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

E

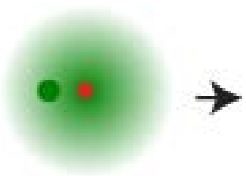
m

v

$M \gg m$

(at rest)

forward scatterng



$E_f < E$

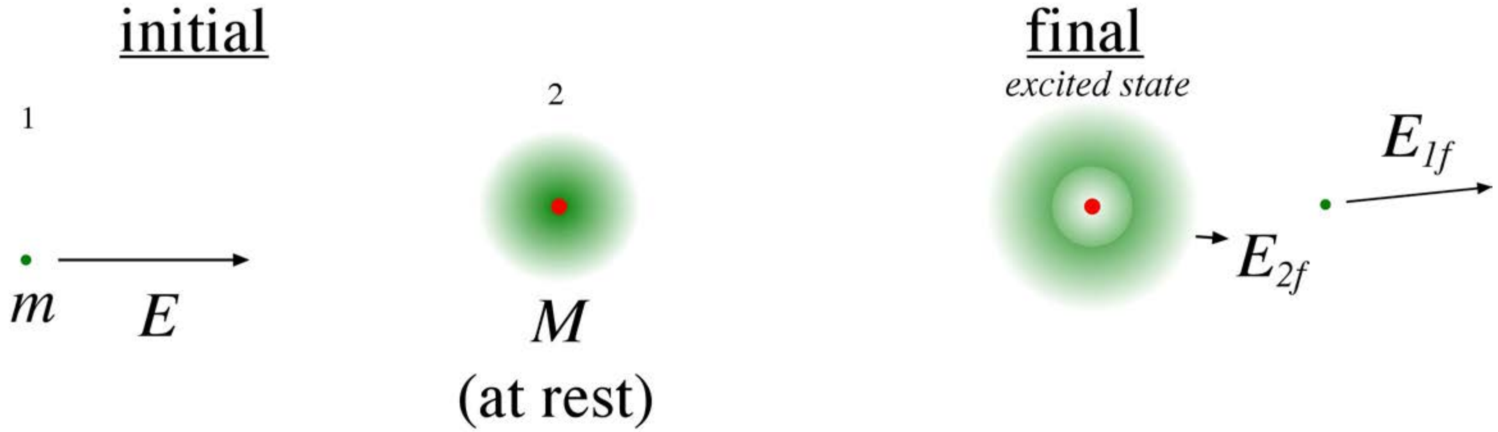
v_f

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

center-of-mass motion:

