Electron scattering

Lecture 8

Electrons, photons, neutrons

Radiation	Elastic Mean Free Path (Å)	Absorption Length (Å)	Minimum Probe Size (Å)
Neutrons	10^8	10^9	10^7
X-rays	10^4	10^6	10^3
Electrons	10^2	10^3	1

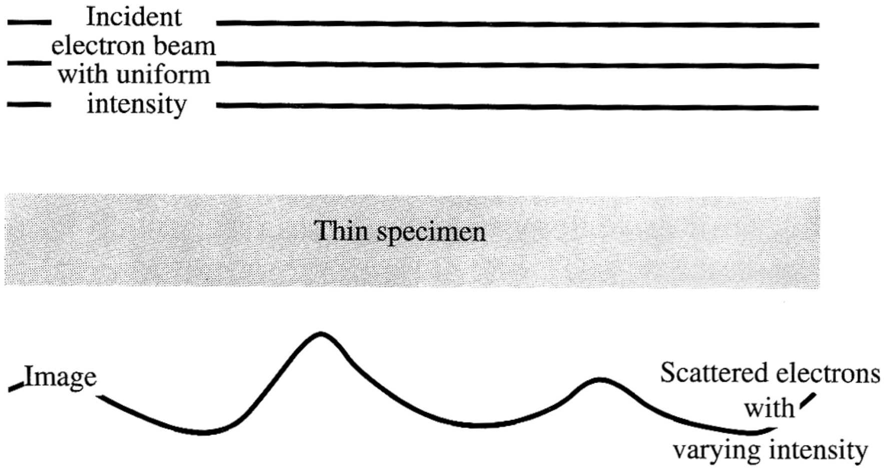
Electrons interact very strongly with matter

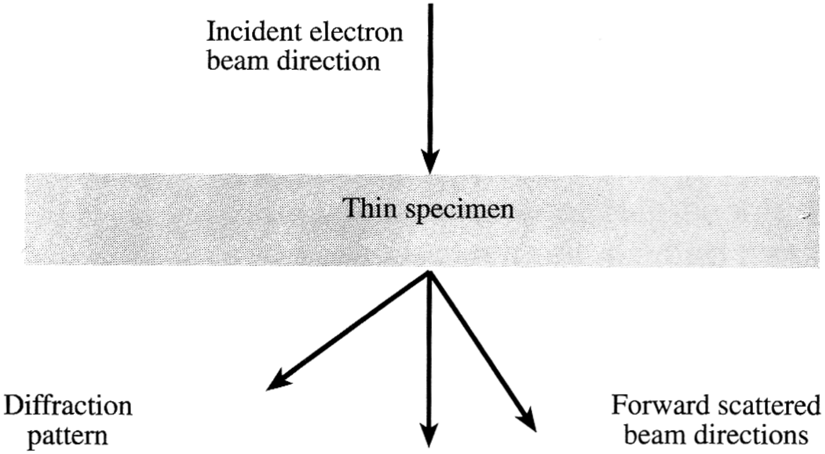
- Electrons: small, negatively charged particles, directly scatter off of atom (either nucleus or electron cloud)
- X-rays: electromagnetic waves, field exchange with electron cloud
- Neutrons: heavy, uncharged particles, scatter by direct interaction with nucleus

Role of scattering in TEM

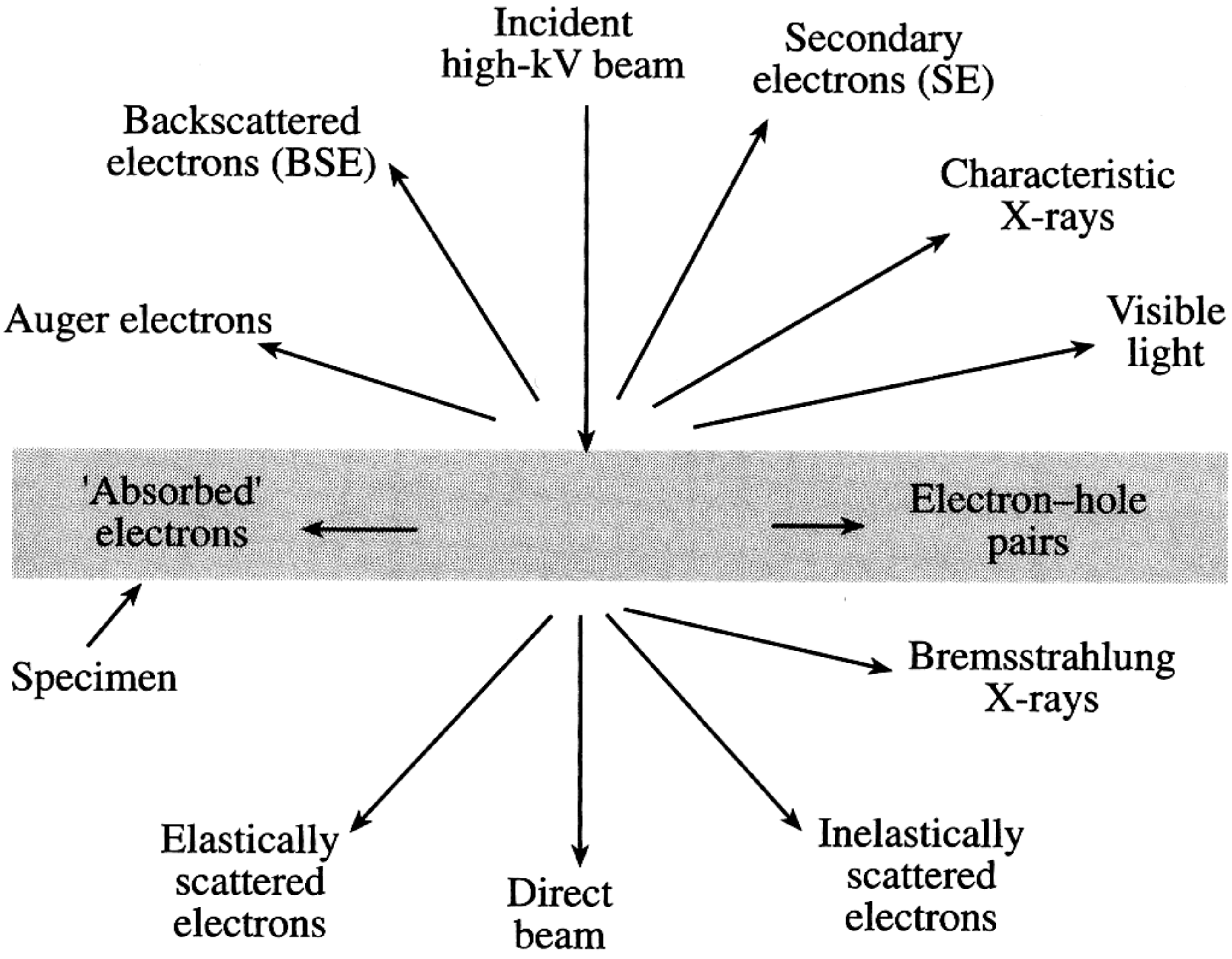
Electron scattering is the underlying physics of TEM

