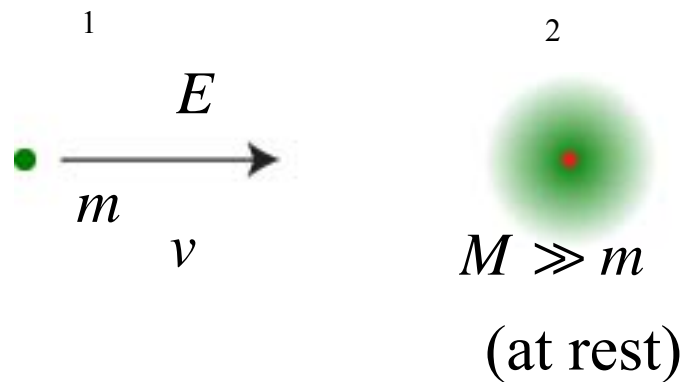


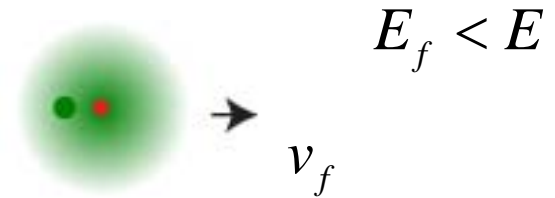
# Some inelastic scattering processes

- 1) Collective Excitations
  - a) Plasmons: Electric-Field Oscillations
  - b) Phonons: Lattice Vibrations
- 2) X-Ray Emission
  - a) Characteristic X-Rays (Ionization of Atoms)
  - b) Bremsstrahlung (Braking Radiation)
- 3) Secondary Electron Generation
  - a) Slow (<50 eV)/Fast
  - b) Auger Electron Emission (By Ionization)
- 4) Electron-Hole Pair Generation→Cathodoluminescence
- 5) Beam Damage
  - a) Radiolysis: Bond Breaking/Alteration
  - b) Knock-On Damage: Displacement of Atoms

# Head-on inelastic collision in 1-D



*forward scattering*

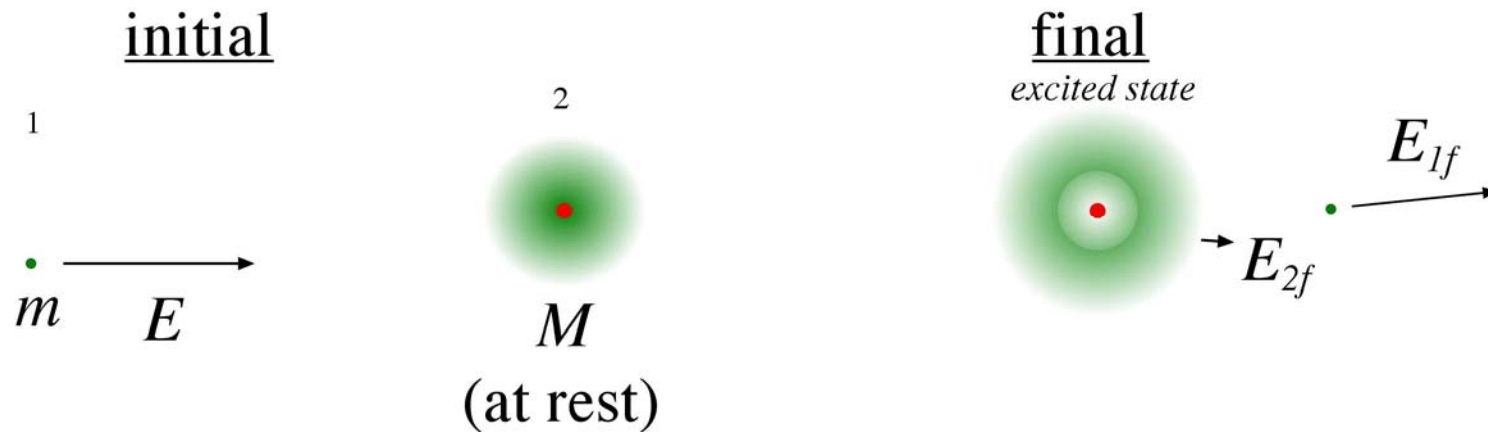


$$E_f = \left( \frac{m}{m+M} \right) \cdot E \quad // \text{inelastic}$$

center-of-mass motion:

$$v_f = v_{COM} = \left( \frac{m}{m+M} \right) \cdot v \quad // \text{forward}$$

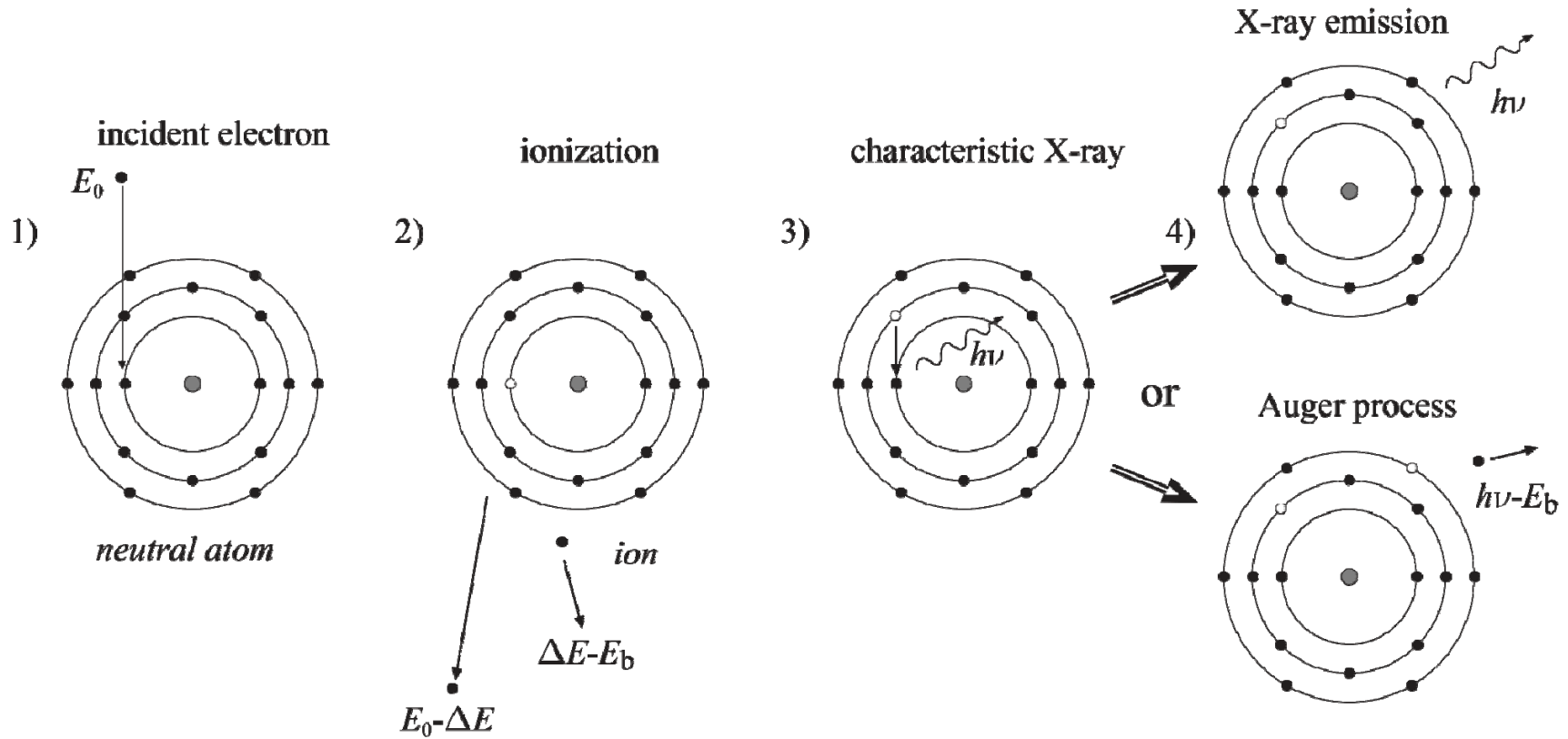
# Inelastic scattering in 2-D



$$\text{inelastic} : E > E_{1f} + E_{2f}$$

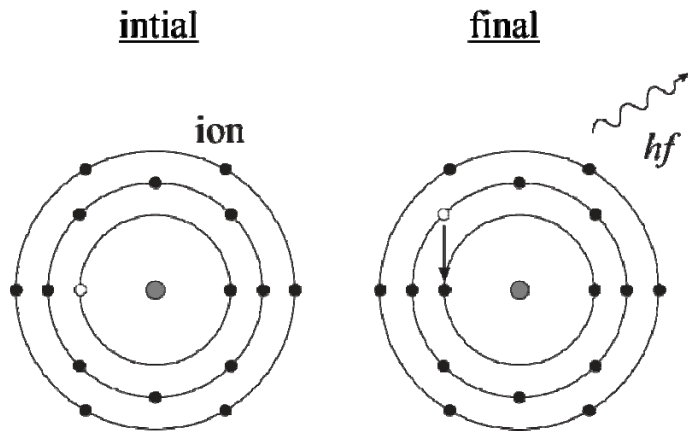
- Change (usually reduction) in total kinetic energy
- Some energy transferred to excitation of atom
- Electron loses energy  $\Rightarrow$  incoherent
- Usually results in forward scattered electrons