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

Inelastic scattering in 2-D



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

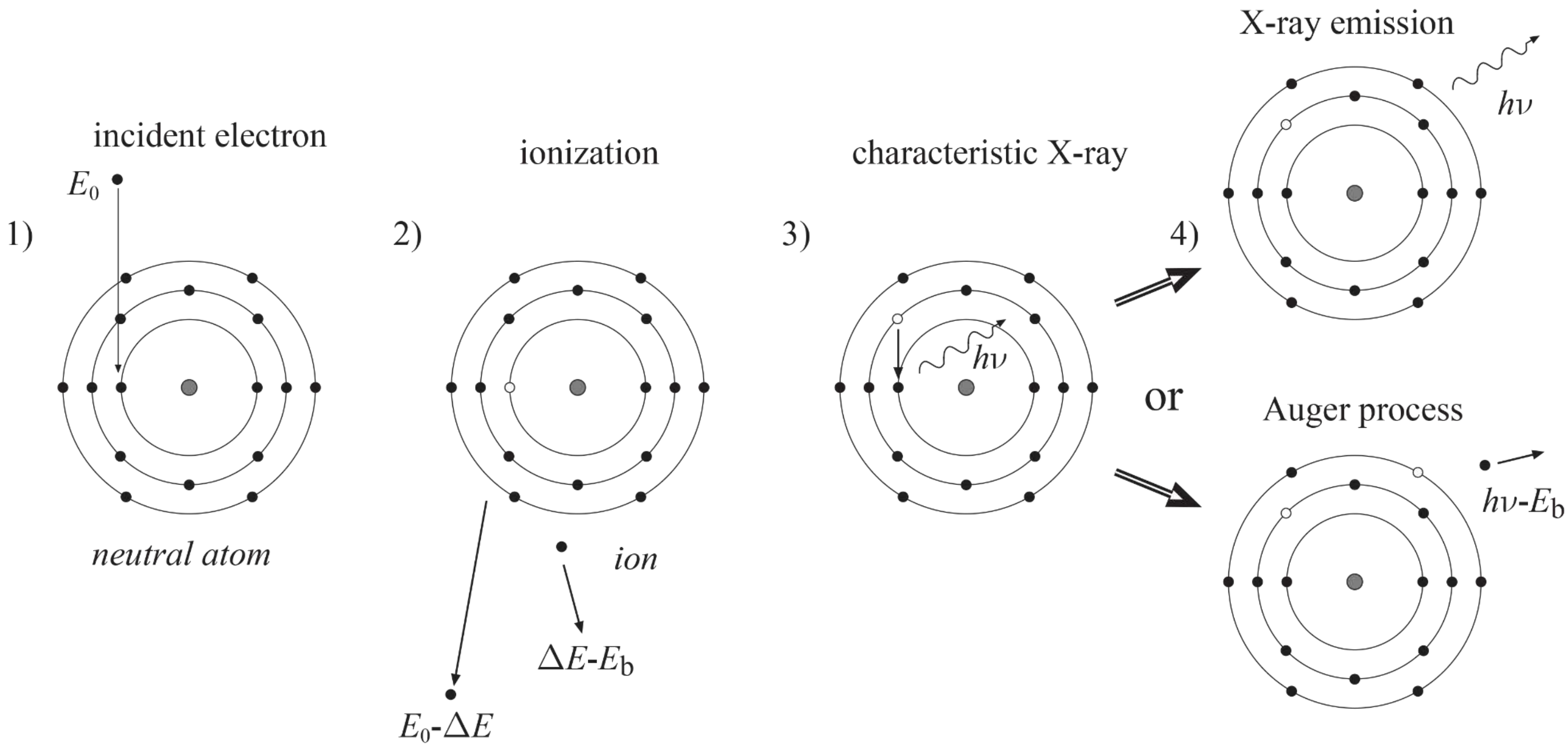
-Change (usually reduction) in total kinetic energy

-Some energy transferred to excitation of atom

-Electron loses energy $\Rightarrow$ incoherent

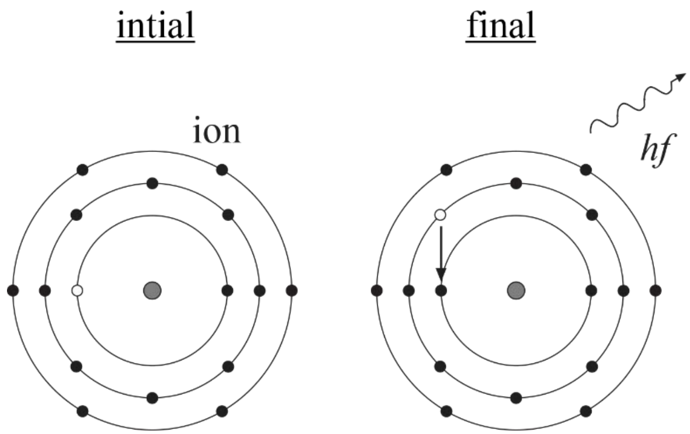
-Usually results in forward scattered electrons

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



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

electron energies:

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

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

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

Change to X-ray wavelength:

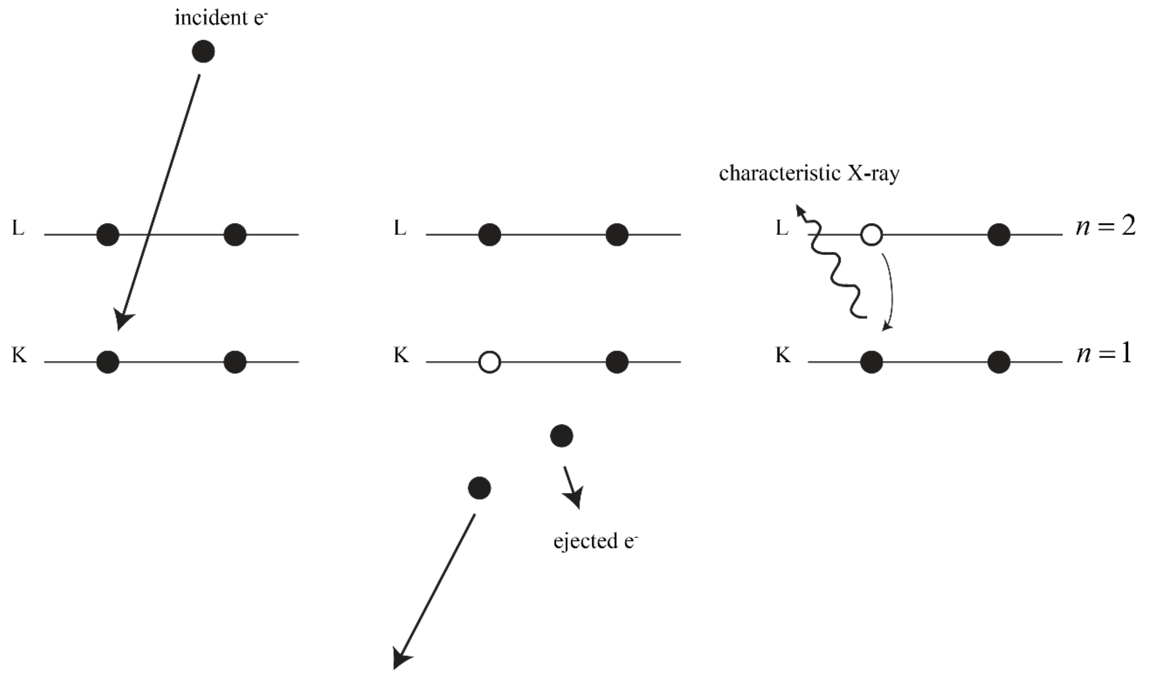
$$hf = \frac{hc}{\lambda}$$

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

Characteristic X-ray: notation

Shells

<u>*n*</u>	<u>letter</u>
1	K
2	L
3	M
…	



Transitions

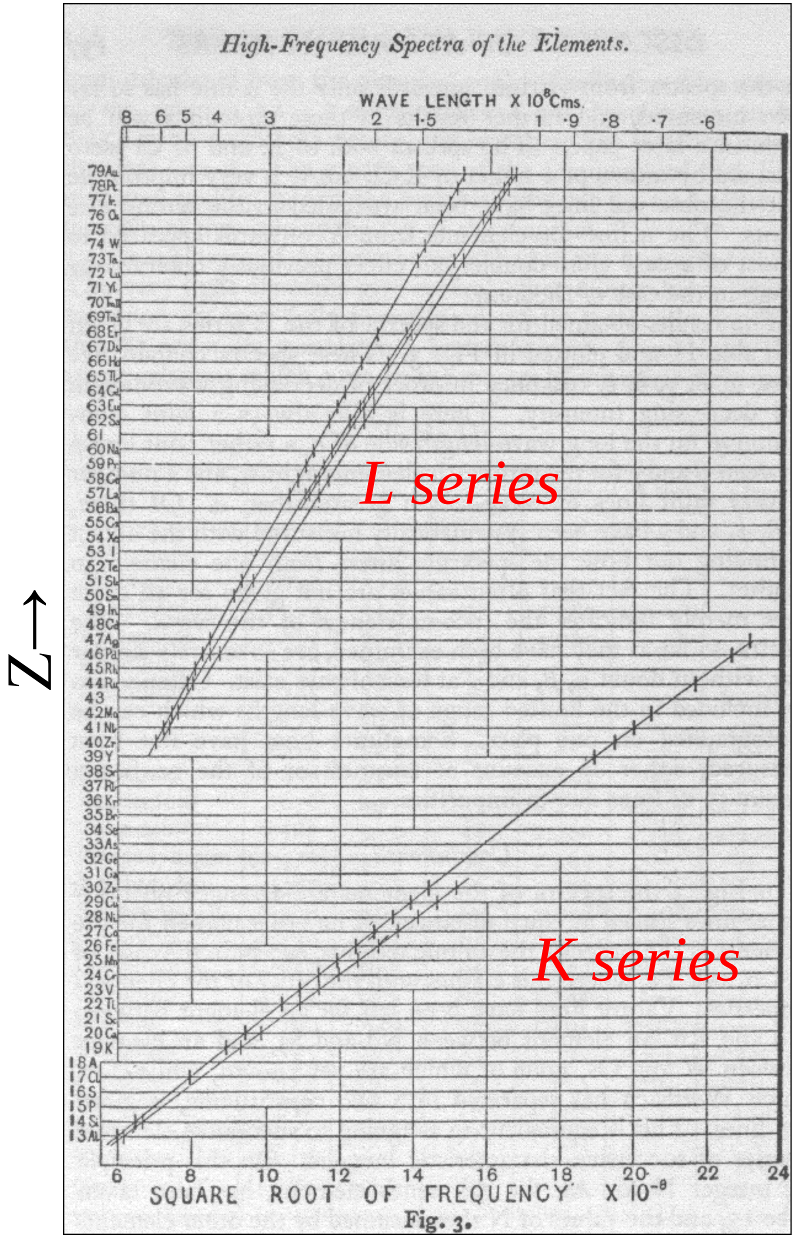
Kα: 2→1 (L →K)

