HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Radiation Damage in Materials

A course in modern knowledge of the fundamentals of radiation damage in all classes of materials

2020 version

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1. Introduction

1.0. Background of course

- The course was first made for the Swedish-speaking physics teaching at the University of Helsinki, Finland in 2014.
  - The file names of the lecture notes derive from this (radiation damage = *strålningsskador* in Swedish)
  - It is still used as a specialist MSc-level course at this university. Since the University is trilingual (Finnish-Swedish-English), all specialist terminology is given translations in *Finnish/Swedish* in blue italic font)
- The course setup and contents are based on the about 30 years experience of the key people behind the course in the field of Radiation damage
  - Literature references are given to more specialist results and topics on the course
- **The course authors do not bear any responsibility** for possible damage caused by learning the materials, whether due to errors in the lecture notes or due to any other means.

Expertise of course lecturers

- Prof. Kai Nordlund (http://www.acclab.helsinki.fi/~knordlun/) has worked 30 years on radiation damage in all classes of materials except biological materials, and published more than 500 papers in the field. He has written 3 MD codes and 1 KMC code

- Prof. Flyura Djurabekova (http://www.acclab.helsinki.fi/~djurabek/) has worked 25 years on radiation damage and materials in extreme environments, and published more than 200 papers in the field . She has written a BCA code and developed new KMC varieties.

- Docent Antti Kuronen (https://researchportal.helsinki.fi/fi/persons/antti-kuronen) has worked more than 30 years on radiation damage in materials, including medical physics dosimetry. He has published more than 100 papers in the field.

- Prof. William J. Weber (University of Tennessee) also provided several valuable comments to the lecture notes

1.1. Practical matters
Aims of the course for the student

- To understand what **radiation damage** (*strålningsskador, säteilyvauriot*) is
- To understand how it is created
- To have an idea how they can affect different kinds of materials properties
  - Comprehensive knowledge not possible – nobody knows this yet!
- To have a basic idea how it is studied experimentally and by computer simulations

- Course home page: http://www.acclab.helsinki.fi/~knordlun/rad_dam_course/

Prerequisites

- Courses at the Department of Physics:
  - Termophysics
    - i.e. Thermodynamics, statistical physics basics
  - Structure of matter I-II
    - Basics of quantum mechanics, the nature of chemical bonding
  - Materials physics I or Solid State Physics I
    - Atomic structure of matter: crystals, amorphous state, etc.
- Or equivalent knowledge from elsewhere

Course materials

- The main material of the course are the lecture notes, and possible other material given on the course web page
- A good book, serving as partial inspiration to this course, is the one by Gary Was: Fundamentals of Radiation Materials Science, Springer 2012
  - £89.99+shipping on amazon.co.uk 23.3.2014
  - Not mandatory to purchase
- Good wide-range review articles (available on course web page):
  - R. S. Averback and T. Diaz de la Rubia. *Displacement damage in irradiated metals and semiconductors.* In H. Ehrenfest and F. Spaepen, editors, Solid State Physics, volume 51, pages 281--402. Academic Press, New York, 1998.
  - K. Nordlund, S. J. Zinkle, A. E. Sand, F. Granberg, R. S. Averback, R. Stoller, T. Suzudo, L. Malerba, F. Banhart, W. J. Weber, F. Willaime, S. Dudarev, and D. Simeone, http://www.acclab.helsinki.fi/~knordlun/pub/Nor18.pdf *Primary radiation damage: a review of current understanding and models*, J. Nucl. Mater. **512**, 450 (2018).
  - A. V. Krasheninnikov and K. Nordlund. *Ion and electron irradiation-induced effects in nanostructured materials*. J. Appl. Phys. (Applied Physics Reviews), 107:071301, 2010.
  - K. Nordlund, http://www.acclab.helsinki.fi/~knordlun/pub/Nor18b.pdf *Historical review of computer simulation of radiation effects in materials*, J. Nucl. Mater. **520**, 273 (2019), Invited review in Diamond Anniversary issue.