# X-Ray generation by ionization



- Core electron ejected (ionization)
- Hole filled by outer shell electron
- X-ray emission
- Possible Auger process

# Characteristic X-rays: Moseley's Law



$$hf \approx (Z - Z_{enc})^2 \cdot E_R \cdot \left( \frac{1}{n_i^2} - \frac{1}{n_j^2} \right)$$

electron energies:

$$E_i \approx -\frac{(Z - Z_{i,enc})^2}{n_i^2} \cdot E_R \quad E_j \approx -\frac{(Z - Z_{j,enc})^2}{n_j^2} \cdot E_R$$

$$hf = \frac{hc}{\lambda}$$

$$Z_{i,enc} \approx Z_{j,enc} = Z_{enc}$$

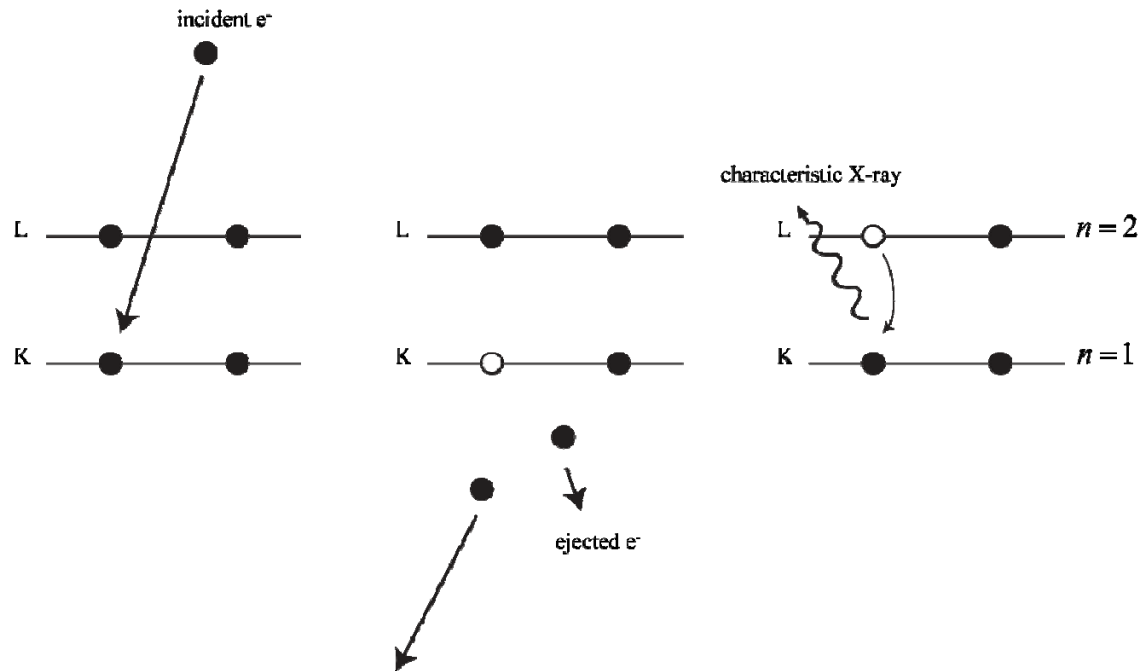
$$\lambda \approx \frac{hc}{(Z - Z_{enc})^2 \left( \frac{1}{n_i^2} - \frac{1}{n_j^2} \right) \cdot E_R} = \frac{B}{(Z - C)^2}$$

$$E_R = 13.6 \text{ eV}$$

# Characteristic X-ray: notation

## *Shells*

<u><math>n</math></u>	<u>letter</u>
1	K
2	L
3	M
...	

