Neutron-nuclear Interactions

Was 2nd Edition, Section 1

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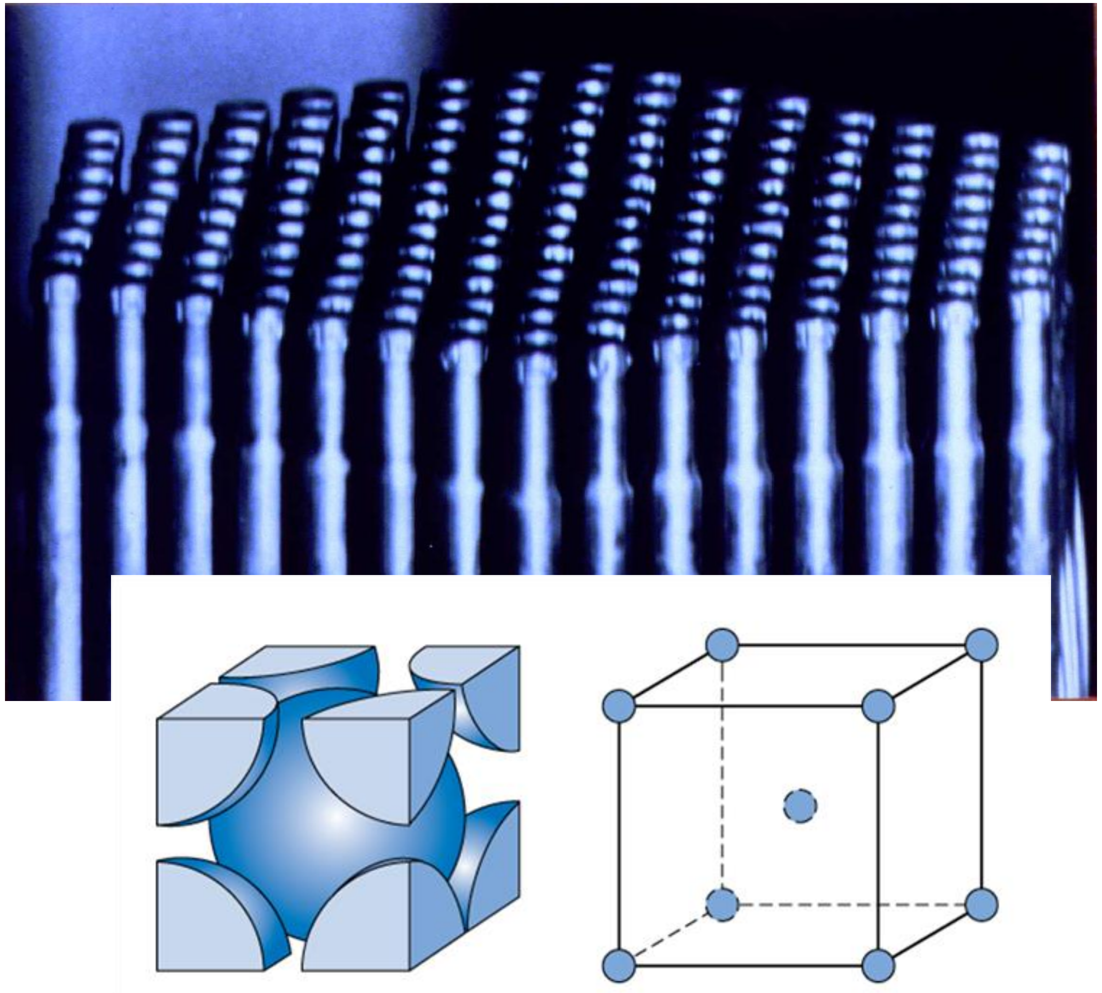
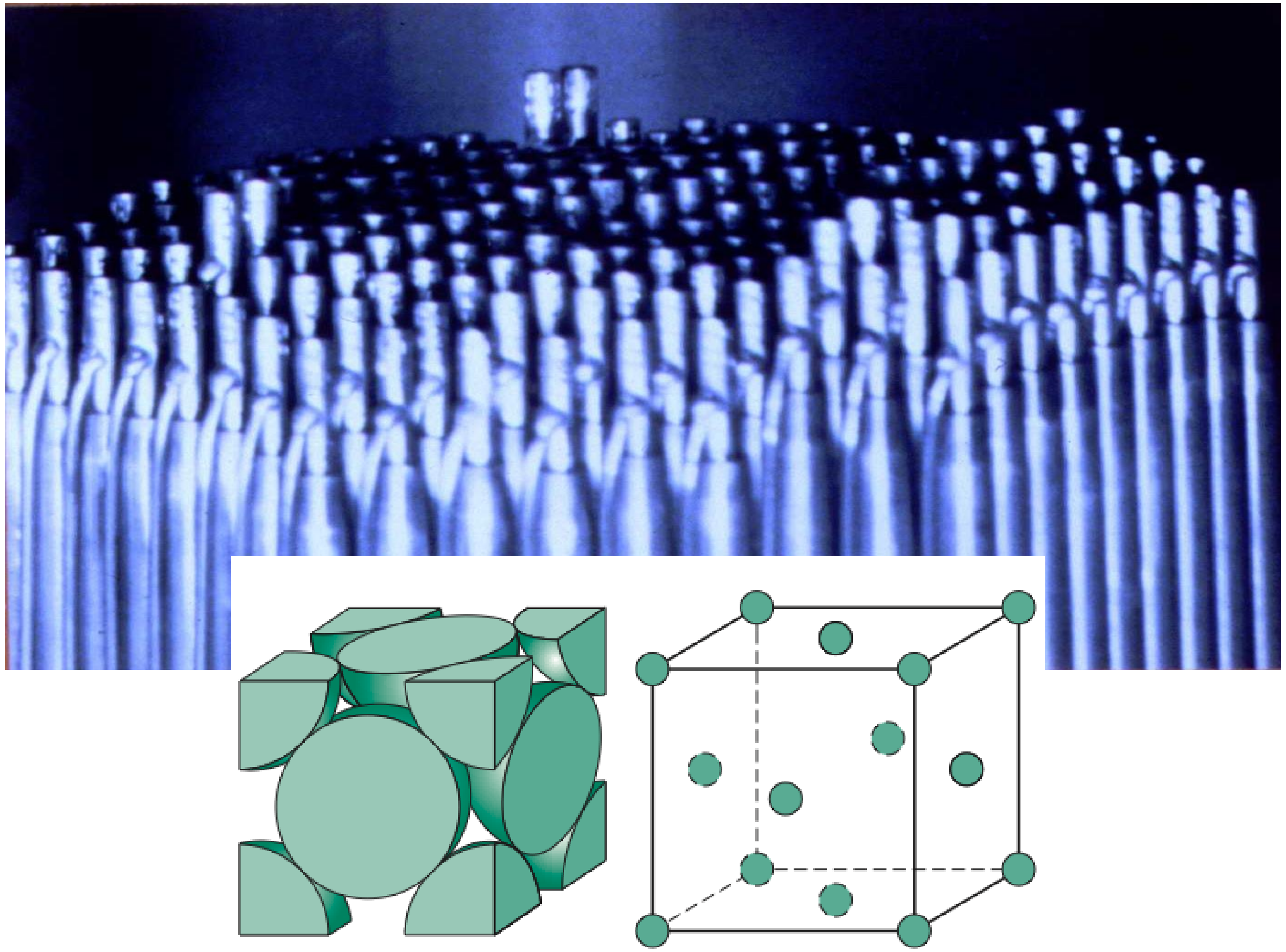
Our last lecture we talked about this:

HT-9, no swelling



Body centered cubic (BCC)

316-Ti stainless, swelling



Face centered cubic (BCC)

Source: F. Garner & Callister

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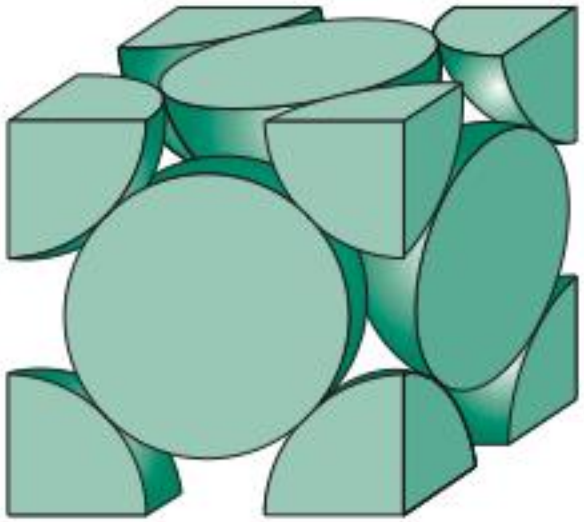
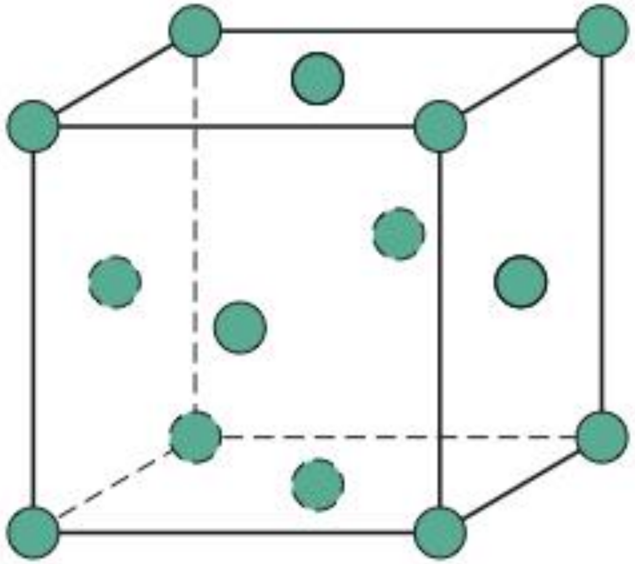
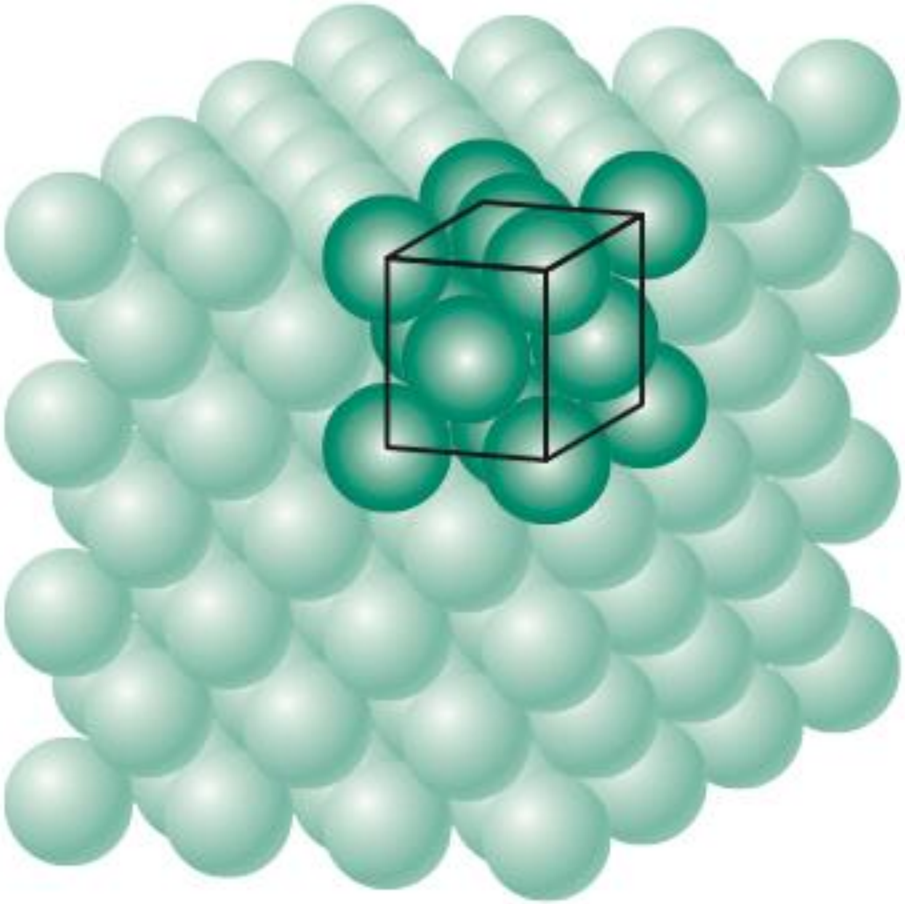
Units cells are the building blocks of a material



