Neutron-nuclear Interactions

Was 2nd Edition, Section 1

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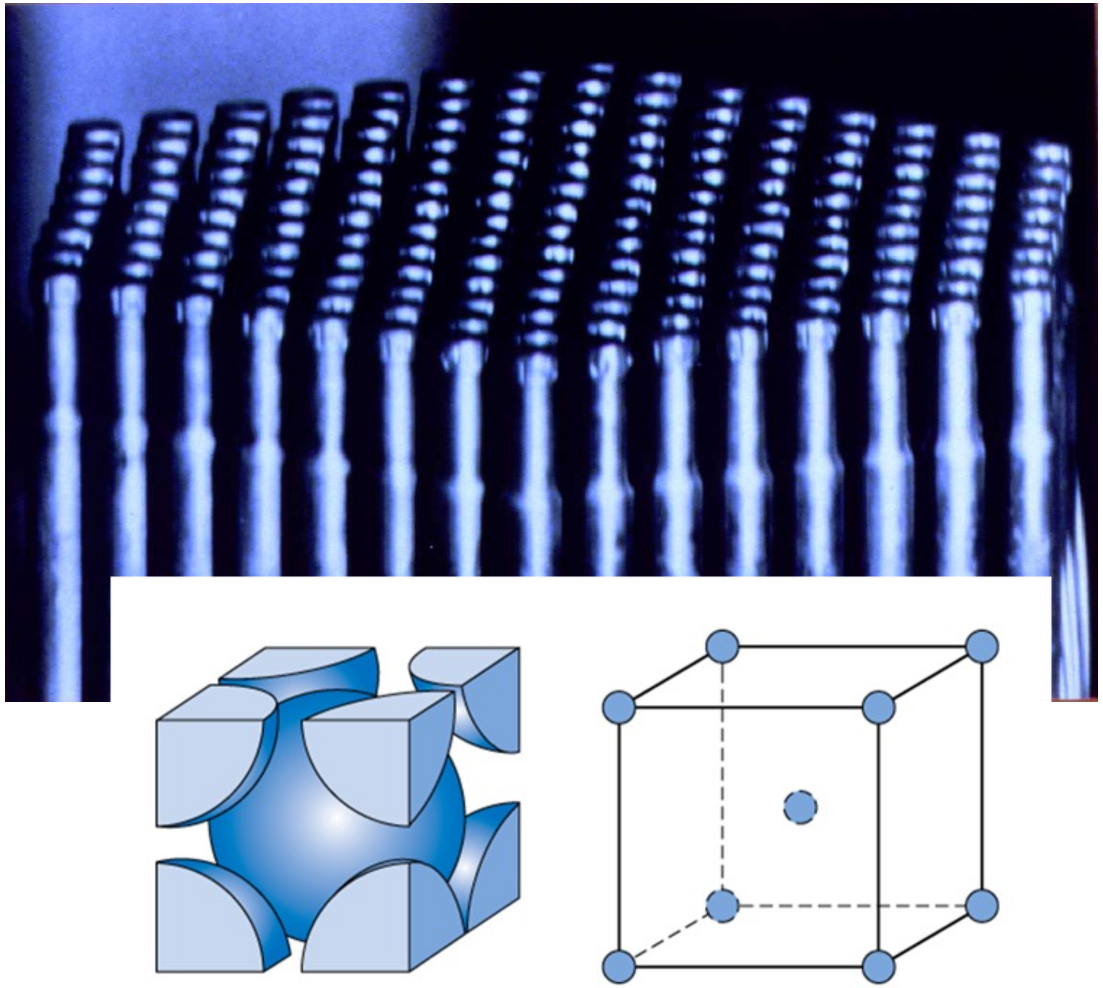
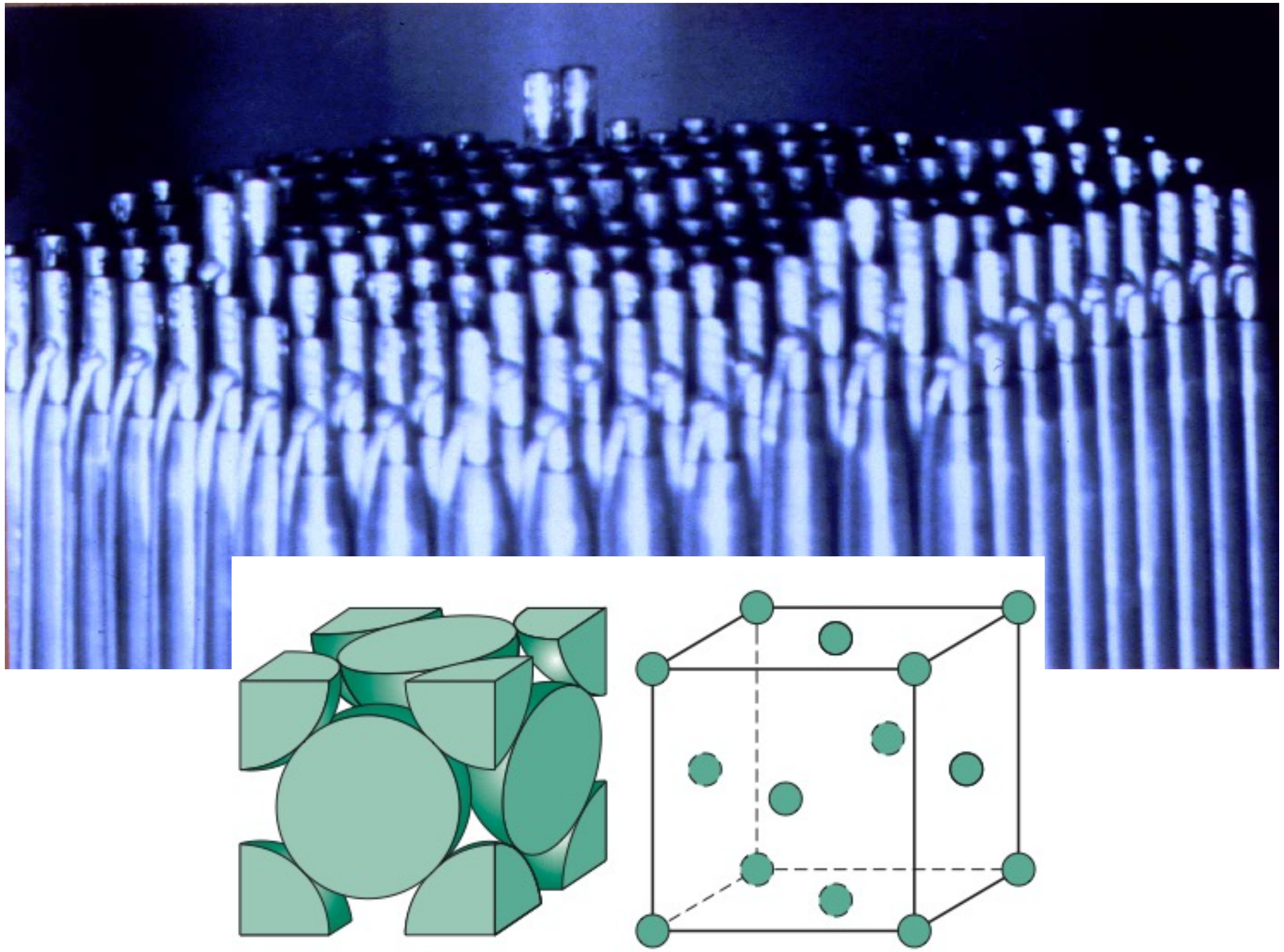
Our last lecture we talked about this:

HT-9, no swelling



Body centered cubic (BCC)

