EE213. Microscopic Nanocharacterization of Materials
Spring 2016

Lecture 3

Tentative Outline

Week 1: Introduction: What is Micro/Nano Characterization?

Week 2: Electron Beam Induced Excitation Methods

A. Reflection Scanning Electron Microscopy
B. Auger Electron Microscopy/Spectrosopy
C. Electron Beam Induced X-Ray Analysis
D. Electron Energy Loss Spectrosopy
E. Transmission Electron Microscopy
   a. Scanning Transmission Electron Microscopy (STEM)
   b. Conventional Transmission Electron Microscopy (TEM)
   c. Energy Filtered Electron Microscopy

interactions

prob, $P = \sigma n \, dx$

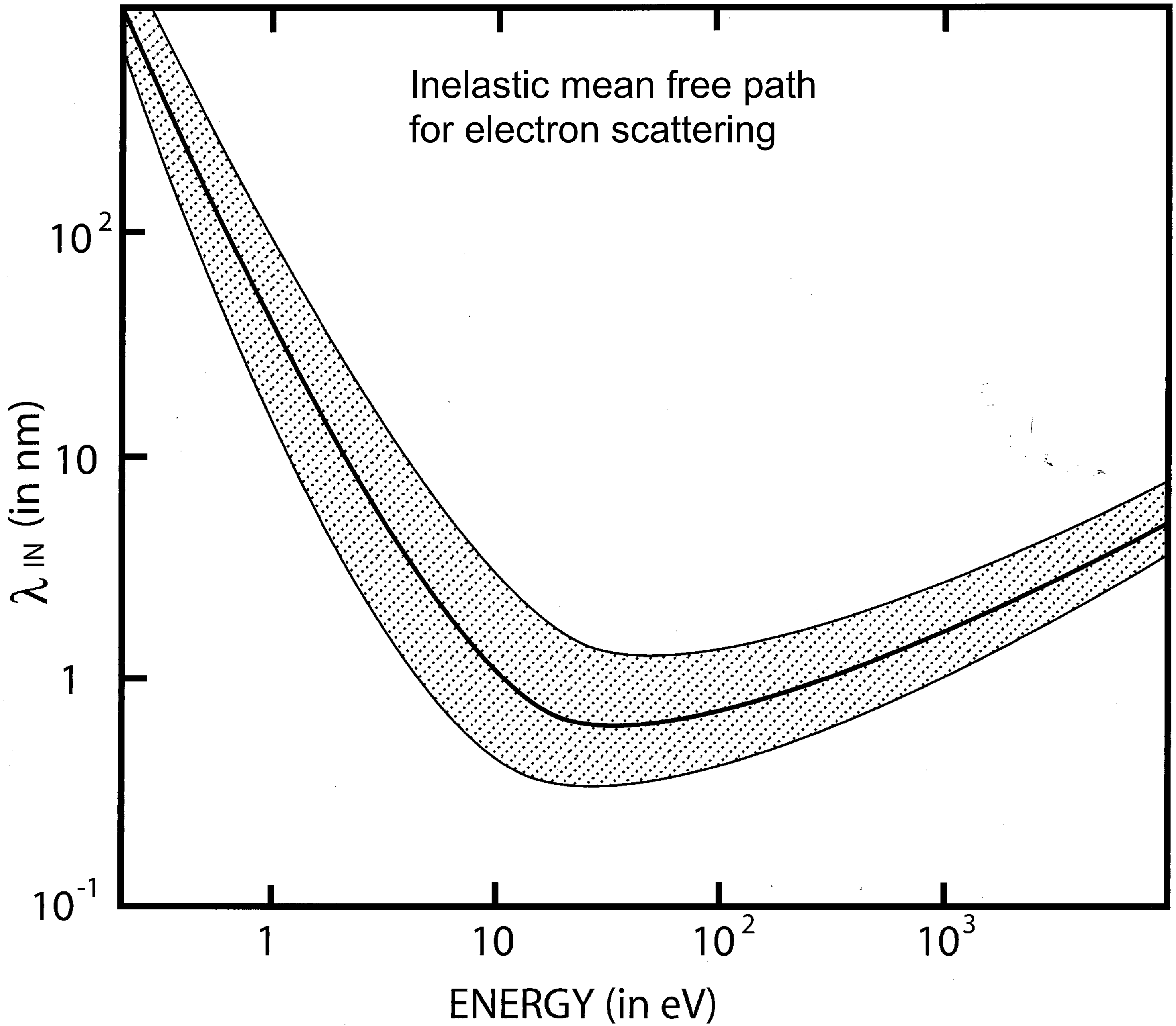
$$dJ = -JP = -J\sigma n \, dx$$

$$\int_0^x \frac{dJ}{J} = -\int_0^x \sigma n \, dx$$

$$J(x)/J(0) = e^{-n\sigma \cdot x}$$

$\Lambda = \frac{1}{n\sigma}$, mean free path

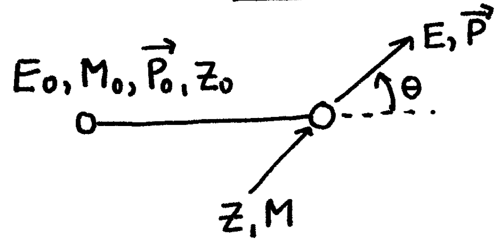
mfp = avg. dist. between interactions



From Seah and Dench, 1979. Surf. and Interface Anal.1.36

Rutherford Scattering (coulomb scatt)

Phil. Mag. 21. 669 (1911)



$$\frac{d\sigma}{d\Omega} \propto \frac{(eZ_0)^2(eZ)^2}{E_0^2}\left[\frac{4\left(\cos\theta + \sqrt{1-X^2\sin^2\theta}\right)^2}{\sin^4\theta\sqrt{1-X^2\sin^2\theta}}\right]$$

where $X = M_0/M$ same for RBS

for electrons $X \ll 1$ and $Z_0 = 1$

$$\therefore \frac{d\sigma}{d\Omega} \propto \frac{e^4 Z^2}{E_0^2}\frac{1}{\sin^4(\theta/2)}$$ OK for larger θ

for electrons / Ruth Scatt ~ elastic

ie, virtually no energy loss —

$$\Delta E_{MAX} \cong \frac{4 m_e}{M} E_0$$ max. energy that can be transferred in collision

$\frac{m_e}{m_p} = 5.46\times10^{-4}$ | eg, 100 keV electrons
iron, $A = 55.8$ amu
$\therefore \Delta E_{MAX} \cong 3.9$ eV

Correction to "Rutherford" scattering

when incident e^- comes close to nucleus,
Ruth. scatt. OK $\Rightarrow$ probability $\propto Z^2$.

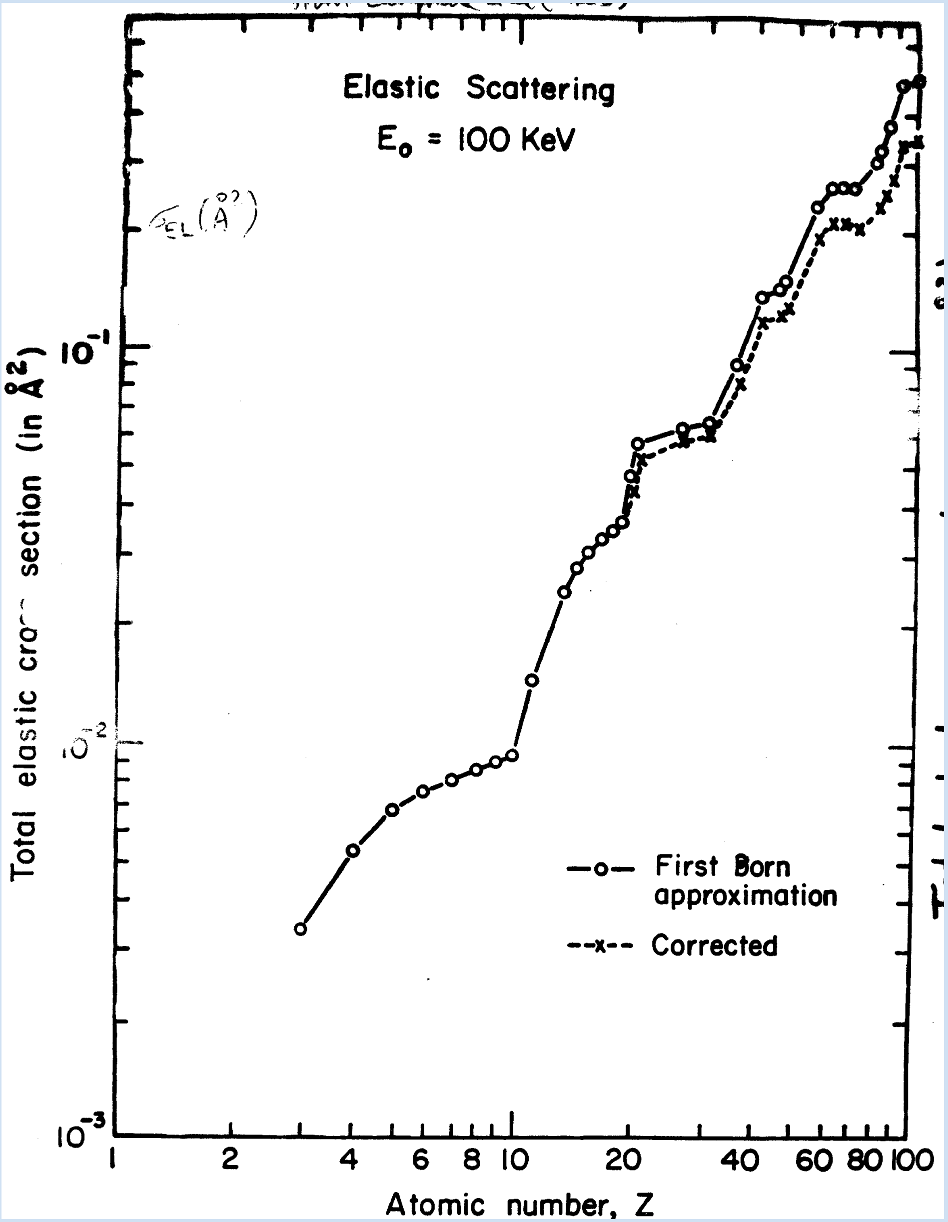
BUT, if e^- not so close,
nuclear charge "shielded" by atomic electrons
so incident e^- doesn't see full Z
but a $Z_{EFF} < Z$.

