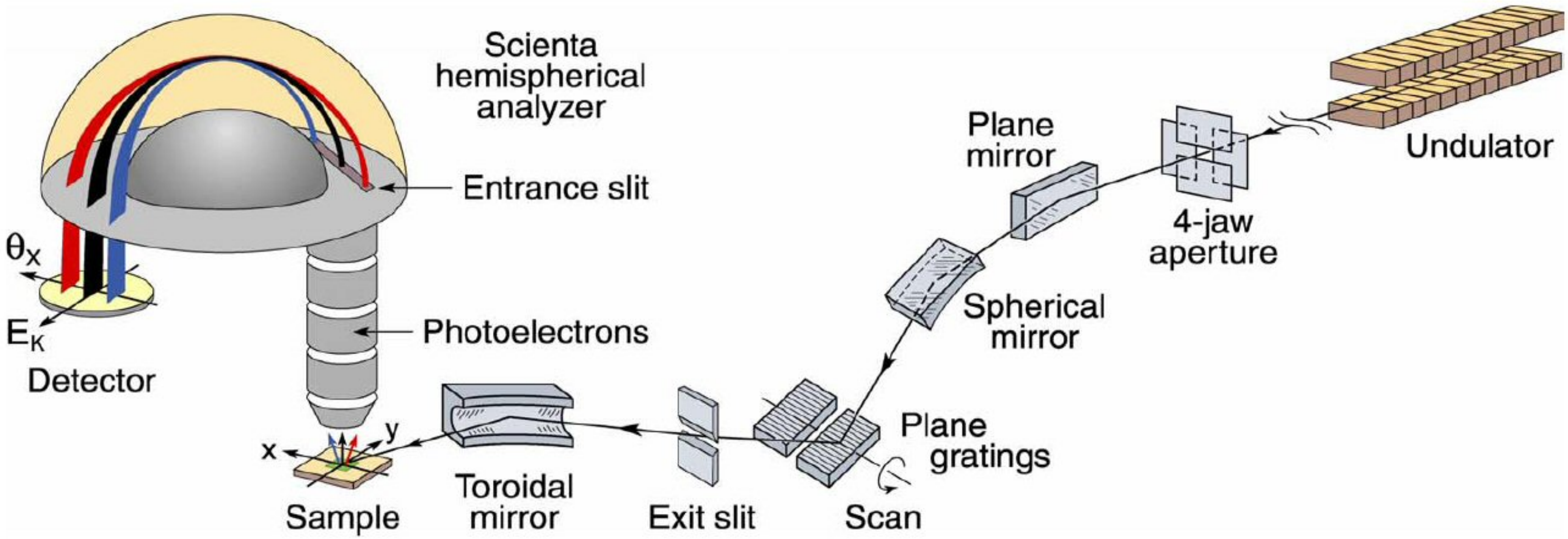
ADVANCED PHOTON SOURCE · Stanford Linear Accelerator Center · SSRL · LLNL · UCLA · nsls · Los Alamos science serving society

Angle-Resolved Photo-Emission Spectroscopy (ARPES)

Working of ARPES

- An atomically flat sample is illuminated by a beam of monochromatic light.
- Due to the photoelectric effect, the sample emits electrons.
- The kinetic energy and direction of these electrons are measured by the rotatable spectrometer.
- The obtained data are used to map out the Fermi surface of the sample material.

ARPES setup



Parallel multi-angle recording

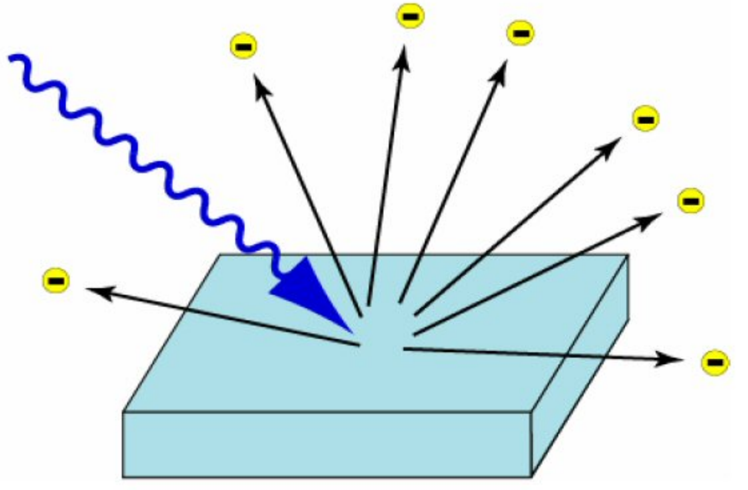
- Improved **energy resolution**
- Improved **momentum resolution**
- Improved **data-acquisition efficiency**

	ΔE *(meV)*	$\Delta\theta$
past	*20-40*	*2°*
now	*2-10*	*0.2°*

Photoelectric Effect

- Explained by Einstein (1905):

$$E_{k_{\max}} = hf - \phi$$



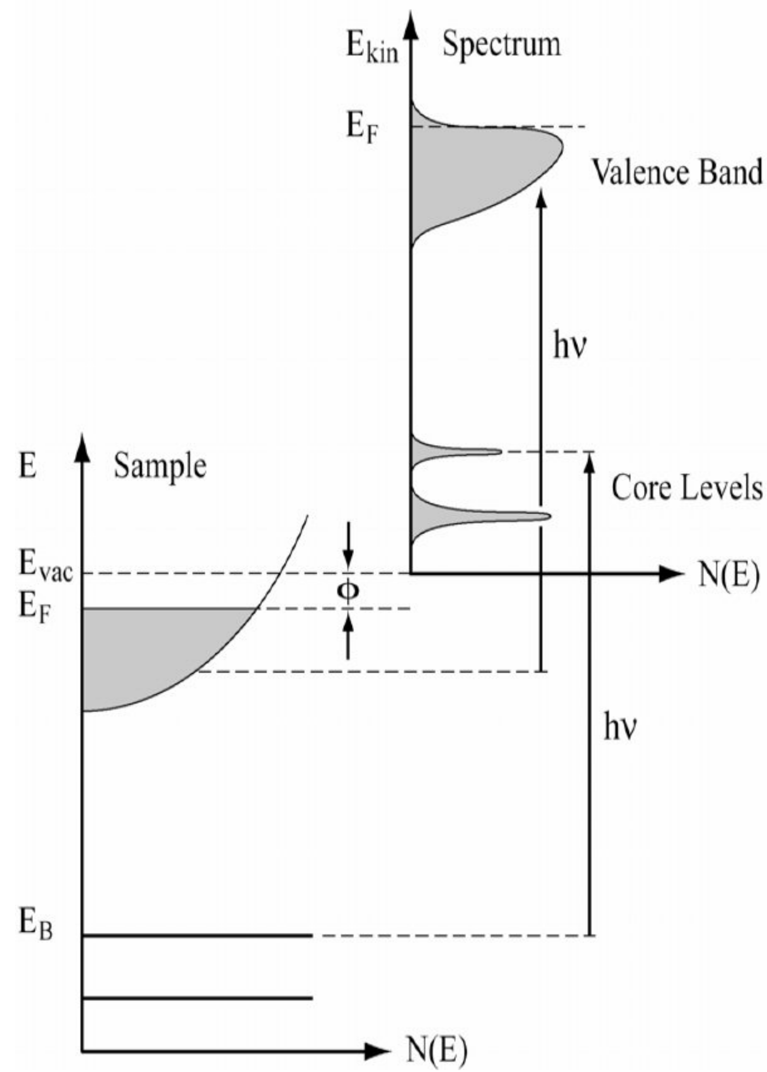
- More generally,

$$E_k = hf - \phi - |E_B|$$

where E_B is the binding energy of the electron.

Photoemission Spectra

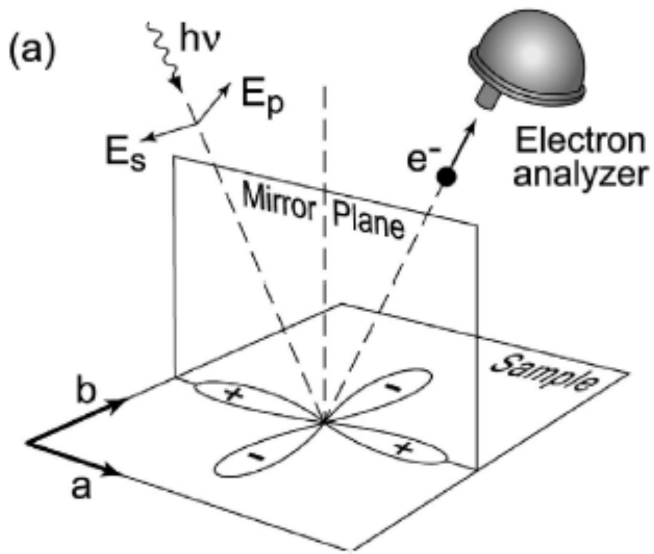
- The work function is known/ measurable.
- The photon energy is known.
- We can calculate the energy of the electron in the solid!

