X-ray Diffracrtometer

Pecharsky Chapter 6

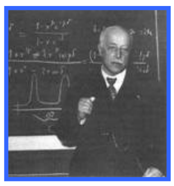
Cullity Chapter 1

Krawitz Chapter 3

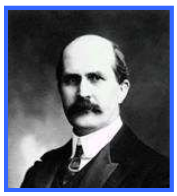
Jenkins & Snyder – Chapter 1, 4, 5, 6

X-ray

- W.C. Röntgen
  - ✓ 1895: Discovery of X-ray
  - ✓ 1901: First Nobel prize for Physics
- M.T.F. von Laue
  - ✓ 1912: X-ray diffraction, in cooperation with Friedrich and Knipping
  - ✓ Laue equation, Laue reflections
  - ✓ 1914: Nobel prize for Physics

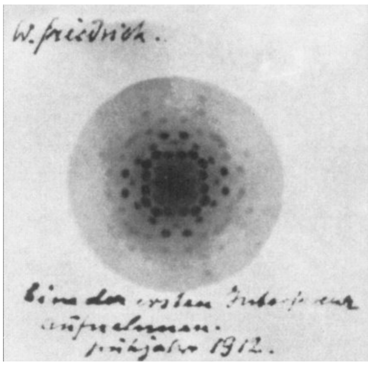


- C.G. Darwin
  - ✓ 1912: Dynamical scattering theory
  - ✓ Darwin width
- W.H. and W.L. Bragg
  - ✓ 1914: X-ray diffraction from powder samples
  - ✓ Bragg's equation, Bragg reflections
  - ✓ 1915: Nobel prize for Physics



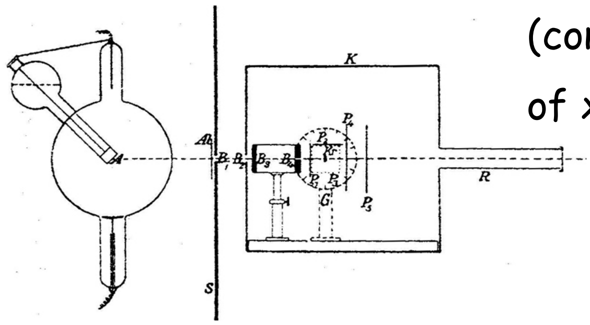
- P.P. Ewald
  - ✓ 1916: Theoretical description of X-ray diffraction
  - ✓ Ewald construction, reciprocal space

X-ray



X-ray diffraction pattern of a single crystal of Zinc Blende (ZnS)

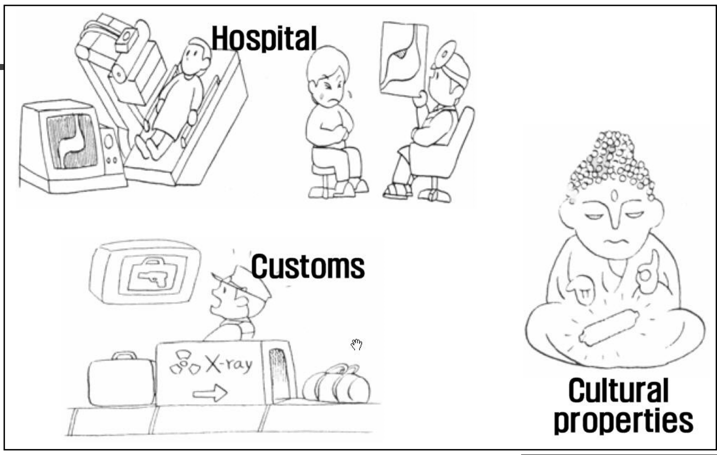
Friedrich, Knipping and von Laue, 1912, University of Munich



(confirmation of the wave character of x-rays)

Nobel Prizes for Research with X-Rays

1901 W. C. Röntgen in Physics for the discovery of x-rays.
1914 M. von Laue in Physics for x-ray diffraction from crystals.
1915 W. H. Bragg and W. L. Bragg in Physics for crystal structure determination.
1917 C. G. Barkla in Physics for characteristic radiation of elements.
1924 K. M. G. Siegbahn in Physics for x-ray spectroscopy.
1927 A. H. Compton in Physics for scattering of x-rays by electrons.
1936 P. Debye in Chemistry for diffraction of x-rays and electrons in gases.
1962 M. Perutz and J. Kendrew in Chemistry for the structure of hemoglobin.
1962 J. Watson, M. Wilkins, and F. Crick in Medicine for the structure of DNA.
1979 A. McLeod Cormack and G. Newbold Hounsfield in Medicine for computed axial tomography.
1981 K. M. Siegbahn in Physics for high resolution electron spectroscopy.
1985 H. Hauptman and J. Karle in Chemistry for direct methods to determine x-ray structures.
1988 J. Deisenhofer, R. Huber, and H. Michel in Chemistry for the structures of proteins that are crucial to photosynthesis.

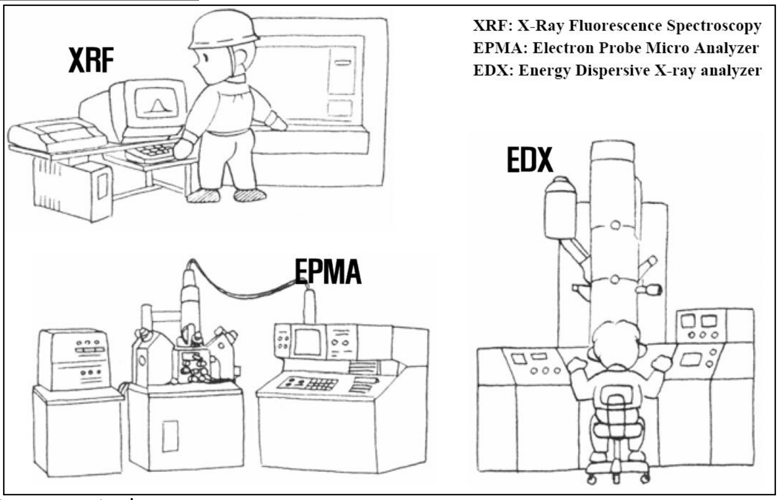


X-ray Transmission

XRF;
X-ray fluorescence spectroscopy

EPMA;
electron probe micro analyzer

EDX;
energy dispersive X-ray analyzer



X-ray Fluorescence

Characteristics of X-rays

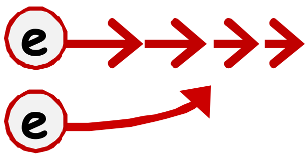
- Electromagnetic wave; wavelength 0.3Å ~3 Å
  - ✓ Strong penetration through matters
  - ✓ Invisible in air
  - ✓ No interaction with electric and magnetic field
- Photographic → detection
- Fluorescent (e.g. on ZnS, CdS, NaI, etc.) → detection
- Ionizing → detection
- Diffraction ← wavelength ~ atomic distance
- Transmission → medical, nondestructive evaluation (NDE)

Wavelength
≈
Object Size
≈
Angstroms for Condensed Matter Research

$$\lambda[\text{Å}] = \frac{12.398}{E_{ph}[\text{keV}]}$$

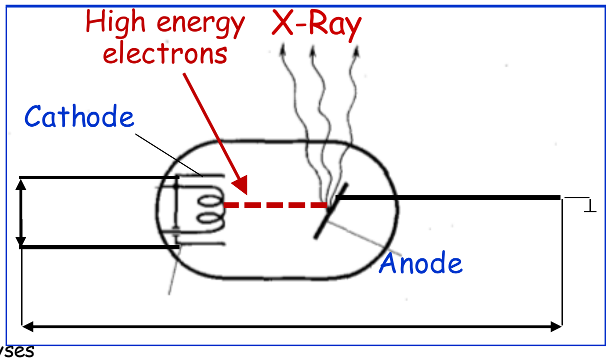
Generation of X-rays

- X-rays are produced when any electrically charged particle of sufficient kinetic energy rapidly decelerates
  - ✓ change of speed of matter
  - ✓ change of direction of movement



- Bombardment of a target by electrons
- Anode (Cu, Mo, W, Ag ..), Cathode (W, LaB6)
- $10^{-3} \sim 10^{-4}$ Torr chamber, high voltage (10 ~ 50kV)

Sealed X-ray tube



Generation of X-rays

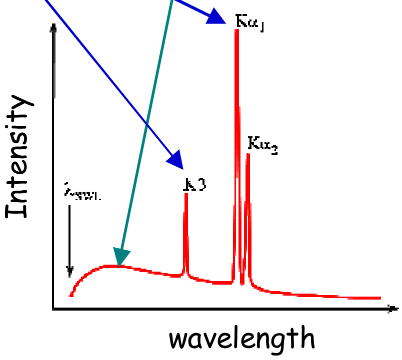
Loss of energy of the electrons caused by

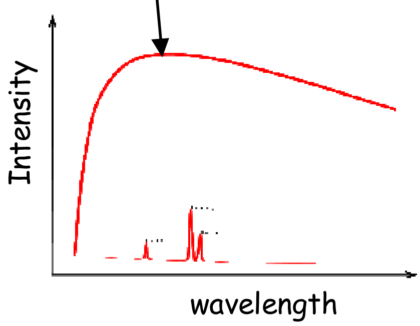
- atomic transitions → Characteristic radiation → emission of spectrum lines
- deceleration → Continuous radiation / White radiation / Bremsstrahlung
- direction change → Synchrotron radiation

Sealed X-ray tube

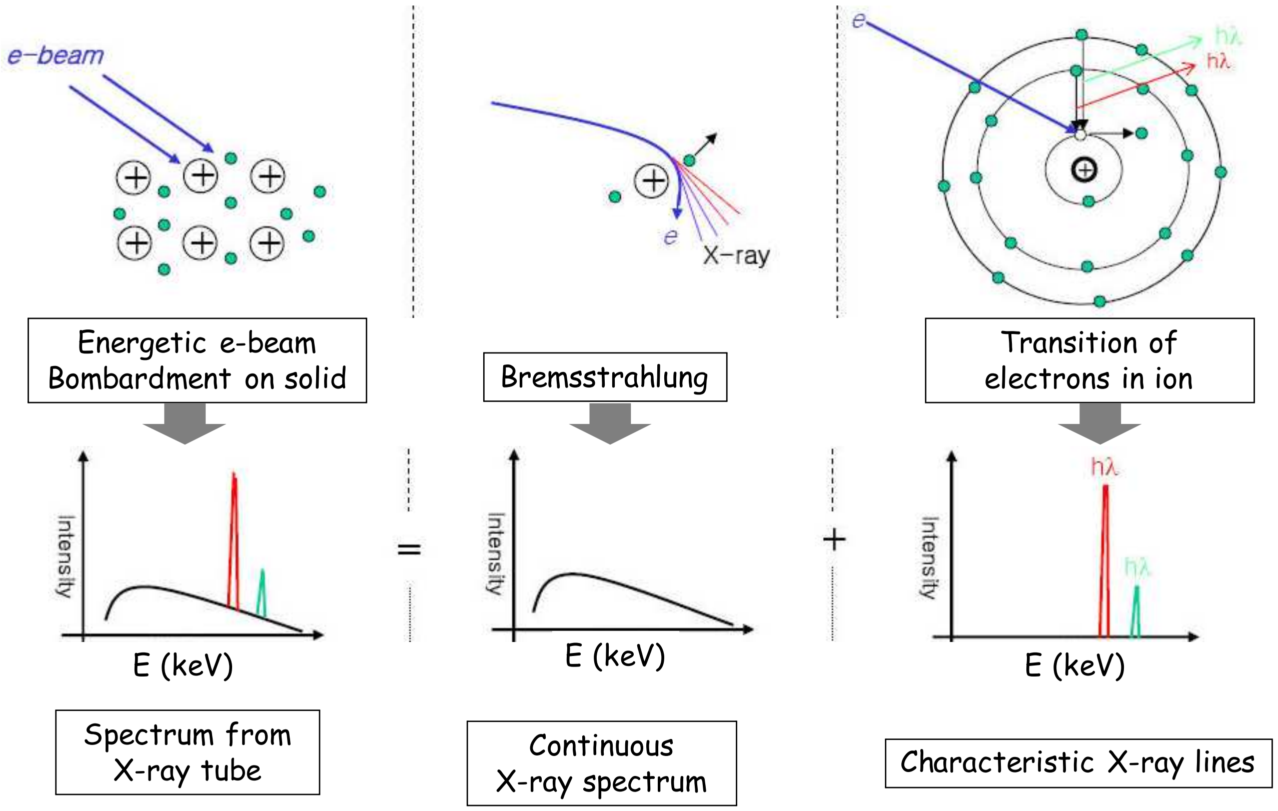
Rotating anode tube

Synchrotron

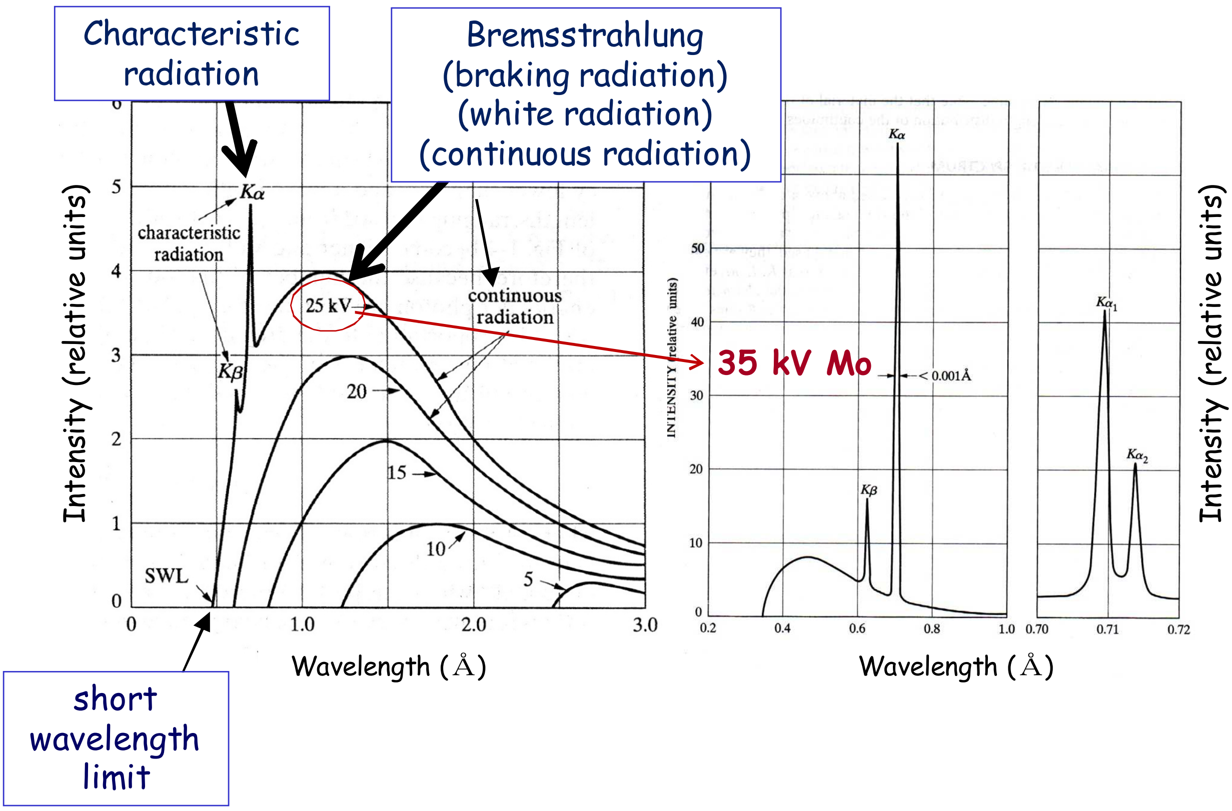




Generation of X-rays



X-ray spectrum of molybdenum



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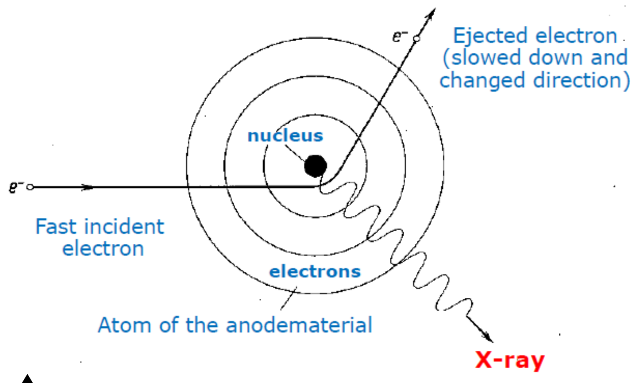
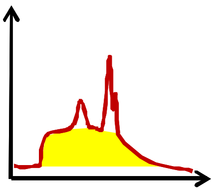
X-ray Generation

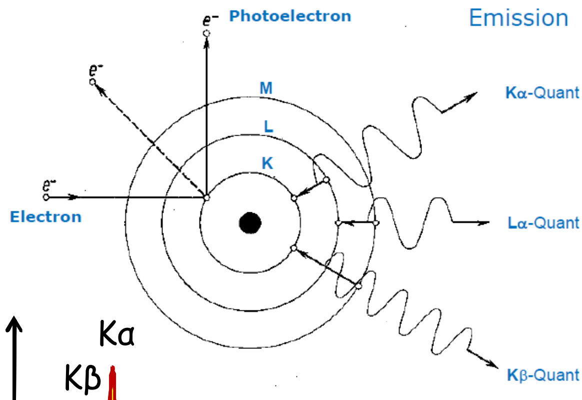
"Bremsstrahlung" Radiation

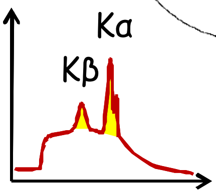




1/E

Characteristic Radiation





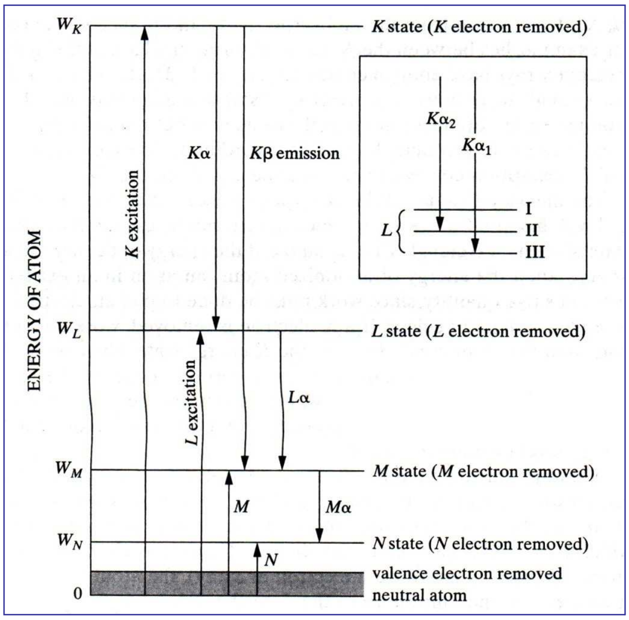
1/E

Cross Sections of Excitation

$K_{\alpha1}$;$K_{\alpha2}$;K_{β} = 10:5:2

BRUKER

Atomic energy level



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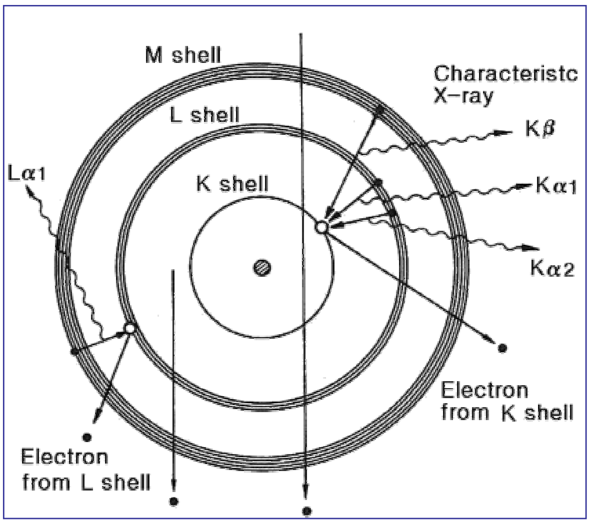


