

# Neutron-nuclear Interactions

## Was 2<sup>nd</sup> Edition, Section 1

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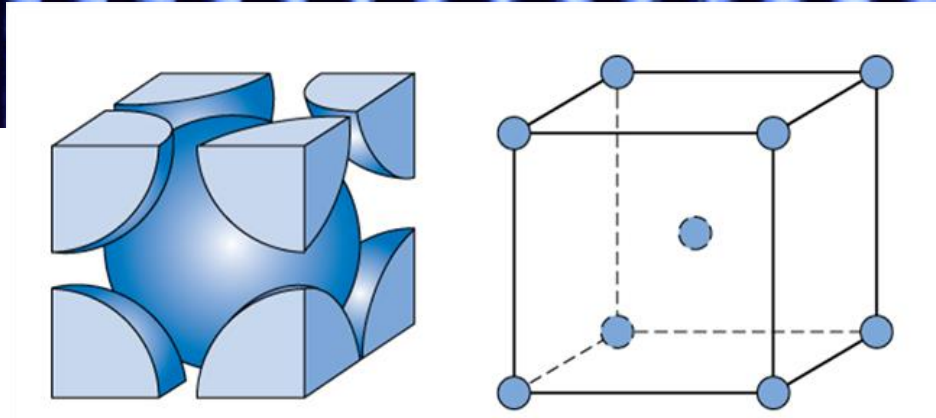
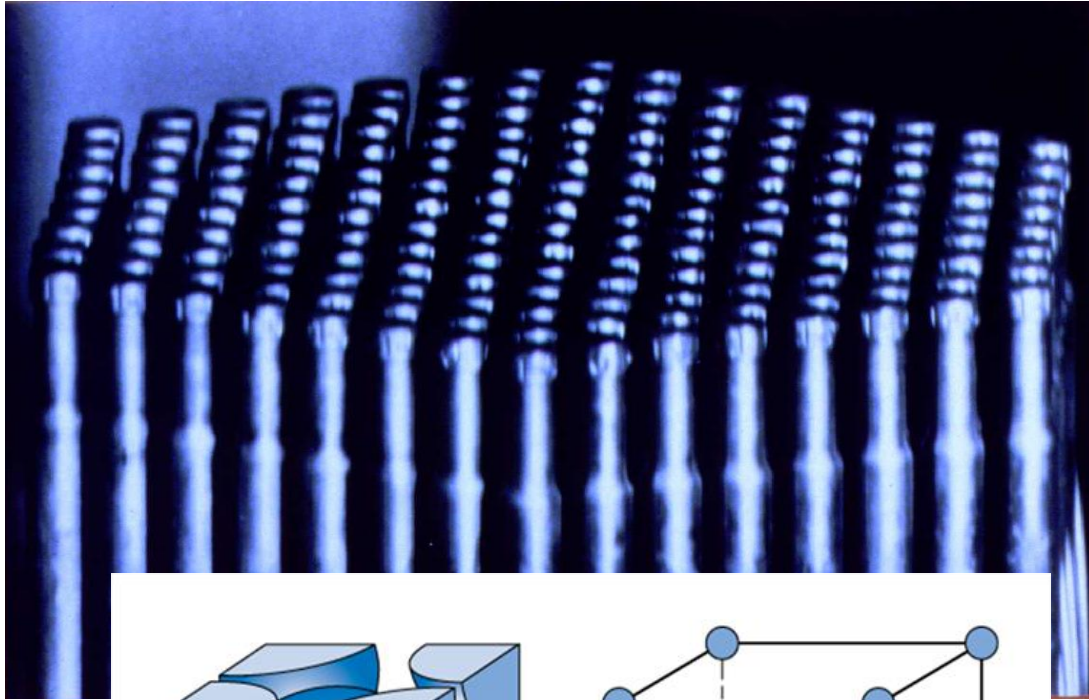
<sup>1</sup>University of Michigan