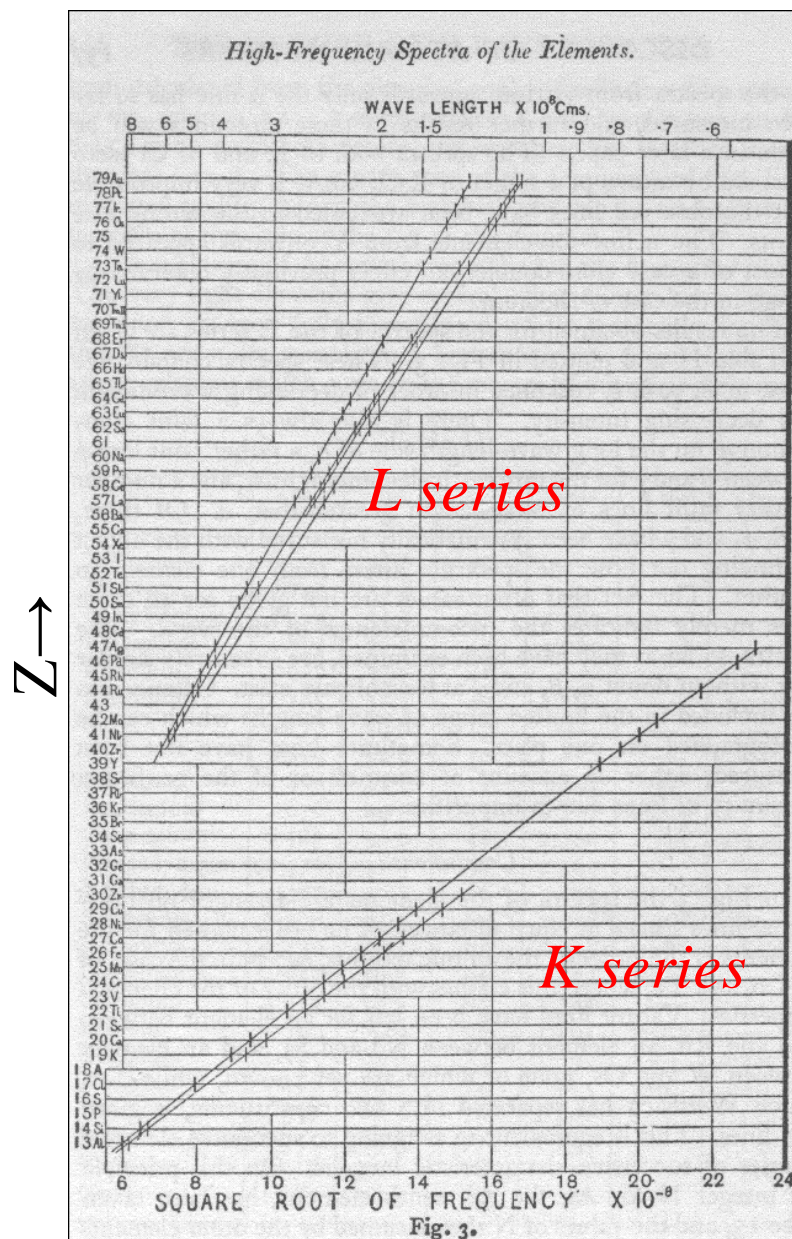


## *Transitions*

$K\alpha$ :  $2 \rightarrow 1$  (L  $\rightarrow$  K)  
 $K\beta$ :  $3 \rightarrow 1$  (M  $\rightarrow$  K)  
 $L\alpha$ :  $3 \rightarrow 2$  (M  $\rightarrow$  L)

...

# Moseley's Law



Energies of characteristic X-ray lines depend on atomic number.