1.2. Radiation
What is radiation?

- To understand what radiation damage means, one first needs to know what **radiation** (*strålning, säteily*) means
- In general, in all three languages the word radiation has a very general meaning of some sort of transfer of a physical quantity for far distances
  - In electrodynamics, Maxwells equations imply that a moving charged particle induces an electromagnetic field, but not energy transport. An accelerated particle induces an electromagnetic field that transports energy to infinity **= electromagnetic radiation** *(elektromagnetisk strålning, sähkömagneettinen säteily).*
    - E.g. radiowaves
    - Photon energy in electromagnetic radiation can be anything
- Of course also radioactive decay causes radiation, the sun, the stars, the headlights of a car, …

Definition of ionizing radiation

- For this course we are specifically interested in the kinds of radiation that can damage materials or living beings
- This kind of radiation is defined to be "**ionizing radiation**" (joniserande strålning, ionisoiva säteily)
- This is also a **legal** term, defined in the radiation protection legislation
- Unfortunately, in common language the terms often get confused: physicists tend to drop the preword ”ionizing”, and much of the common public believes all radiation is dangerous
  - There is also a minor misleading physical feature in this terminology: there are types of high/energy radiation that cause damage in materials, even though they don't cause practically any ionization of atoms (e.g. cluster ion bombardment)…
    - But this is fairly uncommon, and don't tell this to the lawyers, it would just confuse them

In some other languages

- The same terminology problem exists in many other languages
- E.g.
  - German: Strahlung und Ionisierender Strahlung
  - Russian: облучение, ионизирующее облучение

Physics behind term ”ionizing”

- **There is a fairly definite physics explanation for the border of what damaging / ionizing radiation is:**
- The strength of chemical bonds is of the order of ~ 2-5 eV
- Hence radiation where the particles have an energy high enough to break chemical bonds well enough to leave them permanently broken, damages a material
- I.e. particle energy > 5 eV or so (since a single bond break is seldom stable) may be ionising
  - But the exact limit is fuzzy and depends a lot on case; in many cases fundamental physics is not known
- Hence laser irradiation in the visible range **is not** ionizing – even though if the intensity is high enough, it can sure damage a material

The Finnish law [http://plus.edilex.fi/stuklex/en/]

Radiation Act
Chapter 3
Definitions
Section 8
Radiation

For the purposes of this Act, the term:

1. *Radiation* shall denote ionizing and non-ionizing radiation,
2. *Ionizing radiation* shall denote radiation capable of producing ions in a medium,
3. *Non-ionizing radiation* shall denote ultraviolet radiation, visible light, infrared radiation, radio-frequency radiation, and low-frequency and static electric and magnetic fields,
4. *Natural radiation* shall denote ionizing radiation originating in space, or from radioactive substances occurring in nature and not used as radiation sources.

- Note that the law states that ultraviolet is non-ionizing, even though physically this is not well motivated!

Same in Swedish,

Strålskyddslagen 27.3.1991/592

3 kap

Definitioner

8 §

Strålning

I denna lag avses med

1) *strålning* både joniserande och icke-joniserande strålning,

2) *joniserande strålning* sådan strålning som bildar joner i mediet,

3) *icke-joniserande strålning* ultraviolett strålning, synligt ljus, infraröd strålning, radiofrekvent strålning samt lågfrekventa och statiska elektriska och magnetiska fält,

4) *naturlig strålning* joniserande strålning som härstammar från rymden eller från naturliga radioaktiva ämnen då dessa inte används som strålkällor.

Same in Finnish

Säteilylaki 27.3.1991/592

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Määritelmiä

8 §

Säteily

Tässä laissa tarkoitetaan:

1) *säteilyllä* ionisoivaa ja ionisoimatonta säteilyä;

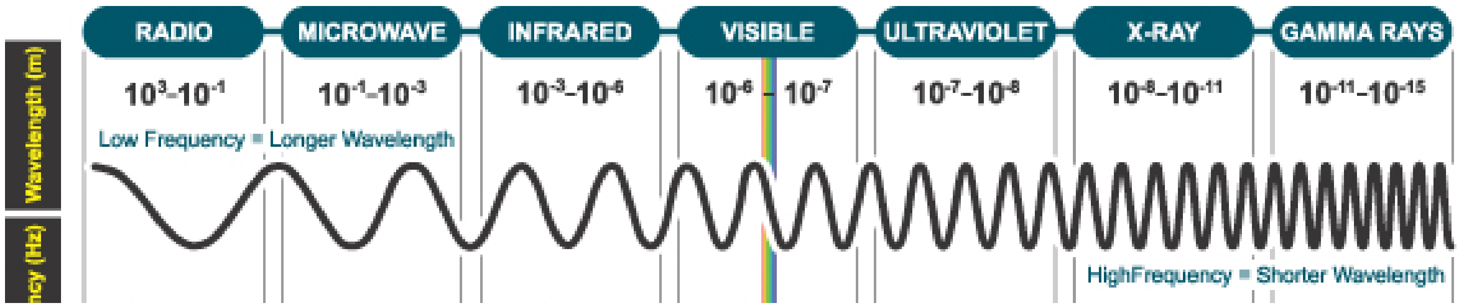
2) *ionisoivalla säteilyllä* säteilyä, joka muodostaa väliaineessa ioneja;