**NUCLEAR ENGINEERING &  
RADIOLOGICAL SCIENCES**  
UNIVERSITY OF MICHIGAN

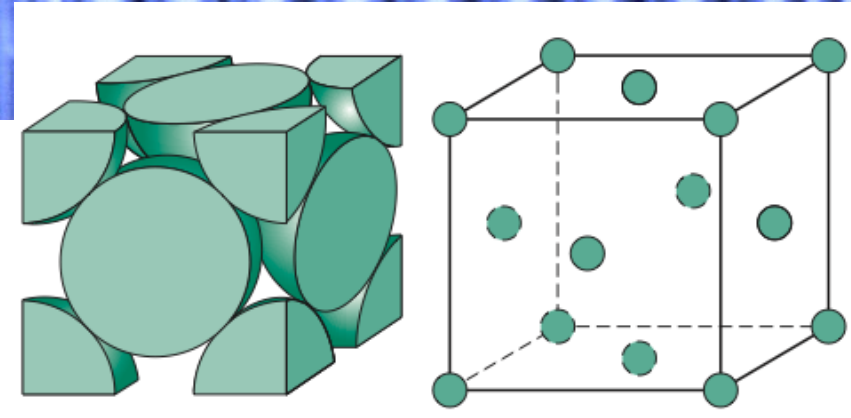
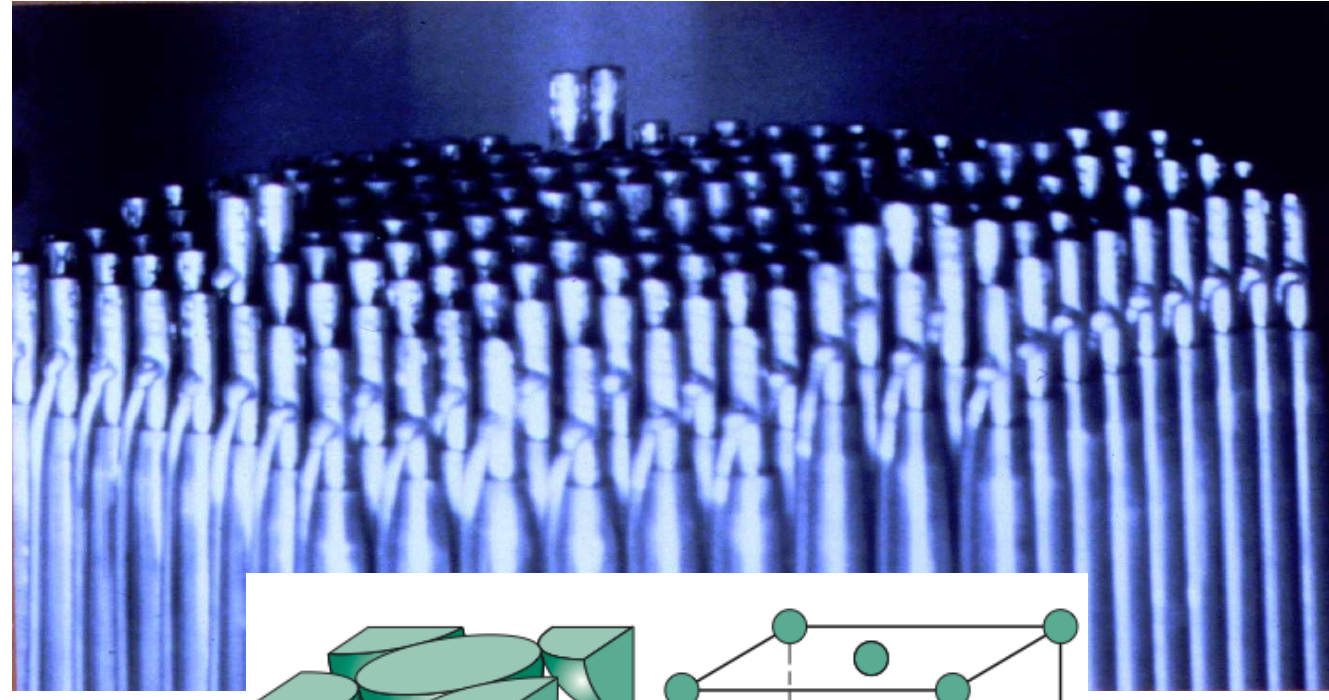
# Our last lecture we talked about this:

HT-9, no swelling



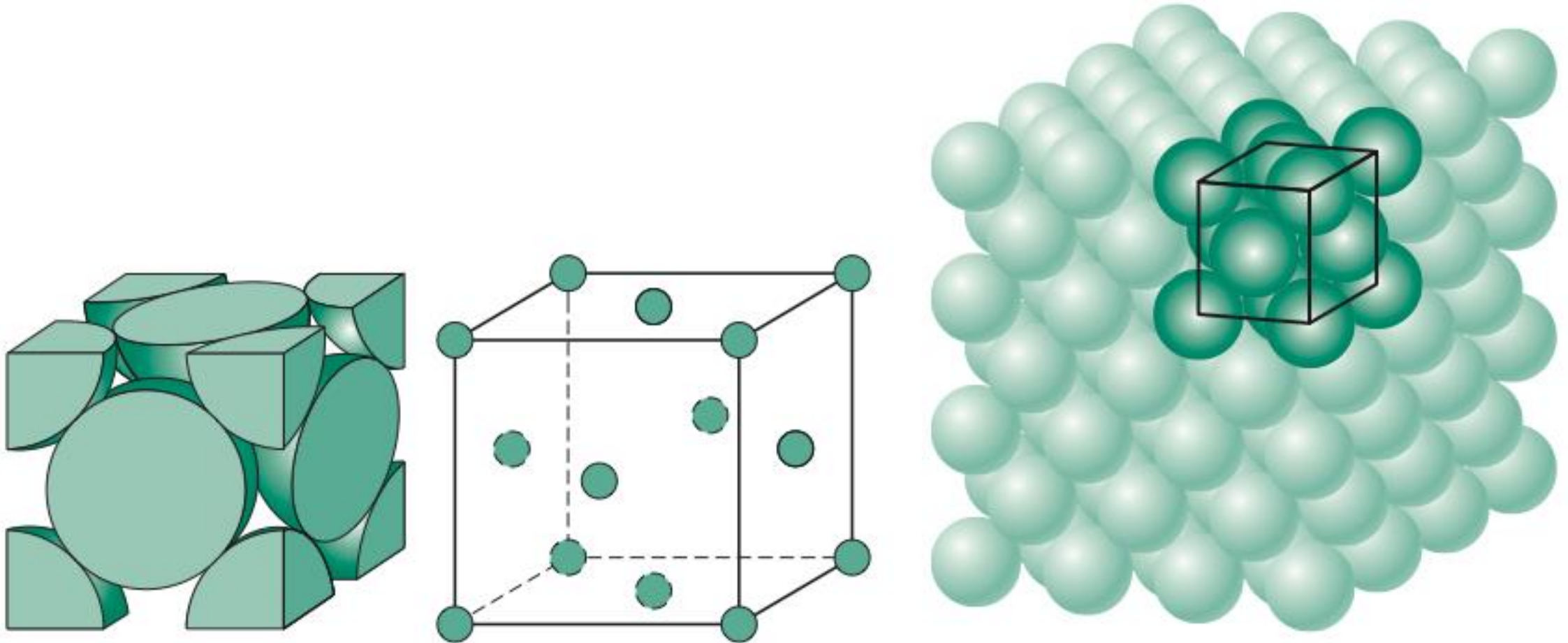
Body centered cubic (BCC)

316-Ti stainless, swelling



Face centered cubic (FCC)