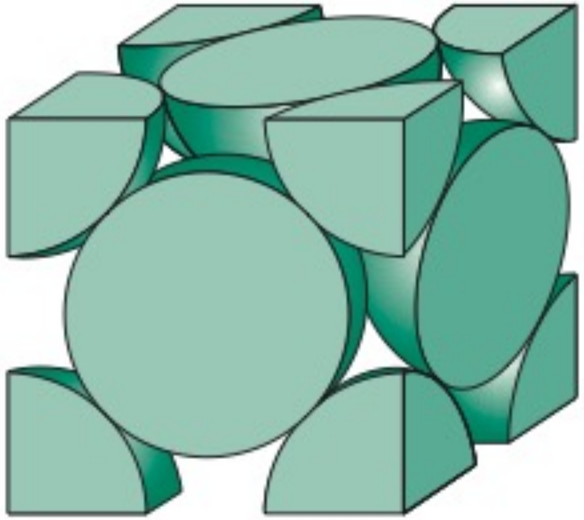
316-Ti stainless, swelling

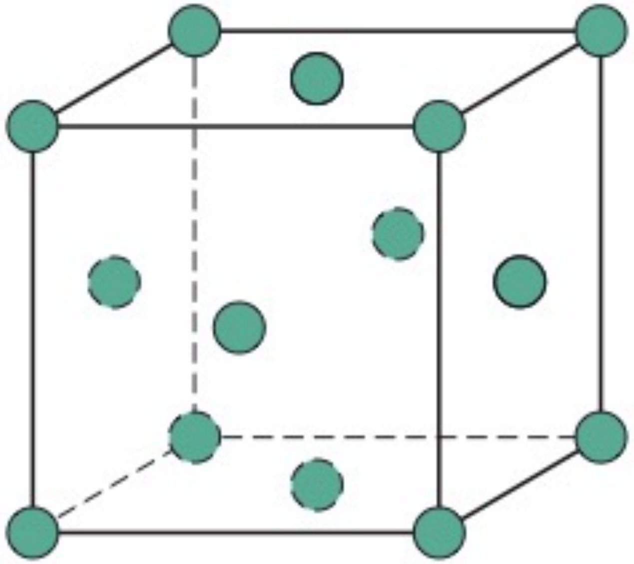


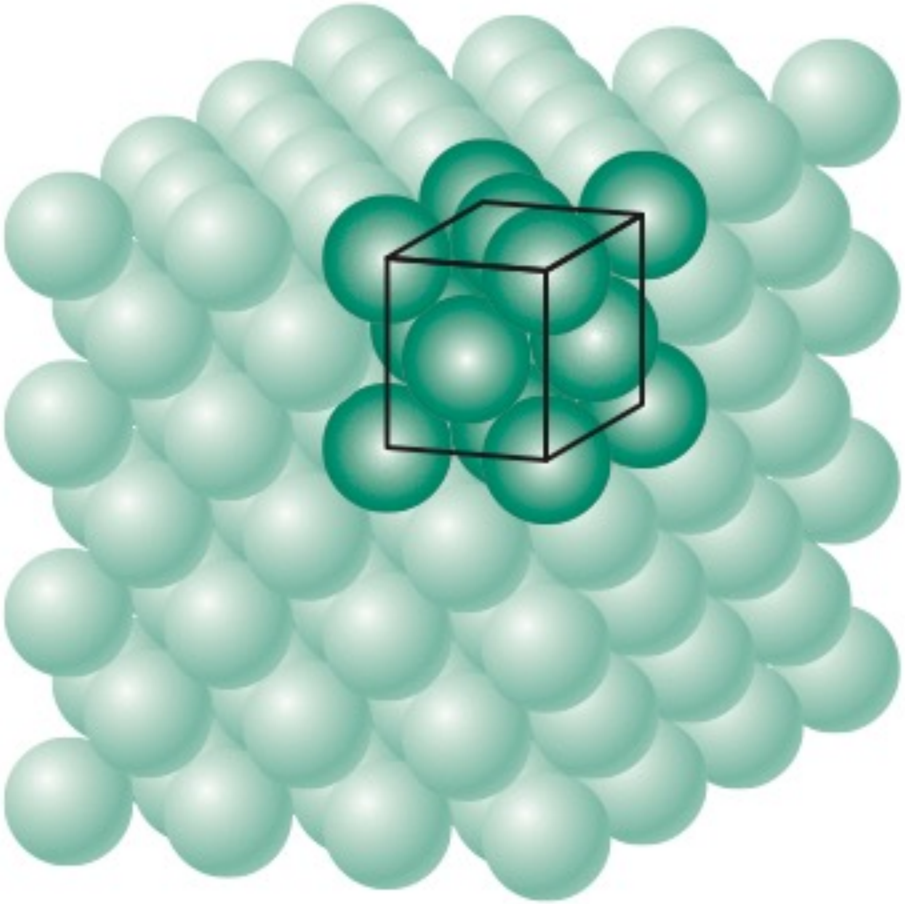
Face centered cubic (BCC)

Source: F. Garner & Callister

Units cells are the building blocks of a material



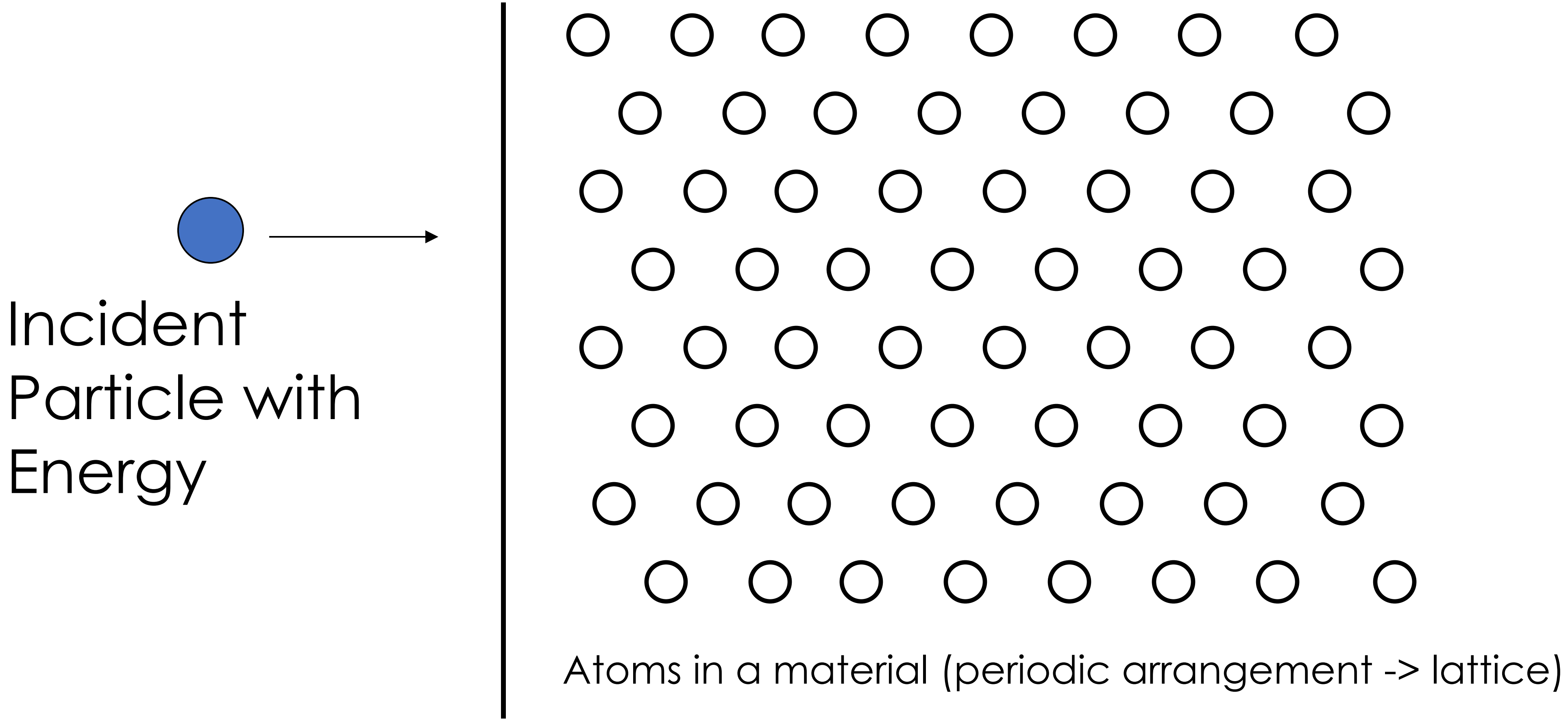




Atoms in a material (periodic arrangement -> lattice)

Radiation Damage: the basics

- All of radiation damage boils down to a common step: **collisions between energetic particles and atoms composing a material**



Source: T.R. Allen

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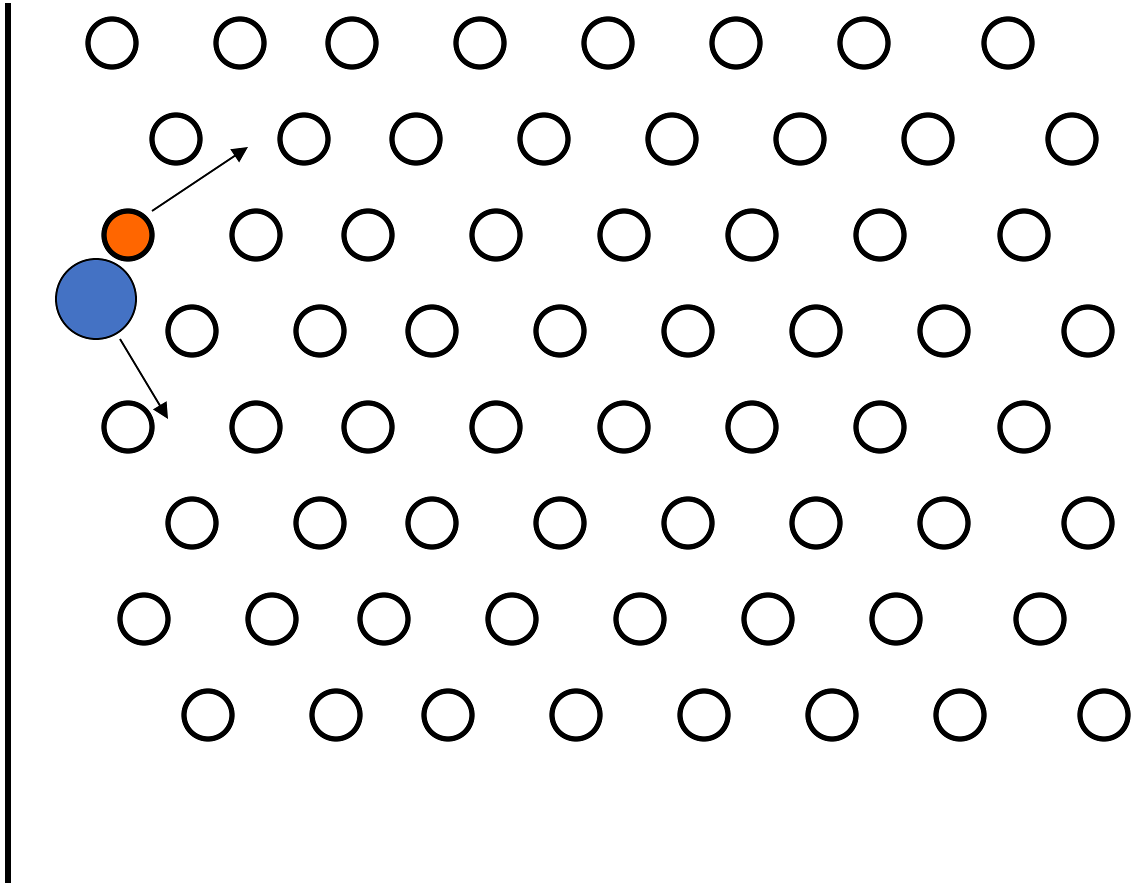