3) *ionisoimattomalla säteilyllä* ultraviolettisäteilyä, näkyvää valoa, infrapunasäteilyä, radiotaajuista säteilyä sekä pientaajuisia ja staattisia sähkö- ja magneettikenttiä;

4) *luonnonsäteilyllä* ionisoivaa säteilyä, joka on peräisin avaruudesta tai luonnon radioaktiivisista aineista silloin, kun niitä ei käytetä säteilylähteinä.

1.3. Types of particles that can cause radiation
1.3.1. Photons

- Electromagnetic waves, whose quantum is the photon, are of course extremely central in physics
- The electromagnetic spectrum by photon energy:



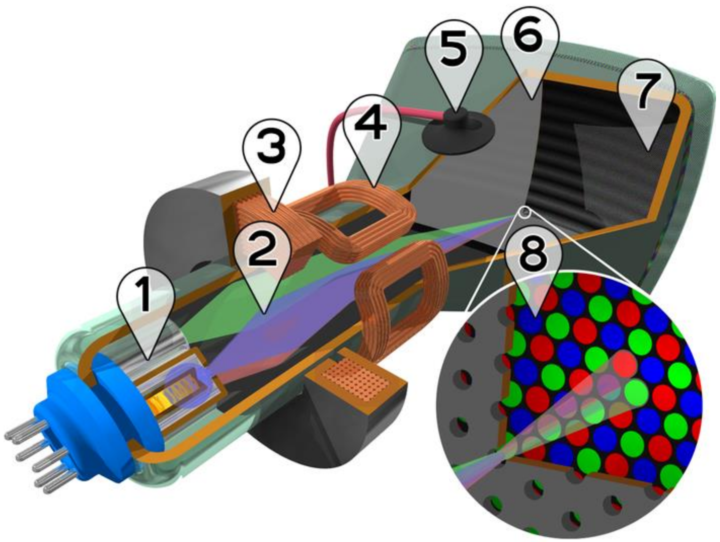
- Upper Ultraviolet, X-ray and gamma radiation are ionizing
- Terminology note:
  - **X-rays photons (**röntgenfotoner, röntgenfotoni**)** come by definition from transitions in atoms
  - Gamma photons come by definition from nuclei
  - **Synchrotron radiation** (*synkrotron-strålning, synkrotronisäteily tai syvävalo*) comes from bremsstrahlung in high-energy accelerators and overlaps completely with the X-ray energies

1.3.2 Electrons

- Electrons can be accelerated to high energies with electromagnetic fields, and in that case become a source of ionizing radiation
- Classical examples: x-ray tubes (electrons accelerated and hit a metal to produce x-rays), **cathode-ray** (*katodstråle, katodisäe*) tubes (also known as the old-fashioned non-flat <<TV’s)…
- Electron-microscopes, high-energy electron accelerators
- Certain natural radioactive decays also produce MeV electrons
- **Electron beam welding** (*elektronstrål-svetsning, elektronisuihkuhitsaus*)

Cathode ray tubes

- Typical old TV's worked with a 25 kV electron accelerator
- The electron beam was deflected by magnets in a rastered manner over fluorescent elements to produce the picture!
- The electrons were ionizing, and did produce a little bit of x-rays when hitting the screen
  - Hence all the warnings not to be too close to the TV!