2 pt. charges

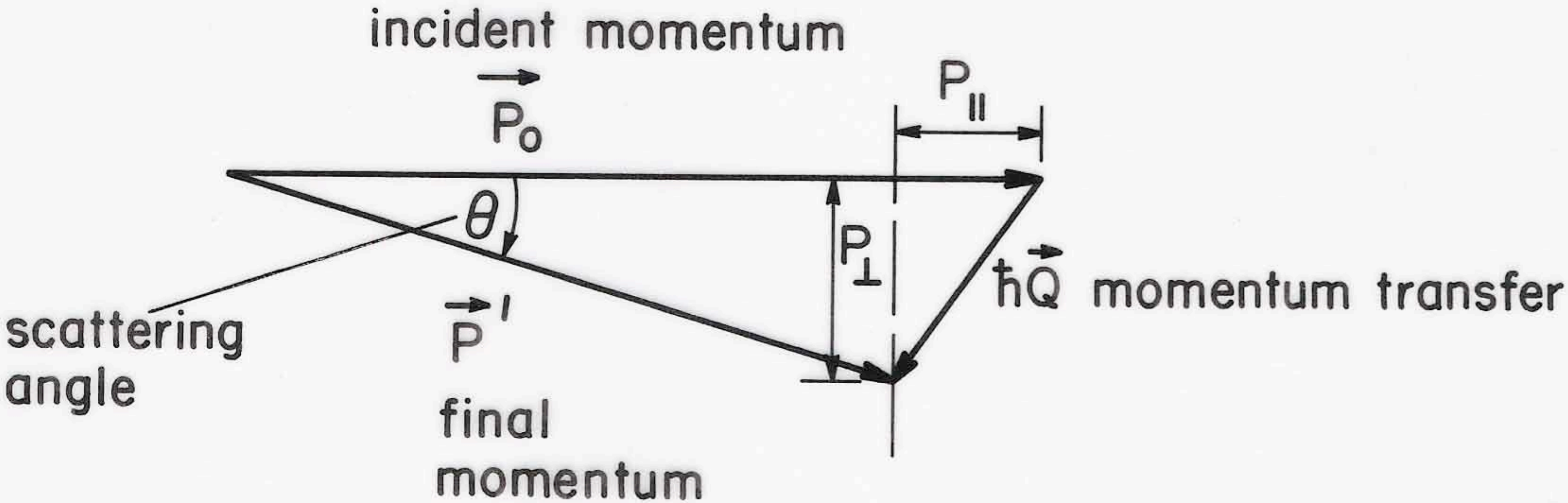
this means potential is not $V(r) \propto \frac{Ze^2}{r}$, Coulomb
but rather more like $\frac{Ze^2}{r} e^{-r/a}$

where $Ze^{-r/a}$ is like an effective nuclear charge.
and a = "screening" radius

there are different atomic models which take
this into account.
analytic ones are approximate
1930's Lenz-Wentzel / $a = a_0 Z^{-1/3}$
1970's more accurate / $a = 0.9 a_0 Z^{-1/4}$
both show $a \searrow$ as $Z \nearrow$



Langmore, Wall and isaacson. Optik.38(4).(1973).335-350.



incident momentum
$\vec{P}_0$
$P_{\parallel}$
θ
$P_{\perp}$
$\hbar\vec{Q}$ momentum transfer
scattering angle
$\vec{P}'$
final momentum

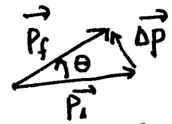
inelastic scattering

elec → elec / Z electrons in atom

$$\therefore \frac{d\sigma}{d\Omega} \longrightarrow \sum_{i=1}^{Z} \frac{(e^2)(e^2)}{\text{same stuff}} \rightarrow \frac{e^4 Z}{\text{stuff}}$$

when you go through details
not quite free electrons –
wind up with $\dfrac{d^2\sigma}{dE\,d\Omega} \propto \dfrac{1}{(\Delta p)^2}$

kinematics



$$\Delta p = \hbar q = \left[p_f^2 + p_i^2 - 2 p_i p_f \cos\theta \right]^{1/2}$$

for small energy loss, $\Delta E \ll E_{inc}$
and small angles ($< 20°$)
we get $\Delta E \approx \dfrac{p_i}{m}(p_i - p_f)$

min. momentum transferred ($\theta = 0$)

$$\Delta p_{min} = p_i - p_f \approx \frac{m\Delta E}{p_i} = \frac{\Delta E}{v_i}$$

so for small θ, we write

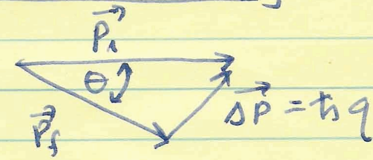
$$\Delta p \cong \Big[\underbrace{(p_i - p_f)}_{\Delta E / v_i}{}^2 + p_i p_f \theta^2 \Big]^{1/2} = p\left[\left(\frac{\Delta E}{p_i v}\right)^2 + \theta^2 \right]^{1/2}$$

$p_i \sim p_f$

$\theta_E = \dfrac{\Delta E}{pv}$ characteristic inelastic scatt ∡ → take $\Delta E = 50\,\text{eV}$
$E = 100\,\text{keV}$
$\theta_E \cong \dfrac{\Delta E}{2E} = \dfrac{1}{4}$ mrad

$$\therefore \boxed{\frac{d\sigma}{d\Omega} \rightarrow \frac{1}{\theta^2 + \theta_E^2}}$$

Inelastic scattering (ie, $e^- \to e^-$)



$$\Delta p = \hbar q = \left[P_f^2 + P_i^2 - 2 P_f P_i \cos\theta \right]^{1/2}, \quad \vec{P}_i = \vec{P}_0$$

for small angles, $\theta \lesssim 10-20^\circ$

$$\cos\theta = 1 - \frac{1}{2!}\theta^2 + \cdots$$

$$\therefore \Delta p = \left[P_f^2 + P_i^2 - 2 P_i P_f (1 - \theta^2/2) \right]^{1/2}$$

$$\boxed{\Delta P = \left[(P_i - P_f)^2 + P_i P_f \theta^2 \right]^{1/2}}$$

for small $\Delta E \ll E_i$ energy loss.

$$E_i \cong P_i^2/2m_e \quad \text{non-rel.}$$

$$E_f \cong \frac{P_i^2}{2m_e} - \Delta E$$

$$\therefore P_i = \sqrt{2mE_i} \quad \text{non-rel.} \left(\text{ie } E_i = \frac{P_i^2}{2m} \right)$$

$$P_f = \sqrt{2m(E_i - \Delta E)} = \sqrt{2mE_i} \left[1 - \frac{\Delta E}{E_i} \right]^{1/2}$$

$$\therefore P_f = P_i \sqrt{1 - \frac{\Delta E}{E_i}} \cong \boxed{P_i \left(1 - \frac{1}{2}\frac{\Delta E}{E_i} \cdots \right) = P_f}$$

$$\therefore P_i - P_f \cong \frac{1}{2} P_i \frac{\Delta E}{E_i} = \frac{1}{2} P_i \Delta E \left(\frac{2m}{P_i^2} \right) = \frac{m}{P_i} \Delta E \;//$$

inelastic scattering . 2 (cont)

$$\therefore \boxed{\Delta E = \frac{P_i}{m}(P_i - P_f)}$$

$$\Delta P = \left[(P_i - P_f)^2 + P_i P_f \theta^2 \right]^{1/2}$$

ΔP_{MIN} when $\theta = 0 \Longrightarrow \Delta P_{min} = P_i - P_f$

we lose momentum even if $\theta = 0$!!

$$\therefore \boxed{\Delta P_{min} = \frac{m}{P_i} \Delta E}$$

. now $P_i \approx P_f$ to 1st order

ie $P_i P_f \cong P^2$

$$\therefore \quad \Delta p = \left[\left(\frac{m \Delta E}{P_i} \right)^2 + P_i P_f \theta^2 \right]^{1/2}$$

$$\cong \left[\left(\frac{\Delta E}{v_i} \right)^2 + P_i P_f \theta^2 \right]^{1/2}$$

$$\Delta P \cong p \left[\left(\frac{\Delta E}{p v} \right)^2 + \theta^2 \right]^{1/2}$$

$$\boxed{\Delta P \cong p \left(\theta_E^2 + \theta^2 \right)^{1/2}}$$ where $\theta_E = \frac{\Delta E}{p v}$

the characteristic inelastic scatt. $\measuredangle$

inelastic scattering - 3 (cont)

now $\frac{d\sigma}{d\Omega} \propto \frac{Z^2}{\Delta p^4}$; pure Rutherford Scattering

more generally, $Z^2 \Rightarrow |F(q)|^2$ where $\Delta p = \hbar q$
to account for "screening" of nuclear charge
by atomic electrons.