- Diffraction: elastic scattering
- Imaging: elastic & inelastic scattering
- Spectroscopy: inelastic scattering





Myriad of scattering processes



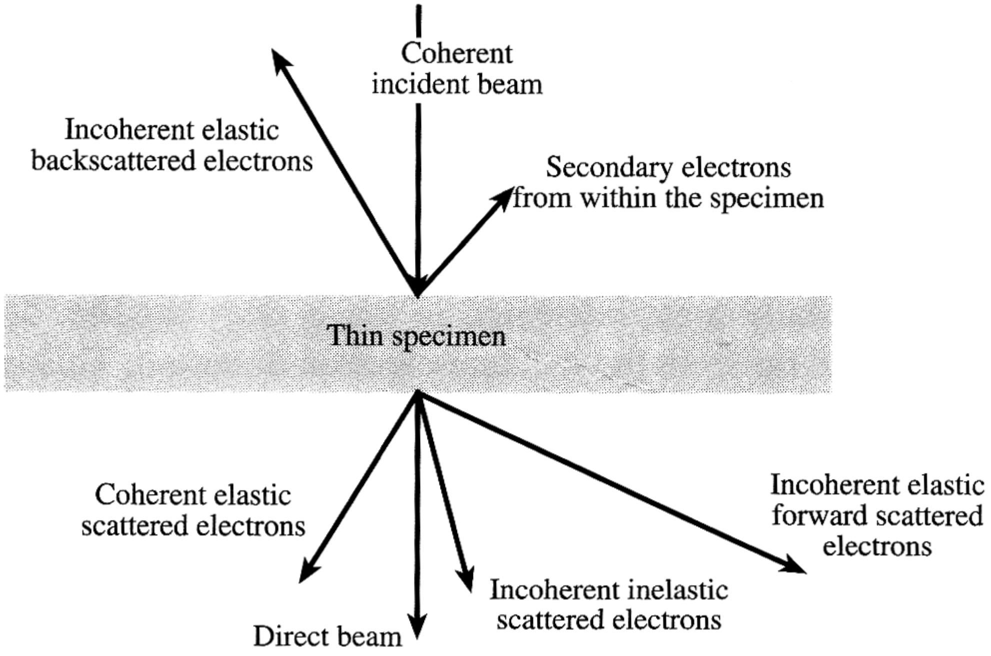
Particle vs. wave …

Particle perspective:

- Collision between electron and atom
- No energy loss: elastic
- Energy loss: inelastic

Wave perspective:

- Coherent - maintains phase
- Incoherent - does not maintain phase



Scattering terminology

Forward scattering - *thin samples*

- Elastic forward scattering is usually low angle (1-10°), coherent
- Elastic scatter is less coherent at angles > 10°
- Inelastic scatter is not coherent
  - Most is very low angle (< 1°)
  - At high angles, inelastic scatter is very sensitive to atomic weight

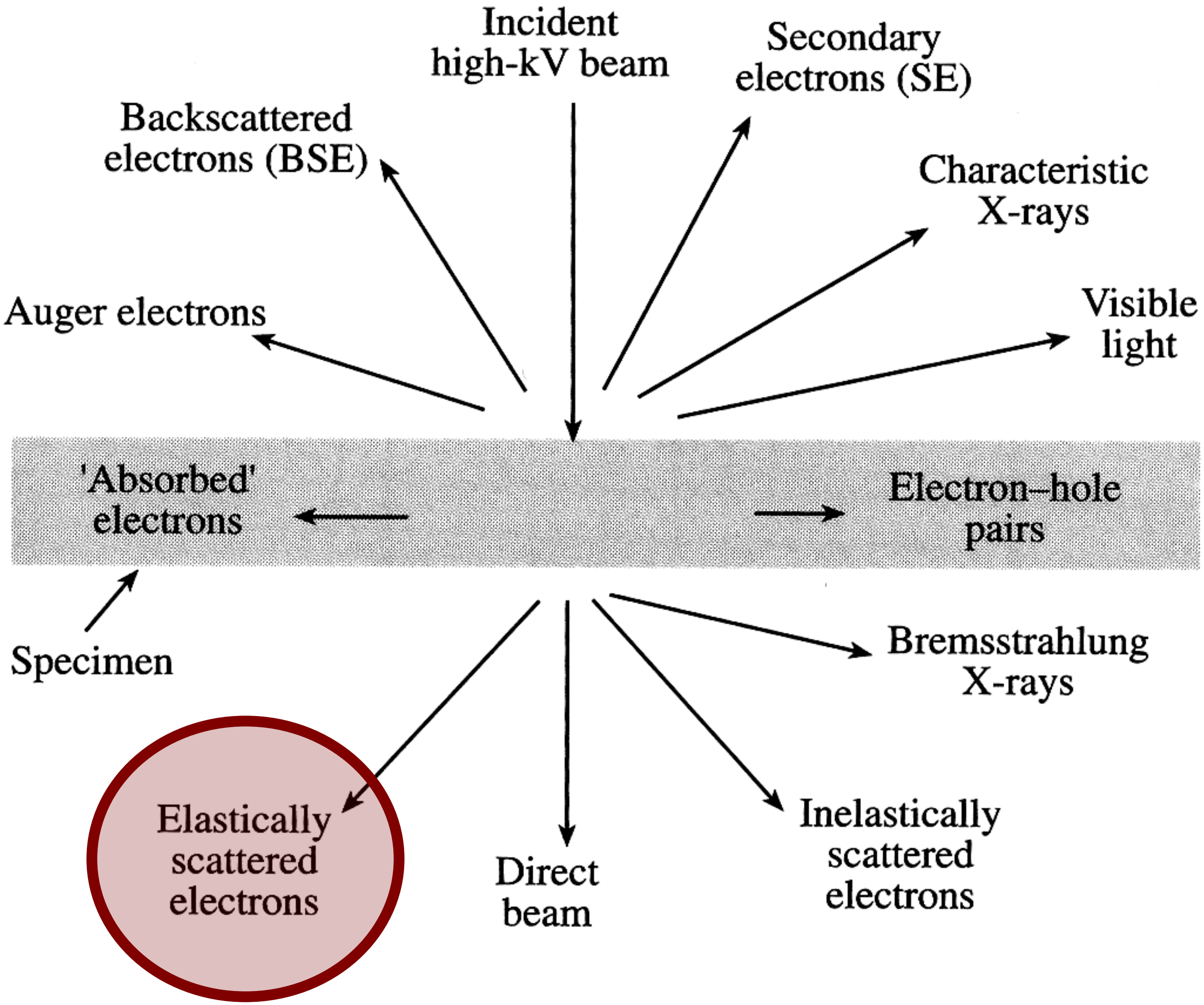
Backscattering - *thick samples*

Single scattering, vs. plural scattering vs. multiple scattering (>20 events)

- General want to be in the single to (low #) plural scattering range

Elastic scattering

particle approach only



Incident high-kV beam

Backscattered electrons (BSE)