Source: *T.R. Allen*

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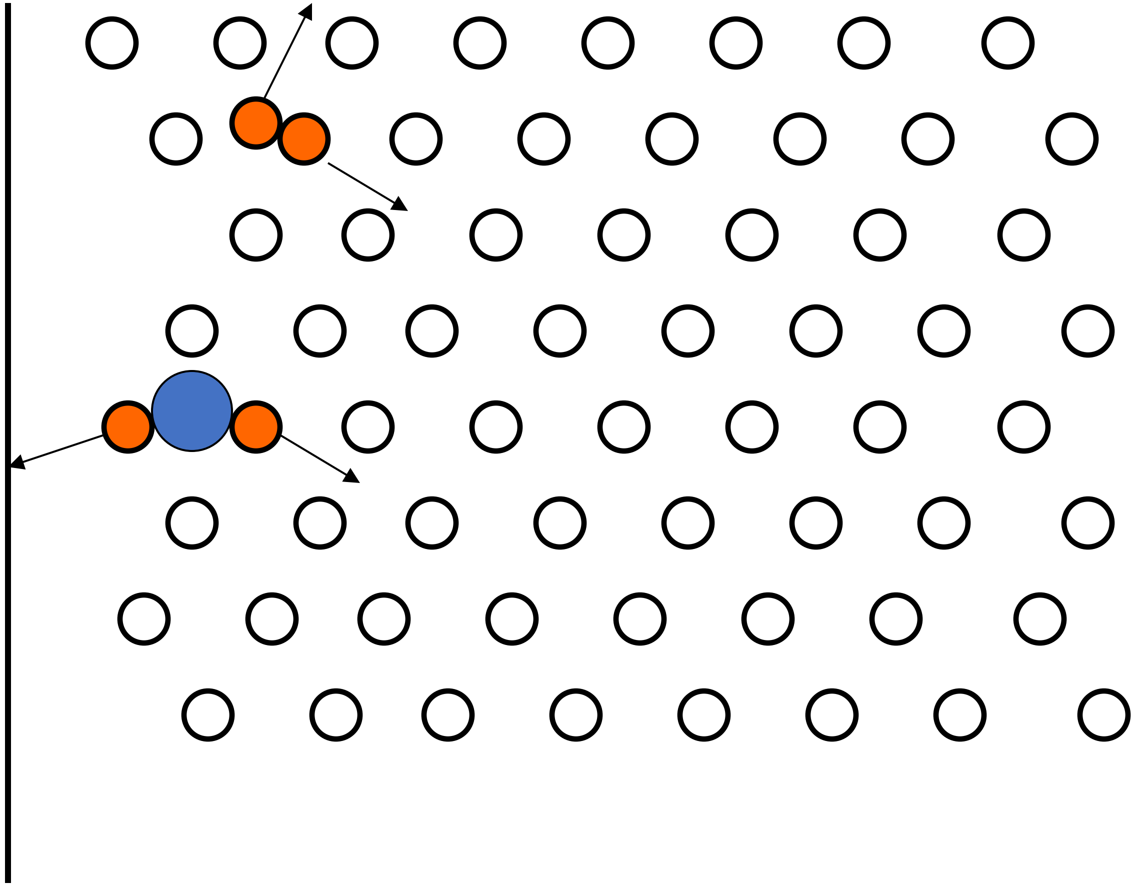

Source: T.R. Allen

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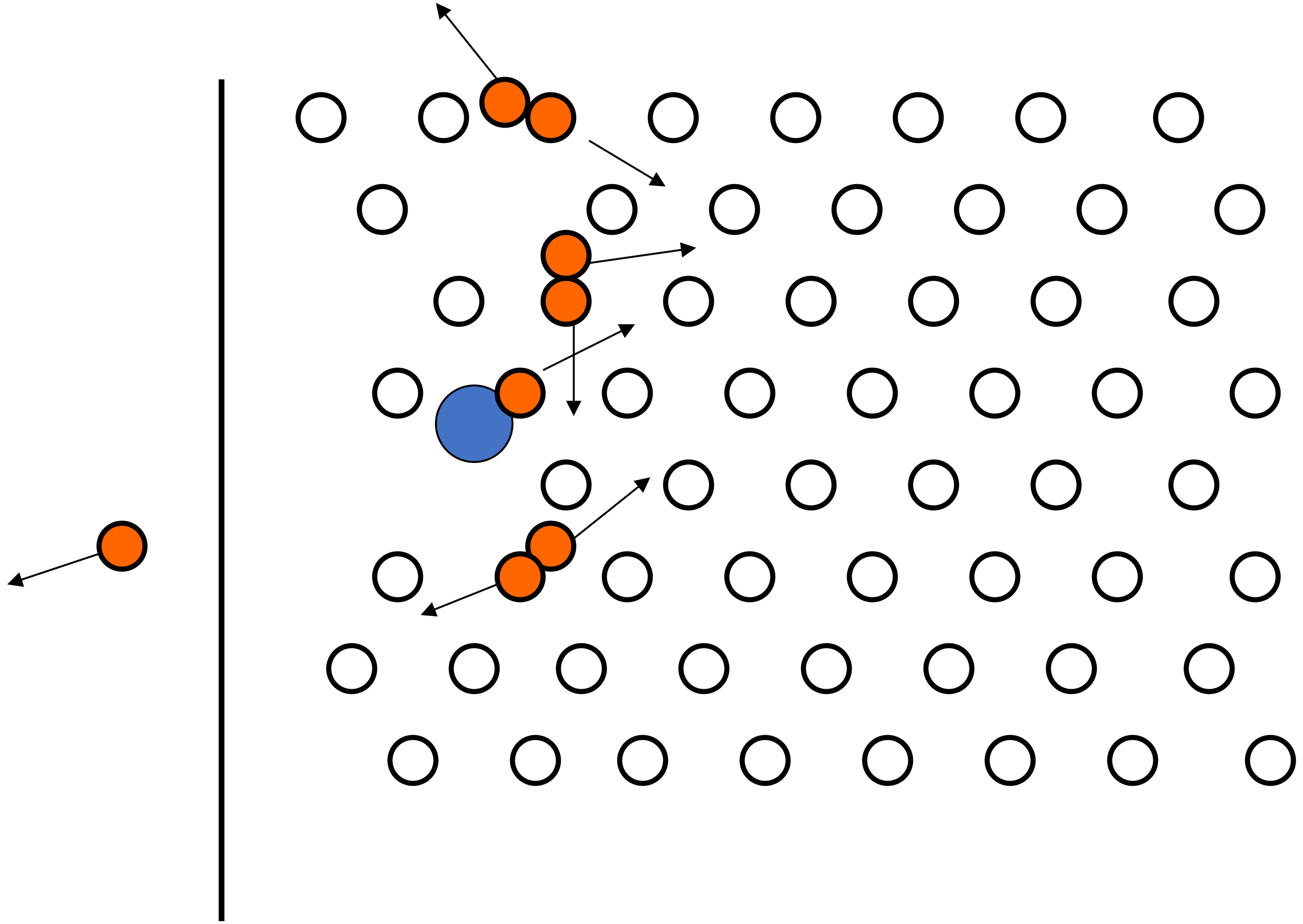

Source: *T.R. Allen*

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Radiation Damage: the basics

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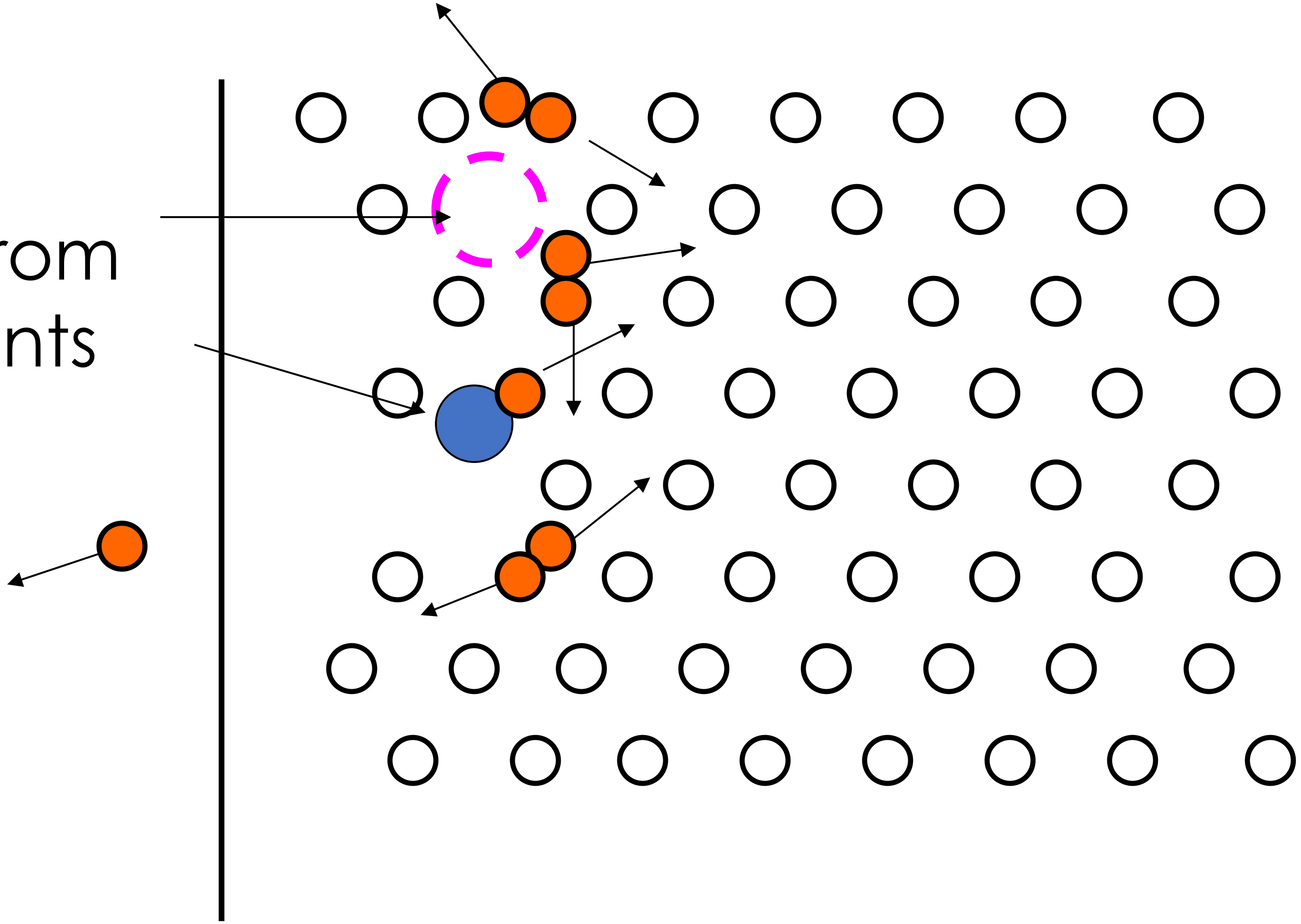
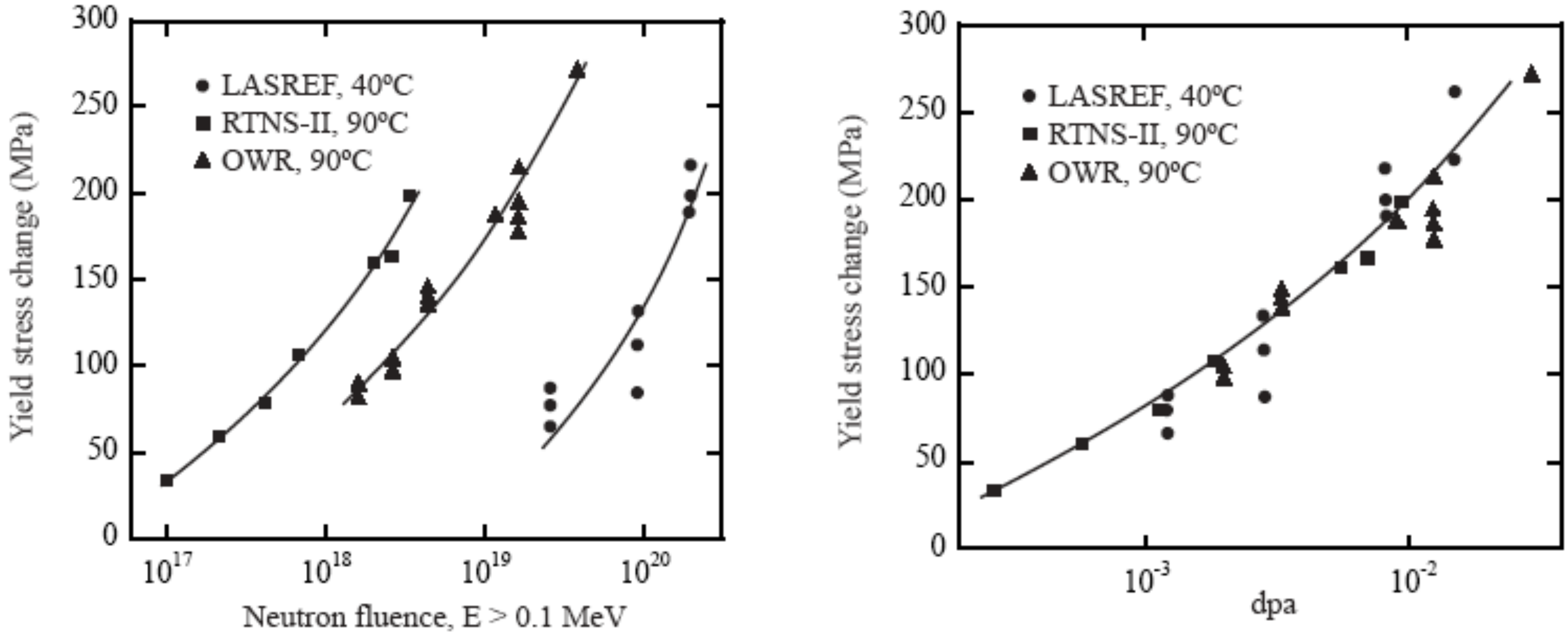
Defects produced from displacements



