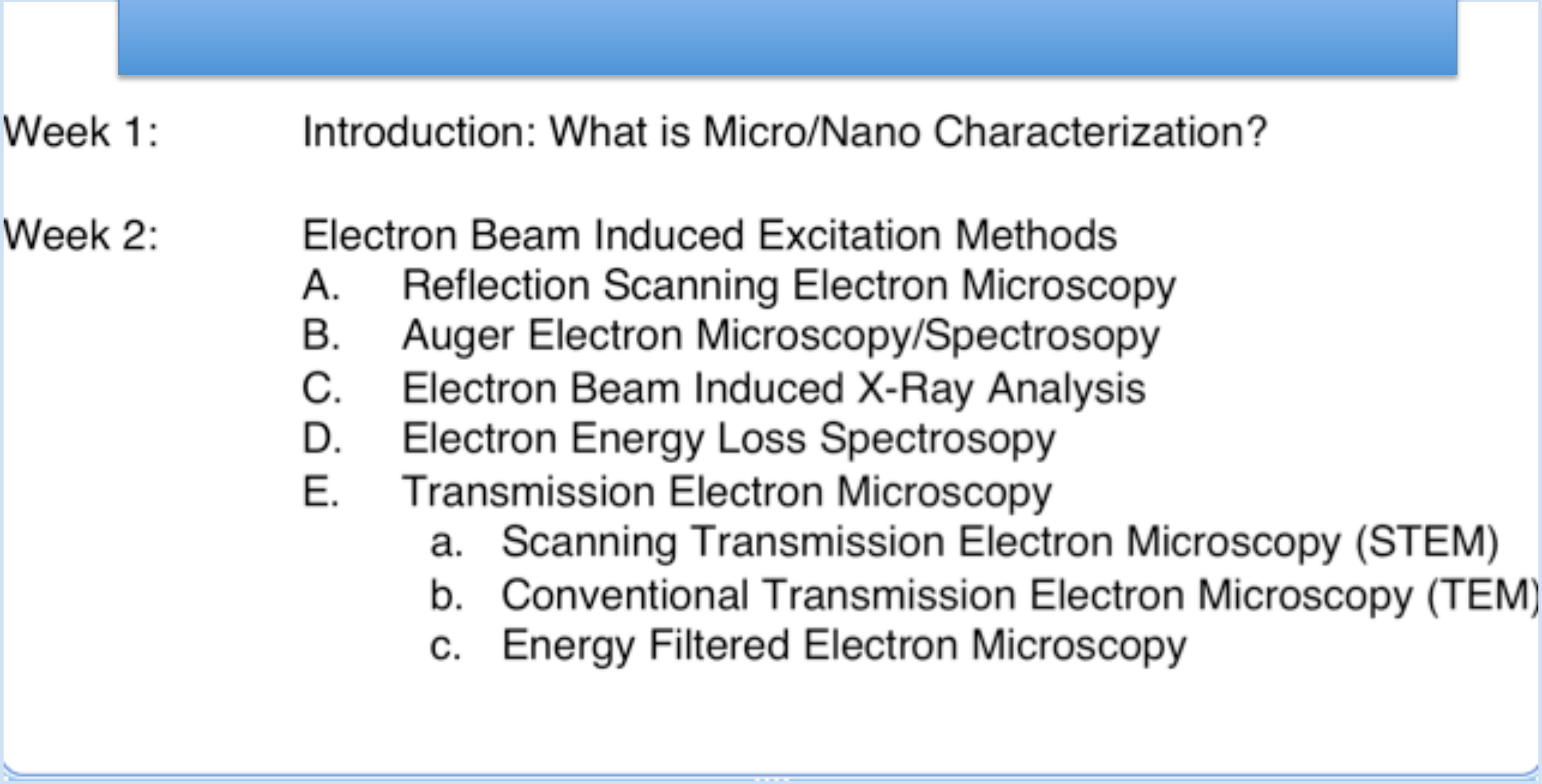
EE213. Microscopic Nanocharacterization of Materials
Spring 2016

Lecture 3

Tentative Outline

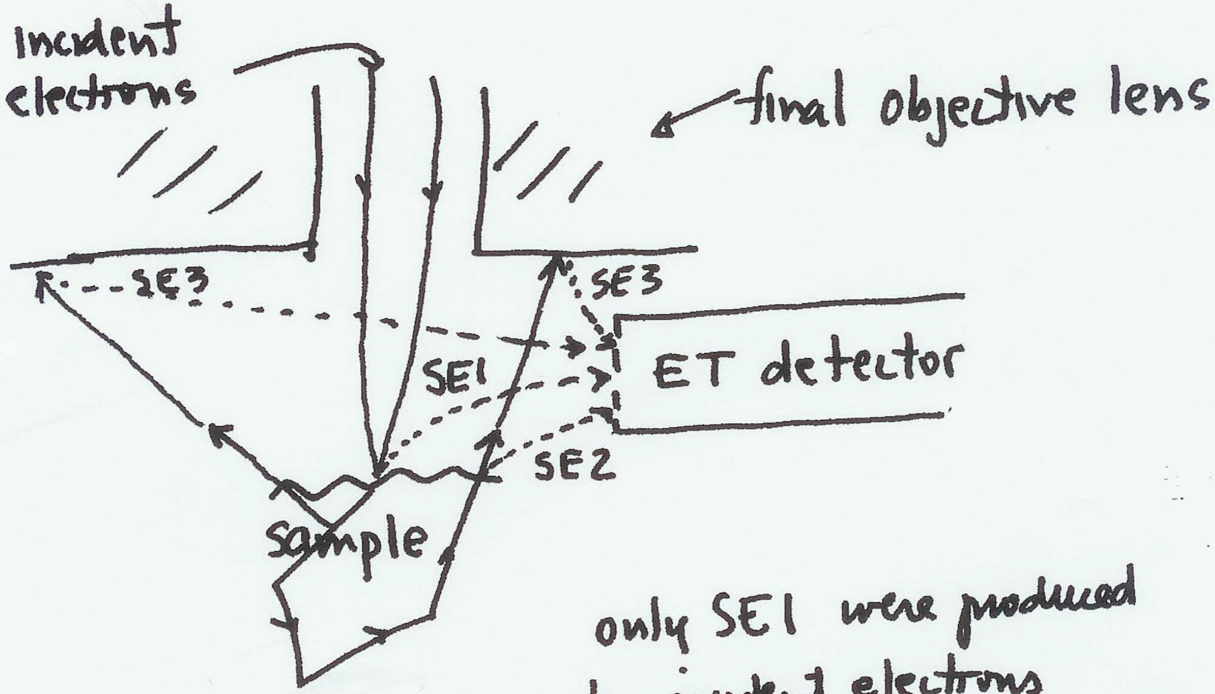


Week 1: Introduction: What is Micro/Nano Characterization?

Week 2: Electron Beam Induced Excitation Methods

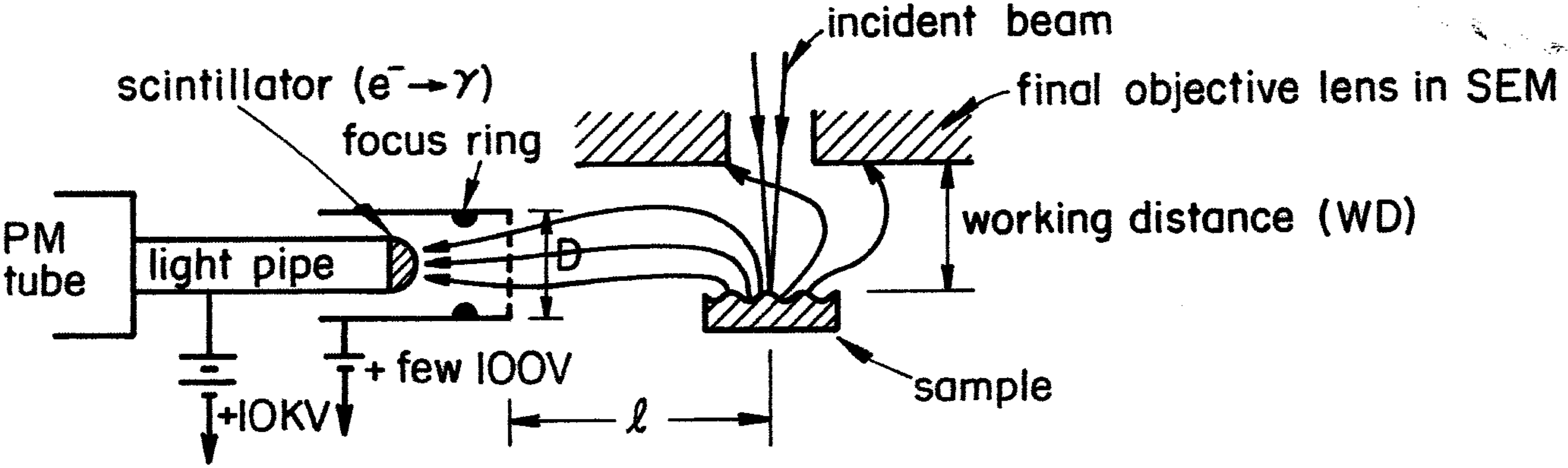
- A. Reflection Scanning Electron Microscopy
- B. Auger Electron Microscopy/Spectrosopy
- C. Electron Beam Induced X-Ray Analysis
- D. Electron Energy Loss Spectrosopy
- E. Transmission Electron Microscopy
  - a. Scanning Transmission Electron Microscopy (STEM)
  - b. Conventional Transmission Electron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

From Where do the secondaries Come?

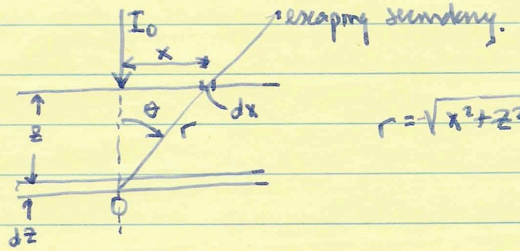


only SE1 were produced by incident electrons at point of impact near surface.

- 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
ℓ
sample

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 ~~is~~ 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 $I(z) \approx I_0$
∴ rate of productions of inelastic events at Z is:

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

Secondary Electrons 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

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

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

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

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

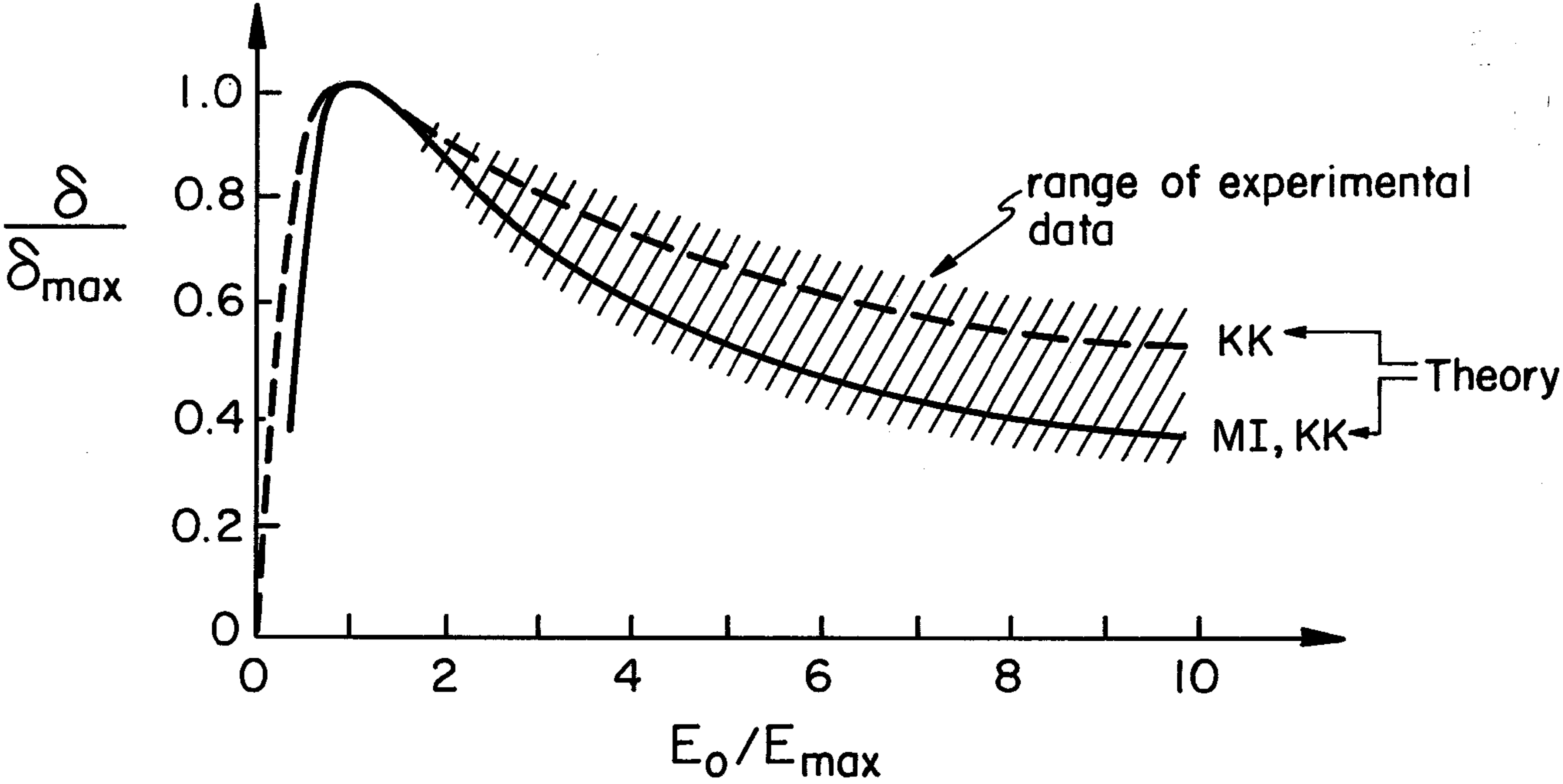
∴ for bulk solids $$\boxed{\delta_{SEC}(\infty) \cong \frac{1}{2} \frac{\overrightarrow{E_{in}^{loss}}}{\overline{E}_{sec}} \frac{\Lambda_{sec}}{\Lambda_{in}(E_{n})}}$$