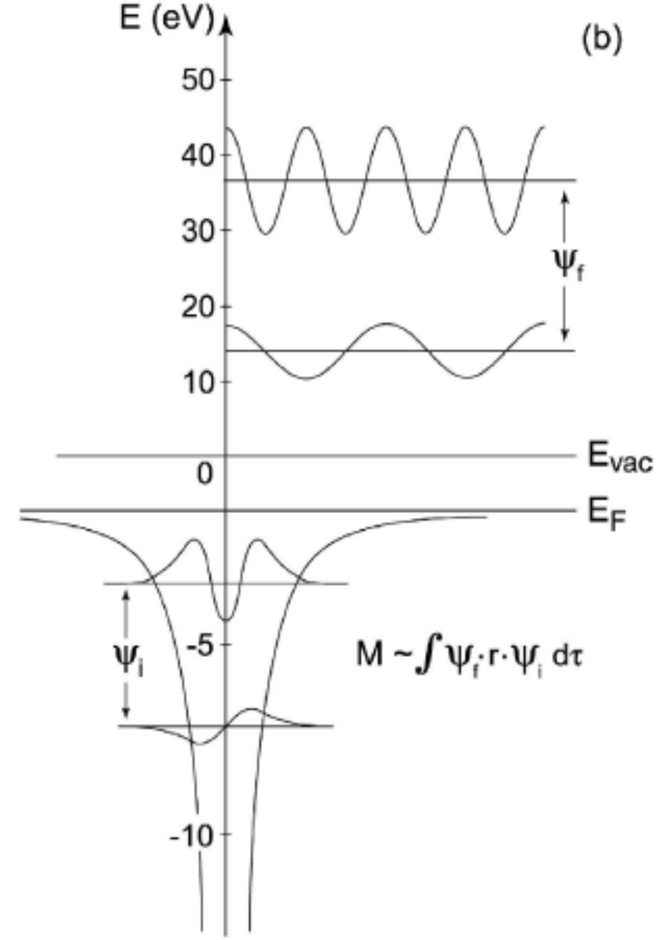


Basis of ARPES

ARPES is directly measuring the components of electron momentum that are parallel to the surface

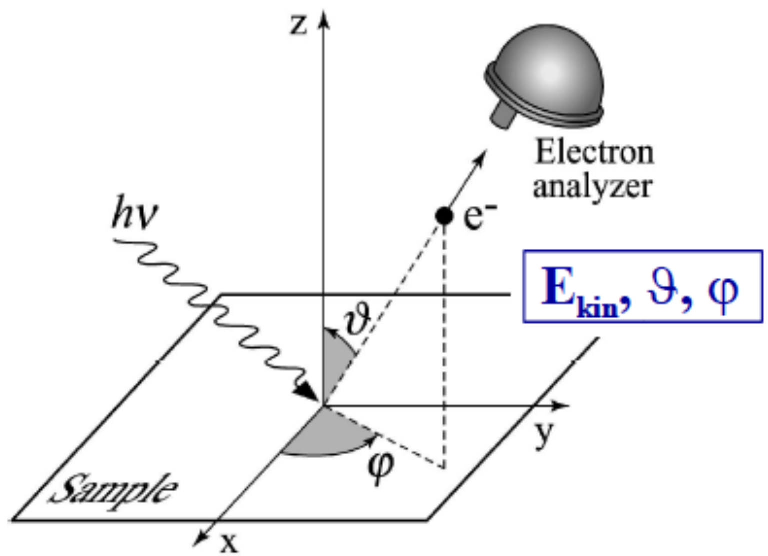
- The flat surface of the sample has translational symmetry. Therefore, as electrons escape from the solid, linear momentum is conserved parallel to the surface.
- The photon momentum is small and can be neglected.





$$w_{fi} = \frac{2\pi}{\hbar} \left| \langle \Psi_f^N | H_{int} | \Psi_i^N \rangle \right|^2 \delta(E_f^N - E_i^N - h\nu)$$

$$H_{int} = -\frac{e}{2mc}(\mathbf{A}\cdot\mathbf{p} + \mathbf{p}\cdot\mathbf{A}) = -\frac{e}{mc}\mathbf{A}\cdot\mathbf{p}$$

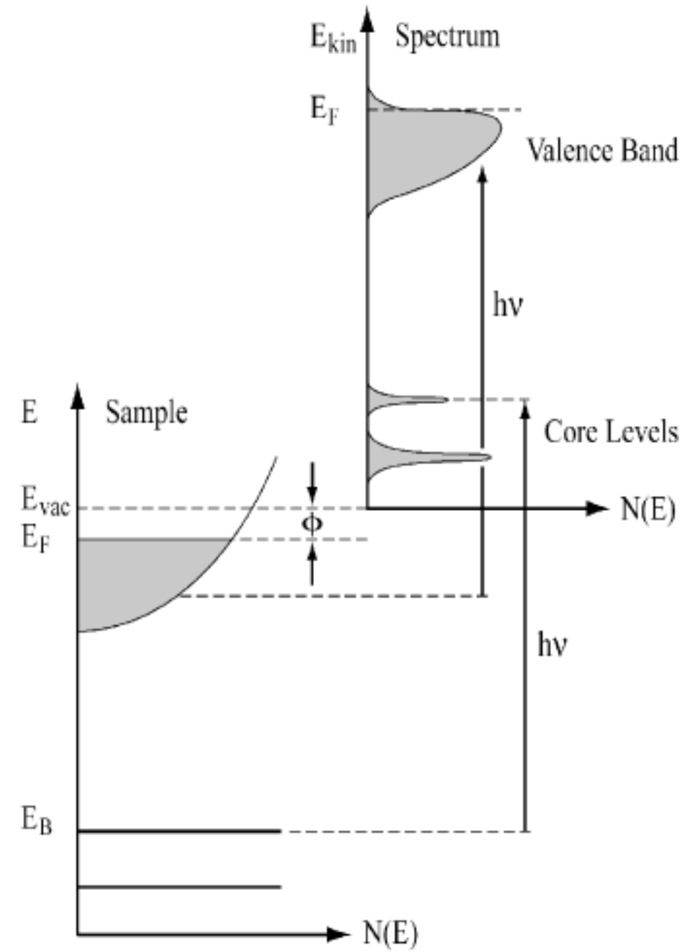


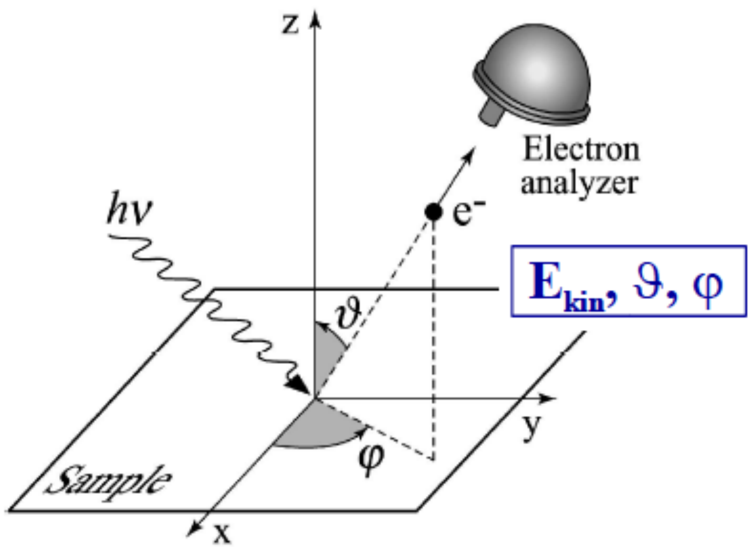
Energy Conservation

$$E_{kin} = h\nu - \phi - |E_B|$$

Momentum Conservation

$$p_{\parallel} = \hbar k_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$





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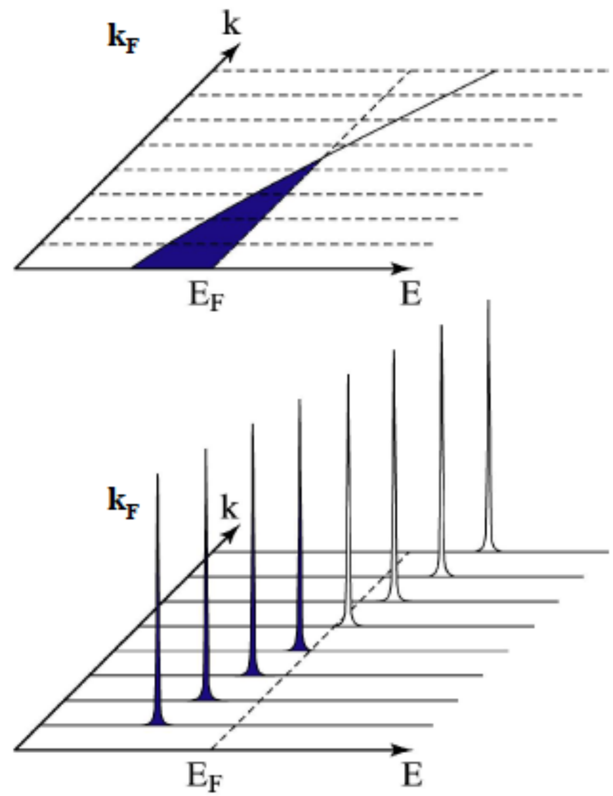
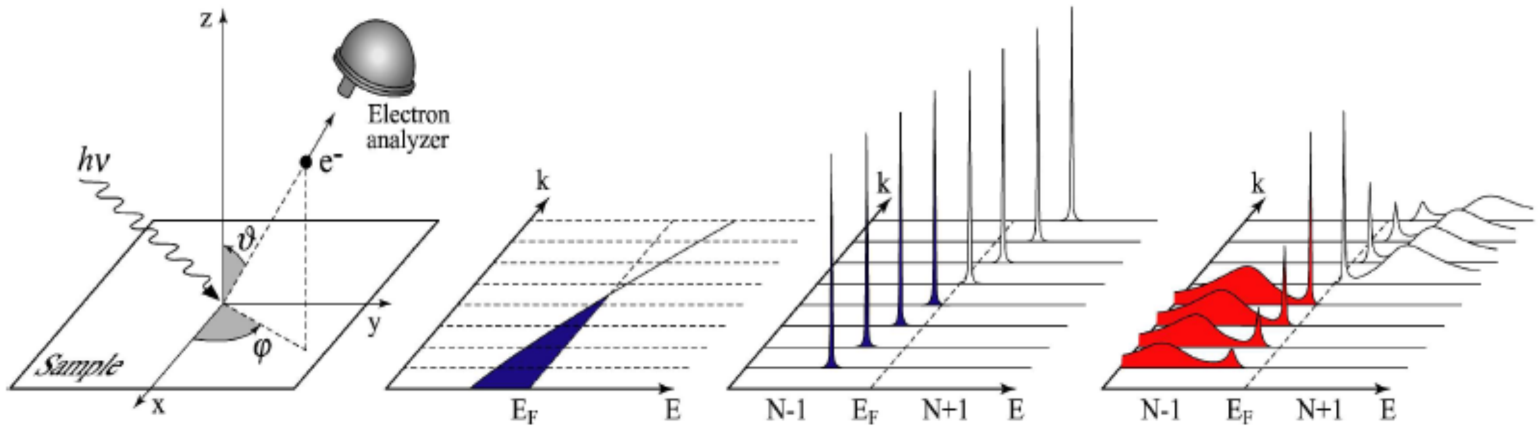
$$E_{kin} = h\nu - \phi - |E_B|$$

Momentum Conservation

$$\mathbf{p}_{\parallel} = \hbar \mathbf{k}_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$

Electrons in Reciprocal Space





Photoemission geometry — Non-interacting electron system — Fermi liquid system

Photoemission intensity: $I(k,\omega)=I_0\,|M(k,\omega)|^2 f(\omega)\, A(k,\omega)$

Single-particle spectral function

$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega-\epsilon_{\mathbf{k}}-\Sigma'(\mathbf{k},\omega)]^2+[\Sigma''(\mathbf{k},\omega)]^2}$$

$\Sigma(k,\omega)$: the "self-energy" - captures the effects of interactions

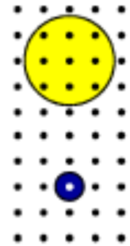
What is ARPES used for?