Source: T.R. Allen

Importance of displacement versus fluence for this class

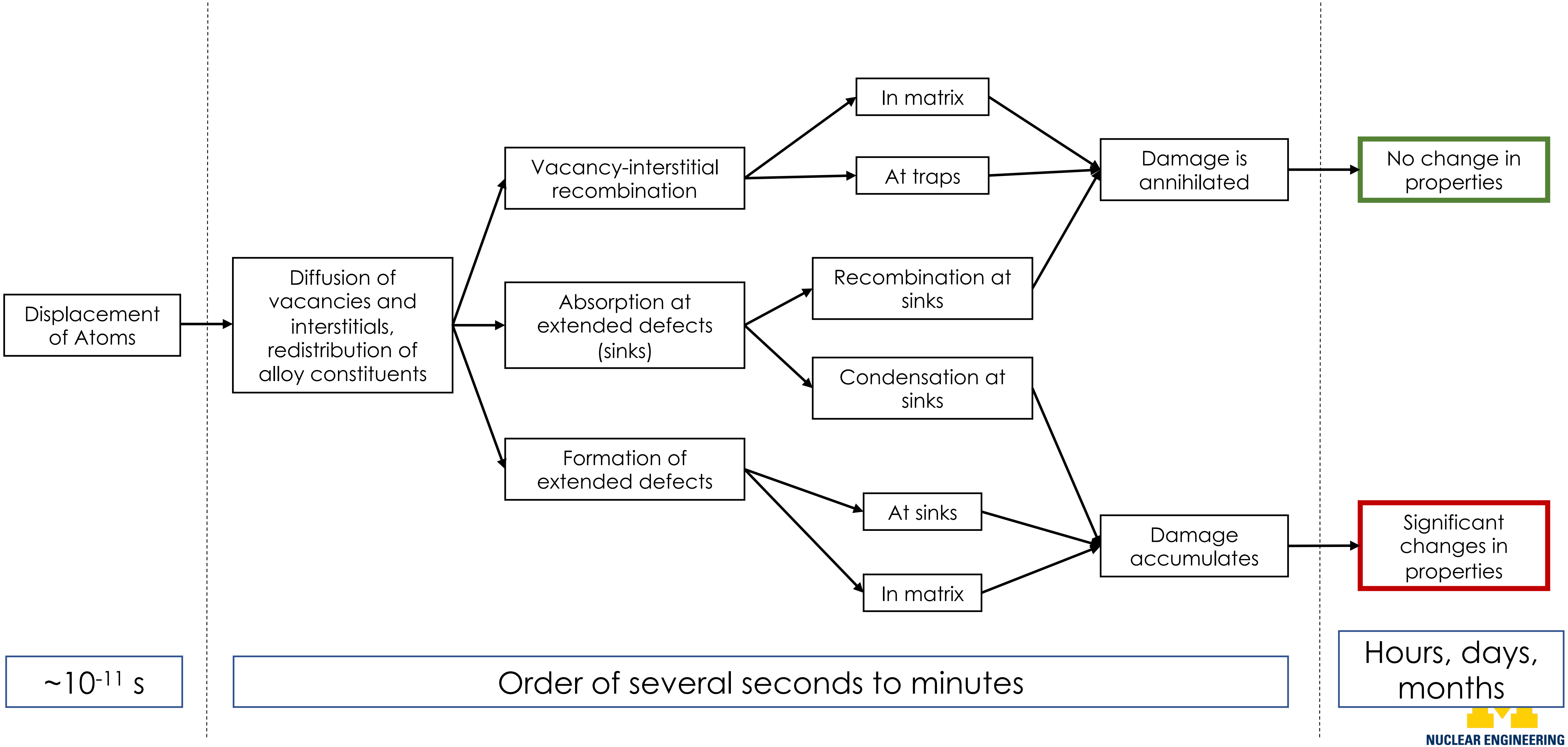


Comparison of yield stress change in 316 stainless steel irradiated in different reactors

Flow chart for radiation damage

Louis Mansur, “Mechanisms & Kinetics of Radiation Effects in Metals and Alloys”, in: Kinetics of Nonhomogeneous Processes, 1987

Flow chart for radiation damage



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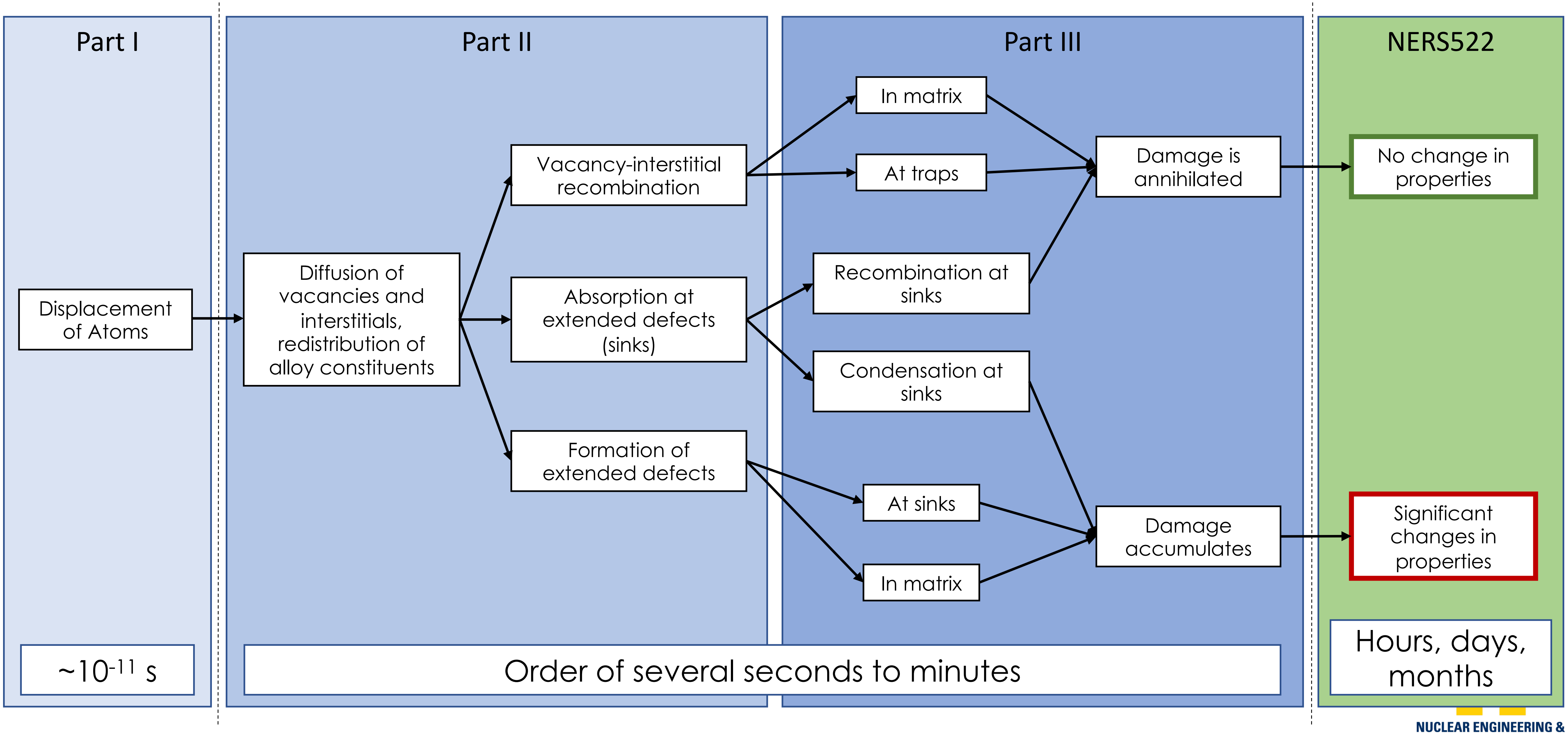

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Displacement of Atoms in Detail

Part I

Displacement of Atoms

(Radiation Damage Event)

~10^{-11} s

Displacement of atoms is primarily evaluated as the **radiation damage event** which is composed of the following sequence of events:

1. The *interaction* of an energetic particle with a lattice atom
2. The *transfer of kinetic energy* to the lattice atom resulting in the primary knock-on atom (PKA)
3. The *displacement* of the lattice atom from it's lattice site
4. The *passage* of the displaced atom through the structure and the potential accompanying creation of additional knock-on atoms
5. The *production of a displacement cascade*
6. The *termination of the PKA* as an interstitial in the structure

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Displacement of Atoms in Detail

Part I

Displacement of Atoms

(Radiation Damage Event)

~10^{-11} s

Next two lectures

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Outline

- There are four major interacting particles of interest:
  1.
  2.
  3.
  4.
- From these, there are different types of collisions to consider:
  1.
  2.
  3.
  4.