Secondary electrons (SE)

Characteristic X-rays

Auger electrons

Visible light

'Absorbed' electrons

Electron–hole pairs

Specimen

Bremsstrahlung X-rays

Elastically scattered electrons

Direct beam

Inelastically scattered electrons

Elastic scattering

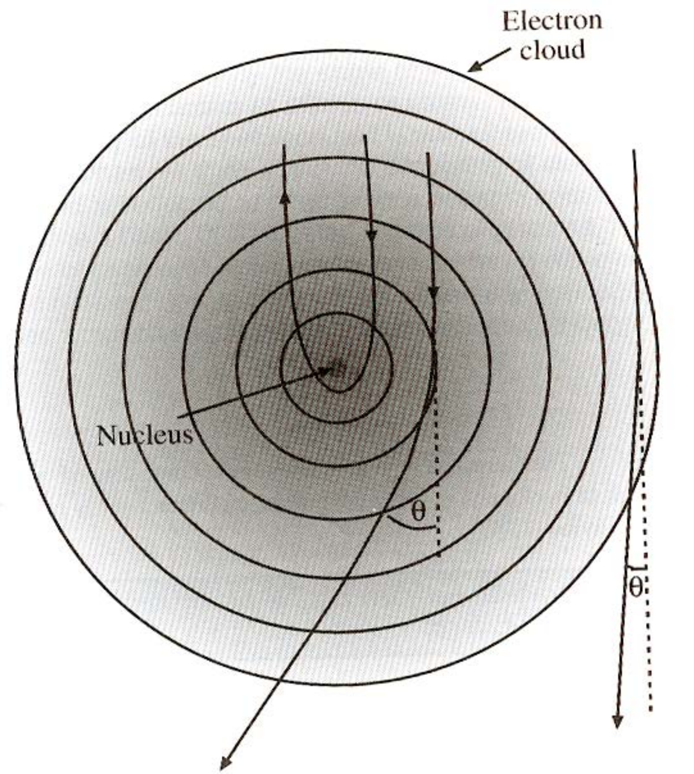
single electron / isolated atom

Interaction between electron & atom is Coulombic

- Incident electron & electron cloud
- Incident electron & nucleus

We'll want to understand:

- Interaction cross section
- Mean free path
- Differential cross section



Elastic scattering

single electron / isolated atom

Interaction cross section expresses the probability of a given scattering event. Generally:

$$\sigma = \pi \mathbf{r}^2$$

Elastic scattering radius has the form:

$$r_{\text{electron}} = \frac{e}{V\theta} \quad ; \quad r_{\text{nucleus}} = \frac{Ze}{V\theta}$$

Z = atomic weight
e = charge of the electron
V = potential of the electron
θ = angle

Implications:

$$V \Uparrow \quad \sigma \Downarrow$$

$$Z \Uparrow \quad \sigma \Uparrow$$

$$\theta \Uparrow \quad \sigma \Downarrow$$

Elastic scattering

through specimen thickness

Consider instead specimen of N atoms / unit thickness.

Total cross section for scattering from specimen:

$$Q_T = N\sigma_T = \frac{N_o \sigma_T \rho}{A}$$

N = # atoms / unit volume
r = density
A = atomic weight

Scattering probability for a sample of thickness t:

$$Q_T t = \frac{N_o \sigma_T \rho t}{A}$$

ρt ⇔ *'mass-thickness'*

Can re-arrange to give another useful concept:

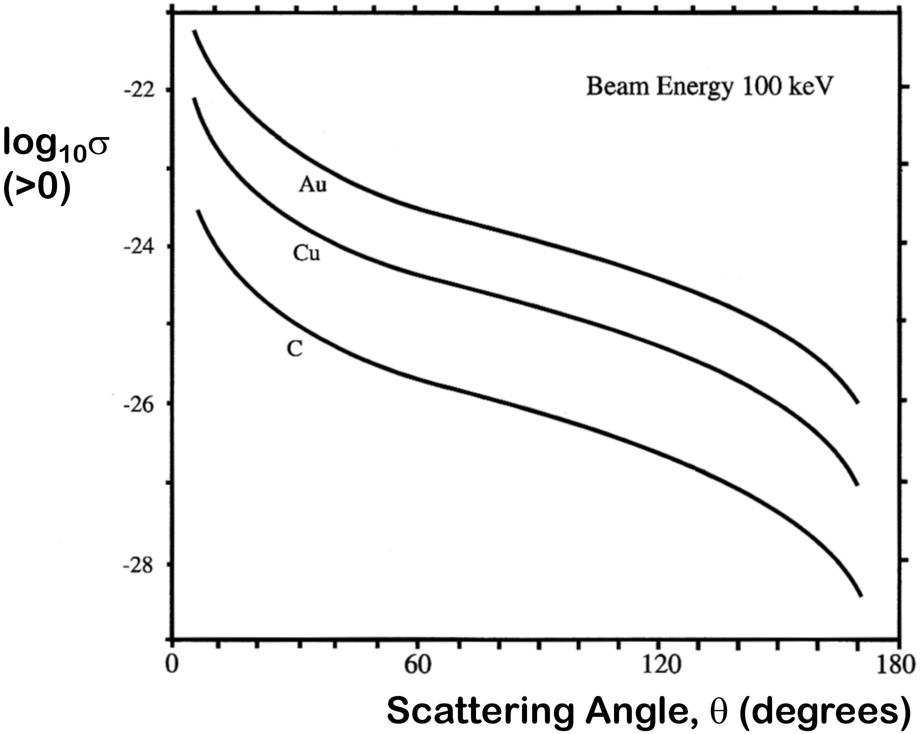
Mean free path: mfp or λ

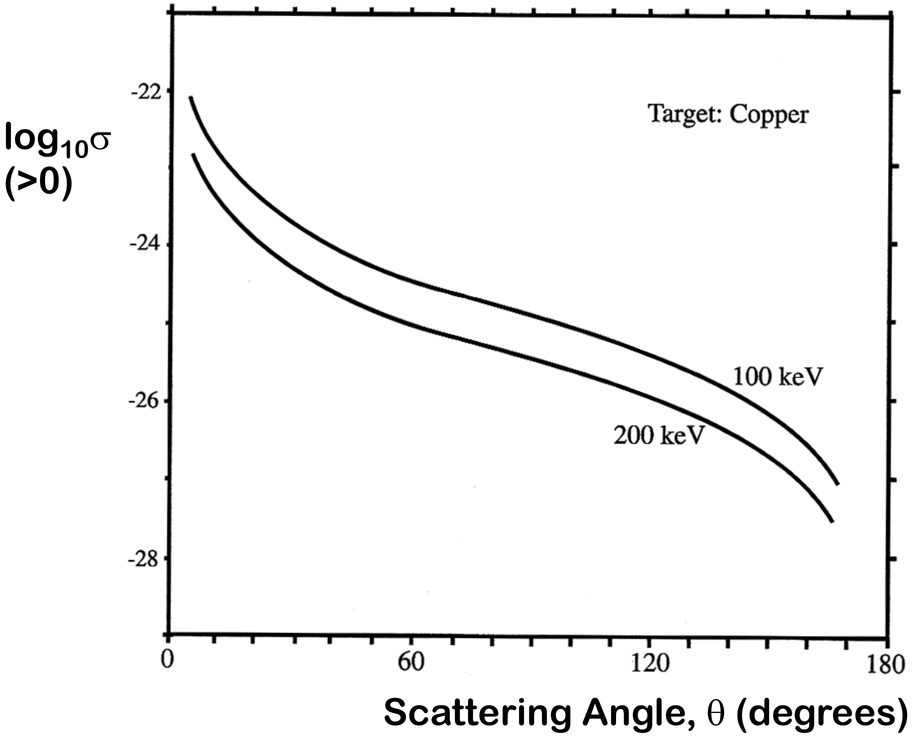
$$\text{mfp} = \frac{1}{Q} = \frac{A}{N_o \sigma_T \rho}$$