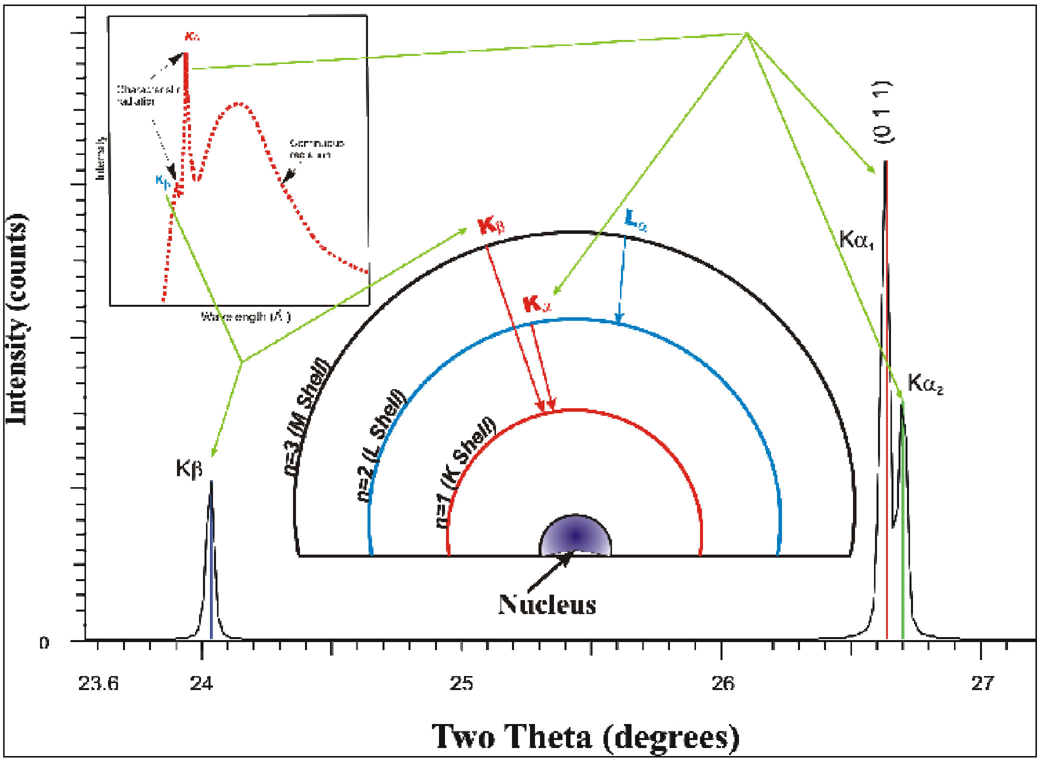
$K_{\alpha}=(2K_{\alpha1}+K_{\alpha2})/3$

β-filter, monochromator

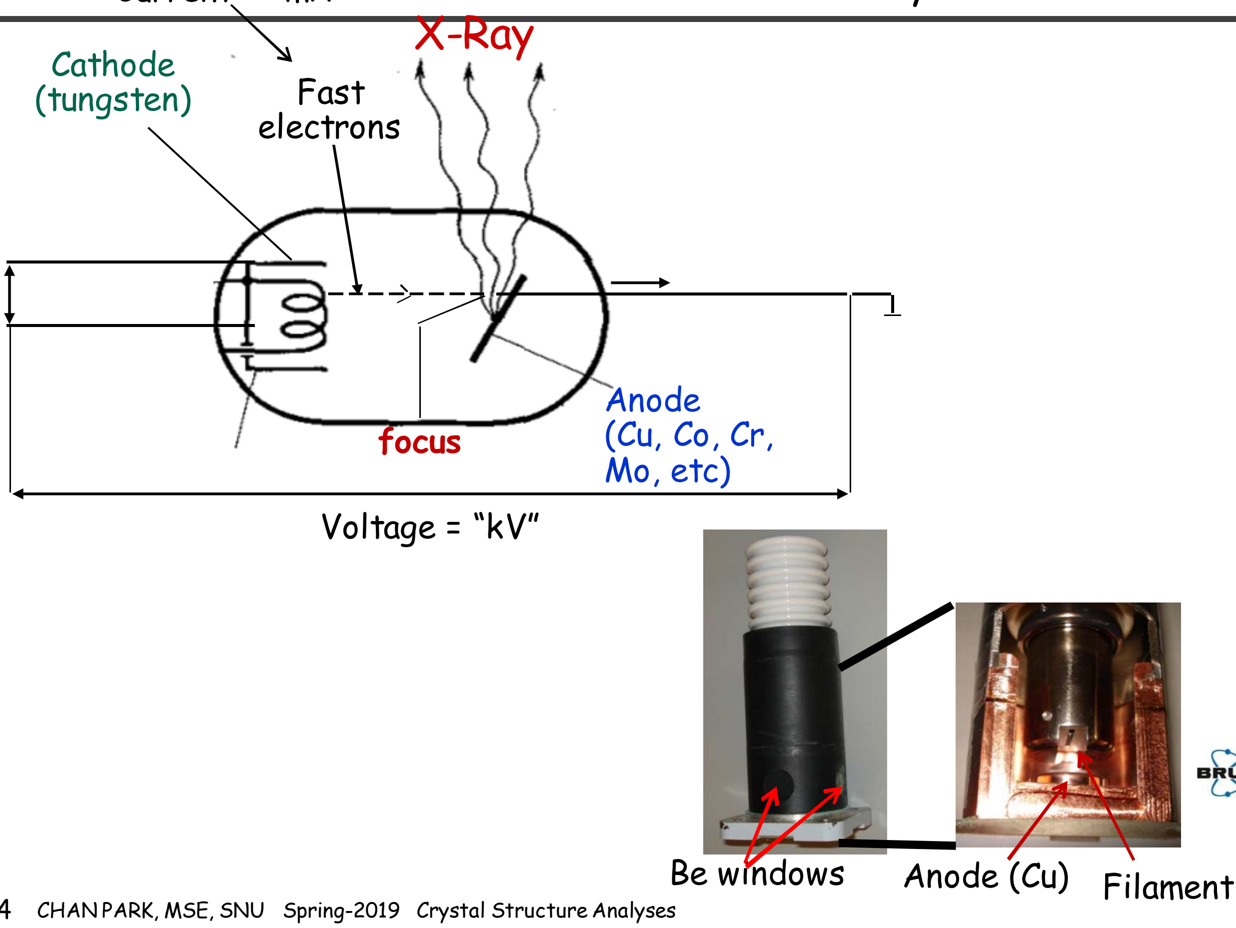
Intensity ratios

$K_{\alpha1} : K_{\alpha2} : K_{\beta} = 10 : 5 : 2$

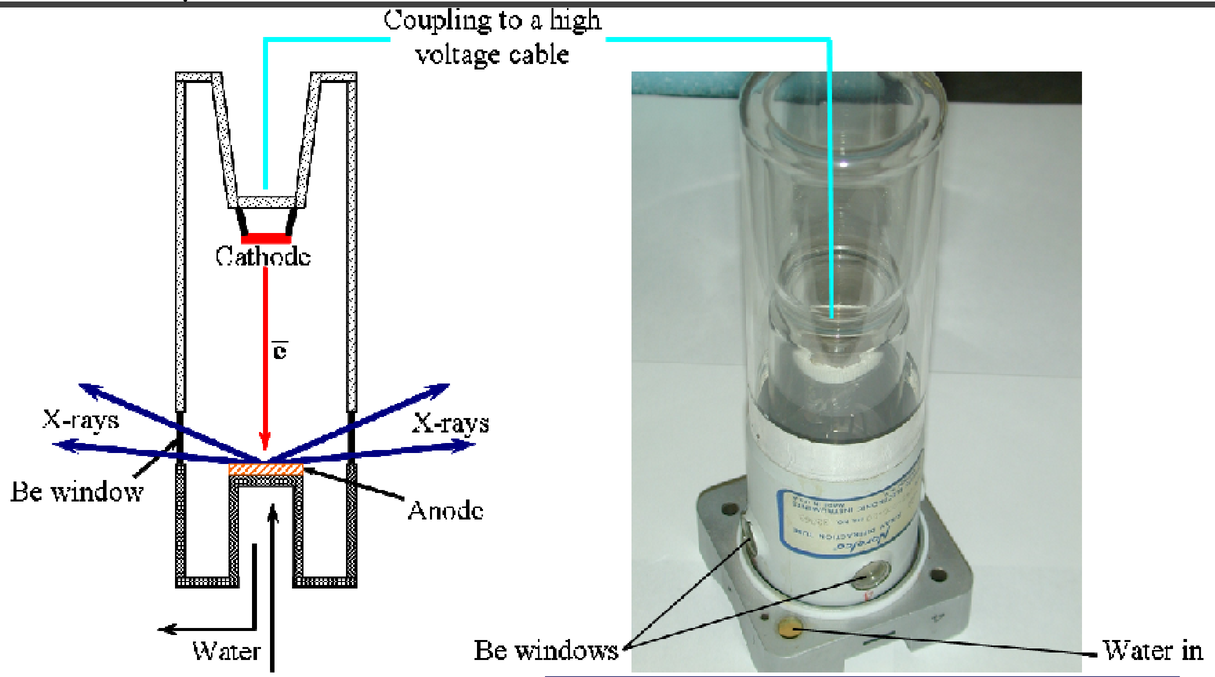
Characteristic Radiation



Sealed X-ray tube



Sealed X-ray tube

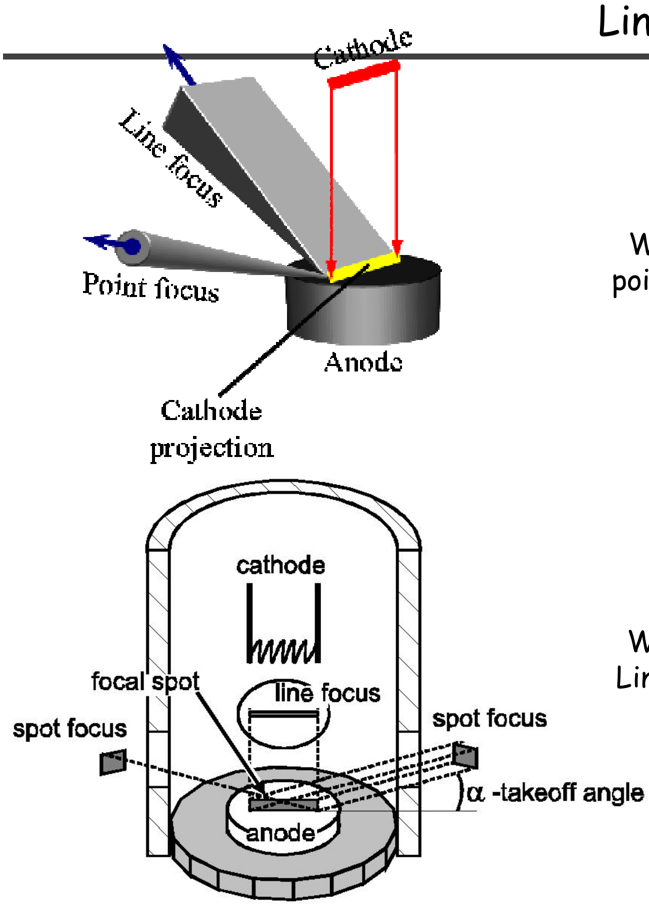


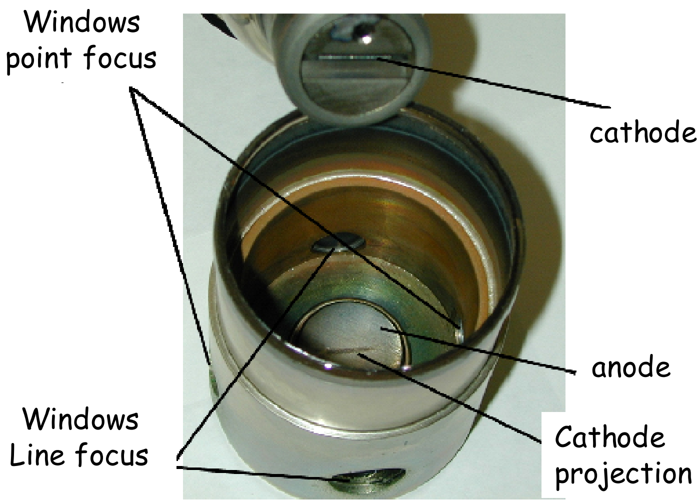
Overall efficiency very low ← heat

Most of the kinetic energy striking the target is converted into heat →
< 1% is transformed into X-ray

Pecharsky

Line focus, Point focus



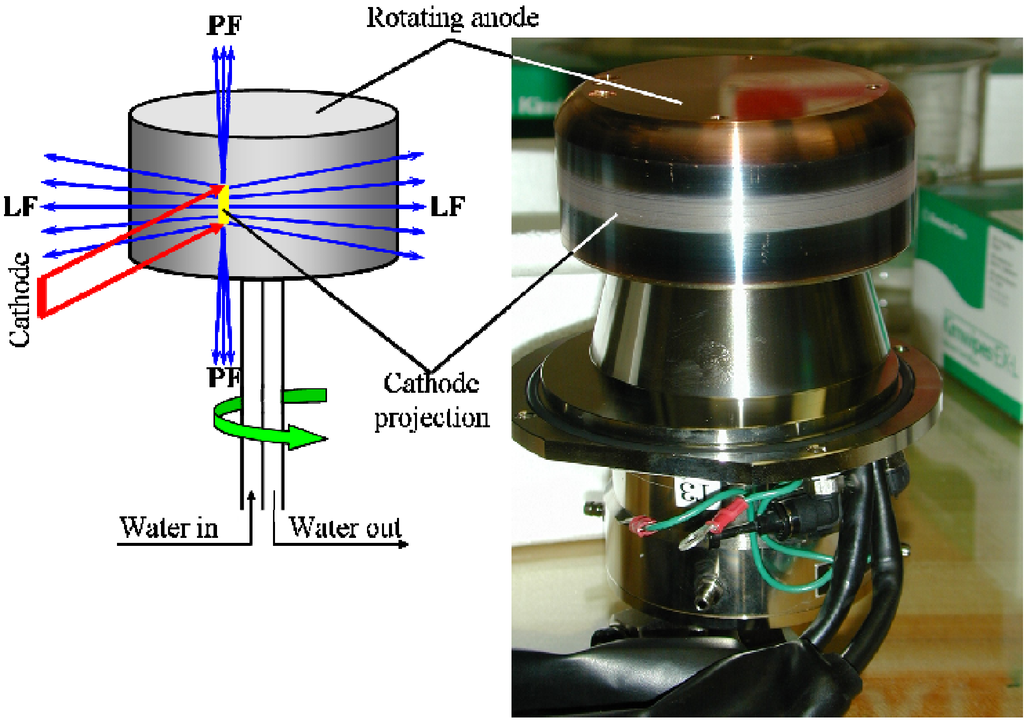


Pecharsky

X-ray from sealed tube

Anode	$K\alpha_1$ (Å)	
Cu	1.54060	- Best for inorganics - Fe and Co fluorescence
Cr	2.28970	- High Resolution for large d-spacing - High attenuation in air
Fe	1.93604	- Used for ferrous alloys to reduce Fe fluorescence - Causes Cr fluorescence
Co	1.78897	- Used for ferrous alloys to reduce Fe fluorescence
Mo	0.70930	- Short wavelength used for small unit cells

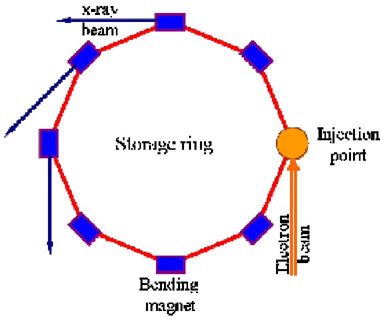
Rotating anode X-ray source

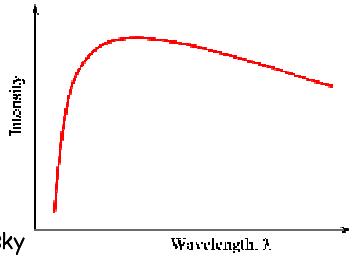


Pecharsky

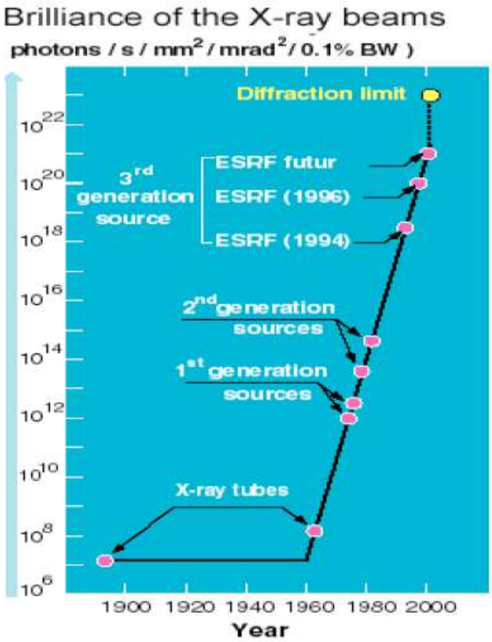
Synchrotron X-ray

- Most powerful X-ray radiation source
- High brilliance X-ray beam
- Distribution of beam intensity as a function of wavelength

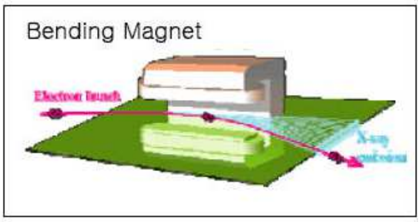


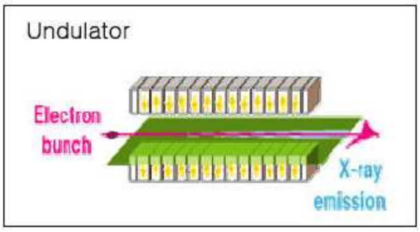


Pecharsky



Synchrotron X-ray





Synchrotron Radiation.
- Very High Dense Source.
- Good Coherent Property.
- Continuous Spectrum.
- Huge Apparatus.