Goal: understand the energy transferred to lattice atoms from these interacting particles and the various collision types

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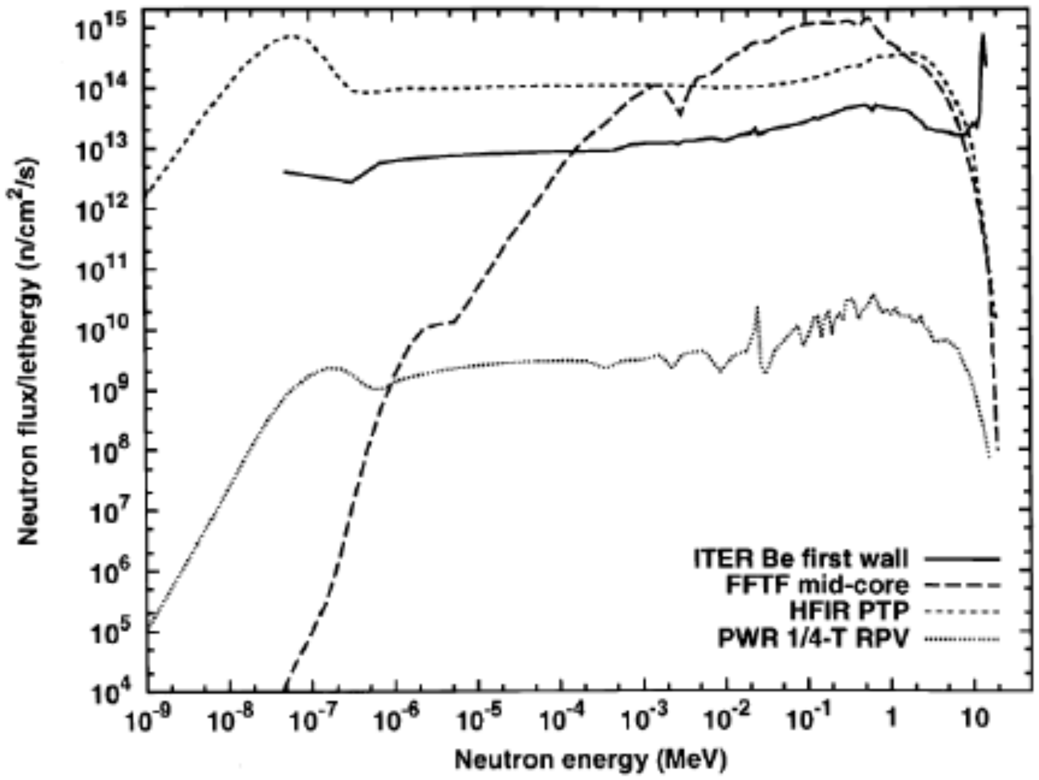
Let's first start with neutrons

- Produced from fission and fusion
- Mass similar to proton
- No charge – all damage is due to ballistic (hard-sphere) collisions



Energy dependence of neutron flux in various irradiation environments: ITER (DT fusion), HFIR (light water moderated fission), FFTF (sodium moderated fission), and a commercial PWR (light water moderated fission) Source: R.E. Stollerand L.R. Greenwood, J. Nucl. Mater. 271-272 (1999)

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Billiard Ball Relaxation Video

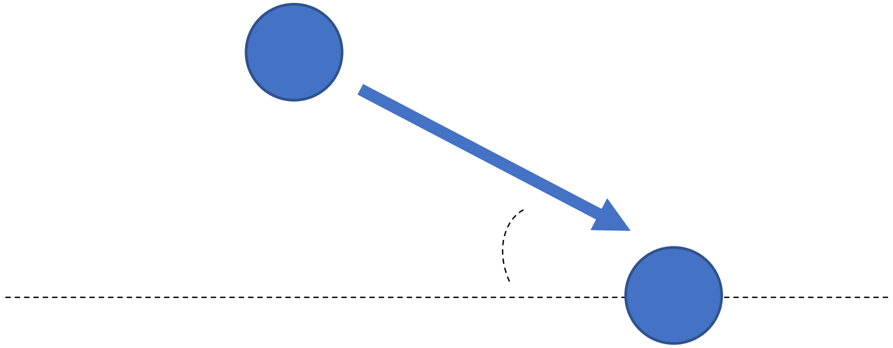
https://www.youtube.com/watch?v=pZqkaJDaz2A

How do we determine energy transfer?

- Situation: Incident neutron – target atom interaction

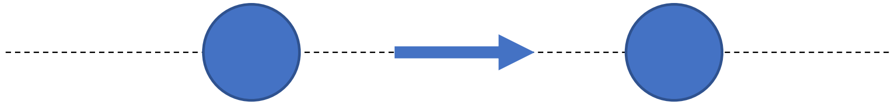
Case 1:

Case 2:



Case 3:

Case 4:



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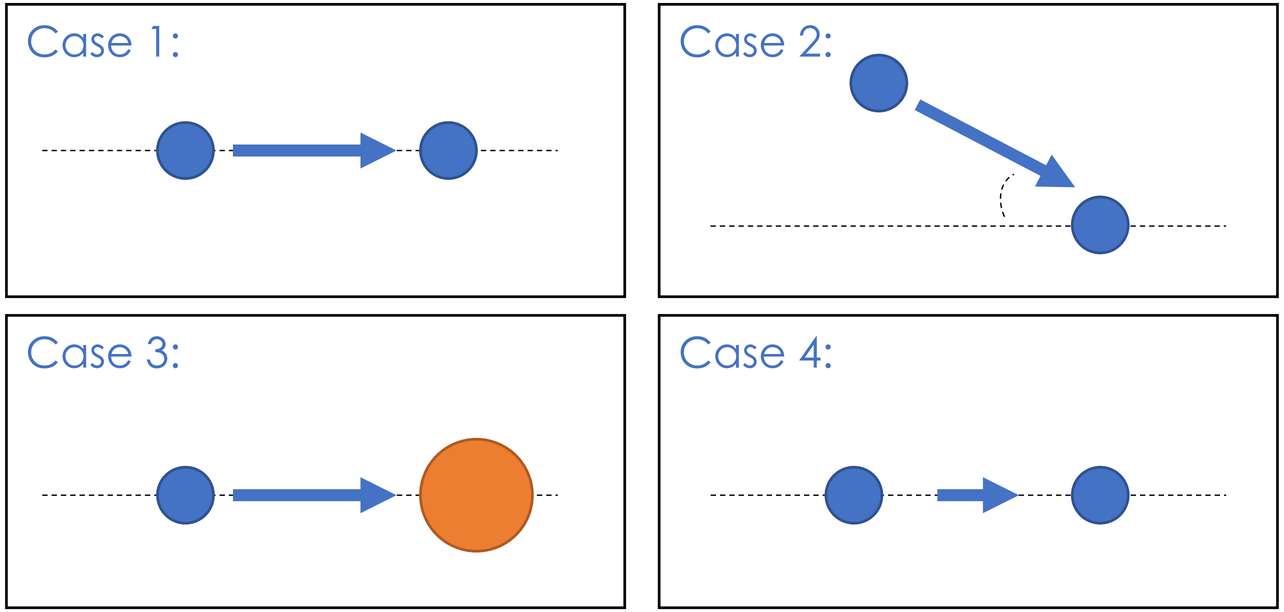

$$T = f(E_i, m_1, m_2, \theta)$$

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Lecture Break: The longest F1 track in the 2022 calendar is Circuit de Spa-Francorchamps which hosted it's first Grand Prix in 1925. To the nearest ten of a kilometer, what is the length of Spa?

A two-body collision in laboratory (L) coordinates

- The momentum of the recoiling (displaced) atom is the parameter that determines the damage and thus our first goal of this class is to calculate it.
  - Thus, we first make several simplifying **<u>assumptions</u>**:
    - We'll only consider the asymptotic values of momentum at distances far from the collision
      - Does not violate quantum laws
    - Assume the collision is elastic
    - Velocities are small enough for non-relativistic mechanics to apply

Principles of Conservation of Momentum and Energy are all that are required to calculate!