Elastic scattering

Screened relativistic Rutherford cross section

Can take into account relativistic effects, screening of the nucleus by the electron cloud (see W&C, pp. 39&40).



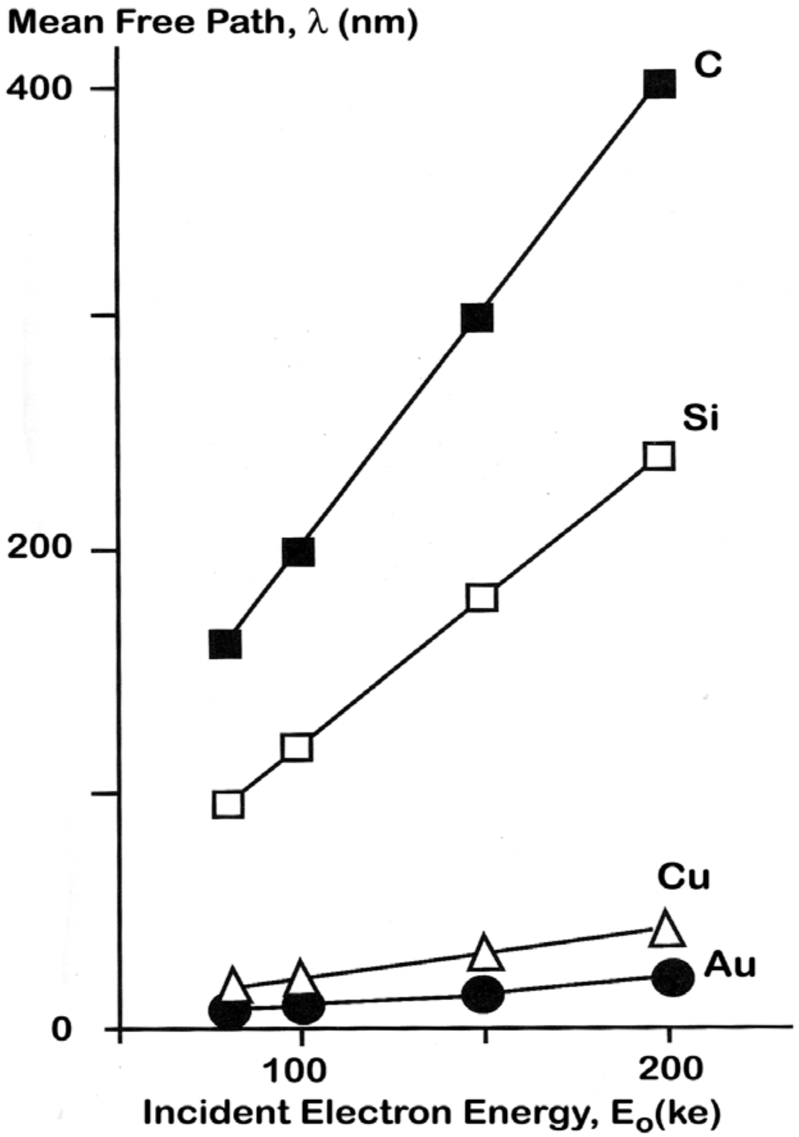


Elastic scattering

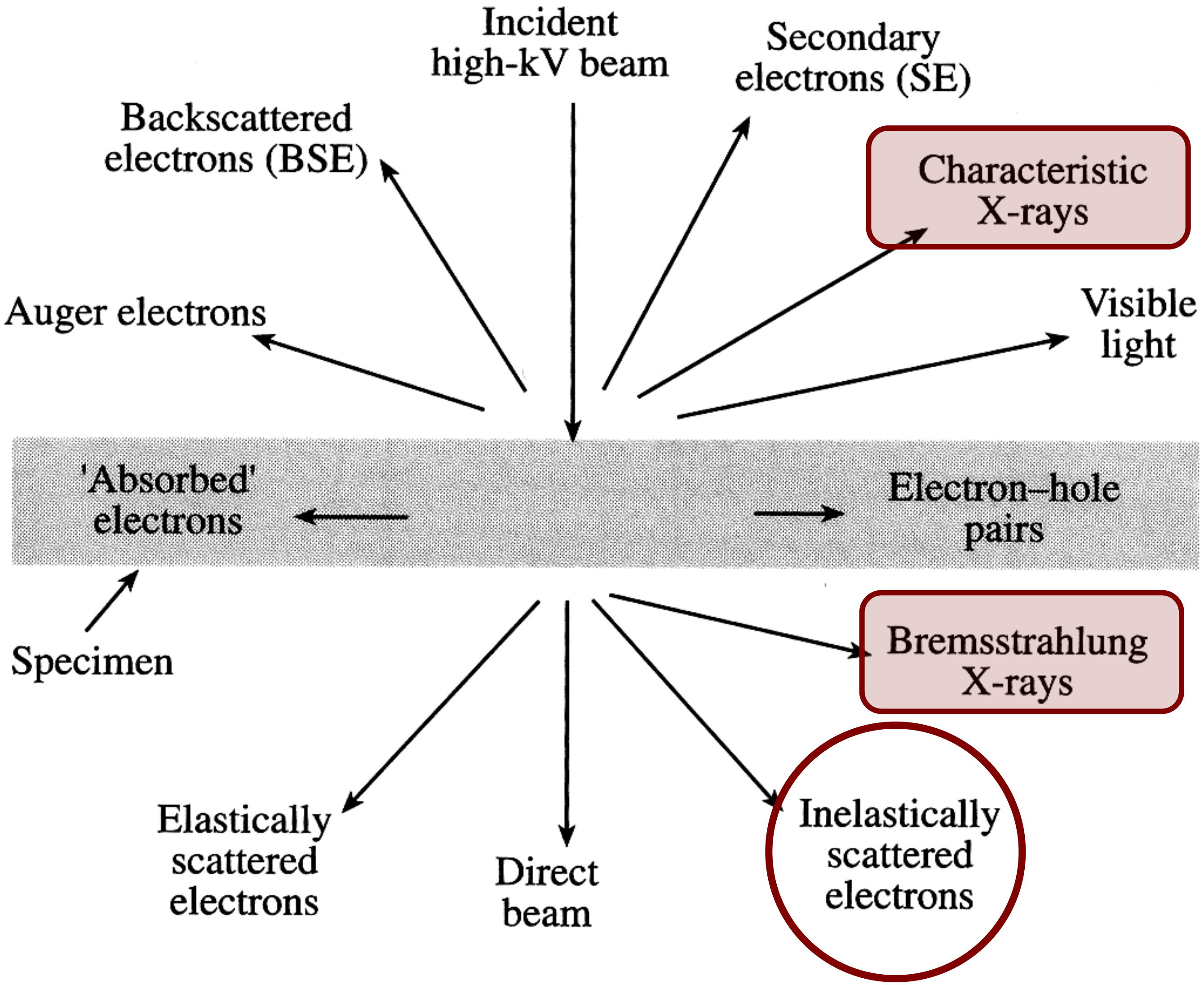
Screened relativistic Rutherford cross section

