EE 213, Microscopic Nanocharacterization of Materials
Lecture 4. W2016

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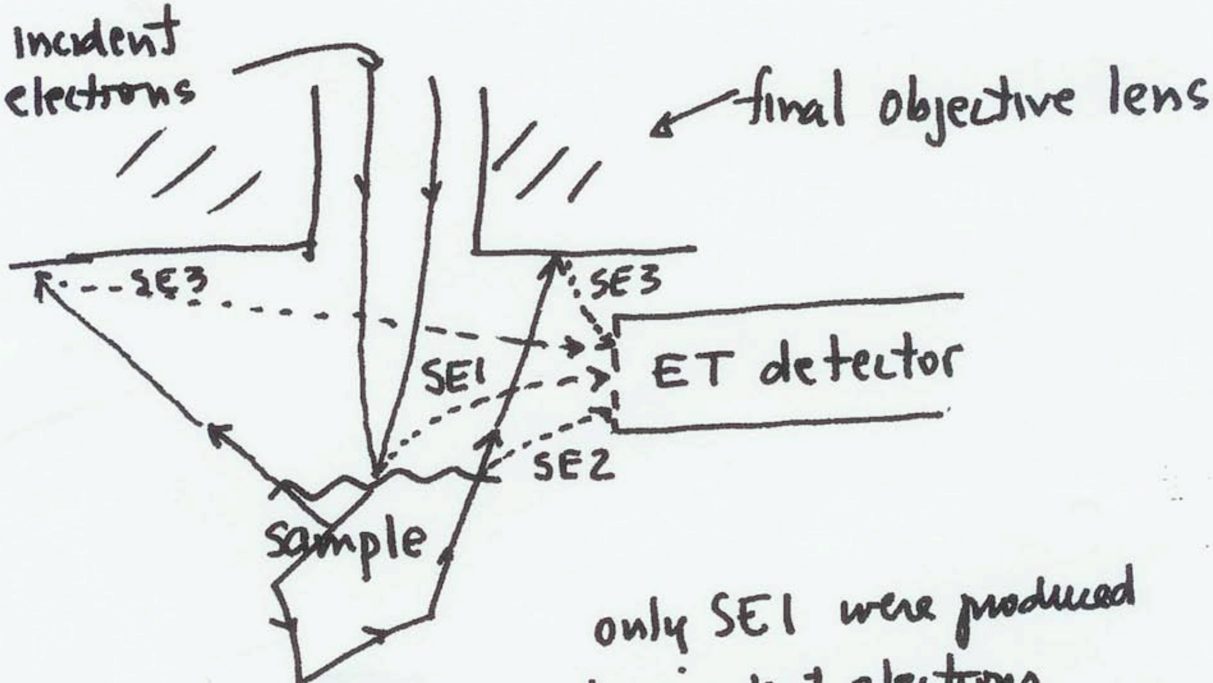
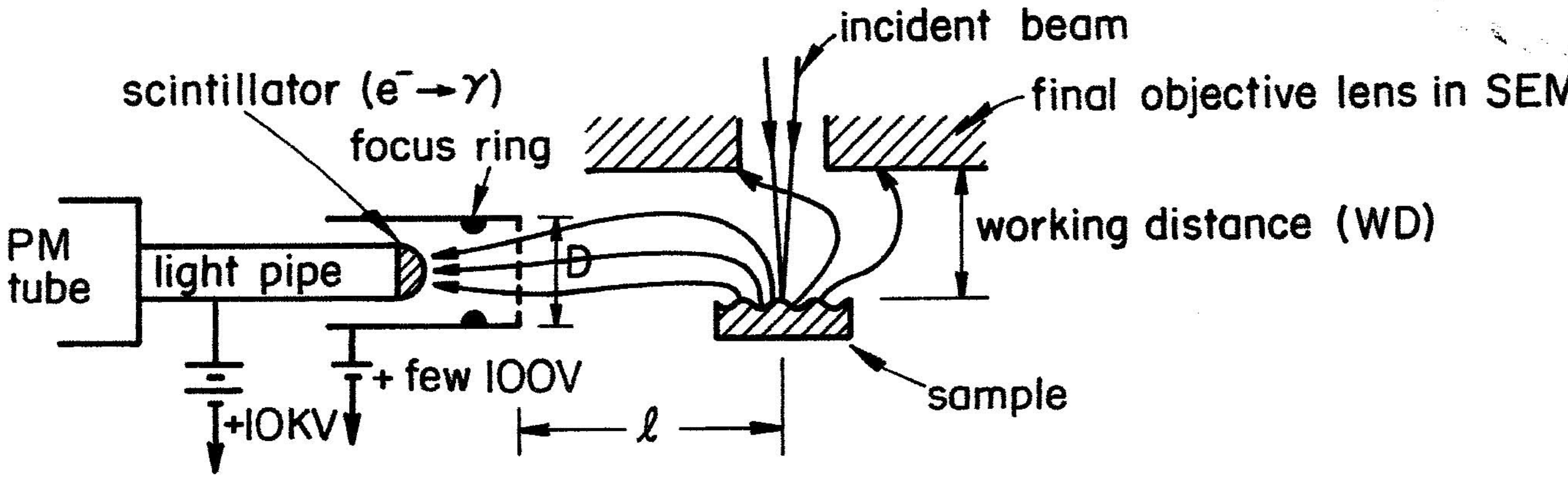
From Where do the secondaries Come?



only SE1 were produced by incident electrons at point of impact near surface.

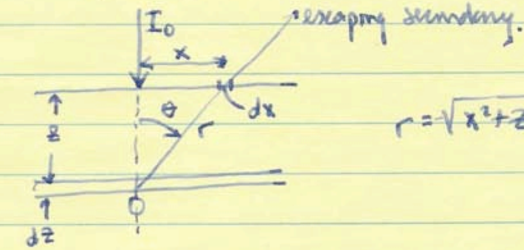
— SE2 depends on sample

— SE3 indep. of sample



incident beam
scintillator ($e^- \rightarrow \gamma$)
final objective lens in SEM
focus ring
PM tube
light pipe
D
working distance (WD)
+ few 100V
+10KV
sample
ℓ

Secondary Electron Yield (1)



$r = \sqrt{x^2 + z^2}$

1. secondary e^- produced at depth z will have probability of escape of $P(z)/P(0) = e^{-r/\Lambda_{esc}}$. Beer's law.

2. assume isotropic emission of secondaries in the solid. then # produced at depth z at point O which escape:

$$dI(z) = \int_0^\infty \frac{1}{4\pi r^2} e^{-r/\Lambda_{sec}} \cdot \underbrace{2\pi x\,dx}_{\text{ring at surface.}}$$

3. probability of incident electron of energy E_0 produce inelastic collision at depth Z is:

$$P_{in}(z) = dz/\Lambda_{in}(z)$$

4. if current at depth z is $I(z)$, then rate of production at z is $I(z)P_{in}(z)$.

if we assume that most secondaries that escape are within Λ_{in} of surface ($\Lambda_{sec} < \Lambda_{in}$) then $I(z) \approx I_0$

$\therefore$ rate of productions of inelastic events at z is:

$$\boxed{I_0\,dz/\Lambda_{in}(z)}$$

Secondary Electron Yield - 2

5. if we assume that if there is enough energy lost in an inel. collision, we produce a secondary e^-, then # secondaries / inel. collision, Nsec

$$N_{sec}/N_{inel} \approx \frac{E_{in}^{loss}}{E_{sec}}$$ — the secondary e^- energy

6. now just use average energy lost per collision and avg. energy of secondary e^-
then rate at which secondaries produced at depth z escape surface is:

$$dI_{sec}(z) = I_0 \frac{dz}{\Lambda_{in}} \frac{\overline{E}_{in}^{loss}}{\overline{E}_{sec}} dI(z)$$

7. for sample t thick then

$$I_{sec} = \int_0^t I_0 \frac{dz}{\Lambda_{in}} \frac{\overline{E}_{in}^{loss}}{\overline{E}_{sec}} \int_0^\infty \frac{1}{4\pi r^2} e^{-r/\Lambda_{sec}} \, 2\pi x \, dx$$

8. if $\Lambda_{sec} \ll \Lambda_{in}$ so $\Lambda_{in}(z) = \Lambda_{in}(E_i)$, or if $\overline{E}_{in}^{loss} \ll E_i$

then $$\delta_{sec} = \frac{I_{sec}}{I_0} \cong \frac{1}{2} \frac{\overline{E}_{in}^{loss}}{\overline{E}_{sec}} \frac{1}{\Lambda_{in}(E_i)} \underbrace{\int_0^t dz \int_0^\infty dx \frac{x e^{-r/\Lambda_{sec}}}{r^2}}_{\text{results in exponential integral of 2nd kind}}$$

9. ∴ $$\boxed{\delta_{sec} \cong \frac{1}{2} \frac{\overline{E}_{in}^{loss}}{\overline{E}_{sec}} \frac{\Lambda_{sec}}{\Lambda_{in}(E_i)} \left[1 - E_2(t/\Lambda_{sec})\right]}$$

Secondary Electron Yield - 3

$$\delta_{SEC} \cong \frac{1}{2} \frac{\overline{E_{in}^{loss}}}{\overline{E}_{sec}} \frac{\Lambda_{sec}}{\Lambda_{in}(E_A)} \left[1 - E_2(t/\Lambda_{sec})\right]$$

where $E_2(t/\Lambda_{sec}) = \int_1^\infty \frac{dy}{y} e^{-ty/\Lambda_{sec}}$ | tables.

$E_2(t/\Lambda_{sec}) \to 0$ as $t/\Lambda_{sec} \to \infty$, ie bulk solid

$\to 1$ as $t/\Lambda_{sec} \to 0$

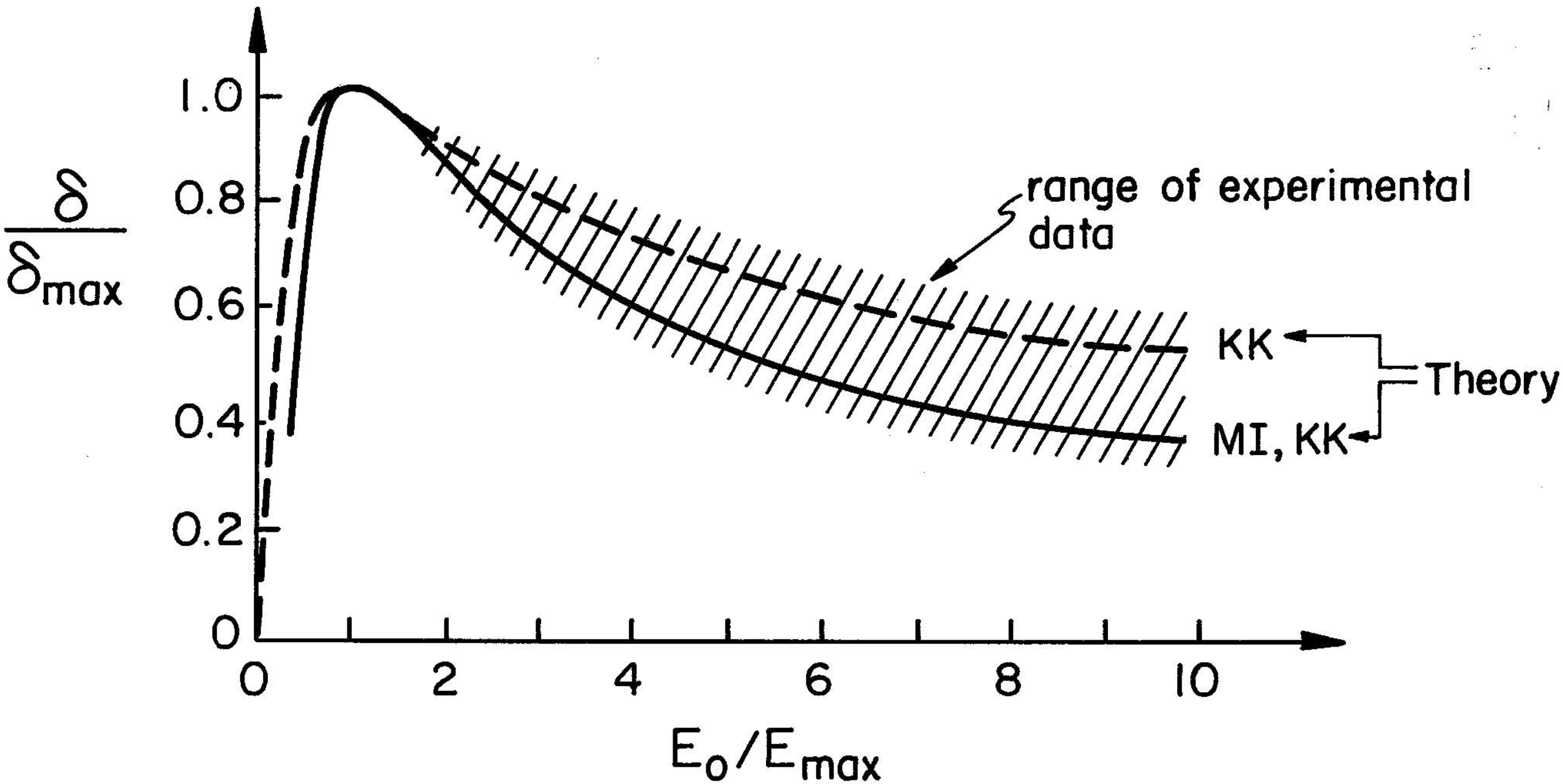
∴ for bulk solids $\boxed{\delta_{SEC}(\infty) \cong \frac{1}{2} \frac{\overline{E_{in}^{loss}}}{\overline{E}_{sec}} \frac{\Lambda_{sec}}{\Lambda_{in}(E_A)}}$

should be valid for $E_A > E_m$, energy where secondary yield is max.

