# A Tutorial on *Radiation Dose and Dose Rate*

Kurt Sickafus

# Dose = Absorbed Energy Density

Absorbed energy normalized by weight, volume, atoms, etc.

$$1\ \mathrm{Gy} = 1\ \frac{\mathrm{J}}{\mathrm{kg}}$$

SI units

# Water: heat to boiling point

$$c_p^{H_2O} = 4.1813 \ \frac{\mathrm{J}}{\mathrm{g \cdot K}} \quad (@\ 25°\mathrm{C})$$

specific heat of water

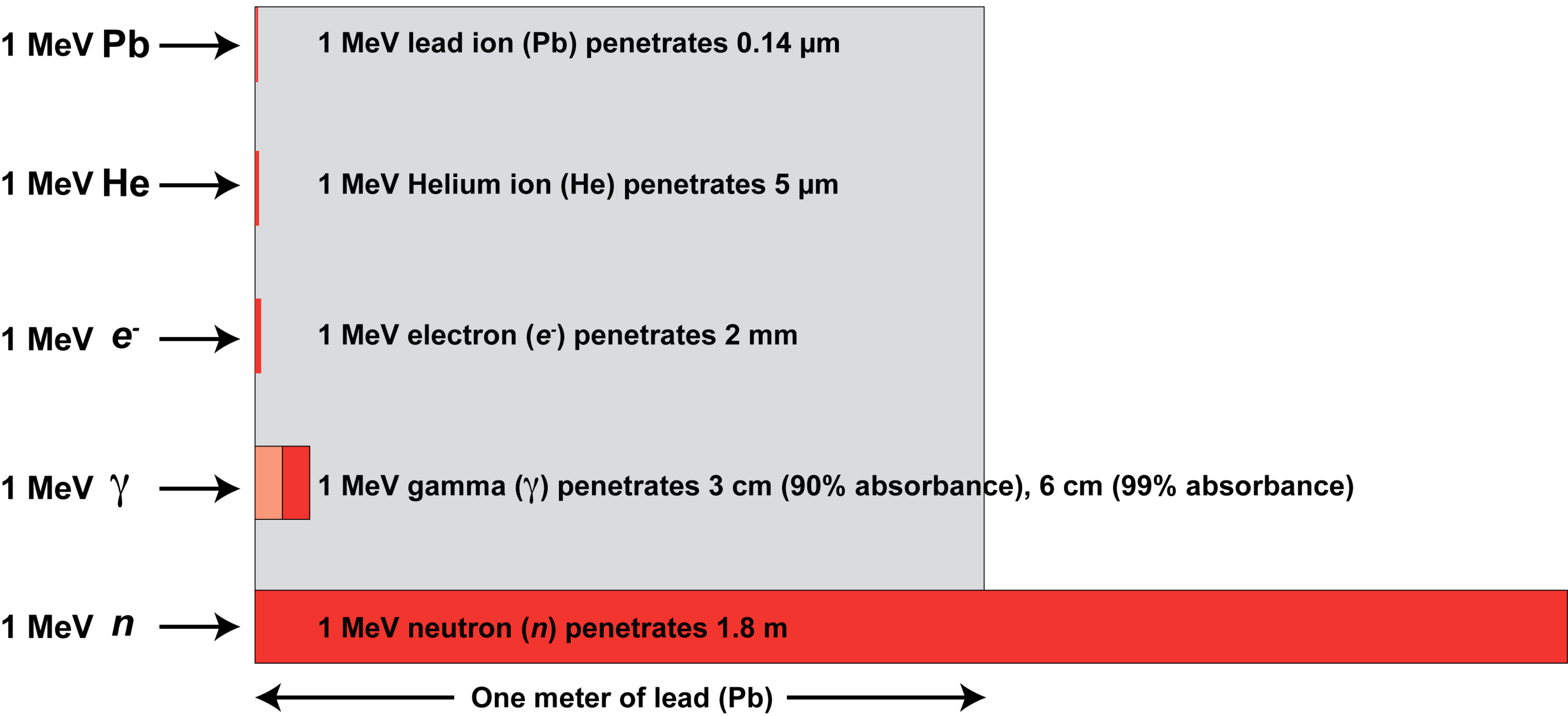
$$\Delta T = 80\ \mathrm{K}$$

$$c_p^{H_2O}\ \Delta \mathrm{T} = 334.5\ \frac{\mathrm{J}}{\mathrm{g}} \times \frac{10^3\ \mathrm{g}}{\mathrm{kg}}$$

$$= 3.345 \cdot 10^5\ \frac{\mathrm{J}}{\mathrm{kg}}$$

$$= 0.3345\ \mathrm{MGy}$$ Absorbed Energy

# Range of 1 MeV energetic particles in lead (Pb)



# Projectile-Target Interactions

$$\frac{\#\ \text{events}}{\text{<volume> or <weight>}} = \rho \cdot \sigma \cdot \varphi \cdot t$$

# Projectile-Target Interactions

atomic density • cross-section • flux • time

$$\frac{\text{\# events}}{\text{volume}} = \rho_a\left[\frac{\text{atoms}}{\text{volume}}\right]\sigma\left[\frac{\text{area}}{\text{atom}}\right]\varphi\left[\frac{\text{projectiles}}{\text{area}\bullet\text{time}}\right]t\left[\text{time}\right]$$

$$\frac{\text{\# events}}{\text{weight}} = \rho_w\left[\frac{\text{atoms}}{\text{weight}}\right]\sigma\left[\frac{\text{area}}{\text{atom}}\right]\varphi\left[\frac{\text{projectiles}}{\text{area}\bullet\text{time}}\right]t\left[\text{time}\right]$$

# Projectile-Target Interactions

fluence = flux • time

$$\Phi\left[\frac{\text{projectiles}}{\text{area}}\right] = \varphi\left[\frac{\text{projectiles}}{\text{area} \bullet \text{time}}\right] t\,[\text{time}]$$

# Projectile-Target Interactions

atomic density • cross-section • fluence

$$\frac{\#\text{ events}}{\text{volume}} = \rho_a \left[ \frac{\text{atoms}}{\text{volume}} \right] \sigma \left[ \frac{\text{area}}{\text{atom}} \right] \Phi \left[ \frac{\text{projectiles}}{\text{area}} \right]$$

$$\frac{\#\text{ events}}{\text{weight}} = \rho_w \left[ \frac{\text{atoms}}{\text{weight}} \right] \sigma \left[ \frac{\text{area}}{\text{atom}} \right] \Phi \left[ \frac{\text{projectiles}}{\text{area}} \right]$$

# Projectile-Target Interactions

cross-section • fluence

$$\frac{\frac{\#\text{ events}}{\text{volume}}}{\rho_a\left[\frac{\text{atoms}}{\text{volume}}\right]} = \sigma\left[\frac{\text{area}}{\text{atom}}\right]\Phi\left[\frac{\text{projectiles}}{\text{area}}\right]$$

# Projectile-Target Interactions Leading to Atomic Displacements

| *dpa* | = | displacement cross-section | • | fluence |
|---|---|---|---|---|

$$\frac{\dfrac{\#\ \text{atomic displacements}}{\text{volume}}}{\rho_a\left[\dfrac{\text{atoms}}{\text{volume}}\right]} = \sigma\left[\frac{\text{area}}{\text{atom}}\right]\Phi\left[\frac{\text{projectiles}}{\text{area}}\right]$$

*Ballistic* *Dose* ➡

$$\frac{\text{displacements}}{\text{atom}} = \sigma\left[\frac{\text{area}}{\text{atom}}\right]\Phi\left[\frac{\text{projectiles}}{\text{area}}\right]$$