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

NOTE: this predicts correct shape of yield curve vs energy

as well as agreement with experiment ✓

Electron Beam Induced Secondary Electron Emission



Backscattered Produced Secondaries - 1

$$\boxed{\delta_{SEC} \cong \frac{1}{2}\,\frac{\overline{E_{IN}}}{\overline{\overline{E_{SEC}}}}\,\frac{\Lambda_{SEC}}{\Lambda_{IN}(E_i)}}$$

sec. yield by primary electrons of energy E_i

secondaries produced by BSE

$$\boxed{\delta_{BSEC} \cong \eta\,\frac{I_{BSEC}}{I_B}}$$

where $\eta = \frac{I_B}{I_0}$, the BSE yield.

$$\frac{I_{BSEC}}{I_B} \cong 2\left[\frac{1}{2}\,\frac{\overline{E_{IN}}}{\overline{\overline{E_{SEC}}}}\,\frac{\Lambda_{SEC}}{\Lambda_{IN}(\bar{E}_B)}\right]$$

, $\bar{E}_B$ = avg. energy of BSE

→ 2 is due to fact that BSE are NOT ISOTROPICALLY emitted but rather follow a cosine distrib.

∴ total secondary yield $\delta = \underset{\overset{\uparrow}{SE1}}{\delta_{SEC}} + \underset{\overset{\nwarrow}{SE2}}{\delta_{BSEC}}$

Angular Distribution of Backscattered Electrons

From Reimer,
1985

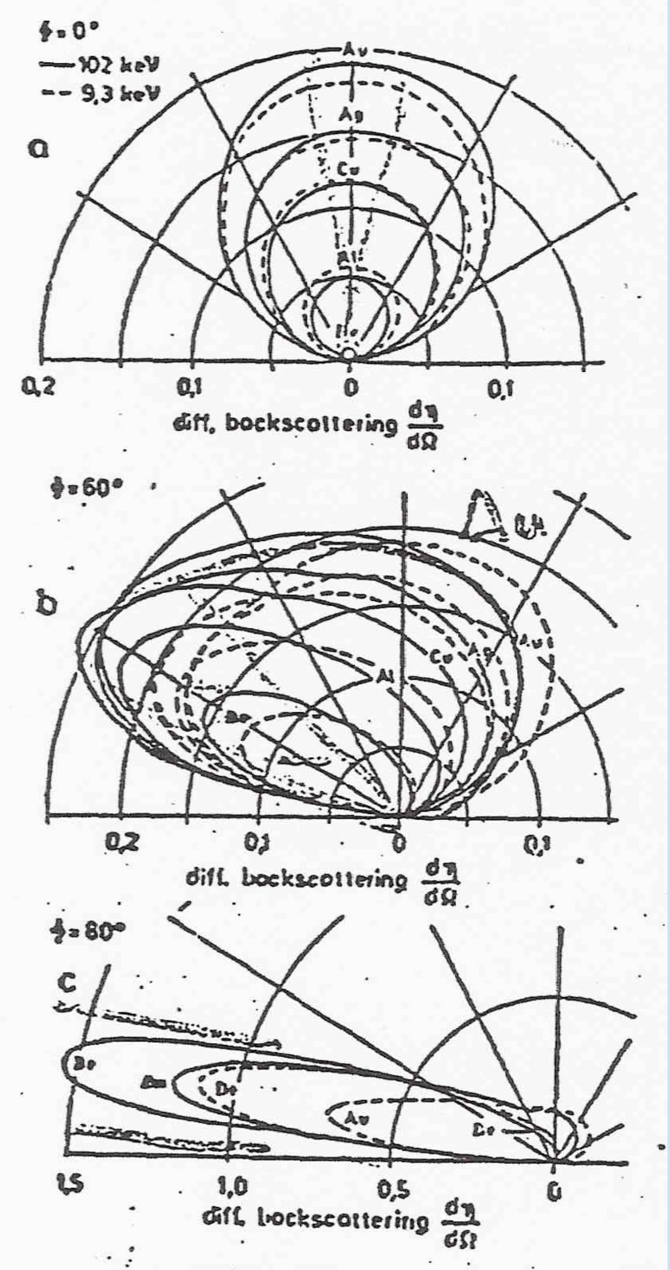


Fig.10

Backscattered Produced Secondaries 2

$$\delta = \delta_{SEC} + \delta_{BSEC}$$

$$= \delta_{SEC}\left(1 + \frac{\delta_{BSEC}}{\delta_{SEC}}\right)$$

$$= \delta_{SEC}\left[1 + \eta\left(\frac{\bar{E}_{IN}}{\bar{E}_{SEC}}\,\frac{\Lambda_{SEC}}{\Lambda_{in}(\bar{E}_B)}\right)\Big/\left(\frac{1}{2}\,\frac{\bar{E}_{IN}}{\overrightarrow{E}_{SEC}}\,\frac{\Lambda_{SEC}}{\Lambda_{in}(E_i)}\right)\right]$$

$$\delta = \delta_{SEC}\left[1 + \eta\left\{2\,\frac{\Lambda_{in}(E_i)}{\Lambda_{in}(\bar{E}_B)}\right\}\right]$$

define $\beta = 2\,\dfrac{\Lambda_{IN}(E_0)}{\Lambda_{in}(\bar{E}_B)}$, sometimes called Γ in literature

then total secondary yield is:

$$\boxed{\delta = \delta_{SEC}\left[1 + \beta\eta\right]}$$

β is usually around 1.5 – 2.5 //

thus a significant fraction of secondaries can be produced by BSE.

Effect of Electron Backscattering on Secondary Electron Yield

2109 Ryuichi Shimizu: Secondary electron yield

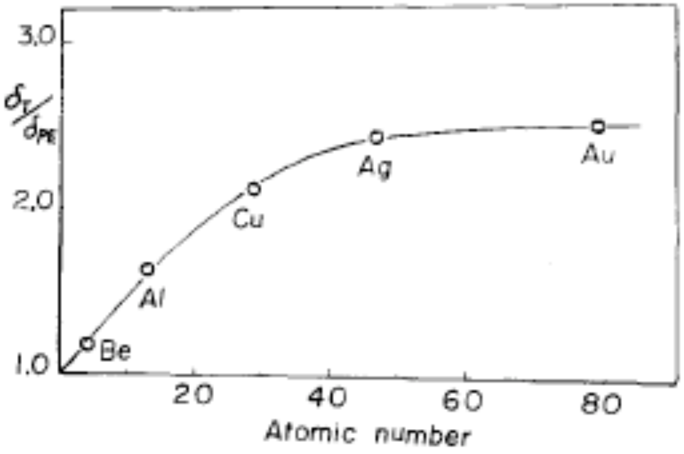


FIG. 5. The ratio of the secondary yield due to the primary electron to the total secondary yield, calculated for various metals at normal incidence.

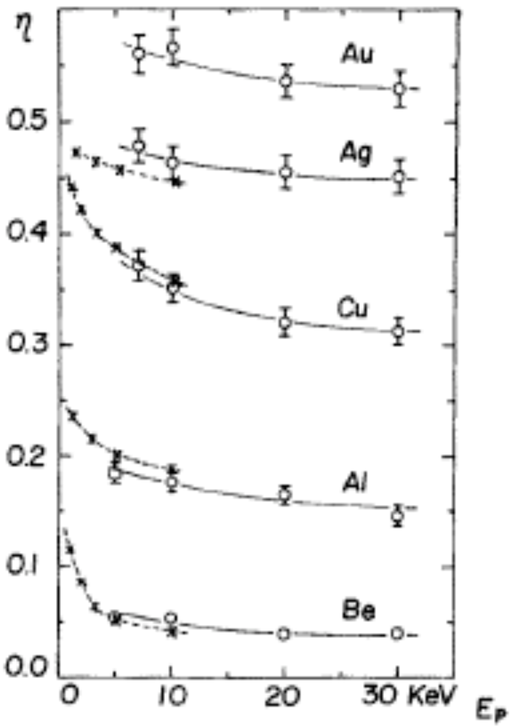


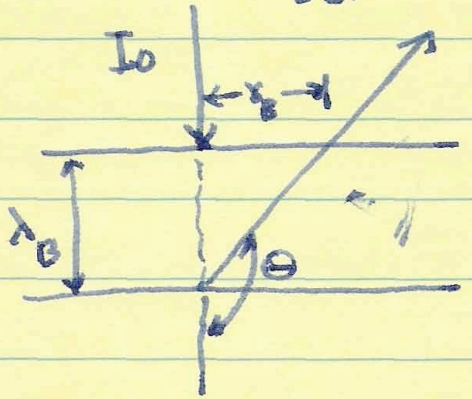
FIG. 4. Backscattering coefficient η obtained from Monte Carlo calculations and the experiment. Dotted line: experiment; solid line: Monte Carlo calculations.

From Shimizu. J.Appl.Phys. 45(%).2107-2111 (1974)

Backscattered Produced Secondaries - 3.

thus, the emitted secondaries have different spatial distributions

$$\text{ie } \delta = \underset{\substack{\uparrow \\ SE1}}{\delta_{SEC}} + \underset{\substack{\uparrow \\ SE2}}{\delta_{BSEC}}$$



$$x_B \cong \lambda_B \tan(\pi - \theta)$$

∡ of elastic scattering

to get x_B we just find avg $(\pi-\theta)$.