Can be plotted as an equivalent mean free path vs. incident energy

This gives you a good sense on allowable sample thickness!



Inelastic scattering



Inelastic scattering

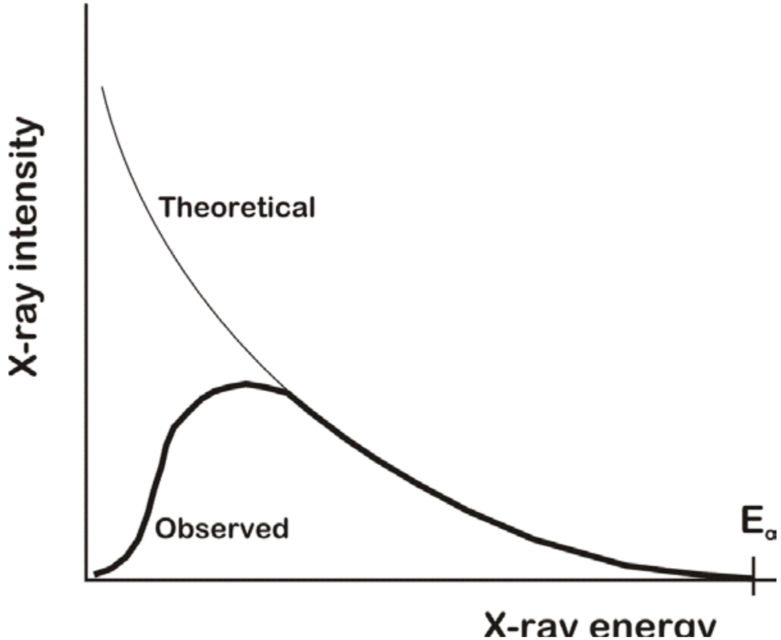
Bremsstrahlung X-ray emission

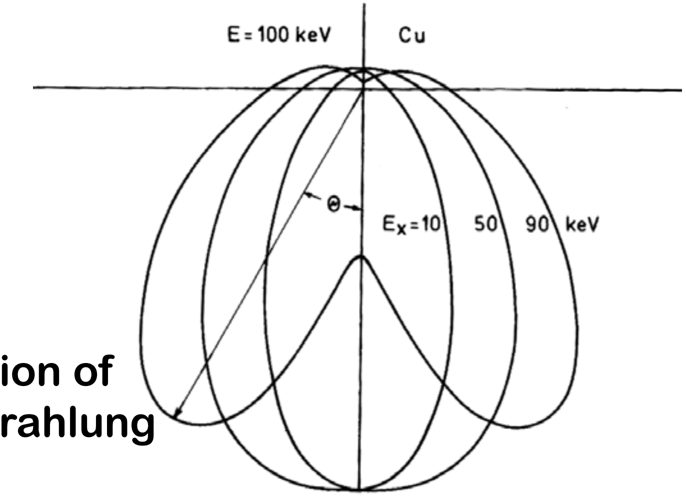
“Braking” radiation

Electron is decelerated by Coulomb (charge) field of the nucleus, electromagnetic radiation (photon) is emitted