"quantum mechanically", the scattered wave function

$$\psi(r) = \psi_0 \Big[\underset{\substack{\uparrow \\ \text{incident} \\ \text{wave}}}{e^{i\vec{q}\cdot\vec{r}}} + \underbrace{f(\vec{q}) \frac{e^{i\vec{q}\cdot\vec{r}}}{r}}_{\text{scattered wave}} \Big]$$

where $|f(\vec{q})|^2 = \frac{d\sigma}{d\Omega}$ //

and $\underline{f(q) \propto \frac{1}{q^2} F(q)}$, $F(q) = Z - \underbrace{F_x(q)}_{\substack{\text{scatt factor} \\ \text{for X Rays}}}$

(FT of atomic charge distribution)

remembering that $\vec{\Delta p} = \hbar \vec{q}$

then $\frac{d\sigma}{d\Omega} \propto \frac{|F(q)|^2}{q^4} = \frac{|f(q)|^2}{q^2}$

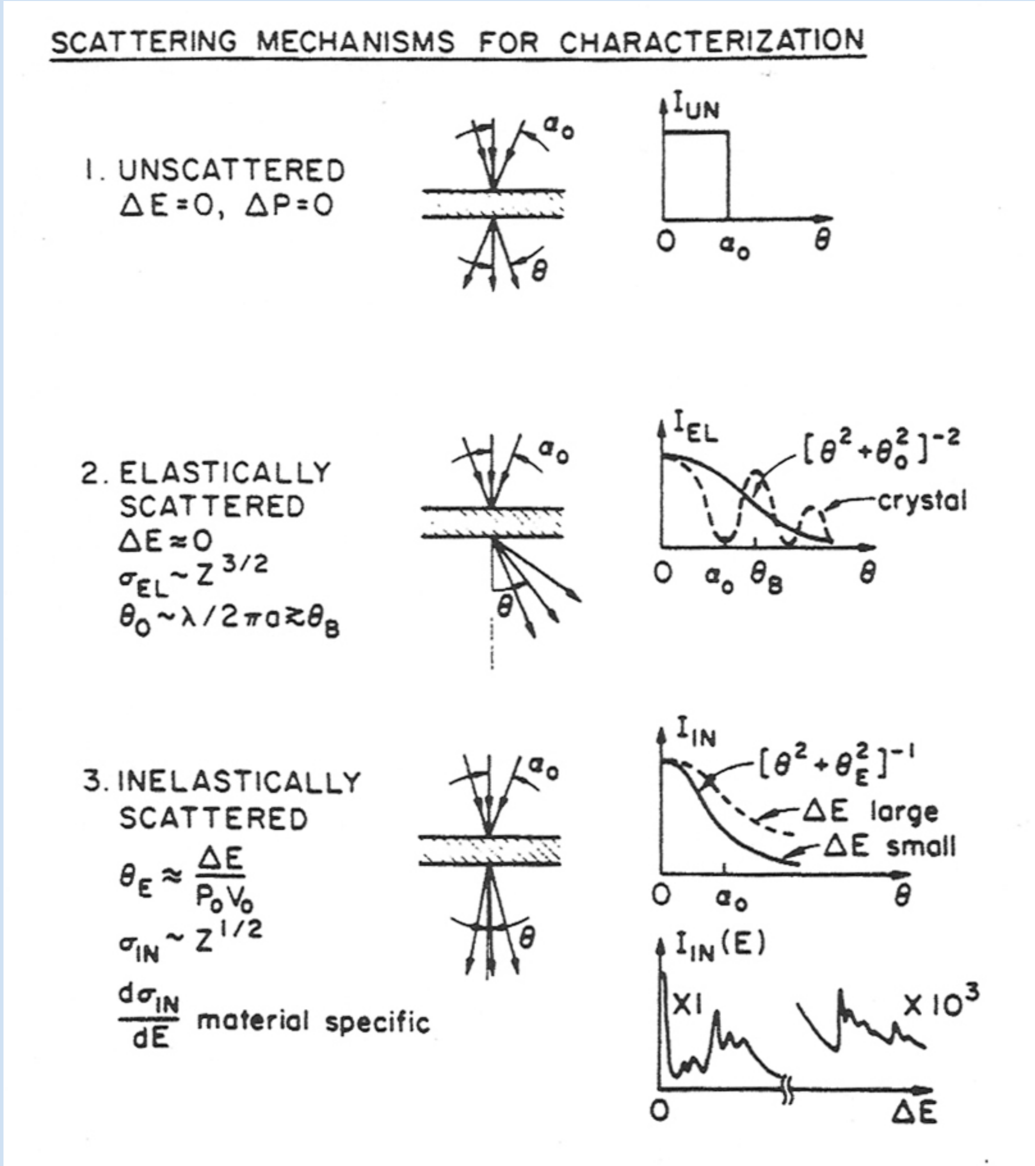
for "inelastic" scatt : $f(q) \rightarrow |F_{in}|$

$$\therefore \frac{d}{dE}\left(\frac{d\sigma_{IN}}{d\Omega}\right) \propto \frac{1}{q^2} \underbrace{\frac{1}{dE}\left(|F_{in}|\right)^2}_{= \frac{1}{E}\frac{df}{dE}}$$

$$\therefore \boxed{\frac{d^2\sigma_{IN}}{dE\,d\Omega} \propto \frac{1}{q^2} \frac{1}{E} \frac{df}{dE}}$$

where $\underline{\int_0^\infty \frac{df}{dE} dE = Z}$

$\frac{1}{q^2} \rightarrow \propto (\theta^2 + \theta_E^2) \equiv$


SCATTERING MECHANISMS FOR CHARACTERIZATION
1. UNSCATTERED
ΔE=0, ΔP=0
2. ELASTICALLY SCATTERED
ΔE≈0
σ_EL ~ Z^3/2
θ_0 ~ λ/2πa ≳ θ_B
3. INELASTICALLY SCATTERED
θ_E ≈ ΔE/P_0V_0
σ_IN ~ Z^1/2
dσ_IN/dE material specific
I_UN
I_EL
[θ^2+θ_0^2]^-2
crystal
I_IN
[θ^2+θ_E^2]^-1
ΔE large
ΔE small
I_IN(E)
X1
X10^3
α_0
θ
θ_B
0
ΔE

inelastic cross-sections. I

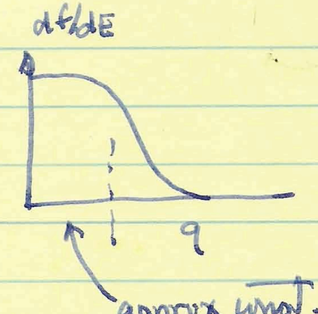
$$\frac{d^2\sigma_{IN}}{dE\,d\Omega} \propto \frac{1}{q^2}\,\frac{1}{E}\,\frac{df}{dE}$$

$$\hbar q = \left[P_i^2 + P_f^2 - 2P_iP_f\cos\theta\right]^{1/2}$$

$$dq = P_iP_f\sin\theta\,d\theta/\hbar^2 q$$

$$d\Omega = 2\pi\sin\theta\,d\theta$$

$$\therefore\ \boxed{dq = \frac{P_iP_f}{2\pi\hbar^2}\,\frac{d\Omega}{q}}$$



$$\therefore\ \frac{d^2\sigma_{IN}}{dE\,dq} \propto \frac{1}{P_i^2}\,\frac{1}{q}\left[\frac{1}{E}\,\frac{df}{dE}\right]$$

$$\frac{d\sigma_{IN}}{dE} \propto \frac{1}{P_i^2}\int_{q_{min}}^{q_{max}} \frac{1}{q}\,\frac{1}{E}\,\frac{df}{dE}\,dq$$

$$\therefore\ \frac{d\sigma_{IN}}{dE} \propto \frac{1}{P_i^2}\,\frac{1}{E}\left(\frac{df}{dE}\right)_{AVG}\int_{q_{min}}^{q_{max}}\frac{dq}{q}$$

inelastic cross sections 2 (cont)

now $\Delta E = E = \frac{P^2}{2m}$ free electron

$\therefore \Delta P_{max} = \sqrt{2mE}$ where $E = \Delta E$ energy loss

$$\therefore \boxed{\hbar q_{max} = \sqrt{2mE}}$$

$\hbar q_{min} = \frac{E}{v_i}$ from before / $v_i = \sqrt{\frac{2E_i}{m}}$ non rel.