[wikipedia: cathode ray tube]

1.3.3 Neutrons

- The neutron is not a stable elementary particle, but has a half-life of about 11 minutes
- But free neutrons still exist in man situations of practical interest:
  - Natural radioactive decay
    - Produces neutrons with energies of a few MeV, which can cause additional nuclear reactions, but usually slow down in matter down to meV energies before being absorbed or decaying into a proton+electron+neutrino
  - Nuclear fission reactors (and nuclear fission bombs)
    - Operation relies on chain reaction among U or Pu isotopes mediated by neutrons.
    - Initially MeV, but need to be **thermalized** (*termaliserad, termalisoitu*) down to sub-eV energies for efficient absorption into other atoms
  - Nuclear fusion reactors (and the hydrogen bombs)
    - Produce 14 MeV neutrons

Classification of neutrons by energy

- Neutrons can be classified by their energy:

Category	Energy
Cold neutrons	<0.003 eV
Slow (thermal) neutrons	0.003 – 0.4 eV
Slow (epithermal) neutrons	0.4 – 100 eV
Intermediate neutrons	100 eV – 200 keV
Fast neutrons	200 keV – 10 MeV
High energy (relativistic) neutrons	>10 MeV

[https://www.msm.cam.ac.uk/teaching/partIII/courseM17/M17H.pdf]

1.3.4 Ions

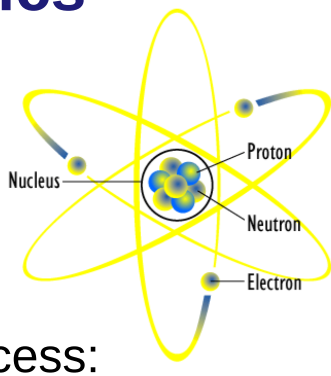
- Any charged atom or molecule can be called an ion
- Any ion can be accelerated with electromagnetic fields to high energies with various **accelerator** (*accelerator, kiihdytin*) technologies
  - Accelerator energy range: from about 10 eV (small ion guns plus decelerator) to 7 TeV (the Large Hadron Collider at CERN)
  - Accelerator technologies are in wide practical use in silicon chip manufacturing (multibillion-$ industry), thin film synthesis, materials analysis
  - Also wide research use for **ion beam analysis** (*jonstrålanalys, ionisuihkuanalyysi*) and **ion beam modification** (*jonstrålmodifiering, ionisuihkumuokkaus*) of materials
- Ions can also be produced naturally by radioactive decay
- The **solar wind** (*solvinden, aurinkotuuli*) actually mainly consists of energetic (keV, Mev and GeV) protons

1.3.5. More exotic cases

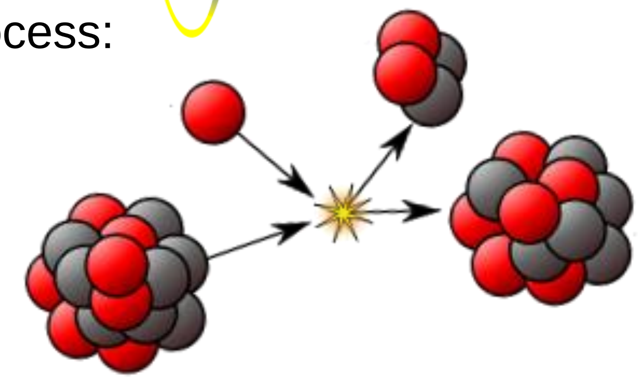
- Energetic neutral atoms can exist, but are very rare (since they cannot be accelerated directly). Behave much like energetic ions with same energy.
- Any elementary particle can at least in principle have an energy > 5 eV and hence cause damage
- Muons, antiprotons, positrons, neutrinos, …
  - Serious issue at particle physics labs like CERN
  - But also some everyday natural effects: **cosmic muons** (*kosmiska myoner, kosmiset myonit*) formed in the uppermost atmosphere) irradiate us every minute and cause upset events in modern electronics
  - Speculatively: due to the earths rotation around the center of the galaxy, we may be hitting dark matter particles in a radiation-like way [Phys. Rev. Lett. **120**, 111301 (2018)]
- Composite particles:
  - Molecules, Nanoclusters
  - Crucial quantity usually for this energy/atom, not total energy

Relation to other fields of physics

- Radiation damage is closely linked to nuclear physics, but not entirely part of it



  - Radioactivity is a nuclear physics process: nuclei decay into other particles
  - Neutron interactions with materials is generally considered a nuclear physics process: they interact only with other nuclei