Kβ: 3→1 (M →K)

Lα: 3→2 (M →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

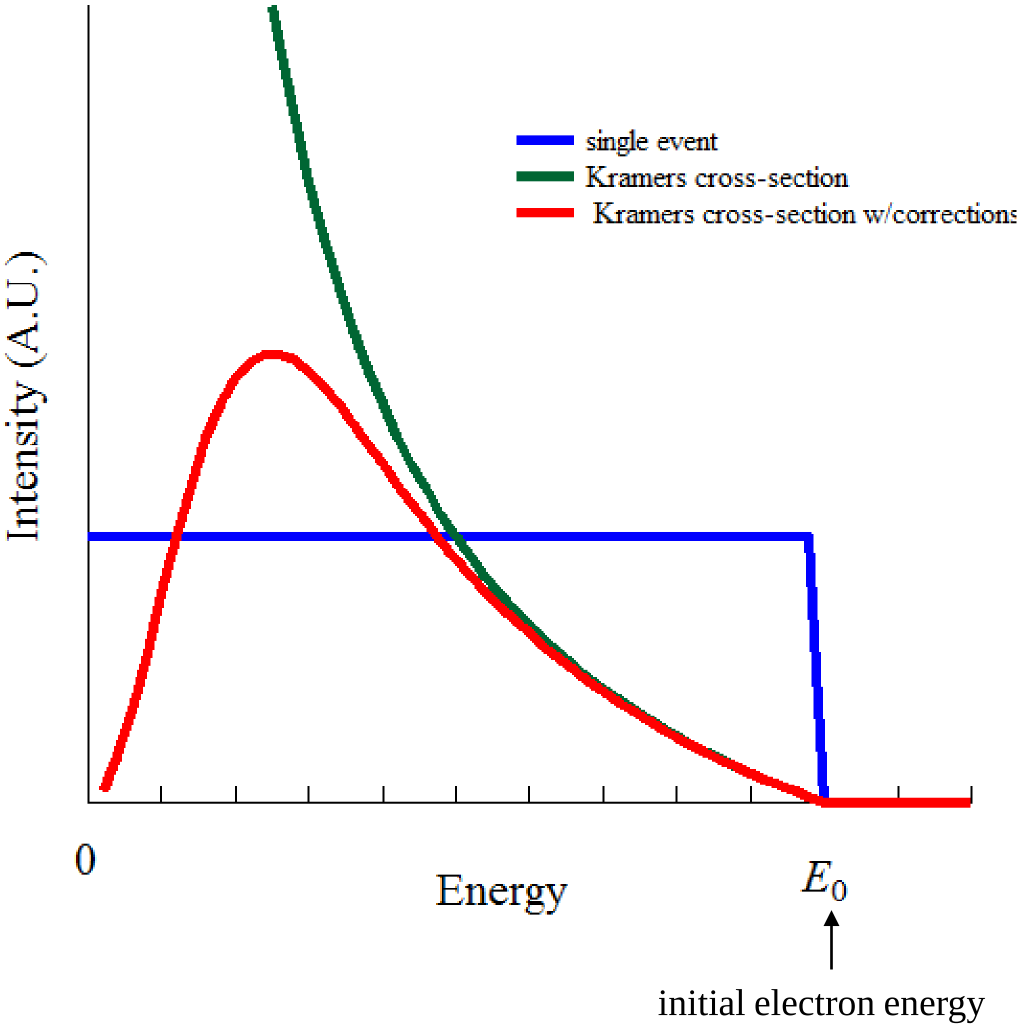
Bremstrahlung spectra

single event:

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