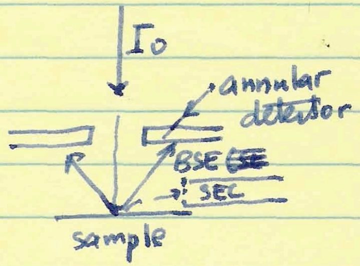
Backscattered Produced Secondaries - 4

How can we eliminate the effect of these BSE produced secondary electrons on the "image"?

$$\delta = \underset{\substack{\uparrow \\ \text{due to} \\ \text{primary} \\ \text{electrons}}}{\delta_{SE1}} + \underset{\substack{\uparrow \\ \text{due to} \\ \text{BSE}}}{\delta_{SE2}} + \underline{\delta_{OTHERS}}$$

we ignore this now. can be removed by exp. design

$$\delta = \delta_{SEC}(1+\beta\eta)$$



use another detector
an annular detector which detects the higher energy BSE. Signal it gets is:

$$I_B/I_0 = \eta \underbrace{f_B}_{\text{efficiency of detector}}$$

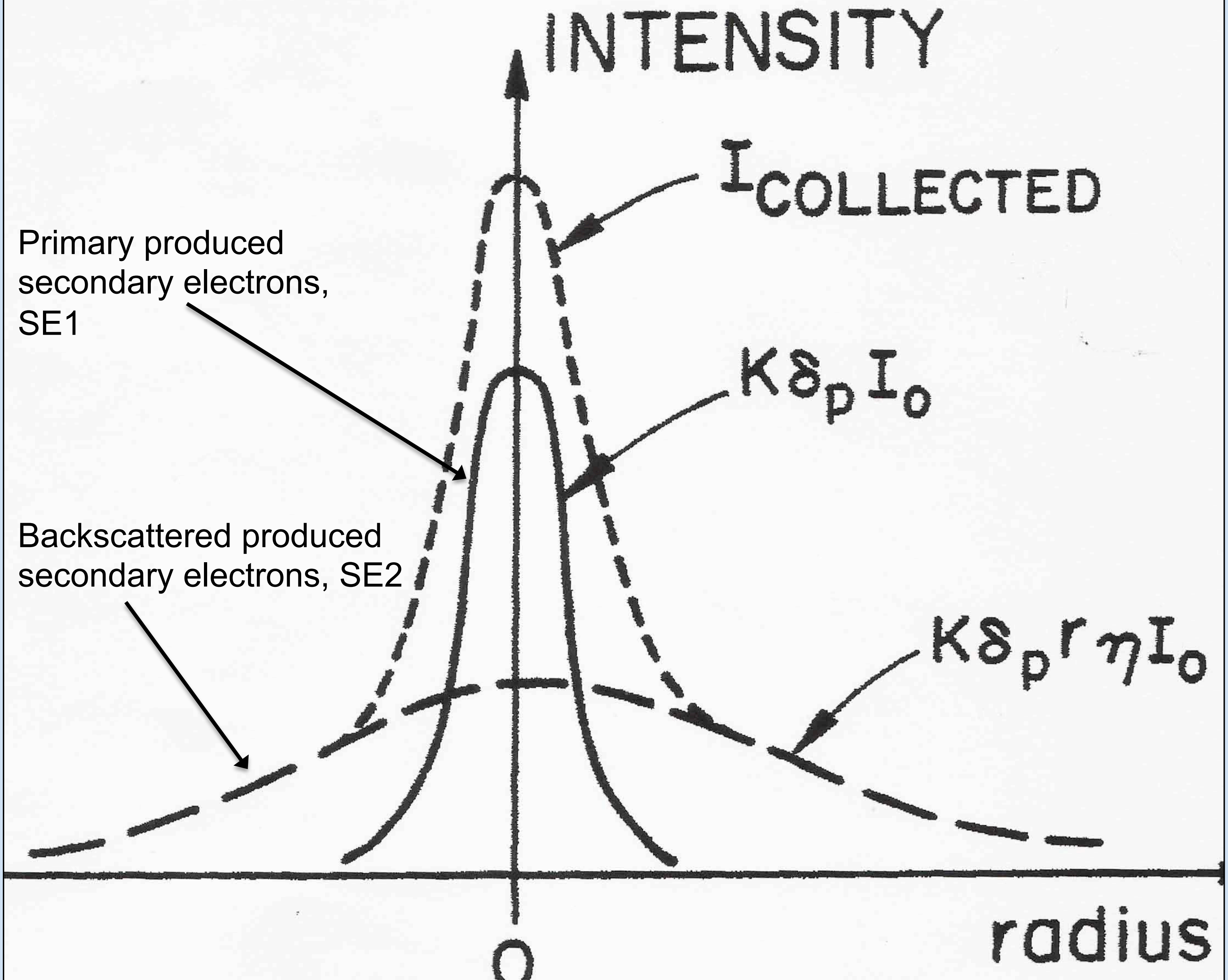
∴ we form a difference signal.

$$\frac{I_{DIFF}}{I_0} = \frac{I_{SEC}}{I_0} - \underbrace{K}_{\text{a constant}}\frac{I_{ANN}}{I_0}$$

$$= \delta_{SEC}(1+\beta\eta)\overset{\text{eff\_sec det}}{f_{SE}} - K\eta\overset{\text{eff-ann. det}}{f_{ANN}}$$

$$\boxed{\frac{I_{DIFF}}{I_0} = \delta_{SEC} f_{SE} + \eta\left[\delta_{SEC}\beta f_{SE} - K f_{ANN}\right]}$$

choose K so that $[\;\sim\;] = 0$ —

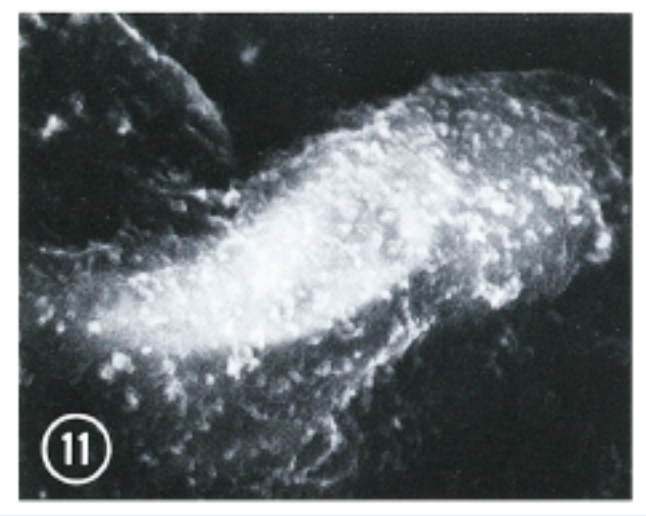


Primary produced secondary electrons, SE1

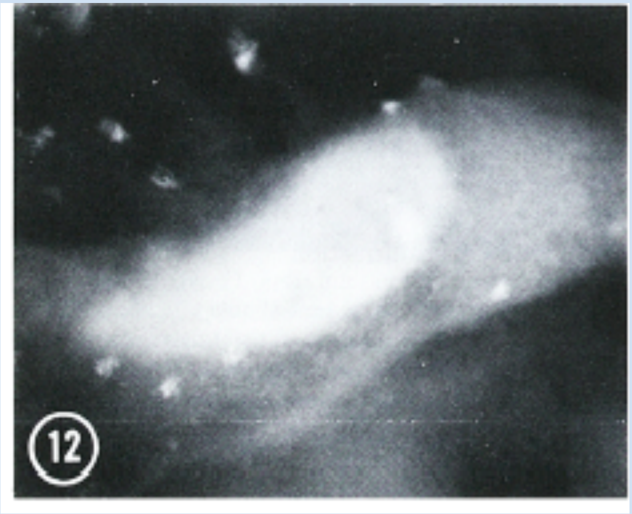
Backscattered produced secondary electrons, SE2

Contribution of Backscattered Electrons to Secondary Electron Image In an SEM (fibroblast cell with Ag stained nucleus)

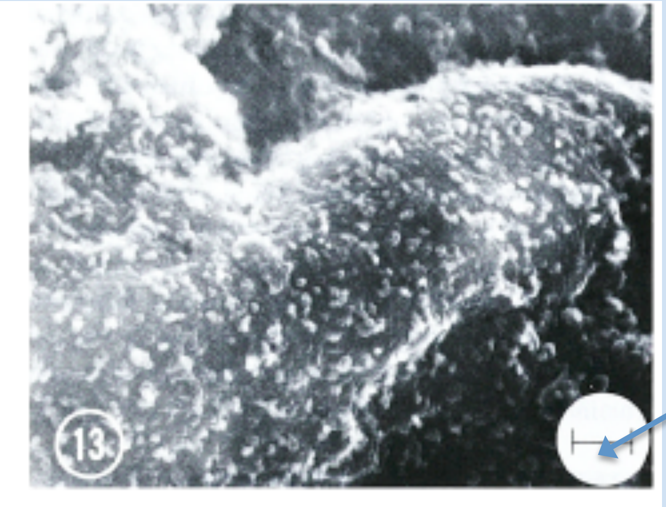
Secondary electron image (S)



Backscattered electron image (B)



S - kB

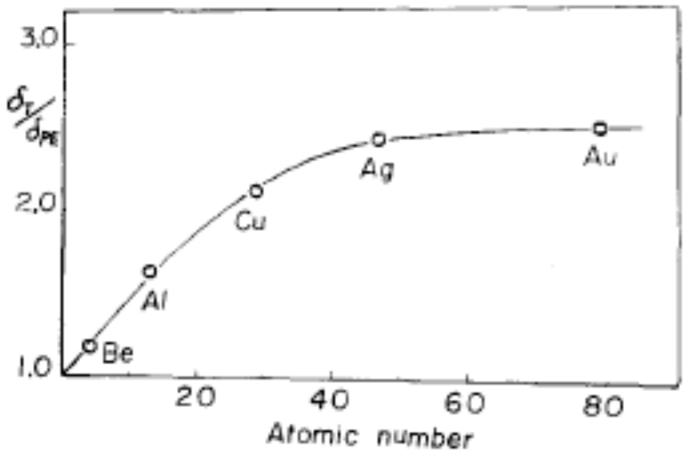


500nm

From Crewe and Lin.
Ultramicroscopy.1.(3-4).231-238(1976)

Effect of Electron Backscattering on Secondary Electron Yield

2109 Ryuichi Shimizu: Secondary electron yield



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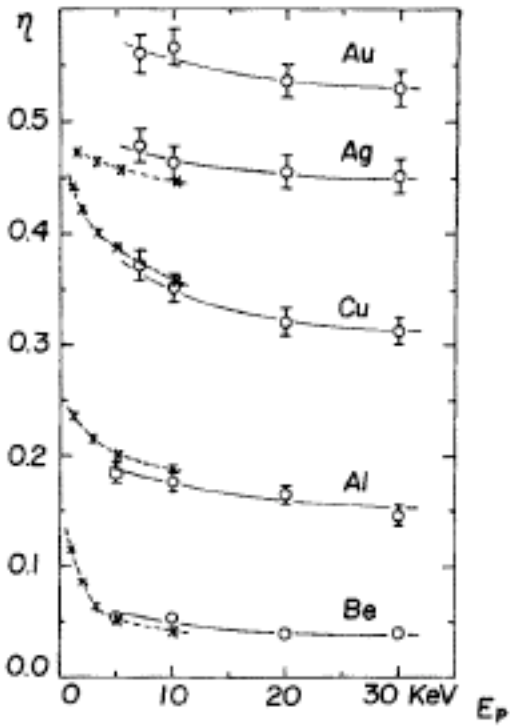

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Spatial Distribution of Secondaries. 1

- delocalization of inelastic scattering,

$$\Delta p \Delta x \sim h$$

$$\Delta p \approx p_i\sqrt{\theta^2+\theta_E^2} = \hbar q \,, \quad \underline{\theta_E = \frac{\Delta E}{p_i v_i}}$$

NOTE: for every energy loss there is a characteristic scatt. ∡ θ_E

- larger $\Delta E \Rightarrow$ larger θ_E

but for most ΔE, $\theta_E \lesssim$ 10-20° !!

- average scattering angle, $\bar{\theta}$

$$\bar{\theta} = \frac{\int_0^{\theta_{MAX}} \theta \cdot \frac{df}{d\Omega} d\Omega}{\int_0^{\theta_{MAX}} \frac{df}{d\Omega} d\Omega} \,, \quad \frac{df}{d\Omega} \propto \frac{1}{\theta^2+\theta_E^2}$$

the inelastic scattering angular distribution.

$$\therefore \bar{\theta} = \frac{\int_0^{\theta_{MAX}} \theta \left[\frac{1}{\theta^2+\theta_E^2}\right] d\Omega}{\int_0^{\theta_{MAX}} \frac{1}{(\theta^2+\theta_E^2)} d\Omega} \,. \quad d\Omega = 2\pi \sin\theta \, d\theta$$

$$\bar{\theta} \cong \frac{\int_0^{\theta_{MAX}} \frac{\theta^2 d\theta}{\theta^2+\theta_E^2}}{\int_0^{\theta_{MAX}} \frac{\theta d\theta}{\theta^2+\theta_E^2}} \,; \quad \text{assuming } \sin\theta \cong \theta$$

Spatial Distribution of Secondaries. 2

since $\theta_E \ll 1$ then $\theta_{MAX} \cong \sqrt{2\theta_E}$

and $\boxed{\bar{\theta} \cong \sqrt{2\theta_E} / \ln(2/\theta_E)} \gg \theta_E$

∴ the average momentum transfer

$$\Delta p \cong P_i \bar{\theta}$$

and with $\Delta p \Delta x \approx h$ we get

$$\Delta x \cong \frac{h}{\Delta p} = \frac{h}{P_i \bar{\theta}} \cong \frac{h}{P_i} \frac{\ln(2/\theta_E)}{\sqrt{2\theta_E}}$$

$\lambda = h/P_i \cong \sqrt{\frac{150}{E_i}}$ non-relativistically (Å, EV)

$$\therefore \Delta x \cong \sqrt{\frac{150}{E_i}} \left(\frac{\ln(4E_i/E)}{\sqrt{E/E_i}} \right), \text{ where } \theta_E \approx \frac{E}{2E_i}$$

$$\therefore \boxed{\Delta x = \sqrt{\frac{150}{E}} \ln(4E_i/E)} \text{ in Å, eV}$$

NOTE: Δx relatively indep. of E_i
and Δx ↓ as E ↗

Spatial Distributions of Secondaries. 3

to find the spatial resolution attainable using secondary electrons we convolute the spatial distribution of them with that of the incident electron beam.

$$\therefore \quad R_{ES}(r) = \int_0^{E_0} dE \int_0^{\infty} 2\pi r' dr' \, \frac{dR_s}{dE}(E, r-r') \, I_B(r')$$

radial distrib. of emerging secondaries produced by energy loss, E

radial distrib. of incident beam.