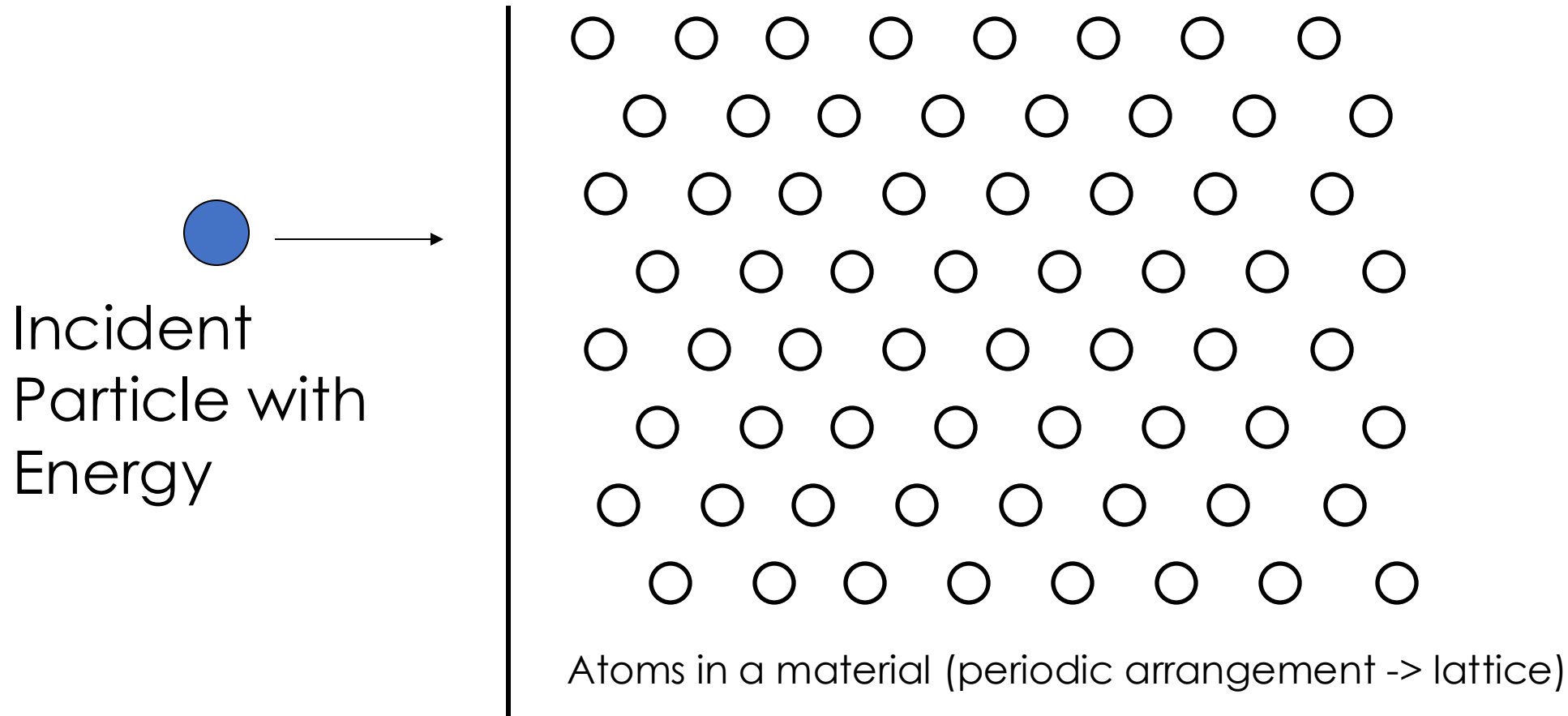
# Units cells are the building blocks of a material



Atoms in a material (periodic arrangement -> lattice)

# Radiation Damage: the basics

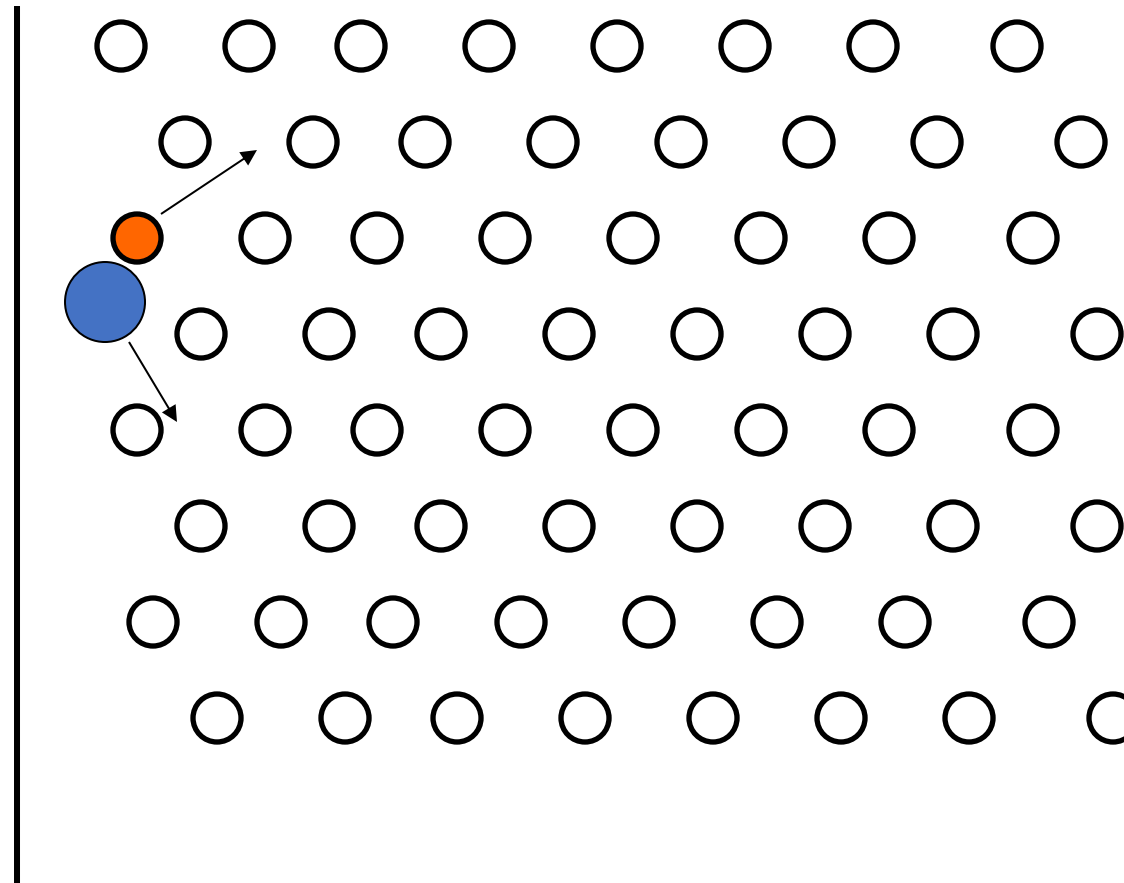
- All of radiation damage boils down to a common step:  
**collisions between energetic particles and atoms composing a material**