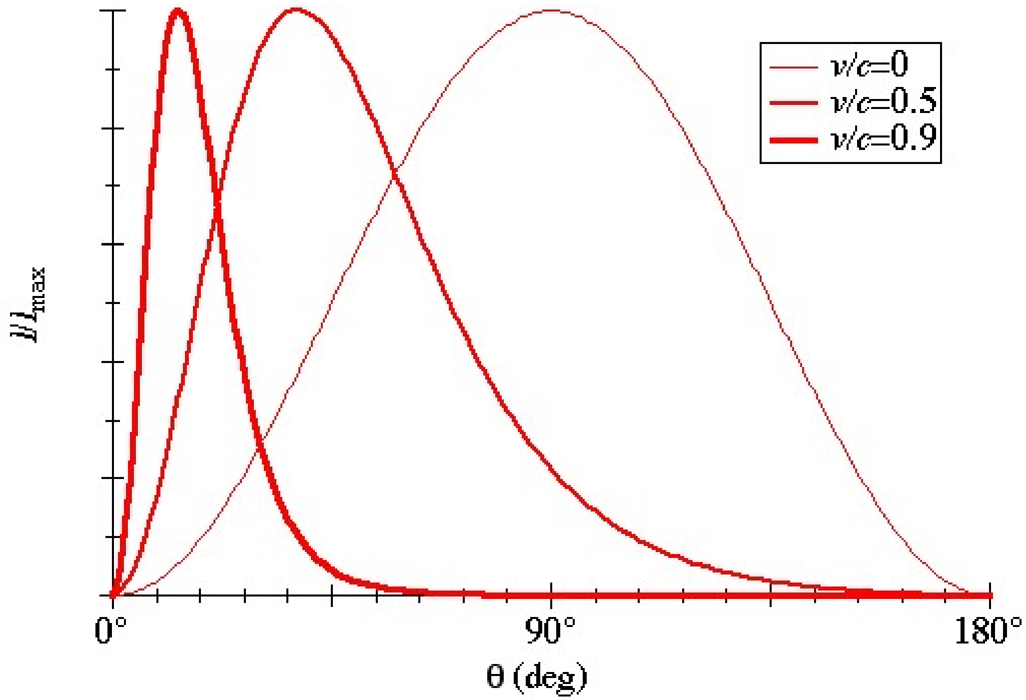
Kramers, multiple events:

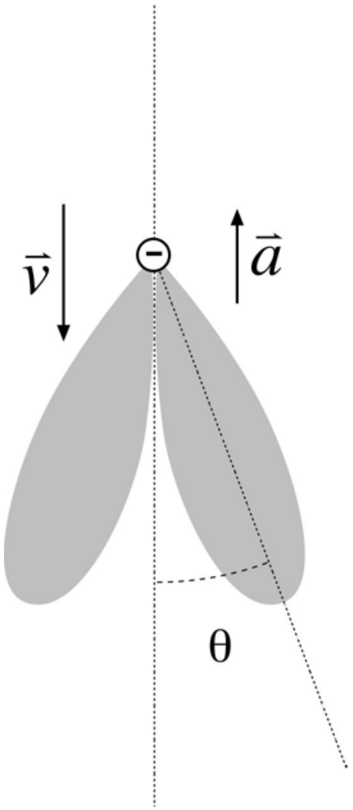
$$I(E) \propto Z \cdot \left(\frac{E_0}{E} - 1 \right)$$