∴ the mean excitation radius, $\bar{r}_E$, becomes

$$\bar{r}_E = \frac{\int_0^{\infty} R_{ES}(r) \, r^2 dr}{\int_0^{\infty} R_{ES}(r) \, r dr}$$

then if we assume "Gaussian" distributions for both the beam and emerging secondaries (not quite true, but simplifies things)

$$\boxed{\bar{r}_E \approx \sqrt{r_B^2 + (\Delta x)^2}} \quad , \; \Delta x \approx \sqrt{\frac{150}{\bar{E}}} \ln\left(\frac{4E_0}{\bar{E}}\right)$$

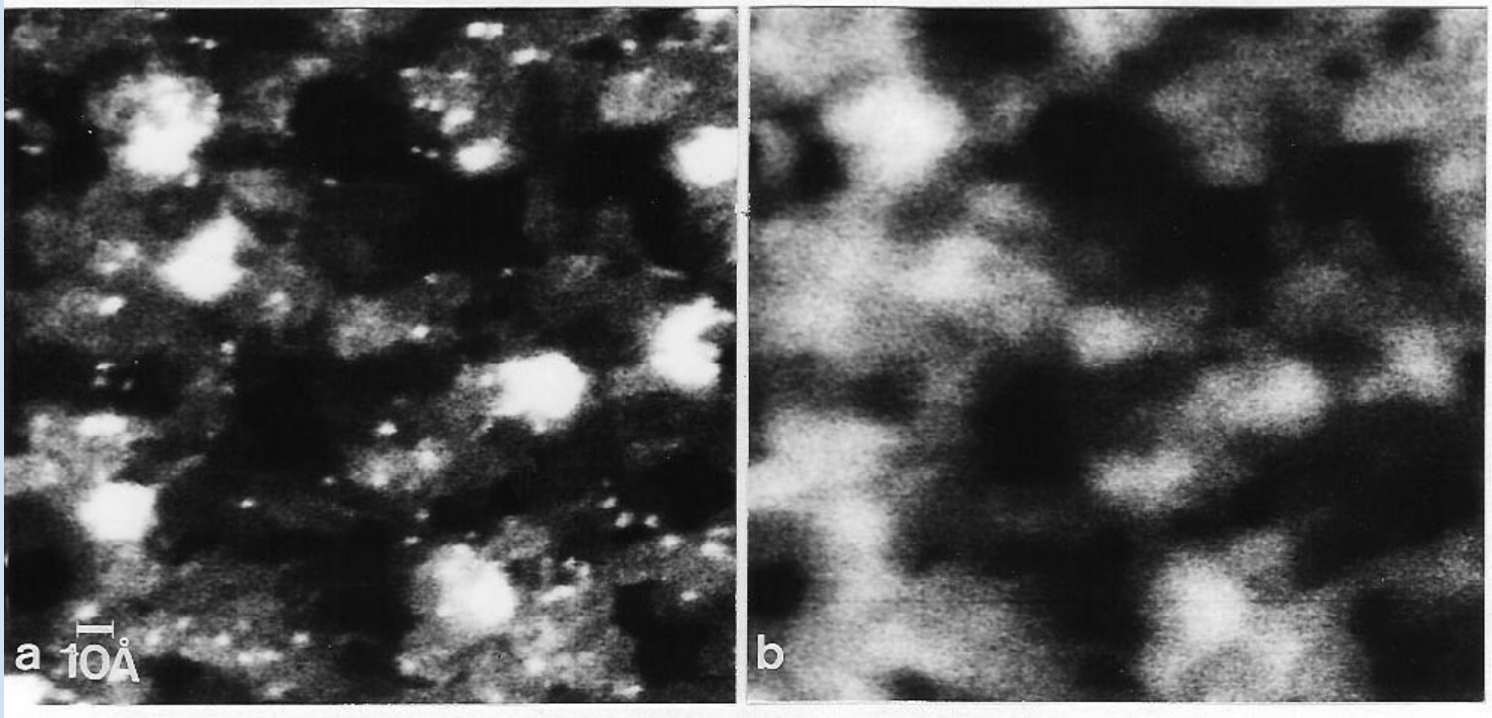
avg. E loss

∴ we only notice effect of $r_B \sim \Delta x$ //—

eg/ for $E_0 = E_i \cong 30$ keV, $\bar{E} = 30.1$ eV $(Z=6)$

$\Delta x \cong 18$ Å //

Demonstration of the Non-Localization of Inelastic Electron Scattering
(*a manifestation of the Heisenberg Uncertainty Principle*)



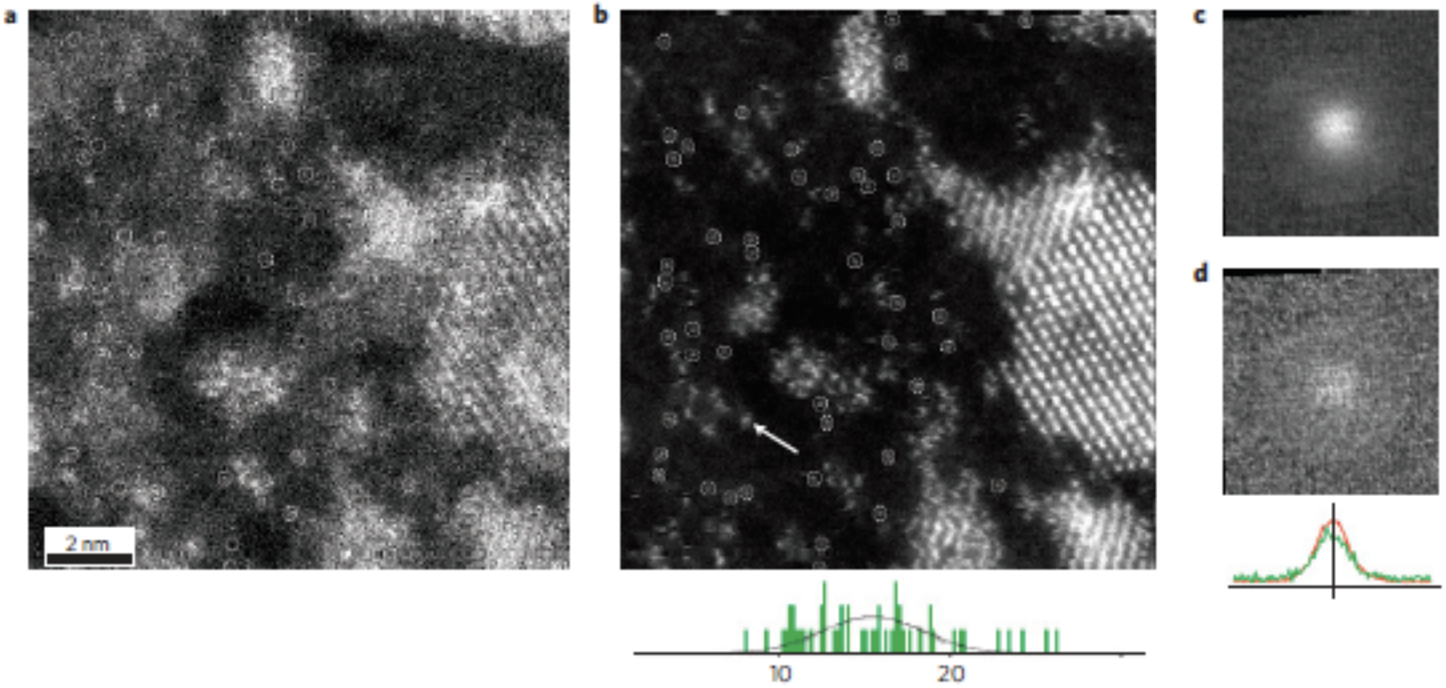
Elastic Scattering

Inelastic Scattering

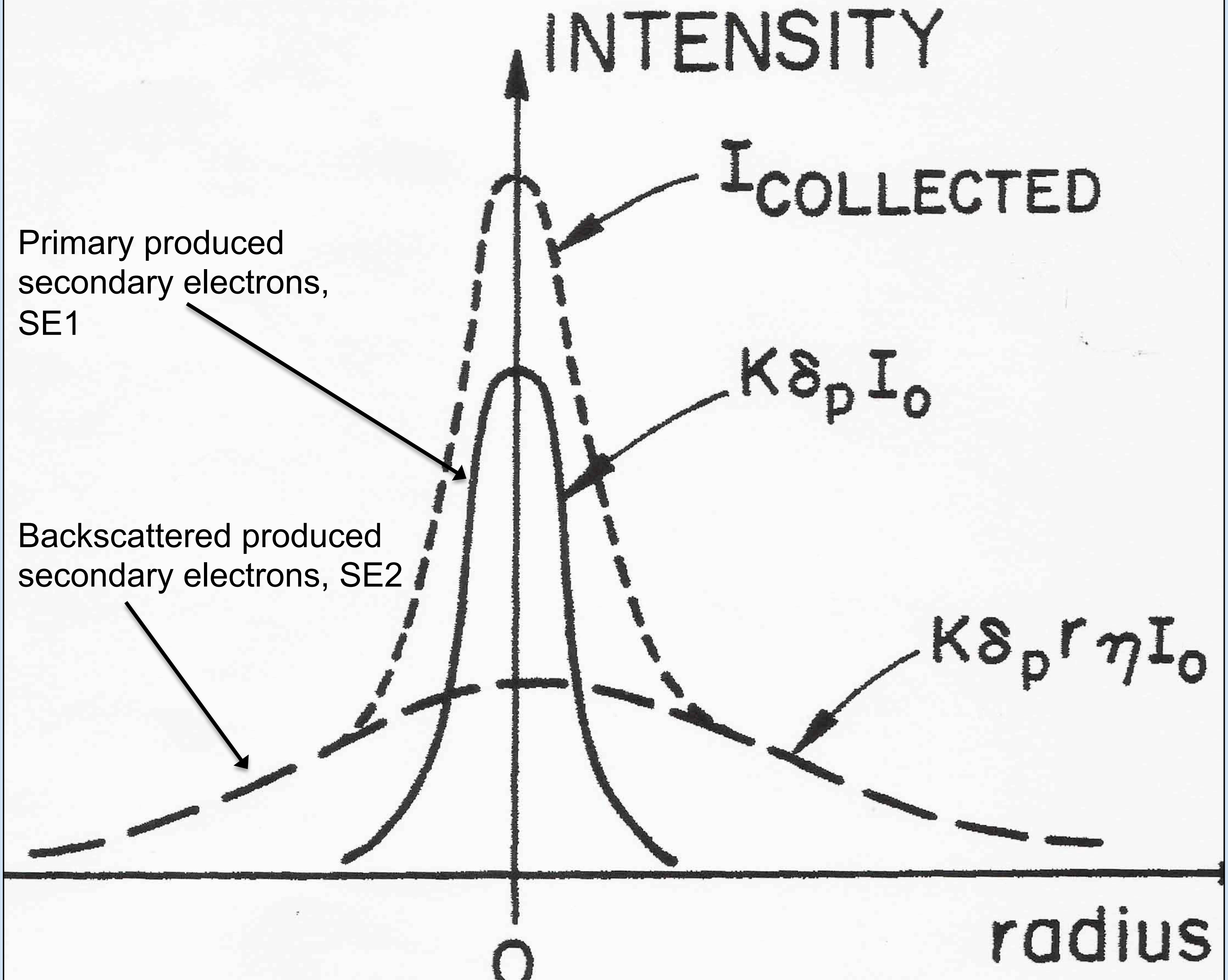
Pt on Thin Carbon Substrate

Isaacson, Utlaut and Kopf, 1980 (in Springer Topics in Current Physics, Vol. 13, Chapter 7)

High Energy Loss, large momentum transfer secondaries



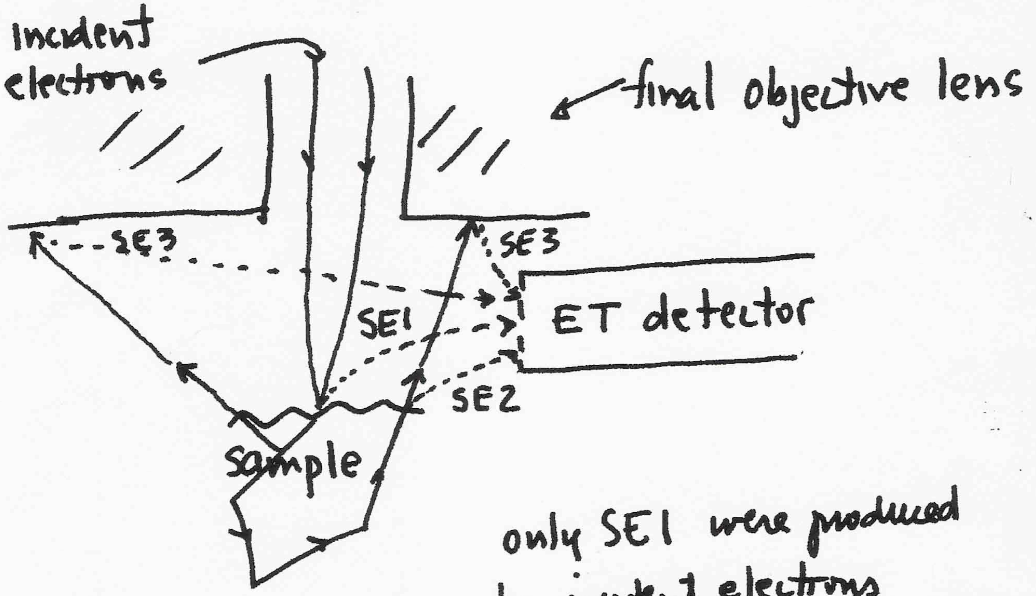
From Zhu, et.al. Nature:Materials.8.(2009).808-811.