Source: T.R. Allen

# Radiation Damage: the basics

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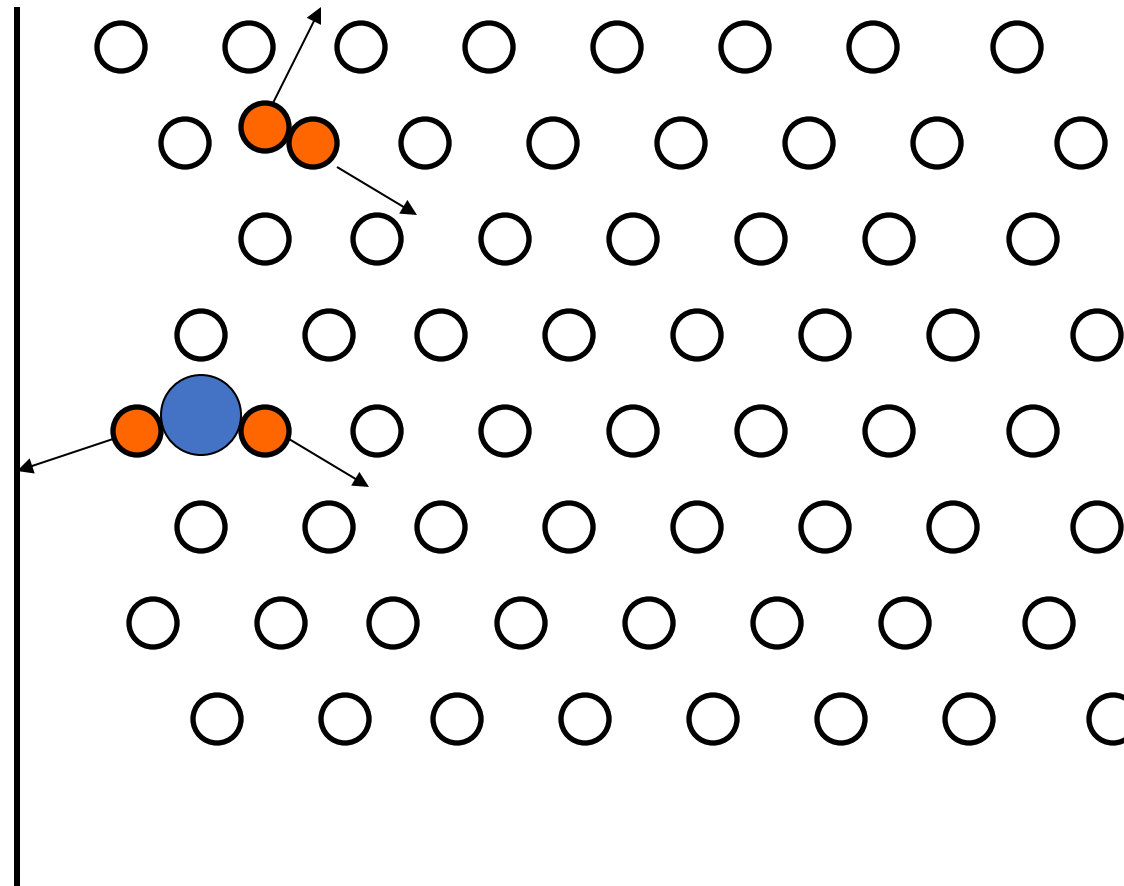