- ARPES is an almost ideal tool for imaging the Fermi surface of 1-D and 2-D solids.

- Since many of the high temperature superconductors are essentially 2-D materials, much of the work in this field is done using ARPES.

Strongly correlated systems

d - f
open shells materials

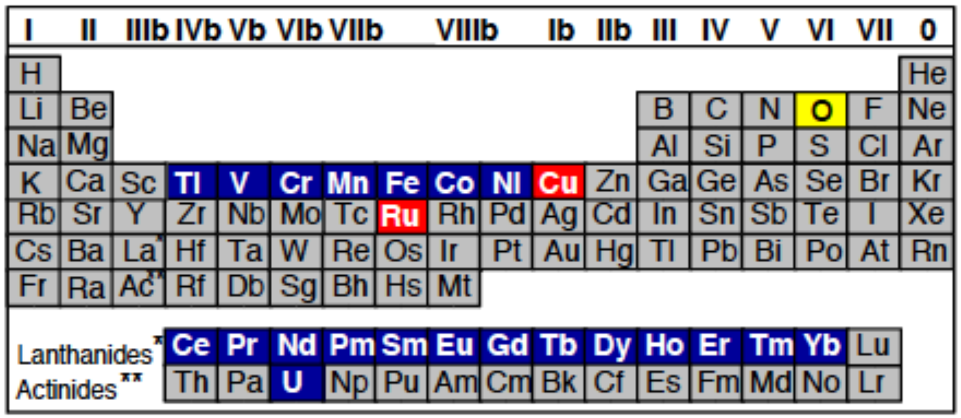


U<<W
Charge fluctuations

U>>W
Spin fluctuations

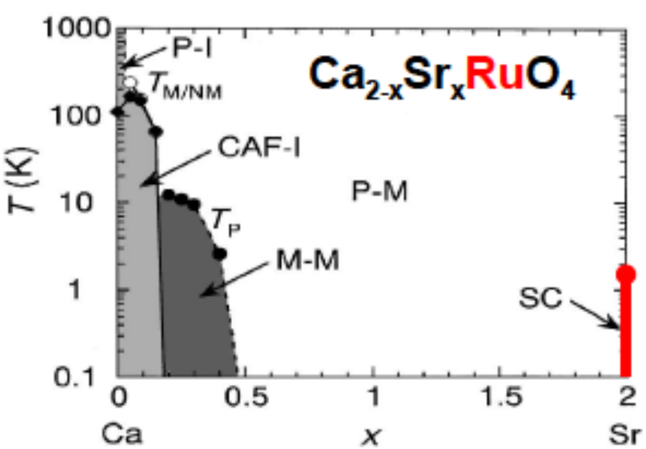
Control parameters

Bandwidth (U/W)
Band filling
Dimensionality

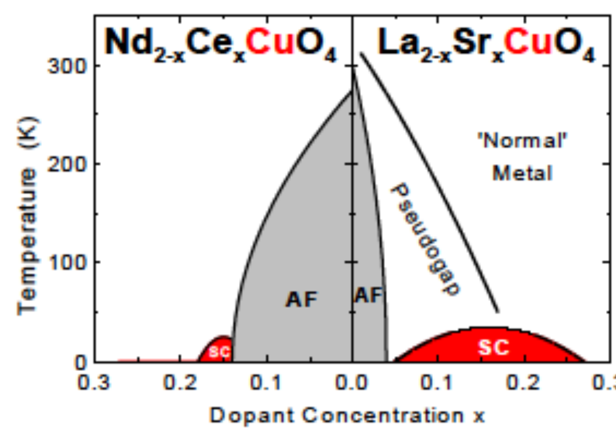


Degrees of freedom

Charge / Spin
Orbital
Lattice



- Kondo
- Mott-Hubbard
- Heavy Fermions
- Unconventional SC
- Spin-charge order
- Colossal MR



Understand the
macroscopic electronic properties
and the role of
competing degrees of freedom

↓

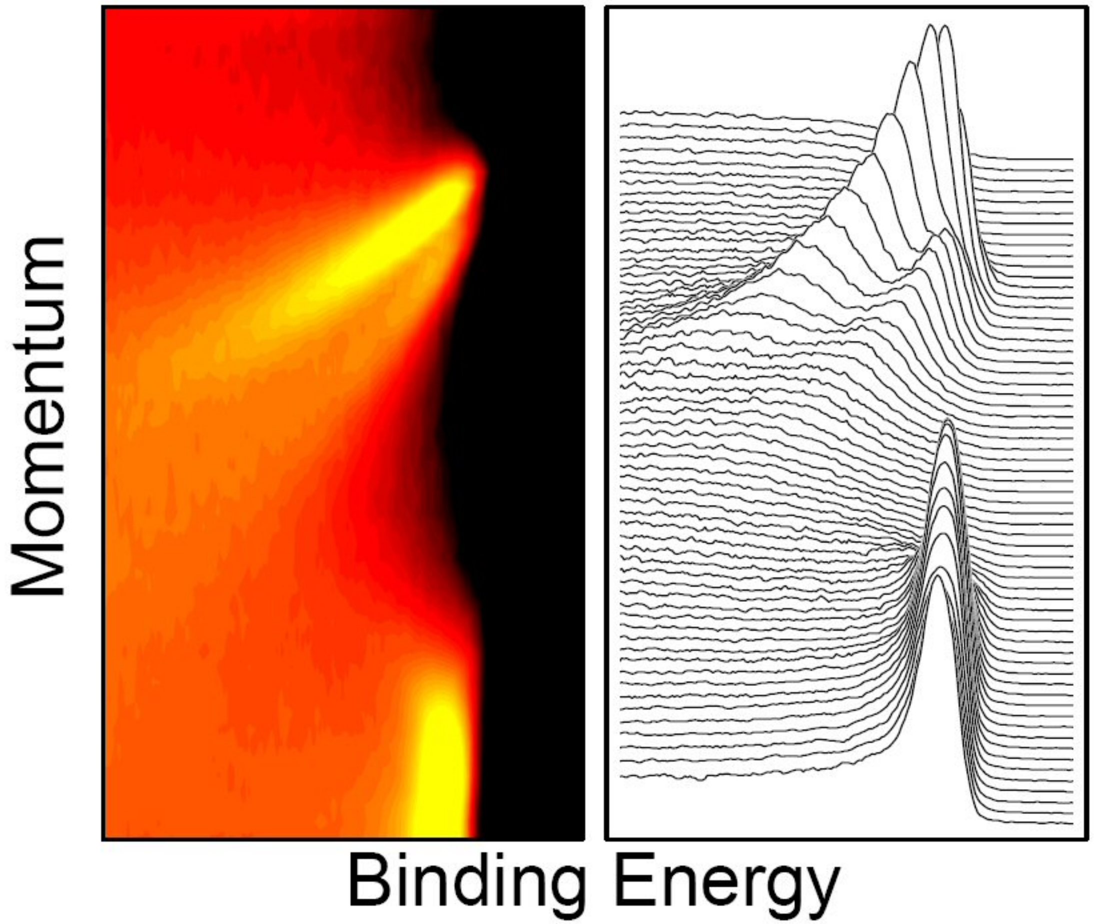
Study the low-energy electronic excitations