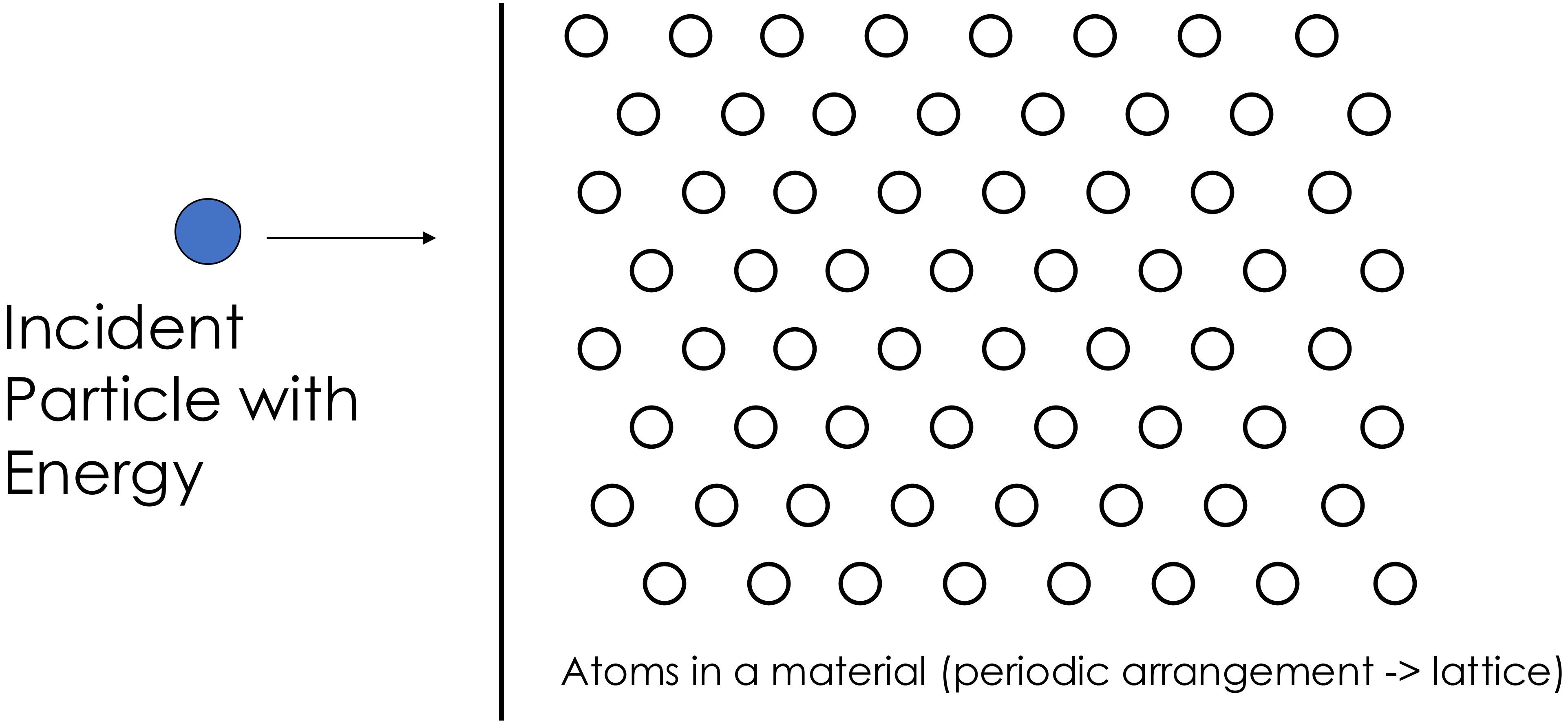




Atoms in a material (periodic arrangement -> lattice)

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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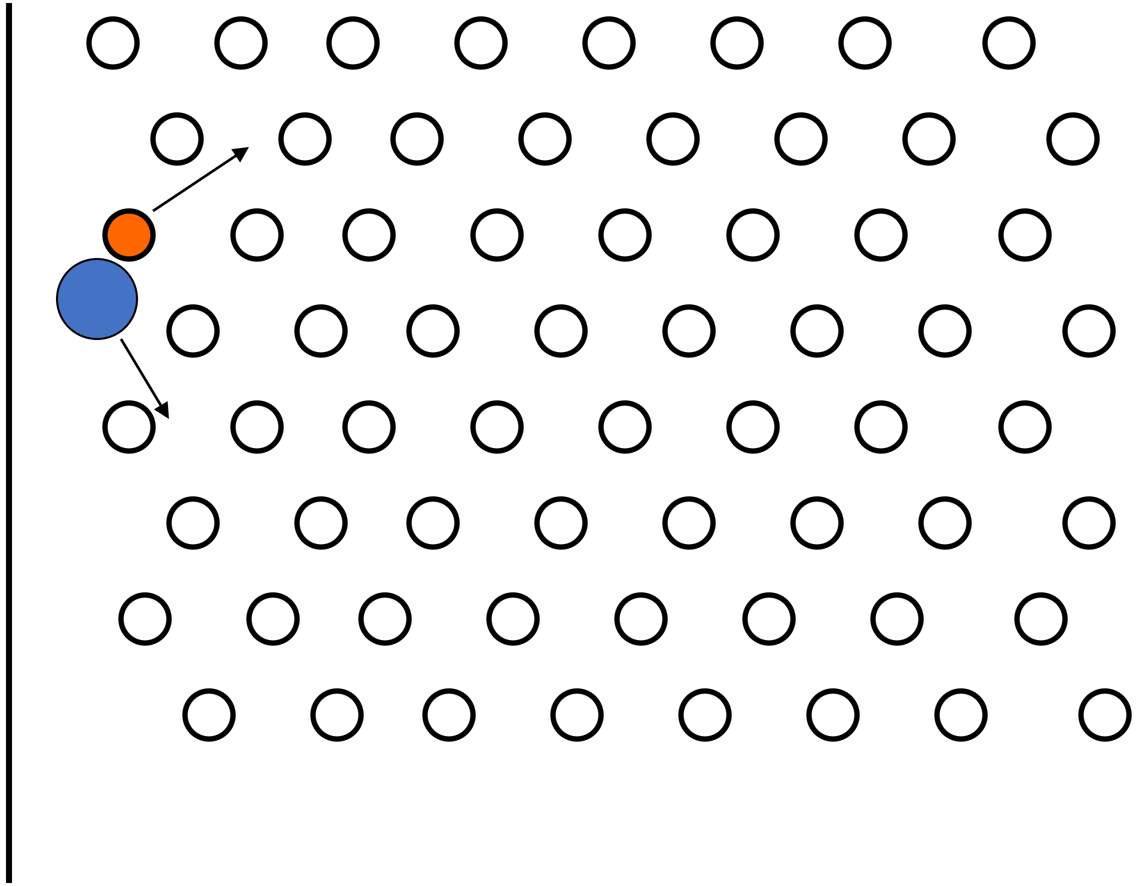