Primary produced secondary electrons, SE1

Backscattered produced secondary electrons, SE2

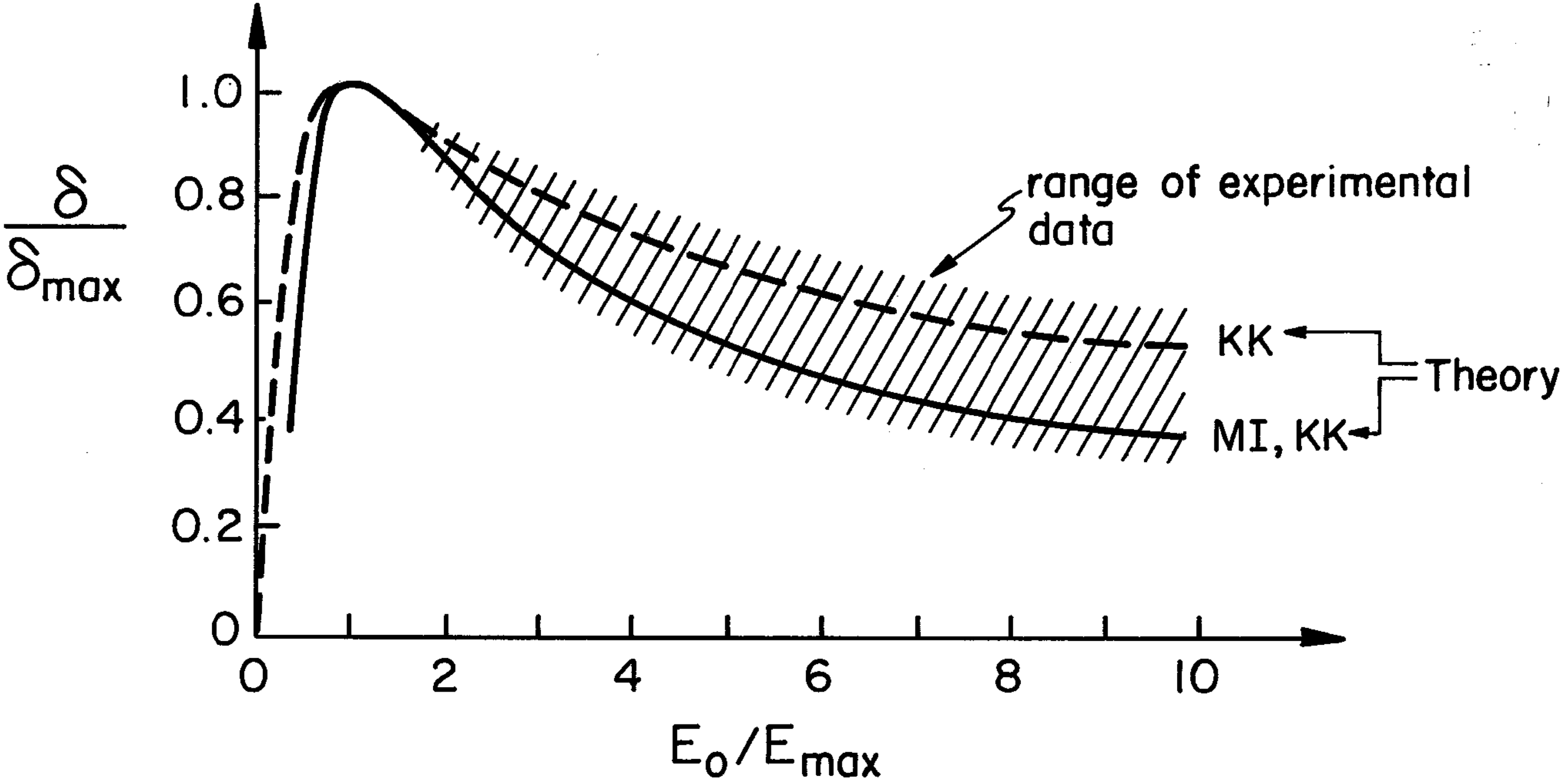
From Where do the secondaries Come?

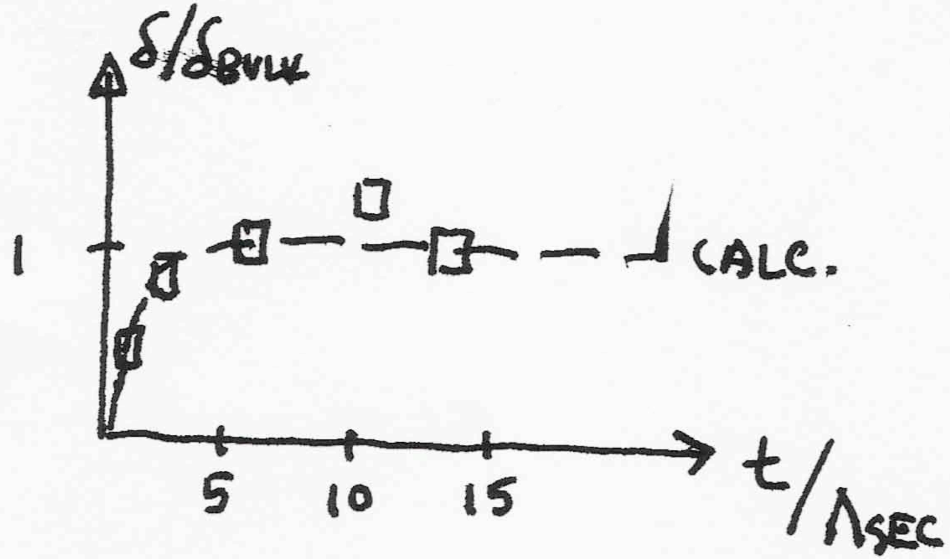


only SE1 were produced by incident electrons at point of impact near surface.

- SE2 depends on sample
- SE3 indep. of sample

Electron Beam Induced Secondary Electron Emission

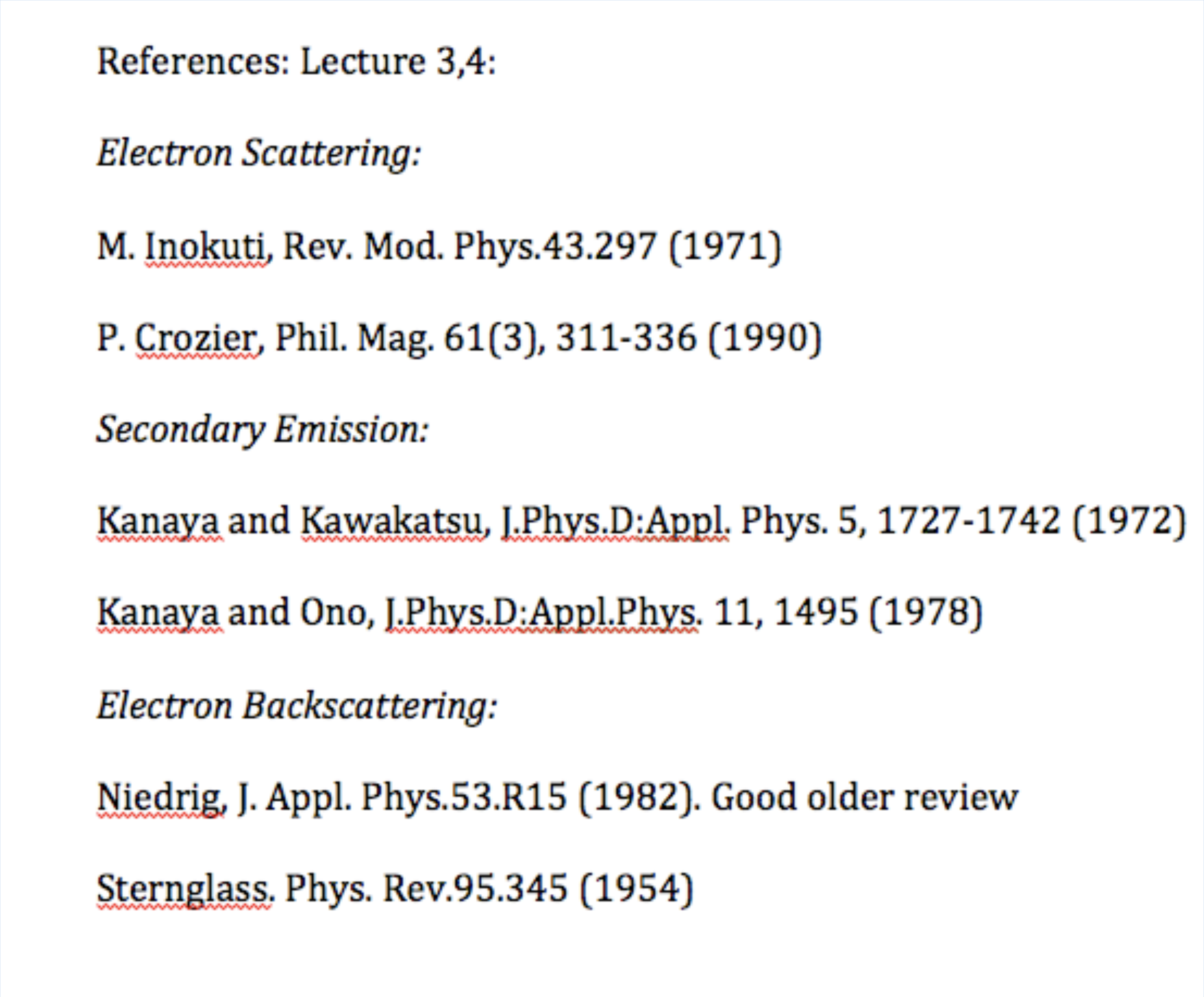




sec. elec. emission/

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

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



References: Lecture 3,4:

Electron Scattering:

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

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

Secondary Emission:

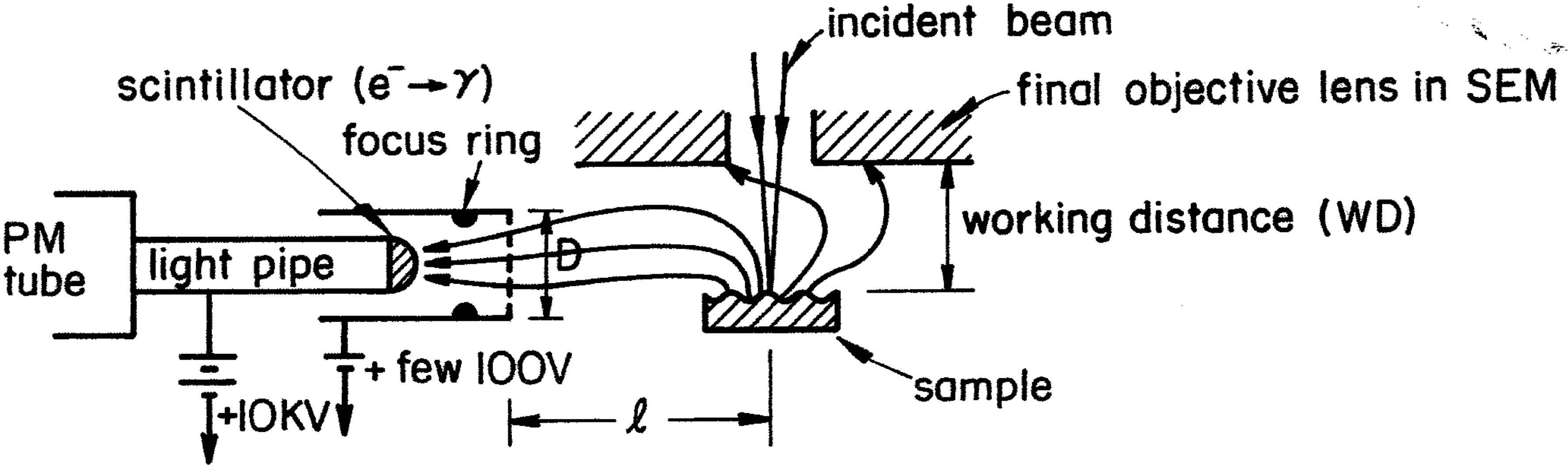
Kanaya and Kawakatsu, J.Phys.D:Appl. Phys. 5, 1727-1742 (1972)