# Electron irradiation-induced amorphization of powellite ($CaMoO_4$)

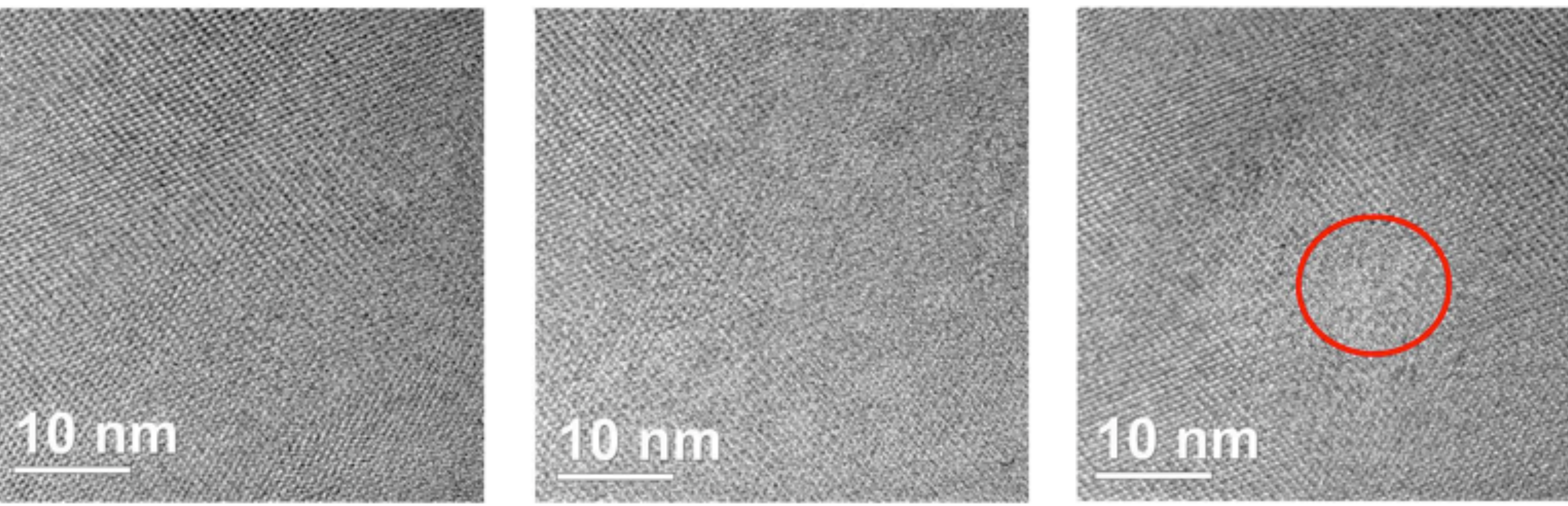
300 keV electrons

room-temperature irradiation conditions

start

After 5 minutes ( ~$1X10^6$ $e/nm^2/s$)

After 5 minutes (focus e beam, ~$1X10^7$ $e/nm^2/s$)



# Electron irradiation-induced amorphization of powellite ($CaMoO_4$)

Two components of damage:

1. electronic component
(electron excitation/ionization; radiolysis)

2. nuclear component
(ballistic or displacement damage)

# 1. Electronic Stopping

# Electron Excitation/Ionization

## Bethe-Ashkin expression for ionization energy loss per unit length

H. A. Bethe, and J. Ashkin, in *Experimental Nuclear Physics. Volume I*, edited by E. Segrè (John Wiley & Sons, Inc., New York, 1953), pp. 166-357.

# Electron Excitation/Ionization

Bethe-Ashkin expression for ionization energy loss per unit length

relativistic expression

$$-\frac{dE}{dx} = \frac{2\pi e^4}{E_0}\frac{\rho_e}{\beta^2}\left\{ \begin{array}{l} \mathrm{Ln}\left(\dfrac{E_0\beta^2 E}{2J^2(1-\beta^2)}\right) \\ -\left(2\sqrt{1-\beta^2}-1-\beta^2\right)\mathrm{Ln}2 \\ +1-\beta^2 \\ +\dfrac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2 \end{array} \right\}$$

$$E_0 = m_e c^2 = \text{ rest energy of the electron}$$

$$m_e = \text{rest mass of the electron}$$

$$c = \text{speed of light}$$

$$e^2 = 14.4 \text{ eV} \cdot \text{Å}$$

$$\beta = \frac{v}{c}$$

$v =$ velocity of electron

$c =$ speed of light

$$\beta = \sqrt{1 - \left( \frac{E_0}{E_0 + E} \right)^2}$$

$E_0 =$ rest energy of the electron

$E =$ kinetic energy of the electron

$$\rho_e = Z \cdot \rho_a$$

$\rho_e =$ electron density

$Z =$ atomic number

$\rho_a =$ atomic density

$$J = 9.76\, Z + 58.5\, Z^{-0.19} \;\; (\mathrm{eV})$$

$$= \;\; \text{mean electron excitation potential}$$

M. J. Berger, and S. M. Seltzer, Nat. Acad. Sci. / Nat. Res. Council Publ. 1133 (Washington, 1964), p. 205.

# Bragg's Rule for Additivity of Stopping Powers

W. H. Bragg, and M. A. Elder, Phil. Mag. **10**, 318 (1905)

# Stopping Power

$$\varepsilon_e = S_e(E) = \frac{1}{\rho_a} \frac{dE}{dx}\bigg|_e \quad \left( \frac{\text{eV} \cdot \text{Å}^2}{\text{atom} \cdot e^-} \right)$$

# Bragg's Rule for Additivity of Stopping Powers

For binary compound with molecular unit, $A_m B_n$ :

$$\varepsilon_e^{A_m B_n} = m\,\varepsilon_e^{A} + n\,\varepsilon_e^{B}$$

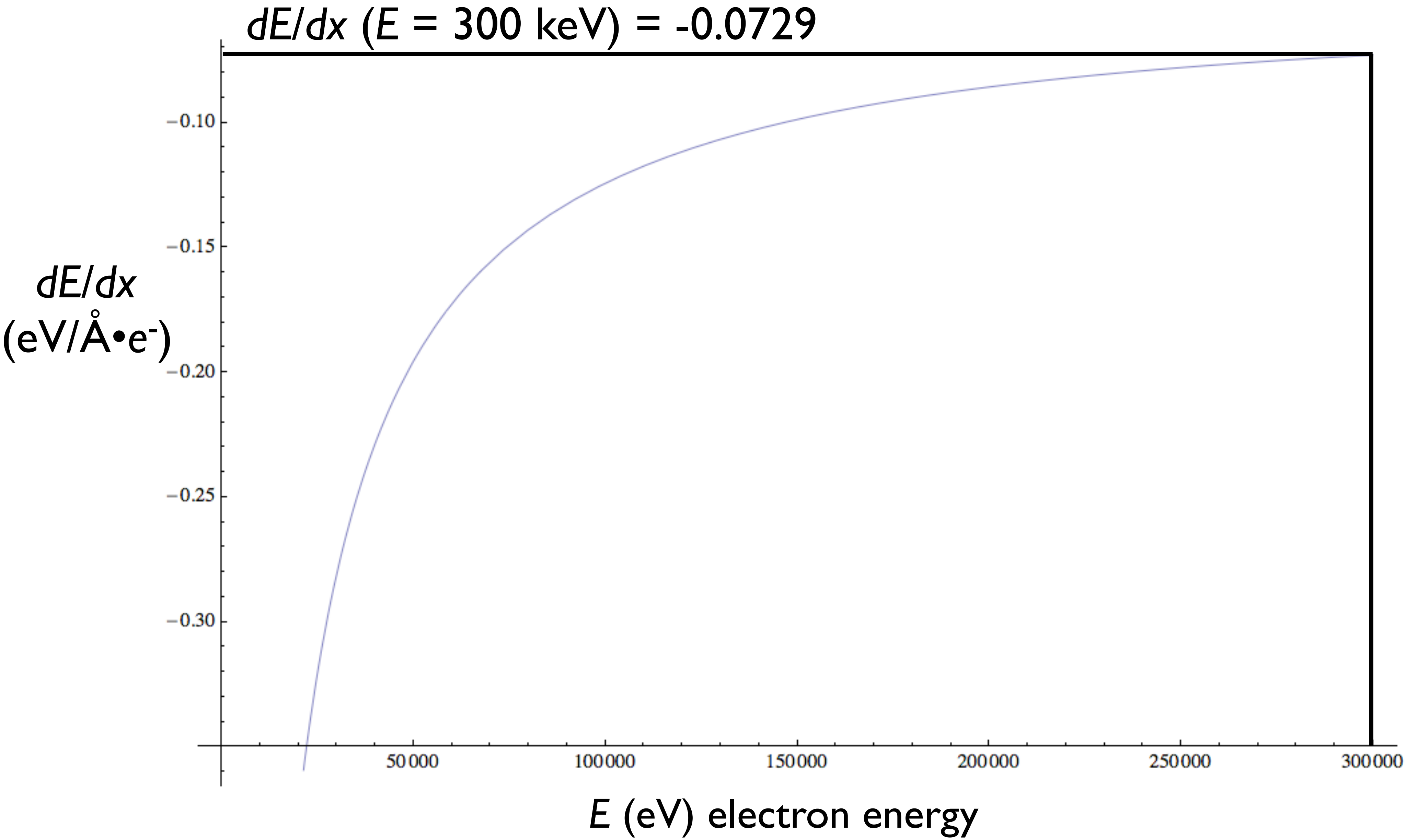
where $m$ is the number of $A$ atoms in molecule $A_m B_n$
and $n$ is the number of $B$ atoms in molecule $A_m B_n$

One can show that:

$$\left.\frac{dE}{dx}\right|_e^{A_m B_n} = \rho_m^{A_m B_n}\ \varepsilon_e^{A_m B_n} = \left.\frac{dE}{dx}\right|_e^{A} + \left.\frac{dE}{dx}\right|_e^{B}$$

where $\rho_m^{A_m B_n}$ is the molecular density of $A_m B_n$
molecules in the compound.