Can have any energy less than the incident energy

Results in a continuous background signal in an intensity vs. energy spectrum



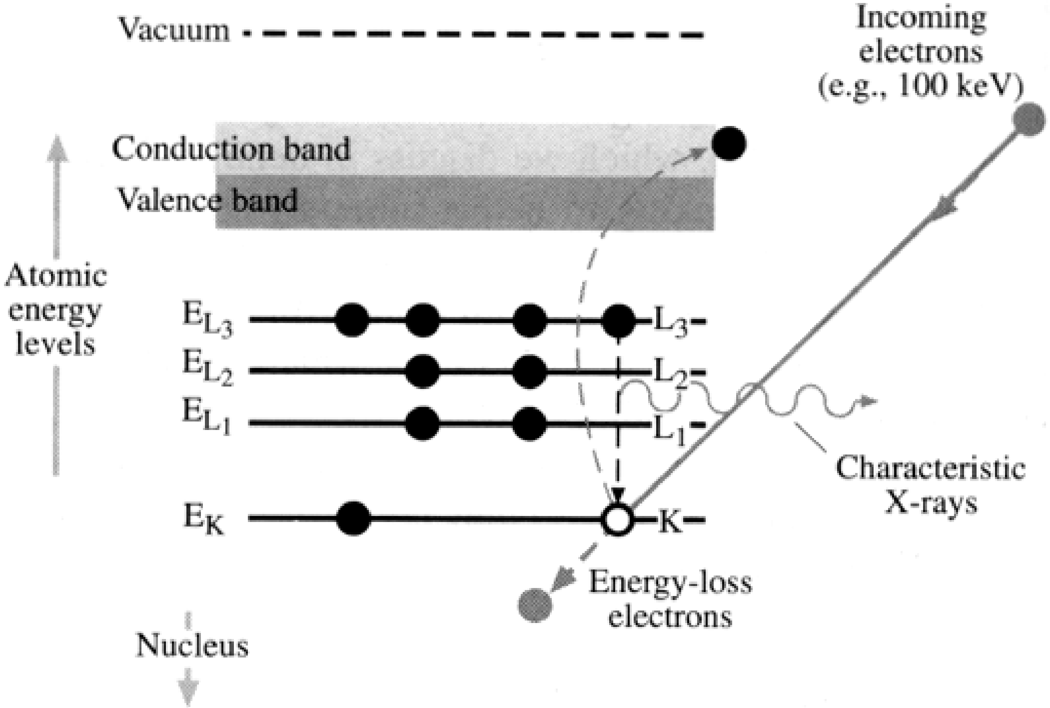


Angular distribution of Bremsstrahlung scatter

Inelastic scattering

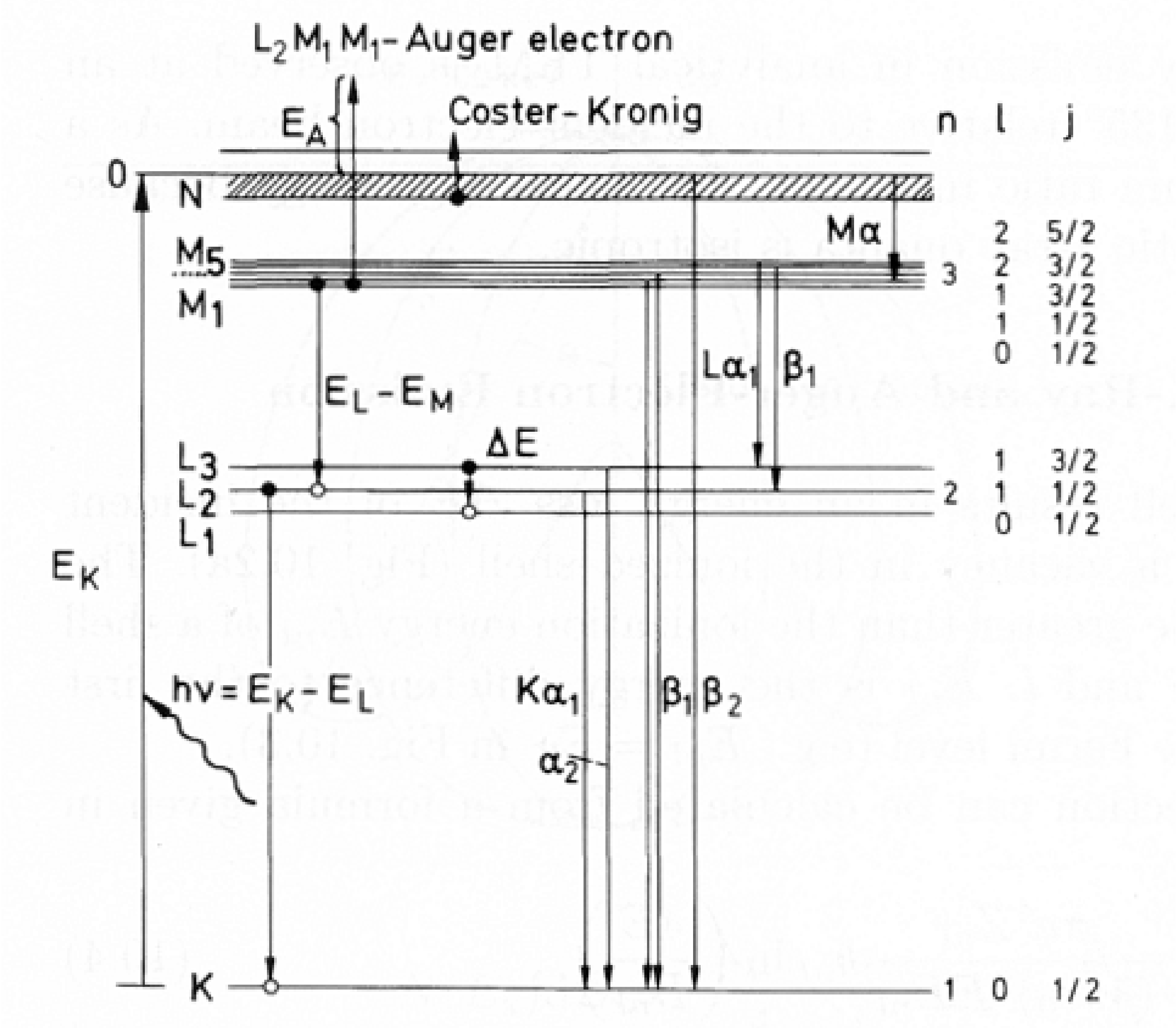
Characteristic X-rays

- Interaction w/ inner shell electrons
- If energy sufficient, inner shell electron ejected
  - –Atom is 'ionized'
- Atom can return to its lowest energy (ground) state
- Electron from outer shell fill the hole in the inner shell
- Energy required is *characteristic* of the atom



Inelastic scattering

Characteristic X-rays - nomenclature



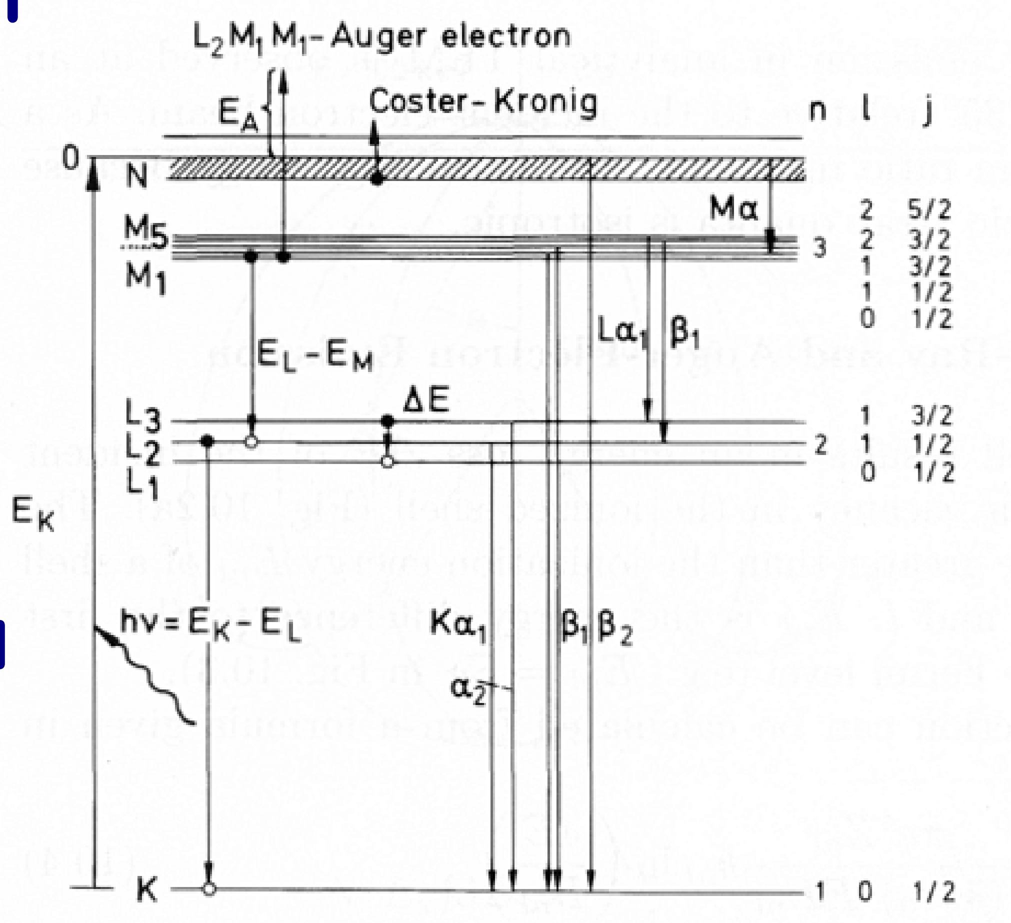
Inelastic scattering

Characteristic X-rays

- **X-rays, as EM radiation can be considered as either waves or photons**
- **Energy related to wavelength:**