Brightness & Fluxes for Neutron & X-Ray Sources

	Brightness $(s^{-1}m^{-2}ster^{-1})$	dE/E (%)	Divergence $(mrad^2)$	Flux $(s^{-1}m^{-2})$
Neutrons	10^{15}	2	10×10	10^{11}
Rotating Anode	10^{20}	0.02	0.5×10	5×10^{14}
Bending Magnet	10^{27}	0.1	0.1×5	5×10^{20}
Undulator (APS)	10^{33}	10	0.01×0.1	10^{24}

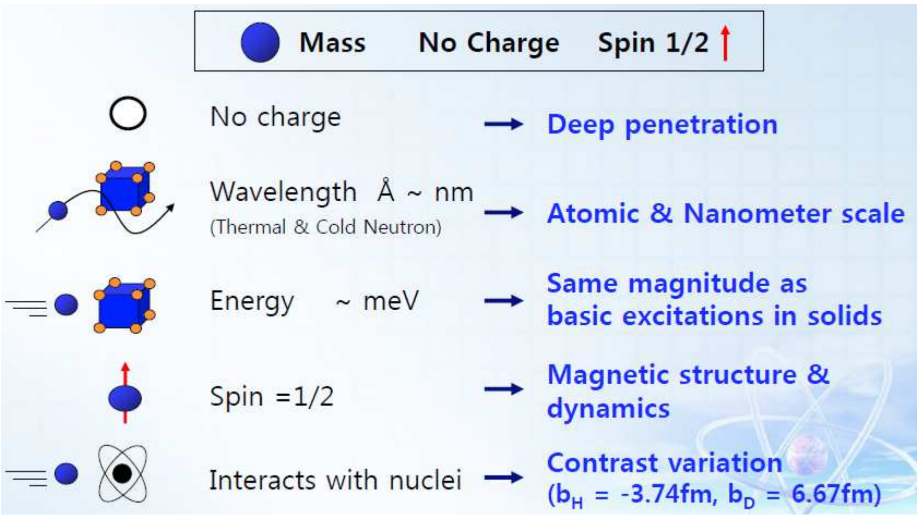
Neutron diffraction

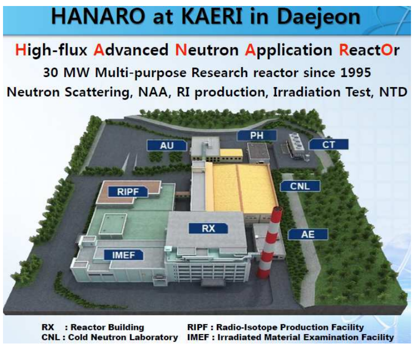
- Produced in nuclear reactors, White spectrum
- **Scattered by nuclei (electron clouds in X-ray)**
- Scattering factor remains constant over the whole range of Bragg angles
- **Scattering factors not proportional to atomic number**
- Scattering factors are different for different isotopes of the same element
- Neutrons have **spins** → interact with unpaired e' spins (magnetic moments), can be used to determine ordered **magnetic structures**

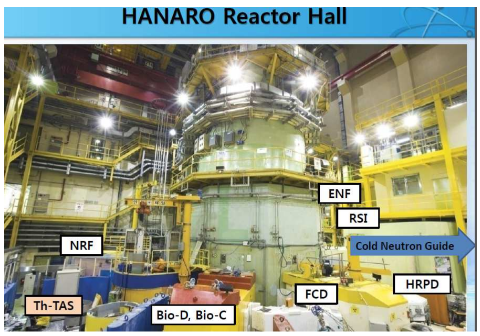
Electron diffraction

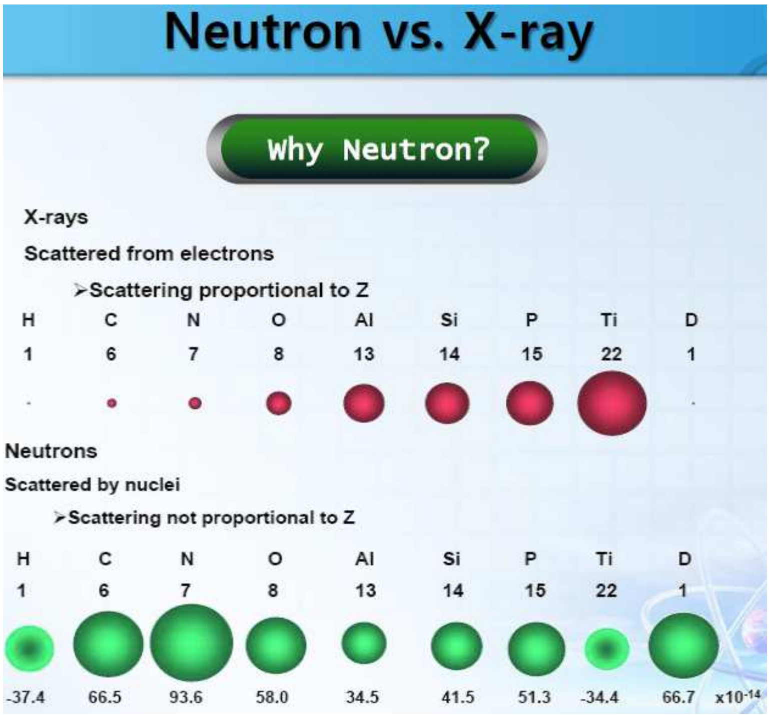
- High vacuum is needed
- e's strongly interact with materials → dynamical theory of diffraction
- Cost of equipment

Properties of Neutron

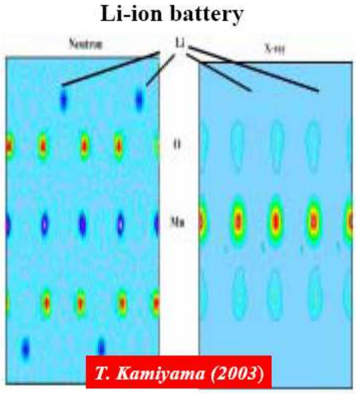


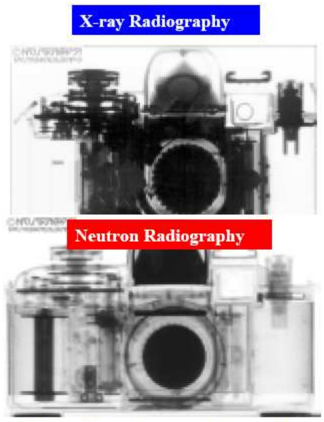






Presentation of Shin Ae Kim, KAERI





http://neutra.web.psi.ch

X-ray, neutron, & electron

	X-ray (conv/sync)	Neutron	Electron
nature	wave	particle	particle
medium	atmosphere	atmosphere	high vacuum
Scattering by	**e' density**	**nuclei, magnetic spins of e's**	**electrostatic potential**
Range of λ (Å)	0.5~2.5 (0.1~10)	~1	0.01~0.05
l selection	fixed/variable	variable	variable
Lattice image	**reciprocal**		**direct, reciprocal**
Direct structure image	no		yes
Applicable theory of diffraction	kinematical		dynamical

Safety (XRD)

- Electric shock
- Radiation hazard
  - ✓ Burns
  - ✓ Radiation sickness
  - ✓ Genetic mutation
- Be window

Beryllium - MSDS

- Appearance: silvery solid or grey foil
  Melting point: 1278 C Boiling point: 2970 C
- Very toxic by inhalation - risk of serious damage to health. May act as a human carcinogen for which there is no safe exposure level. May act as a sensitizer.
- Toxicity data IVN-RAT LD50 0.5 mg kg-1
- Risk phrases R26 R27 R37 R39.

IVN – intravenous
LD50 – lethal dose 50% kill

R26 – very toxic by inhalation
R27 – very toxic in contact with skin
R37 irritating to respiratory system
R39 – danger of very serious irreversible effects

- No special health risks with Be in solid form
- Skin Contact with Beryllium
  - ✓ No effect on contact or temporary embedding.
  - ✓ Solvents will not generate beryllium dust, but some acids will. Don't etch beryllium.
  - ✓ Wear clean gloves to protect the skin and to protect the beryllium.

MATERION

Collimation

Monochromatization

Diffractometer

Collimation & Monochromatization

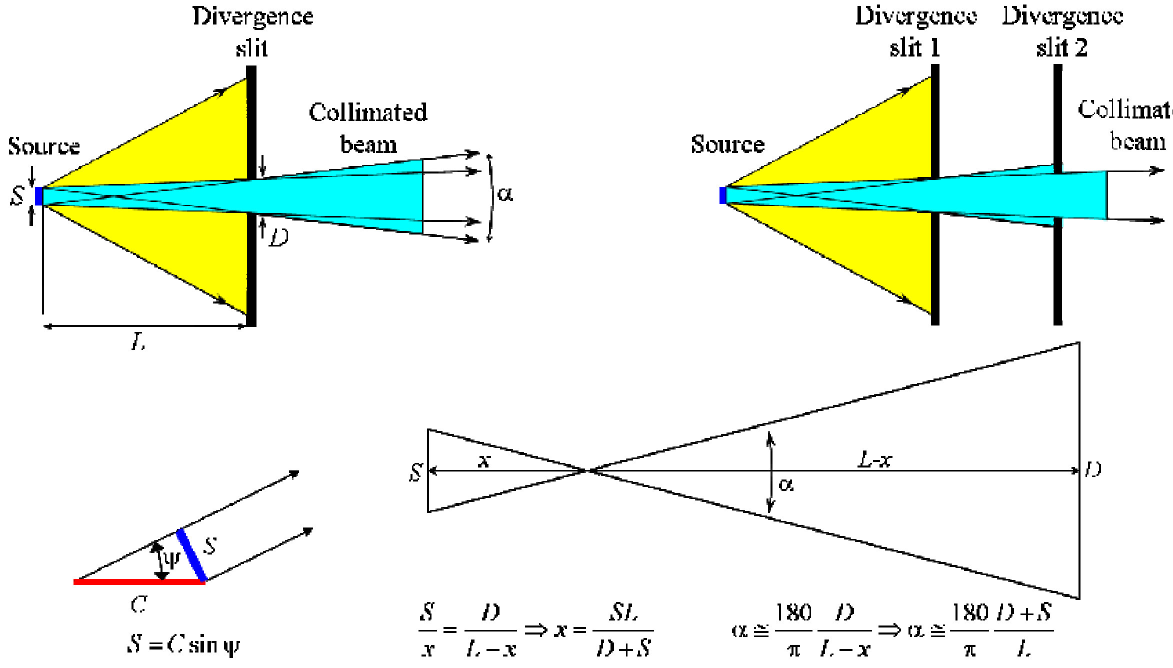
- Conventional X-ray (sealed tube, rotating anode tube) has
  - ✓ Polychromatic nature → monochromatization
  - ✓ Angular divergence → collimation

1. White radiation → high background
2. Three intense characteristic lines ($K_{\alpha 1}$, $K_{\alpha 2}$, K_{β}) → three Bragg peaks from each (hkl)
3. Angular divergence → broad & asymmetric Bragg peaks

- **Incident X-ray beam needs to be conditioned** to improve the quality of diffraction pattern
- How to reduce both the angular & wavelength dispersion?
- How to reduce both with minimal loss of intensity of incident & diffracted beams?

Collimation slits

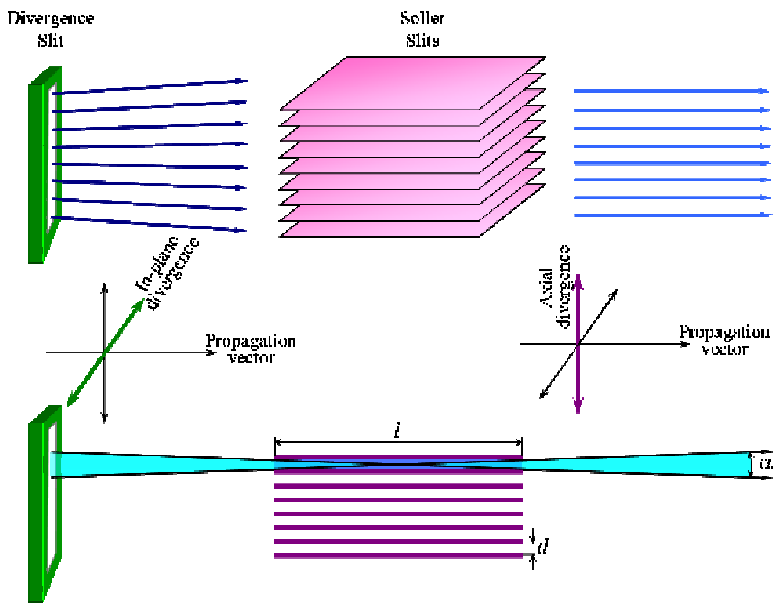
Divergence slit



- Reduce angular dispersion of the incident X-ray beam in the plane ⊥ to goniometer axis (reduce in-plane divergence)

Pecharsky

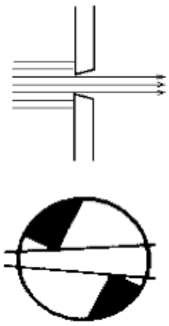
Divergence slit & Soller slit



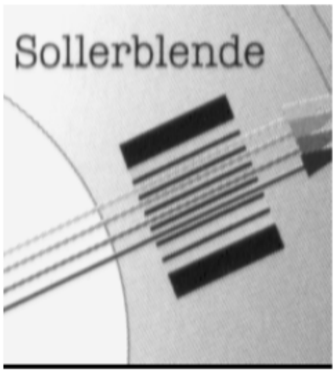
- Soller slit - reduce angular divergence of the incident X-ray beam in the direction // to goniometer axis (reduce axial divergence)

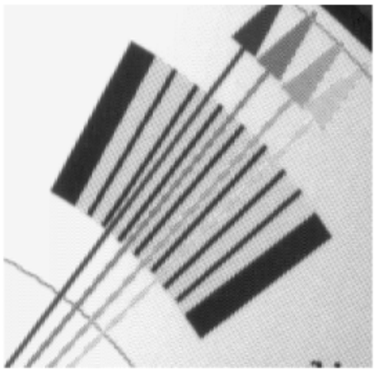
Pecharsky

Slit assemblies and soller slits



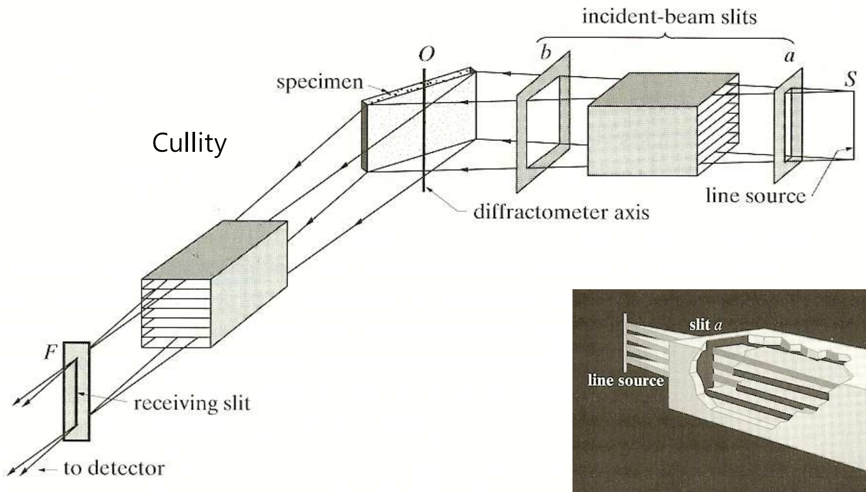
The normal slit consists of two blades, limiting the beam width. For automatic changing of the slit width, turnable edges are used.