Source: *T.R. Allen*

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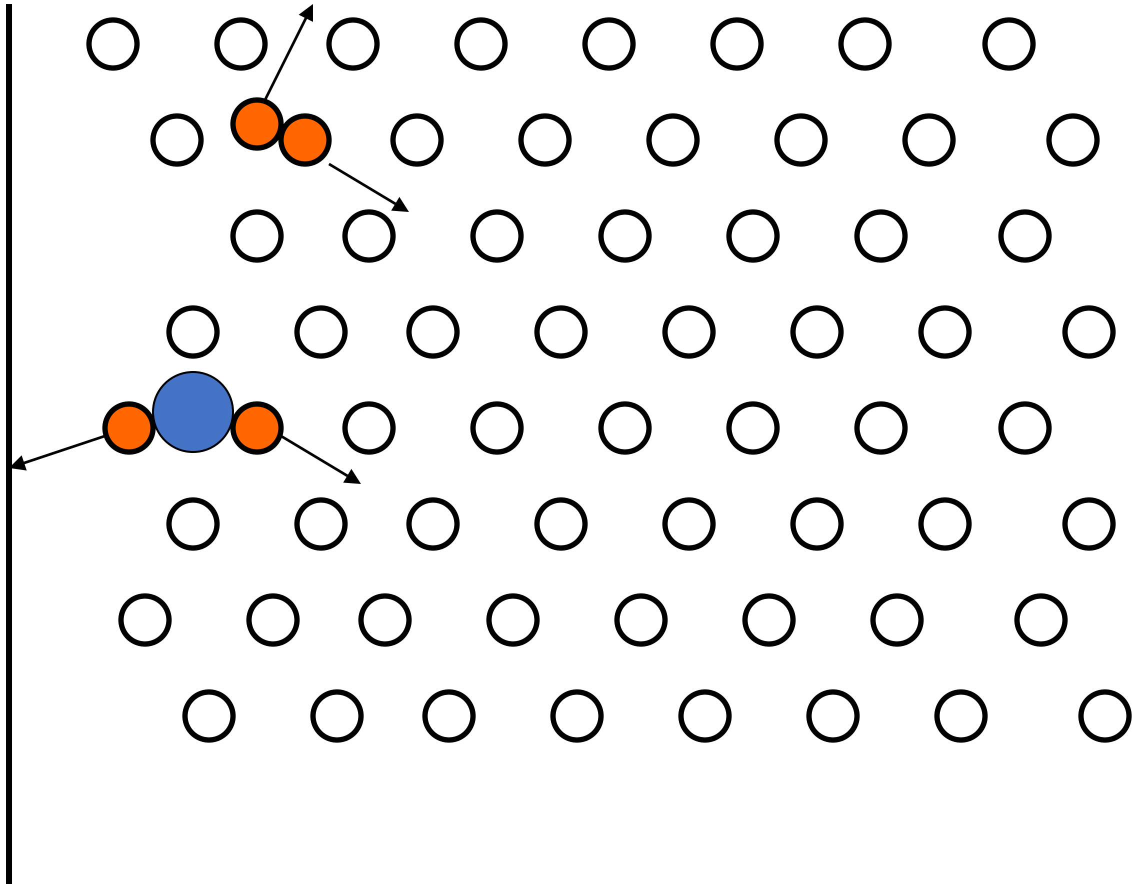

Source: T.R. Allen

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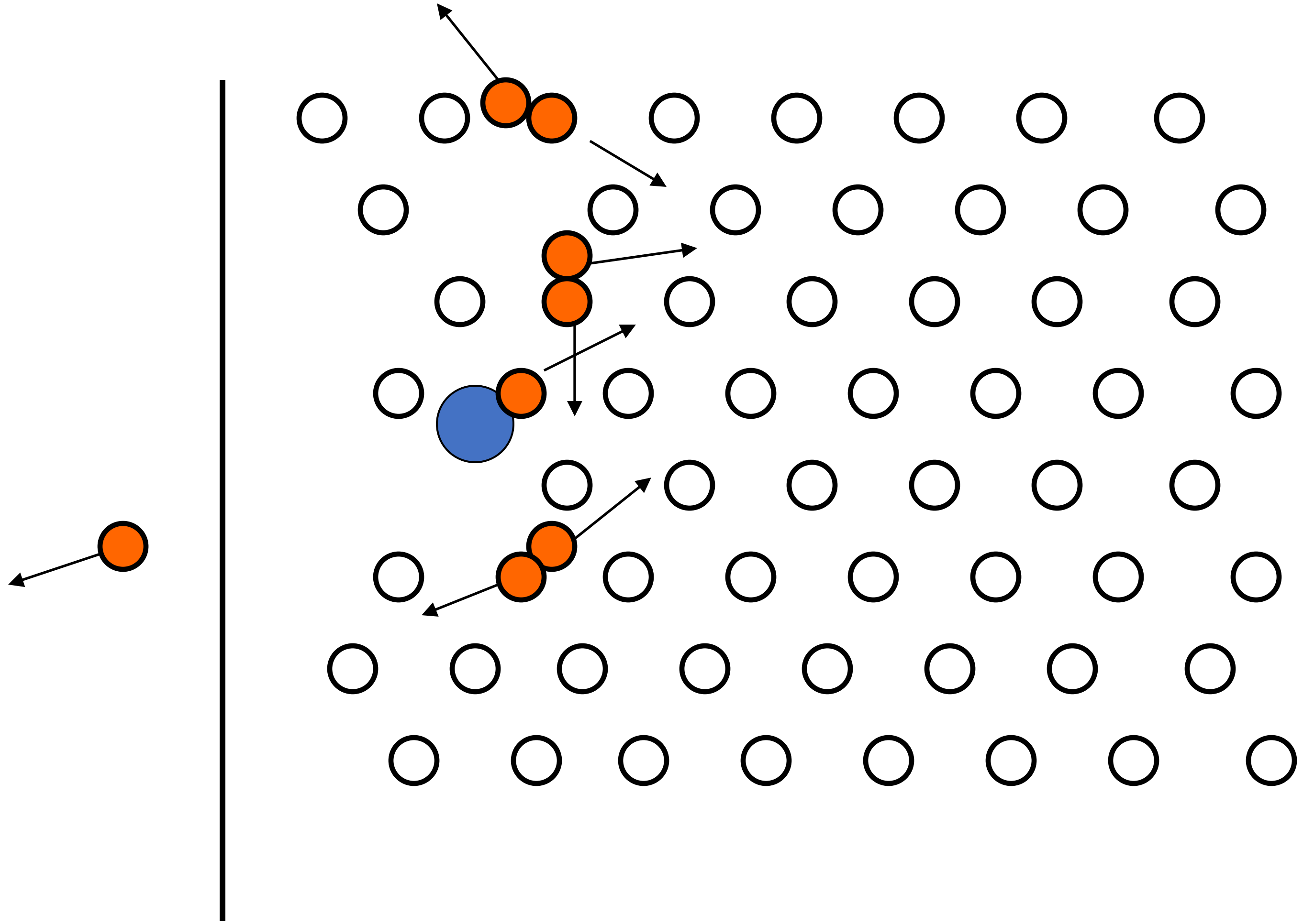

Source: *T.R. Allen*

Radiation Damage: the basics

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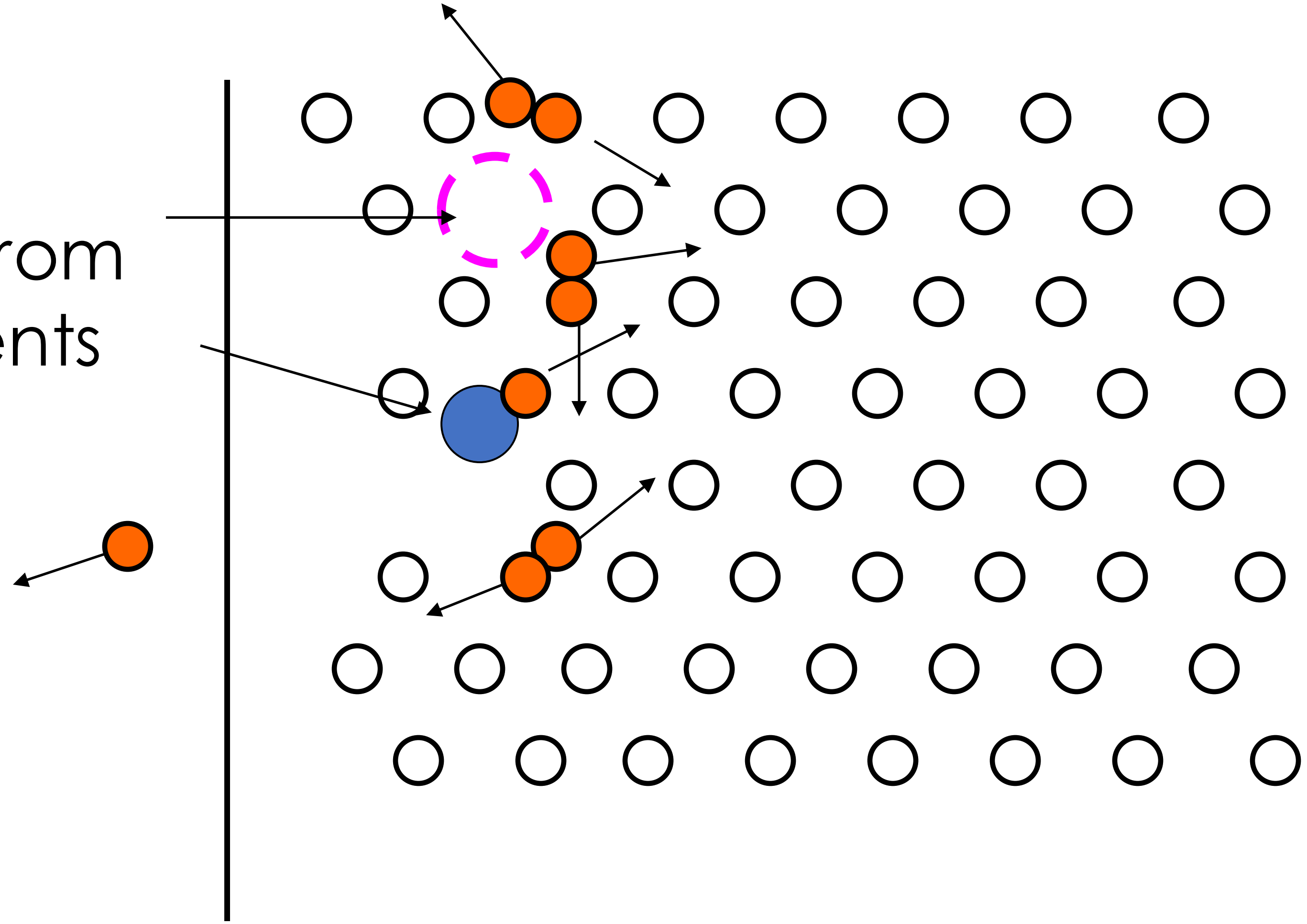
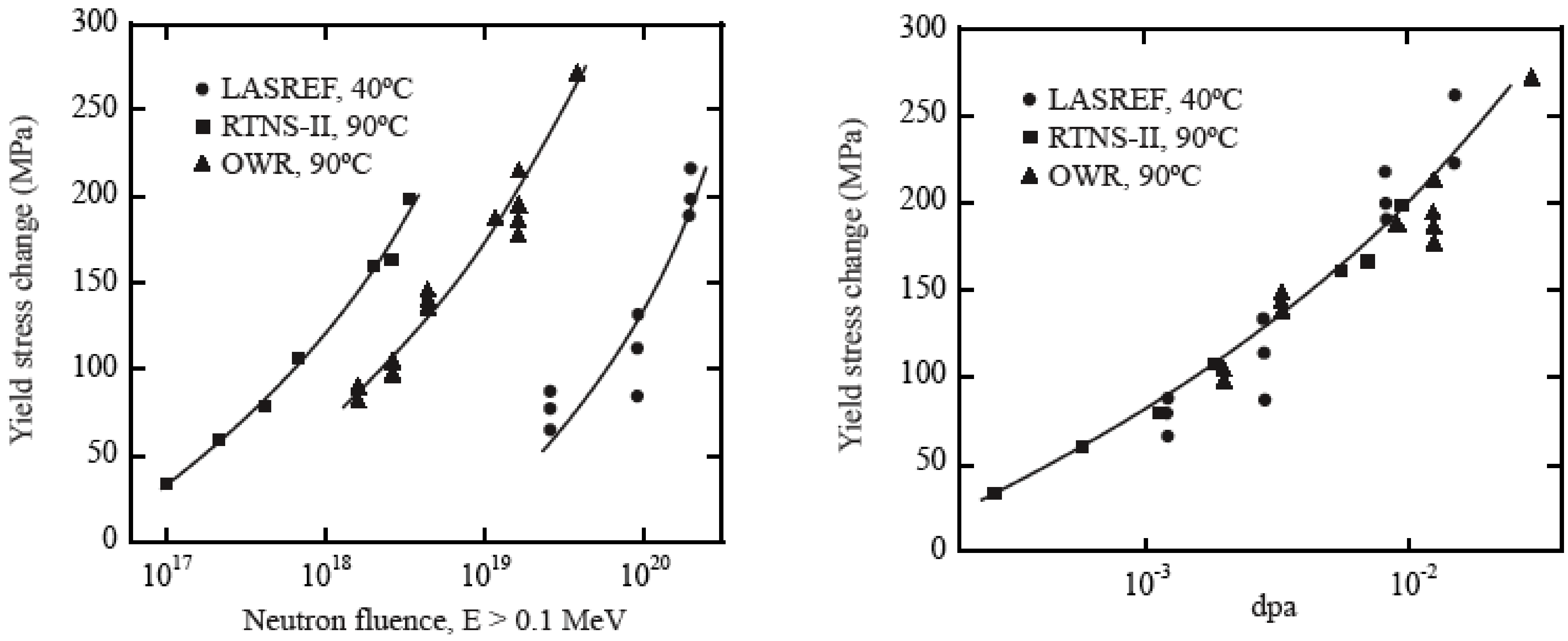
Defects produced from displacements