$$\therefore \boxed{\hbar q_{min} = E\sqrt{\frac{m}{2E_i}}}$$

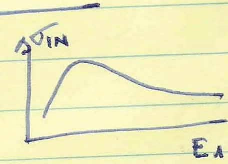
$$\int_{q_{min}}^{q_{max}} \frac{dq}{q} = \left[\ln\left(\frac{q_{max}}{q_{min}}\right)\right] = \left[\ln\left(\frac{\sqrt{2mE}}{E\sqrt{\frac{m}{2E_i}}}\right)\right]$$

$$= \left[\ln\left(\sqrt{\frac{4E_i}{E}}\right)\right] = \underline{\underline{\frac{1}{2}\ln\left(\frac{4E_i}{E}\right)}}$$

$$\therefore \boxed{\frac{d\sigma_{IN}}{dE} \propto \frac{1}{P_i^2}\frac{1}{E}\left(\frac{df}{dE}\right)_{ave} \ln\left(\frac{4E_i}{E}\right)}$$ Bethe cross section

$$\sigma_{IN} \propto \int_{E_{min}}^{E_i} \frac{1}{E}\left(\frac{df}{dE}\right)_{ave} \ln\left(\frac{4E_i}{E}\right) dE$$

$$\boxed{\sigma_{nl} \propto \frac{Z_{nl}}{E_i}\frac{b_{nl}}{E_{nl}} \ln\left(\frac{C_{nl}E_i}{E_{nl}}\right)}$$



Inelastic cross-sections. 3

define $U_{nl} = \dfrac{E_i}{E_{nl}}$ over voltage

$E_{nl} \rightarrow$ binding energy of n,l shell.

then $\sigma_{nl} \propto \dfrac{Z_{nl} b_{nl}}{E_i E_{nl}} \ln\left(\dfrac{c_{nl} E_i}{E_{nl}}\right)$

$$\sigma_{nl} \propto \frac{Z_{nl} b_{nl}}{U_{nl} E_{nl}^2} \ln(c_{nl} U_{nl})$$

$$\boxed{\sigma_{nl} E_{nl}^2 \propto \frac{Z_{nl} b_{nl}}{U_{nl}} \ln(c_{nl} U_{nl})}$$

Inelastic Cross-Sections. 4 (cont)

$$\sigma_{nl} E_{nl}^2 \propto \frac{Z_{nl} b_{nl}}{U_{nl}} \ln\left(C_{nl} U_{nl}\right), \text{ non-relatavistic}$$

where $U_{nl} = E_1 / E_{nl}$

$$\therefore \boxed{\sigma_{nl} = \left(\frac{h^2 R}{2\pi m}\right) \frac{Z_{nl} b_{nl}}{E_1 E_{nl}} \ln\left(\frac{C_{nl} E_1}{E_{nl}}\right),}$$

$R = 13.6\text{eV}$ (Rydberg)

relatavistically correct becomes:

$$\sigma_{nl} = \left(\frac{h^2 R}{2\pi m}\right)\left[\frac{Z_{nl} b_{nl}}{E_1 E_{nl}}\right]\left\{\left(1 + \frac{E_1}{mc^2}\right)^2 \ln\left(\frac{C_{nl} E_1^*}{E_{nl}}\right) - \frac{2E_1^*}{mc^2}\right\}$$

where $E_1^* = E_1\left(1 + \frac{1}{2}\frac{E_1}{mc^2}\right)$, rel. corrected kinetic energy

go back to non-rel. for simplicity —

to get the "total" inelastic cross sections (ie integrate over all electrons, nl)

start with $\frac{d\sigma}{dE} = \left(\frac{h^2 R}{2\pi m}\right) \frac{1}{E_1 E} \left(\frac{df}{dE}\right)_{AVG}^{\text{over } q} \ln\left(\frac{4E_1}{E}\right)$

$$\sigma_{inel} = \left(\frac{h^2 R}{2\pi m}\right) \frac{1}{E_1} \int_{E_1}^{E_1} \frac{1}{E}\left(\frac{df}{dE}\right)_{AVG}^{q} \ln\left(\frac{4E_1}{E}\right) dE$$

$$\frac{h^2 R}{2\pi m} = 651\text{eV-}\text{Å}^2$$

Inelastic Cross-Sections .5 (cont)

∴ we make the approximation that we just use averaged values of $\frac{1}{E}\left(\frac{df}{dE}\right)^{q}_{AVG}$ and average of $\ln\left(\frac{4E_i}{E}\right)$ over the energy integration

$$\therefore\ \sigma_{inel} \cong \text{const.} \times \left[\int \frac{1}{E}\frac{df}{dE}\,dE\right]_{AVG} \times \left[\ln\left(\frac{4E_i}{E}\right)\right]_{AVG}$$

This gives:

$$\sigma_{inel} \cong \frac{3}{4}\left(\frac{h^2R}{2\pi m}\right)\frac{\sqrt{Z}}{RE_i}\ln\left(\frac{4E_i}{\bar{E}}\right)$$

with $\bar{E} \cong 12.3\sqrt{Z}$ in eV

$$\therefore\ \boxed{\sigma_{inel} \cong 35.9\frac{\sqrt{Z}}{E_i}\ln\left(\frac{4E_i}{\bar{E}}\right) \text{ in } \mathring{A}^2 \text{ if } \bar{E}, E_i \text{ in eV}}$$

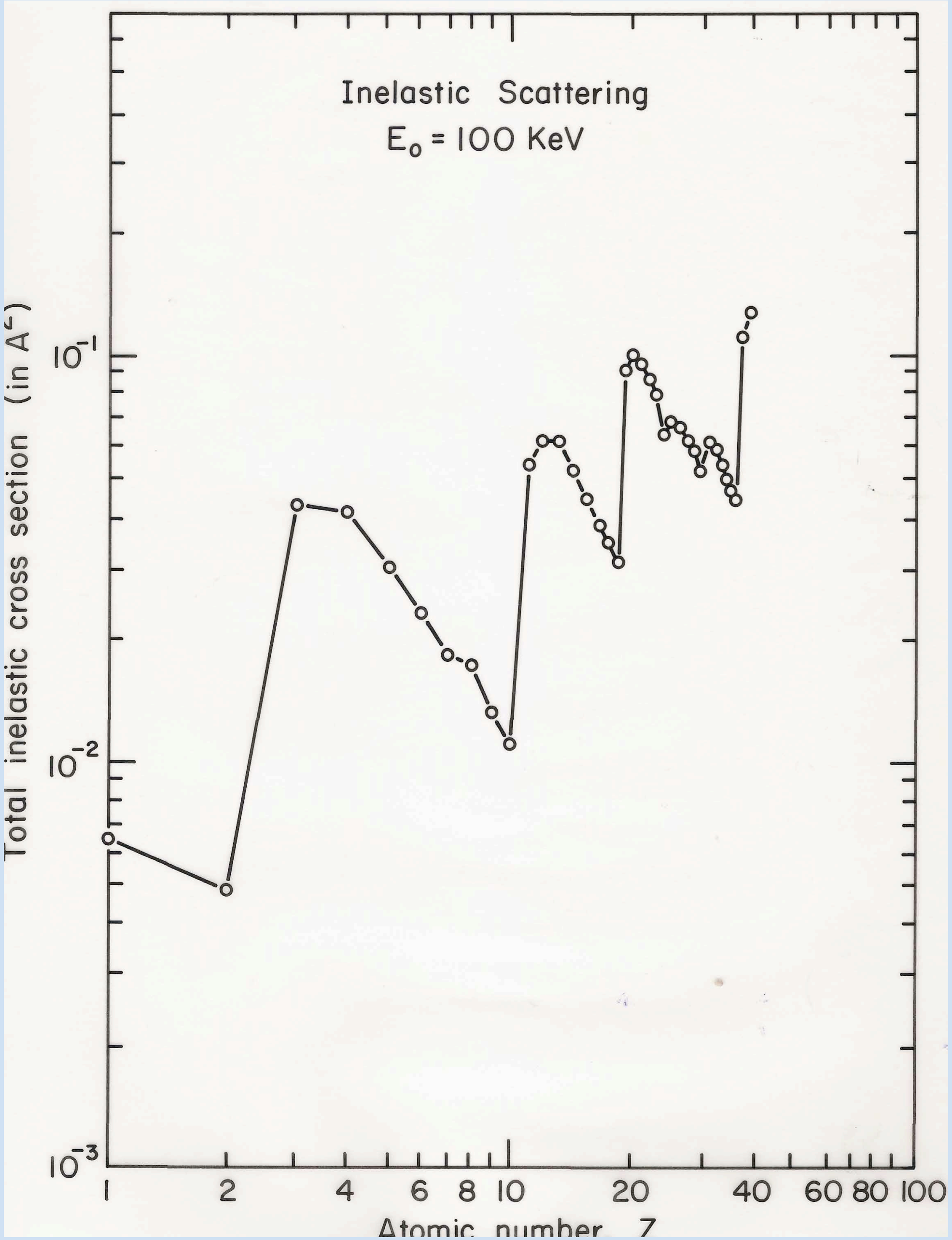
handy-dandy expression for inel scatt.