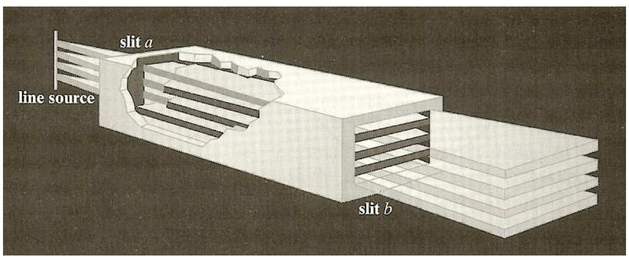


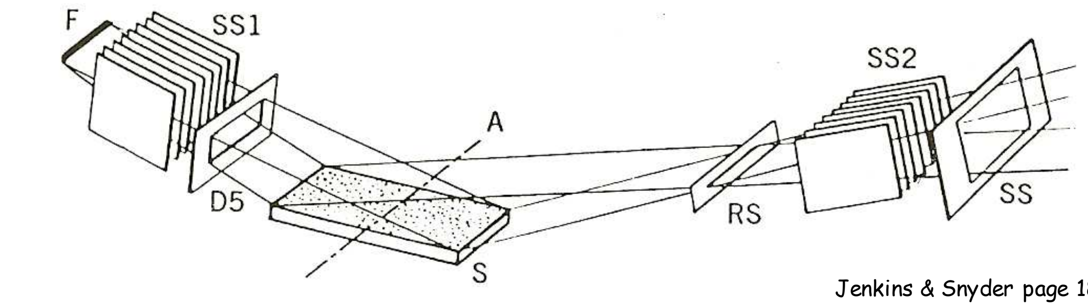


Soller slit

Cullity







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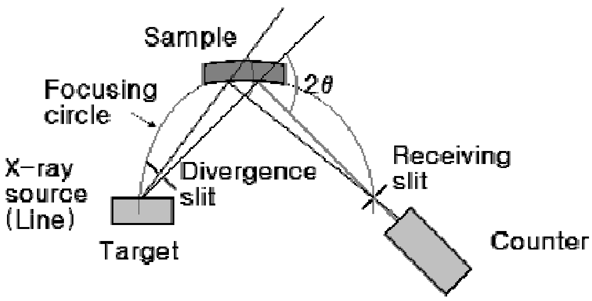
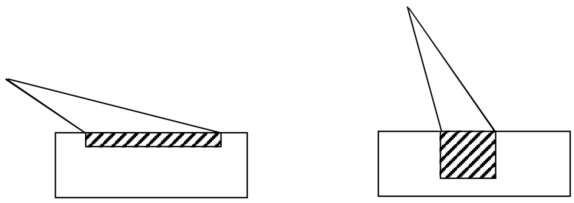
Slit

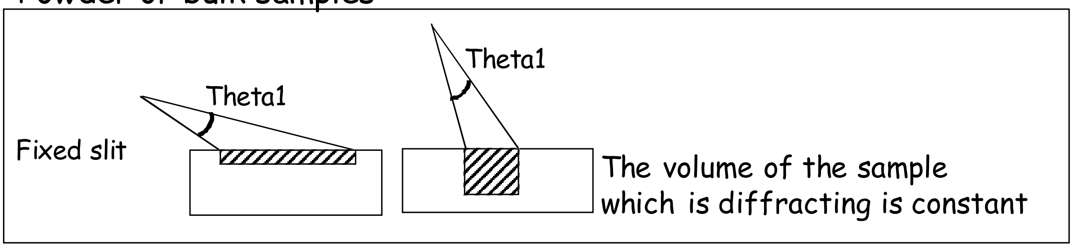
- In case the line intensities are to be compared over the whole range of 2θ, the same divergence must be used and specimen must be larger than the beam at all angles
- Variable divergence slit → irradiated area constant at all 2θ angles
- Fixed divergence slit → irradiated volume constant at all 2θ angles
- Receiving slit defines the width of beam admitted to the detector. Increase of receiving slit → increase of maximum intensity, loss of resolution



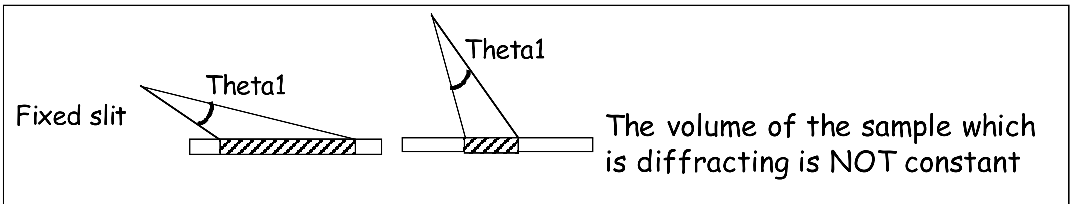


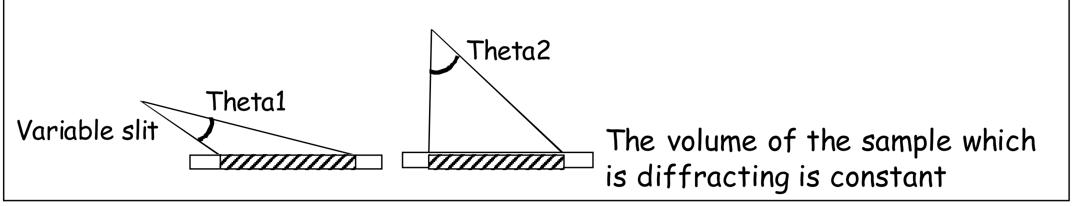
Variable slit vs. Fixed slit

Powder or bulk samples



Thin samples





Monochromators

Monochromatic radiation

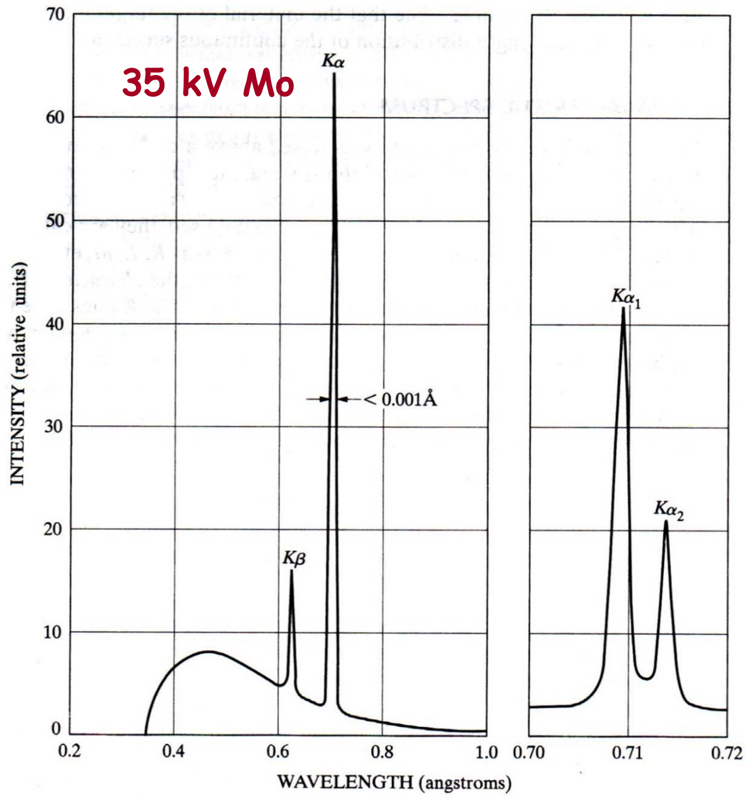
- Problems caused by polychromatic nature of diffracted beam & variability of angular dispersion
- XRD pattern from multiple wavelength, or that from unknown wavelength → difficulty in interpreting the pattern
- Why monochromatic beam is wanted? – we want to obtain experimental pattern from a single wavelength
- Monochromatization by reducing the intensity of white radiation & by eliminating undesirable characteristic wavelengths from X-ray spectrum
  - ✓ β filter
  - ✓ Diffracted beam monochromator
  - ✓ Primary beam monochromator
  - ✓ Pulse height selection using proportional counter
  - ✓ Use of solid state detector (high resolution energy resolving detector)

X-ray spectrum of molybdenum

2p → 1s

α1, α2 doublet
β1, β3 doublet

3p → 1s



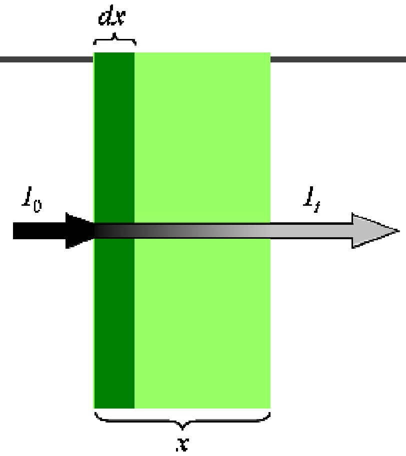
Cullity page 8

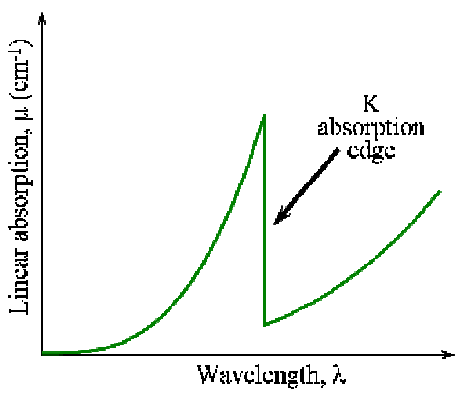
Absorption of X-rays

$$I_x = I_0 e^{-(\mu/\rho)\rho x}$$

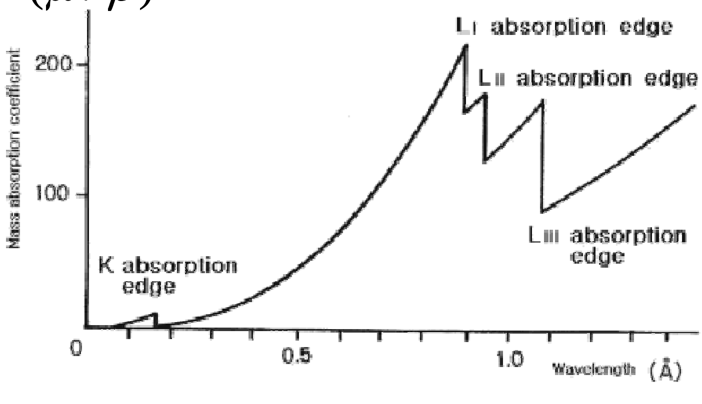
μ linear absorption coefficient

<u>μ/ρ mass absorption coefficient</u>



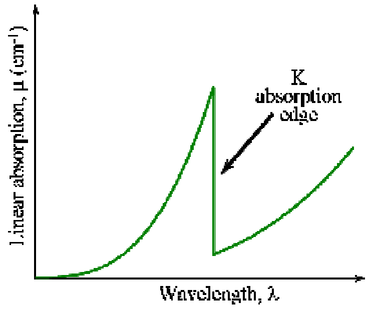


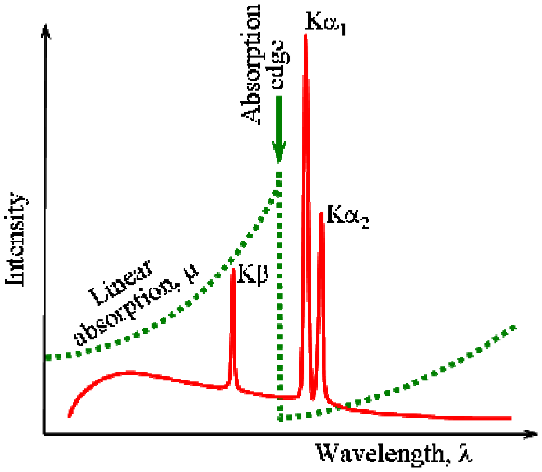
(μ/ρ)

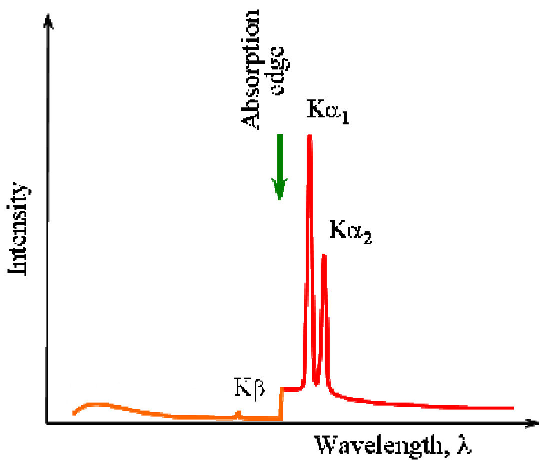


Pecharsky

β-filter

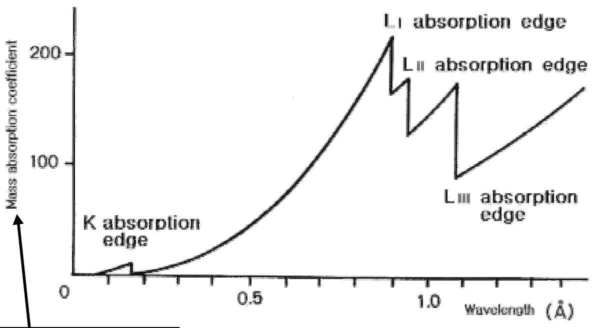






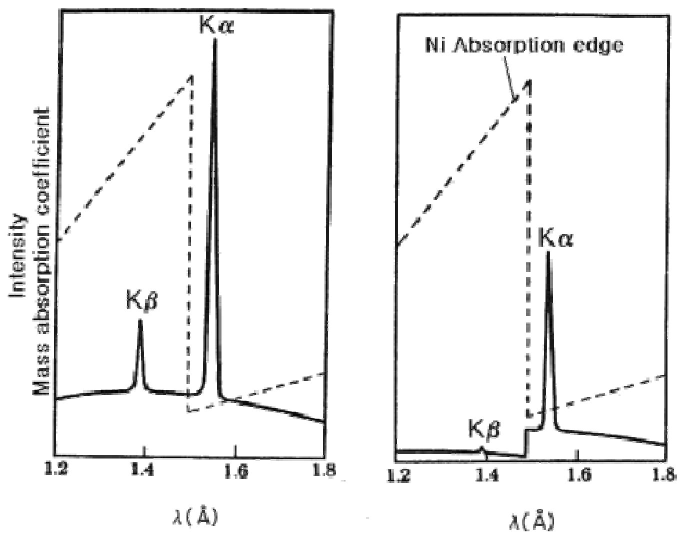
Pecharsky

β-filter
K_α vs. K_β



$$(\mu / \rho)$$

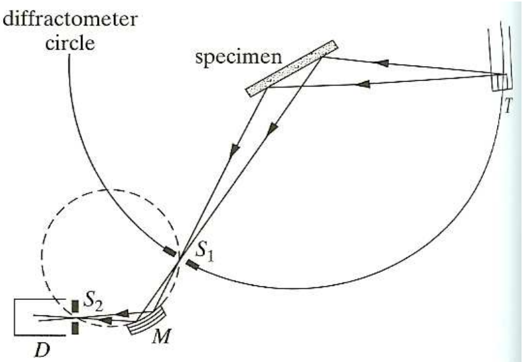
$$I_x = I_0 e^{-(\mu/\rho)\rho x}$$



Cullity page 18

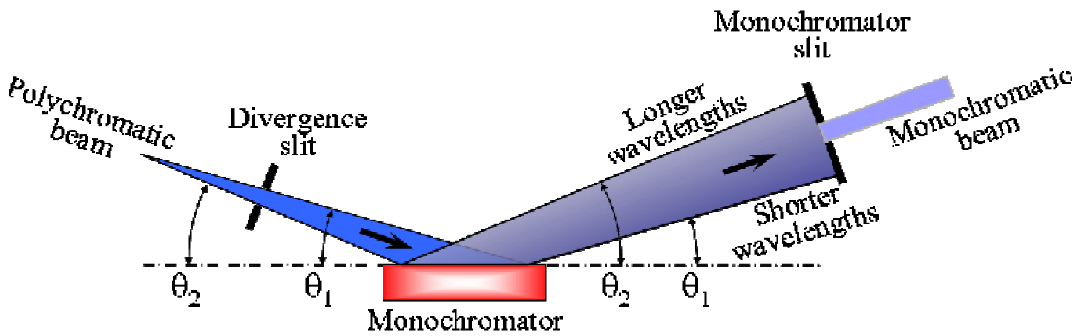
Monochromators

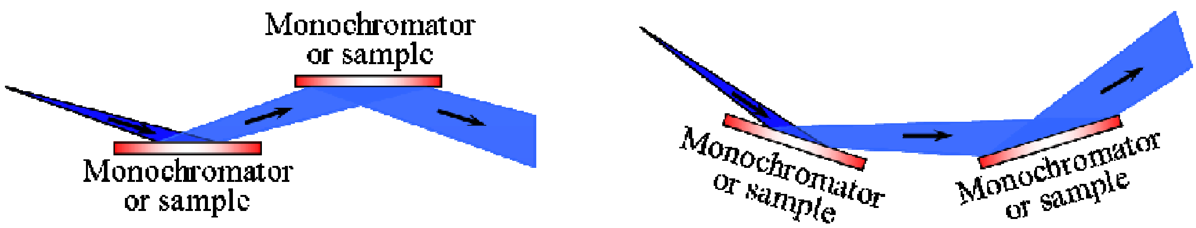
- Ways to reduce BKG
  - ✓ Pulse-height analyser
  - ✓ Diffracted beam monochromator → suppress BKG radiation originating at the specimen (flourescent radiation, incoherent scattered radiation)
  - ✓ Balanced filter
- Monochromator can be placed in diffracted beam in diffractometer (not in the area detector)
- Incident beam monochromator → Lp factor has to be changed (has to include contribution from the diffraction at the monochromator)
- LiF, graphite, Si, Ge, SiO_2 (quartz), etc



Cullity

Single crystal monochromator





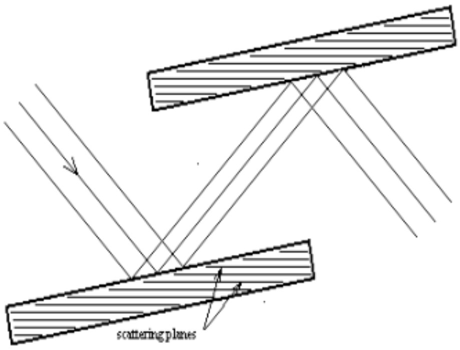
Parallel arrangement

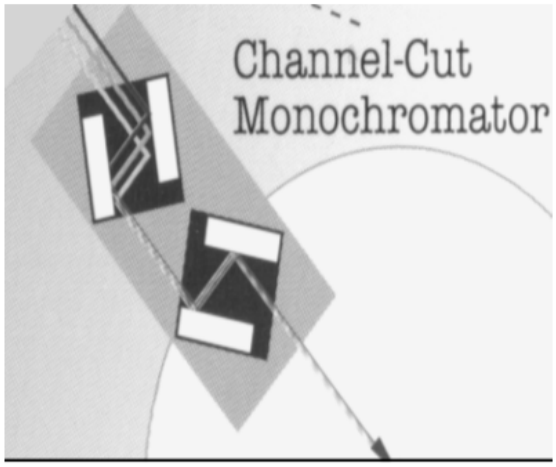
Angular arrangement

Pecharsky

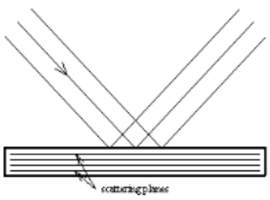
Multi bounce single crystal Monochromators

An arrangement of two or four plane crystals provides a beam with very low wavelength dispersion and divergence. Using special channel cut crystals, a high brilliance source is yielded.

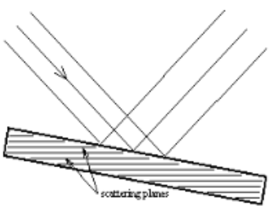


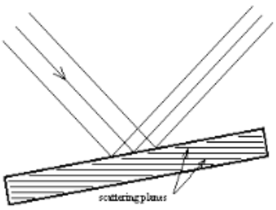


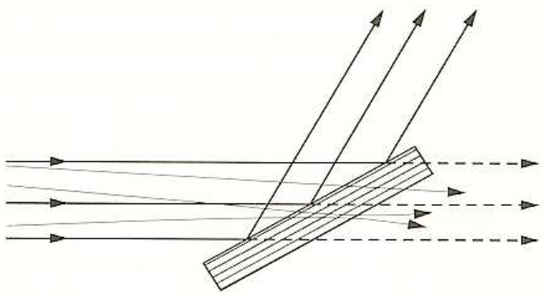
Plane unbent crystal Monochromators



- A single crystal may reflect the primary beam, according to Bragg's law, if well aligned.
- It will reject radiation from the wrong direction or the wrong wavelength. → intensity low
- A perfect single crystal will show high resolution in angles or wavelength.
- A poly-domain crystal will show low resolution.
- The better the resolution, the more carefully it must be aligned.