Source: *T.R. Allen*

Importance of displacement versus fluence for this class

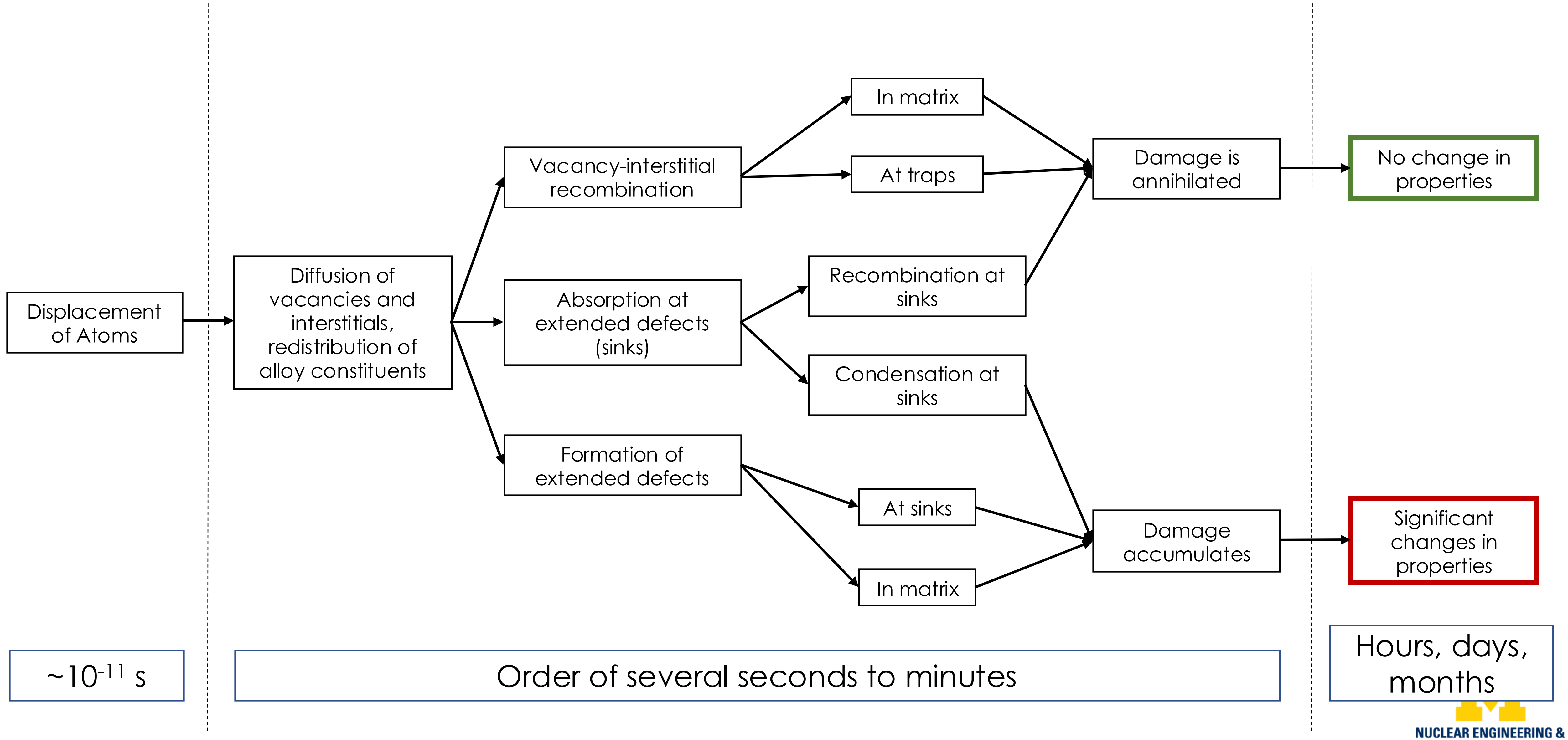


Comparison of yield stress change in 316 stainless steel irradiated in different reactors

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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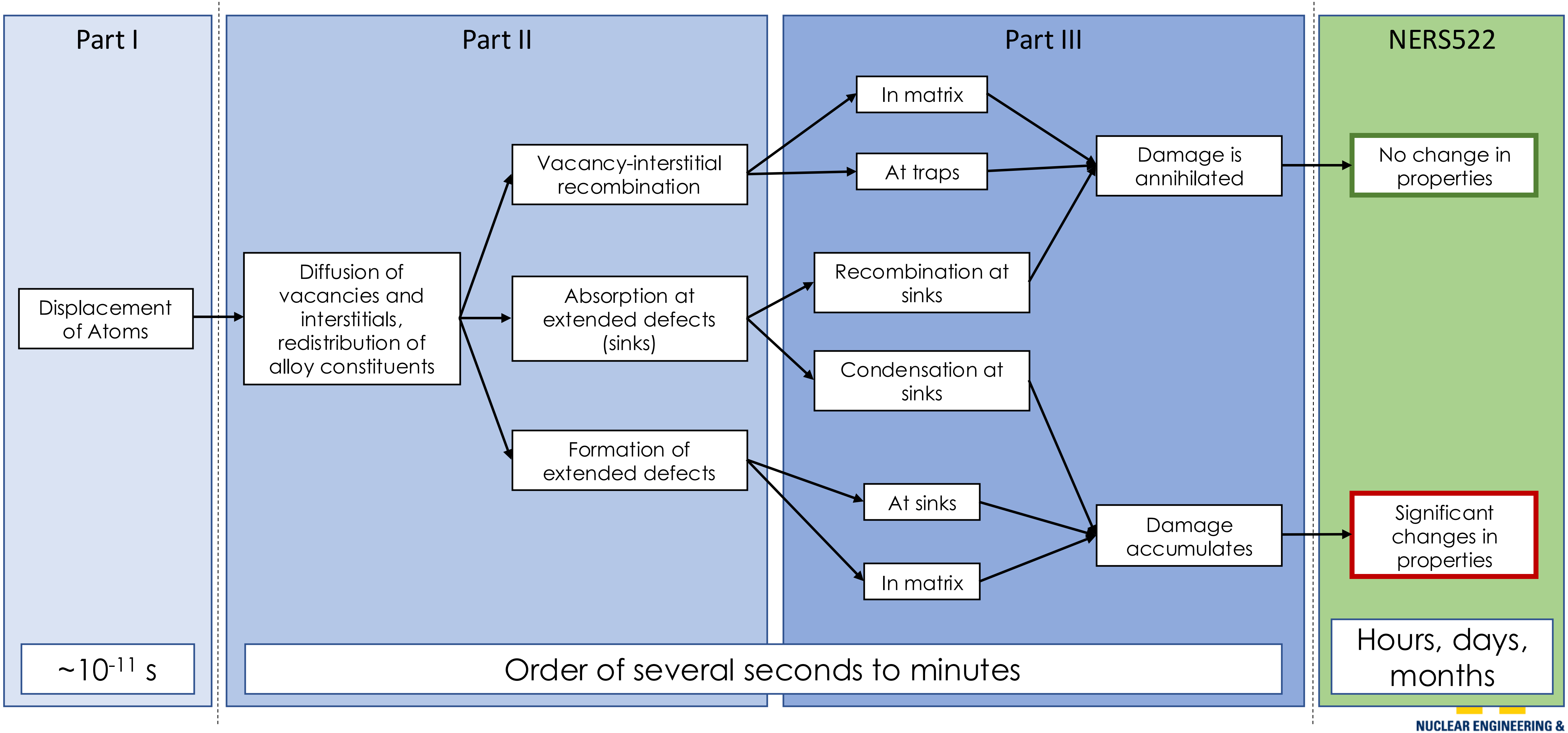