Source: T.R. Allen



# Radiation Damage: the basics

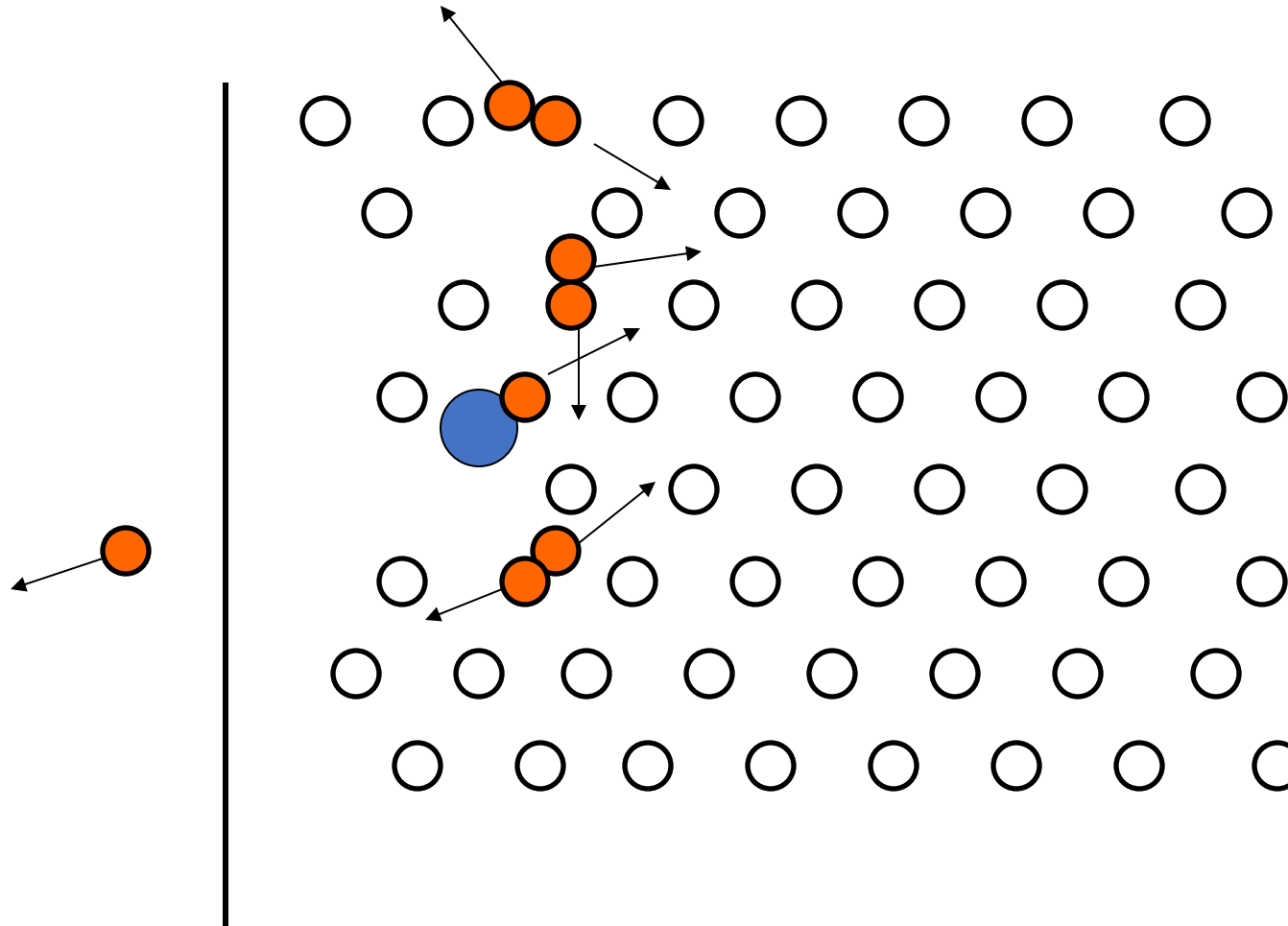
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# Radiation Damage: the basics

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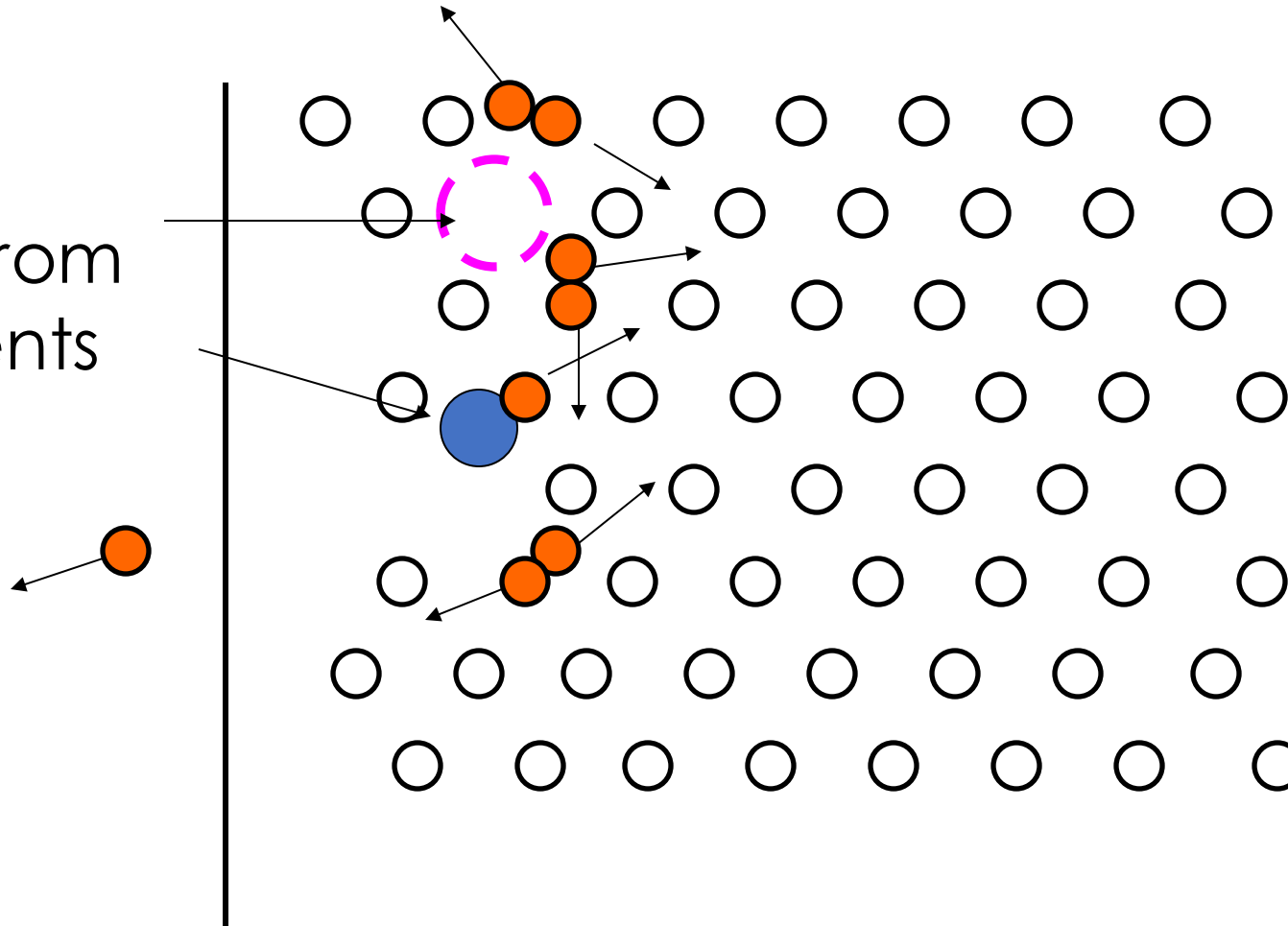