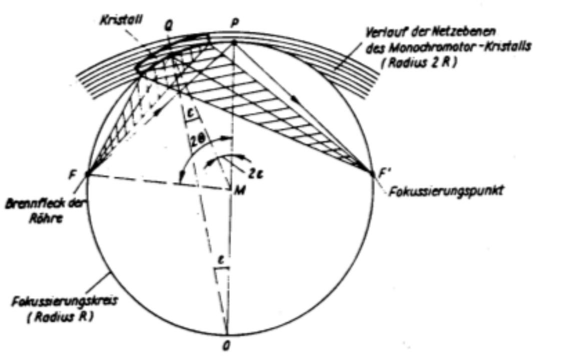


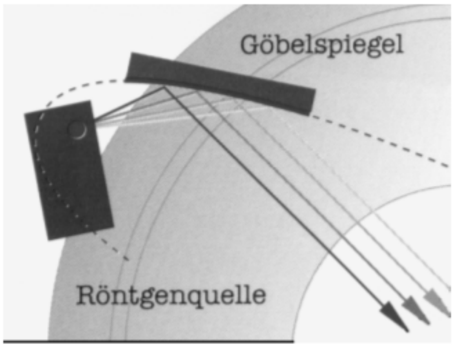




Bent crystal primary Monochromators

A monochromator of type Johannson is special cut and bent single crystal. It enables the focal spot or the divergent primary beam to be focused to a point again.

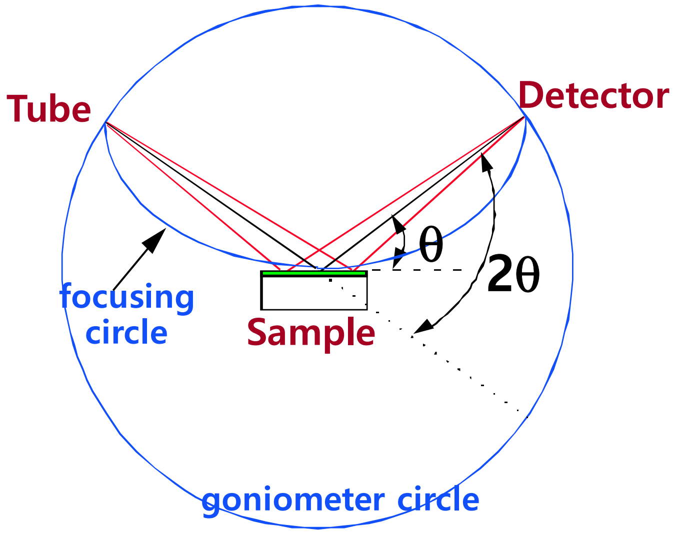


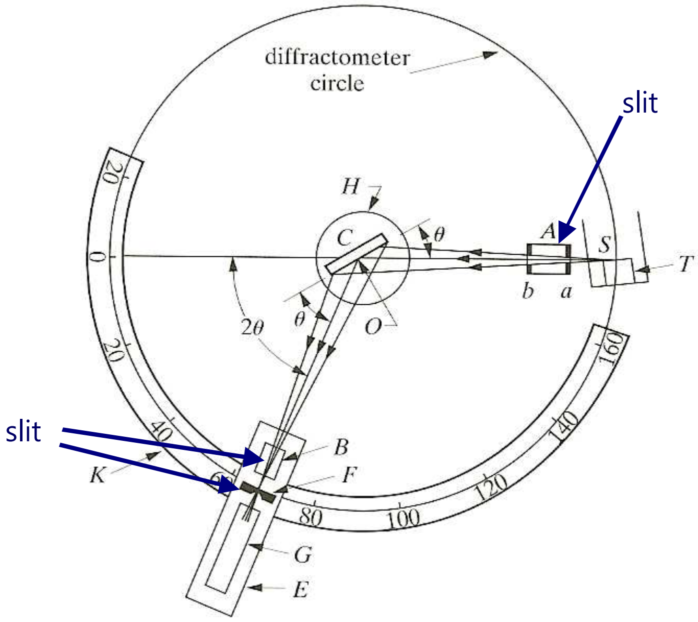


The **Göbel Mirror** is bent like a parabola. The divergent beam emitted by the X-ray tube is converted into a parallel one illuminating the sample. Mounted in the diffracted beam, the beam off the mirror is reflected into the receiving slit.

X-ray Diffractometer

Bragg-Brentano geometry (parafocusing geometry)

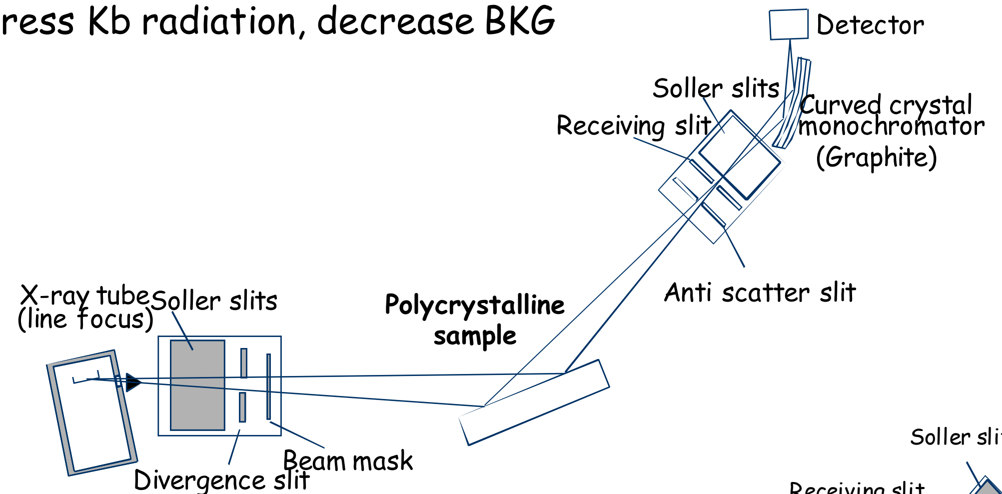


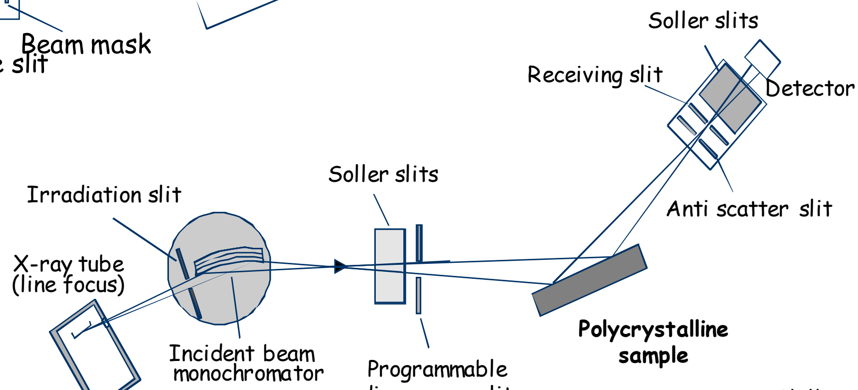


Cullity

X-ray diffractometer > Bragg-Brentano

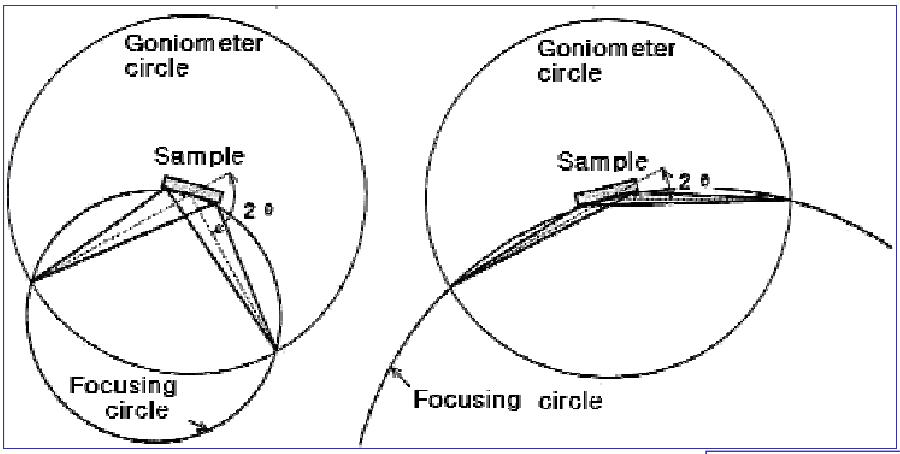
- monochromator or filter in diffracted beam
  - suppress Kb radiation, decrease BKG

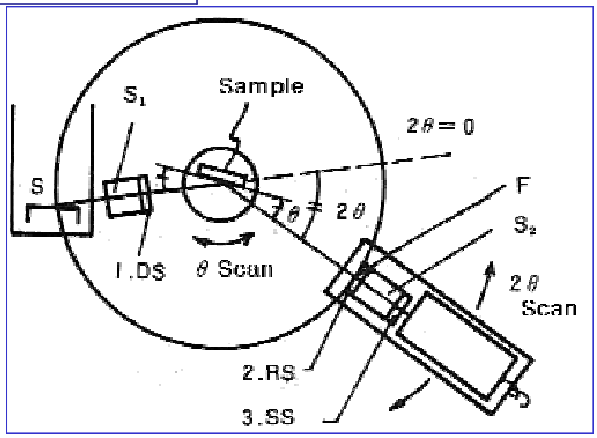




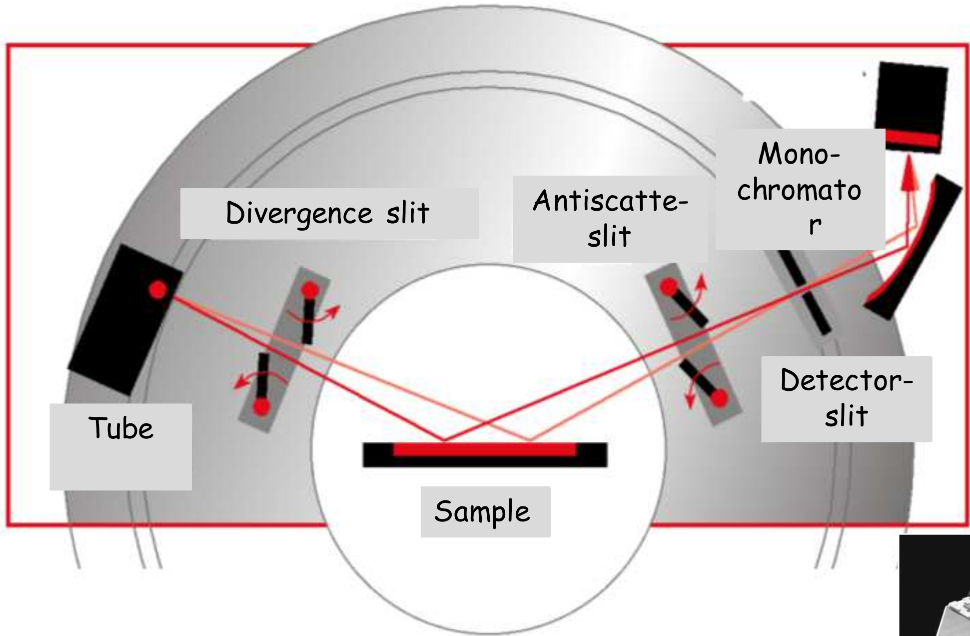
Phillips

Bragg-Brentano Geometry (parafocusing geometry)