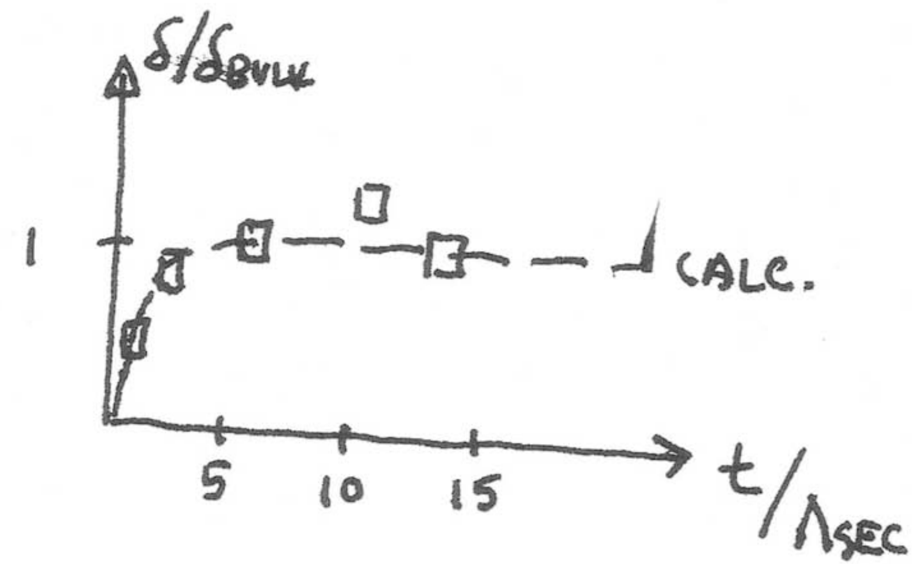
NOTE: this predicts correct shape of yield curve vs energy as well as agreement with experiment ✓

Secondary emission from bulk targets

Electron Beam Induced Secondary Electron Emission



Secondary emission from thin films



sec. elec. emission ✓

$$\delta_{SEC} \cong \frac{1}{2} \frac{\overline{E_{IN}}}{\overline{\overline{E_{SEC}}}} \frac{\Lambda_{SEC}}{\Lambda_{IN}(E_0)} \left[1 - E_2(t/\Lambda_{SEC})\right]$$

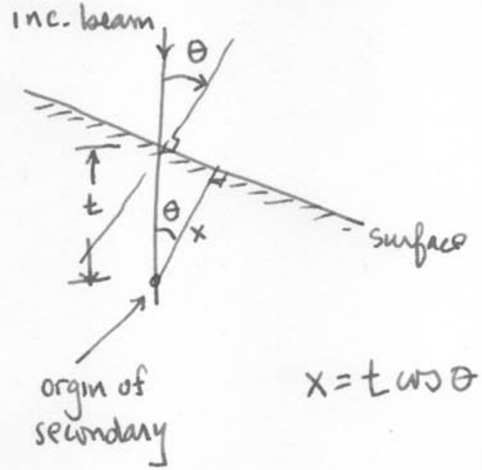
exp. from Voreades. (1976). Surf. Sci. 60. 325-348.

$$\delta_{SEC} \cong \frac{1}{2} \frac{\overline{E_{INC}^{LOSS}}}{\overline{E_{SEC}}} \frac{\Lambda_{SEC}}{\Lambda_{IN}(E_{INC})}$$

assumed $\perp$ incidence

what if non-$\perp$ incidence ?

Angular Dependence of Secondary Electron Emission



$$x = t\cos\theta$$

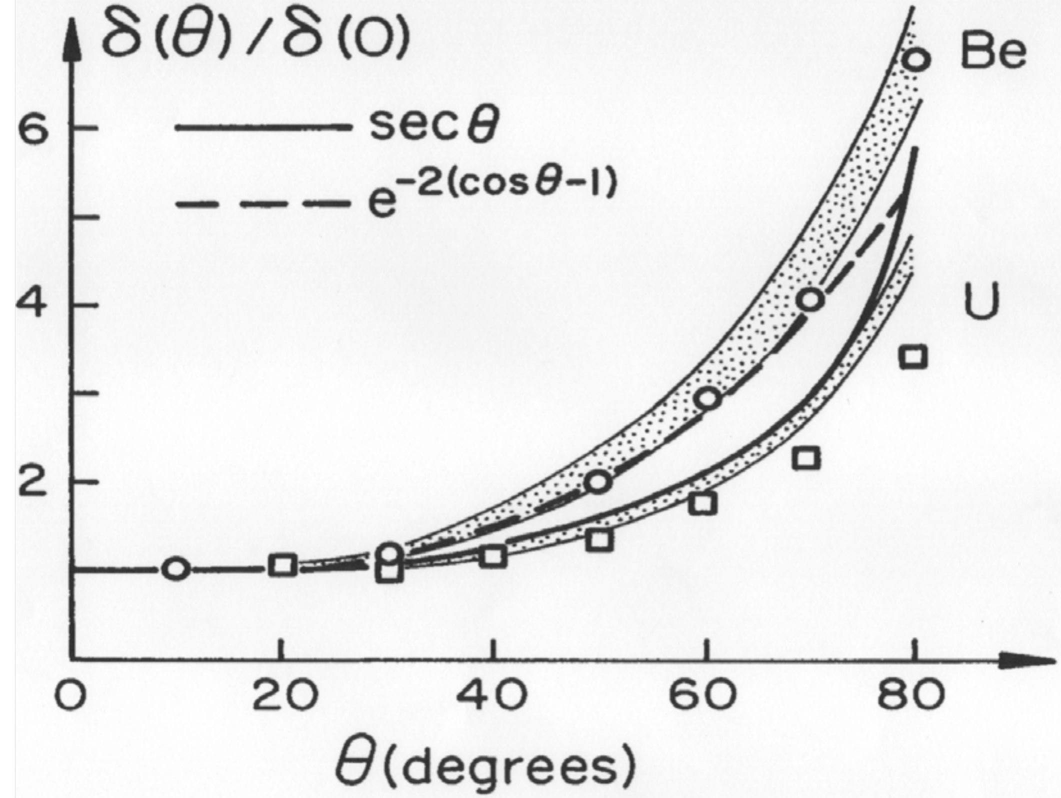
mfp of secondary electrons

$$\frac{I_{esc}}{I_{produced}} = e^{-t\cos\theta/\lambda_{SEC}}$$

secondary yield $= \delta = I_{esc}/I_{inc}$

$$\therefore \frac{\delta(\theta)}{\delta(0)} = \frac{e^{-t\cos\theta/\lambda_{SEC}}}{e^{-t/\lambda_{SEC}}} = \underline{e^{-\frac{t}{\lambda_{SEC}}(\cos\theta - 1)}}$$

Angular Dependence of Secondary Electron Emission



references

Electron Scattering:

M. Inokuti, Rev. Mod. Phys.43.297 (1971)

P. Crozier, Phil. Mag. 61(3), 311-336 (1990)

Secondary Emission:

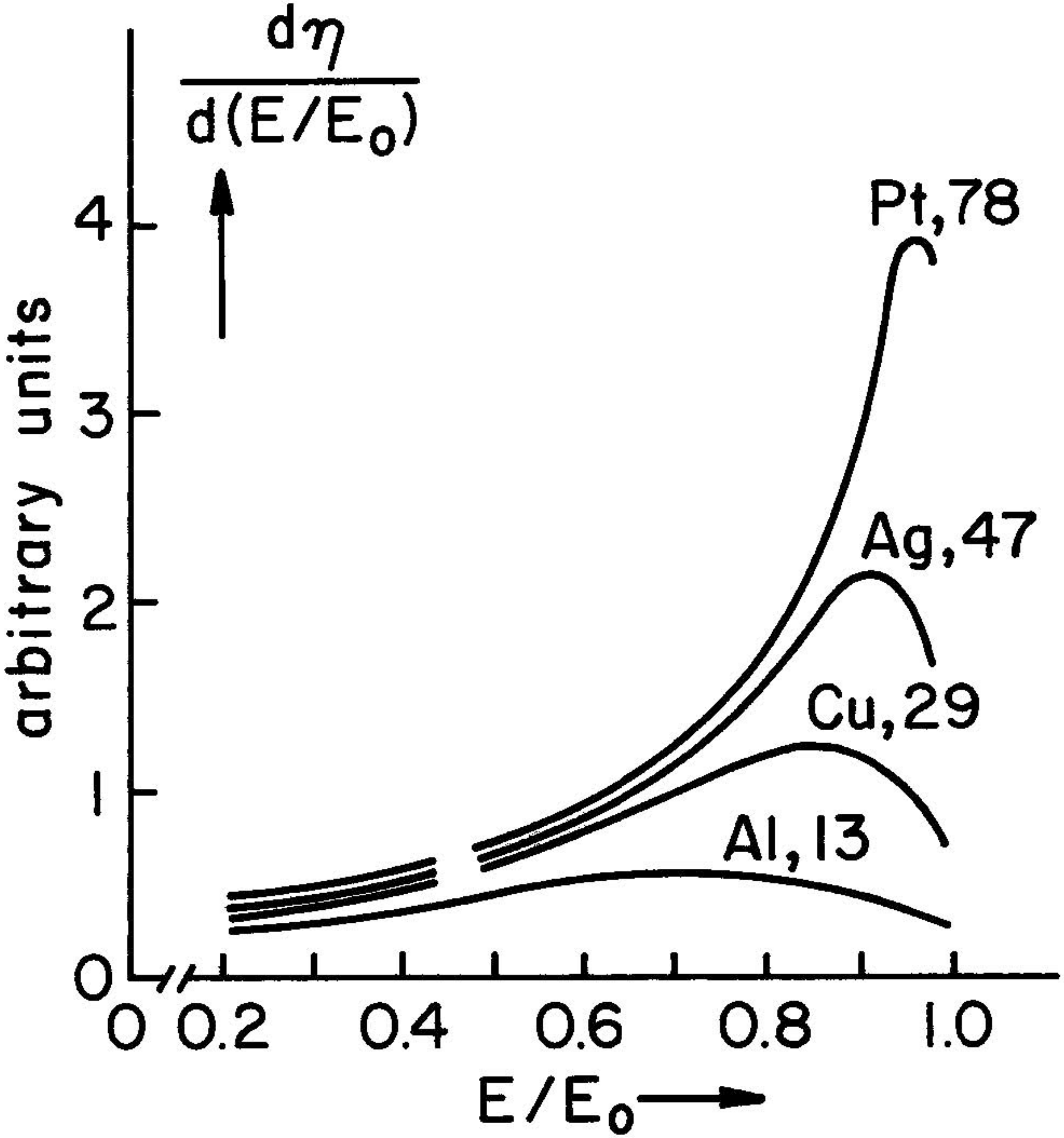
Kanaya and Kawakatsu, J.Phys.D:Appl. Phys. 5, 1727-1742 (1972)