$$\text{and } \Lambda_{in} = \frac{1}{n\sigma_{inel}} = \boxed{\frac{E_i}{35.9\,n\sqrt{Z}\ln\left(\frac{4E_i}{\bar{E}}\right)} = \Lambda_{in}} \text{ (in } \mathring{A})$$

n = # density in #/$\mathring{A}^3$ ///

<note the shapes>

From M.Isaacson. In “Principles and techniques of Electron Microscopy. Vol.7.(ed. M.A.Hayat) Van Nostrand, NY. 1-78 (1976)



From Inokuti, et.al.
Phys. Rev.A.23,
95-109 (1980)

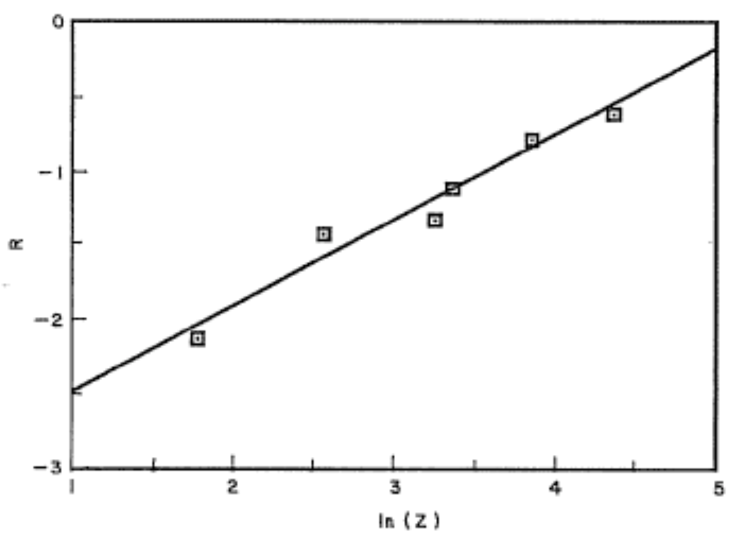
Electron Inelastic scattering cross-sections in solids (experimental)

Table 2. Experimental total inelastic cross-sections together with theoretical data: W, eqn. (5), HS, eqn. (7), FE, eqn. (4) and I, eqn. (6). The cross-sections are in units of 10 cm^2.

Atomic number	Total cross-section (this work)	W	HS	FE	I
6	$1{\cdot}11 \pm 0{\cdot}03$	2·50	2·32	1·24	1·35
13	$2{\cdot}03 \pm 0{\cdot}05$	2·96	6·11	1·49	1·82
26	$2{\cdot}05 \pm 0{\cdot}15$	3·43	6·76	1·71	2·36
29	$2{\cdot}50 \pm 0{\cdot}07$	3·50	4·85	1·40	2·46
47	$3{\cdot}28 \pm 0{\cdot}2$	3·85		2·54	2·93
79	$3{\cdot}66 \pm 0{\cdot}2$	4·25		3·45	3·53

Simple MSI

Fig. 3



Plot of $R = \ln[\sigma/\ln(2/\theta_E)]$ against $\ln Z$; the gradient of the line of best fit is 0·57.

From, P. Crozier, Phil. Mag.(1990). 61(3).95.

Inelastic cross-sections. 3

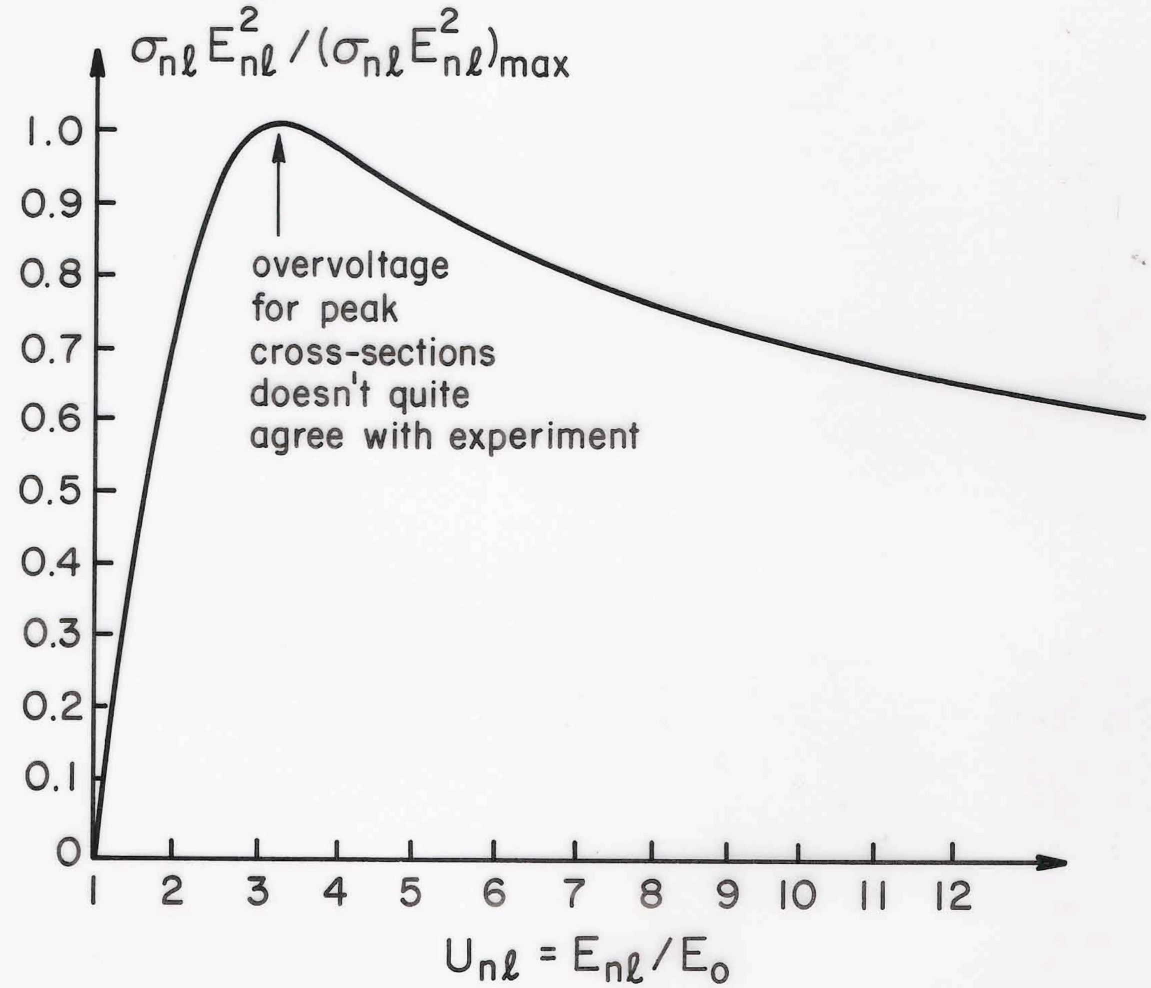
define $U_{n\ell} = \dfrac{E_i}{E_{n\ell}}$ over voltage

$E_{n\ell} \rightarrow$ binding energy of n,ℓ shell.

then $\sigma_{n\ell} \propto \dfrac{Z_{n\ell} b_{n\ell}}{E_i E_{n\ell}} \ln\left(\dfrac{c_{n\ell} E_i}{E_{n\ell}}\right)$