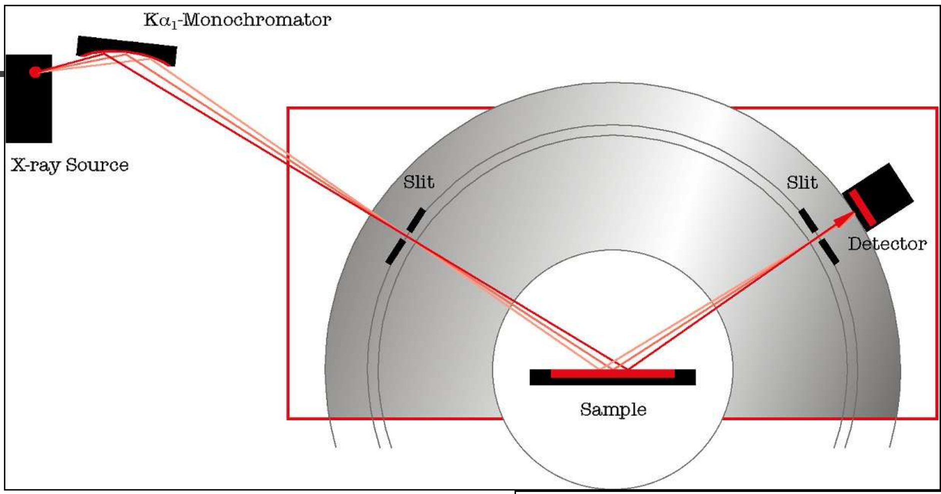


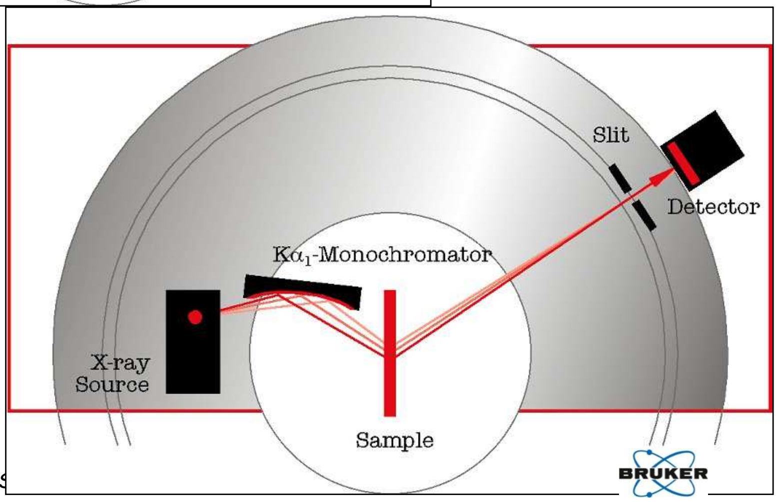


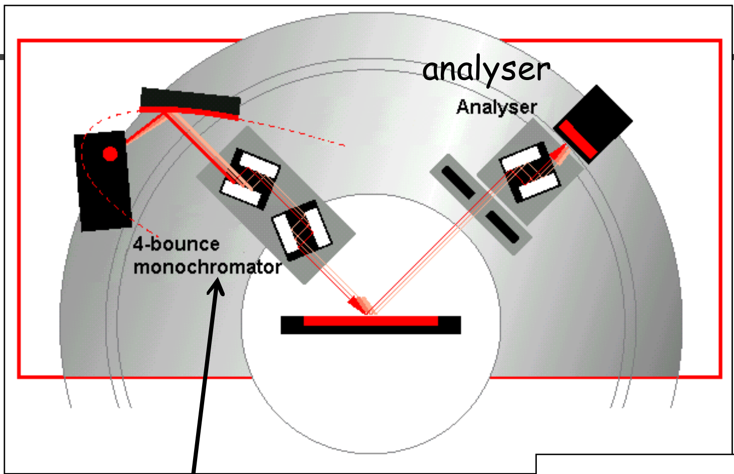
The Bragg-Brentano Geometry



BRUKER

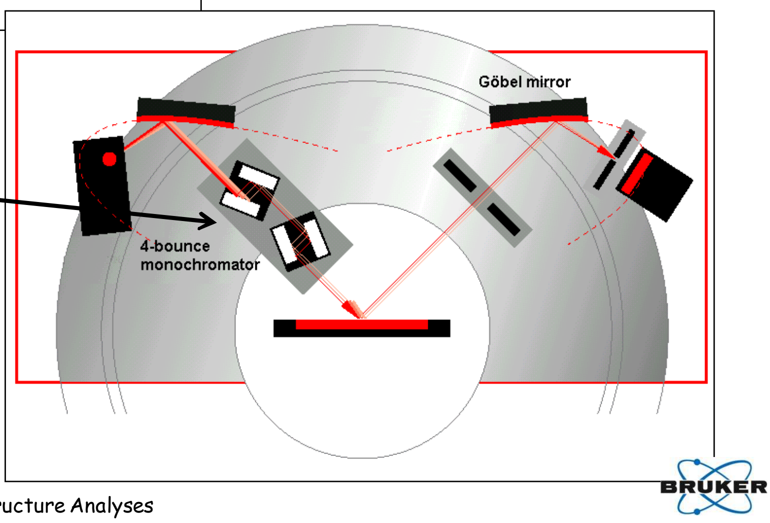




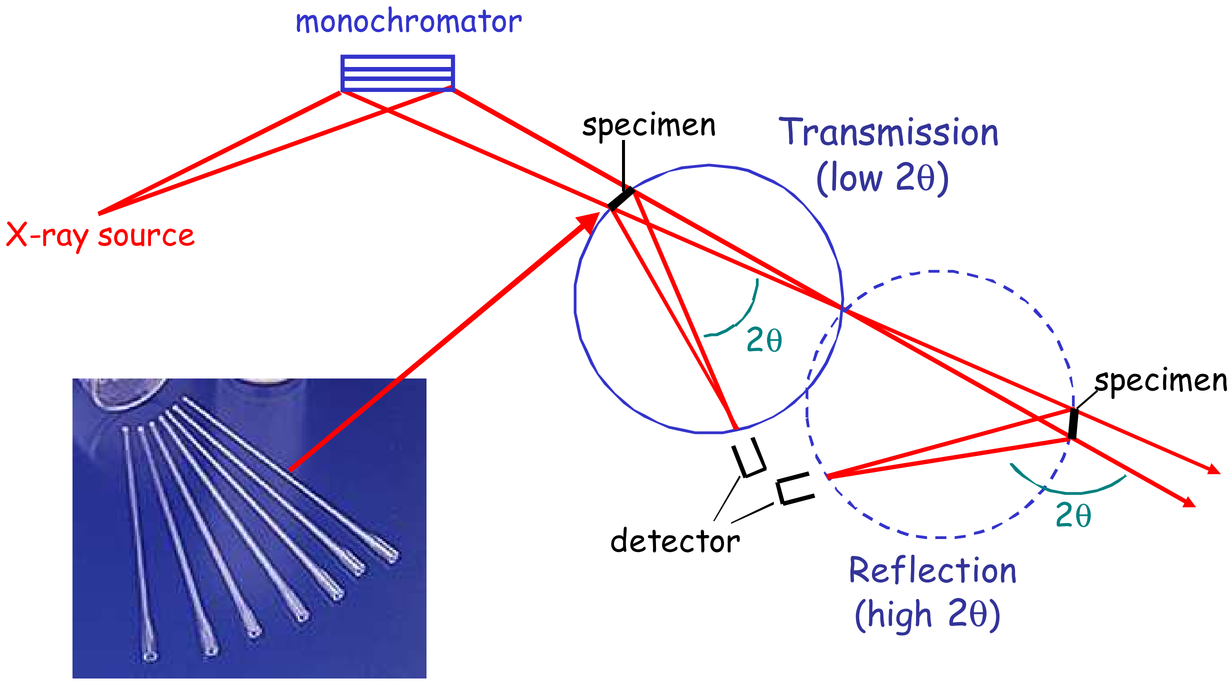


Göbel Mirror

4-bounce monochromator



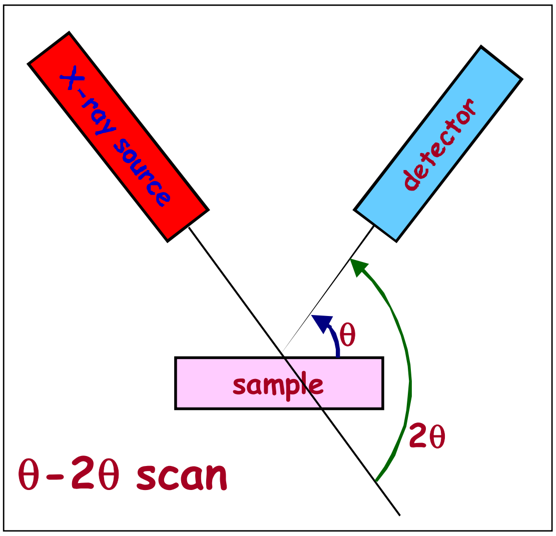
Guinier Diffractometer

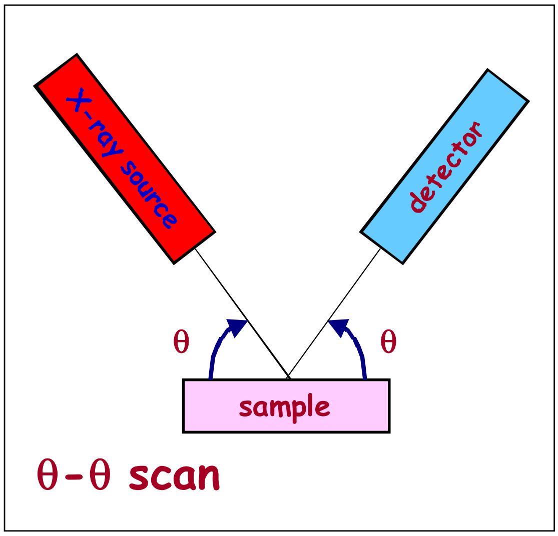


Capillary tube
quartz, glass, alumina
0.01mm thick, 80mm long, 0.1~5mm OD

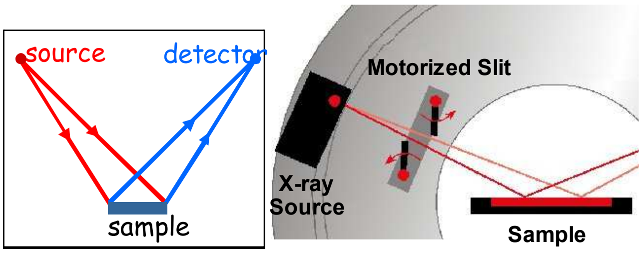
Alfred Univ.

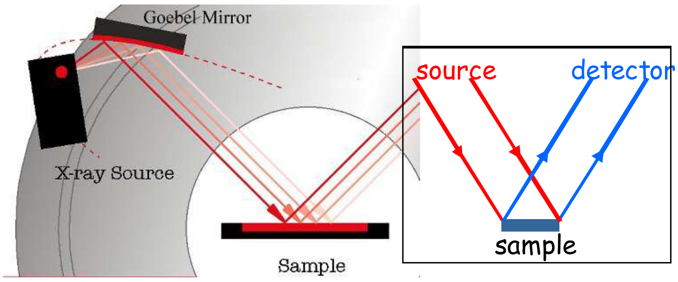
θ-2θ scan vs. θ-θ scan





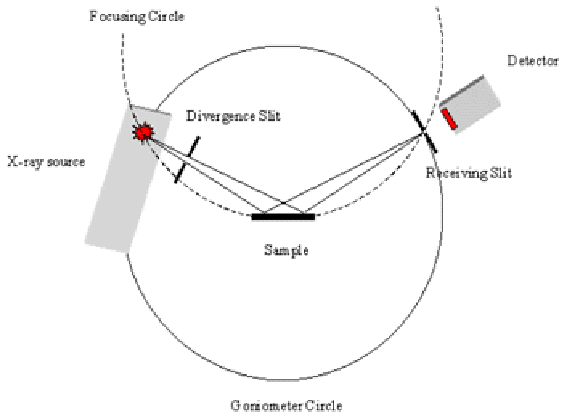
Bragg-Brentano vs. Parallel Beam Geometry

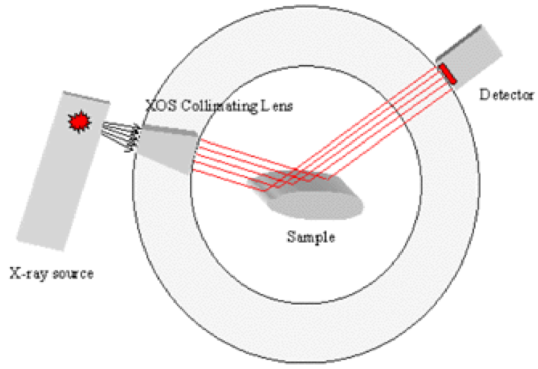




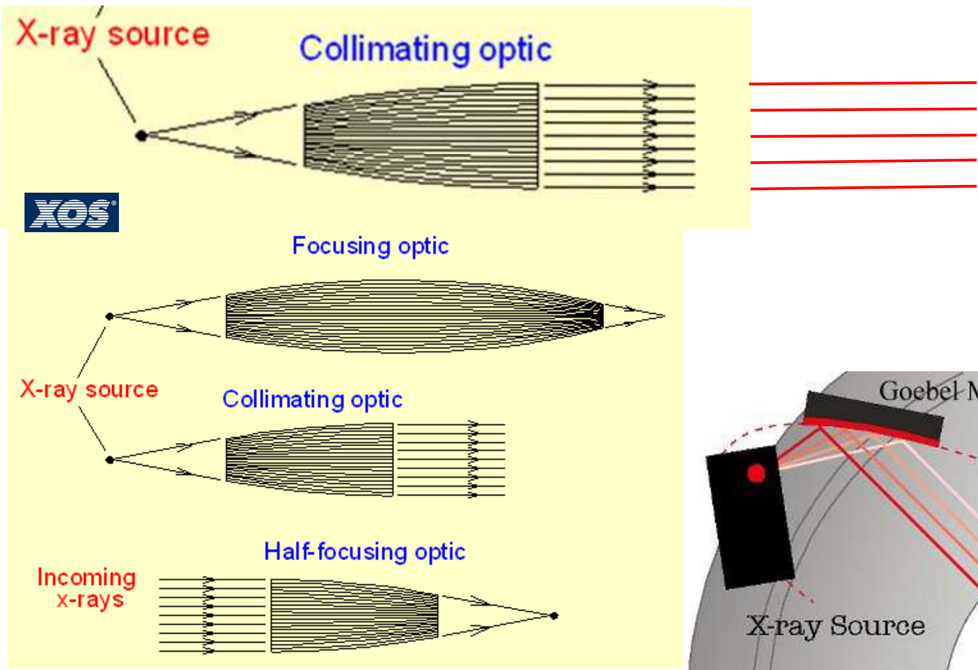
Bragg-Brentano Geometry
(para-focusing geometry)

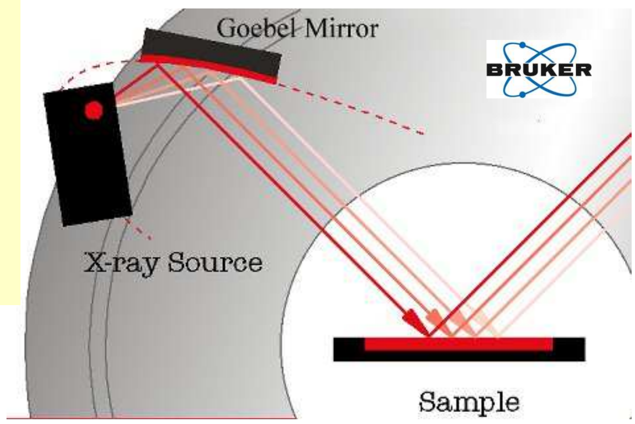
Parallel Beam Geometry
generated by Göbel Mirrors



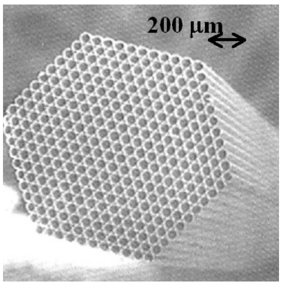


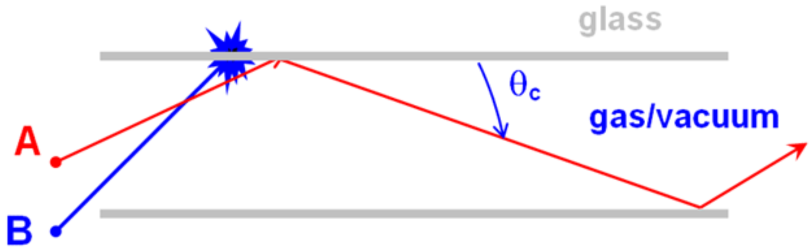
Parallel beam optics → no sample displacement error





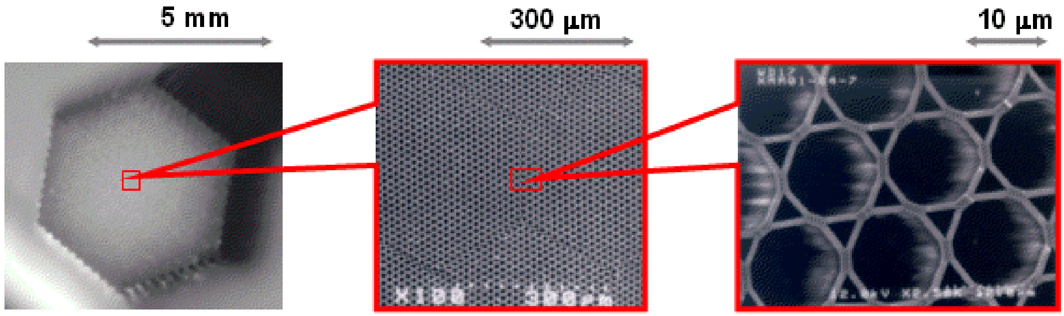
X-ray optical systems (XOS)





Incident photon "A" angle ≤ critical angle (θ_c)
Incident photon "B" angle > critical angle (θ_c)

$$\theta_c\,(mrad) \cong \frac{30}{energy\,(keV)}$$



XOS

Parallel beam geometry can be used for

- analysis of samples with non-flat surfaces, e.g. corrosion on pipes
- samples you would prefer not to grind to a powder, e.g. jewelry, archaeology or forensic samples

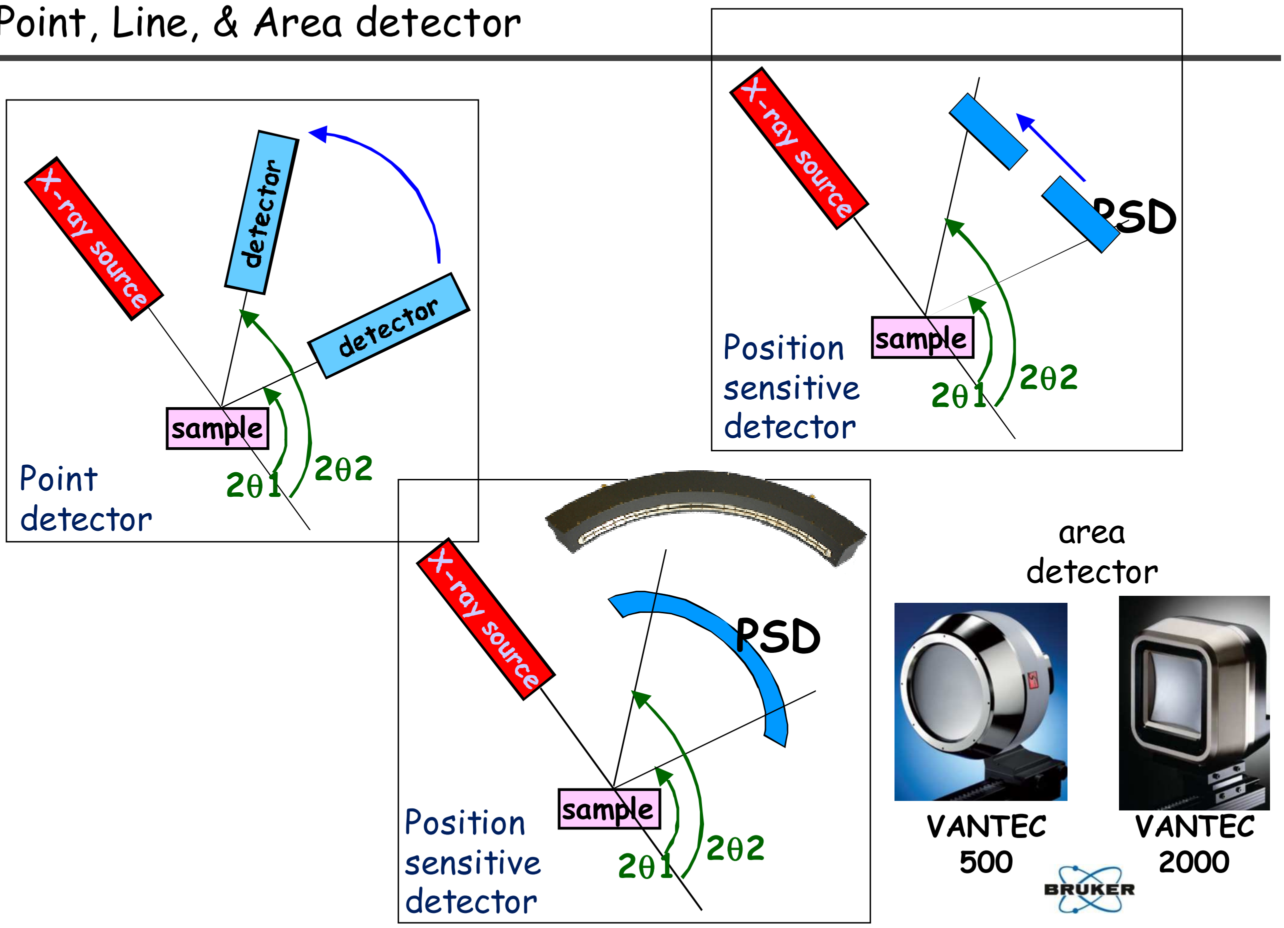
Sodalite Bracelet

Vesuvianite Pebble

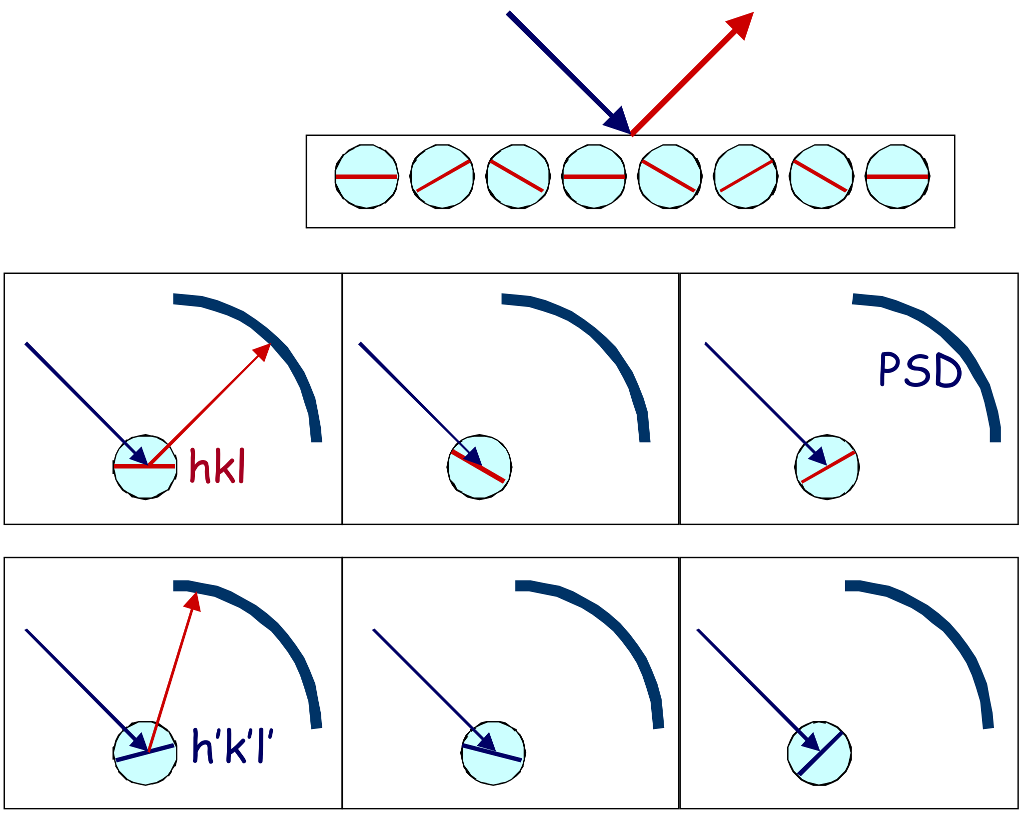
- measure thermal expansion and contraction when using the heating/cooling stage
- grazing incidence diffraction (GID) of layers on substrates
- reflectometry for thin film thickness and roughness