Kanaya and Ono, J.Phys.D:Appl.Phys. 11, 1495 (1978)

Electron Backscattering:

Niedrig, J. Appl. Phys.53.R15 (1982). Good older review

Sternglass. Phys. Rev.95.345 (1954)



$\frac{d\eta}{d(E/E_0)}$
arbitrary units
4
3
2
1
0
Pt, 78
Ag, 47
Cu, 29
Al, 13
0
0.2
0.4
0.6
0.8
1.0
E/E_0

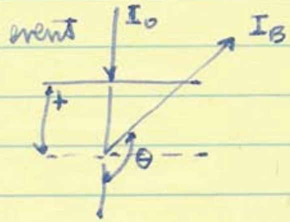
Electron Backscattering. 1

probability of interaction, $P = n\sigma\,dx$

$\therefore$ current scattered into a solid ∡ $d\Omega$ by elastic scatt,

$$\frac{dI_{EL}}{d\Omega} = I_0\, n t \frac{d\sigma_{EL}}{d\Omega} \quad (\text{from thickness } t)$$

– if we assume 1 large scattering event takes electrons out of sample



$\therefore$ the backscattering yield is then:

$$\eta = \frac{I_B}{I_0} = \int_{\pi/2}^{\pi} 2\pi \sin\theta\, d\theta \frac{dI_B}{d\Omega}$$

assuming large ∡ events are only Rutherford scattering

then $\frac{dI_B}{d\Omega} = \frac{dI_R}{d\Omega} = I_0 n t \frac{d\sigma_R}{d\Omega}$ → the Rutherford ∡ section.

but $\frac{d\sigma_R}{d\Omega} \Rightarrow \text{const}\, \frac{Z^2}{E_0^2} \frac{1}{\sin^4(\theta/2)}$

$$\therefore \eta = \int_{\pi/2}^{\pi} 2\pi \sin\theta\, d\theta\, I_0 n t (\text{const}). \frac{Z^2}{E_0^2} \frac{1}{\sin^4(\theta/2)}$$

$\boxed{\eta = K n t Z^2}$ where $K = \gamma^2 \frac{\lambda^4}{16\pi^3 a_0^2}$

with $\gamma = (1 - v^2/c^2)^{-1/2}$

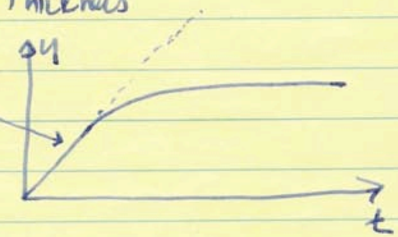
$\lambda = \left[\frac{h^2}{2mE_0\left(1 + \frac{E_0}{2mc^2}\right)}\right]^{1/2}$ relativistic wavelength

NOTE: K is material independent only depends on the electrons//

Electron Backscattering. 2.

$\boxed{\eta = K n t Z^2}$ so this says the BSE yield is linear with thickness

But, if t too large, multiple scattering, so electron can get scattered back into material.



And if $t \to$ Range of electrons in material, $\eta \to$ constant.

One other problem.

if t in the linear region of η, K is too small by 2-3x experimental values.

(reasonable since we assumed only 1 scatt. event)

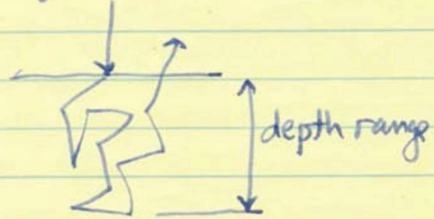
But all other properties of η are predicted by this simple expression.

Let's see if we can now get the expression for a solid target. To do this we just need to find the "effective" depth from which the backscattered electrons come. t_{EFF}.

To do this, we need to find the range (depth) of the electrons in the material.

Electron Backscattering - 3

The "depth" range or "maximum interaction depth" is the depth in the material beyond which few electrons travel. It is not the "total range" or total path of the electrons before stopping.



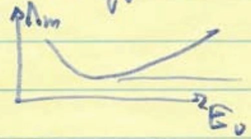
the depth range is less than total range because of sideways scattering (primarily elastic)

We calculate the "Bethe Range" which is path due to inelastic events. and such calculate Λ_{in} for every collision until electron loses almost all its energy.

$$R_i(E_0) = \int_{E_s}^{E_0} \frac{\Lambda_{in}(E)\,dE}{\overline{E_{IN}}}$$

avg. energy lost/collision

E_s is the "stopping energy", it is an energy beyond which there is little additional effect on range because Λ_{in} is so small.



E_0 = inc. energy

$$\boxed{\Lambda_{in}(E_0) = \frac{E_0}{35.9\, n\sqrt{Z}\, \ln(4E_0/\overline{E_{in}})}}$$

our handy-dandy simple expression

where Λ_{in} in Å, E_0, $\overline{E_{in}}$ in eV, n in #/Å^3/

Electron Backscattering - 4

the "Bethe Range" or inelastic range is:

$$R_i(E_0) = \int_{E_s}^{E_0} \frac{\Lambda_{in}(E)\,dE}{\overline{E_{IN}}}$$

expression not accurate at low energies, since if $E_s < \overline{E_{IN}}/4$, then $\ln[4E_0/\overline{E_{IN}}]$ blows up.

so we generally take $E_s > \overline{E_{IN}}$

using $\overline{E_{in}} \cong 12.3\sqrt{Z}$ in eV we can evaluate $R_i(E_0)$ analytically.

For $E_0 \gg E_s$ we get

$$\boxed{R_i(E_0) = \frac{11.32 \times 10^{-4}}{nZ} \frac{E_0^2}{\ln\left(\frac{.325 E_0}{\sqrt{Z}}\right)}}$$

in Å, with E_0 in eV, n in #/Å^3

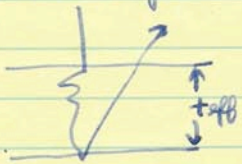
one can show using Monte Carlo calculations that the "depth Range" R is related to R_i as:

$$\boxed{R \cong R_i Z^{-4/3}}$$

ie large atomic # means more sideways scattering

Electron Backscattering .5.

Now we estimate the effective BSE depth.



The avg. energy the backscattered electrons have after escaping the sample is

$\underline{\overline{E}_B = E_0 - 2\Delta E}$ which assumes an energy loss ~~before~~ on the way in and on the way out is about the same.

∴ the effective energy, the electrons has before being backscattered is

$$\underline{E_{eff} \cong E_0 - \Delta E = \tfrac{1}{2}(E_0 + \overline{E}_B)}$$

thus, using this we can find out how far into the solid the electrons has gone before being backscattered.

$\overline{E}_B$ is gotten from experimental measurements or MC ~~calc~~ simulations.

$$\therefore \frac{R_1(E_{eff})}{R_1(E_0)} = 1 - \left(\frac{E_{eff}}{E_0}\right)^2 \frac{\ln(.325 E_0/\sqrt{Z})}{\ln(.325 E_{eff}/\sqrt{Z})}$$

this changes by ~10% from $Z = 14 \to 79$ and with $E_0 = 1 - 50$ keV!!

we get $\boxed{\frac{R_1(E_{eff})}{R_1(E_0)} \cong .45}$ over that range

Electron Backscattering - 6. cont

$\therefore\ t_{EFF} = R_{EFF} = R_1^{EFF} Z^{-1/3}$

or $\boxed{t_{EFF} = .45\, Z^{-1/3} R_1^{EFF}}$

$\therefore\ \underline{\eta = K n\, t_{EFF} Z^2}$

since the K for Rutherford scattering is about 2-3x less than experiment we just multiply the K by 2.5 and get

$$\boxed{\eta \cong \frac{0.21\, Z^{2/3}}{\ln(.325 E_0/\sqrt{Z})}} \qquad E_0 \text{ meV}$$

this gives reasonable agreement with exp. data.