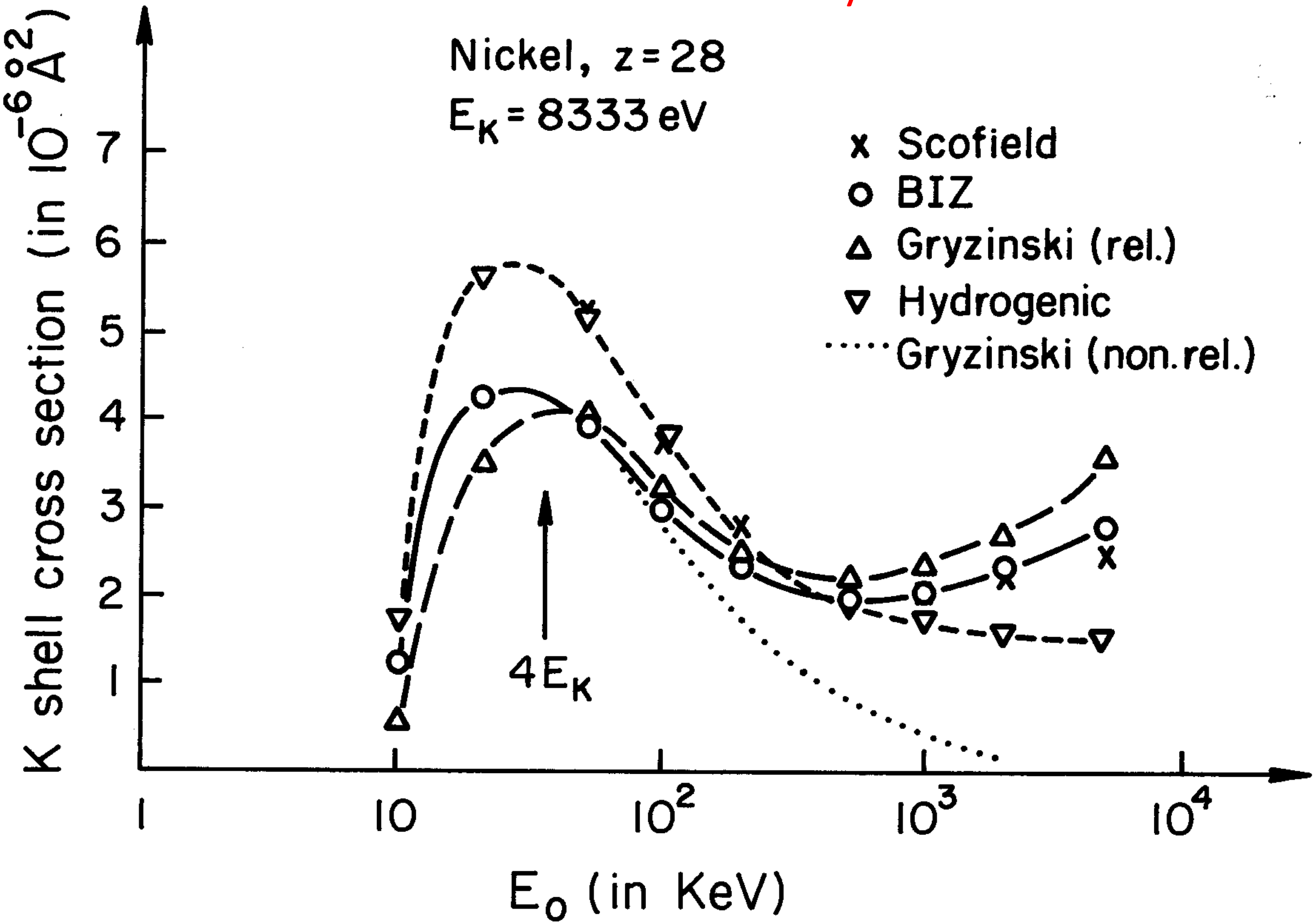
$$\sigma_{n\ell} \propto \frac{Z_{n\ell} b_{n\ell}}{U_{n\ell} E_{n\ell}^2} \ln(c_{n\ell} U_{n\ell})$$

$$\boxed{\sigma_{n\ell} E_{n\ell}^2 \propto \frac{Z_{n\ell} b_{n\ell}}{U_{n\ell}} \ln(c_{n\ell} U_{n\ell})}$$



From C.J.Powell, Rev. Mod.Phys. 48.33 (1976)

Calculations of K shell excitation by electrons



Gryzinski Model of Inelastic Scattering

M. Gryzinski. Phy. Rev. A. 138(1965). 336-358.

1. not quantum mechanically correct
   semi-classical: inc. electron of energy E_1 collides with orbital electrons of energy $E_{n\ell}$.
   - no interactions with atomic nucleus.
   good to 10-30% of exp. value of energy lost $\Delta E > E_{n\ell}$ ..
2. not relativistically correct either.
3. BUT NO FREE parameters

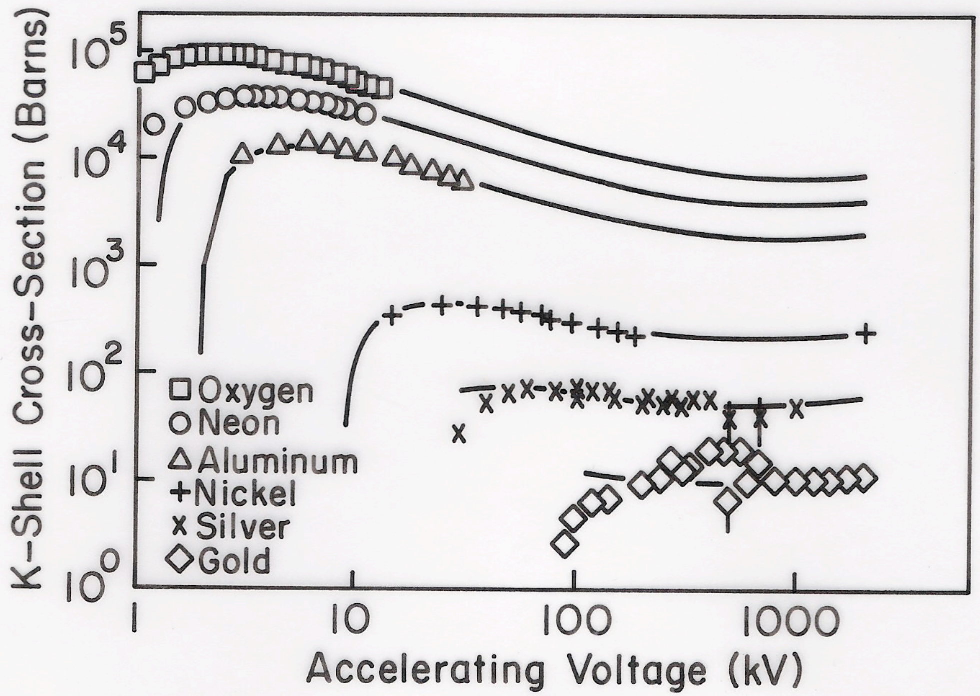
$$\sigma_{n\ell} = \left[\frac{h^2 R}{2\pi m}\right] \frac{Z_{n\ell}}{E_{n\ell}^2} g(U_{n\ell}) \quad \text{where } U_{n\ell} = \frac{E_1}{E_{n\ell}}$$

$$g(U_{n\ell}) = \frac{1}{U_{n\ell}} \left[\frac{U_{n\ell}-1}{U_{n\ell}+1}\right]^{3/2} \left[1 + \frac{2}{3}\left(1-\frac{1}{2U_{n\ell}}\right) \ln\left(2.7+\sqrt{U_{n\ell}-1}\right)\right]$$

used widely in Monte Carlo simulations of electron scattering since it is analytic, no free parameters /

K shell excitation cross-sections

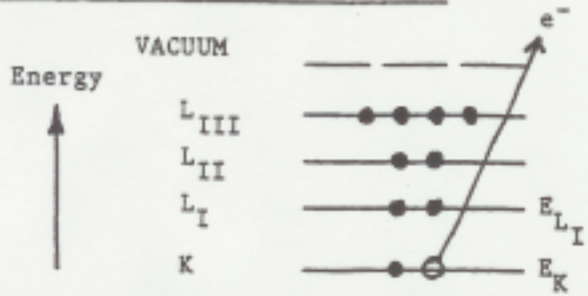
Barn = 10^{-24} A^2



From Zalucec, 1985

Ionization, Excitation and Emission

step
1

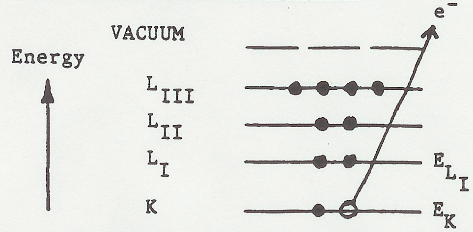


ionization

you need at least E_k energy transferred to atom.

Ionization, Excitation and Emission

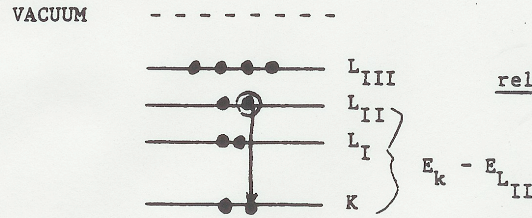
step
1



ionization
you need at least E_k energy transferred to atom.

With a hole in the inner shell the atom is energetically unstable. Relaxation occurs by a more outer shell electron filling the hole; e.g., an L_{II} electron depicted below

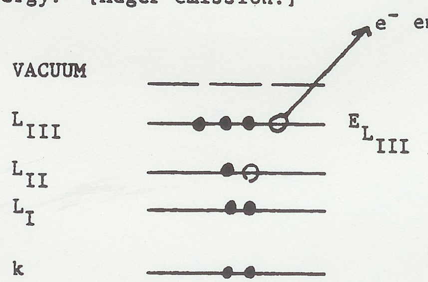
step
2



relaxation

In this step $E_k - E_{L_{II}}$ energy is released. This can be given up either by releasing a photon (X-ray emission) or given to another electron (either in the same level or one with lower binding energy). If the 2nd electron has sufficient excess kinetic energy it will be ejected into the vacuum where we can measure its energy. [Auger emission.]

step
3

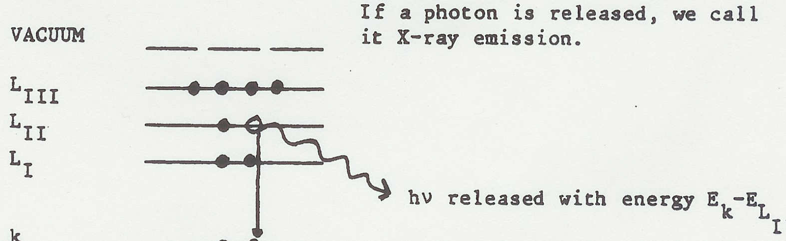


energy $[\underbrace{E_K - (E_{L_{II}})}_{L_{II}\text{ dropping to K}} - E_{L_{III}}]$

In the end, we are left with a doubly ionized atom. This is called Auger emission.