Source: T.R. Allen

# Radiation Damage: the basics

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

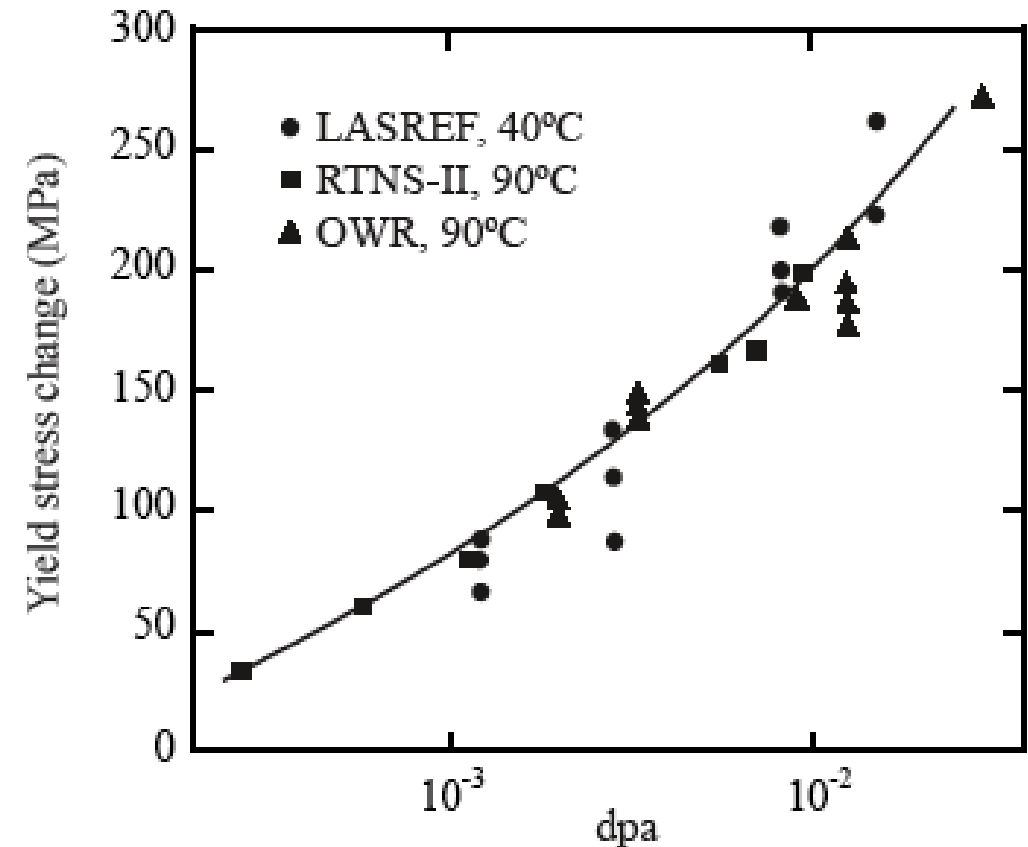
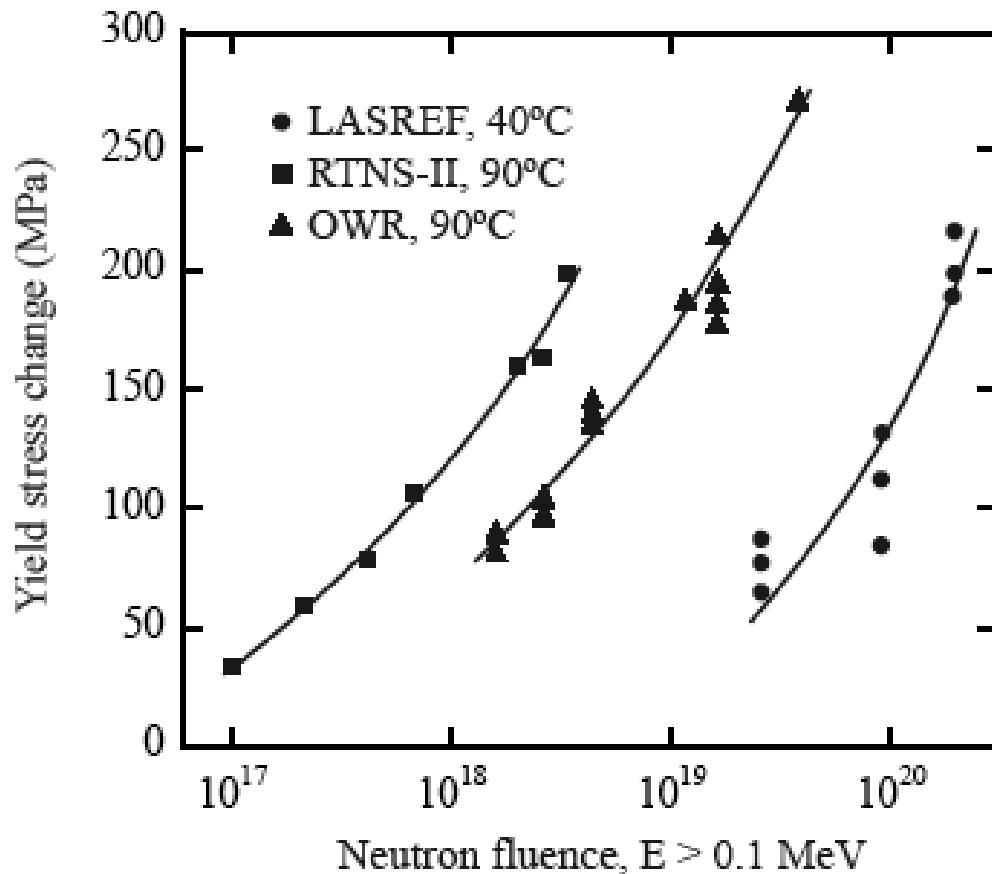
Defects  
produced from  
displacements