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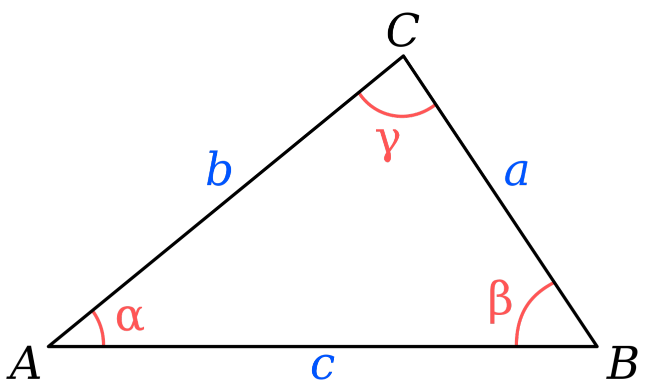
Important equations to remember:

- Momentum: $\rho = mv$
- Energy: $E = \frac{1}{2}mv^2$
- Cosine Law:



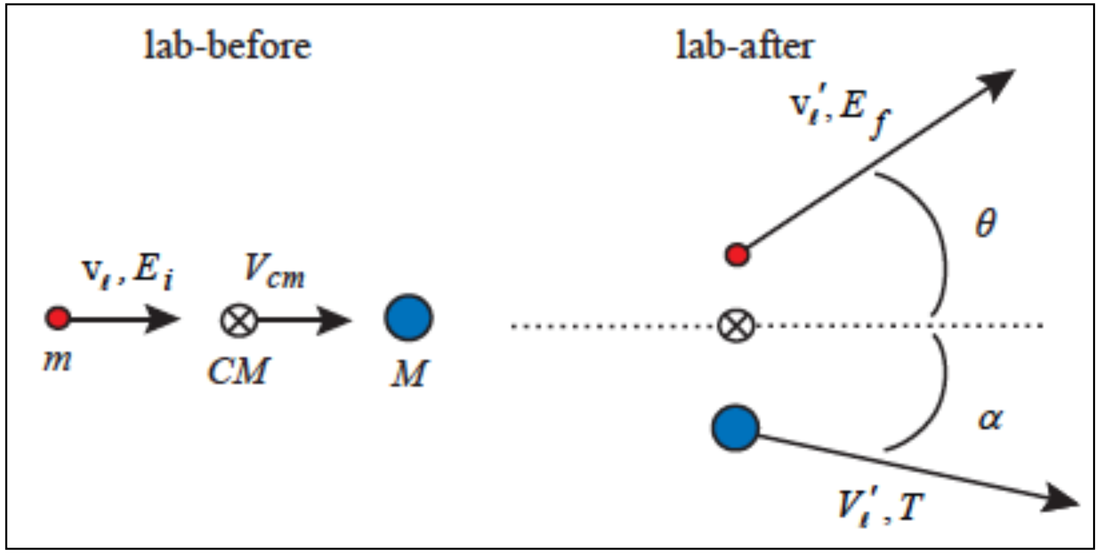
$$c^2 = a^2 + b^2 - 2ab\cos\gamma$$

- Cosine-sine half angle identity:

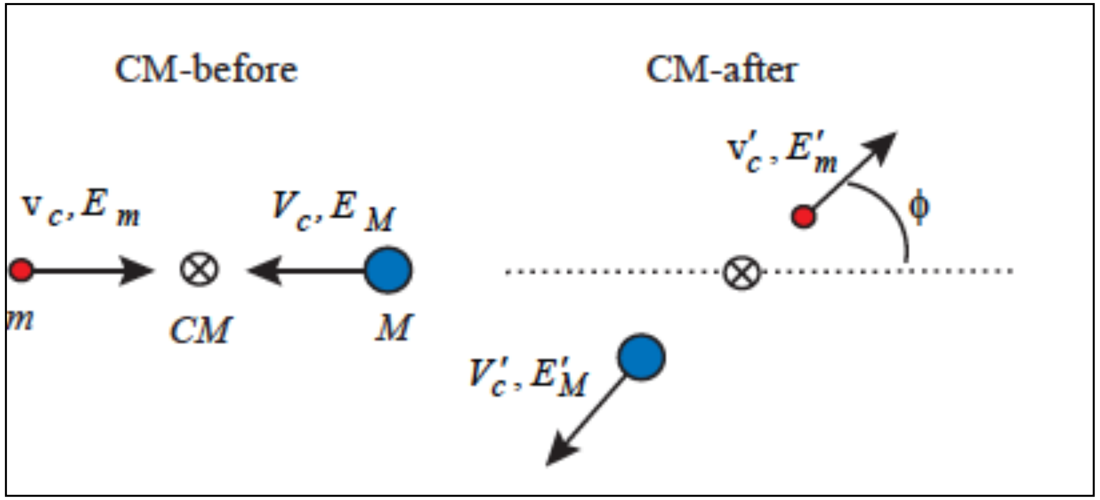
$$\sin\frac{\gamma}{2} = \sqrt{\frac{1-\cos\gamma}{2}}$$

A visual of a simple two body collision:

Lab coordinates (ℓ):



Center of Mass Coordinates (c):



m/M: mass
v/V: velocity
E: energy
θ: scattering angle
α: recoil angle in Lab coord.
ϕ: scattering angle in COM coord.

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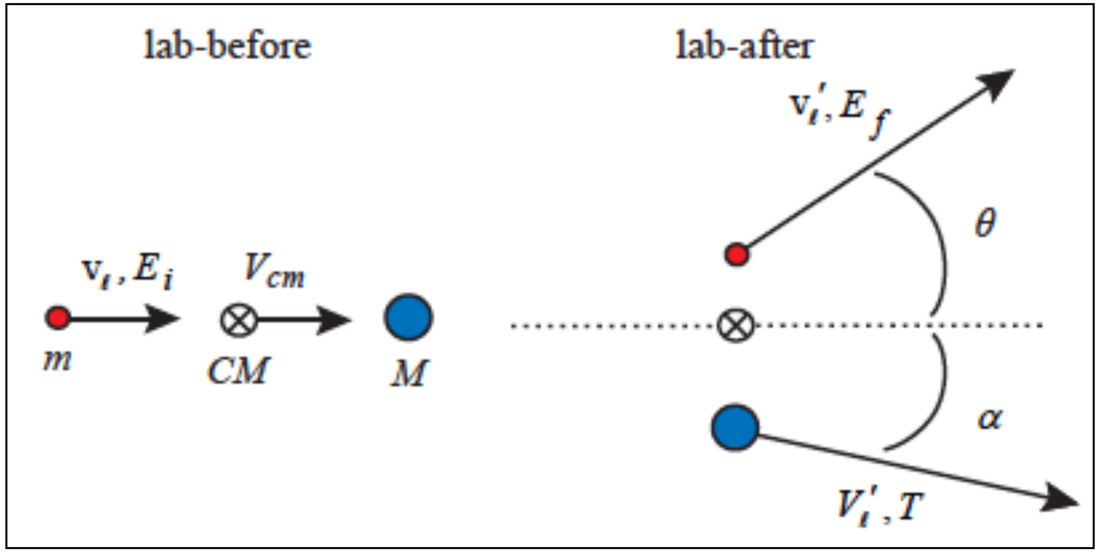
A visual of a simple two body collision:

Lab coordinates:



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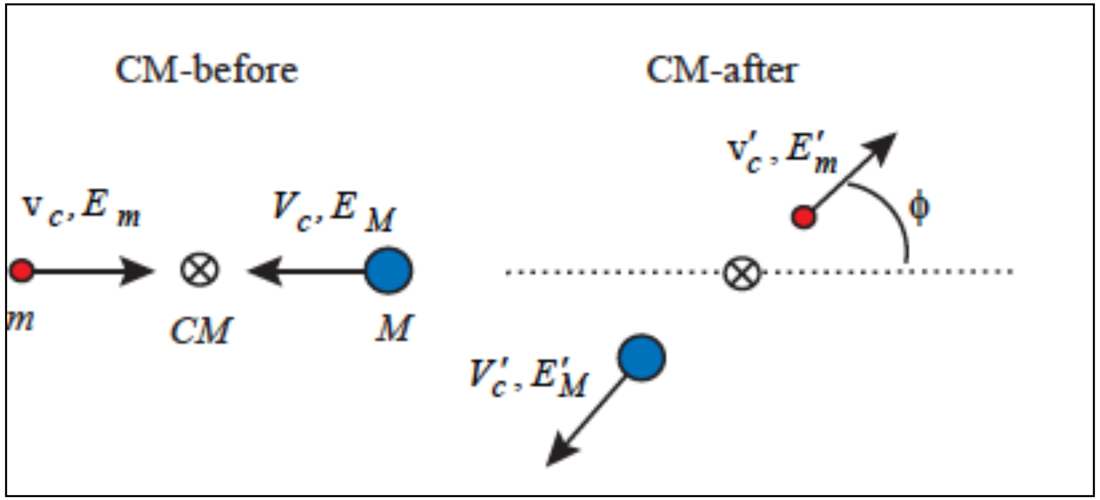
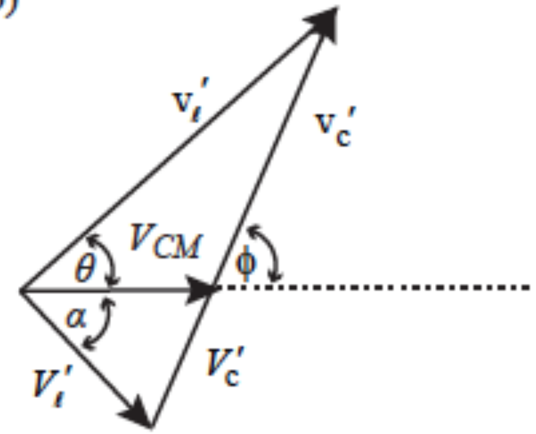


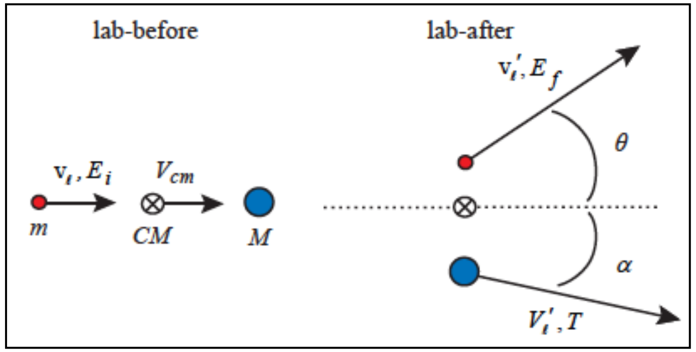
(b)



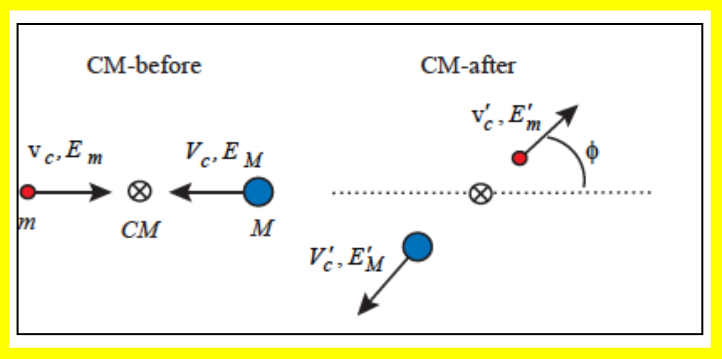
m/M: mass
v/V: velocity
E: energy
θ: scattering angle
α: recoil angle in L coord.
ϕ: scattering angle in G coord.