# Ionization stopping in powellite



$E = 300$ keV

$\beta = 0.776526$

$dE/dx$ ($E = 300$ keV) $= -0.0729$ eV/Å•$e^-$

thickness = 1000 Å
TEM sample thickness

Total ionization energy loss over sample thickness $= 72.9$ eV/$e^-$ $= 1.17\times10^{-17}$ J/$e^-$

$$\varphi = 10^{7} \ \frac{e^{-}}{\mathrm{nm}^{2} \cdot \mathrm{s}} = 10^{5} \ \frac{e^{-}}{\text{Å}^{2} \cdot \mathrm{s}} = 10^{21} \ \frac{e^{-}}{\mathrm{cm}^{2} \cdot \mathrm{s}}$$

electron flux

$$t = 5 \text{ min.} = 300 \text{ s}$$

irradiation time

$$\Phi = 3 \cdot 10^{7} \ \frac{e^{-}}{\text{Å}^{2}}$$

electron fluence

$$\text{Areal Energy Density} = \left.\frac{dE}{dx}\right|_{electronic} \cdot \Phi$$

$$= 3.504 \cdot 10^{-10}\ \frac{\text{J}}{\text{Å}^2}$$

$$\text{Total Energy Density} = \frac{\text{Areal Energy Density}}{\text{thickness}}$$

$$= 3.504 \cdot 10^{-13}\ \frac{\text{J}}{\text{Å}^3}$$

$$\rho_w = 4.259 \cdot 10^{-27} \ \frac{\text{kg}}{\text{Å}^3}$$

$$\text{Dose} = 8.2 \cdot 10^{13} \ \frac{\text{J}}{\text{kg}} = 82 \ \text{TGy}$$

Magnitude of dose: Tens of TeraGray !!

# 2. Nuclear Stopping

# Electron displacement damage calculation

Primary damage cross-section after Seitz & Koehler (1956):
F. Seitz, and J. S. Koehler, in *Solid State Physics: Advances in Research & Applications*, edited by F. Seitz, and D. Turnbull (Academic Press, 1956), pp. 305-448.

Based on the relativistic electron cross-section expression derived by McKinley & Feshbach (1948):
W. A. McKinley, Jr., and H. Feshbach, Physical Review **74**, 1759 (1948).

Total cross-section (primary plus secondaries) after Oen (1973):
O. S. Oen, (Oak Ridge National Laboratory, Oak Ridge, TN, 1973), pp. 204.

# Differential displacement cross-section, $d\sigma$

$$d\sigma(T) = \frac{\pi b'^2}{4} T_m \left[ 1 - \beta^2 \frac{T}{T_m} + \pi\alpha'\beta \left\{ \sqrt{\frac{T}{T_m}} - \frac{T}{T_m} \right\} \right] \frac{dT}{T^2}$$

where $T$ is the kinetic energy of the electron

$$\beta = v / c = \sqrt{1 - \left( \frac{E_0}{E_0 + E} \right)^2}$$

$$\alpha' = \alpha Z$$

where $\alpha$ is the fine structure constant (~1/137)

$$b'^2 = 4\, Z^2 \left( \frac{e^2}{E_0} \right)^2 \frac{1}{\beta^4\, \gamma^2}$$

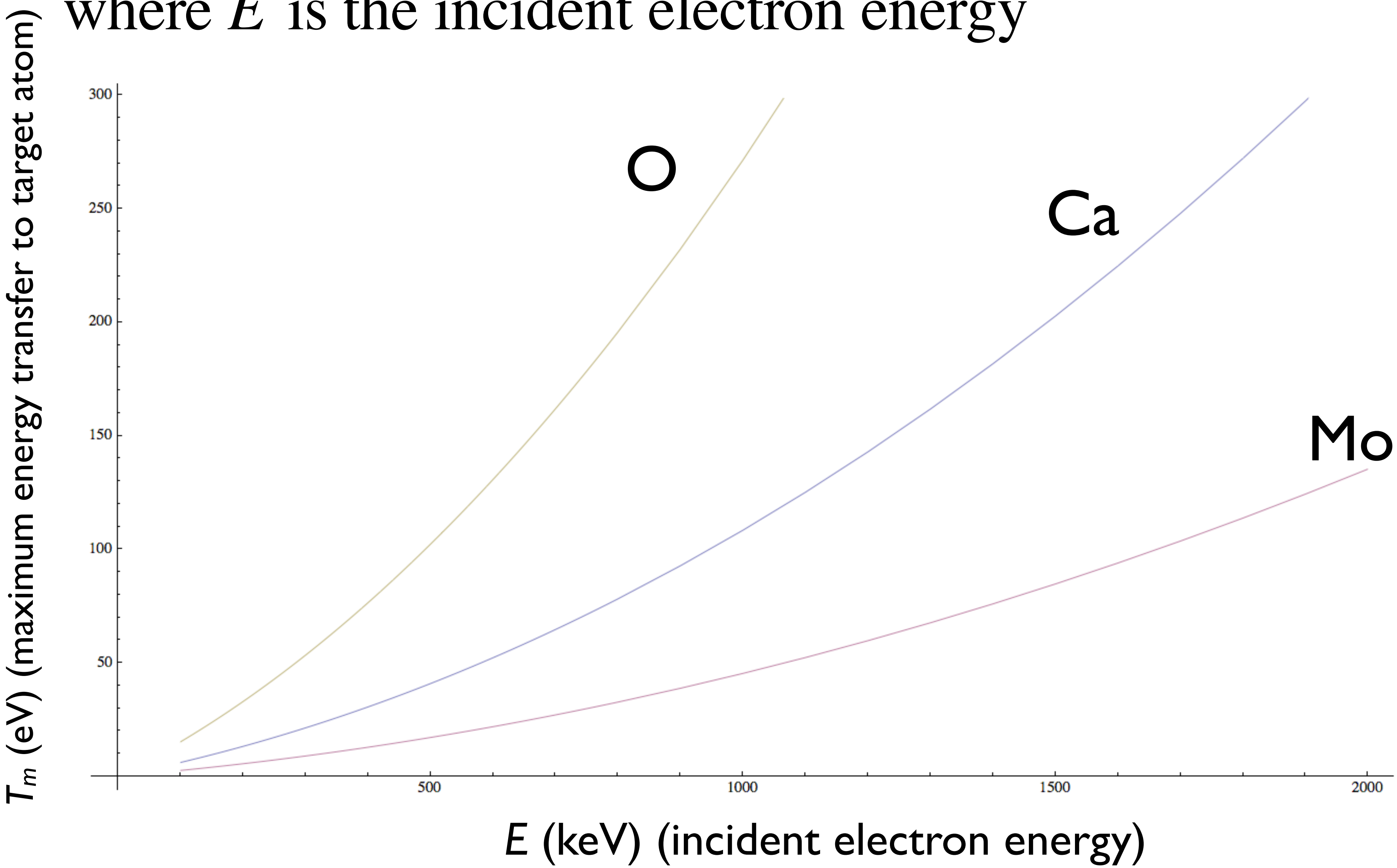
where

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$T_m$ = maximum energy transfer from $e^-$ to target atom

$$T_m = \frac{4\, m_e\, M}{\left(m_e + M\right)^2} E \left(1 + \frac{E}{2\, E_0}\right)$$