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Displacement of Atoms in Detail

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

Displacement of Atoms in Detail

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$\sim 10^{-11}$ s

Next two lectures

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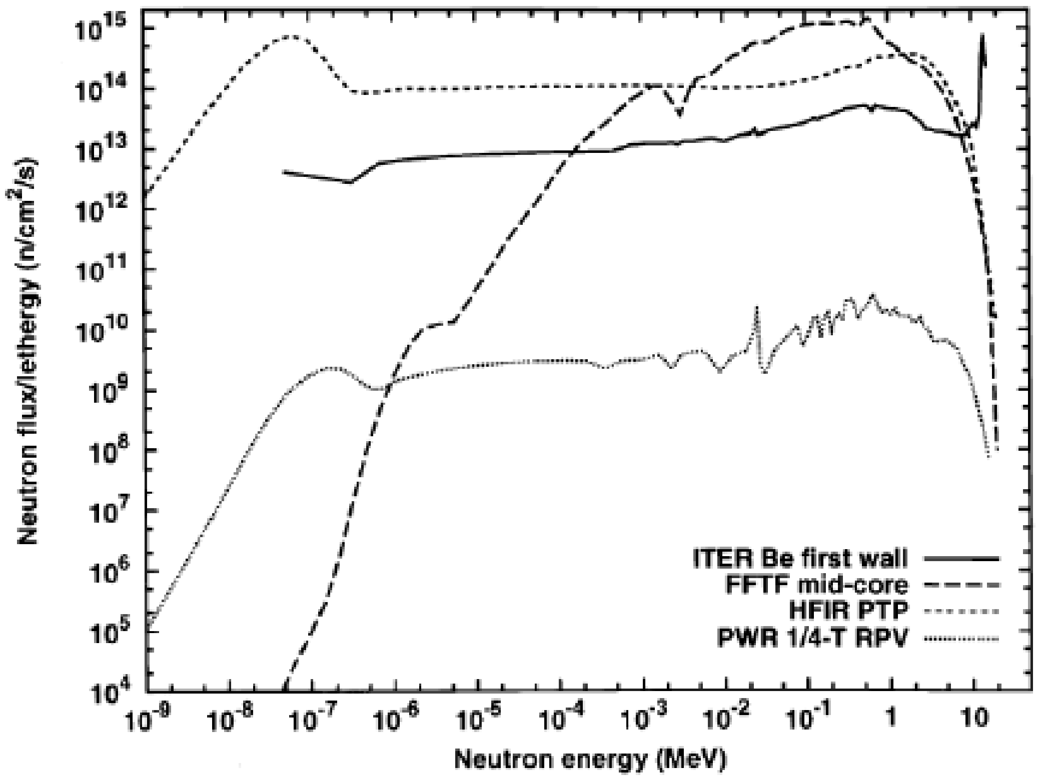
Outline

- 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

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

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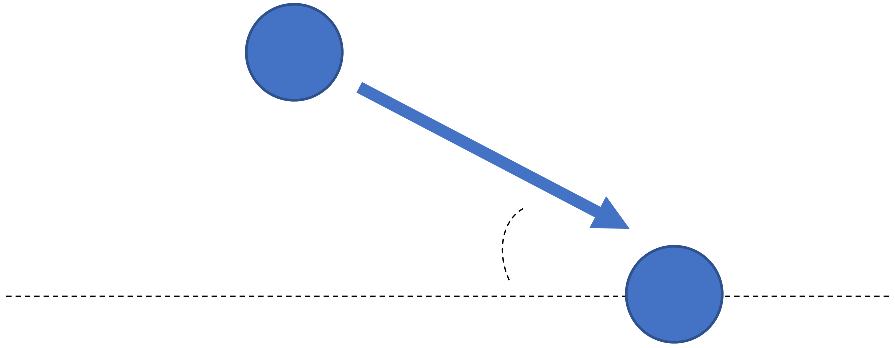
How do we determine energy transfer?

- Situation: Incident neutron – target atom interaction

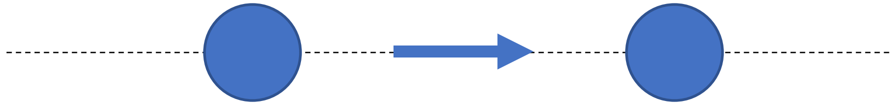
Case 1:

Case 2:



Case 3:

Case 4:



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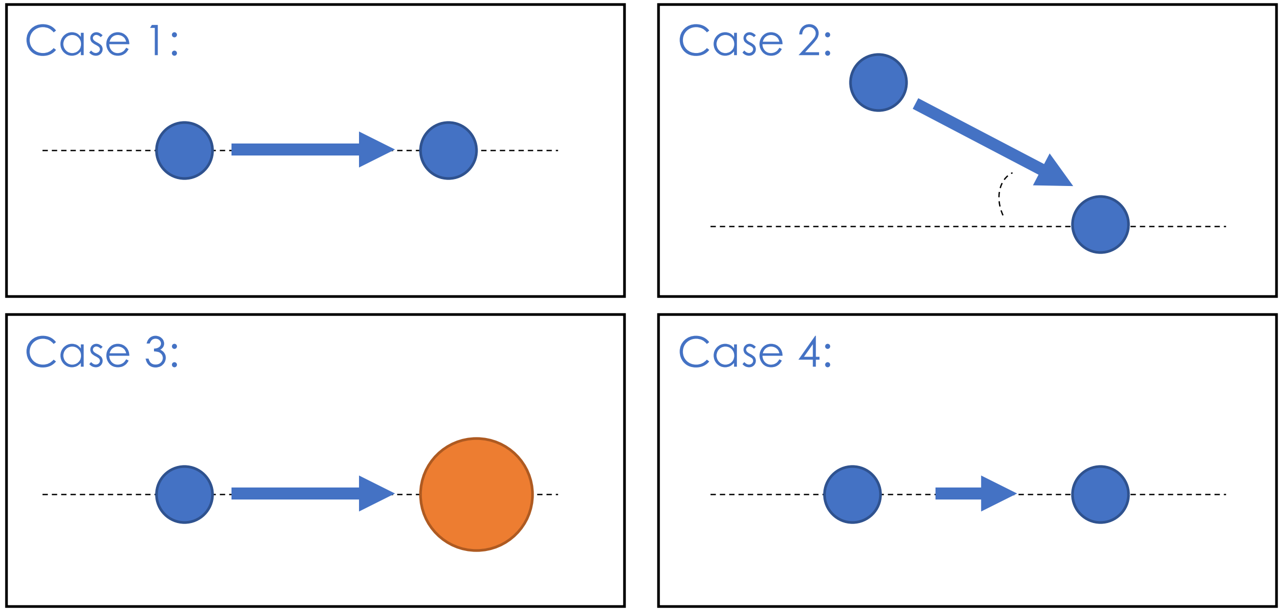
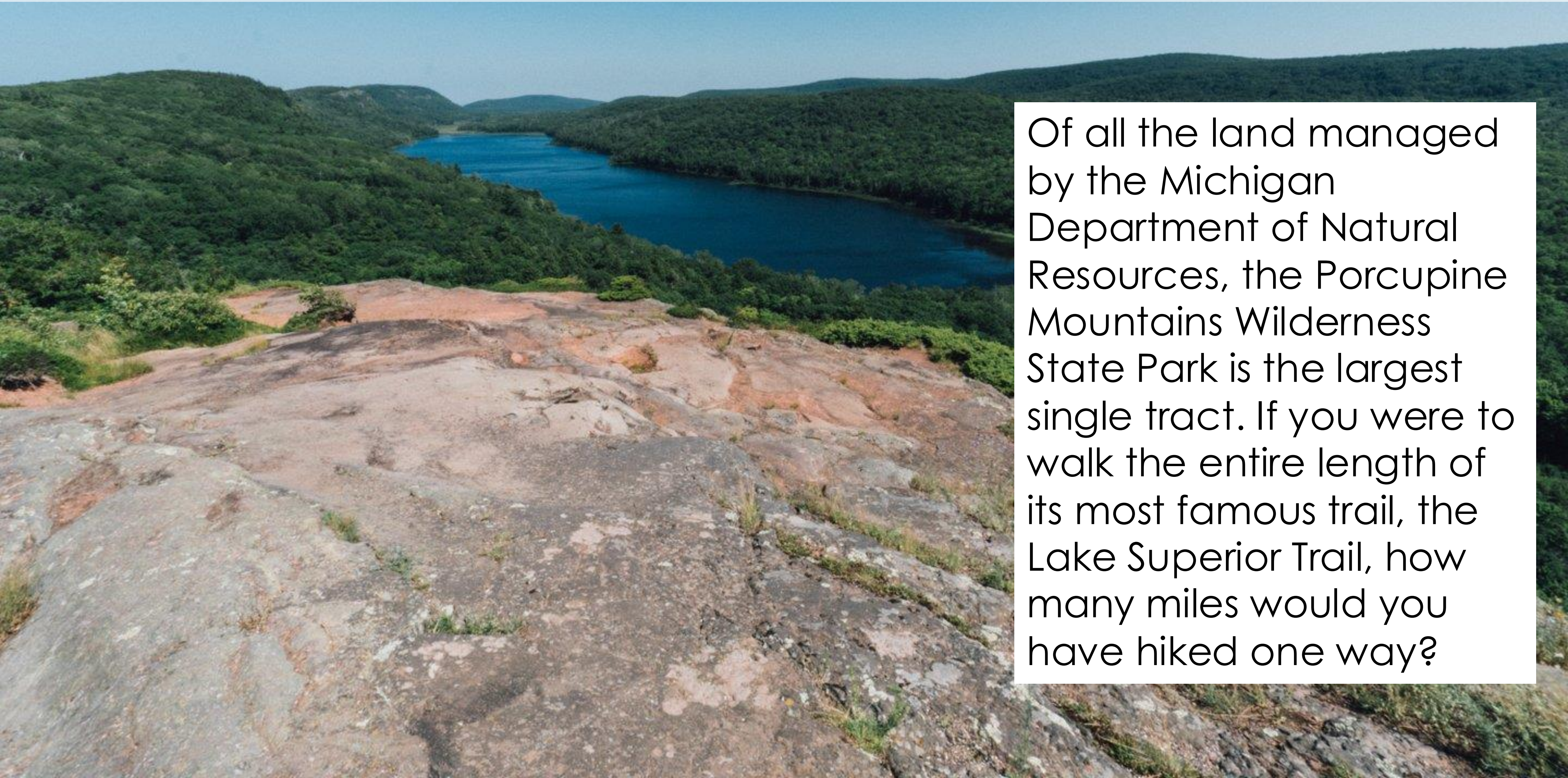


$$T = f(E_i, m_1, m_2, \theta)$$

Half Time!