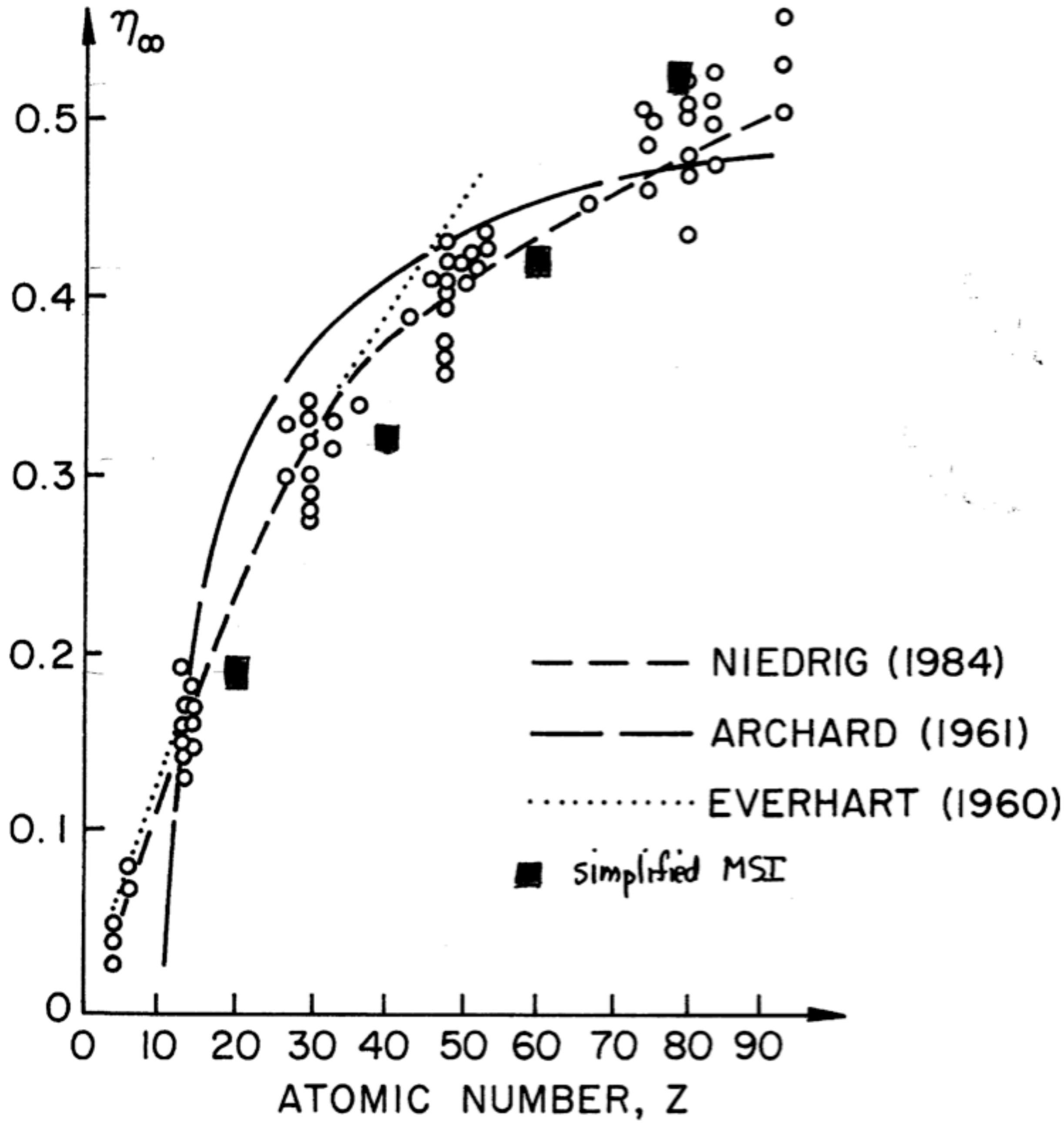
it is a bit high at high Z

and is off a ~~bit~~ bit at low E_0 //

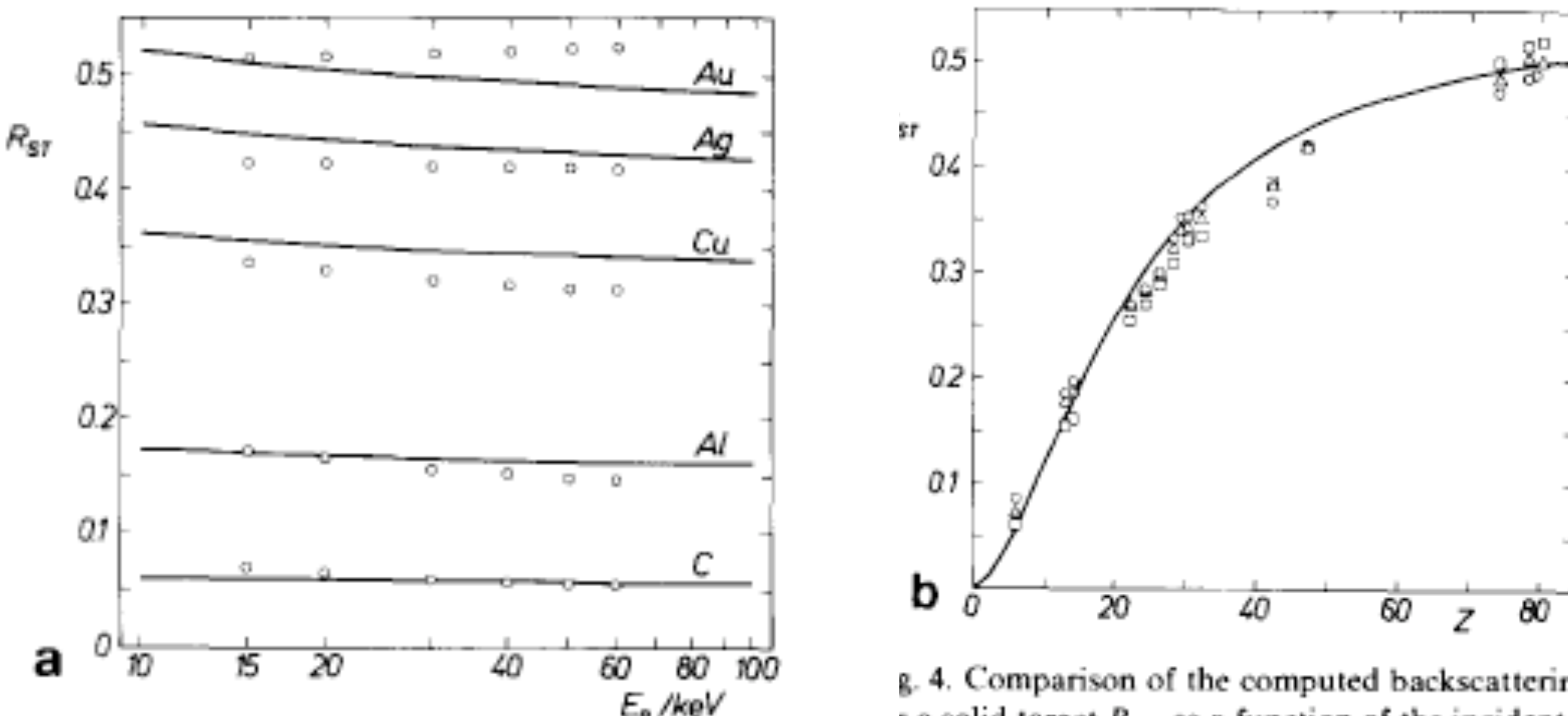
but agrees within 20% with experiment

and monte carlo simulations

Electron Backscattering Yield

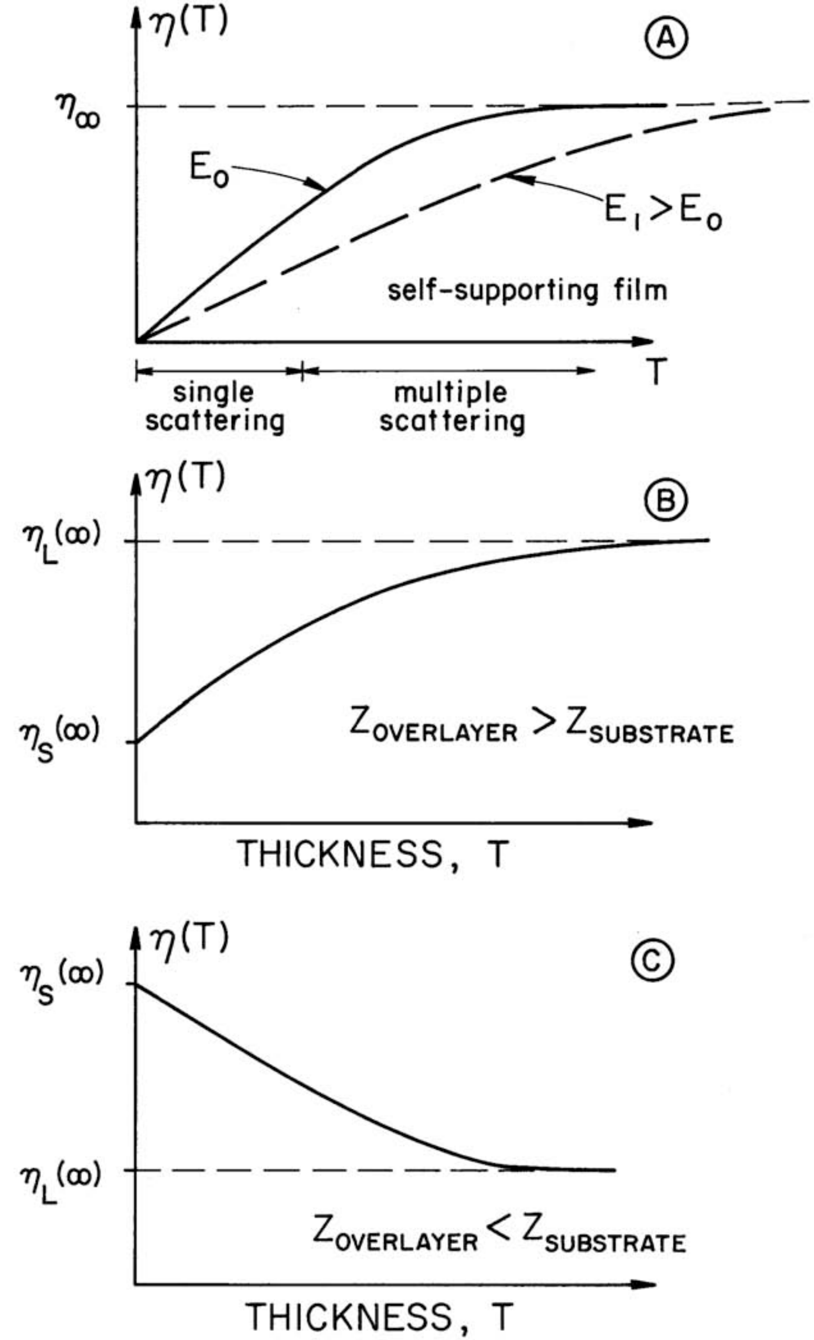


Electron Backscattering Yield Measurements

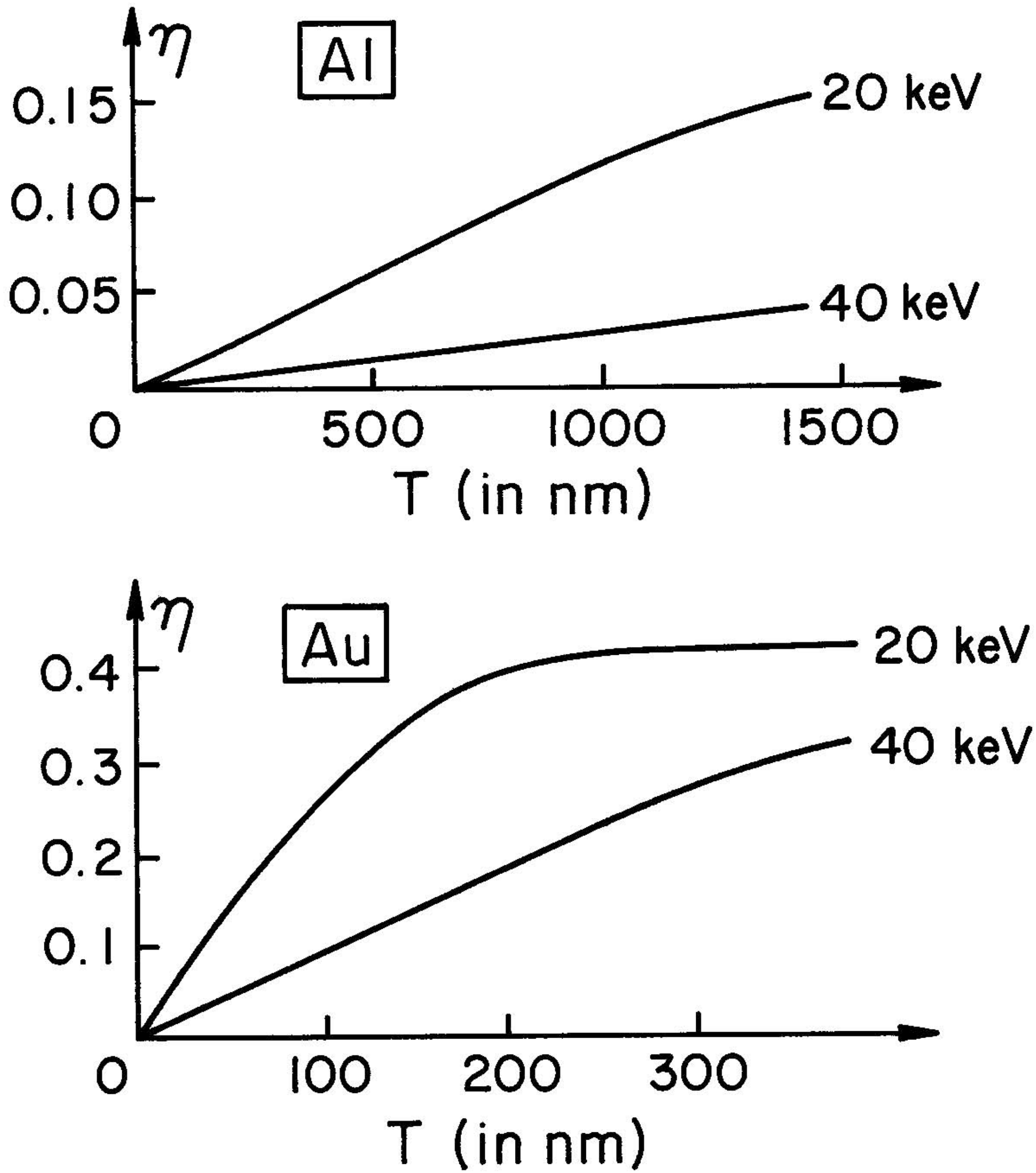


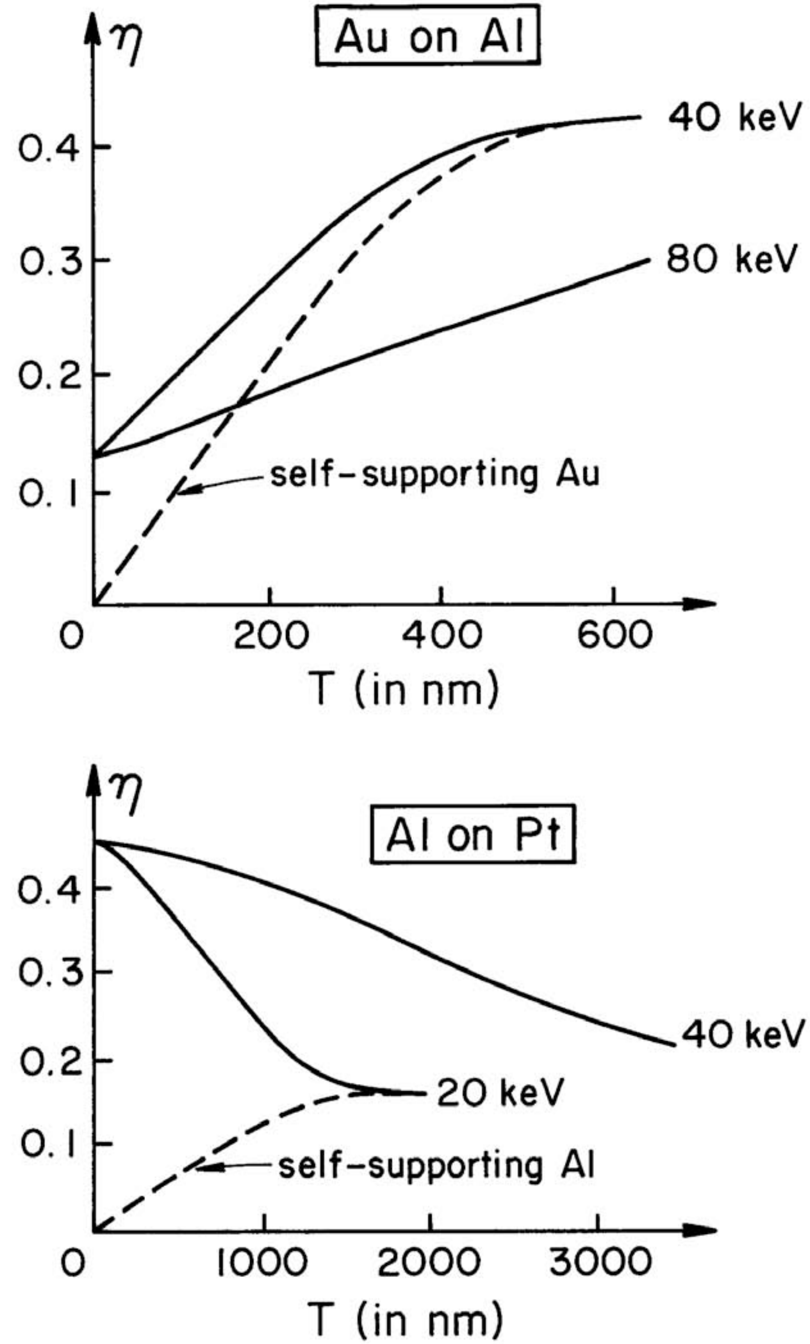
g. 4. Comparison of the computed backscattering probability r a solid target R_{ST} as a function of the incident energy E_0 (a) and the atomic number Z (b) with results of measurements from Neubert and Rogaschewski [13] (a) and from Bishop [15] for 5 (○), 10 (△) and 30 keV (□) (b).

from Werner, et.al..Ultramicroscopy.8(4).417. (1982)



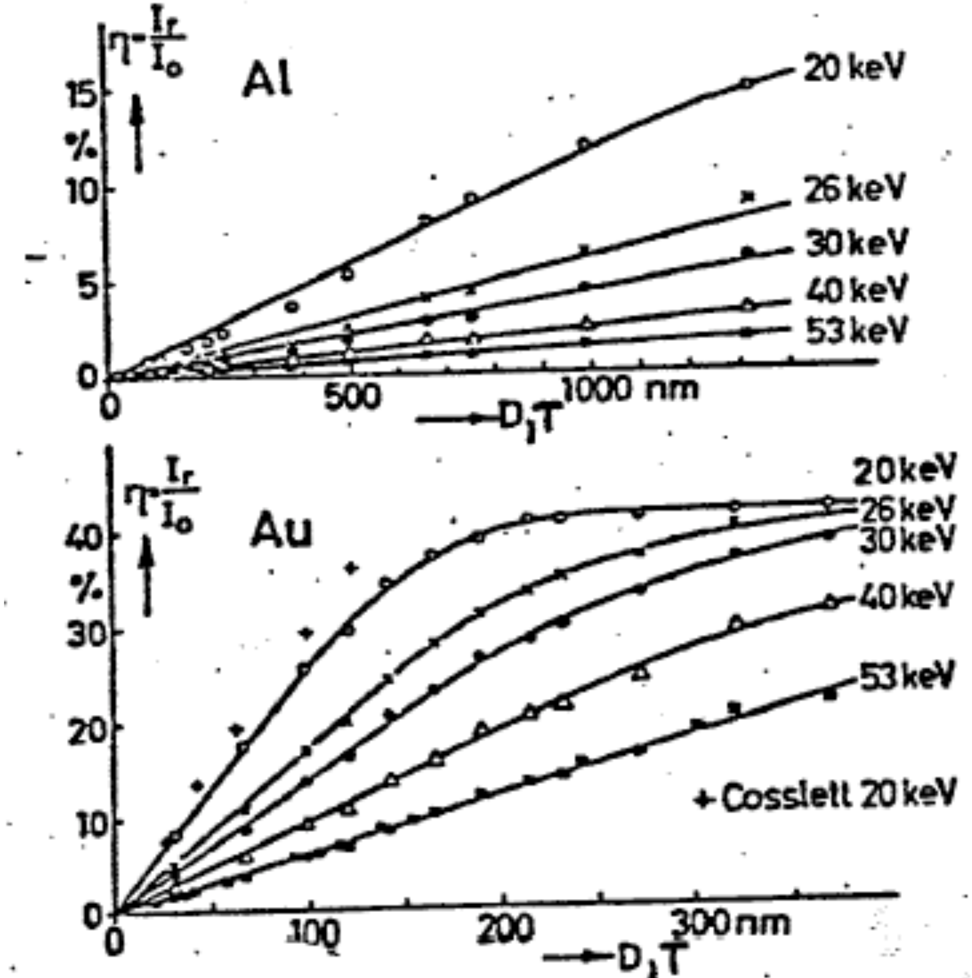
$\eta(T)$
A
η_∞
E_0
$E_1 > E_0$
self-supporting film
T
single scattering
multiple scattering
$\eta(T)$
B
$\eta_L(\infty)$
$\eta_S(\infty)$
$Z_{OVERLAYER} > Z_{SUBSTRATE}$
THICKNESS, T
$\eta(T)$
C
$\eta_S(\infty)$
$\eta_L(\infty)$
$Z_{OVERLAYER} < Z_{SUBSTRATE}$
THICKNESS, T


Al
η
0.15
0.10
0.05
20 keV
40 keV
0
500
1000
1500
T (in nm)
Au
η
0.4
0.3
0.2
0.1
20 keV
40 keV
0
100
200
300
T (in nm)



Au on Al
η
0.4
0.3
0.2
0.1
0
200
400
600
T (in nm)
40 keV
80 keV