↓

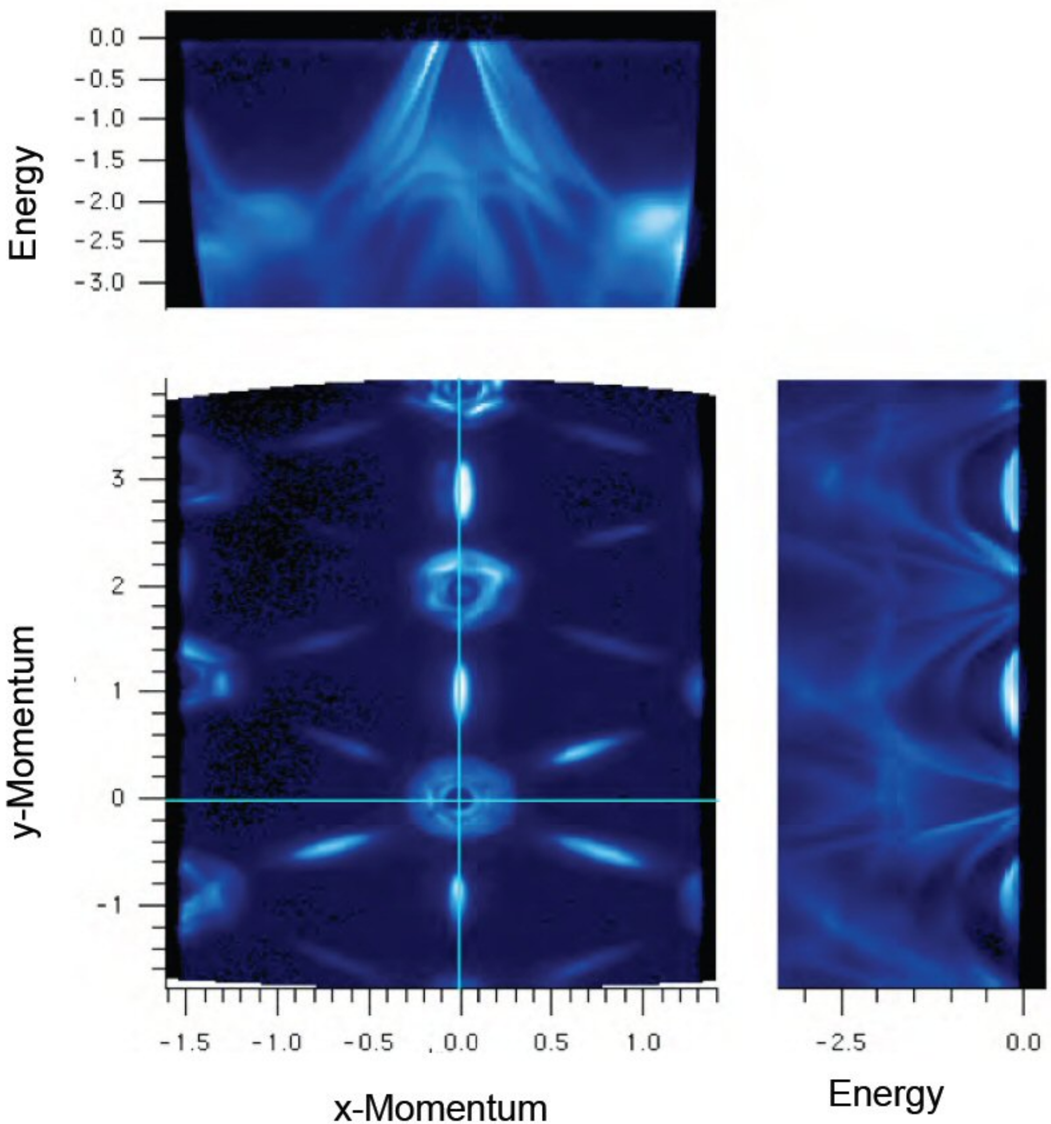
ARPES

Velocity and direction of the electrons in the solid

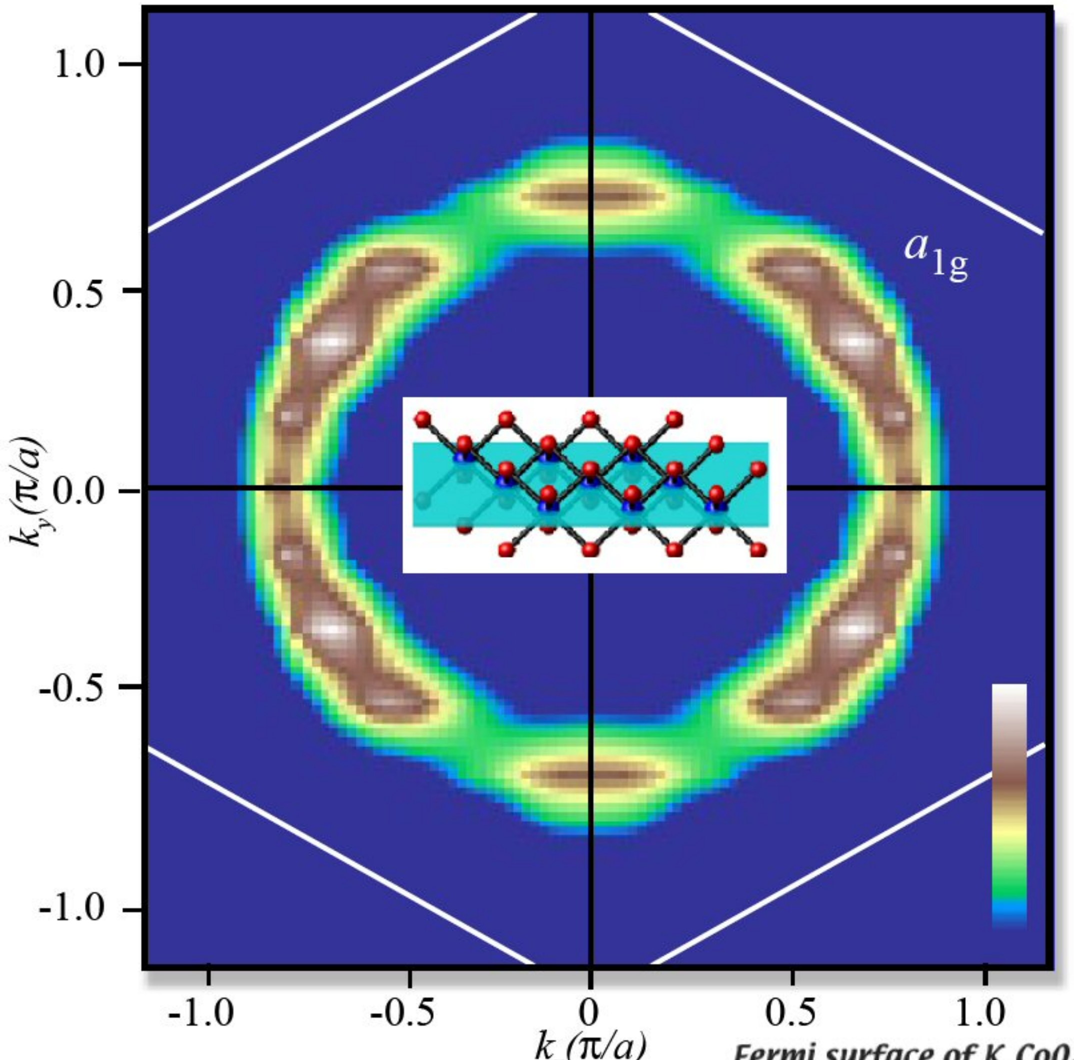
Momentum and Binding Energy



Direct *k* Space Imaging

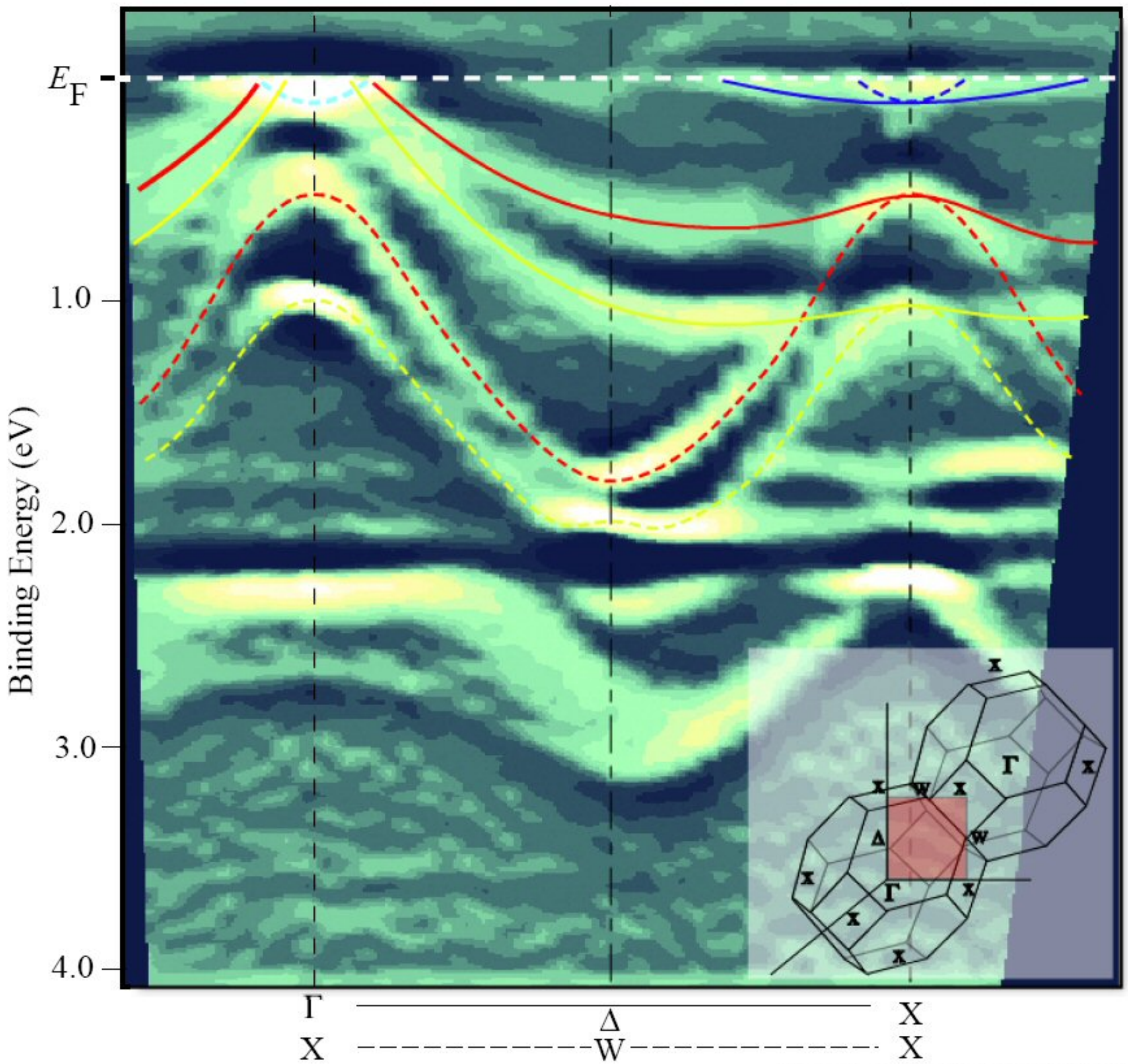


Fermi Surface Images



Fermi surface of K_xCoO_2

Band Structure Images

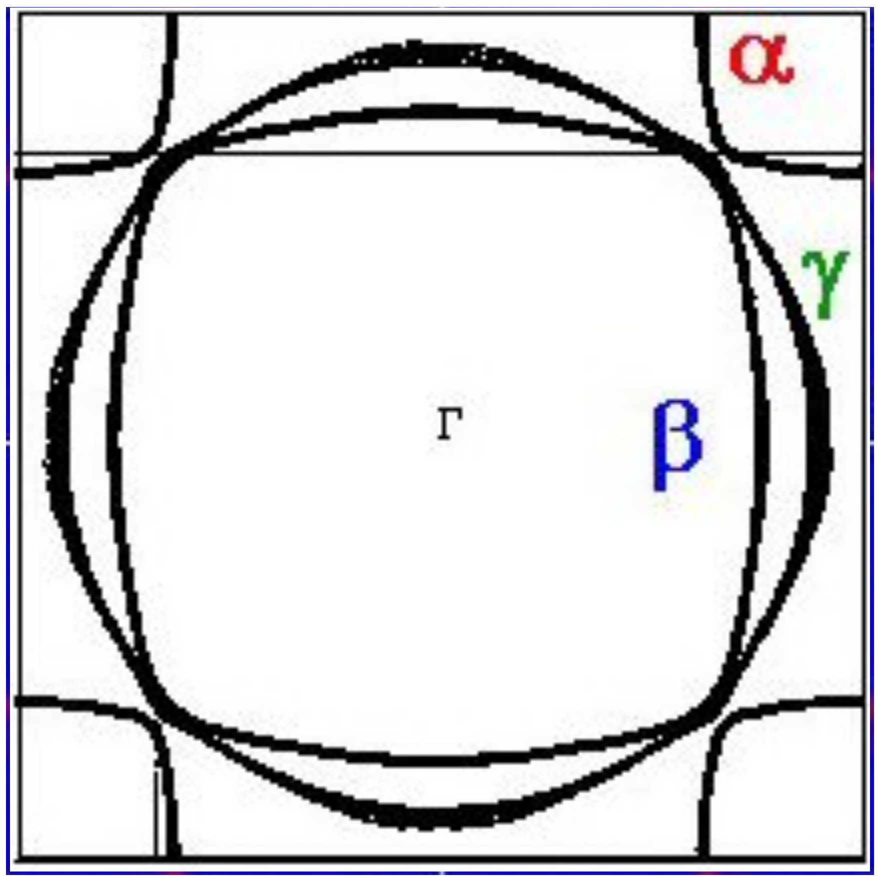


Band structure of CeSb

Validation of Predictions

Sr_2RuO_4 : Theoretical Calculation

ARPES Measurement



Advantages

• **Direct information about electronic states!**

• Straightforward comparison with theory - little or no modelling.