  - But ion or electron irradiation at energies < 100 keV does usually not involve any nuclear reactions at all, and the nuclei don’t even meet each other (electron cloud shielding) => often considered a materials but not nuclear physics method
- The final damage is in any case a materials physics issue, not one of nuclear physics

1.3.6. Historically important definitions: α, β, γ, δ

- When radiation was initially found stepwise in the latter 19’th century and early 20’th century, there was not a good understanding of what the observed particles were in origin
- Without going into a science history lesson, we can now just in retrospect state what the observed particles are in modern terminology:
- α particles = Helium nuclei (two protons + two electrons)
  - Widely used still
- β particles = Electrons (free electrons)
  - Nowadays pretty rarely used except in nuclear physics
- γ rays = high-energy photons from nuclei
  - Widely used still
- δ electrons = Secondary electrons produced when another energetic particle interacts with matter
  - Nowadays still used in certain branches of solid state physics

1.4 Damage and dose terminology

- Ionizing radiation does usually damage materials
- Some central damage terminology:
  - **Radiation damage** (*strålningsskador, säteilyvauriot*): any kind of damage to a material produced by radiation
  - **Defects** (*defekt, kidevirhe*): atoms that deviate from the reqular equilibrium order in a crystal or amorphous material

- Not all radiation damage is in the kind of defects: for instance, irradiation can amorphize a material into a stable phase. In this case the material may not have any defects, but the amorphized region is still radiation damage
- **Defects produced by irradiation have sometimes beneficial properties.** In this case it is misleading to call it damage

Dose terminology

- **Exposure** (*exponering , altistus*) is the process when a material is exposed to some kind of radiation
- Measures for the amount of exposure
  - **Dose** (*dos, annos*): amount of energy deposited by radiation per mass or volume (units of Energy/mass or Energy/volume)
  - **Dose rate** (*dosrat, annosnopeus*): Dose/time (units of Energy/(mass x time) or Energy/(volume x time))
  - **Fluence**: amount of energetic particle deposited per area (units of particles/area i.e. 1/area)
    - Problematic to translate to Swedish/Finnish*, totalflöde* or *kokonaisvuo* could be used
  - **Flux** (*flöde, vuo*): Fluence/time (units of particles/(area x xtime) i.e. 1/(area x time)
- **Activity** (*(strålnings)aktivitet, (säteily)aktiivisuus*): amount of radiation produced by a radioactive sample

Dose units: some common ones

- Dose D:
  - SI unit **Gray** (J of radiation / kg of material)
  - Many historical units also exist…
  - Common units in physics research: **eV/atom, eV/Å^3**
  - Special unit: **displacements-per-atom (dpa)** widely used in nuclear engineering and ion beam physics. This will be returned to later on during the course
  - For damage in living tissue special unit that include an estimate of how sensitive human tissue is to difference kinds of radiation: **rem = radiation-equivalent-man**. Not part of this course.
- Dose rate:
  - **Gray/s**
- Fluence:
  - **particles/cm^2, particles/m^2 = 1/cm^2, 1/m^2**
- Flux:
  - **particles/(cm^2 s), particles/(m^2 s) = 1/(cm^2 s), 1/(m^2 s)**

Radiation protection units

- Equivalent dose H (*ekvivalent dos, ekvivalenttiannos*) (used only for living humans): Dose multiplied with a quality factor depending on kind of irradiation Q: $H = QD$
  - Unit: Sievert (Sv)
  - Q = 1 for 200 keV photons (per definition)
  - Q = 2 for protons > 2 MeV
  - Q = 20 for few MeV alphas
  - Function of linear energy transfer (LET) i.e. radiation energy loss per length travelled, a.k.a. stopping power, e.g. keV/µm or eV/Å
- Older unit: rem (radiation equivalent man); 1 Sv = 100 rem
- Nice list of different doses and their effects: http://en.wikipedia.org/wiki/Sievert
  - Annual average natural dose in Finland: 3.7 mSv
  - About 5 Sv lethal dose

What should you have learned from this section?

- You understand the difference between ionizing and non-ionizing radiation
- You know the basic terminology in the field: what kind of particles can have a high energy, meaning of α, β, γ, δ radiation
- You know that legal laws and physical laws do not always exactly match ☺
- You have a basic idea of how energetic particles are produced in nature and by humans
- You know the basic exposure nomenclature and units for radiation damage