self-supporting Au
Al on Pt
η
0.4
0.3
0.2
0.1
0
1000
2000
3000
T (in nm)
40 keV
20 keV
self-supporting Al

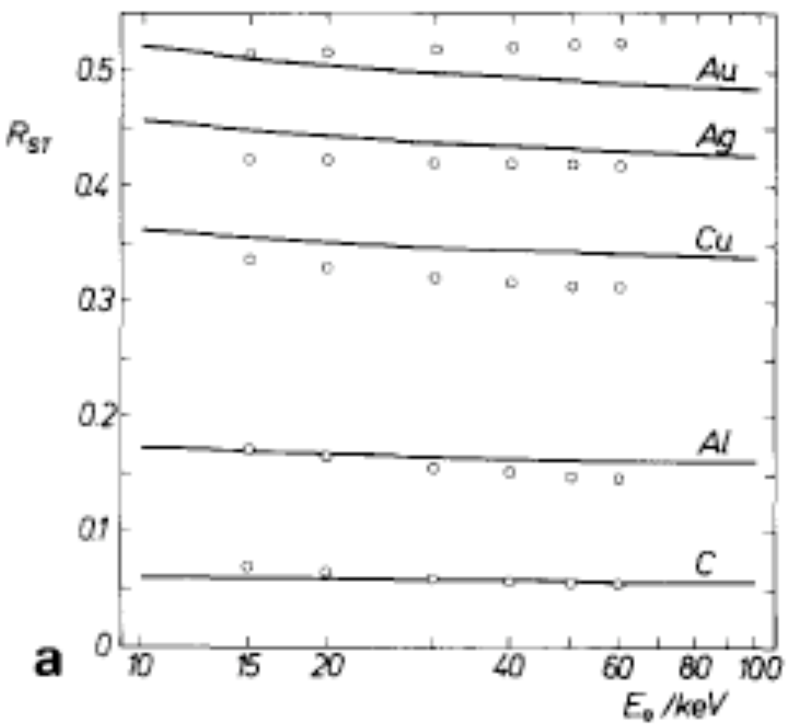
Experimental Measurements of Electron Backscattering in Thin Films

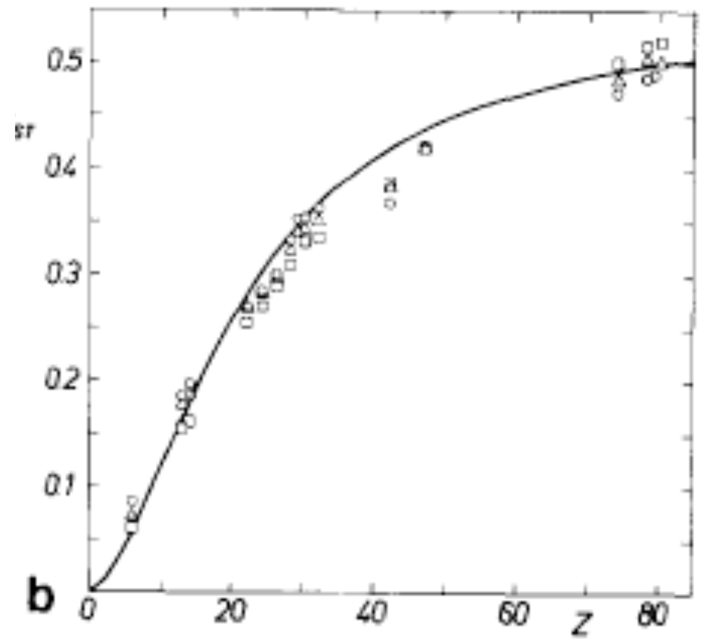


From H. Niedrig. J. Appl. Phys.53, R15 (1982)

Experimental values of the backscattering ratio versus film thickness for aluminium and gold. Normal incidence. Parameter: energy of the incident electrons (Niedrig and Sieber[4], Hohn and Niedrig[6]).

Electron Backscattering Yield Measurements





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from Werner, et.al..Ultramicroscopy.8(4).417. (1982)

Electron Backscattering. 1.

for thin films, we got for simple Rutherford scatt.

$$\eta = C_R \, n t Z^2$$

where $C_R = \dfrac{\lambda^4}{16\pi^3 a_0^2}$, $a_0 = 0.529\text{Å}$

λ = elec. wavelength

for bulk films we found effective depth of BSE, $t_{EFF} \approx 0.45 Z^{-1/3} R_I(E_0)$

"Bethe" or inelastic range

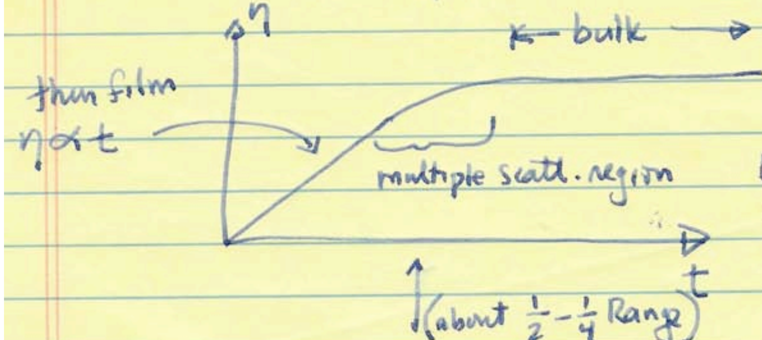
that gave,

$$\boxed{\eta_{BULK} = \frac{0.21 Z^{2/3}}{\ln\left(0.325 E_0/\sqrt{Z}\right)}}$$

bulk BSE weff

E_0 in eV//

reasonable agreement with experiment



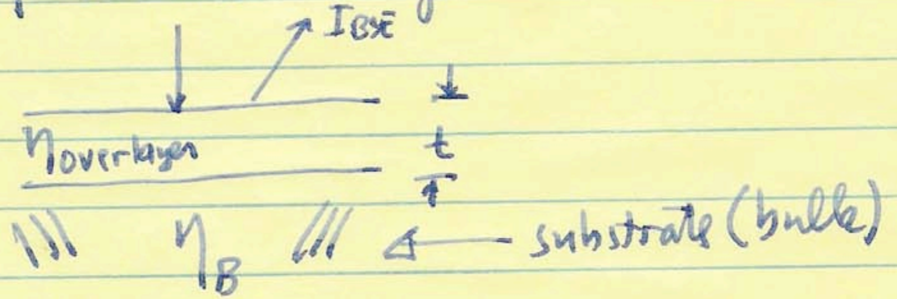
thickness limits for linear region.