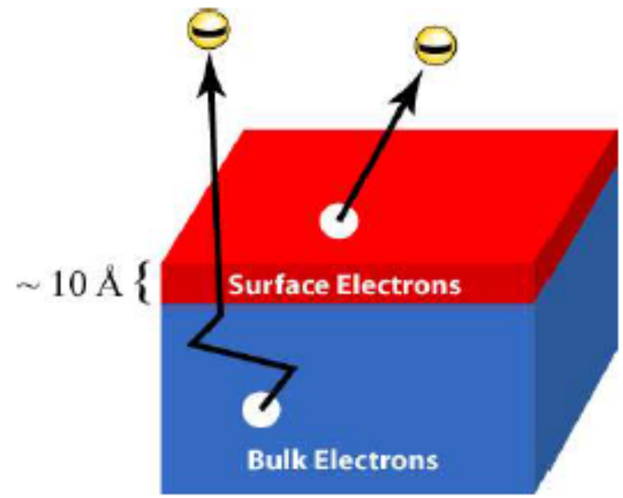
• High-resolution information about **BOTH energy** and **momentum**

• **Surface-sensitive probe**

• Sensitive to “many-body” effects

• Can be applied to small samples (100 μm x 100 μm x 10 nm)

Limitations



• **Not bulk sensitive**

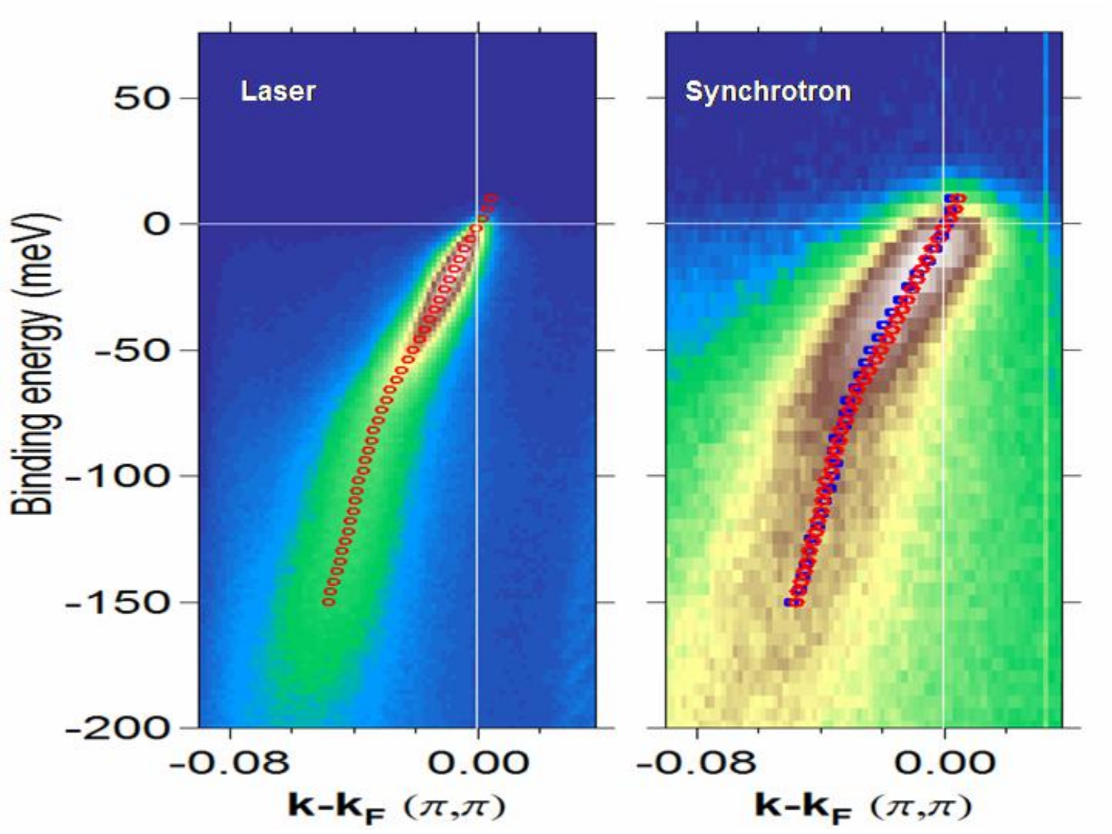
• Requires clean, atomically flat surfaces in **ultra-high vacuum**

• Cannot be studied as a function of pressure or magnetic field

Further Advances

- Laser ARPES: lower energy means sharper pictures

(image of $Bi_2Sr_2CaCu_2O_8$ in "nodal" direction)



Neutron Scattering

Neutrons have No Charge!

- **Highly penetrating**
- **Nondestructive**
- **Can be used in extremes**

Neutrons have a Magnetic Moment!

- **Magnetic structure**
- **Fluctuations**
- **Magnetic materials**

Neutrons have Spin!

- **Polarized beams**
- **Atomic orientation**
- **Coherent and incoherent scattering**

The Energies of neutrons are similar to the energies of elementary excitations!

- **Molecular Vibrations and Lattice modes**
- **Magnetic excitations**

The Wavelengths of neutrons are similar to atomic spacing!

- **Sensitive to structure**
- **Gathers information from 10^{-10} to 10^{-7} m**
- **Crystal structures and atomic spacings**

Neutrons probe Nuclei!

- **Light atom sensitive**
- **Sensitive to isotopic substitution**

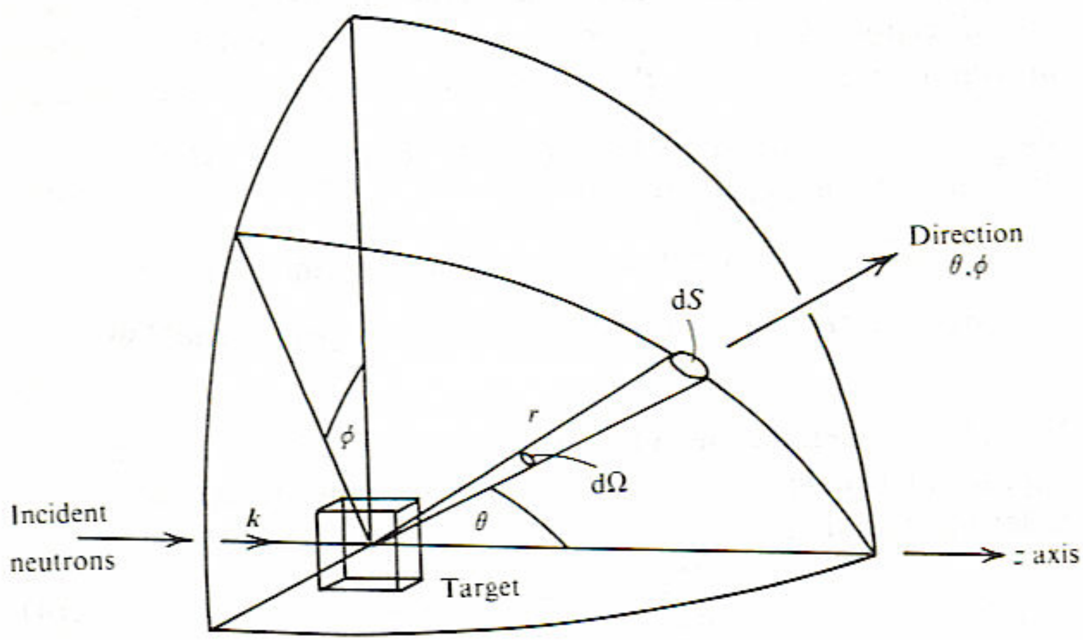
de Broglie Wavelength

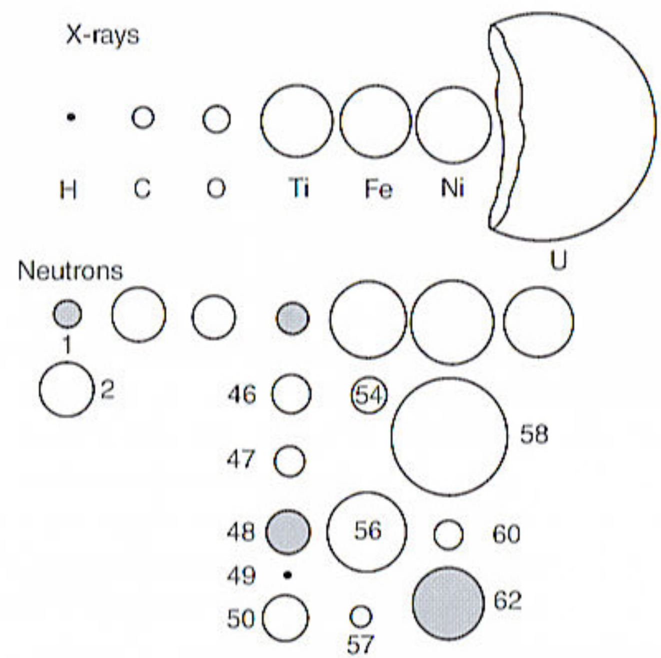
$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}$$