$$Z \propto \sqrt{f} + C$$

H. G. J. Moseley, Phil. Mag. (1913), p. 1024

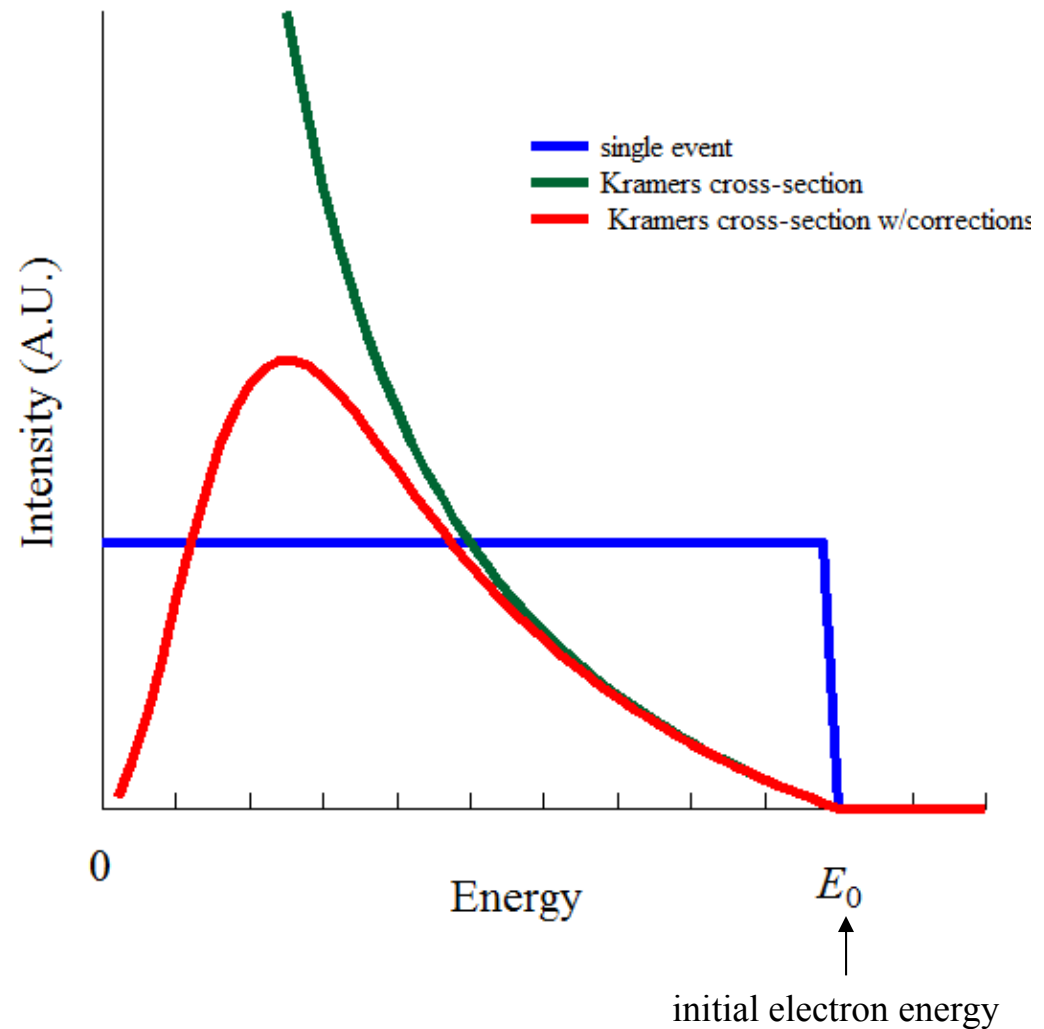
# Bremstrahlung spectra

single event:

$$\frac{dN}{dE} = \begin{cases} \text{constant,} & E \leq E_0 \\ 0, & E_0 < E \end{cases}$$

Kramers, multiple events:

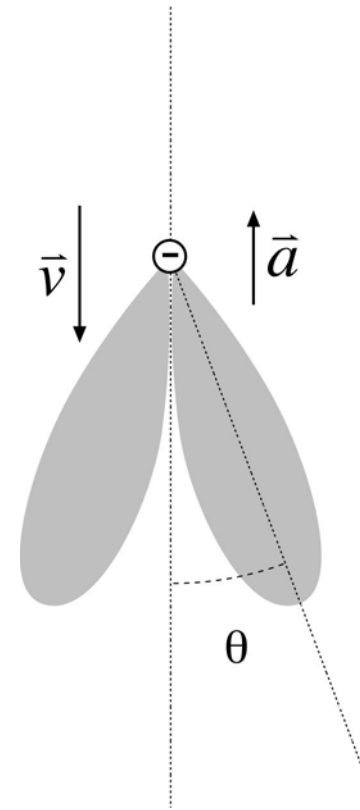
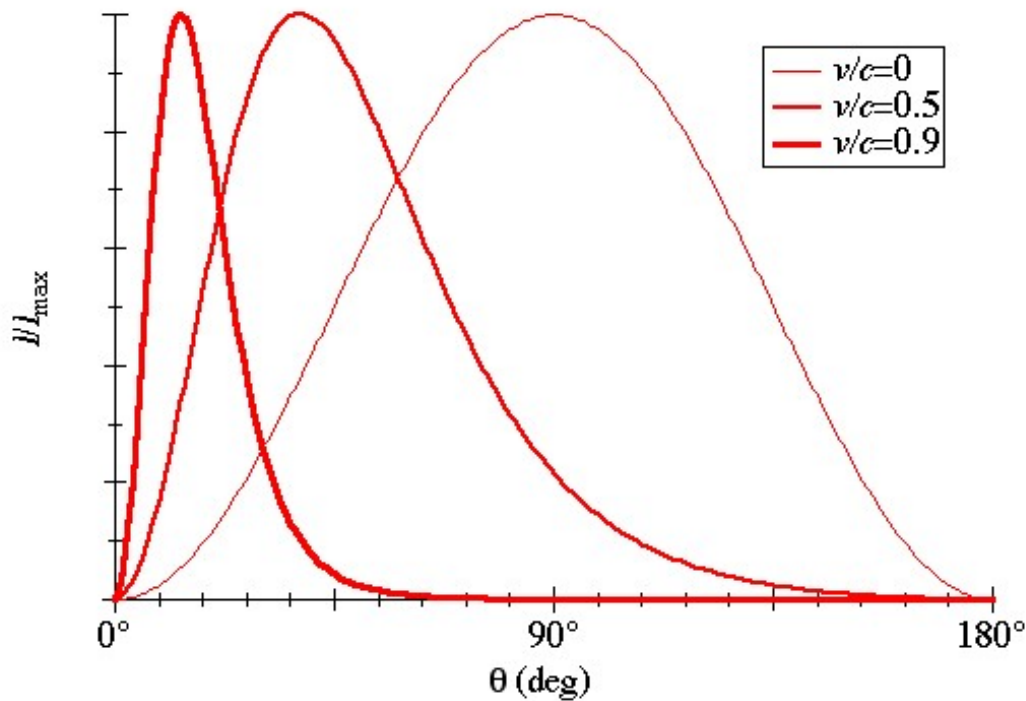
$$I(E) \propto Z \cdot \left( \frac{E_0}{E} - 1 \right)$$