http://www.csec.ed.ac.uk/Instruments/D8_diffractometer/D8_parallel-beam.html

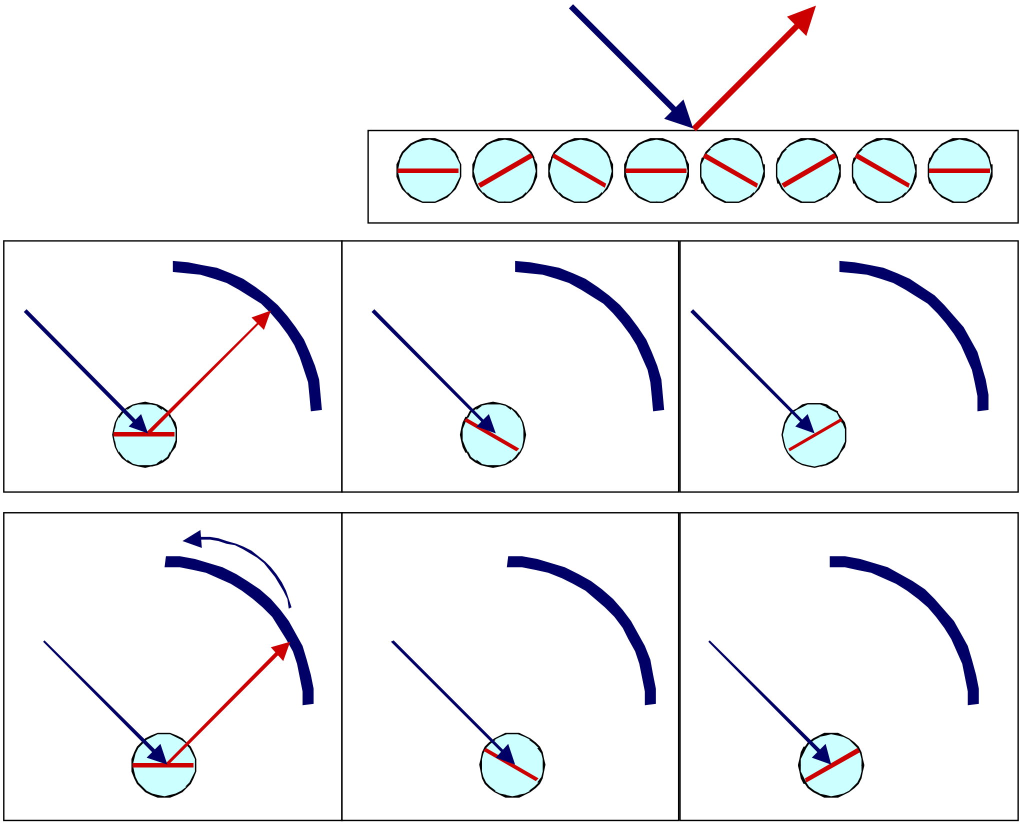
Point, Line, & Area detector



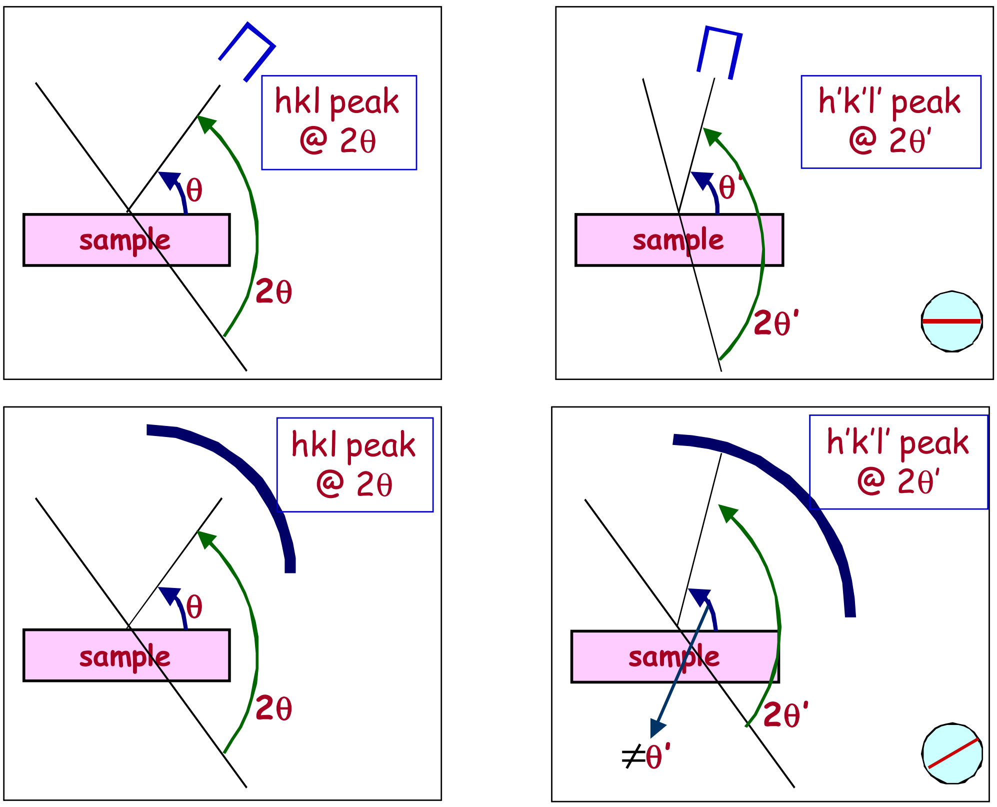
Line detector, PSD



Line detector, PSD

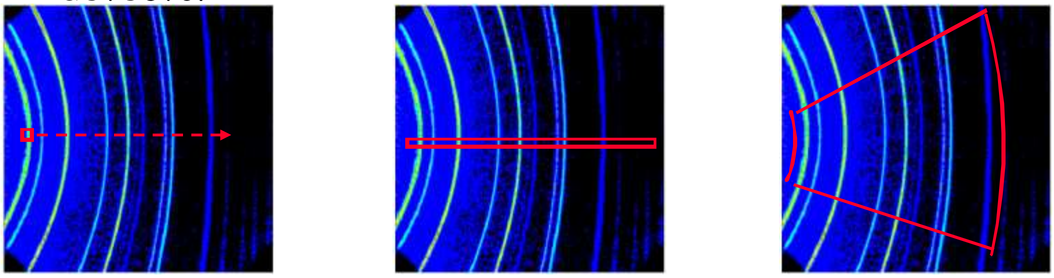


Point detector vs. Line detector



Point, Line, and Area detector

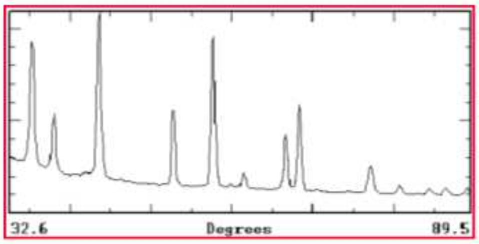
Scintillation detector	Line detector (PSD)	Area detector



- ✓ small spot measured
- ✓ scan necessary
- ✓ long collection time

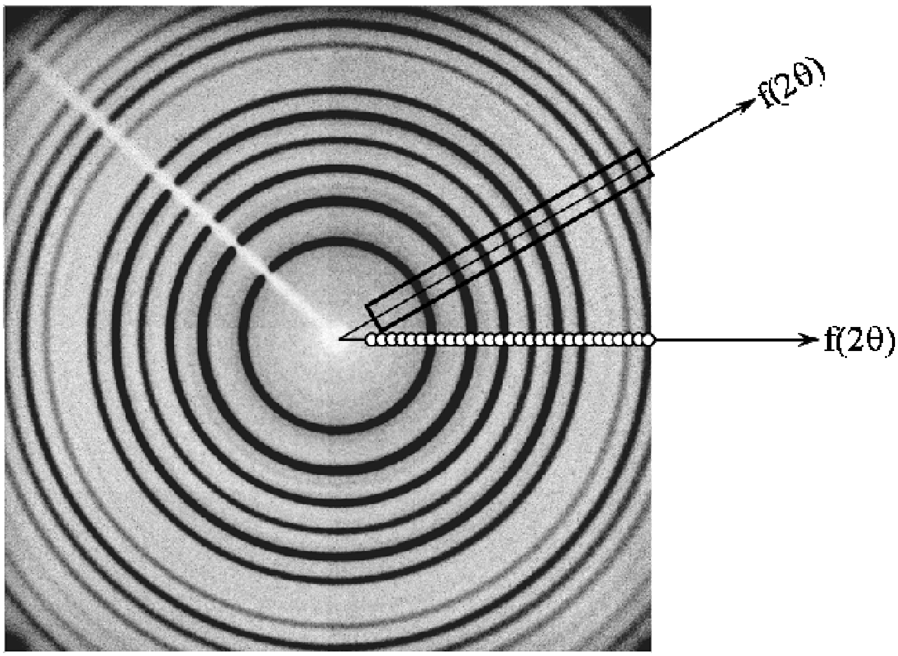
- ✓ large 2θ range measured simultaneously
- ✓ medium collection time

- ✓ large 2θ and chi range measured simultaneously
- ✓ measurement of oriented samples
- ✓ very short collection times
- ✓ intensity versus 2θ by integration of the data



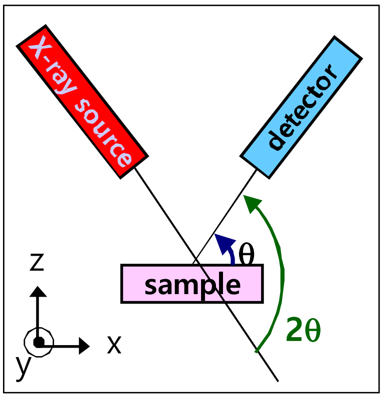
BRUKER

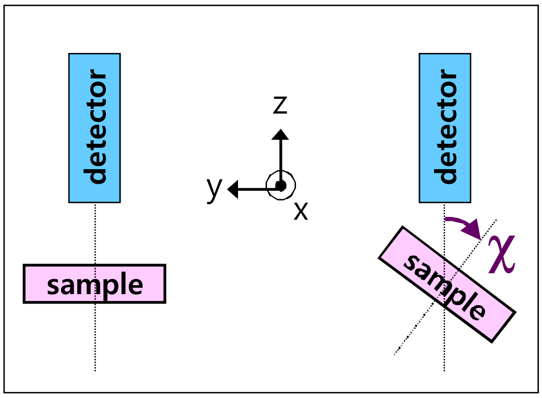
Point, Line, and Area detector

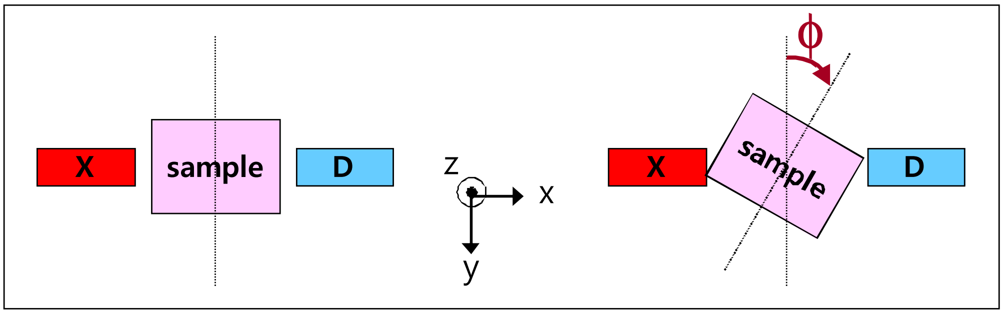


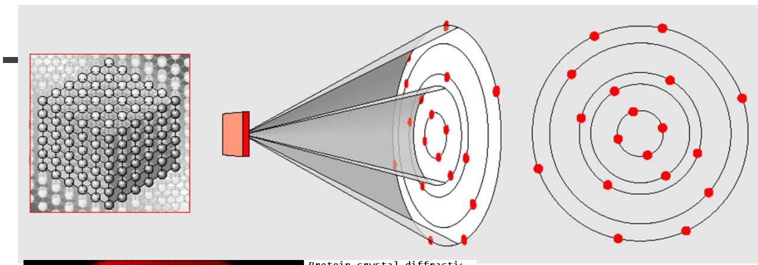
Pecharsky

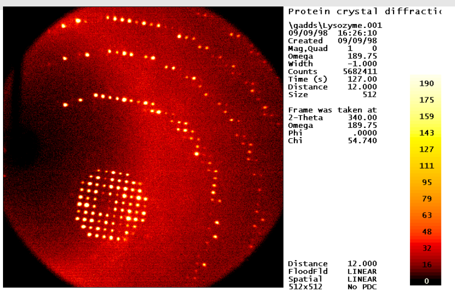
Angles - $\theta(\omega)$, 2θ, ϕ, χ





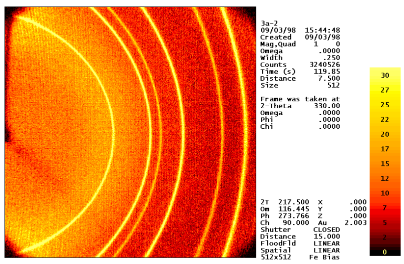


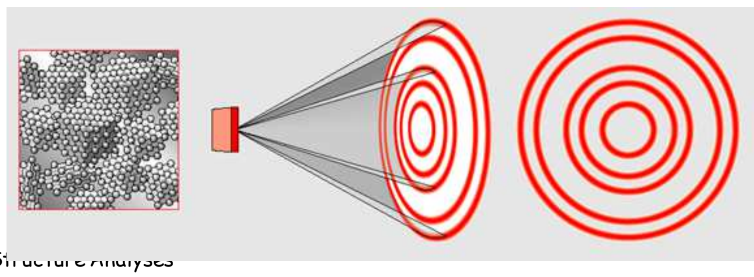




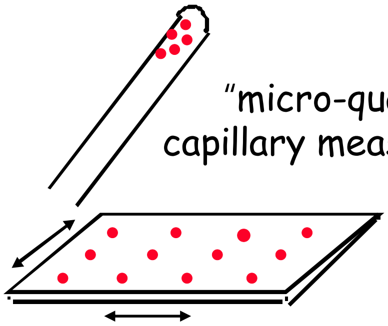
Single Crystal Diffraction

Powder Diffraction





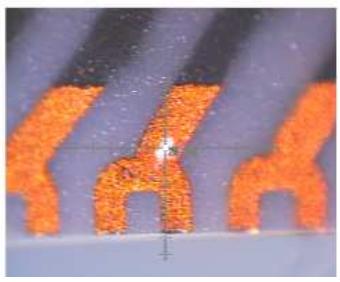
Microdiffraction

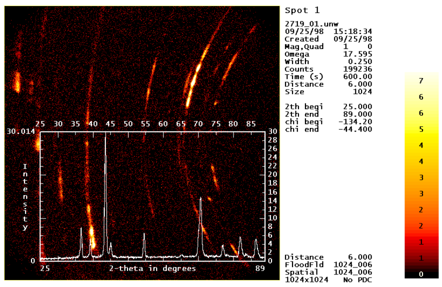


"micro-quantity"
capillary measurements

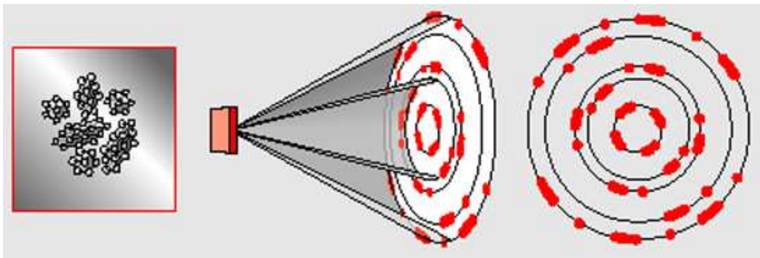
"micro-area"
X-ray microprobe

- qualitative phase analysis
- micro-texture
- quick point-and-shoot operation



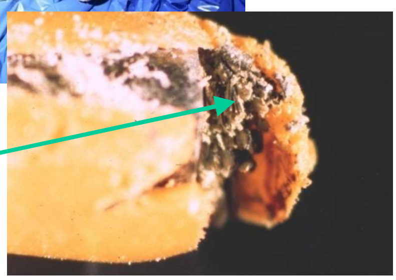


Inspection of a gold pad

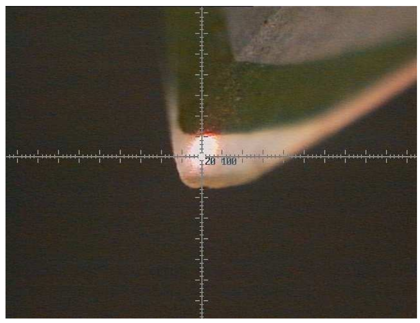


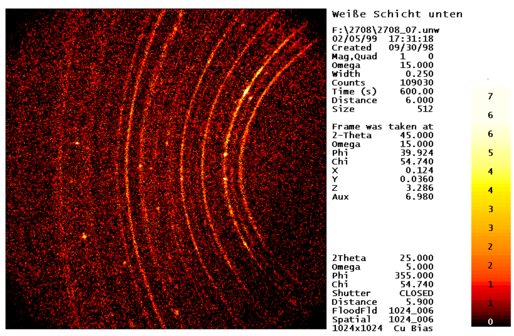
Forensic Application

Fatal Bicycle Accident Collection of Evidence



traces of car paint found on the bicycle





Dr. W. Kugler
Landeskriminalamt
Baden-Württemberg
Stuttgart, Germany

Detector

Detectors

- X-ray detector = transducer + pulse formation circuit
- Transducer – convert the energies of X-ray photons to electric currents
- Pulse formation circuit – convert current into voltage pulses that are counted/integrated by counting equipment
- Transducer = detector or counter

- Gas proportional counter, scintillation counter, Si(Li) detector, intrinsic germanium detector → all use the ability of X-rays to ionize matter

Characteristics of detector

- **Quantum efficiency**
  - ✓ How efficiently it collects x-ray photons and then converts them into a measurable signal
- **Linearity**
  - ✓ Linear when there is a linear dependence between the photon flux and the rate of signals generated by the detector per second
  - ✓ Dead time
- **Proportionality**
  - ✓ How the size of the generated voltage pulse is related to the energy of the x-ray photon
- **Resolution**
  - ✓ Ability to resolve x-ray photons of different energy and wavelength

Table 5.3. Properties of Common X-ray Detectors

	Scintillation			Xe Sealed Gas			Si(Li)		
Property	Cr	Cu	Mo	Cr	Cu	Mo	Cr	Cu	Mo
Quantum efficiency (%)	60	98	100	90	90	75	90	95	80
Linearity—loss at 40,000 c/s	Less than 1%			Up to 5%			Up to 50%		
Proportionality	Very stable			Pulse shift at high c/s			Pileup, etc., at moderate c/s		
Resolution (%)	55	45	31	17	14	10	3	2	1

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Photographic film

- Silver halide → metallic silver, when exposed to x-ray photons
- Once developed (darkened), further incoming X-rays can change nothing
  → loss of information (dead time in electronic counters)
- Film darkening is proportional to the intensity of exposing X-rays over LINEAR RANGE of the film
- When measuring intense sources
  - ✓ (1) Have to reduce X-ray intensity with filters or reduce incident beam flux
  - ✓ (2) extend linear range of the film
- Low proportionality range, limited spatial & energy resolution

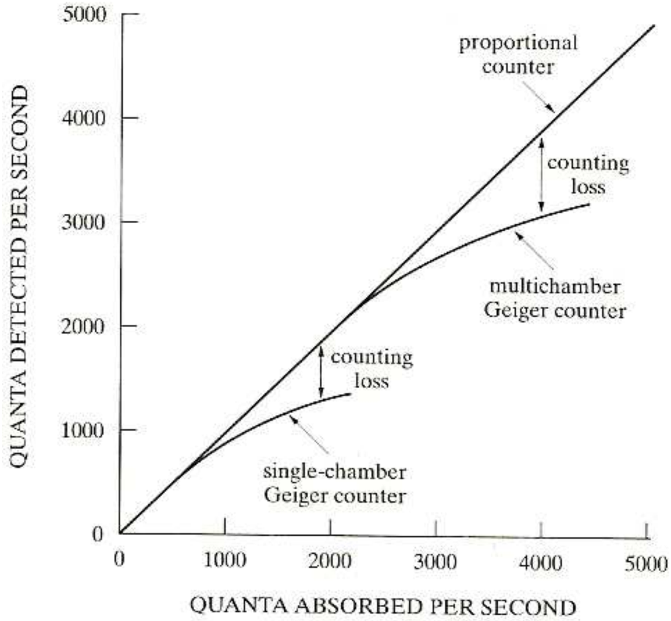
Detector

- all use the ability of X-rays to ionize matter
  - ✓ Matter = gas → Proportional, Geiger
  - ✓ Matter = solid → Scintillation, semiconductor

- Proportional
- Geiger
- Scintillation
- Semiconductor

Counting loss

- When time interval between pulses is very small, adjacent pulses may not be counted as separate pulses → counting loss begins
- Resolving time (t_s)– minimum time between two resolvable pulses



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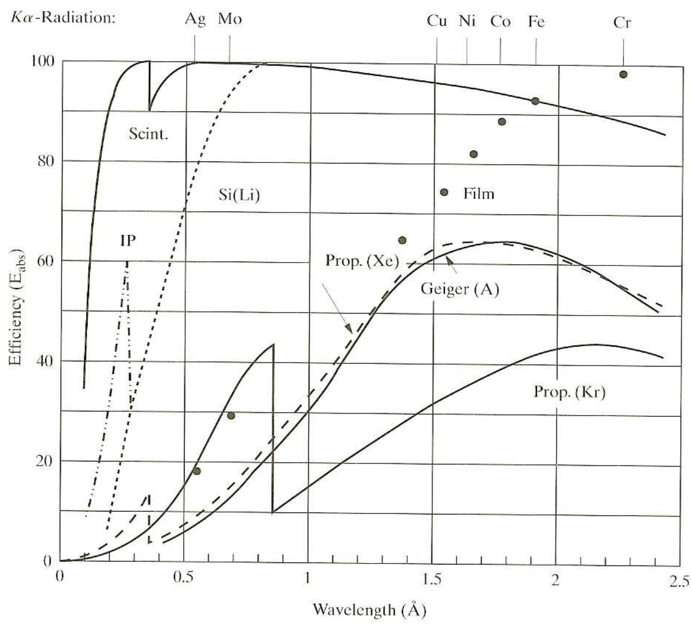
Counting efficiency

- Efficiency of detector in collecting radiation incident upon it
- Most detectors designed for XRD are optimized for the measurement of Cu Ka radiation. Loss of efficiency can result when different l is used.