$$E = 81.6 \ meV$$
$$v = 3950 \ m/s$$
$$\lambda = 1 \times 10^{-10} \ m$$

$$E = 1 \ meV$$
$$v = 437 \ m/s$$
$$\lambda = 9 \times 10^{-10} \ m$$

Neutrons vs. X-rays

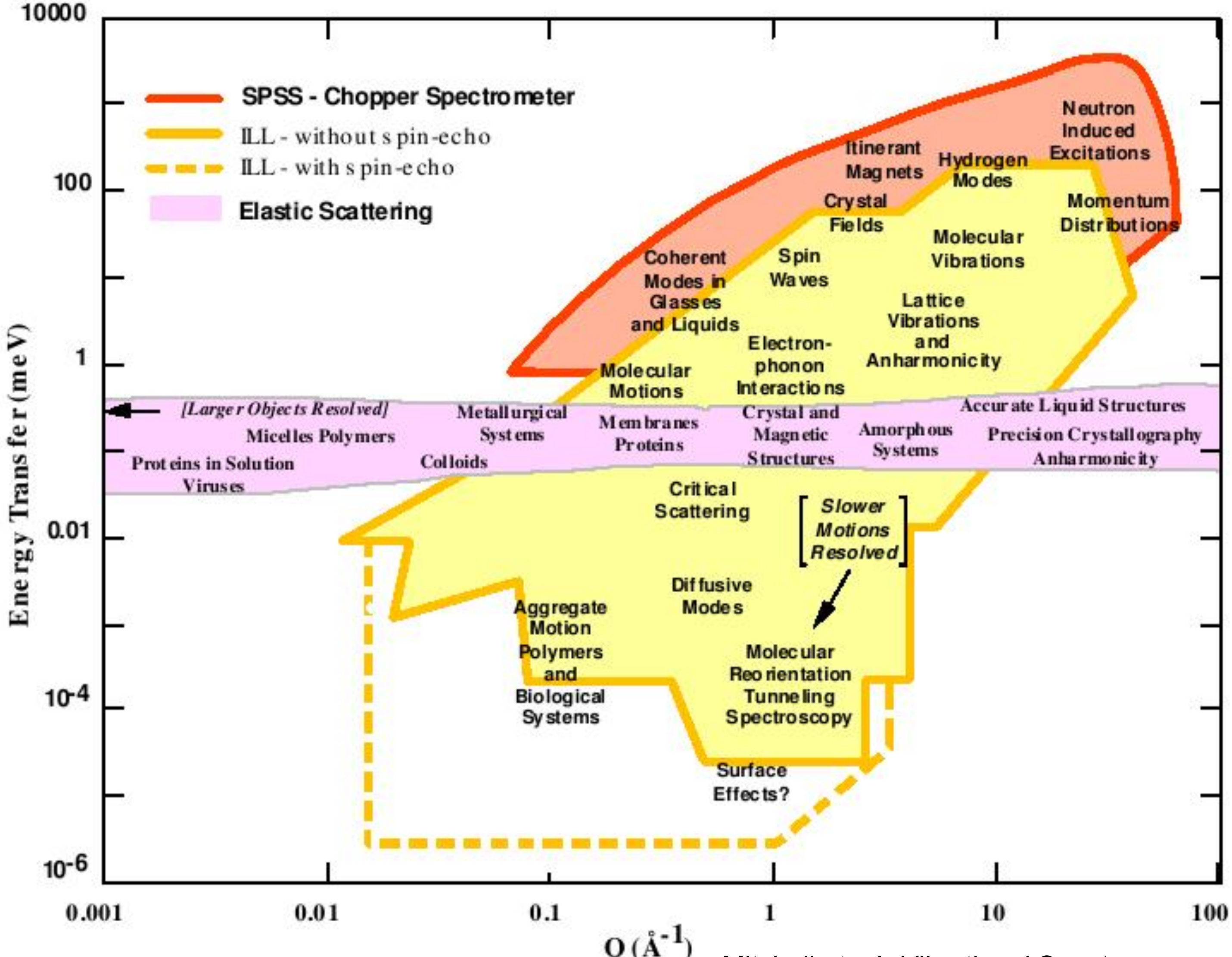




Chatterji, *Neutron Scattering from Magnetic Materials* (2006)

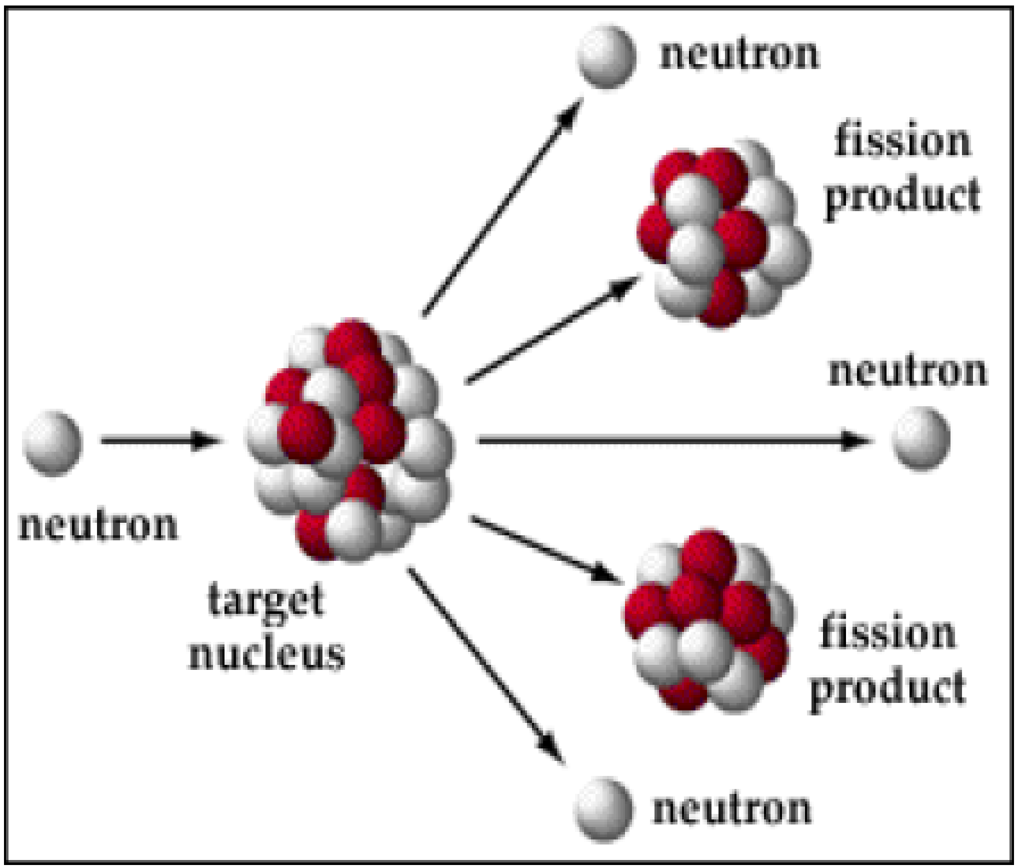
Neutrons allow easy access to atoms that are usually unseen in X-ray Scattering

How are neutrons useful?



Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

Neutrons from Reactor Sources

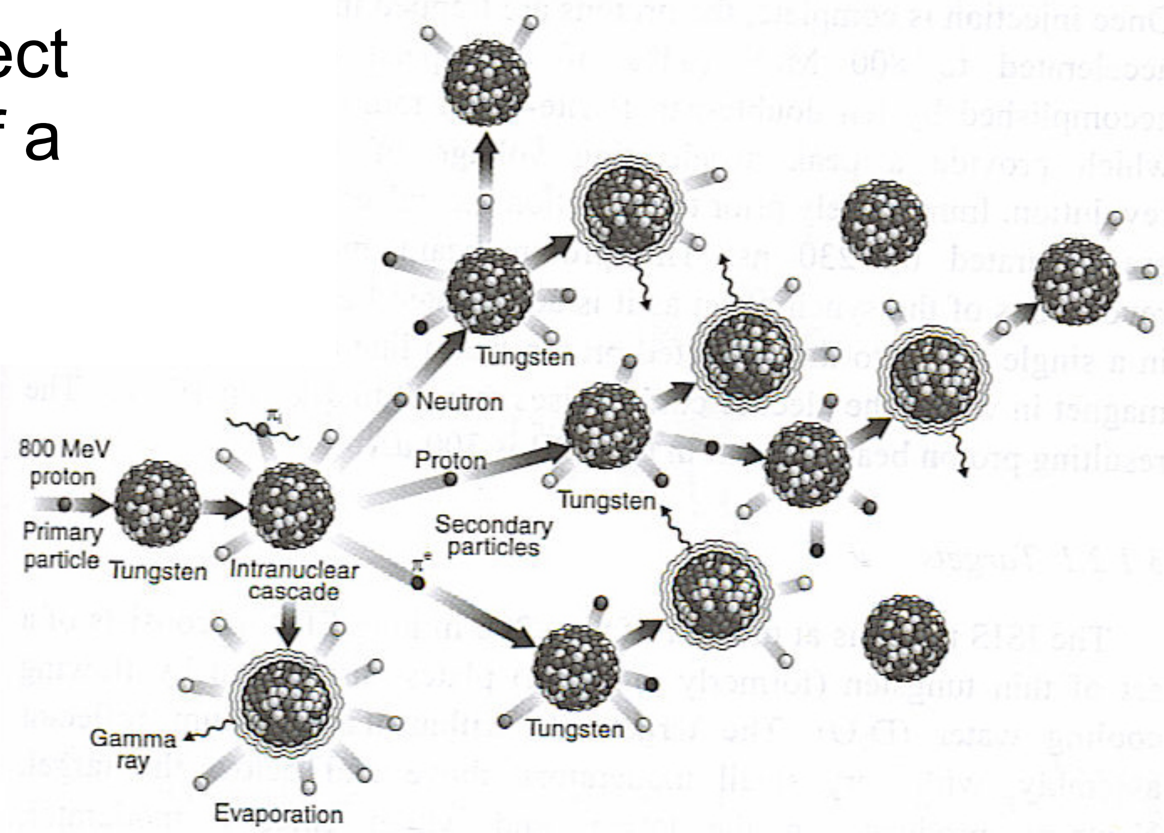


- Uses nuclear fission to create neutrons
- Continuous neutron flux
- Flux is dependent on fission rate
- Limited by heat flow in from the reaction
- Creates radioactive nuclear waste