# Bremsstrahlung X Rays: Direction of emission

- Plume of X-rays emitted by accelerating electric charge
- Continuous spectrum



# Bremsstrahlung: Angular distribution

$$I(\theta) \propto \frac{a^2 \cdot \sin^2 \theta}{(1 - \beta \cdot \cos \theta)^5}$$

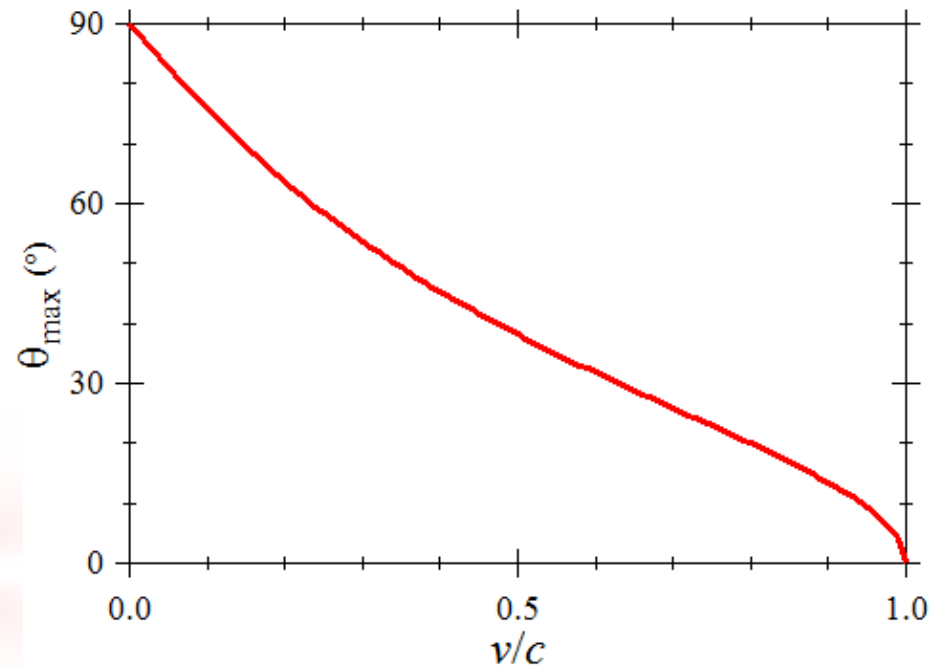
//angular distribution of radiation

$$\left. \frac{dI}{d\theta} \right|_{\theta_{\max}} = 0$$

↓

$$\theta_{\max} = \cos^{-1} \left[ \frac{1}{3\beta} \left( \sqrt{1 + 15\beta^2} - 1 \right) \right]$$