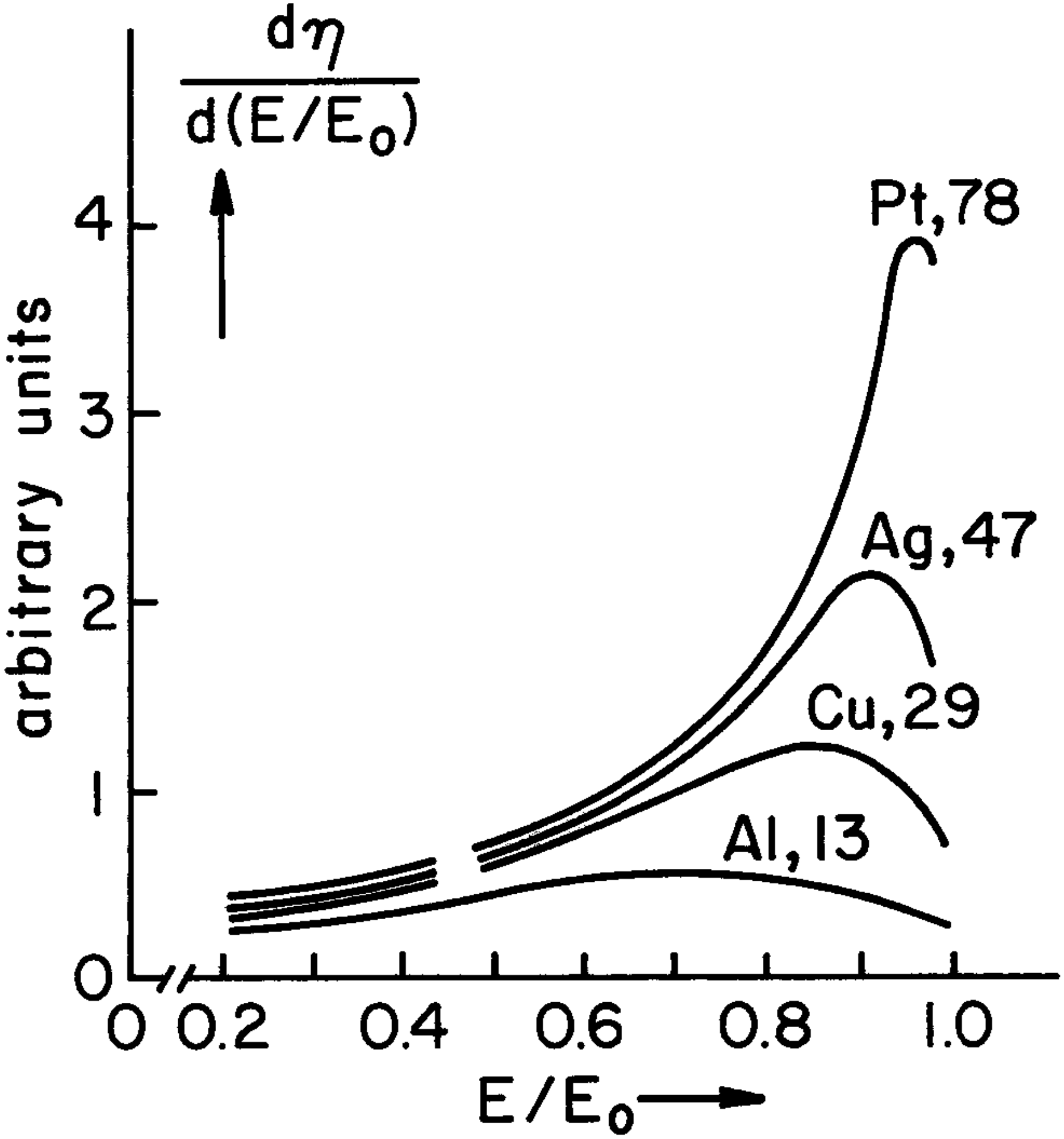
Kanaya and Ono, J.Phys.D:Appl.Phys. 11, 1495 (1978)

Electron Backscattering:

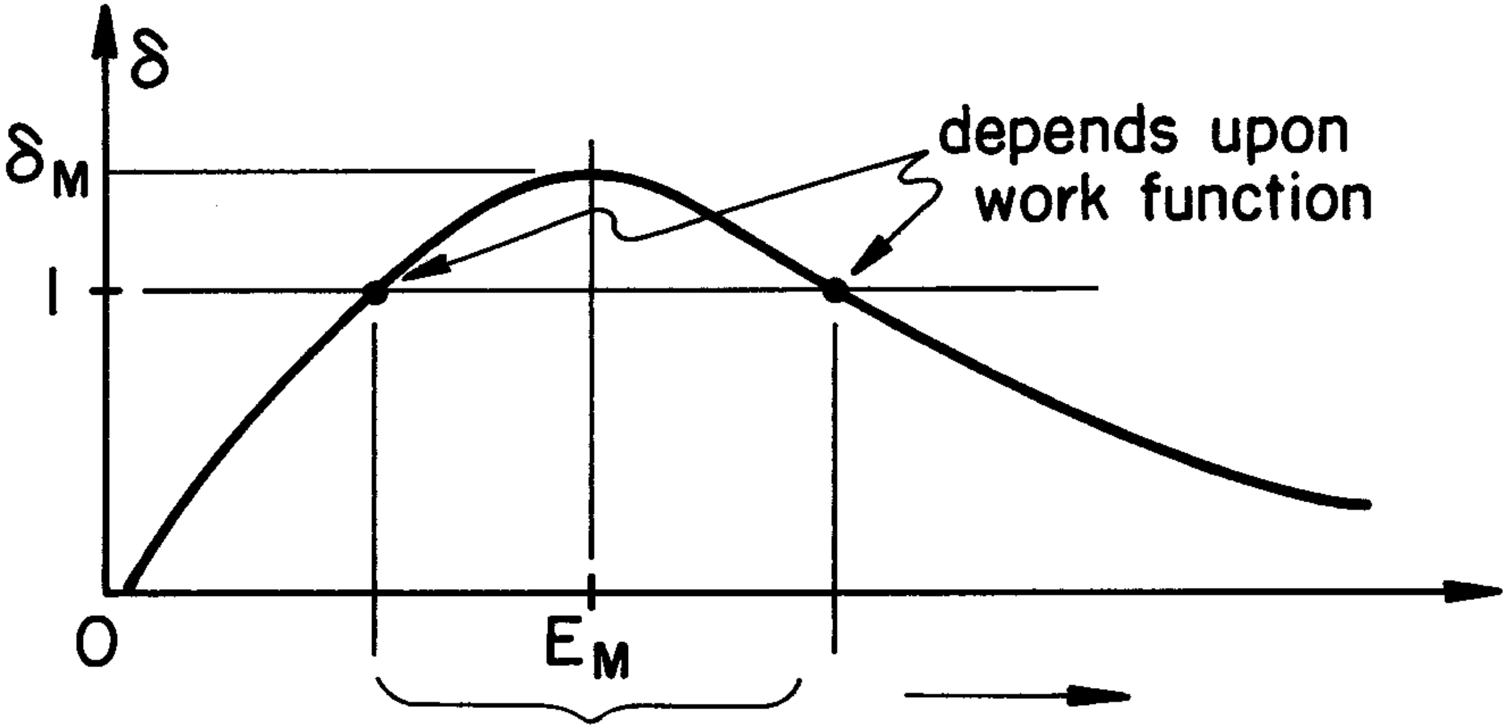
Niedrig, J. Appl. Phys.53.R15 (1982). Good older review

Sternglass. Phys. Rev.95.345 (1954)


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


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

Secondary electron emission



depends upon work function

≈300-800eV
in this region
sample can
charge up
positively

≳KeV
in this region sample can
charge up negatively

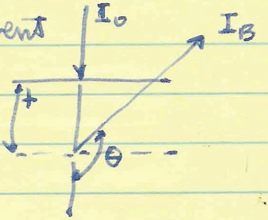
Electron Backscattering.1

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

∴ 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



∴ 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 $\frac{dI_B}{d\Omega} = \frac{dI_B}{d\Omega} = I_0 n t \frac{d\sigma_R}{d\Omega}$ → the Rutherford x-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 $\gamma = (1 - v/c)^{-1/2}$

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

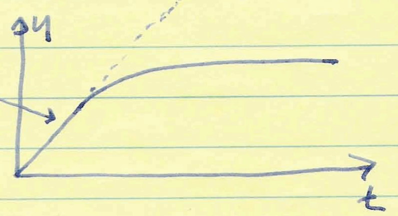
NOTE: K is material independent only depends on the electrons//

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 → Range of electrons in material, η → 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)

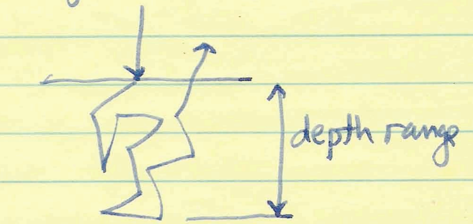
But all other properties of η are predicted by this simple expression.

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.



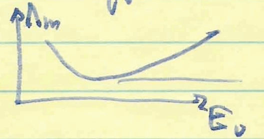
the depth range is less than total range because of sideways scattering (primarily elastic)

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.

$$R_B(E_0) = \int_{E_s}^{E_0} \frac{\Lambda_{in}(E)\,dE}{\bar{E}_{IN}}$$

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

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

our handy-dandy simple expression

where Λ_{in} in Å, E_0, $\bar{E}_{in}$ in eV, n in #/Å³

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

$$\boxed{R_i(E_0) = \frac{11.32\times10^{-4}}{nZ}\,\frac{E_0^2}{\ln\left(\frac{.325E_0}{\sqrt{Z}}\right)}}$$

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:

$$\boxed{R \cong R_i Z^{-1/3}}$$

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

$$\underline{\bar{E}_B = E_0 - 2\Delta E}$$

which assumes an energy loss ~~before~~ on the way in and on the way out is about the same.

$\therefore$ the effective energy, the electrons has before being backscattered is

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

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

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

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

this changes by ~10% from Z = 14 → 79 and with E_0 = 1 – 50 keV !!