Source: T.R. Allen



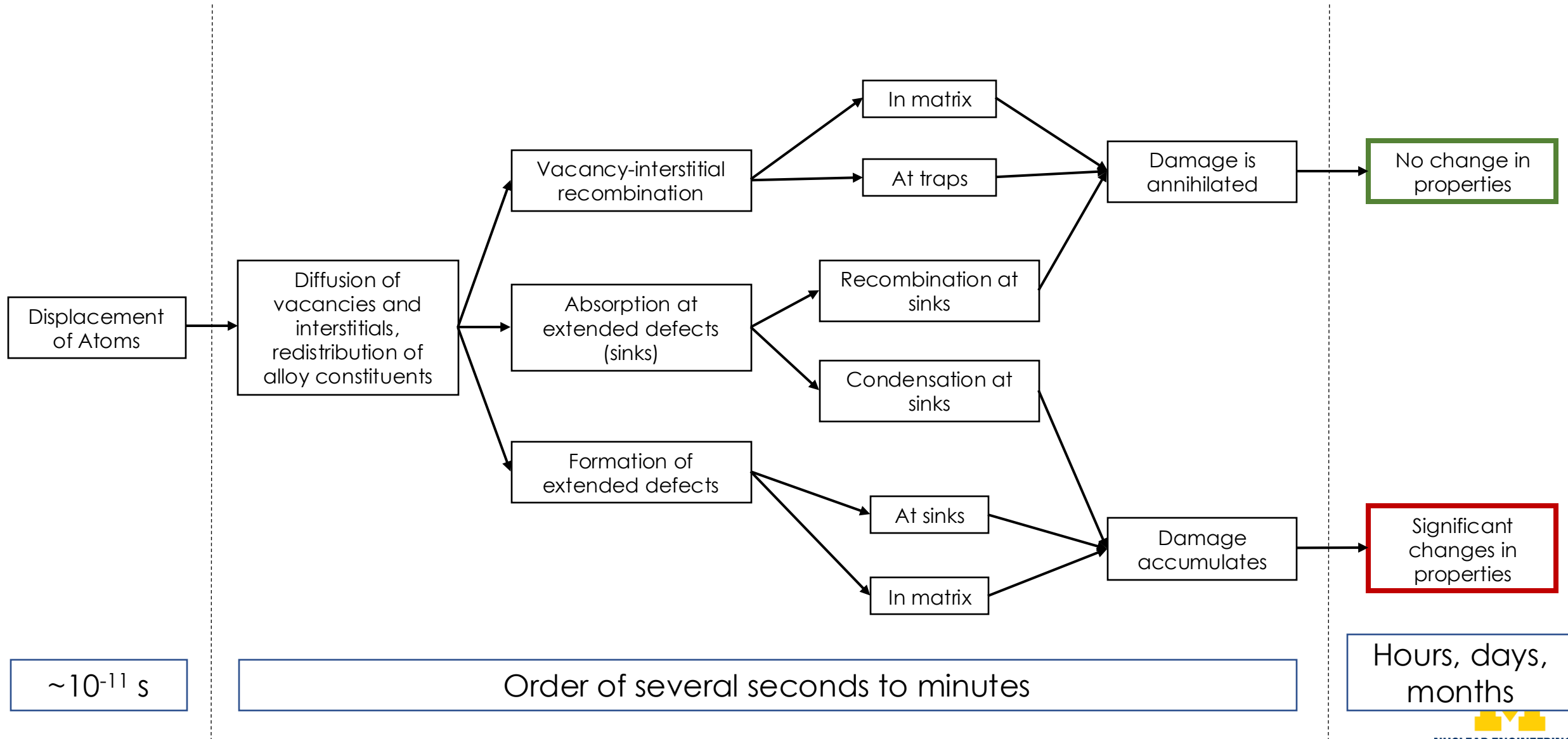
# Importance of displacement versus fluence for this class