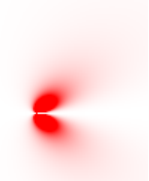
$$\beta = v/c$$



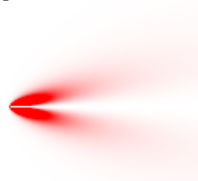
$\beta = 0$



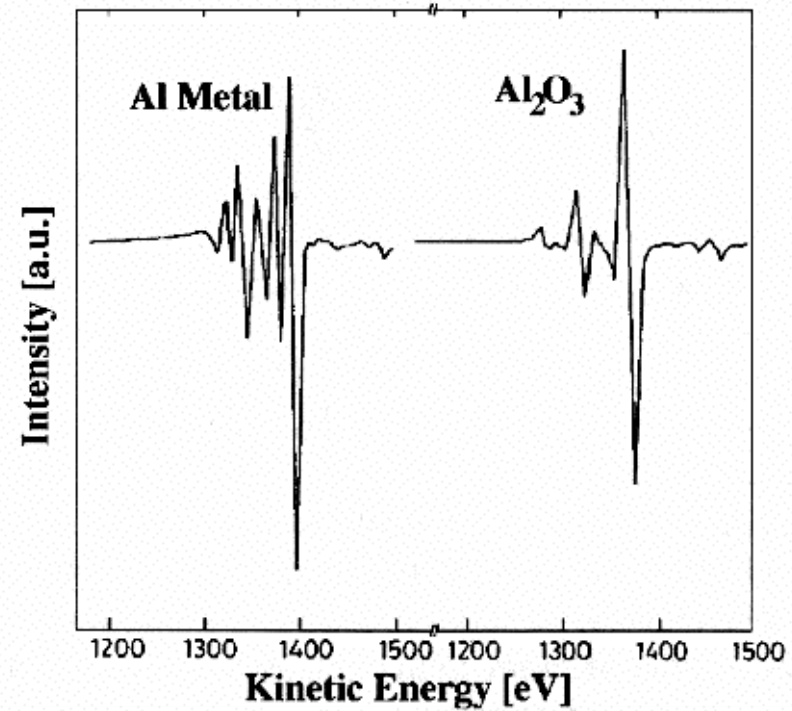
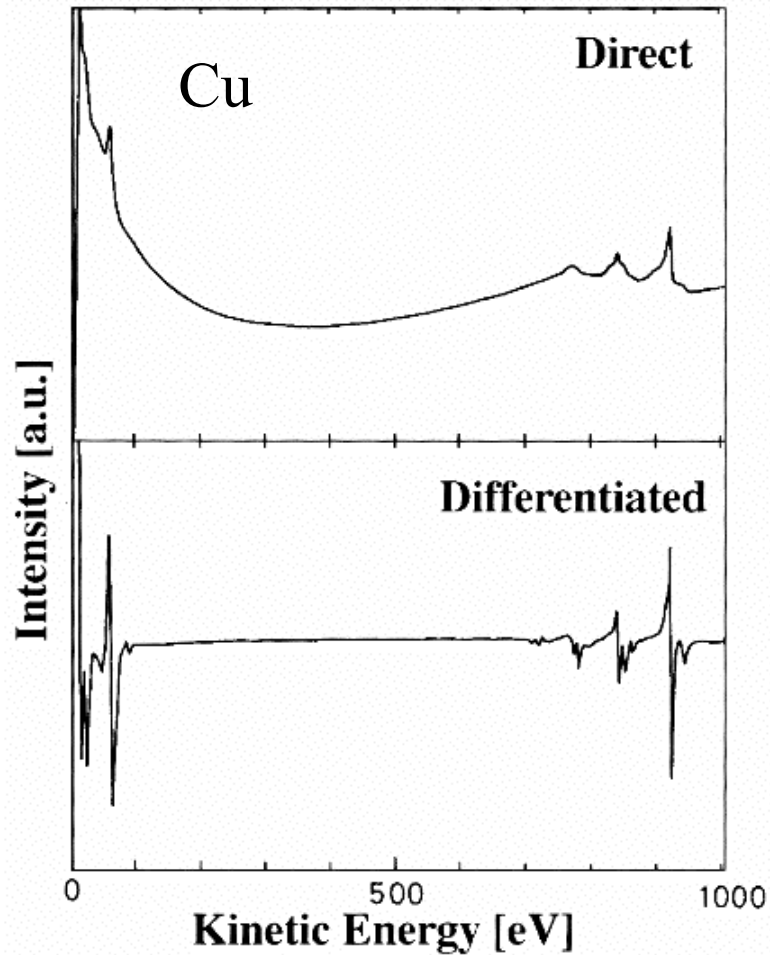
$\beta = 0.5$