Pynn, *Neutron Scattering: A Primer* (1989)

Neutrons from Spallation Sources

- Uses a cascade effect from the collision of a proton on a heavy metal.
- Pulsed Source
- High Intensity
- Heat production is relatively low



Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

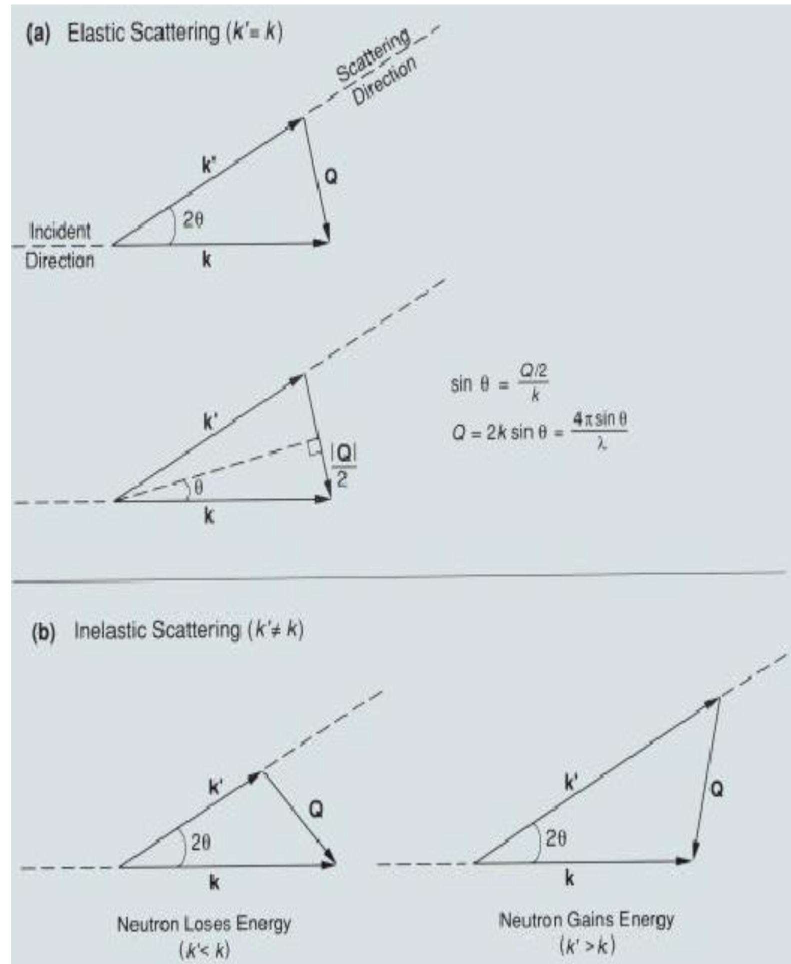
Neutron scattering

Elastic Neutron Scattering

- No loss of energy
- Examines the change in momentum or angle of the neutrons.

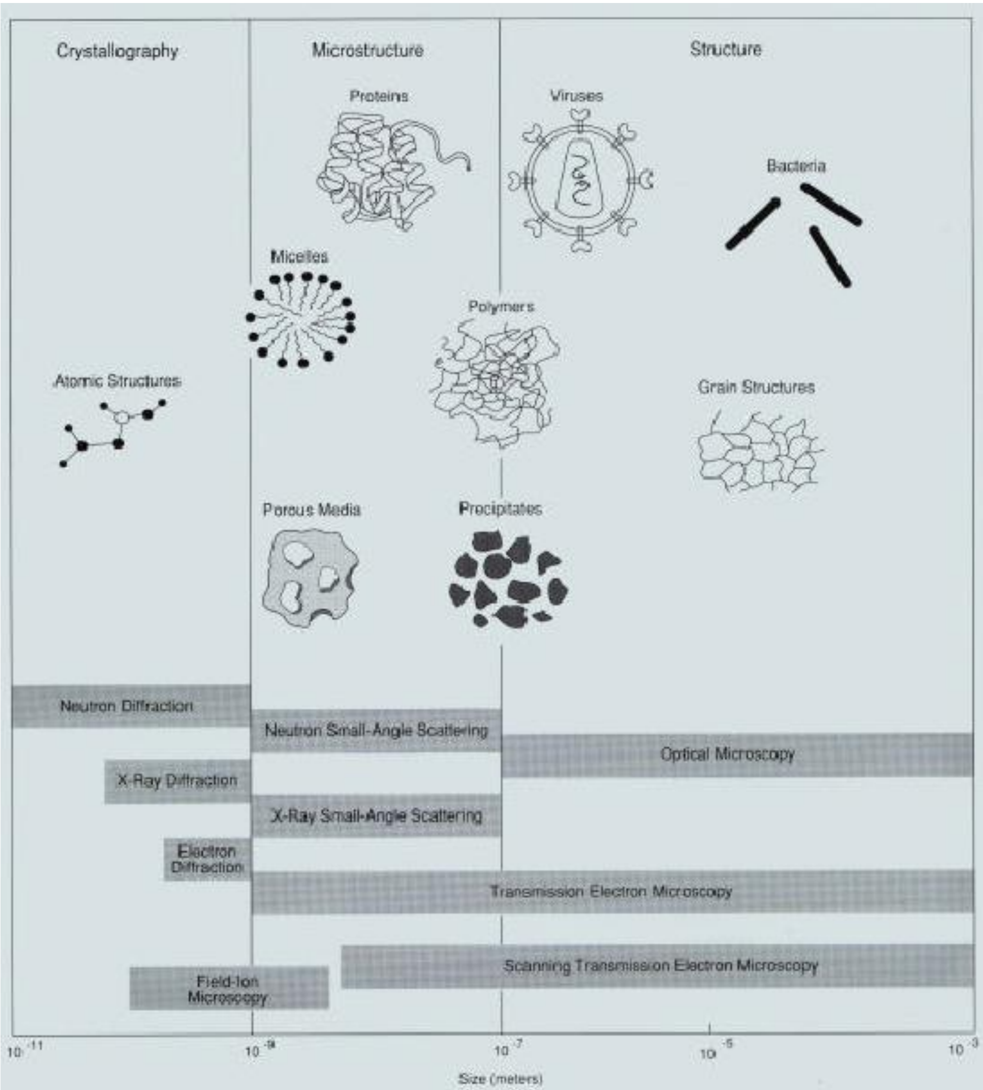
Inelastic Neutron Scattering

- Examines both momentum and energy dependencies.

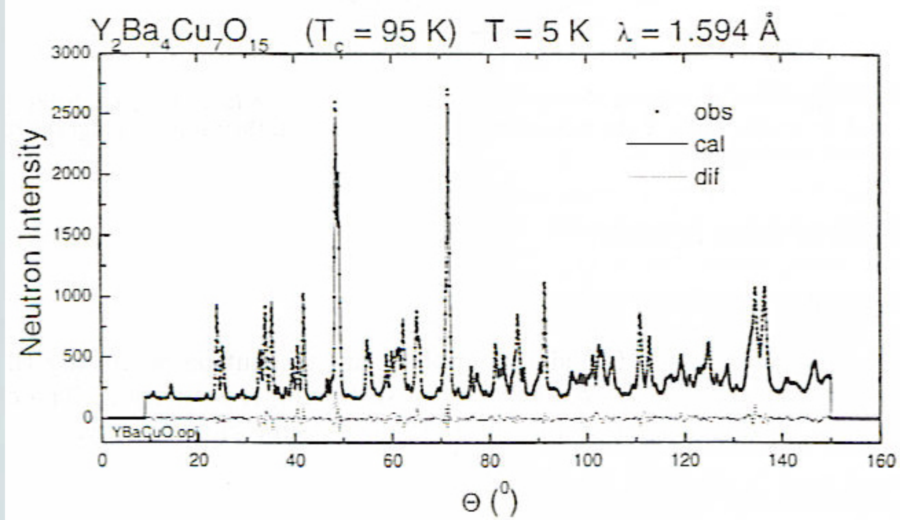


Pynn, *Neutron Scattering: A Primer* (1989)

Elastic Neutron Scattering



Pynn, *Neutron Scattering: A Primer* (1989)