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

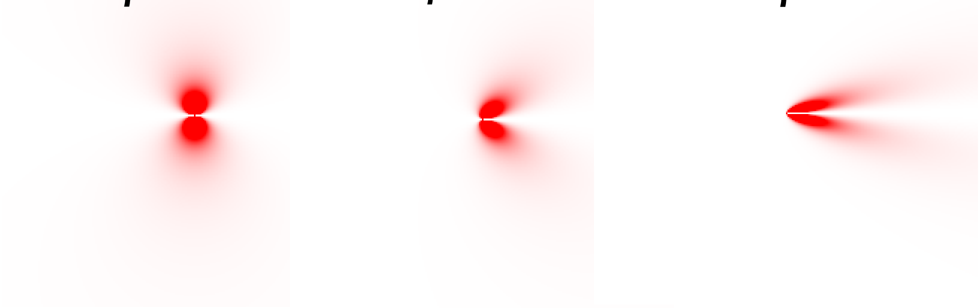
$$\beta = v/c$$

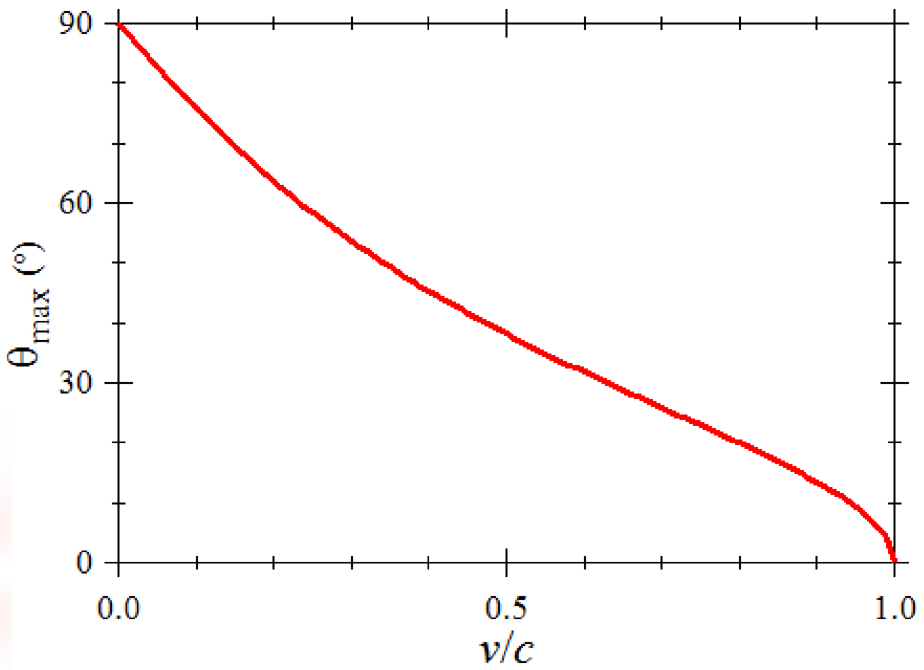
$$\left.\frac{dI}{d\theta}\right|_{\theta_{max}} = 0$$