Niedrig & Sieber.

Zeit. Ang. Phys. 31, 27 (1971)

Electron Backscattering - 2.

what is η for an "overlayer"



here we have BSE from "overlayer" as well as from the bulk substrate..

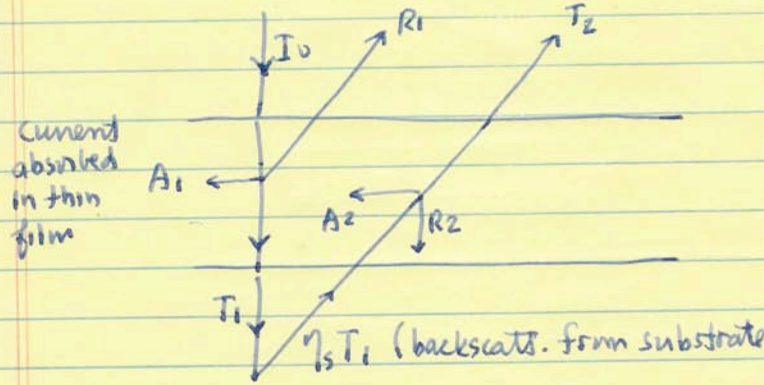
but it is not just simple

$$\eta \neq \eta_0 + \eta_s$$

the backscatt. yield of a self-supporting film of thickness t !!

we need to look carefully at what is going on.

Electron Backscattering. 3



$R_1 = \eta_0 I_0$ BSE from film directly (hasn't gone to substrate)

$T_1 = \eta_T I_0$ current transmitted to substrate

where η_T = transmission yield $= e^{-\mu_F t}$

μ_F = transmission coefficient of film

A_1 = absorbed current in film

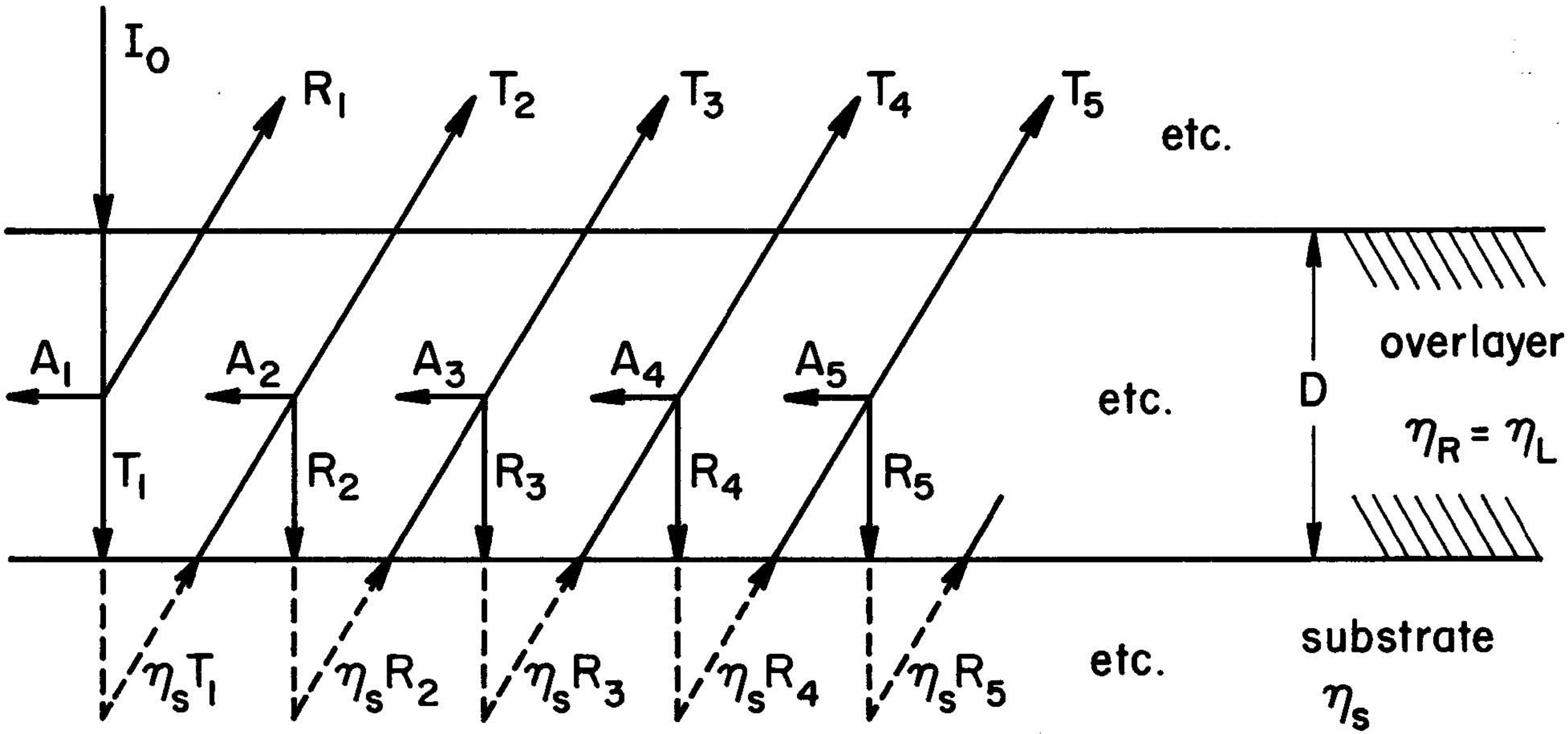
$\eta_s T_1$ = current that gets backscattered back into overlayer film.

$T_2 = \eta_T [\eta_s T_1]$ is fraction through overlayer that makes it out without being scattered back into film.

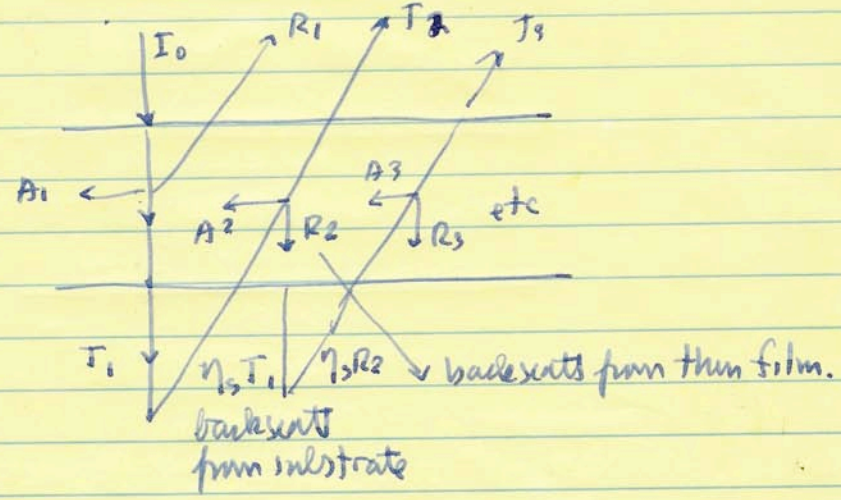
transmission yield thru substrate

$$\therefore\ T_2 = \eta_T [\eta_s (\eta_T I_0)] = \boxed{\eta_T^2 \eta_s I_0 = T_2}$$

Electron Backscattering from Multiple Layers



Electron Backscattering. 4



trans. yield.

$$\therefore \; R_1 = \eta_0 I_0$$

$$R_2 = \eta_0(\eta_s T_1) = \eta_0 \eta_s \eta_T I_0$$

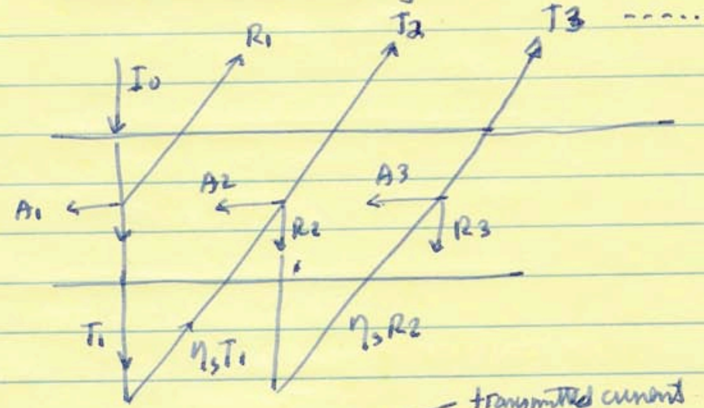
$$R_3 = \eta_0(\eta_s R_2) = \eta_0 \eta_s(\eta_0 \eta_s \eta_T I_0)$$
$$= \eta_0^2 \eta_s^2 \eta_T I_0$$

$$R_4 = \eta_0(\eta_s R_3) = \eta_0 \eta_s(\eta_0^2 \eta_s^2 \eta_T I_0)$$
$$= \eta_0^3 \eta_s^3 \eta_T I_0$$

etc

$$\boxed{R_n = (\eta_0 \eta_s)^{n-1} \eta_T I_0}$$ for the n^{th} reflection

Electron Backscattering - #5



transmitted current back through overlays

Similarly, $T_2 = \eta_T(\eta_s T_1)$

$$T_3 = \eta_T(\eta_s R_2)$$
$$= \eta_T(\eta_s \eta_0 \eta_s \eta_T I_0)$$
$$\underline{T_3 = \eta_s^2 \eta_T^2 \eta_0 I_0}$$

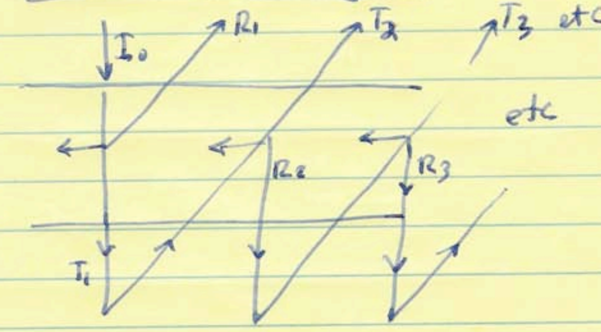
$$T_4 = \eta_T(\eta_s R_3) = \eta_T \eta_s(\eta_0^2 \eta_s^2 \eta_T I_0)$$
$$\underline{\therefore T_4 = \eta_s^3 \eta_T^2 \eta_0^2 I_0}$$

etc

$$T_n = \eta_T^2 \eta_s^{n-1} \eta_0^{n-2} I_0$$

$$\underline{T_n = \eta_s \eta_T^2 (\eta_s \eta_0)^{n-2} I_0}$$ for the beams transmitted back out from the substrate

Electron Backscattering. #6



$$\therefore \boxed{I_{BACK} = R_1 + \sum_{n=2}^{\infty} T_n}$$

$$= R_1 + \sum_{n=2}^{\infty} \eta_s \eta_T^2 (\eta_s \eta_0)^{n-2} I_0$$

$$I_{BACK} = R_1 + \eta_s \eta_T^2 \sum_{n=2}^{\infty} (\eta_s \eta_0)^{n-2} I_0$$

$$\therefore \boxed{\eta_{BACK} = \eta_0 + \underbrace{\eta_s \eta_T^2 \sum_{n=2}^{\infty} (\eta_s \eta_0)^{n-2}}}$$

backscatt from unsupported overlayer

backscatt from bulk substrate

for self supporting films, $(t < \frac{1}{2} - \frac{1}{4} R)$

refl. coeffn

$\eta_0(t) = \mu_R t$, where $\mu_R = C_R n Z^2$ / Rutherford scatt

(linear portion)

Electron Backscattering - #7

$$\therefore \quad \eta_{BACK} = \eta_0 + \eta_s \eta_T^2 \sum_{n=2}^{\infty} (\eta_s \eta_0)^{n-2}$$

thin film overlayer on substrate

$$\therefore \quad \eta_{BACK} = \eta_0 + \eta_s \eta_T^2 \sum_{n=0}^{\infty} (\eta_s \eta_0)^{n}$$

overlayer by itself

substrate

density

$\eta_0 = \mu_R t$ where $\mu_R = C_R n Z^2$

at. #

in linear region ($t <$ Range)

Ruth scatt const (or corr.)