$\beta = 0.9$

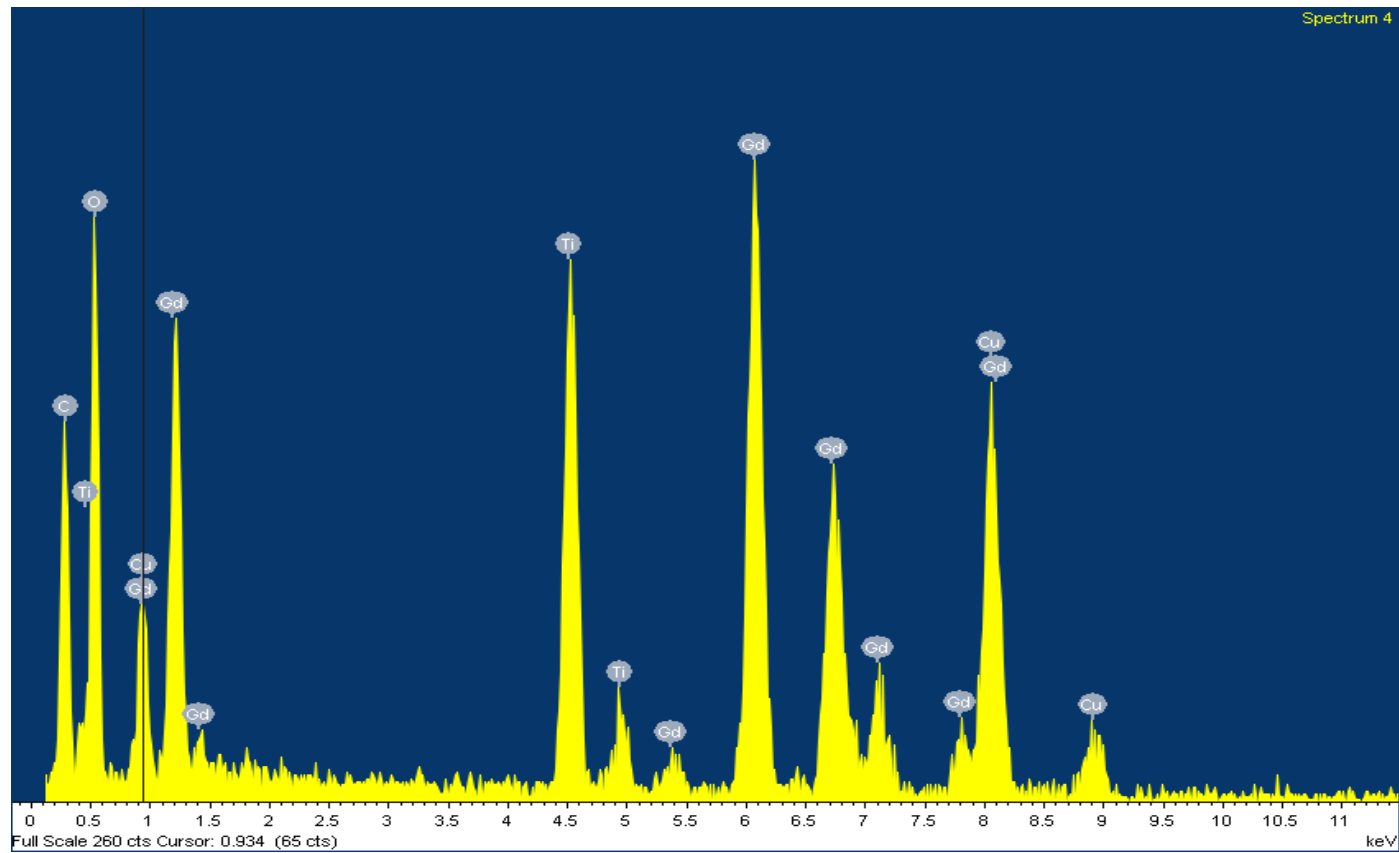


# Auger Spectra



Sensitive to chemical bonding

# EDX Spectra



E (KeV)

# Minimizing Beam Damage

Steps to Minimize Damage:

- 1) Minimize beam dose
  - a) Divert beam from region of interest, when possible
  - b) Use STEM (only imaged region is irradiated)
- 2) Operate at higher KV: reduces specimen heating
- 3) Operate at lower KV: reduces local damage
- 4) Cool the specimen
- 5) Coat the specimen with a conducting film

$$[\text{dose}]: \frac{\text{C}}{\text{m}^2} \text{ or } \frac{\text{electrons}}{\text{nm}^2}$$