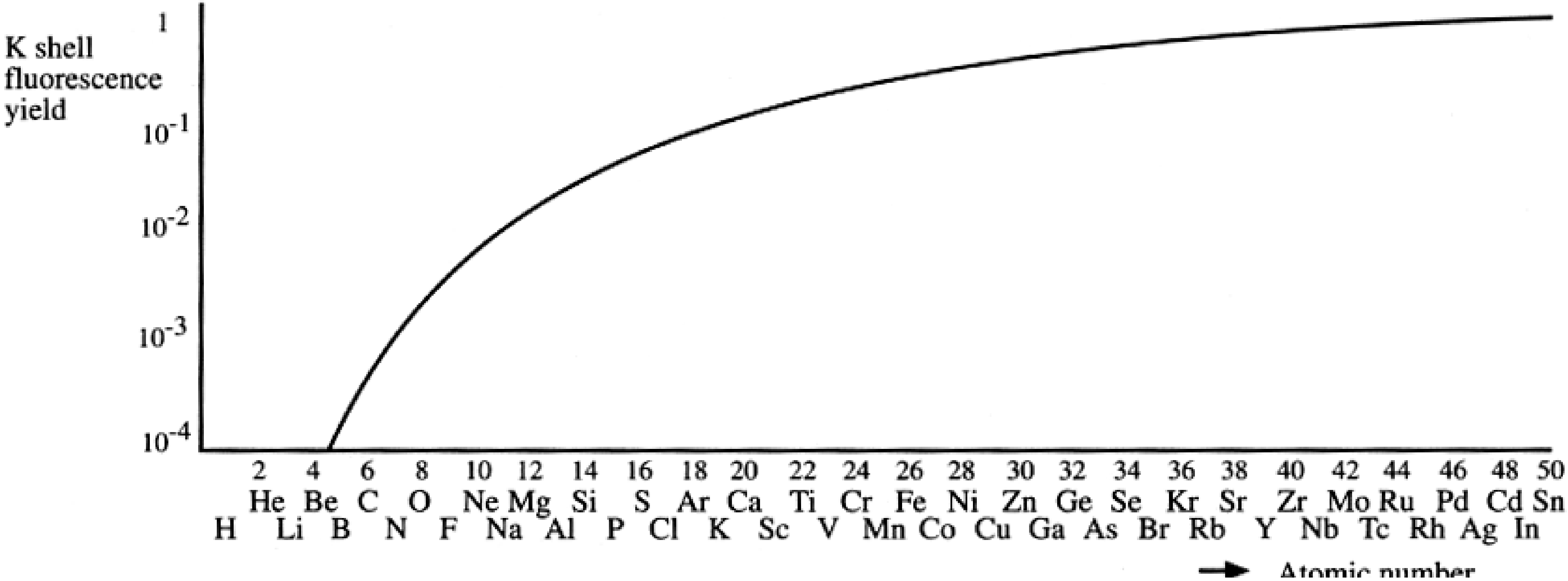
$$E = h\upsilon = \frac{hc}{\lambda}$$

- **Each transition has a specific energy associated with it (E_K, E_L, E_M)**
  - $E_K, E_L, E_M < E_c$
- **Thus each ionization event sets of a cascade of transitions**



Inelastic scattering

Characteristic X-rays



Fluorescence yield:

Strong atomic # dependence:

- One C K_α X-ray generated per 1000 ionization events
- One Ge K_α X-ray generated per 2 ionization events
  - Difference associated with relative chance of Auger electron production

Inelastic scattering

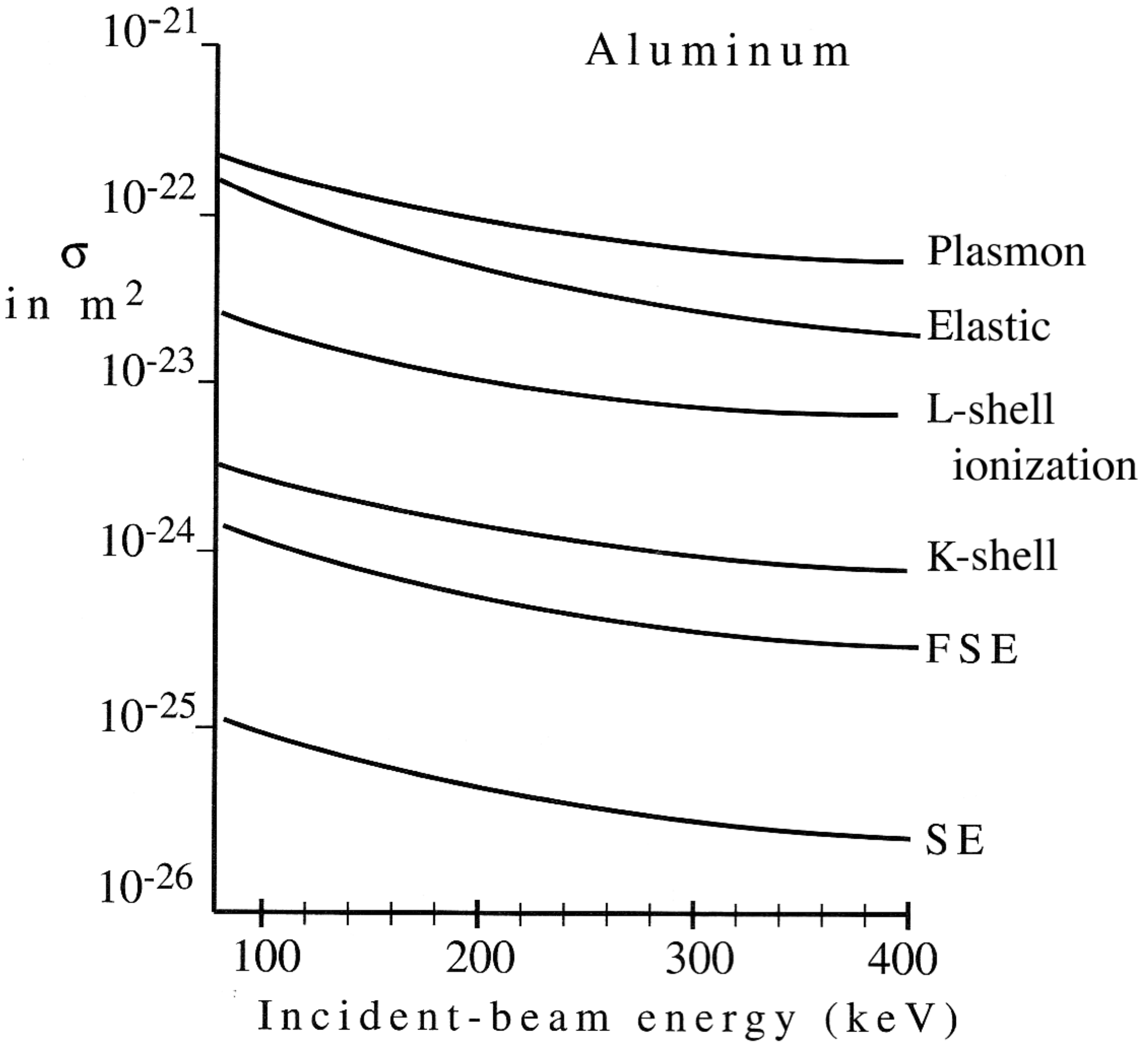
Secondary electron emission

Incident electrons impart energy to electrons in the crystal

- Slow secondary electrons
  - Electrons from the conduction or valence band
  - Require little energy: yields slow, unenergetic (<50 eV or so) electrons
  - These are what you use in the SEM
- Fast secondary electrons
  - Inner shell electrons which are ejected
  - Requires a lot of energy: yields fast, energetic (50 - 200 keV or so) electrons
  - Result in additional scattering processes, degrade microanalysis resolution