where $E$ is the incident electron energy



$$E = 300 \text{ keV}$$

$$Z^{\text{Ca}} = 20 \qquad T_m^{\text{Ca}} = 21.245 \text{ eV}$$

$$Z^{\text{Mo}} = 42 \qquad T_m^{\text{Mo}} = 8.8756 \text{ eV}$$

$$Z^{\text{O}} = 8 \qquad T_m^{\text{O}} = 53.219 \text{ eV}$$

$$Z^{ave} = 15.67 \qquad T_m^{ave} = 25.54 \text{ eV}$$

$$E_d = 40 \text{ eV}$$

$$Z^{\mathrm{Ca}} = 20$$

$$E_{threshold}^{\mathrm{Ca}} = 493 \text{ keV}$$

$$Z^{\mathrm{Mo}} = 42$$

$$E_{threshold}^{\mathrm{Mo}} = 920 \text{ keV}$$

$$Z^{\mathrm{O}} = 8$$

$$E_{threshold}^{\mathrm{O}} = 237 \text{ keV}$$

$$Z^{ave} = 15.67$$

$$E_d = 8 \text{ eV}$$

$$Z^{\mathrm{Ca}} = 20$$

$$E_{threshold}^{\mathrm{Ca}} = 130 \text{ keV}$$

$$Z^{\mathrm{Mo}} = 42$$

$$E_{threshold}^{\mathrm{Mo}} = 275 \text{ keV}$$

$$Z^{\mathrm{O}} = 8$$

$$E_{threshold}^{\mathrm{O}} = 55.3 \text{ keV}$$

$$Z^{ave} = 15.67$$

## Primary displacement cross-section:

$$\sigma_p(E) = \int_{E_d}^{T_m} d\sigma(T) \quad \left[\frac{<area>}{\text{atom}}\right]$$

where $E_d$ is the displacement threshold energy

## Cascade cross-section:

$$\sigma_{tot}(E) = \int_{E_d}^{T_m} \nu(T)\, d\sigma(T) \quad \left[\frac{<area>}{\text{atom}}\right]$$

where $\nu(T)$ is the number of secondary displacements, given most simply by the Kinchin-Pease expression:

$$\nu(T) = 0; \quad T < E_d$$

$$\nu(T) = 1; \quad E_d \leq T < 2E_d$$

$$\nu(T) = \frac{T}{2E_d}; \quad T \geq 2E_d$$

$$E = 300 \text{ keV}$$

$$E_d = 25 \text{ eV}$$

$$Z^{ave} = 15.67$$

$$E_{threshold}^{ave} = 295 \text{ keV}$$

$$T_m^{ave} = 25.54 \text{ eV}$$

$$2E_d = 50 \text{ eV}$$

$$\sigma_{tot}(E) = \sigma_p(E) = 0.588 \text{ barn} = 5.88 \cdot 10^{-9} \ \frac{\text{Å}^2}{\text{atom}}$$

$$1 \text{ barn} = 10^{-24} \text{ cm}^2 = 10^{-8} \text{ Å}^2$$

$$\varphi = 10^7 \ \frac{e^-}{\mathrm{nm}^2 \cdot \mathrm{s}} = 10^5 \ \frac{e^-}{\mathrm{\AA}^2 \cdot \mathrm{s}} = 10^{21} \ \frac{e^-}{\mathrm{cm}^2 \cdot \mathrm{s}}$$

electron flux

$$t = 5 \text{ min.} = 300 \text{ s}$$

irradiation time

$$\Phi = 3 \cdot 10^7 \ \frac{e^-}{\mathrm{\AA}^2}$$

electron fluence

# Total displacement damage dose

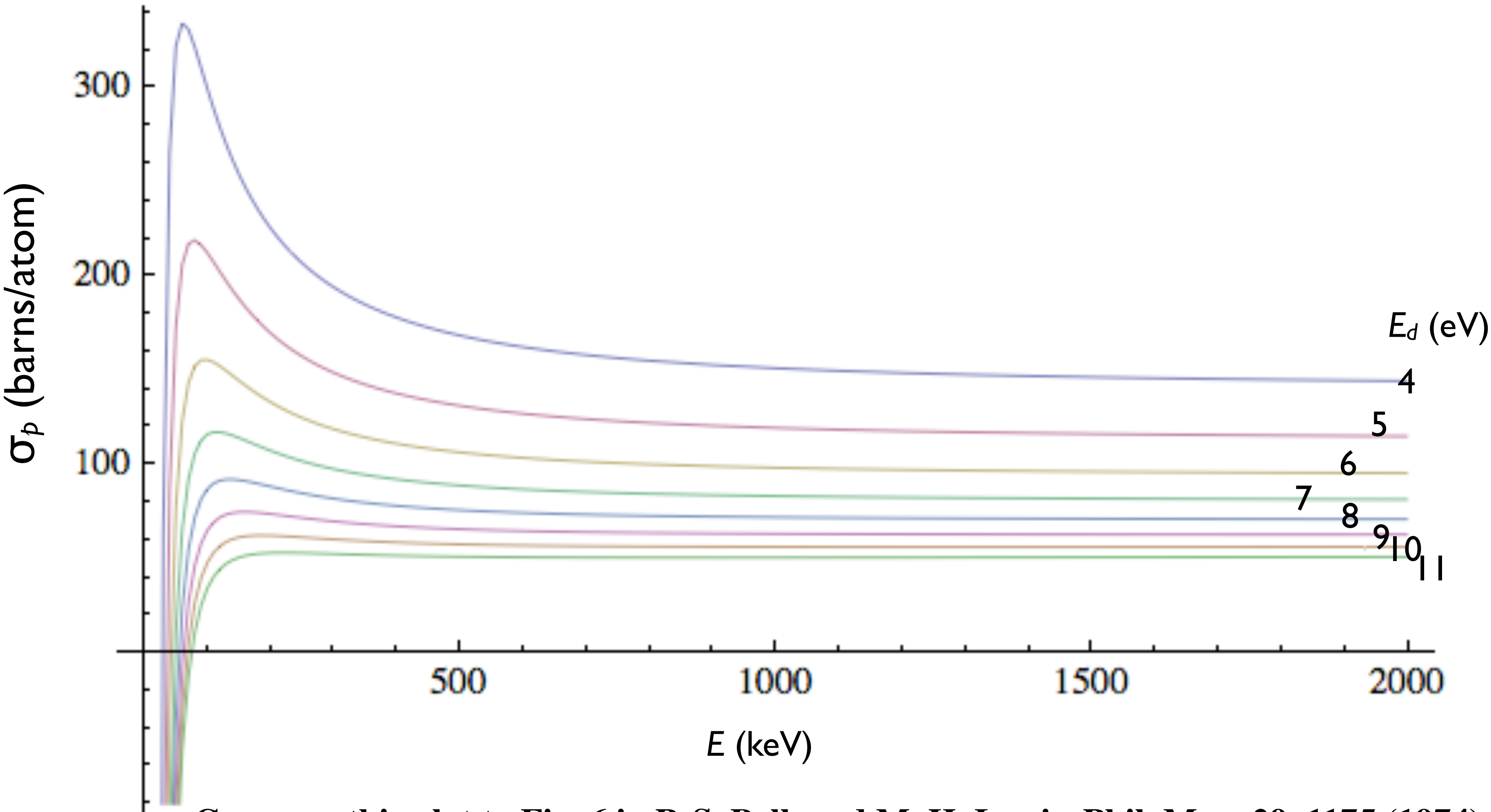
$$\text{displacements per atom} = \sigma_{tot}\ \Phi$$

$$= 5.88\cdot 10^{-9}\ \frac{\text{Å}^2}{\text{atom}} \times\ 3\cdot 10^{7}\ \frac{e^-}{\text{Å}^2}$$