Of all the land managed by the Michigan Department of Natural Resources, the Porcupine Mountains Wilderness State Park is the largest single tract. If you were to walk the entire length of its most famous trail, the Lake Superior Trail, how many miles would you have hiked one way?

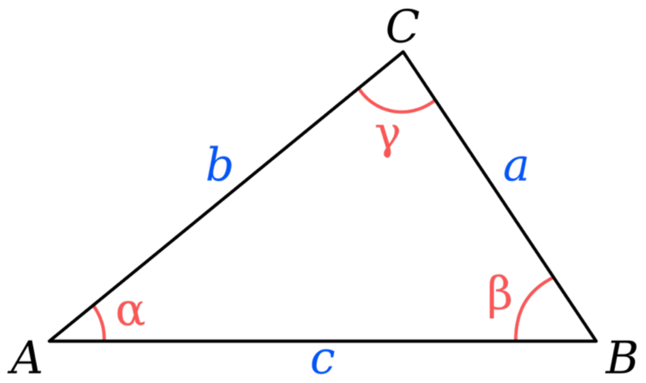
A two-body collision in laboratory (L) coordinates

- 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!

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:

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

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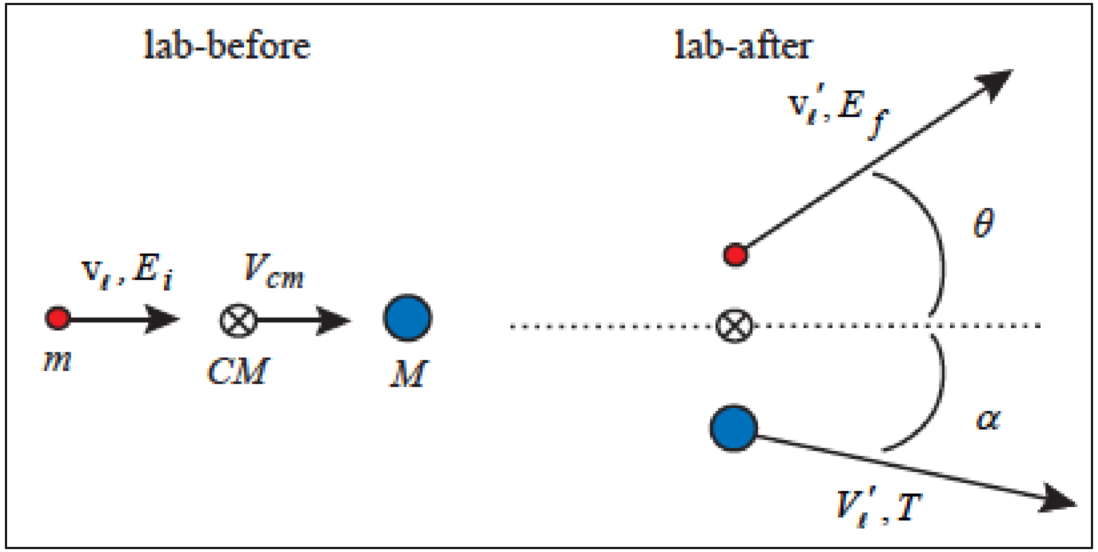
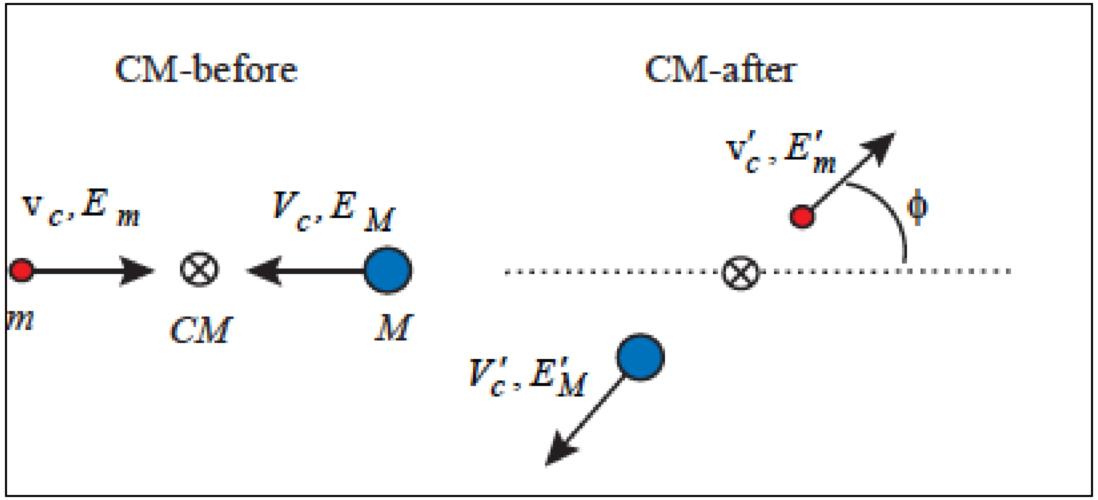
A visual of a simple two body collision:

Lab coordinates (ℓ):



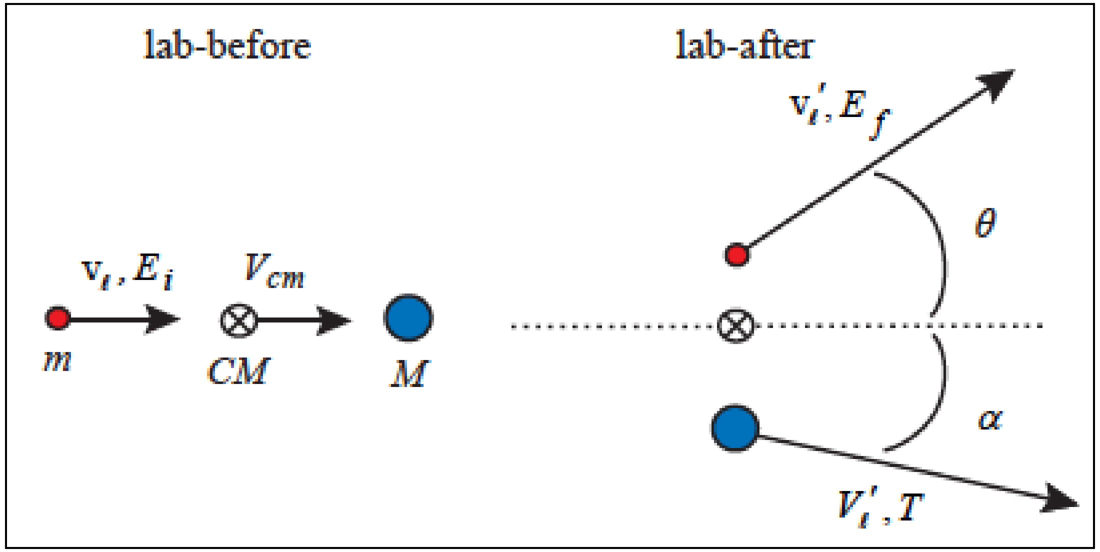
Center of Mass Coordinates (c):



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

A visual of a simple two body collision:

Lab coordinates:



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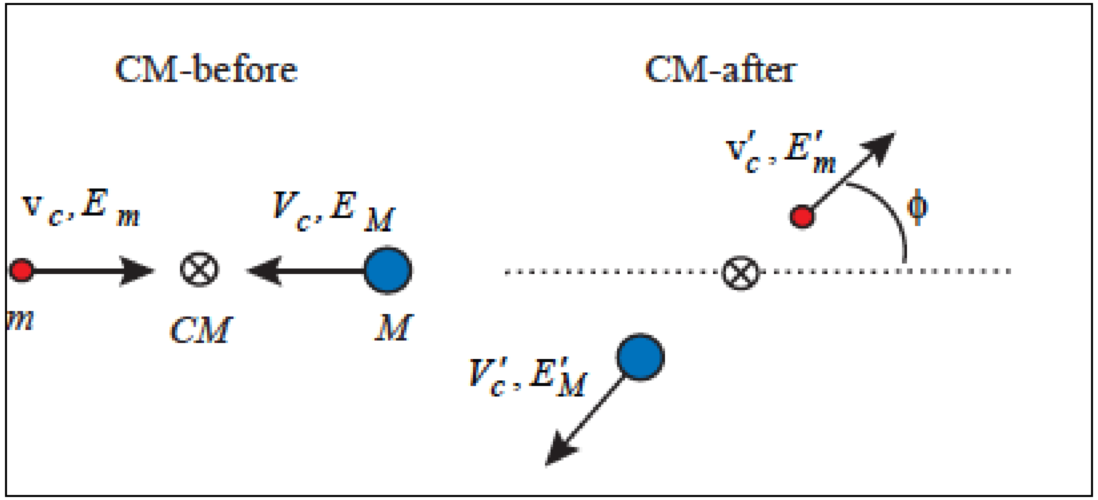
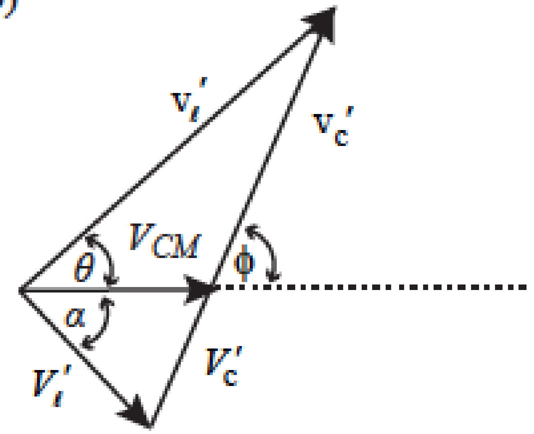