$$\downarrow$$

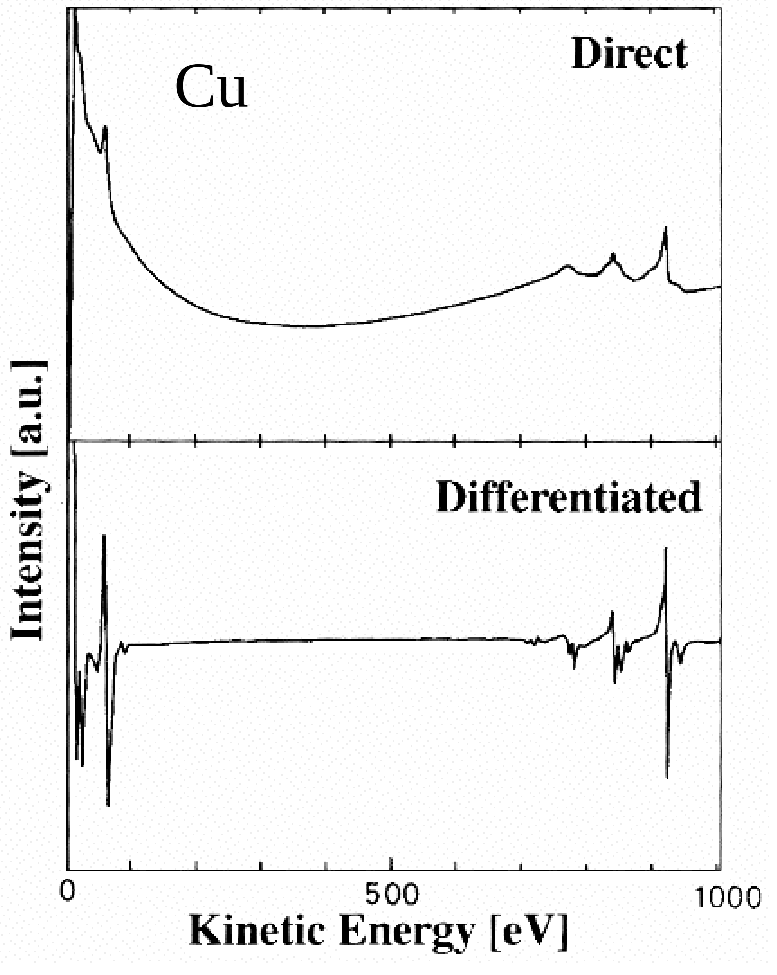
$$\theta_{max} = \cos^{-1}\left[\frac{1}{3\beta}\left(\sqrt{1+15\beta^2}-1\right)\right]$$