Inelastic scattering

comparison



Comparison of relative cross sections

Beam damage

High voltage, high current density electron beam can do considerable damage to a material

Two types:

- Radiolysis: Inelastic scattering ⇒ ionization which breaks bonds
- "Knock-on" damage: direct displacement of atoms

Increasing voltage: less radiolysis, more 'knock-on'

Beam damage

Knock-on thresholds

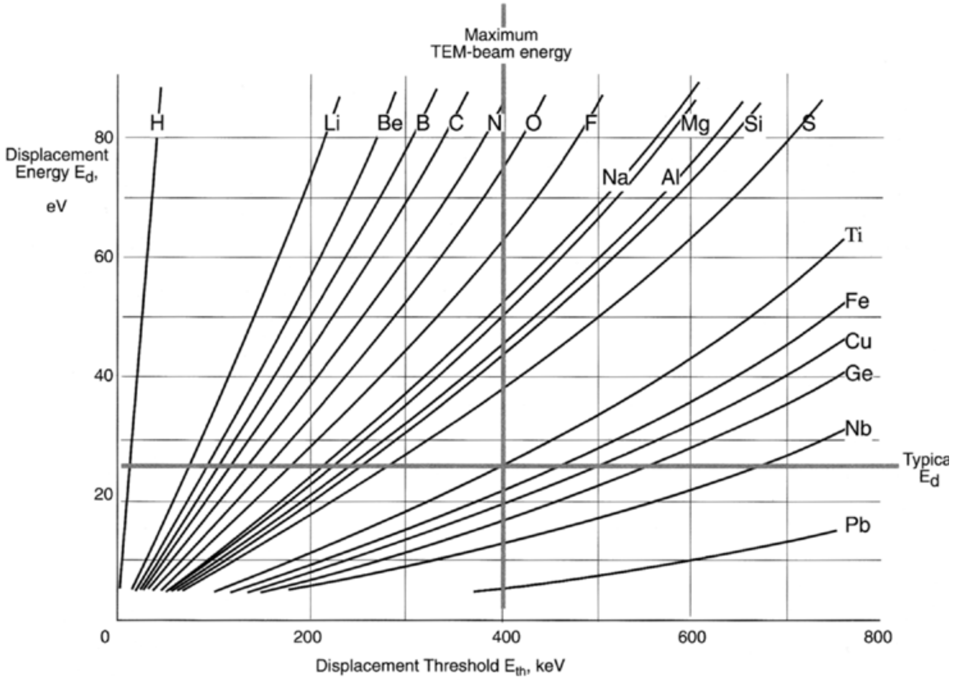
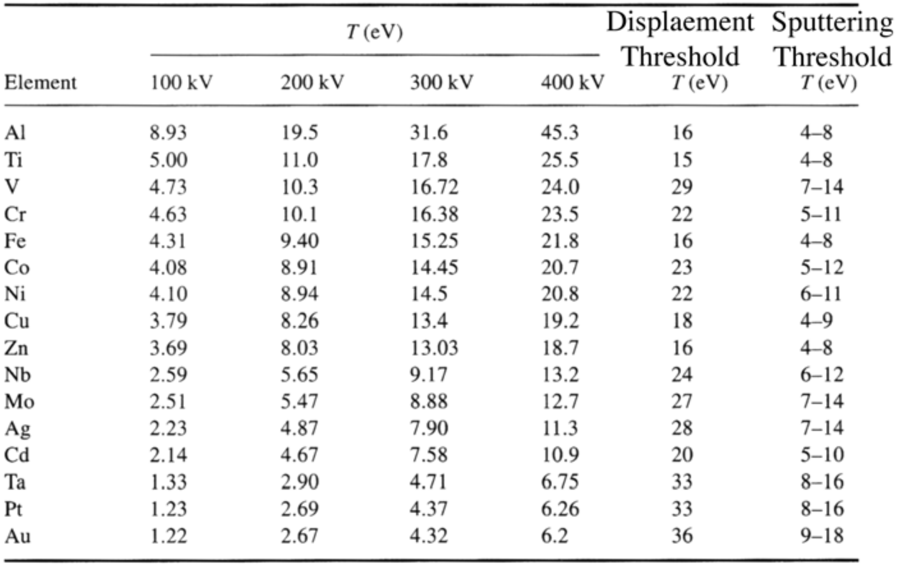


Table 4.2. Comparison of Maximum Transferable Kinetic Energy with Displacement and Sputtering Energies at 100, 200, 300, and 400 kV (from Zaluzec and Mansfield 1987)



	T (eV)				Displaement Threshold	Sputtering Threshold
Element	100 kV	200 kV	300 kV	400 kV	*T* (eV)	*T* (eV)
Al	8.93	19.5	31.6	45.3	16	4–8
Ti	5.00	11.0	17.8	25.5	15	4–8
V	4.73	10.3	16.72	24.0	29	7–14
Cr	4.63	10.1	16.38	23.5	22	5–11
Fe	4.31	9.40	15.25	21.8	16	4–8
Co	4.08	8.91	14.45	20.7	23	5–12
Ni	4.10	8.94	14.5	20.8	22	6–11
Cu	3.79	8.26	13.4	19.2	18	4–9
Zn	3.69	8.03	13.03	18.7	16	4–8
Nb	2.59	5.65	9.17	13.2	24	6–12
Mo	2.51	5.47	8.88	12.7	27	7–14
Ag	2.23	4.87	7.90	11.3	28	7–14
Cd	2.14	4.67	7.58	10.9	20	5–10
Ta	1.33	2.90	4.71	6.75	33	8–16
Pt	1.23	2.69	4.37	6.26	33	8–16
Au	1.22	2.67	4.32	6.2	36	9–18

These figures / tables are useful as a rule of thumb

- Some useful 'known' #'s:
- Al 170kV, Si 190kV, Carbon Nanotubes < 85 kV top surface, 140 kV elsewhere.
- If important to you, you may have to determine this yourself! Argh …

Sputtering is just displacement damage from the surface

Beam damage

specimen heating

Generally, not a worry in metals, semiconductors

Definitely so in ceramics, polymers

Reduce the cross section

- Thinner samples
- Higher voltage

Myths about specimen heating

- Anecdotal evidence from old HVEM's said this was significant
- Due to aperture heating, not sample heating