If a photon is released, we call it X-ray emission.

step
4

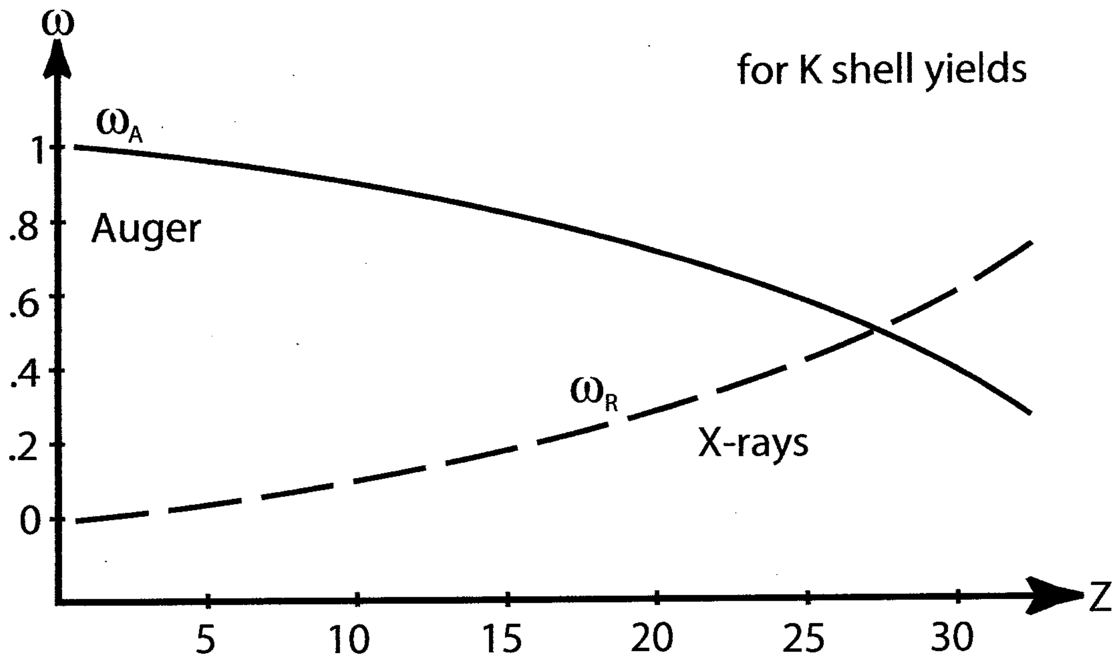


Xray and Auger Electron Yields

$$\omega \approx \frac{Z^4}{Z^4 + b}, \quad b = 1.12 \times 10^6 \text{ K shell}$$
$$= 6.4 \times 10^7 \text{ L3 shell}$$

Burhop, Auger Effect CUP 1952

$$W_{XRAYS} \approx 1 - W_{AUGER}$$



2. ELECTRON BINDING ENERGIES FOR AES

(eV)

	$1s_{1/2}$ K	$2s_{1/2}$ L_I	$2p_{1/2}$ L_{II}	$2p_{3/2}$ L_{III}	$3s_{1/2}$ M_I	$3p_{1/2}$ M_{II}	$3p_{3/2}$ M_{III}	$3d_{3/2}$ M_{IV}	$3d_{5/2}$ M_V	$4s_{1/2}$ N_I	$4p_{1/2}$ N_{II}	$4p_{3/2}$ N_{III}	$4d_{3/2}$ N_{IV}	$4d_{5/2}$ N_V	$4f_{5/2}$ N_{VI}	$4f_{7/2}$ N_{VII}	$5s_{1/2}$ O_I	$5p_{1/2}$ O_{II}	$5p_{3/2}$ O_{III}	$5d_{3/2}$ O_{IV}	$5d$ O_V
1 H	14																				
2 He	25																				
3 Li	55																				
4 Be	111																				
5 B	188		5																		
6 C	284		7																		
7 N	399		9																		
8 O	532	24	7																		
9 F	686	31	9																		
10 Ne	867	45	18																		
11 Na	1 072	63	31		1																
12 Mg	1 305	89	52		2																
13 Al	1 560	118	74	73	1																
14 Si	1 839	149	100	99	8	3															
15 P	2 149	189	136	135	16	10															
16 S	2 472	229	165	164	16	8															
17 Cl	2 823	270	202	200	18	7															
18 A	3 203	320	247	245	25	12															
19 K	3 608	377	297	294	34	18															
20 Ca	4 038	438	350	347	44	26		5													
21 Sc	4 493	500	407	402	54	32		7													
22 Ti	4 965	564	461	455	59	34		5													
23 V	5 465	628	520	513	66	38		2													
24 Cr	5 989	695	584	575	74	43		2													
25 Mn	6 539	769	652	641	84	49		4													
26 Fe	7 114	846	723	710	95	56		6													
27 Co	7 769	926	794	779	101	60		3													
28 Ni	8 333	1 008	872	855	112	68		4													
29 Cu	8 979	1 096	951	931	120	74		2													
30 Zn	9 659	1 194	1 044	1 021	137	87		9													
31 Ga	10 367	1 298	1 143	1 116	158	107	103	18			0	1									
32 Ge	11 104	1 413	1 249	1 217	181	129	122	29				3									
33 As	11 867	1 527	1 359	1 323	204	147	141	41				3									
34 Se	12 658	1 654	1 476	1 436	232	168	162	57				6									
35 Br	13 474	1 782	1 596	1 550	257	189	182	70	69	27		5									
36 Kr	14 326	1 921	1 727	1 675	289	223	214	89		24		11									
37 Rb	15 200	2 065	1 864	1 805	322	248	239	112	111	30	15	14									
38 Sr	16 105	2 216	2 007	1 940	358	280	269	135	133	38		20									
39 Y	17 039	2 373	2 155	2 080	395	313	301	160	158	46		26	3								
40 Zr	17 998	2 532	2 307	2 223	431	345	331	183	180	52		29	3								
41 Nb	18 986	2 698	2 465	2 371	469	379	363	208	205	58		34	4								
42 Mo	20 000	2 866	2 625	2 520	505	410	393	230	227	62		35	2								
43 Tc	21 044	3 042	2 793	2 677	544	445	425	257	253	68		39	2								
44 Ru	22 117	3 224	2 967	2 838	585	483	461	284	279	75		43	2								
45 Rh	23 220	3 412	3 146	3 004	627	521	496	312	307	81		48	3								

	$6s_{1/2}$ P_I	$6p_{1/2}$ P_{II}	$6p_{3/2}$ P_{III}	$6d_{3/2}$ P_{IV}	$6d_{5/2}$ P_V
82 Pb	3	1			
83 Bi	8	3			
84 Po	12	5			
85 At	18	8			
86 Rn	26	11			
87 Fr	34	15			
88 Ra	44	19			
90 Th	60	49	43	2	2