We need to determine T as a function of initial energy and scattering angle:

Lab coordinates:



Center of Mass Coordinates



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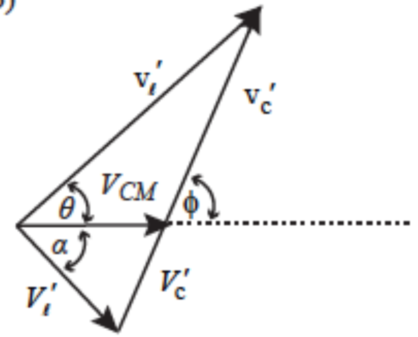
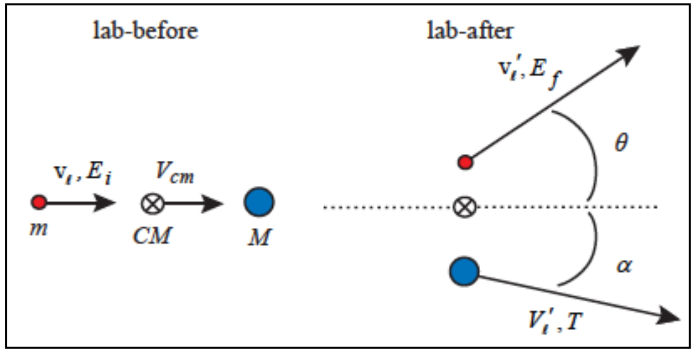


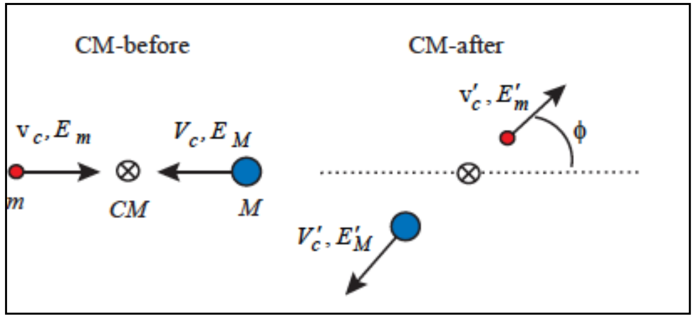
If we assume the CM is stationary in COM coordinates, and v_c' and V_c' are in opposite directions but the same plane, we can use our conversation equations to yield:

We need to determine T as a function of initial energy and scattering angle:

Lab coordinates:



Center of Mass Coordinates



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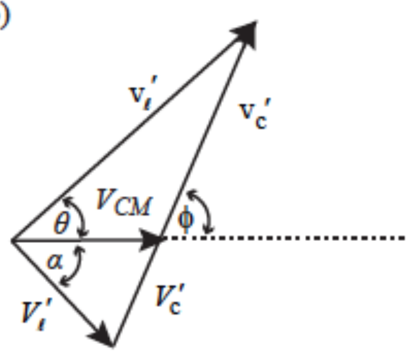


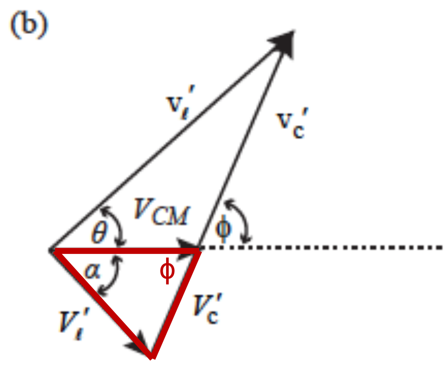
$$\therefore \; V_c = V_c' \qquad v_c = v_c'$$

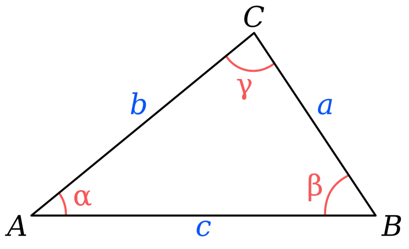
We now need to know how to get V_{CM} in the lab system:

In the lab system, the recoil atom is at rest before collision and moving to the left in COM, then V_{CM} must be moving to the right with the same speed as V_c, then:

And using COM:

We need to determine T as a function of initial energy and scattering angle:





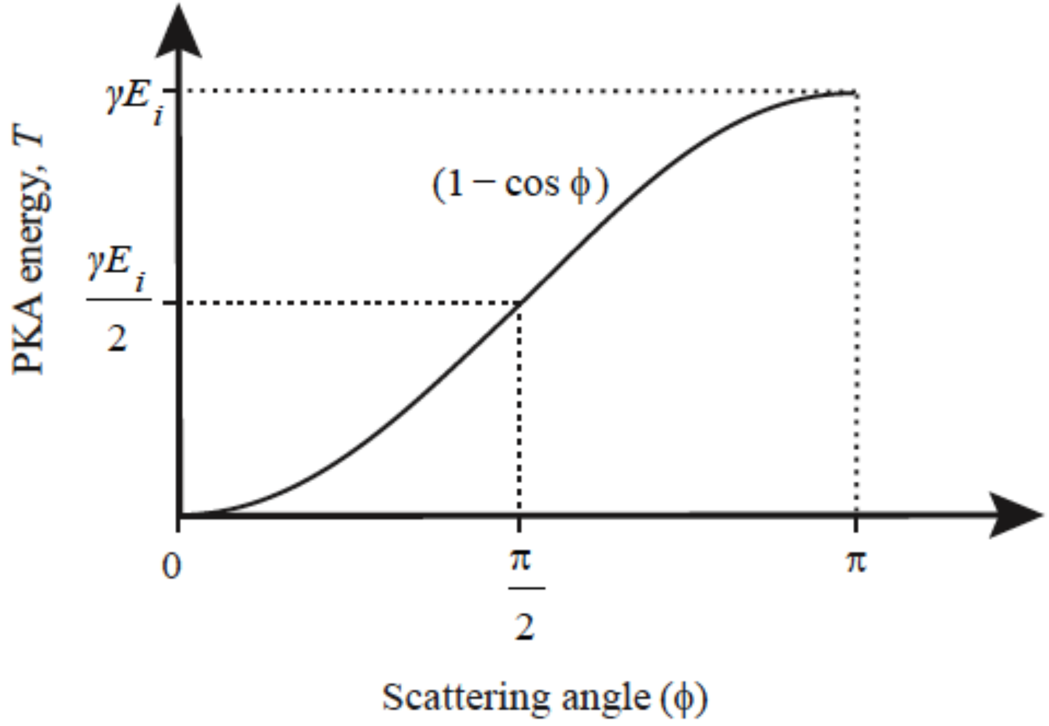
$$c^2 = a^2 + b^2 - 2ab\cos\gamma$$

We need to determine T as a function of initial energy and scattering angle:

$$V_i'^2 = V_{CM}^2 + V_c'^2 - 2V_{CM}V_c' \cos\phi$$

$$\boxed{V_{cm} = V_c'} \longrightarrow V_i'^2 = 2V_{CM}^2 \cos\phi$$

$$V_i'^2 = \frac{2T}{M} \qquad V_{CM}^2 = \frac{2}{m}E_i\left(\frac{m}{M+m}\right)^2$$



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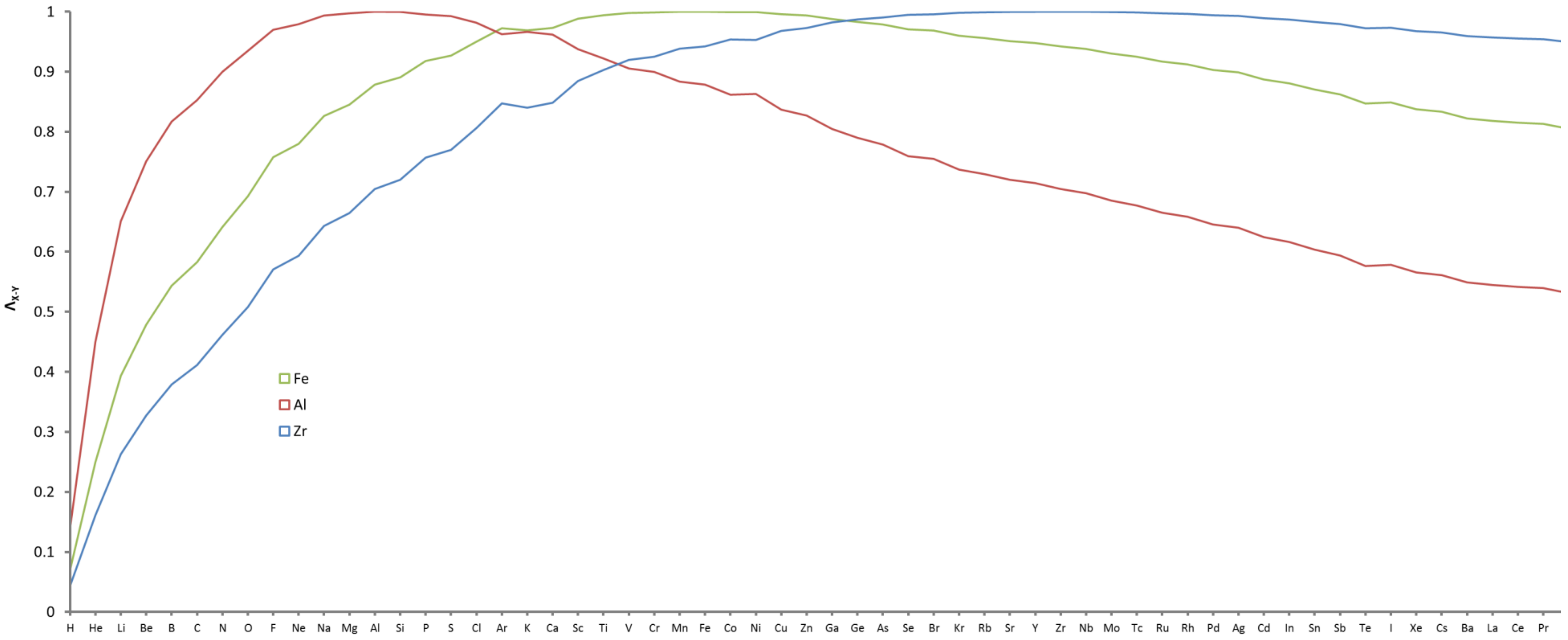
Example problem:

- Calculate the maximum possible energy transferred to an Fe atom from a 1 MeV neutron assuming binary, elastic collisions

Some more discussion:



- Collisions between similar size masses lead to the greatest PKA energy
- All the energy is transferred if the collision is head-on and m=M

Summary

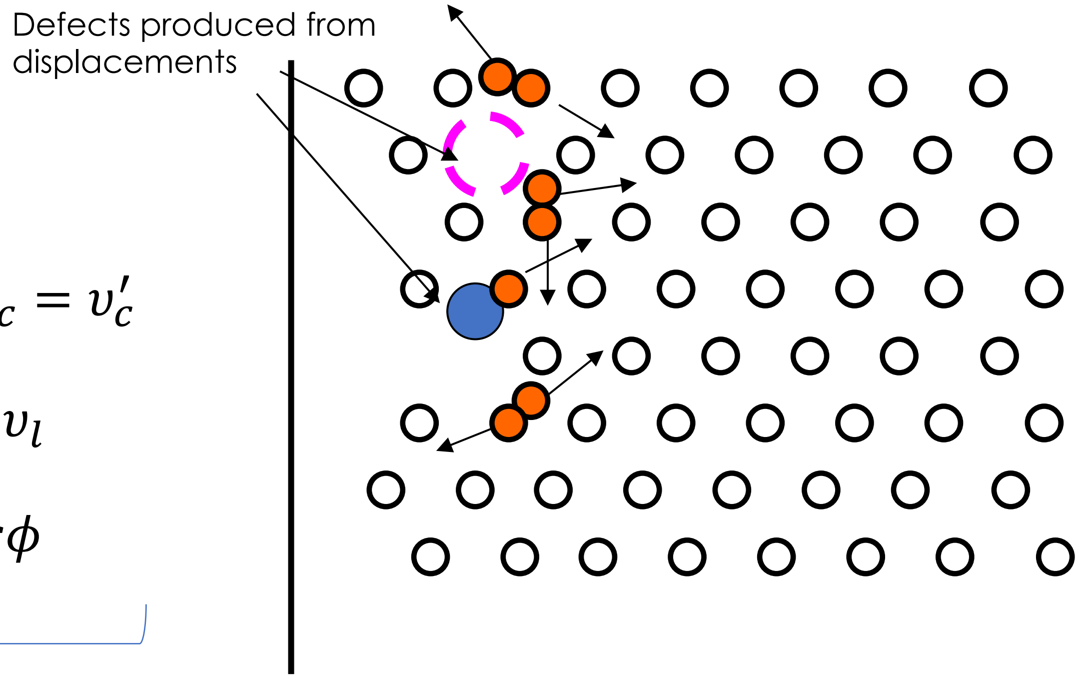
- Using:

1. Momentum conservation
2. Kinetic energy conservation
3. Velocities in LAB and COM:
4. Cosines law:

$$V_c = V_c' \quad \& \quad v_c = v_c'$$

$$V_{CM} = \left(\frac{m}{M+m}\right) v_l$$

$$V_l'^2 = V_{CM}^2 + V_c'^2 - 2V_{CM}V_c' cos\phi$$



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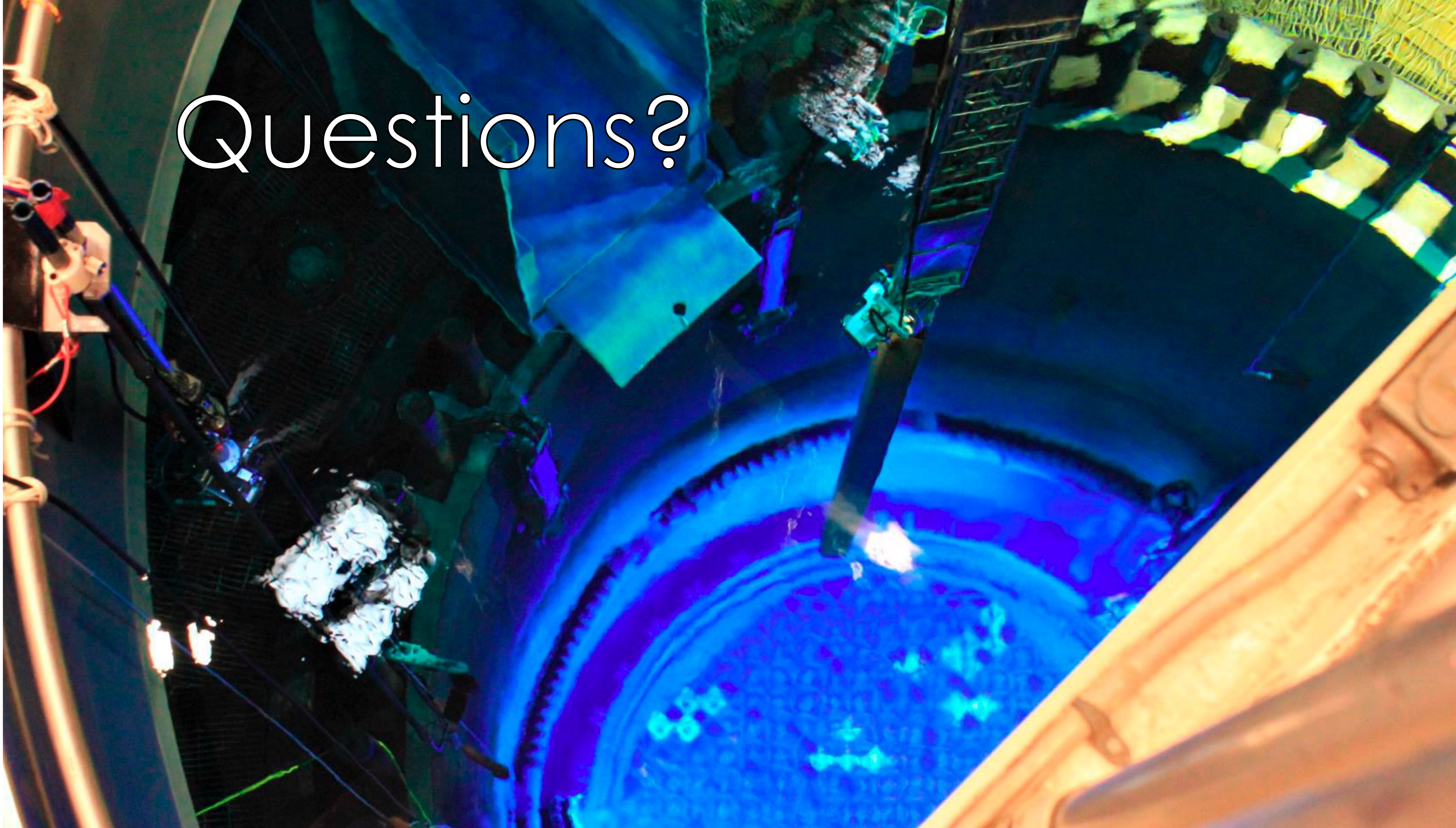
Questions?



Example problem:

- Assuming it takes 40 eV to displace an Fe atom from it’s lattice site, what is the minimum electron energy necessary to displace the iron atom?

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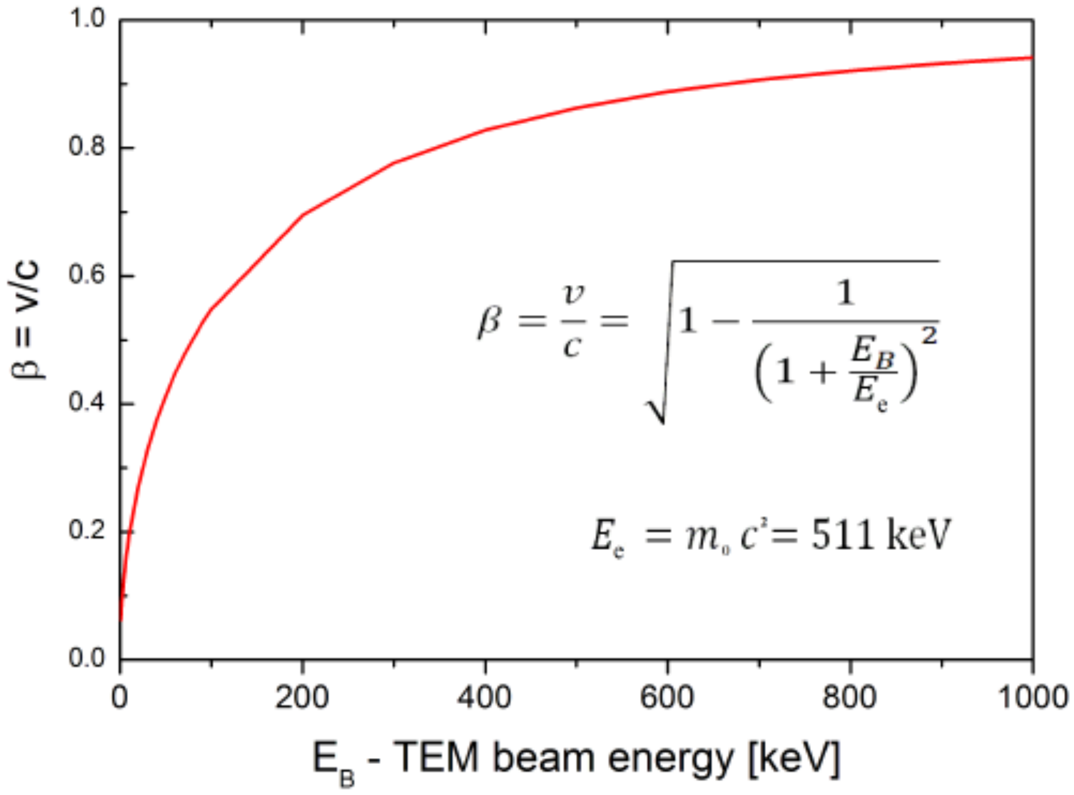

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