$$= 0.18\ dpa$$

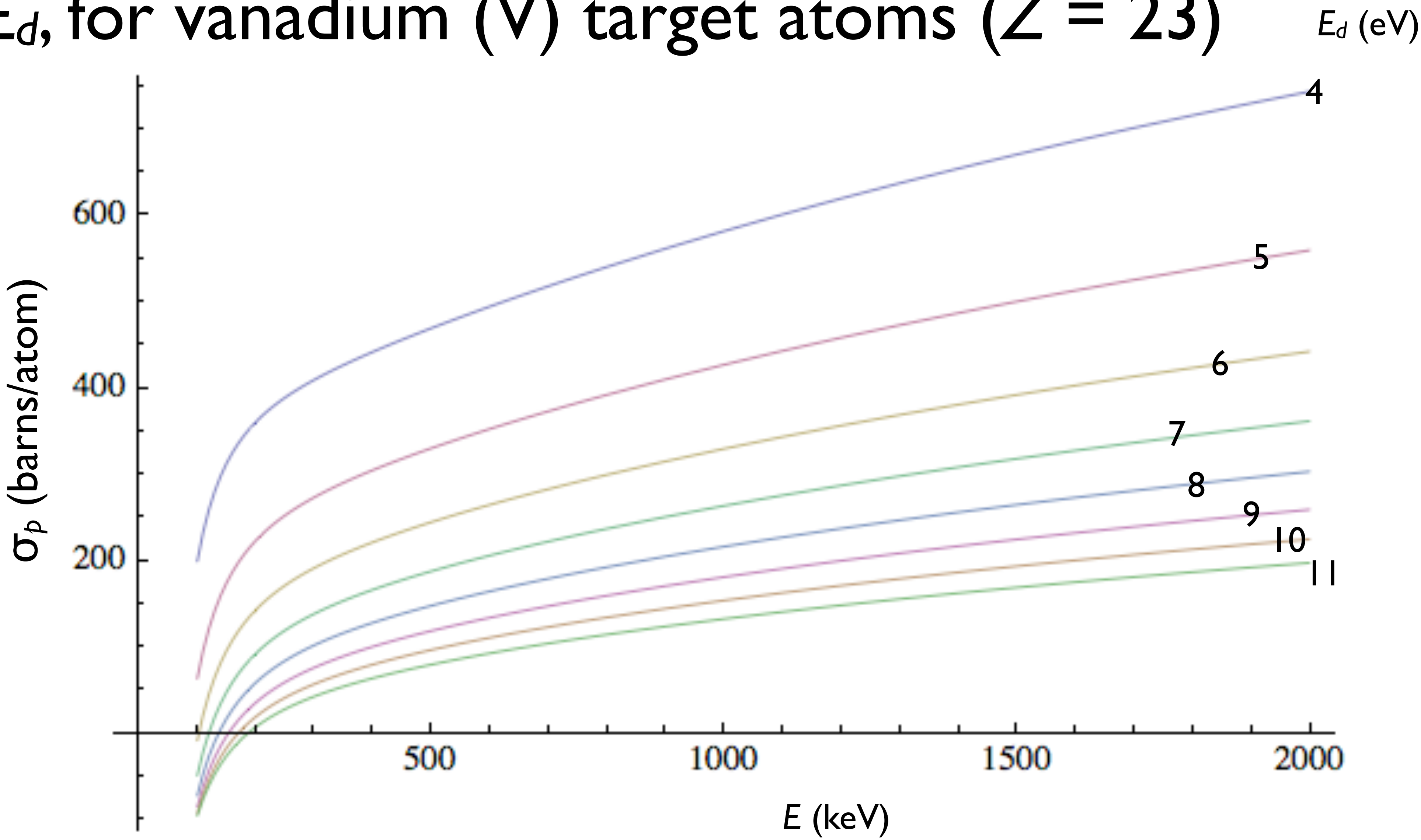
Presumably, this magnitude of displacement damage is not sufficient to induce a crystal-to-amorphous phase transformation

# Displacement cross-section, $\sigma_p(E, E_d)$ versus e$^-$ beam energy, *E*, and displacement threshold energy, $E_d$, for oxygen (O) target atoms ($Z = 8$)




**Compare this plot to Fig. 6 in P. S. Bell, and M. H. Lewis, Phil. Mag. 29, 1175 (1974).**

# Displacement cross-section, $\sigma_p(E, E_d)$ versus e⁻ beam energy, $E$, and displacement threshold energy, $E_d$, for vanadium (V) target atoms ($Z = 23$)




**Compare this plot to Fig. 6 in P. S. Bell, and M. H. Lewis, Phil. Mag. 29, 1175 (1974).**

# Dose Rate

Ming's experiment on $CaMoO_4$:

$$\text{Dose Rate} = \frac{82\ \text{TGy}}{300\ \text{s}} = 0.273\ \frac{\text{TGy}}{\text{s}} = 273\ \frac{\text{GGy}}{\text{s}}$$

$$\varphi = 10^{7}\ \frac{e^{-}}{\text{nm}^{2}\cdot\text{s}} = 10^{5}\ \frac{e^{-}}{\text{Å}^{2}\cdot\text{s}} = 10^{21}\ \frac{e^{-}}{\text{cm}^{2}\cdot\text{s}}$$

electron flux

# Dose Rate

Field Emission Gun (FEG) Scanning Transmission Electron Microscope (STEM) probe:

**1 nA in 1 nm diam. probe**

$$\varphi = 6.24 \cdot 10^{9} \frac{e^{-}}{\mathrm{nm}^{2} \cdot \mathrm{s}}$$

$$= 6.24 \cdot 10^{7} \frac{e^{-}}{\mathrm{\AA}^{2} \cdot \mathrm{s}}$$

$$= 6.24 \cdot 10^{23} \frac{e^{-}}{\mathrm{cm}^{2} \cdot \mathrm{s}}$$

electron flux

6.24 times greater than Ming's experiment

# Dose Rate

Field Emission Gun (FEG) Scanning Transmission Electron Microscope (STEM) probe:

**1 nA in 1 nm diam. probe**

$$\text{Dose Rate} = 6.24 \times 273 \ \frac{\text{GGy}}{\text{s}}$$

$$= 1.7 \cdot 10^{3} \ \frac{\text{GGy}}{\text{s}}$$

$$= 1.70 \ \frac{\text{TGy}}{\text{s}}$$

# Dose Rate

## Field Emission Gun (FEG) Scanning Transmission Electron Microscope (STEM) probe:

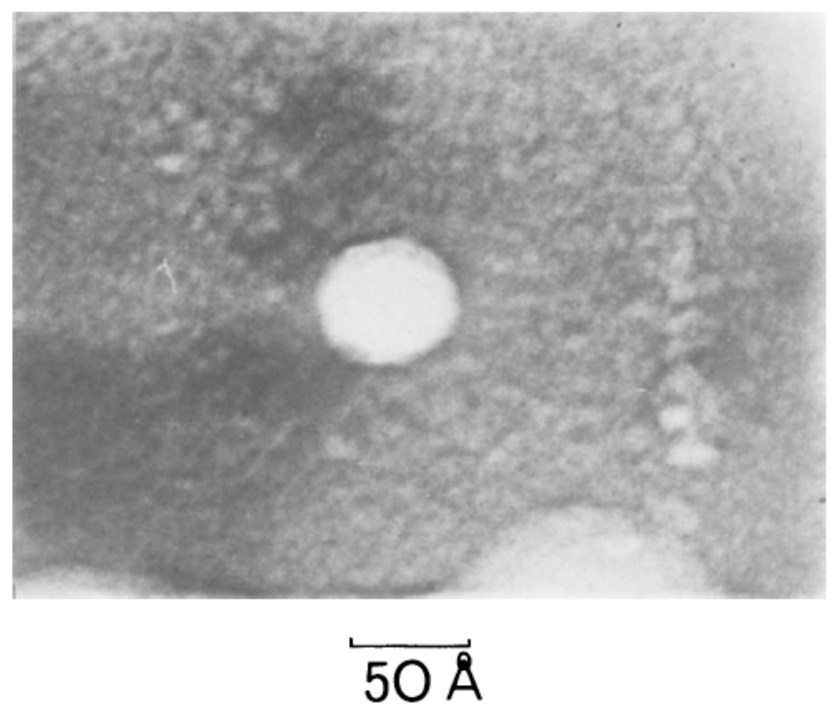
S. D. Berger *et al.*, Philosophical Magazine B-Physics of Condensed Matter Statistical Mechanics Electronic Optical and Magnetic Properties **55**, 341 (1987).

$Al_2O_3$
100 keV $e^{-s}$
Probe Width = 1 nm
Current Density = $5 \cdot 10^7$ A/m$^2$

$$\text{current density} = 0.05\ \frac{\text{nA}}{\text{nm}^2}$$

5% of the STEM analytical probe current density

Hole-drilling in $\alpha$-$Al_2O_3$



# Dose Rate

SrY-16 Source

$^{90}$Sr source: β-decays to $^{90}$Y then to $^{90}$Zr

I. I. Shpak, I. P. Studenyak, and M. Kranjcec, J. Optoelectronics and Adv. Mater. **5**, 1135 (2003).

$As_2X_3$ (X = S, Se)

12.2 Ci $e^-$ source

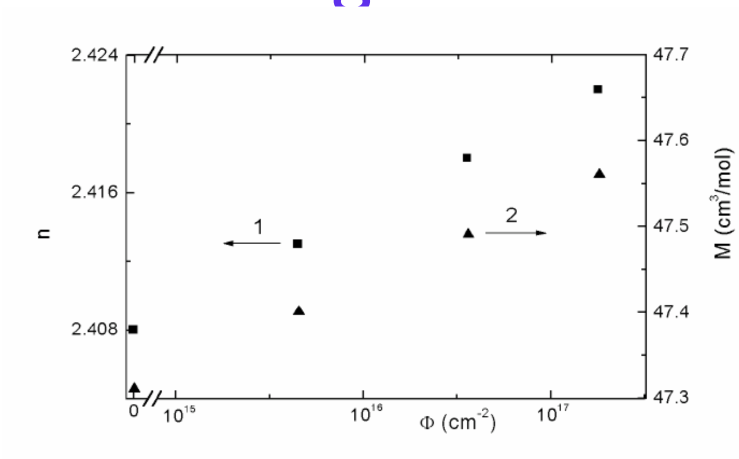
$E$ = 546 keV

Current Density = $1 \cdot 10^{11}$ $e^-/cm^2 \cdot s$

$$\text{current density} = 10^{-3} \frac{e^-}{\text{nm}^2 \cdot \text{s}}$$

One-billionth of Ming's current density!