Siegnahn, et.al. ESCA. 1967

Electron Scattering

differences in "efficiency factors", F

1. EELS (look at primary electron)

$$F_e = \eta^e_{\measuredangle} \cdot \eta_{\Delta E} \cdot \eta^e_{DET}$$

collection solid angle

energy window

detector efficiency

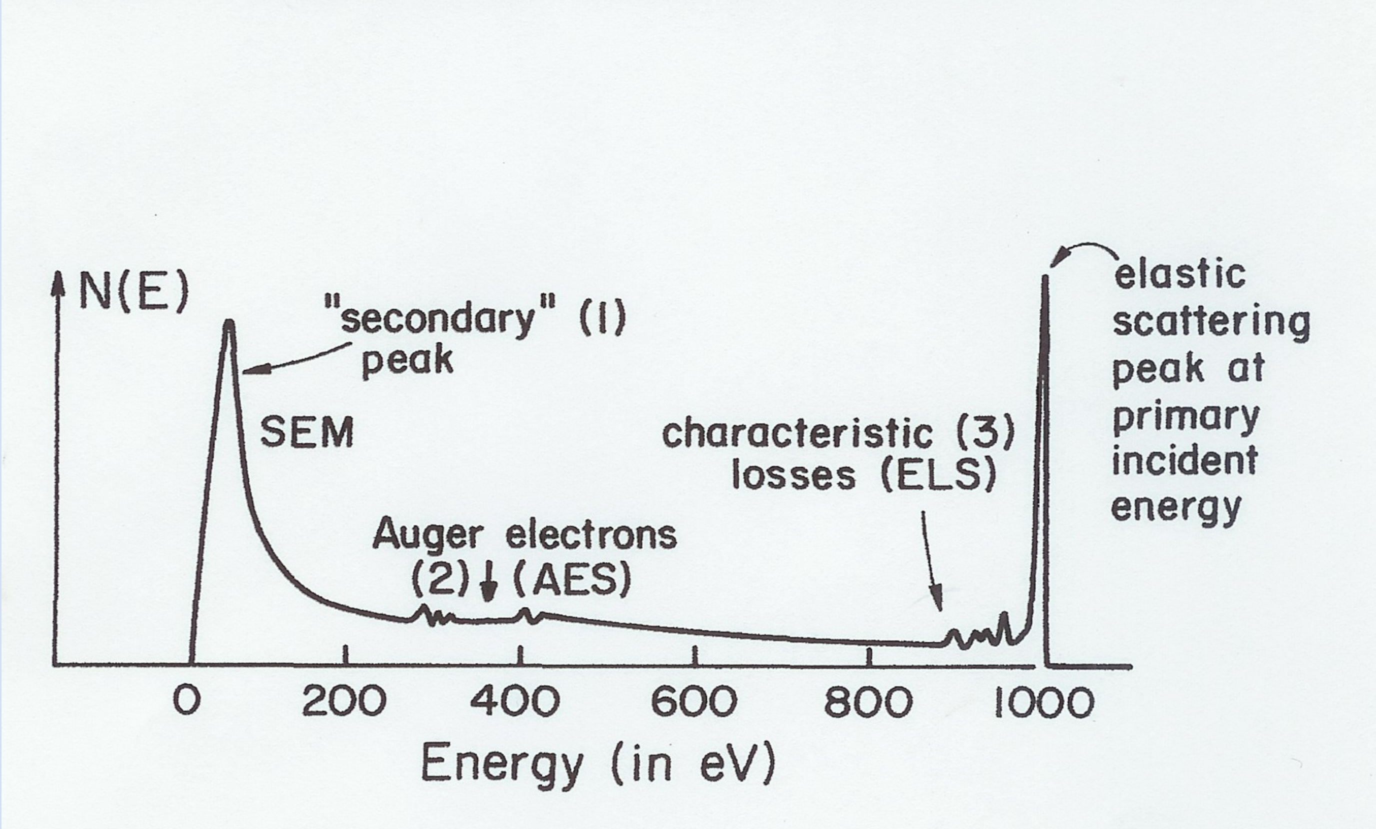
2. XRF (look at xrays emitted)

$$F_x = \eta_{\substack{SAMPLE \\ ATTEN.}} \cdot \eta^x_{\measuredangle} \cdot \eta^x_{DET} \cdot \eta_{other}$$

3. Auger (look at emitted Auger electrons)

$$F_A = \eta^A_{\measuredangle} \cdot \eta_{BSE} \cdot \eta_{SAMPLE} \cdot \eta_{ATTEN}$$

Electron Scattering from Solid Sample ("reflection")



example of simple calculations
of electron scattering

$$\sigma_{inel} \cong \frac{35.9\sqrt{Z}}{E_i} \ln\left(\frac{4E_i}{\bar{E}}\right) \text{ in } \mathring{A}^2 \text{ if } E\text{'s in eV}$$

$$\therefore \Lambda_{inel} \cong \frac{1}{n\sigma_{inel}} = \frac{E_i}{35.9 n\sqrt{Z} \ln\left(4E_i/\bar{E}\right)} \text{ in } \mathring{A} \text{ if } n \text{ in } /\mathring{A}^3.$$

$\bar{E} = 12.3\sqrt{Z}$ in eV

Aluminum. $Z_{Al} = 13 \Rightarrow n_{Al} = 6\times10^{-2}$ atoms$/\mathring{A}^3$

at $E_i = 1$ keV / $\sigma_{inel} = \frac{35.9\sqrt{13}}{10^3} \ln\left(\frac{4\times10^3}{12.3\sqrt{13}}\right) = 0.58\,\mathring{A}^2$

$$\Lambda_{inel} = \frac{1}{n\sigma_{inel}} = \frac{1}{.06\times.58} = 28.7\,\mathring{A}$$

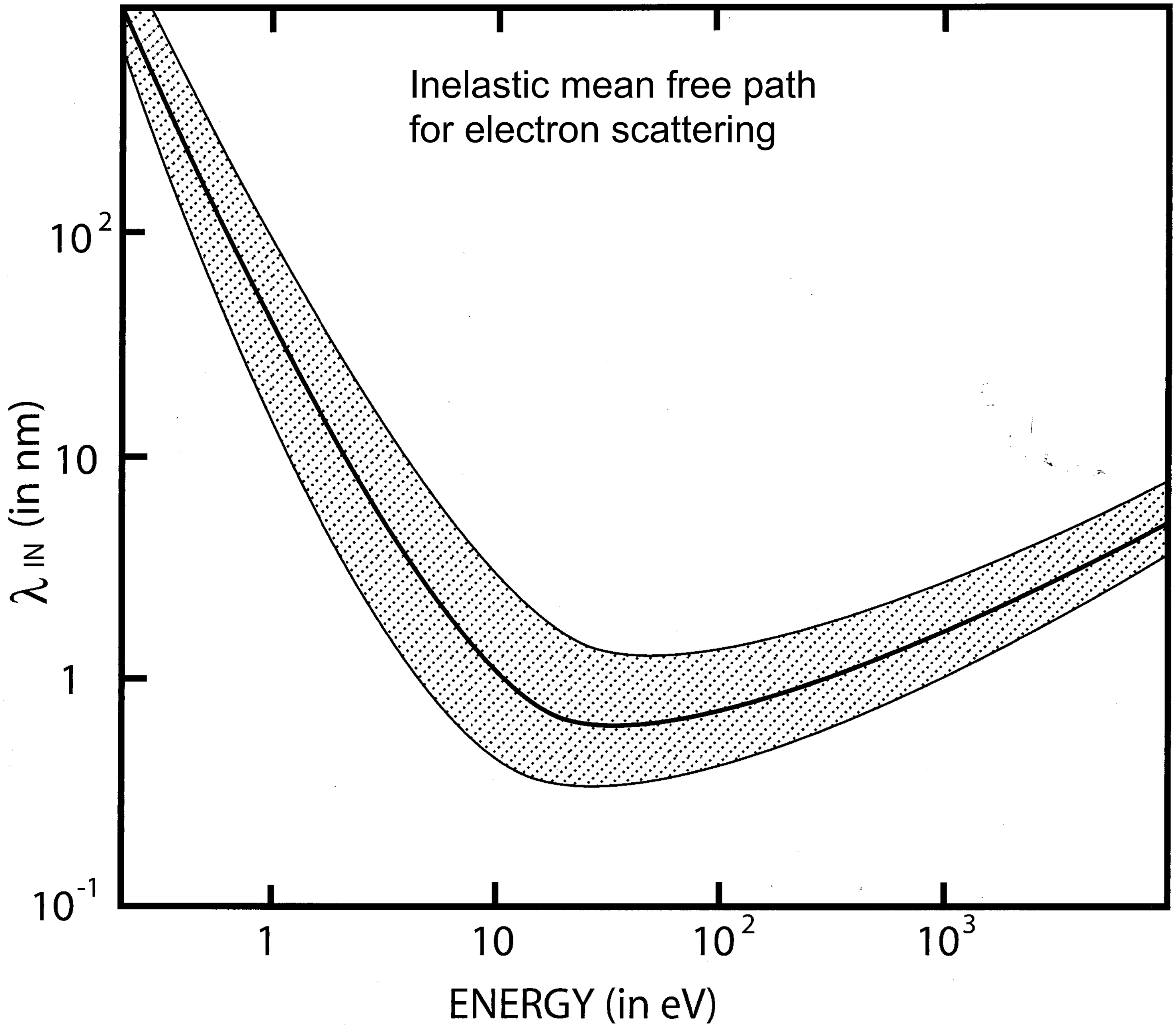
$$\boxed{\Lambda_{inel}^{Al} = 2.87\text{ nm}}$$

Gold $Z_{Au} = 79 \Rightarrow n_{Au} = 5.9\times10^{-2}$ atoms$/\mathring{A}^3$

$$\sigma_{inel} = 1.9\,\mathring{A}^2$$

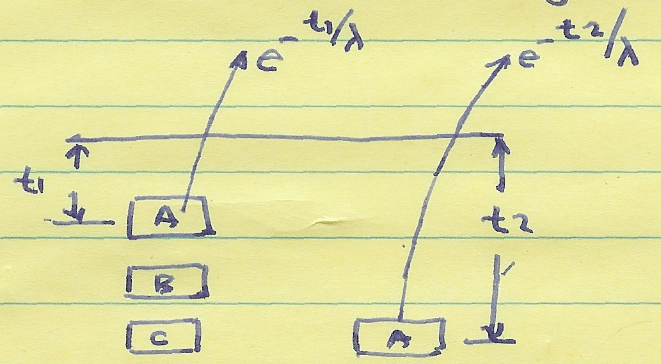
$$\Lambda_{ine} = \frac{1}{.059\times1.9} = 10.55\,\mathring{A} \Rightarrow \boxed{1.06\text{ nm} = \Lambda_{inel}^{Au}}$$

/compare to measurements/



From Seah and Dench, 1979. Surf. and Interface Anal.1.36

Effect of Depth on Auger Signal



if λ = avg. escape depth from matrix, then

$e^{-t_2/\lambda} < e^{-t_1/\lambda}$

even if N_A is same in both cases!

Electron Beam Induced Secondary Electron Emission