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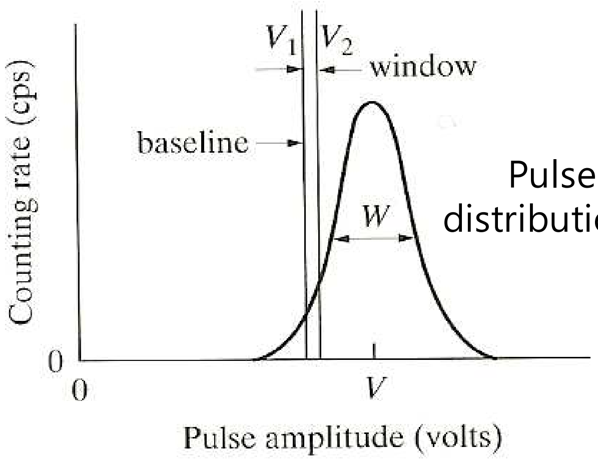
Resolution

- A measure of detector's ability to resolve two X-ray photons of different energy
- Size of voltage pulses produced by detectors are proportional to the energy of the x-ray quantum absorbed
- Resolution R = W/V



Pulse-size distribution curve

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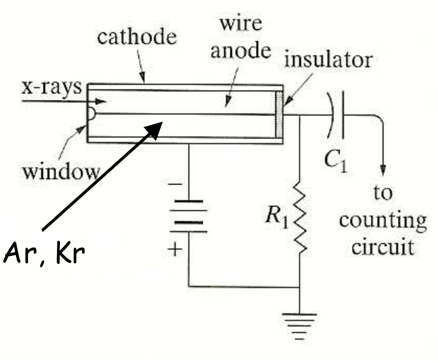
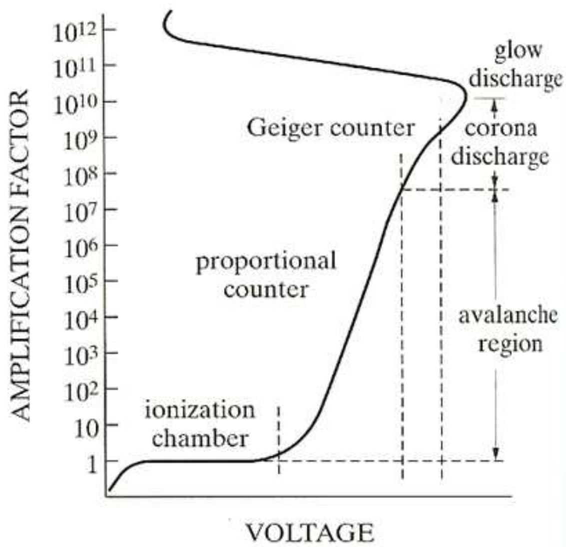
Proportional counters

- Size of pulse ∝ energy of X-ray quantum absorbed → X-ray quanta of different energies can be distinguished
- Gas is ionized by incoming X-ray
- e' → anode, positive ion → cathode (cylindrical metal shell)
- multiple ionization → gas amplification



Gas – Xe, Ar, Kr



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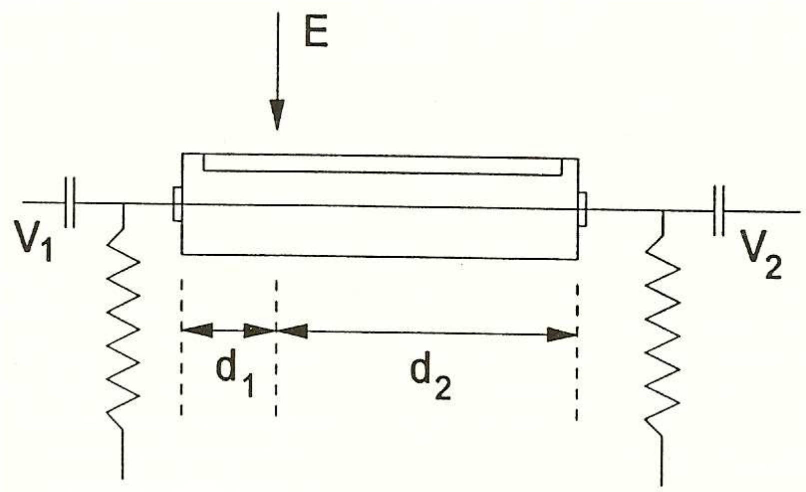
Position sensitive proportional counter

- Increased speed of data acquisition
- Measure "rise time" (rate at which a pulse develops) at each end of the wire → detect position can be located
- Angular resolution not very high



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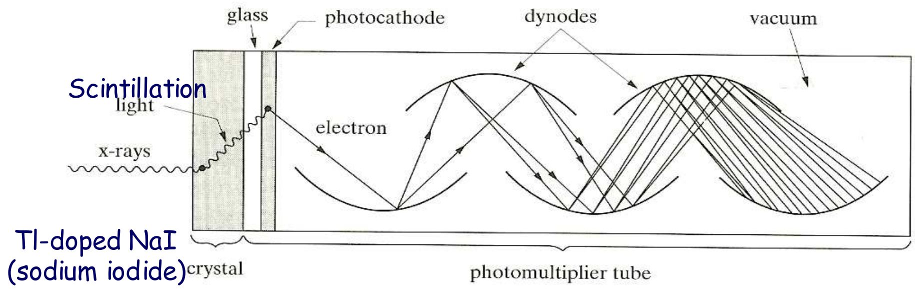
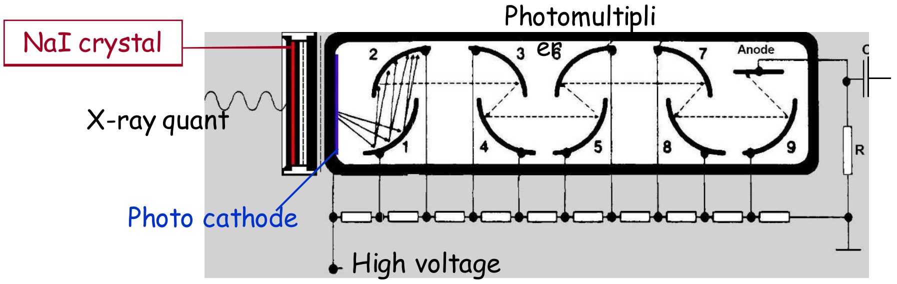
Geiger counter

- Very high voltage in a proportional counter → Geiger counter
- Gas amplification factor much larger than proportional counter
- All pulses have the same size, regardless of the energy of X-ray quanta
- Cannot count at high rates without losses → seldom used in diffractometry

Scintillation detector

- X-ray can cause certain substances to fluoresce visible light
- Amount of light ∝ emitted X-ray intensity
- Pulses produced ∝ energy of X-ray quanta
- Difficult to discriminate between X-ray quanta of different energies → energy resolution not great





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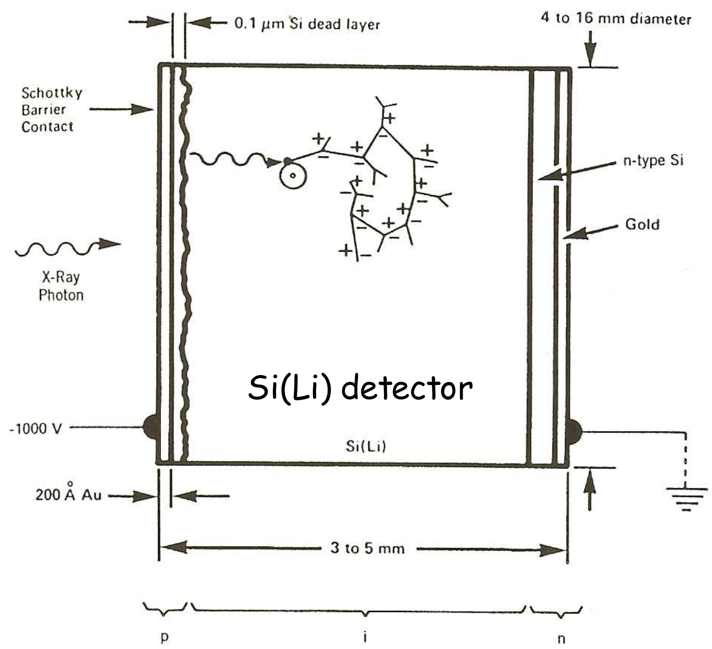
Semiconductor detector

- Best energy resolution
  - ✓ Produces pulses proportional to the absorbed X-ray energy with better energy resolution than any other detector
- Si(Li), Ge(Li), HPGe
- Need LN2 cooling



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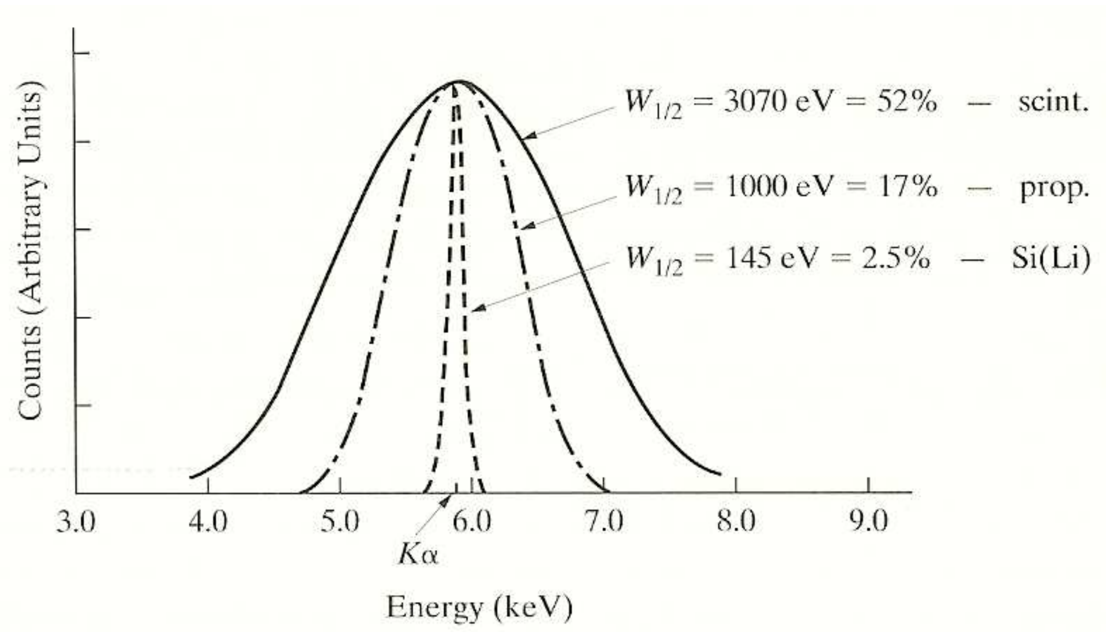
Pulse-height distribution curves



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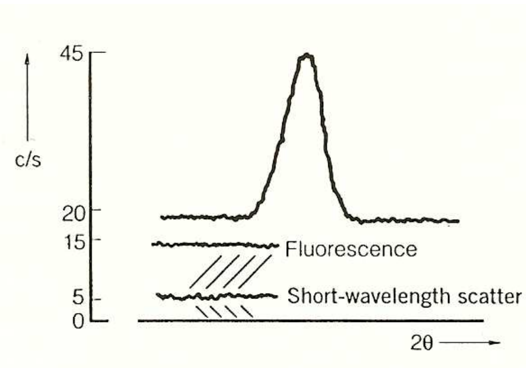
Pulse height selection (PHS)



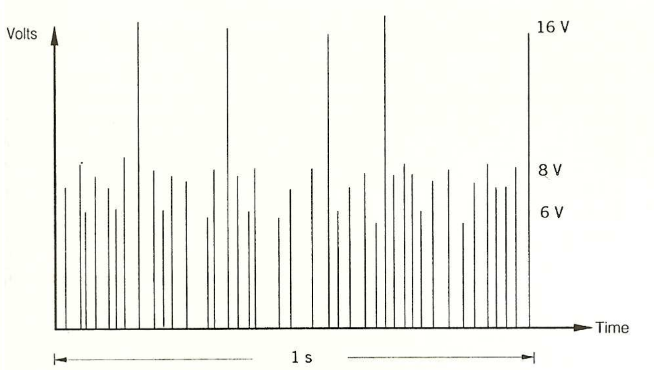
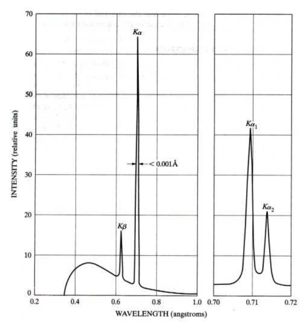


Figure 5.8. The pulse height selector.

- Different energy → different size of voltage pulse → can be electronically discriminated --- PHS, pulse height analyzer (PHA)
- Can remove such effects as sample fluorescence & BKG that may arise from short wavelength X-rays from X-ray tube continuum that pass the b filter



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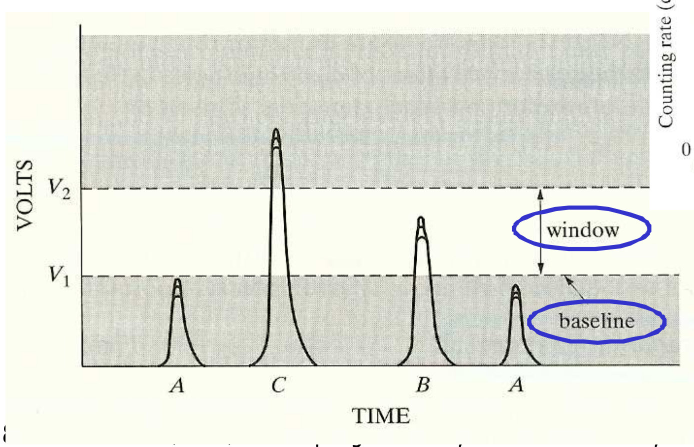
Pulse height selection (PHS)

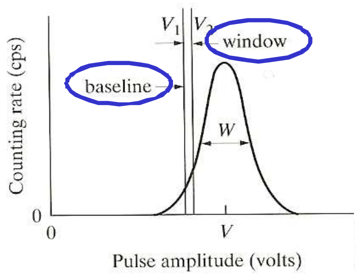
- Proportional, scintillation semiconductor detectors "proportional" ; they produce pulses having a size proportional to the energy of the incident X-rays
- If pulses of different size can be distinguished, X-rays of different energies can be distinguished

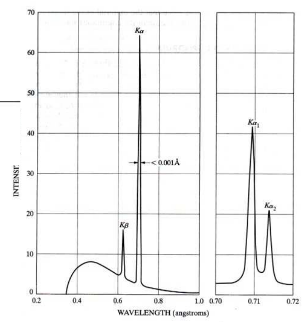
- Pulse-height discriminator
- Single-channel pulse-height analyzer
- Multi-channel pulse-height analyzer (MCA)

Pulse height analysis

- Pulse-height discriminator
  - ✓ Reject any pulses smaller than V_1
- Single-channel pulse-height analyzer
  - ✓ Only pulses having sizes between V_1 & V_2 can pass
  - ✓ Can reduce BKG of diffraction pattern by excluding short l white radiation
- Multi-channel pulse-height analyzer (MCA)
  - ✓ Can separate pulses from a detector that is receiving incident radiation of many wavelengths, by sorting pulses acc



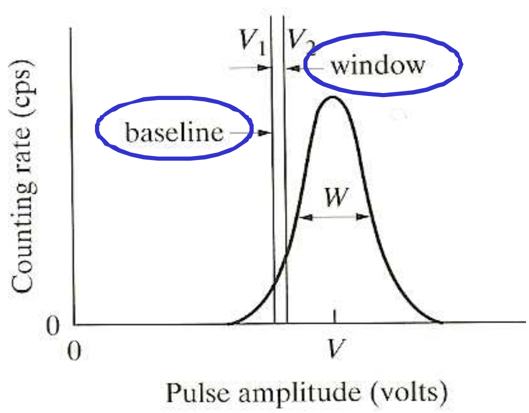




Cullity

Pulse height analysis

- Pulse-height discriminator
- Single-channel pulse-height analyzer
  - ✓ Entire energy range is scanned serially in time by moving channel
- Multi-channel pulse-height analyzer (MCA)
  - ✓ A large number of fixed channels cover the entire range
  - ✓ All channels simultaneously receive the count-rate information appropriate to each channel



Cullity