(b)



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

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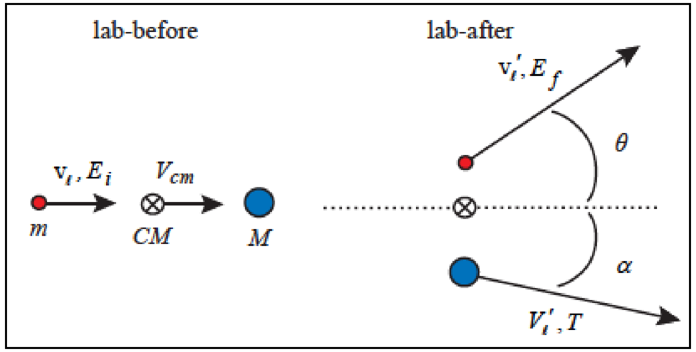
We need to determine T as a function of initial energy and scattering angle:

Lab coordinates:



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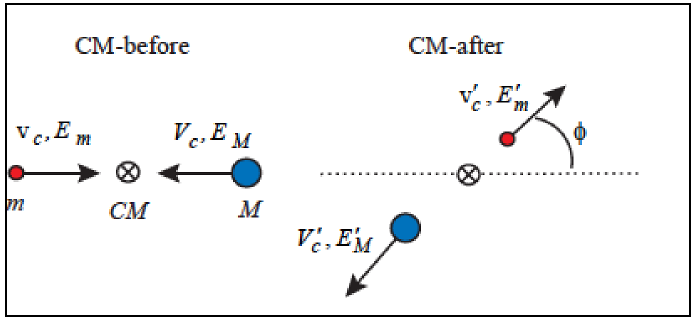

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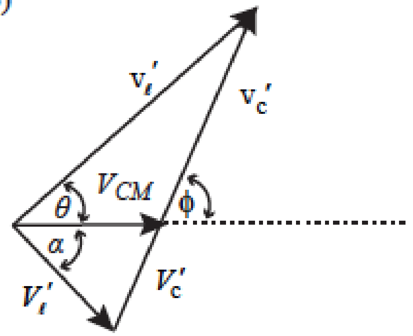

If we assume the CM is stationary in COM coordinates, and v_c' and V_c' are in opposite directions but the same plane, we can use our conversation equations to yield:

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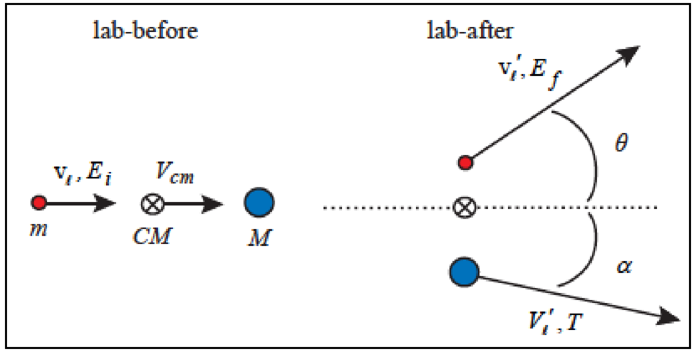
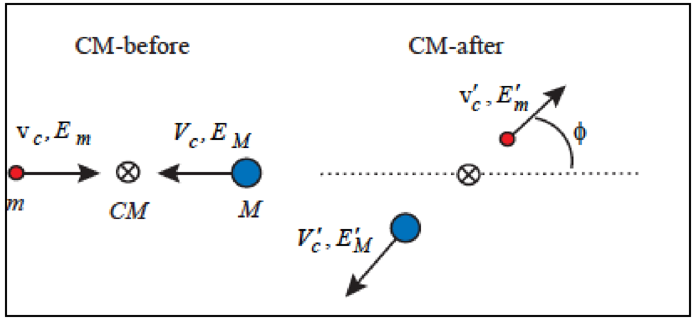
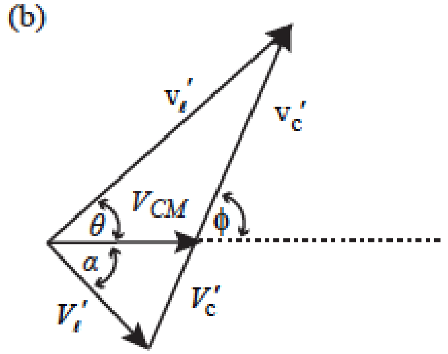


Center of Mass Coordinates





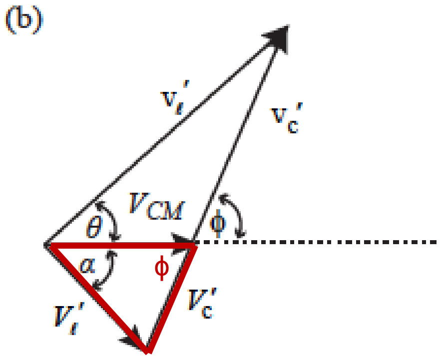
$$\therefore \ V_c = V_c' \qquad v_c = v_c'$$

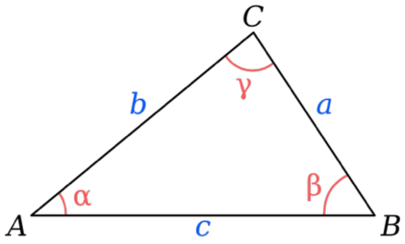
We now need to know how to get V_{CM} in the lab system:

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:





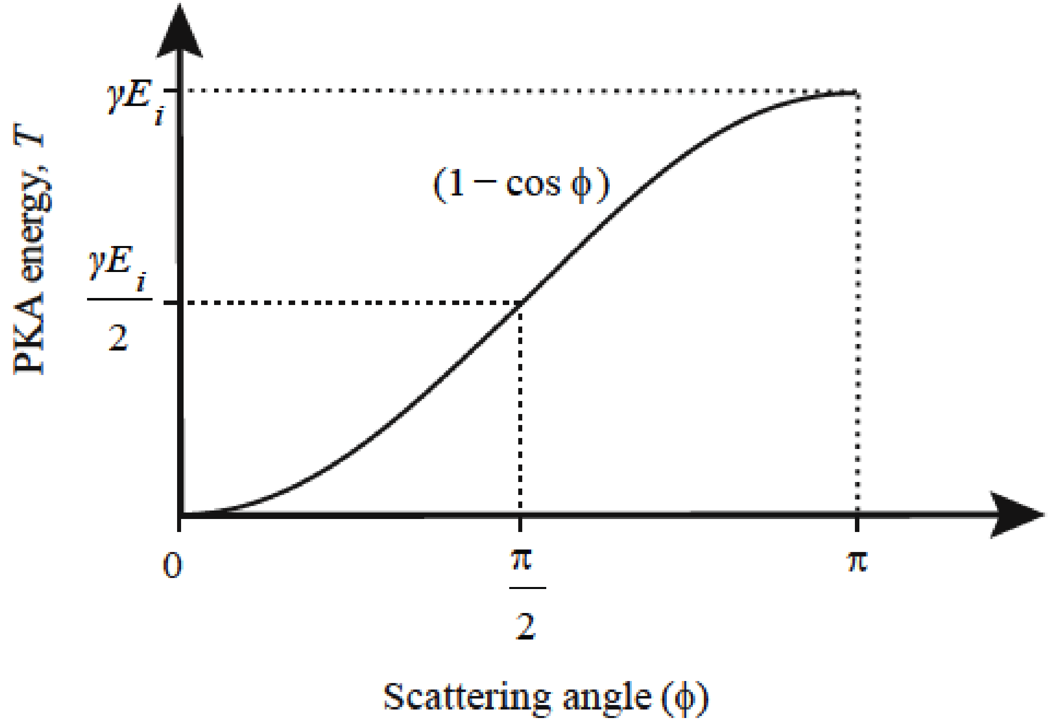
$$c^2 = a^2 + b^2 - 2ab\cos\gamma$$

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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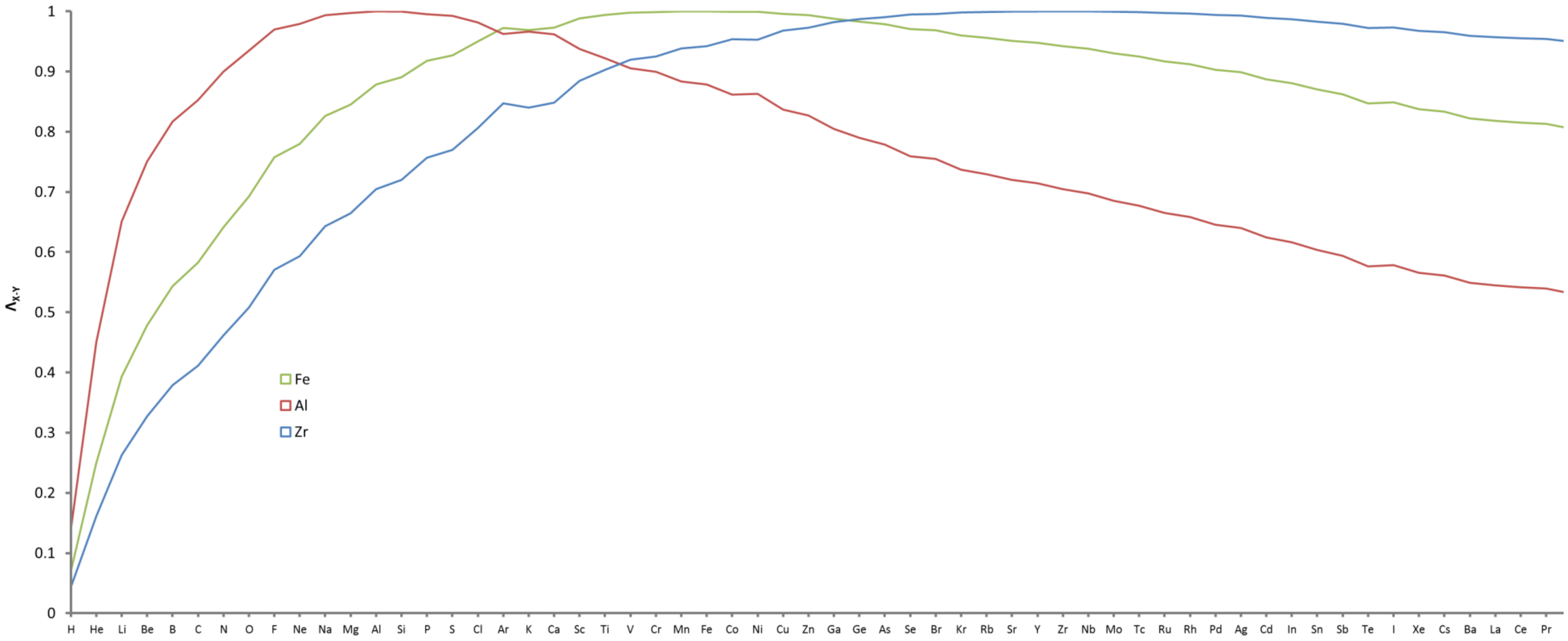
Example problem:

- 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

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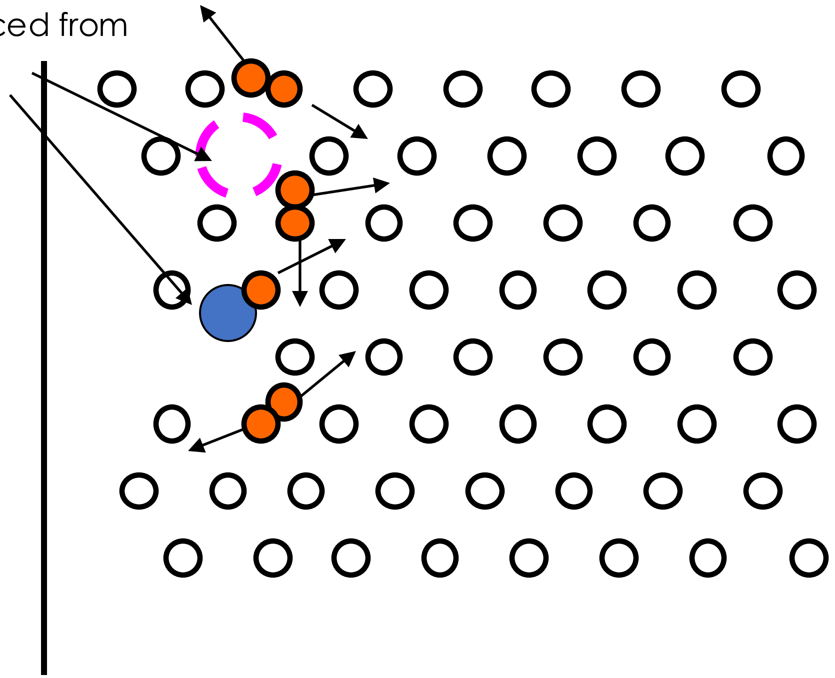
Summary

- Using:

1. Momentum conservation
2. Kinetic energy conservation

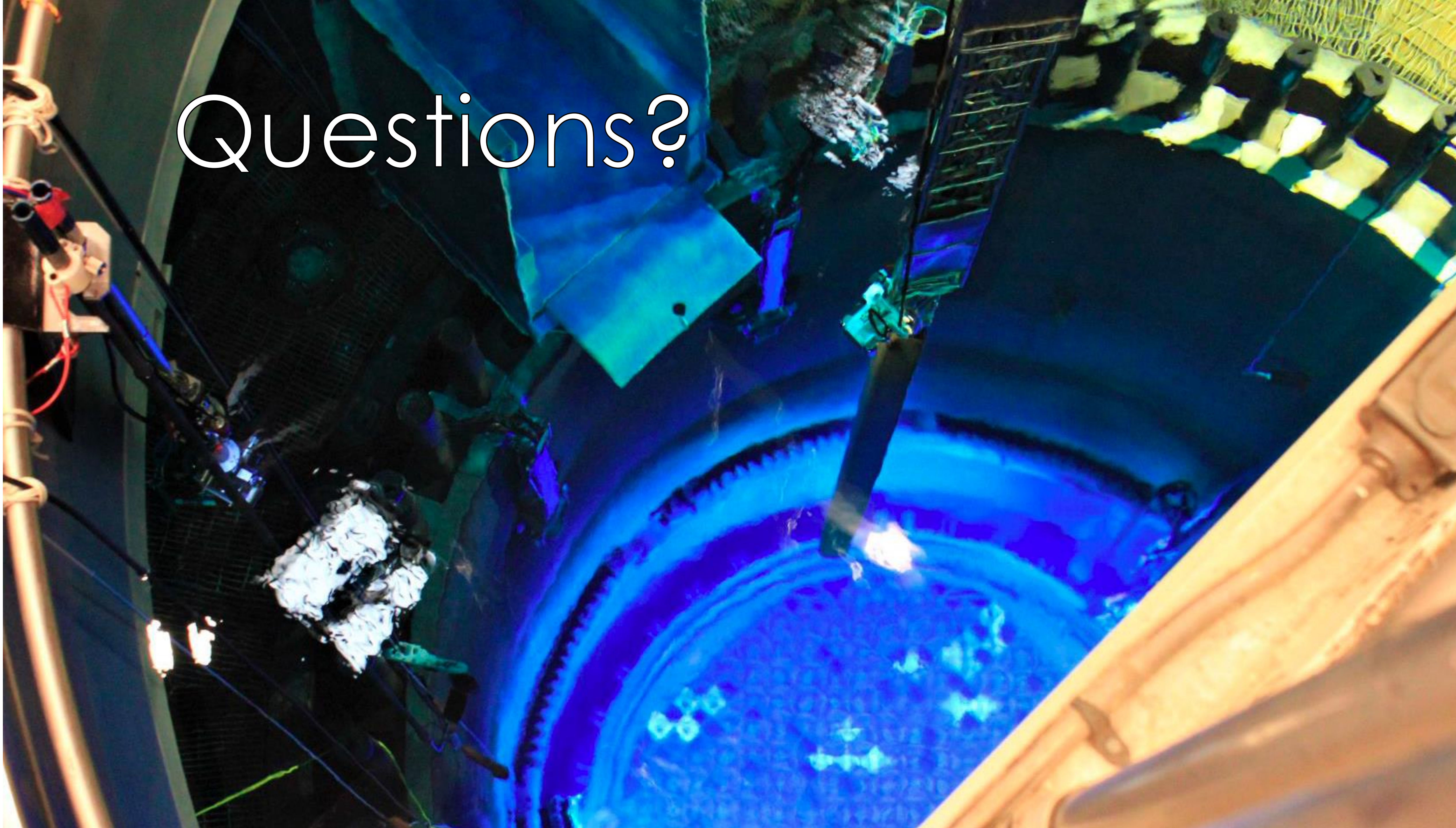
$$V_c = V_c' \quad \& \quad v_c = v_c'$$

3. Velocities in LAB and COM: $V_{CM} = \left(\frac{m}{M+m}\right) v_l$
4. Cosines law: $V_l'^2 = V_{CM}^2 + V_c'^2 - 2V_{CM}V_c' cos\phi$



T=

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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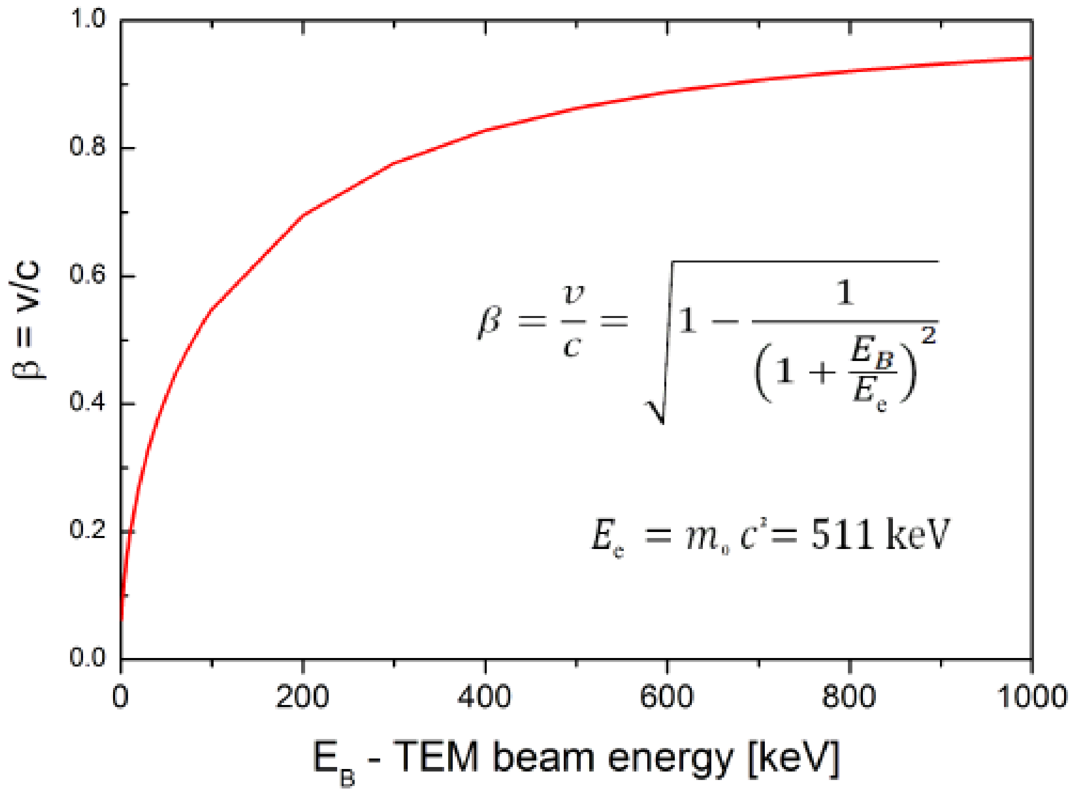

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