## Chalcogenide Glasses




. Dose dependences of refractive index $n$ (1) and molar refraction $M$ (2) at $T$=295 K and $\lambda$=5 μm for $As_2S_3$ glasses.

# Dose Rate

## Febetron 707
## Pulsed Electron Accelerator

B. H. Milosavljevic, and L. Novakovic, Nucl. Instr. Meth. Phys. B **151**, 462 (1999).

Polypropylene
Single pulse dose = 50 kGy
Dose Rate = 2.5 TGy/s
$5 \cdot 10^7$ pulses/s

Compare to $^{60}$Co Gamma Source
Dose Rate = 1 Gy/s

Polypropylene (PP)

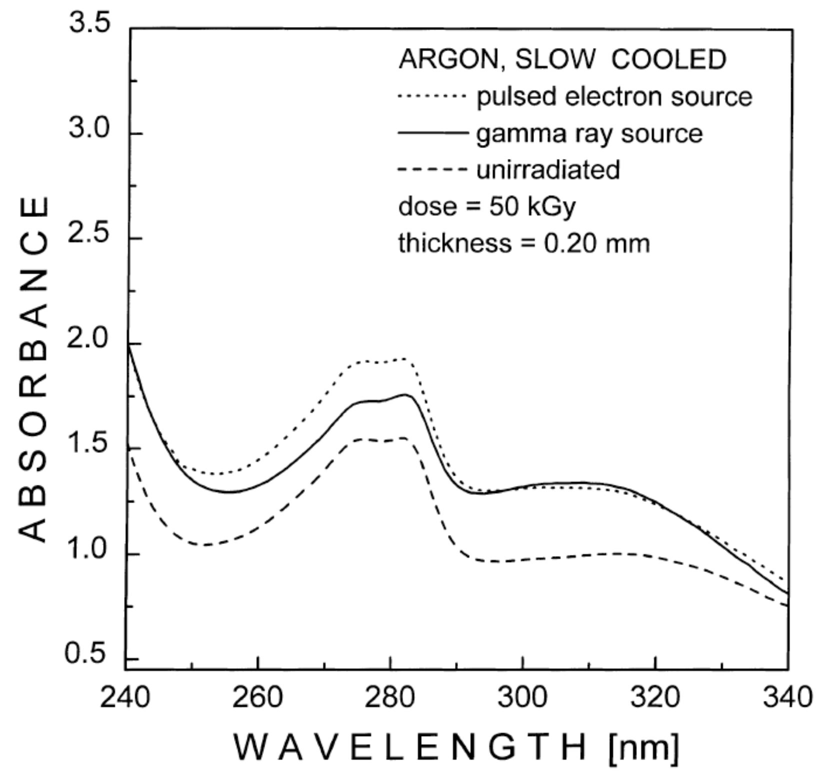



Fig. 4. UV spectra of PP samples prepared at slow cooling rate and irradiated in oxygen free atmosphere.

# Dose Rate

Sandia National Laboratory
Gamma Irradiation Facility (GIF)
Array of $^{60}Co$ sources

$$E_\gamma = 1.3325 \text{ MeV}$$

Dose Rate = 300,000 rads/hr.
= 83.3 rads/s

1 Gy/s = 100 rads/s

Dose Rate = 0.833 Gy/s

## Sandia GIF

The cobalt source arrays move along underwater tracks beneath the test cells and are automatically raised into and lowered out of the chambers to deliver the desired dose of gamma radiation to test objects placed in the cells.

**FRONT ELEVATION of the Sandia building that houses GIF's test chambers.**
Download 300dpi JPEG image, 'GIF6586.jpg', 456K (Media are welcome to download/publish this image with related news stories.)

A test can last seconds to months depending on the customer's gamma needs. Gamma dose rates as low as tens of rads per hour to as high as 300,000 rads per hour can be delivered. (A rad is a unit for measuring absorbed doses of ionizing radiation by a material.)

The GIF has gone through a rigorous and comprehensive safety review process prescribed for all DOE nuclear facilities, says Norm Schwers, Manager of Sandia's Hot Cell and Gamma Facilities department.

# Dose Rate

Pulsed electron radiation therapy

Dose Rate = 0.1 cGy/pulse

Therapeutic Dose = 10-20 Gy/minute

Med Phys. 2005 Jul;32(7):2204-10.

**Ion recombination correction for very high dose-per-pulse high-energy electron beams.**

Di Martino F, Giannelli M, Traino AC, Lazzeri M.

UO Fisica Sanitaria, Sezione di Fisica Medica, Azienda Ospedaliera Universitaria Pisana, via Roma 67, 56126 Pisa, Italy. f.dimartino@aopisa.toscana.it

**Abstract**

The parallel-plate ionization chamber is the recommended tool for the absorbed dose measurement in pulsed high-energy electron beams. Typically, the electron beams used in radiotherapy have a dose-per-pulse value less then 0.1 cGy/pulse. In this range the factor to correct the response of an ionization chamber for the lack of complete charge collection due to ion recombination (ksat) can be properly evaluated with the standard "two voltage" method proposed by the international dosimetric reports. Very high dose-per-pulse electron beams are employed in some special Linac dedicated to the Intra-Operatory-Radiation-Therapy (IORT). The high dose-per-pulse values (3-13 cGy/pulse) characterizing the IORT electron beams allow to deliver the therapeutic dose (10-20 Gy) in less than a minute. This considerably reduces the IORT procedure time, but some dosimetric problems arise because the standard method to evaluate ksat overestimates its value by 20%. Moreover, if the dose-per-pulse value >1 cGy/pulse, the dependence of ksat on the dose-per-pulse value cannot be neglected for relative dosimetry. In this work the dependence of ksat on the dose-per-pulse value is derived, based on the general equation that describes the ion recombination in the Boag theory. A new equation for ksat, depending on known or measurable quantities, is presented. The new ksat equation is experimentally tested by comparing the absorbed doses to water measured with parallel-plate ionization chambers (Roos and Markus) to that measured using dose-per-pulse independent dosimeters, such as radiochromic films and chemical Fricke dosimeters. These measurements are performed in the high dose-per-pulse (3-13 cGy/pulse) electron beams of the IORT dedicated Linac Hitesys Novac7 (Aprilia-Latina, Italy). The dose measurements made using the parallel-plate chambers and those made using the dose-per-pulse independent dosimeters are in good agreement (<3%). This demonstrates the possibility of using the parallel-plate ionization chambers also for the very high dose-per-pulse (> 1 cGy/pulse) electron-beam dosimetry.

# Dose

## Radiation Doses to Humans

Ave. Radiation Dose From Abdominal X-ray = 1.4 mGy

### Dose by source [e

In radiation therapy, the amount of radiation varies depending on the type and stage of cancer being treated. For curative cases, the typical dose for a solid epithelial tumor ranges from 60 to 80 Gy, while lymphomas are treated with 20 to 40 Gy. Preventive (adjuvant) doses are typically around 45–60 Gy in 1.8–2 Gy fractions (for breast, head, and neck cancers).