$\eta_T = e^{-\mu_T t}$ transmission coeff.

$$\therefore \quad \boxed{\eta_{BACK} = \mu_R t + \eta_s e^{-2\mu_T t} \left[\sum_{n=0}^{\infty} (\eta_s \mu_R t)^n \right]}$$

backscatt yield for thin overlayer on substrate

Electron Backscattering - ~~6~~ 8

for films wit $t \ll R$, in linear region.

then $\mu_R t \ll 1$ and $\mu_T t \ll 1$

so we expand

$$\eta_{BACK} = \mu_R t + \eta_s e^{-2\mu_T t}\left[\sum_{n=0}^{\infty} (\eta_s \mu_R t)^n\right]$$

$$= \mu_R t + \eta_s (1 - 2\mu_T t)(1 + \eta_s \mu_R t) \cdots$$

$$\boxed{\eta_{BACK} = \eta_s + t\left[\mu_R (1+\eta_s^2) - 2\mu_T \eta_s\right]}$$

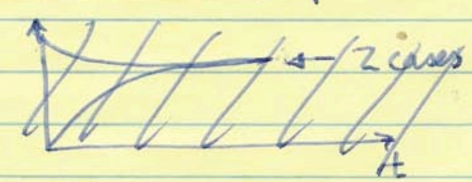
refl. coeff of overlayer.

trans. coeff. of overlayer

note that [ ] can be + or −

∴ backscatt yield of film + substrate can be > or < substrate only!

$$\boxed{t = \frac{\eta_{BACK} - \eta_s}{\mu_R (1+\eta_s^2) - 2\mu_t \eta_s}}$$



Electron Backscattering - ~~6~~ 8

for films with $t \ll R$, in linear region.

then $\mu_R t \ll 1$ and $\mu_T t \ll 1$

so we expand

$$\eta_{BACK} = \mu_R t + \eta_s e^{-2\mu_T t}\left[\sum_{n=0}^{\infty} (\eta_s \mu_R t)^n\right]$$

$$= \mu_R t + \eta_s(1-2\mu_T t)(1+\eta_s \mu_R t) \cdots$$

$$\boxed{\eta_{BACK} = \eta_s + t\left[\mu_R(1+\eta_s^2) - 2\mu_T \eta_s\right]}$$

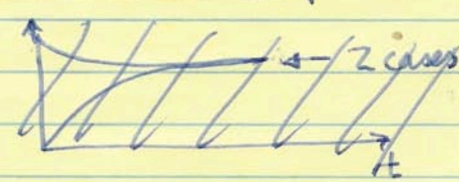
refl. coeff of overlayer.

trans. coeff. of overlayer

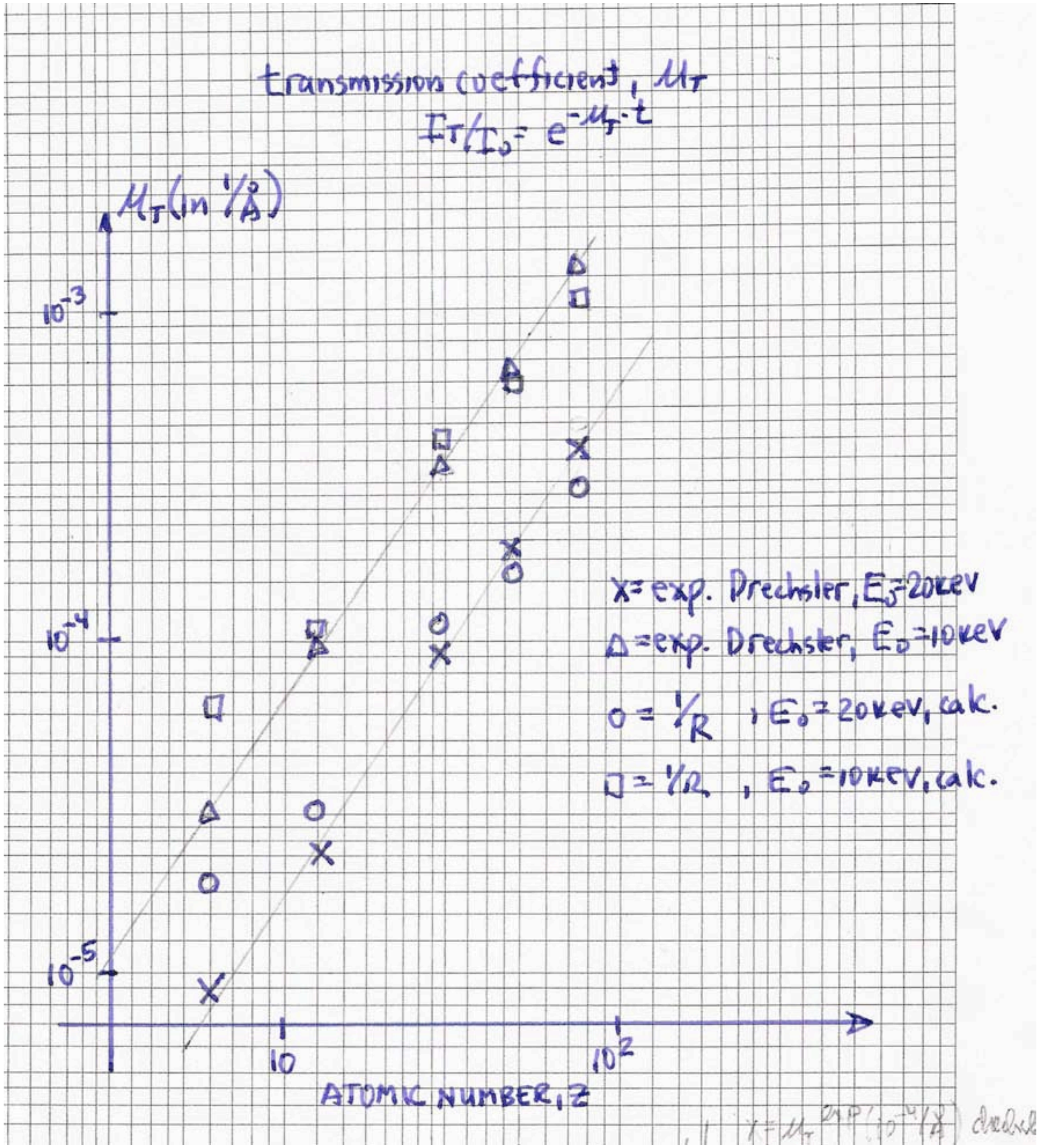
note that [ ] can be + or −

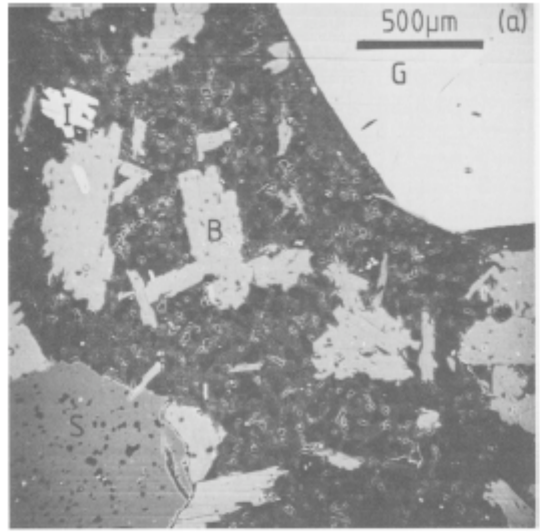
∴ backscatt yield of film + substrate can be > or < substrate only!

$$\boxed{t = \frac{\eta_{BACK} - \eta_s}{\mu_R(1+\eta_s^2) - 2\mu_t \eta_s}}$$

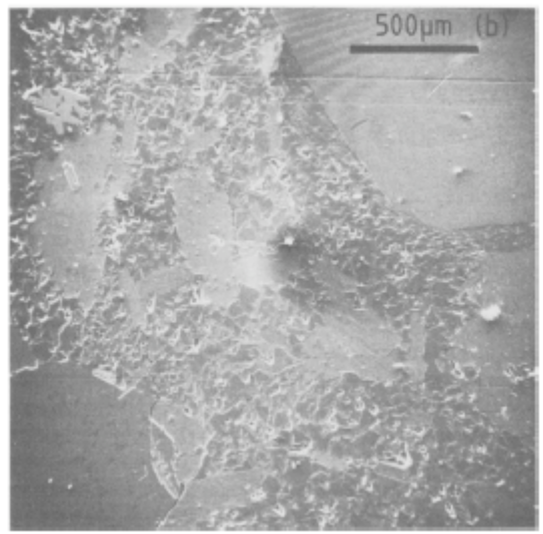


Electron Transmission Coefficients





BSE



SE

FIG. 3. (*a*) Example of backscattered electron *Z*-contrast image: hornfelsed metagreywacke, with the following minerals present (in increasing order of brightness): equant quartz and prismatic muscovite forming the matrix (see Fig. 1*a* for detail), porphyroblastic staurolite (S), biotite (B) and garnet (G), and matrix ilmenite (I). Compare the contrasts shown with those predicted by equation 2 or inferred in Fig. 4*b*. (*b*) Same area imaged using secondary electrons; note the considerably lower *Z*-contrast effect and also the suppression of topographic contrast due to using a specimen which had been polished flat. Both imaged at 30 kV; specimen carbon-coated.

From G.E.Lloyd, Mineralogical Magazine. (1987).V51.3-19.