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

Electron Backscattering-6. cont

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

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

∴ $\underline{\eta = Knt_{EFF} Z^2}$

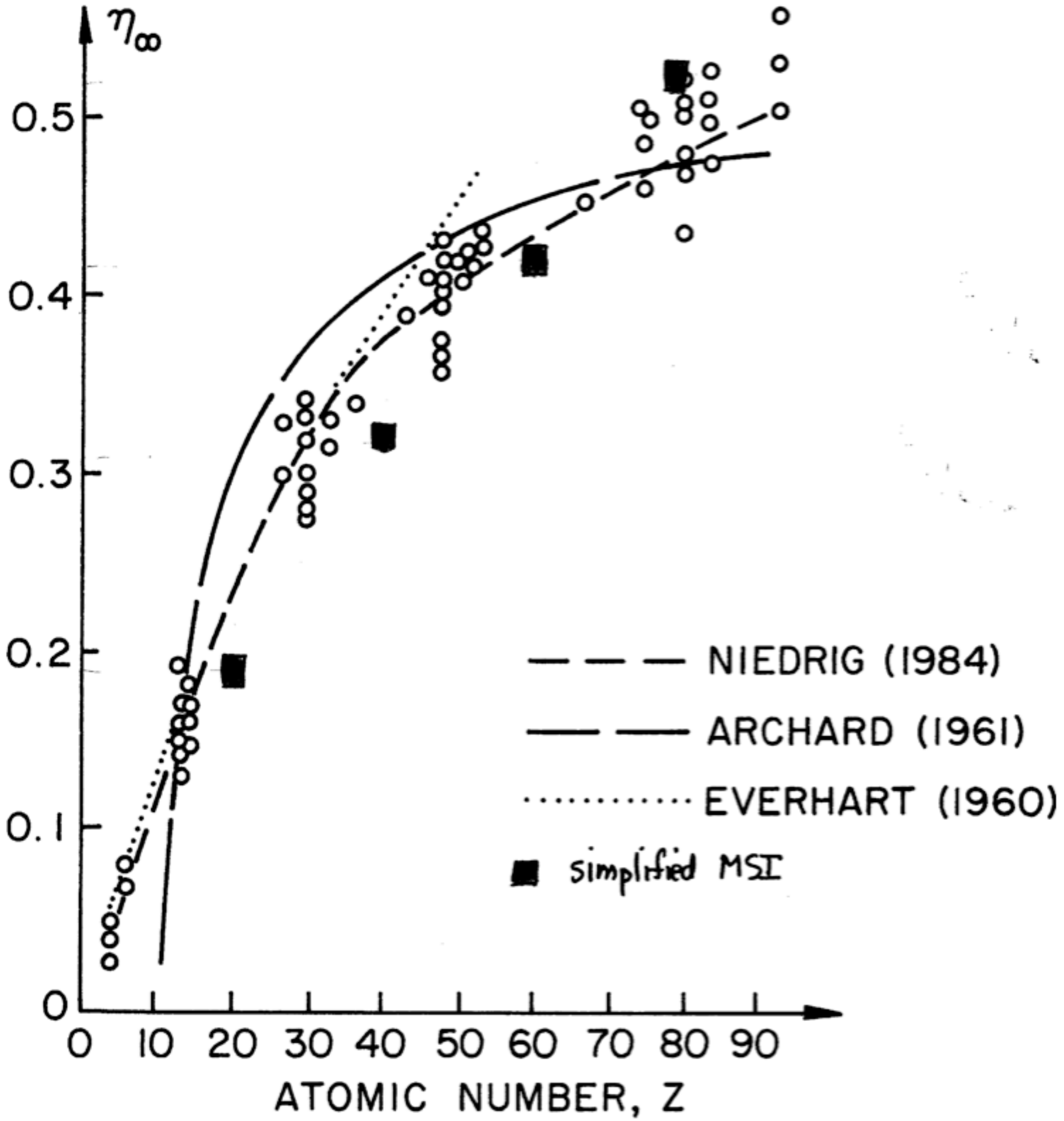
since the K for Rutherford scattering is about 2-3x less than experiment we just multiply the K by 2.5 and get

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

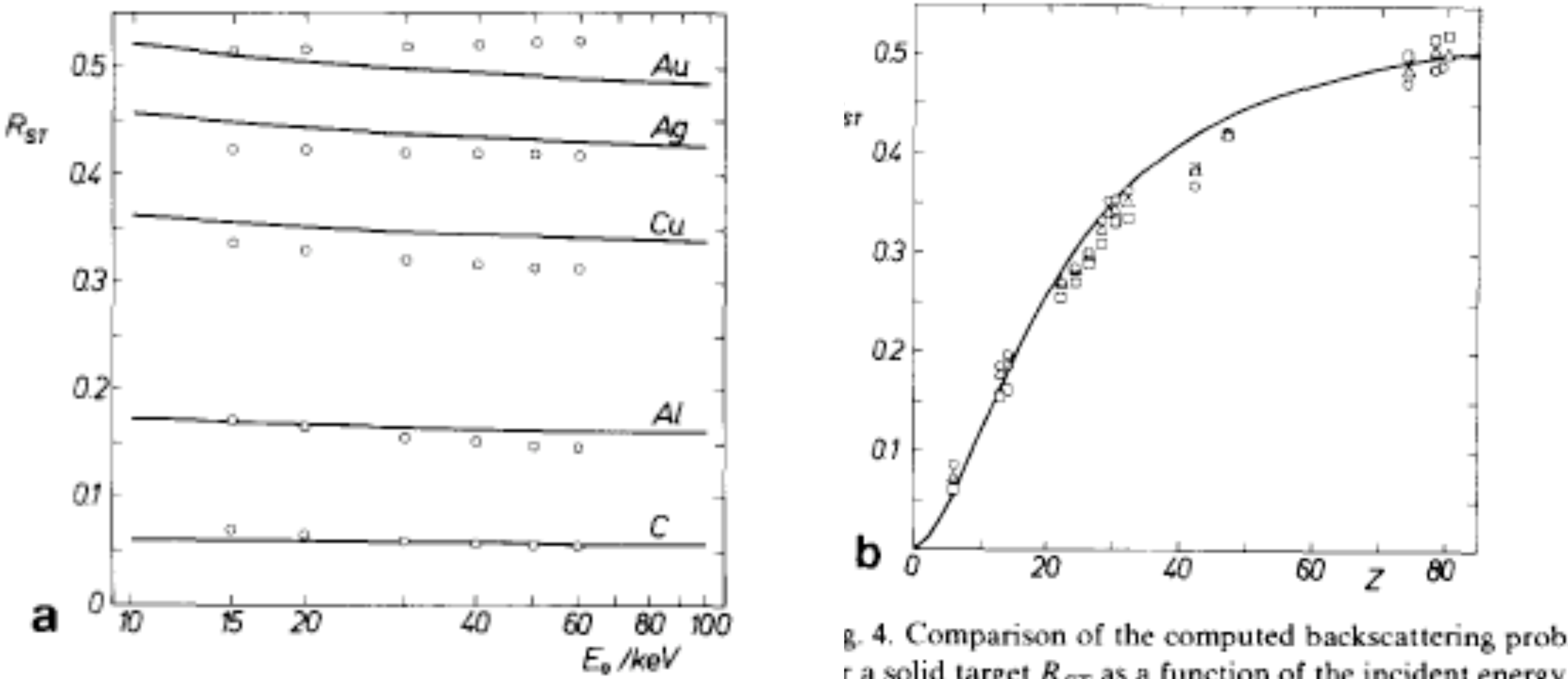
this gives reasonable agreement with exp. data.
it is a bit high at high Z
and is off a bit at low E_0 //

but agrees within 20% with experiment
and monte carlo simulations

Electron Backscattering Yield

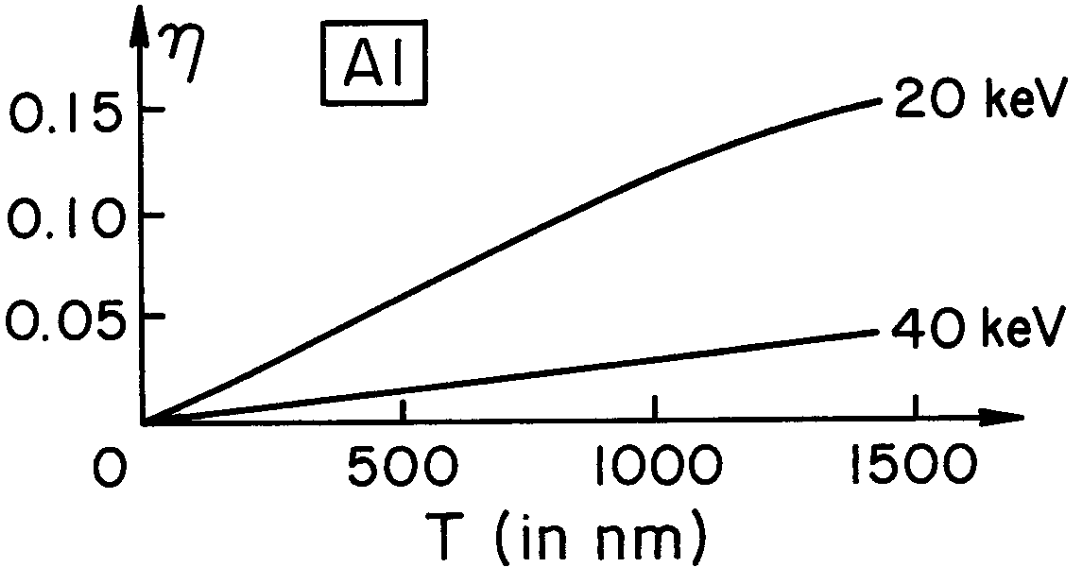


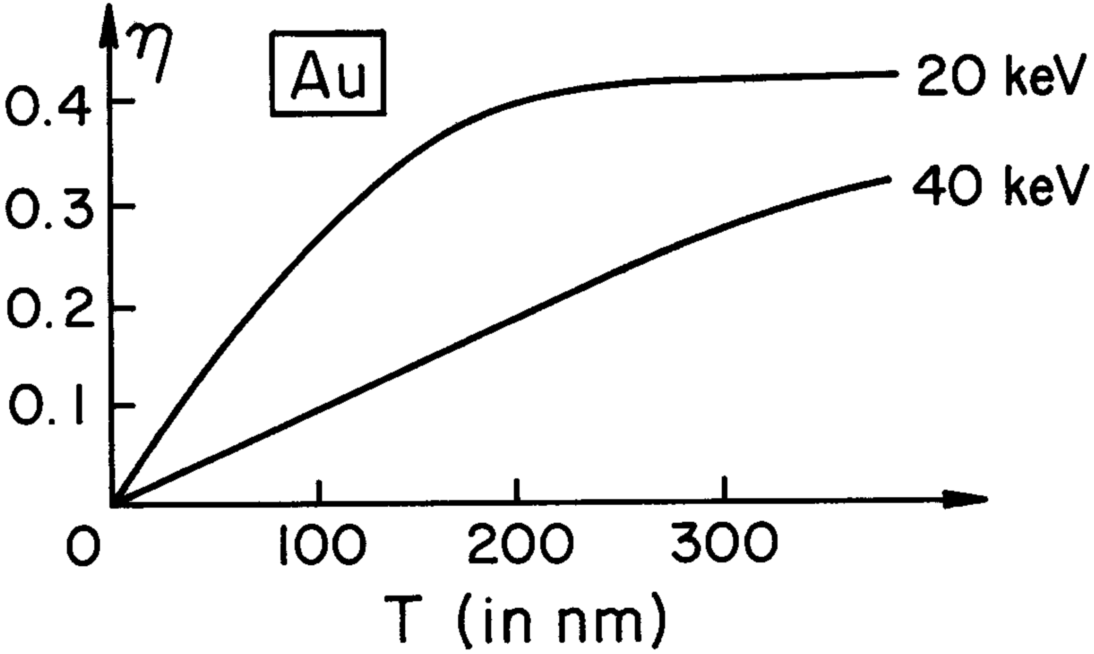
Electron Backscattering Yield Measurements