The average radiation dose from an abdominal X-ray is 1.4 mGy, that from an abdominal CT scan is 8.0 mGy, that from a pelvic CT scan is 25 mGy, and that from a selective CT scan of the abdomen and the pelvis is 30 mGy.[4]

# Dose

## Irradiation of Food for Preservation

On the basis of the dose of radiation the application is generally divided into three main categories:

### Low dose applications (up to 1 kGy) [edit]

- Sprout inhibition in bulbs and tubers 0.03-0.15 kGy
- Delay in fruit ripening 0.25-0.75 kGy
- Insect disinfestation including quarantine treatment and elimination of food borne parasites 0.07-1.00 kGy

### Medium dose applications (1 kGy to 10 kGy) [edit]

- Reduction of spoilage microbes to prolong shelf-life of meat, poultry and seafoods under refrigeration 1.50–3.00 kGy
- Reduction of pathogenic microbes in fresh and frozen meat, poultry and seafoods 3.00–7.00 kGy
- Reducing the number of microorganisms in spices to improve hygienic quality 10.00 kGy

### High dose applications (above 10 kGy) [edit]

- Sterilization of packaged meat, poultry, and their products that are shelf stable without refrigeration 25.00-70.00 kGy
- Sterilization of Hospital diets 25.00-70.00 kGy
- Product improvement as increased juice yield or improved re-hydration

These doses are above those currently permitted for these food items by the FDA and other regulators around the world. The Codex Alimentarius Standard on Irradiated Food does not specify any upper dose limit.[18][19] NASA is authorized to sterilize frozen meat for astronauts at doses of 44 kGy as a notable exception.[20]

Irradiation treatments are also sometimes classified as radappertization, radicidation and radurization.[21]

Irradiations performed with electrons, gamma rays and X-rays

# Radiolysis

L. W. Hobbs, in *Introduction to Analytical Electron Microscopy*, edited by J. J. Hren, J. I. Goldstein, and D. C. Joy (Plenum Press, New York, 1979), pp. 437-480.

TABLE III

Inorganic solids in which radiolysis is known to occur

alkali halides (LiF, LiCl, LiBr, LiI, NaF, NaCl, NaBr, NaI, KF, KCl, KBr, KI, RbF, RbCl, RbBr, RbI, CsF, CsCl, CsBr, CsI)

alkaline earth halides ($CaF_2$, $SrF_2$, $BaF_2$, $MgF_2$)

silver halides (AgCl, AgBr, AgI)

cadmium halides ($CdI_2$)

lanthanum halides ($LaF_3$)

lead halides ($PbI_2$)

perovskite halides ($NaMgF_3$, $KMgF_3$)

silicas (quartz, cristobalite, fused silica)

silicates (alkali feldspars, some amphiboles, mica)

ice ($H_2O$)

alkali hydrides (LiH)

alkali azides ($LiN_3$, $NaN_3$, $KN_3$)

sulfides ($MoS_2$)

carbonates ($CaCO_3$)

alkali perchlorates ($NH_4ClO_3$, $NaClO_3$, $KClO_3$)

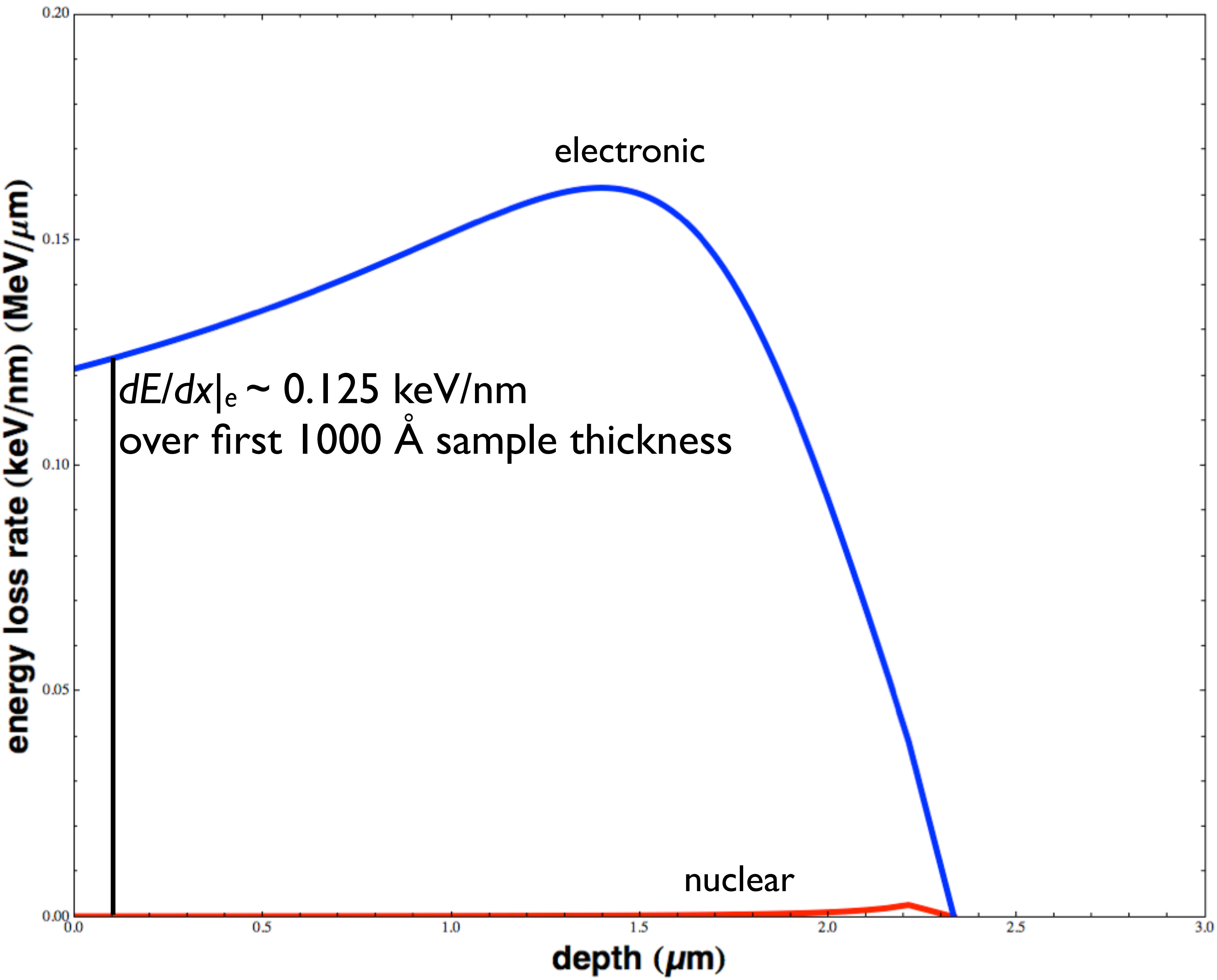
alkali bromates ($NaBrO_3$)

powellite ($CaMoO_4$)

# Extra Note

What about the dose rates in a typical proton irradiation experiment?

# Electronic & Nuclear Stopping
# 300 keV proton ($H^+$) irradiation of $CaMoO_4$



# Electronic & Nuclear Stopping
# 300 keV proton ($H^+$) irradiation of $CaMoO_4$

$$\left.\frac{dE}{dx}\right|_e^{\mathrm{CaMoO_4}} = 0.125 \ \frac{\mathrm{keV}}{\mathrm{nm}\cdot \mathrm{H}^+} = 12.5 \ \frac{\mathrm{eV}}{\mathrm{\AA}\cdot \mathrm{H}^+}$$

TEM thickness = 1000 Å

$$\text{Total Energy Loss Per Proton} = 1.25\cdot 10^{4} \ \frac{\mathrm{eV}}{\mathrm{H}^+}$$

$$= 2.00\cdot 10^{-15} \ \frac{\mathrm{J}}{\mathrm{H}^+}$$

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<u>Typical ion fluence</u>:

$$\Phi = 1 \cdot 10^{16} \ \frac{\mathrm{H}^+}{\mathrm{cm}^2} = 1 \ \frac{\mathrm{H}^+}{\text{Å}^2}$$

Energy Density = Energy Loss Per Proton x Fluence / TEM thickness

$$\text{Energy Density} = 2 \cdot 10^{-18} \ \frac{\mathrm{J}}{\text{Å}^3}$$

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# 300 keV proton ($H^+$) irradiation of $CaMoO_4$

$$\text{energy density} = 2 \cdot 10^{-18} \ \frac{\text{J}}{\text{Å}^3}$$

$$\rho_w^{\text{CaMoO}_4} = 4.26 \cdot 10^{-27} \ \frac{\text{kg}}{\text{Å}^3}$$

$$dose = \frac{\text{energy density}}{\rho_w^{\text{CaMoO}_4}} = \frac{2 \cdot 10^{-18} \ \frac{\text{J}}{\text{Å}^3}}{4.26 \cdot 10^{-27} \ \frac{\text{kg}}{\text{Å}^3}}$$

$$dose = 4.7 \cdot 10^{8} \frac{\text{J}}{\text{kg}} = 0.47 \text{ GGy}$$

# β⁻ Decay Process

$$^{A}_{Z}\mathrm{X} \rightarrow \; ^{A}_{Z+1}\mathrm{Y} + \; ^{0}_{-1}e + \; ^{0}_{0}\overline{\nu}$$