Electron Backscattering from Binary Compounds

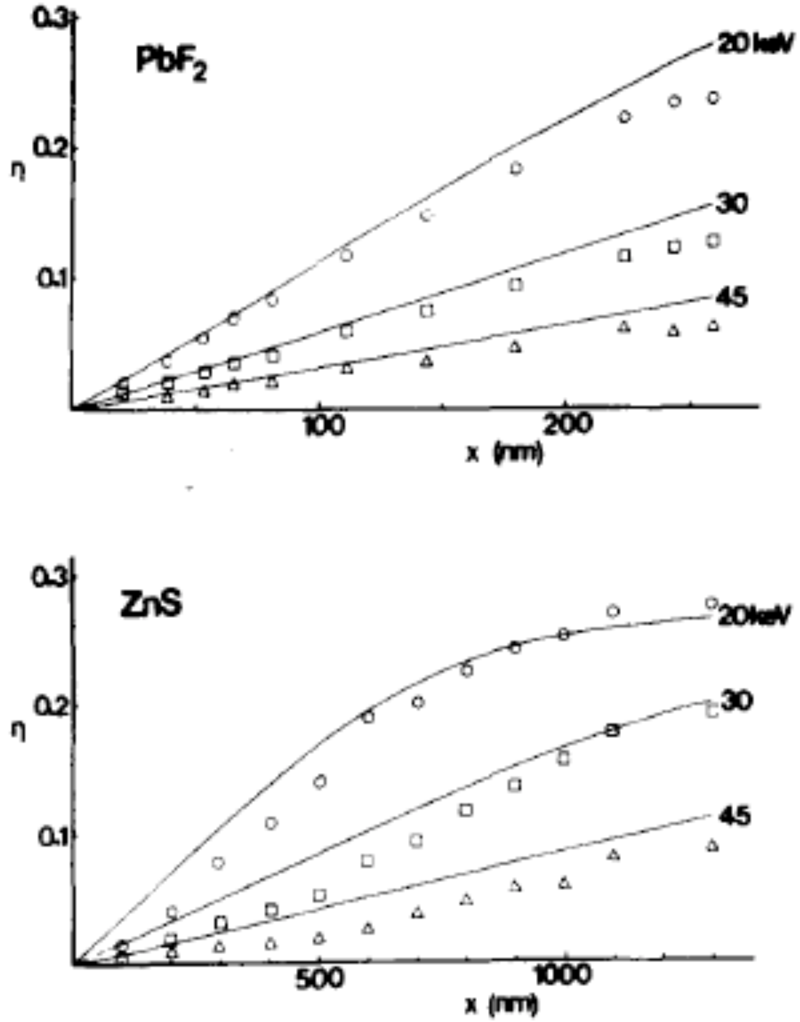
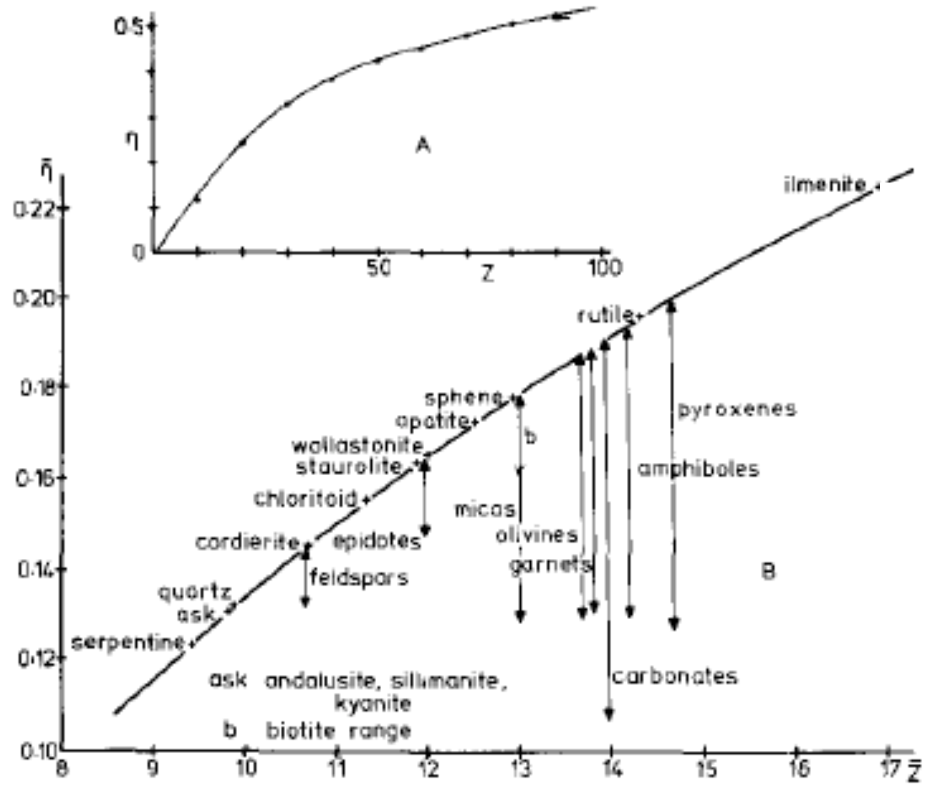


FIG. 10. Comparison of BE data[24] from films of elemental compounds with predictions based on Eq. (17) and the universal fit (solid line).

From M. Sogard. J.Appl. Phys. 51(1981).4417

Electron Backscattering from Compounds



$$\bar{Z} = \frac{\Sigma(NAZ)}{\Sigma(NA)}$$

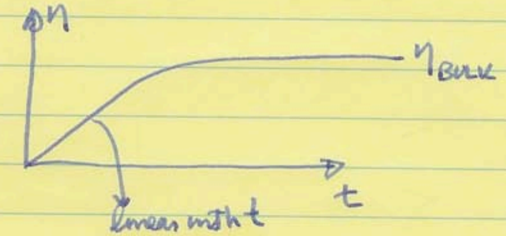
FIG. 4. Relationship between BSE coefficient (η or $\bar{\eta}$) and atomic number (Z or $\bar{Z}$). (A) Pure elements (after Bishop, 1966 and Heinrich, 1964). (B) Major rock-forming minerals (after Hall and Lloyd, 1981). The values of $\bar{\eta}$ and $\bar{Z}$ were determined using the most general formula available for each mineral and the BASIC computer program 'MEATNO'. Note that variations in composition (e.g. amphiboles etc.) lead to a range of $\bar{Z}$ values and hence a range of $\bar{\eta}$ values which in turn causes variations in image contrast.

From G.E. Lloyd. Mineralogical Magazine.17 (1987).3-19.

Backscattering from Compounds

<u>Backscattered Electron, Z contrast Imaging. I</u>

$$\eta_{BULK}(Z) = \frac{0.21\,Z^{2/3}}{\ln\left(0.325\,E_0/\sqrt{Z}\right)} \quad E_0 \text{ in eV}$$



with compound materials, the backscattered yield depends upon several factors —

1. atomic concentrations
2. mass concentrations
3. crystallinity

many discussions in literature of how this is determined?

for bulk materials:

$$\eta = f_A \eta_A + f_B \eta_B \quad \text{where } f_A = \frac{m_A}{m_A + m_B}, \text{ mass fraction}$$

R. Castaing, in <u>Adv. in Elec. and Elec. Phys. V.13 (1960)</u> eds. L. Marton and C. Marton (Acad. Press, NY)

$$\eta = \sum_{i=1}^{n} f_i \eta_i$$

pure element BSE yields

Backscattered Electron Imaging. 2

for very thin films (compound material).

$$\eta = c_A\eta_A + c_B\eta_B \quad \text{where } c_A = \frac{n_A}{n_A+n_B}\text{, atomic fraction}$$

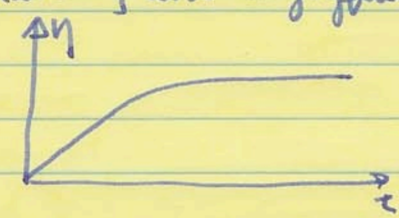
in the intermediate regime,

$$\eta(t) = f_A\eta_A\underbrace{\left(t\cdot \rho/\rho_A\right)}_{\text{a "weighted" film thickness}} + f_B\eta_B\left(t\,\rho/\rho_B\right)$$

$f_A = \frac{m_A}{m_A+m_B}$ as before

→ this is "empirical" result for a binary system. Sogard. J. Appl Phys. 51(8). 1980, 4417–4424

— not as neat as one would like since the BSE gets more complicated as one goes from "linear in t" region to bulk, where multiple scattering and Range effects dominate



Effect of Channeling on BSE Contrast

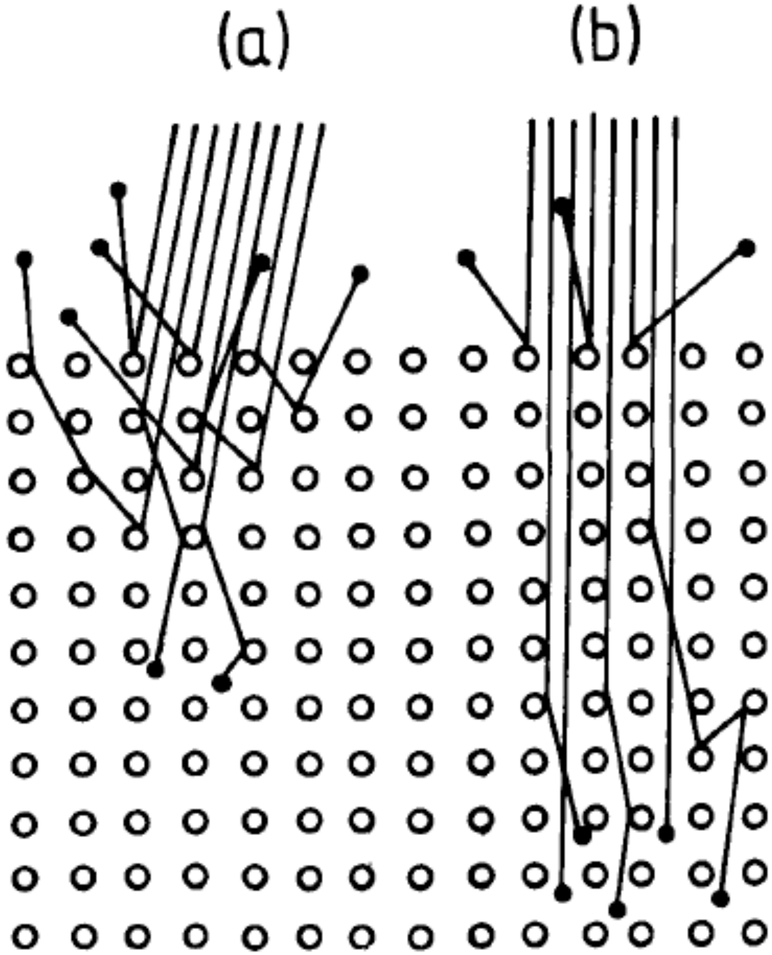
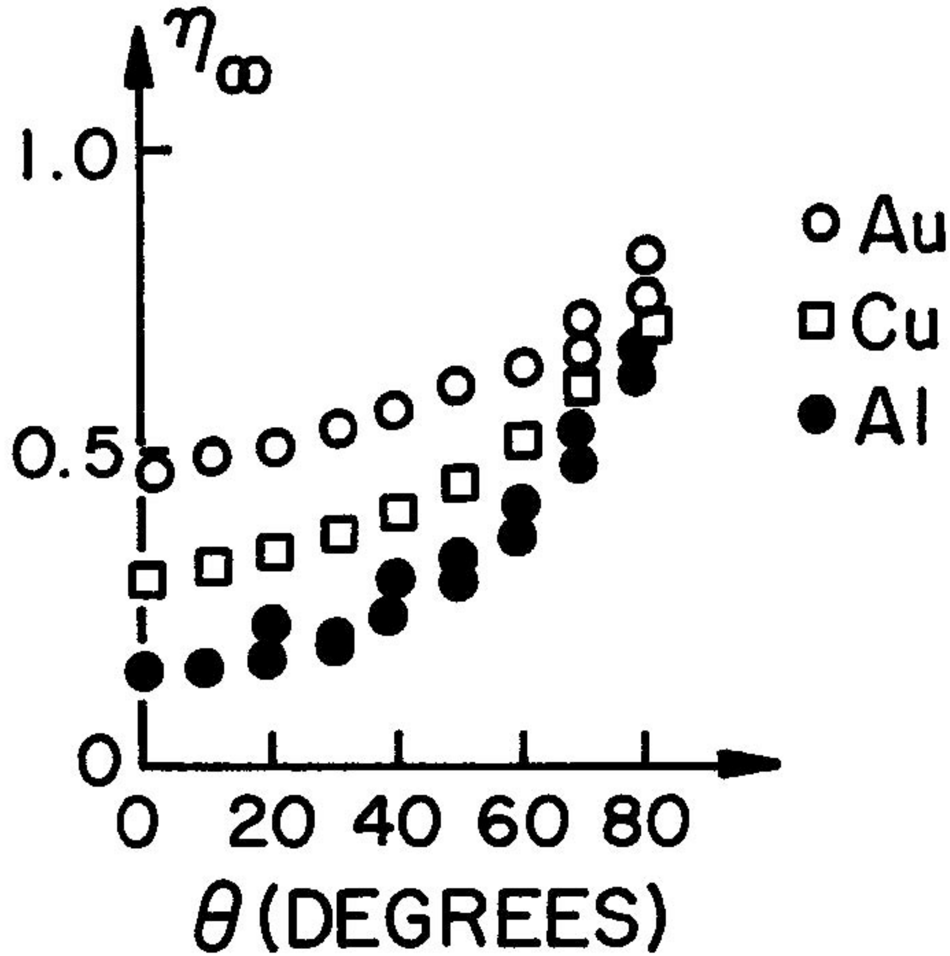


FIG. 6. Electron channelling effect. The variation in depth of electron penetration with angle of incidence relative to the target crystal structure results in either (*a*) near surface interactions and high BSE emission rates (Type II Bloch waves), or (*b*) deep penetration and low BSE emission rates (Type I Bloch waves). After Goldstein and Yakowitz (1975).

Angular Dependence on Electron Backscattering



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