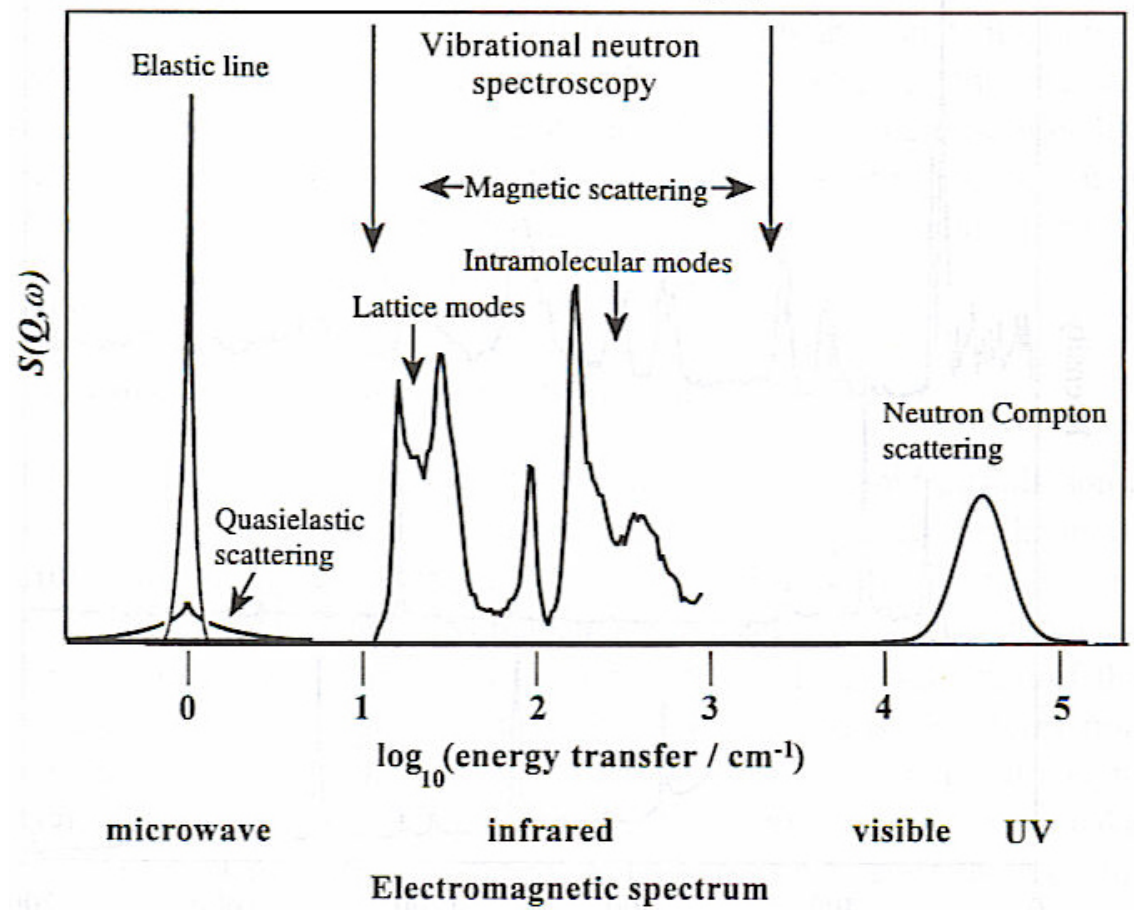


Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

- Determine length scales and differentiate between nano-, micro-, and macro-systems.
- Utilizes position and momentum correlation.

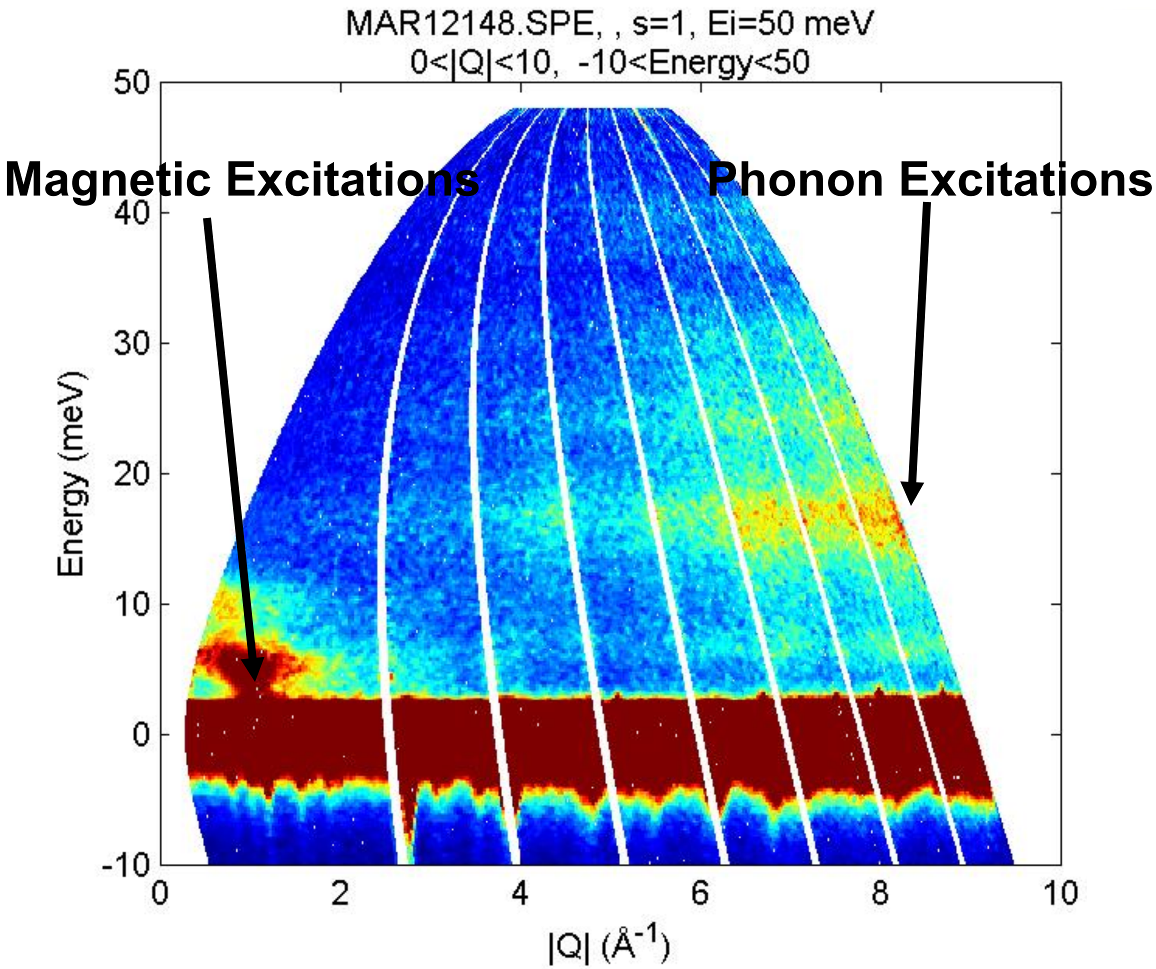
Inelastic Neutron Scattering

Uses both change in momentum and energy to characterize a systems vibrational, magnetic, and lattice excitations.



Mitchell et. al, *Vibrational Spectroscopy with Neutrons* (2005)

Vibrational and Magnetic Excitations



M. B. Stone et al. Unpublished (2007)

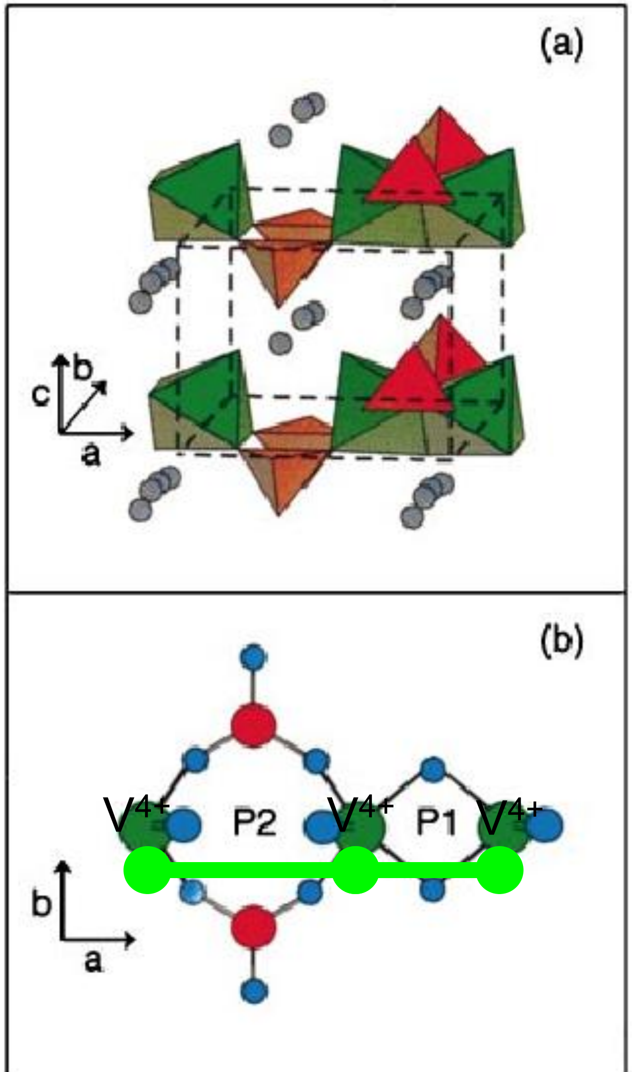
•Vibrational excitations are broad, large excitations.

Neutrons observe all phonon and vibrational excitations. The intensity is determined by the phonons polarization vectors.

•Magnetic excitations are detailed by spin transitions of ΔS = 0 and ± 1.

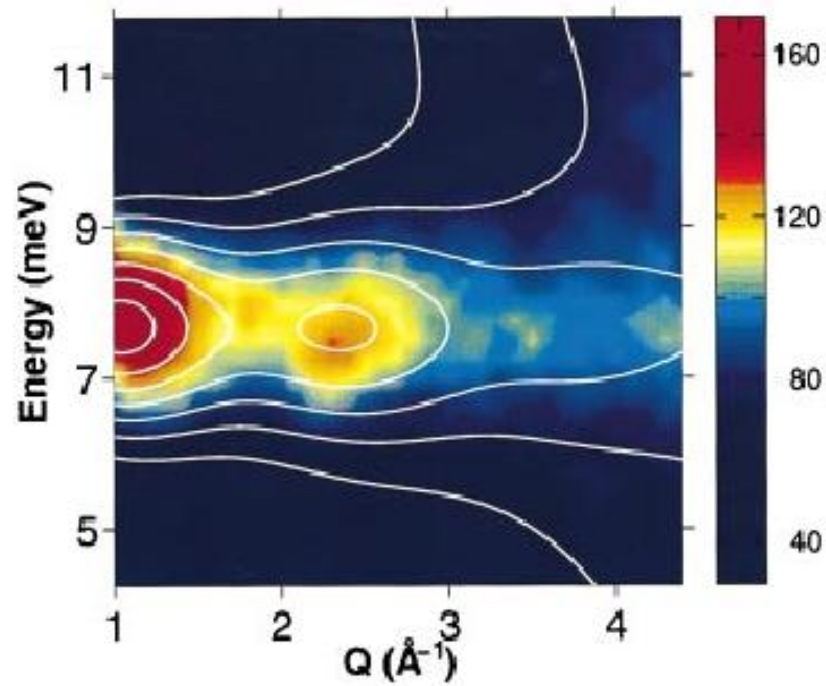
Q-dependence of magnetic excitations help determine the magnetic structure within the material.

Inelastic Neutron Scattering from magnetic sample



Tennant et. al, PRL (1997)

The use of neutron scattering on the material of $VODPO_4 \bullet ½ D_2O$ clarified the magnetic structure of the material.



Summary

- Neutrons are produced in two main ways
  - Research Reactors
  - Spallation Sources
- Utilizes the properties of the neutron.
- Neutrons are useful in determining not only structural properties of a material, but also the vibrational, magnetic, and lattice excitations.