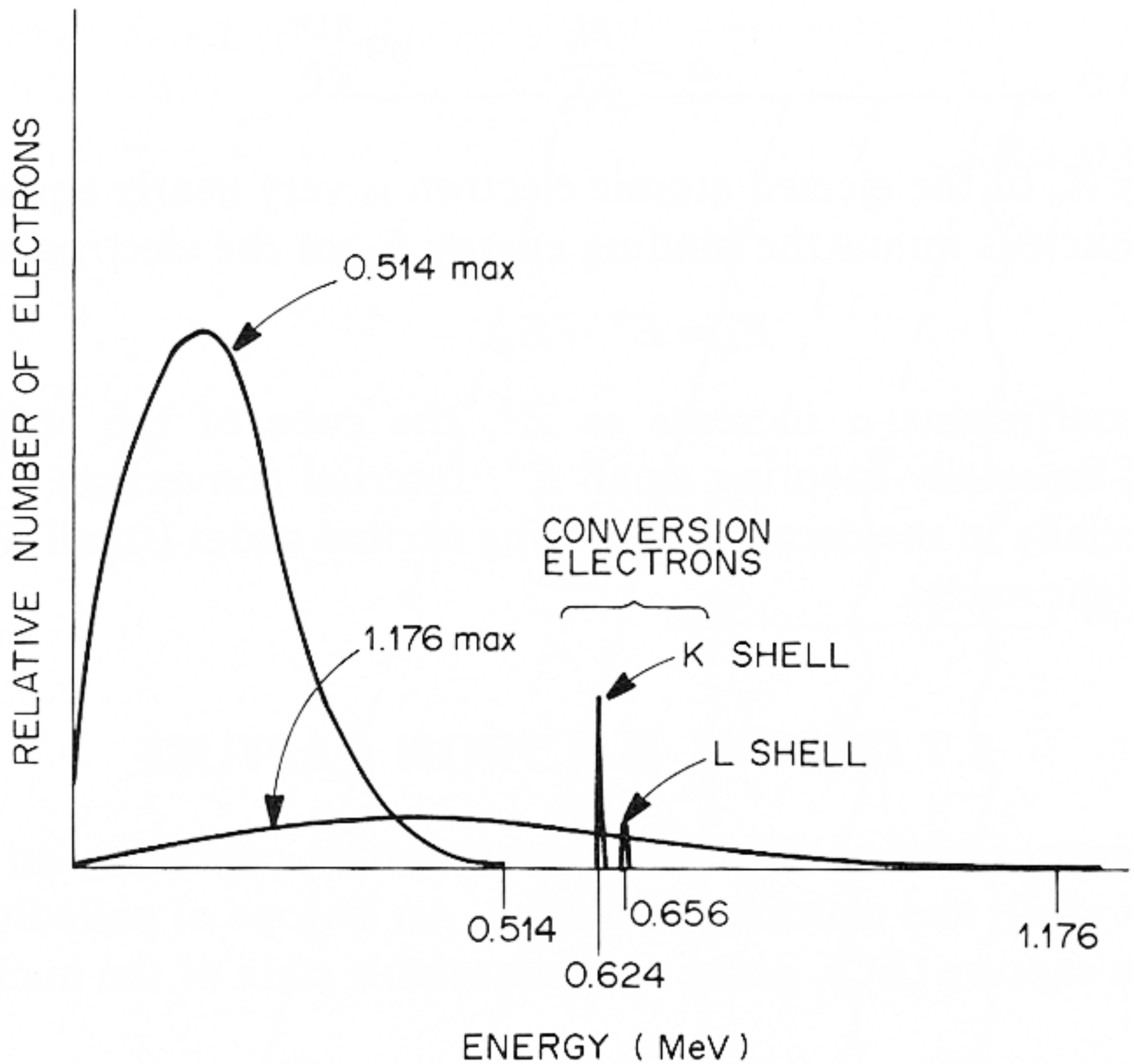
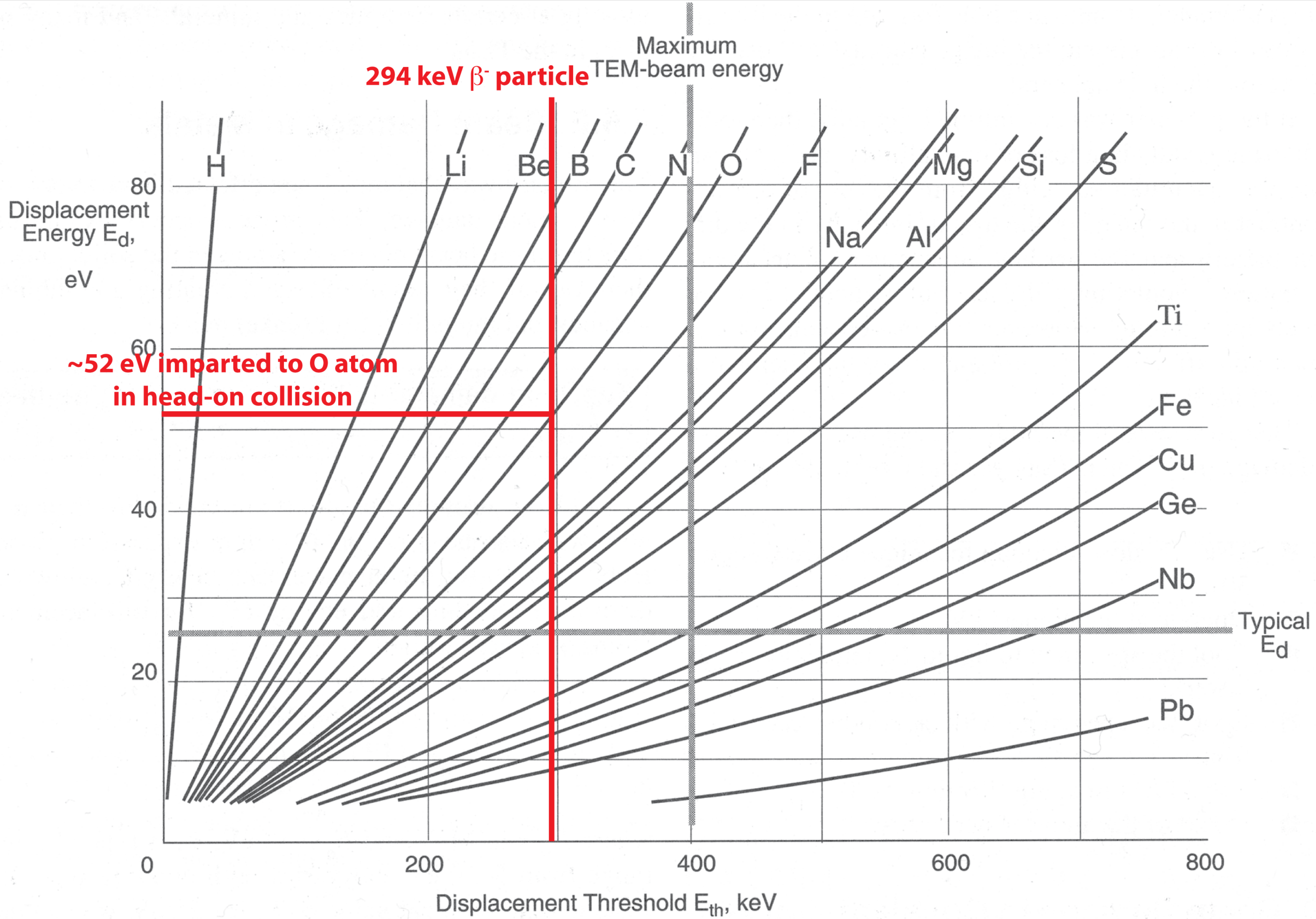



**Figure 3.9.** Sources of electrons from $^{137}_{55}Cs$ and their energy spectra. There are two modes of $\beta^-$ decay, with maximum energies of 0.514 MeV (93%) and 1.176 MeV (7%). Internal conversion electrons also occur at discrete energies of 0.624 MeV (from K shell) and 0.656 MeV (L shell) with a total frequency of 8%. See decay scheme in Fig. 3.8. The total spectrum of emitted electrons is the sum of the curves shown here.



Maximum
TEM-beam energy
294 keV β- particle
~52 eV imparted to O atom
in head-on collision
Displacement
Energy Ed,
eV
80
60
40
20
0
200
400
600
800
H
Li
Be
B
C
N
O
F
Na
Al
Mg
Si
S
Ti
Fe
Cu
Ge
Nb
Pb
Typical
Ed
Displacement Threshold Eth, keV

# Beta Decay of Tc-99