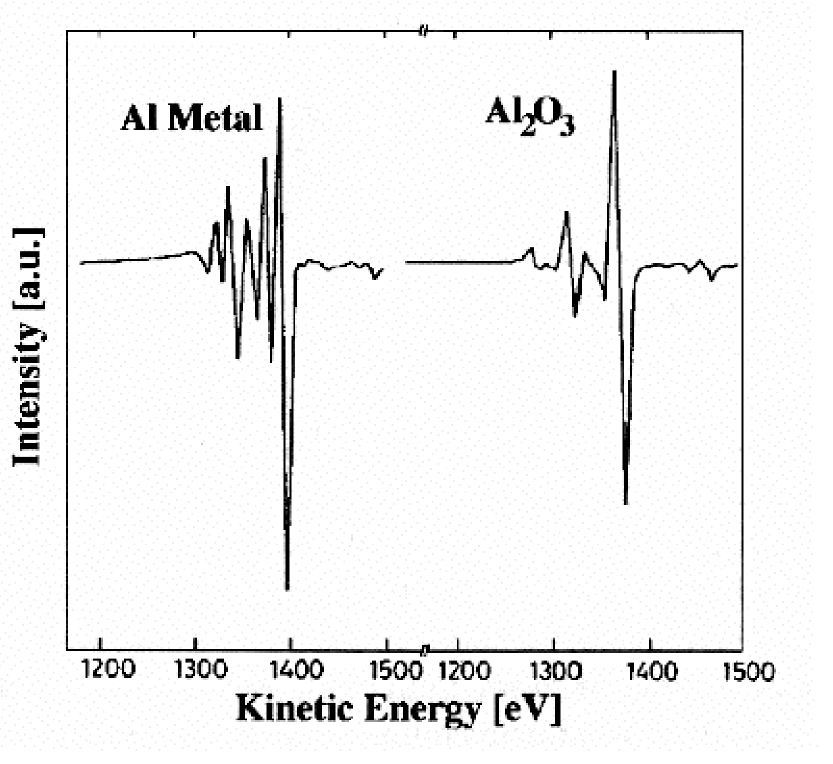
$\beta = 0$ $\beta = 0.5$ $\beta = 0.9$





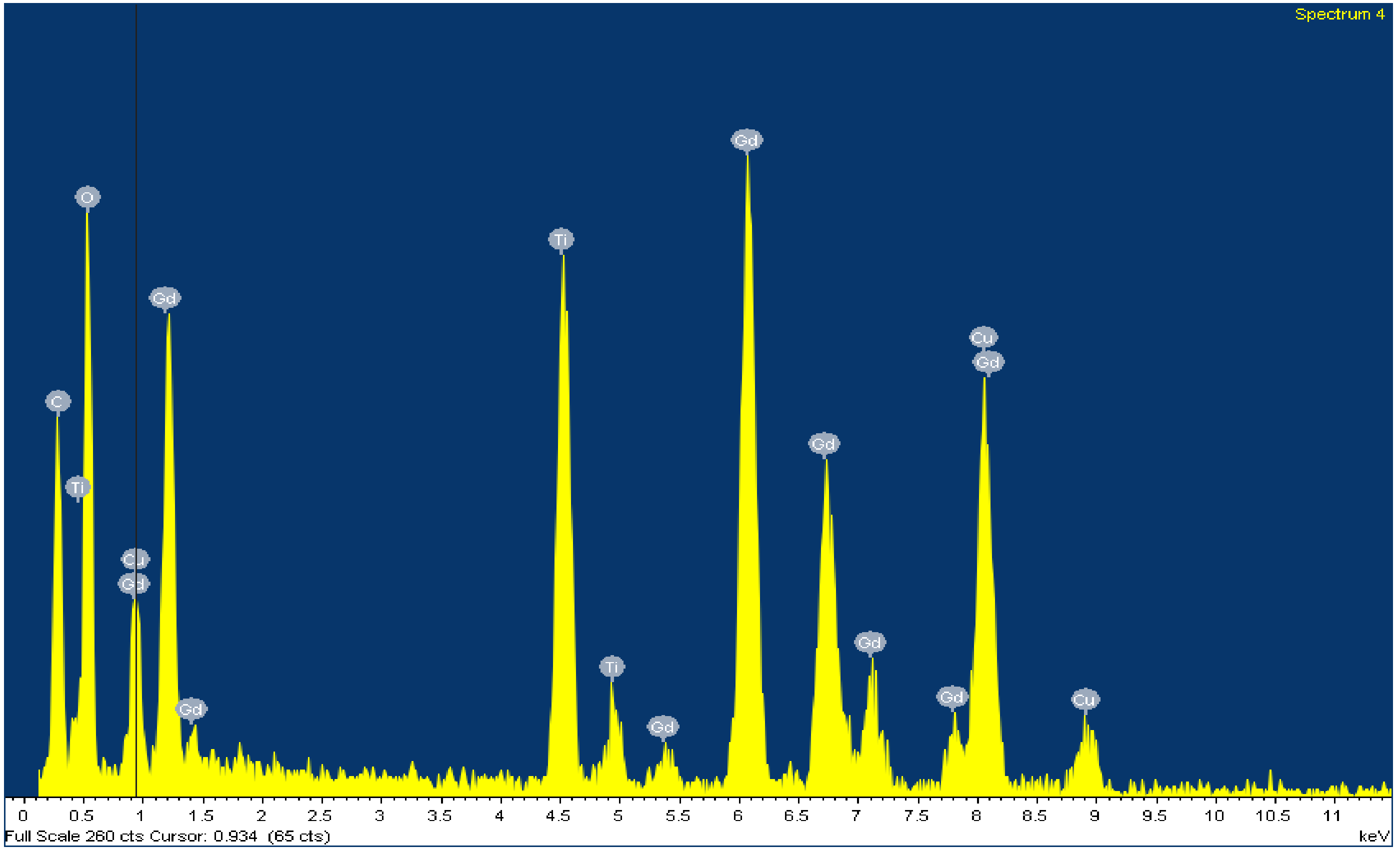
Auger Spectra





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

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