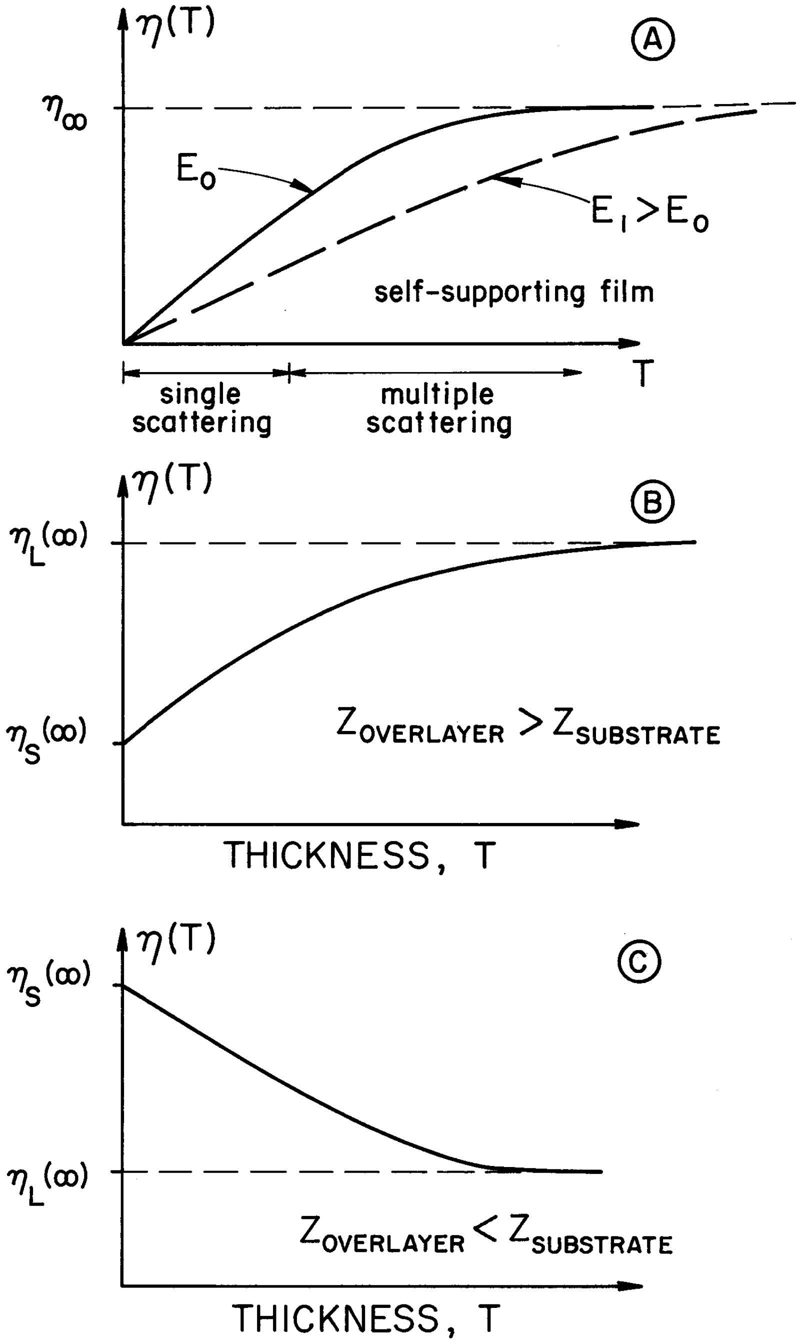


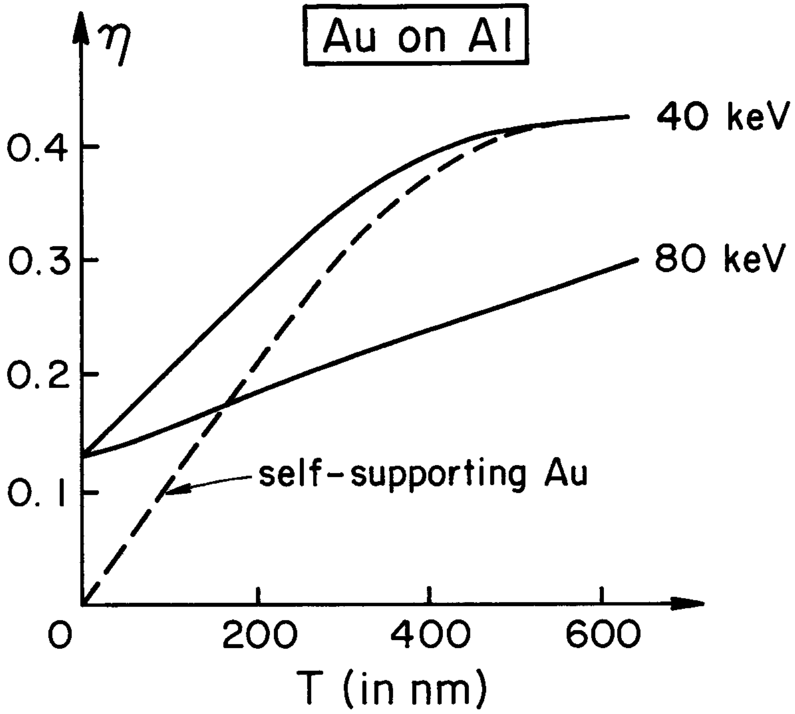
g. 4. Comparison of the computed backscattering probability r a solid target R_{ST} as a function of the incident energy E_0 (a) and the atomic number Z (b) with results of measurements from Neubert and Rogaschewski [13] (a) and from Bishop [15] for 5 (○), 10 (△) and 30 keV (□) (b).

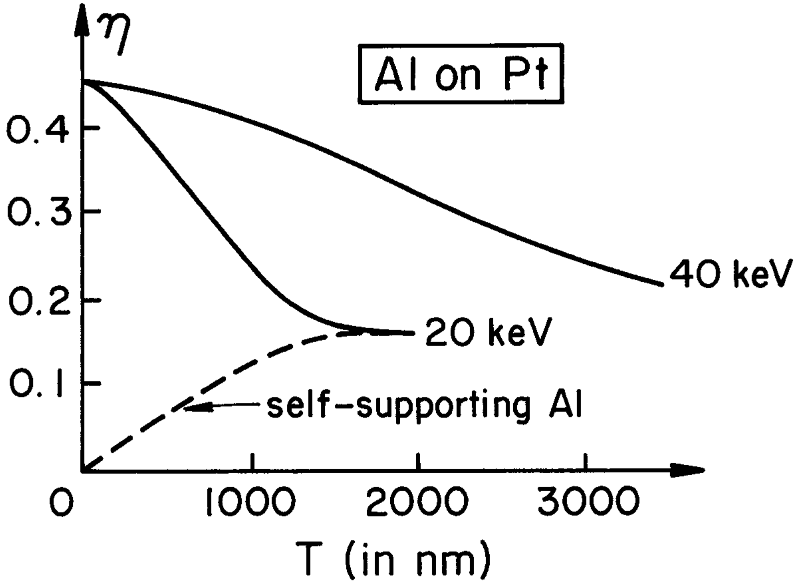
from Werner, et.al..Ultramicroscopy.8(4).417. (1982)


η
Al
0.15
0.10
0.05
20 keV
40 keV
0
500
1000
1500
T (in nm)

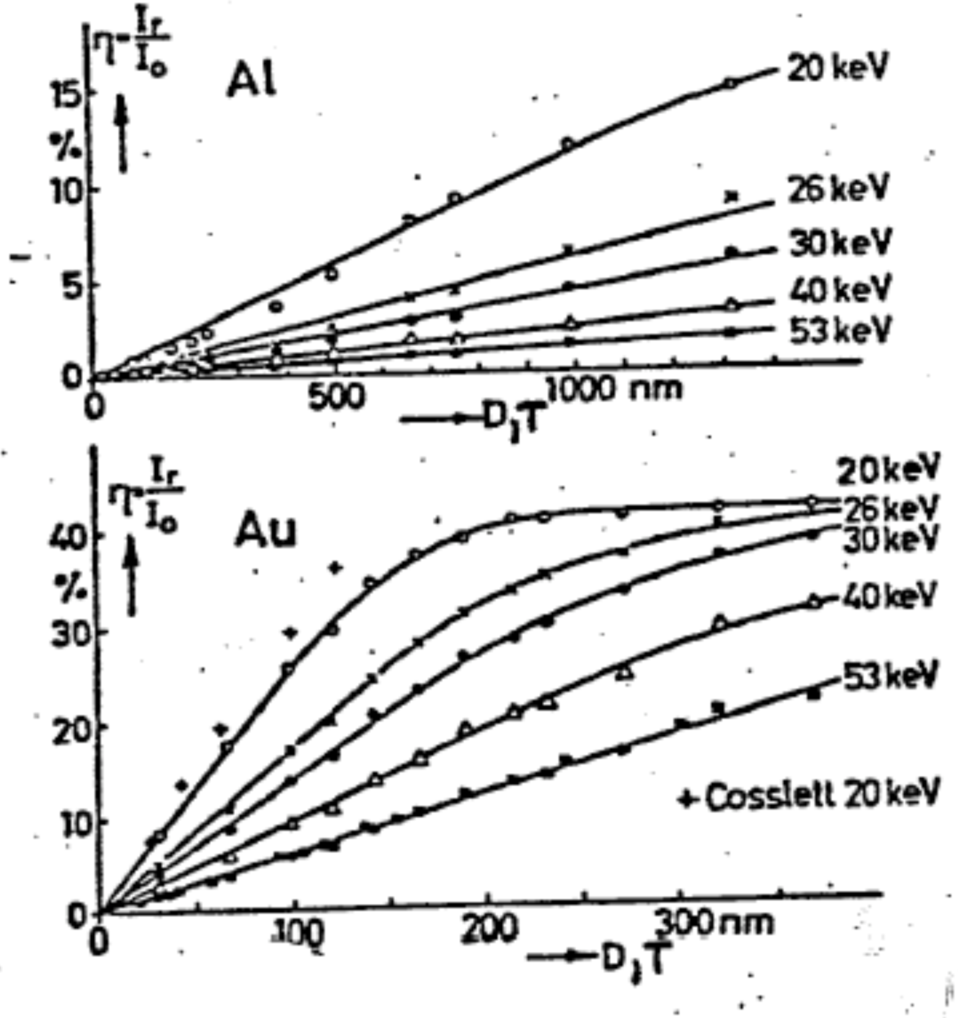

η
Au
0.4
0.3
0.2
0.1
20 keV
40 keV
0
100
200
300
T (in nm)


A
η(T)
η∞
E0
E1 > E0
self-supporting film
T
single scattering
multiple scattering
B
η(T)
ηL(∞)
ηS(∞)
Z OVERLAYER > Z SUBSTRATE
THICKNESS, T
C
η(T)
ηS(∞)
ηL(∞)
Z OVERLAYER < Z SUBSTRATE
THICKNESS, T


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

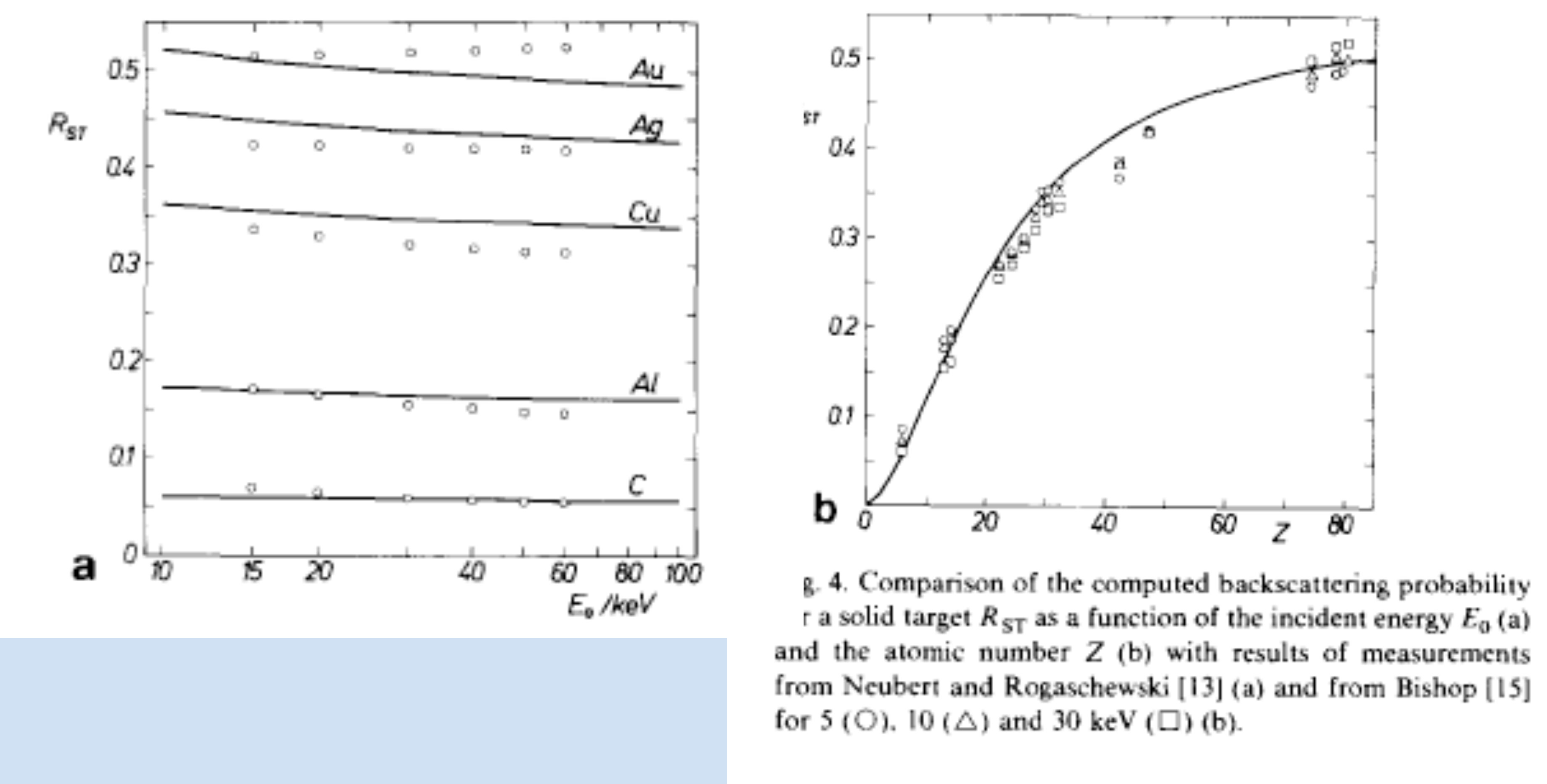
Experimental Measurements of Electron Backscattering in Thin Films



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]).

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

Electron Backscattering Yield Measurements



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