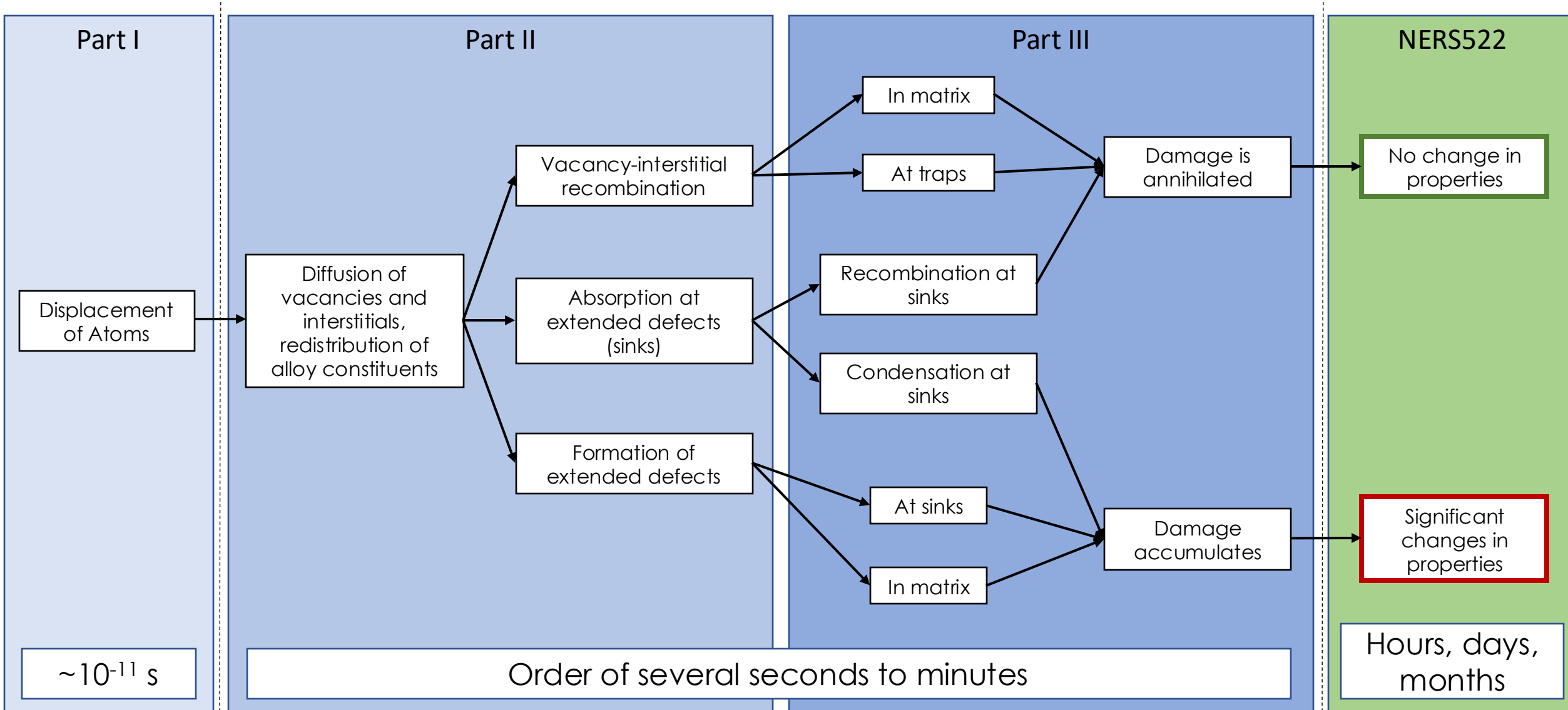
Comparison of yield stress change in 316 stainless steel irradiated in different reactors

# Flow chart for radiation damage

# Flow chart for radiation damage



# Flow chart for radiation damage



# Displacement of Atoms in Detail

Part I

Displacement  
of Atoms

(Radiation  
Damage  
Event)

$\sim 10^{-11}$  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 its 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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Next two  
lectures

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# Outline

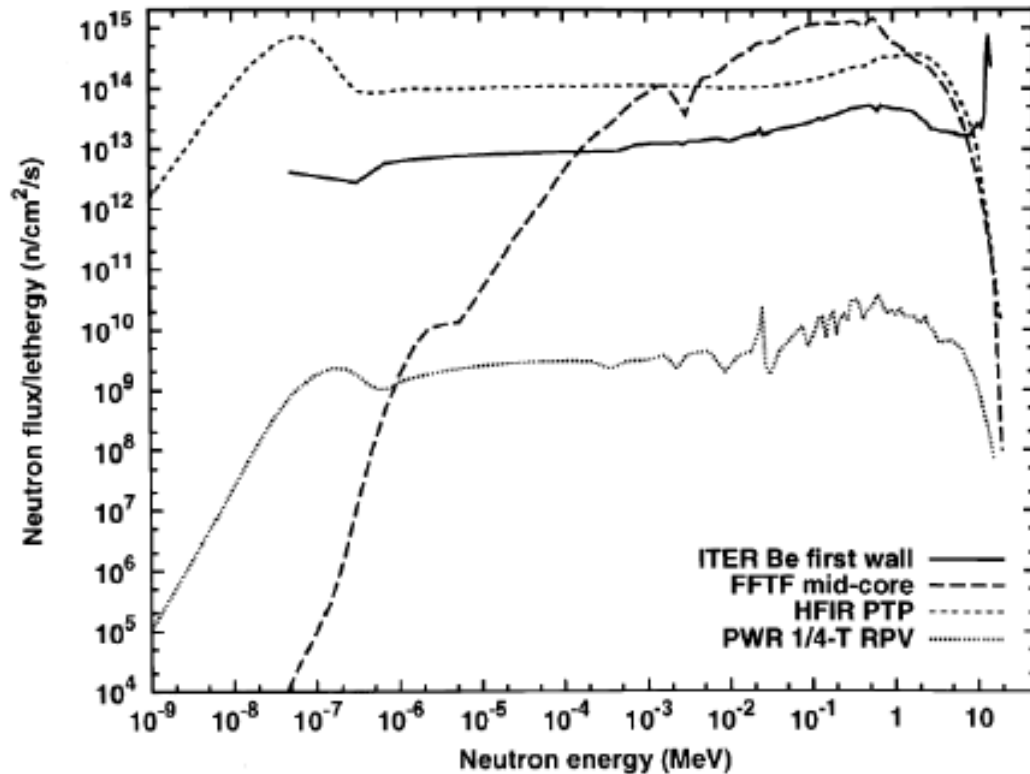
- There are four major interacting particles of interest:
  - 1.
  - 2.
  - 3.
  - 4.
- From these, there are different types of collisions to consider:
  - 1.
  - 2.
  - 3.
  - 4.

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. Stoller and L.R. Greenwood, J. Nucl. Mater. 271-272 (1999)*

# Billiard Ball Relaxation Video

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

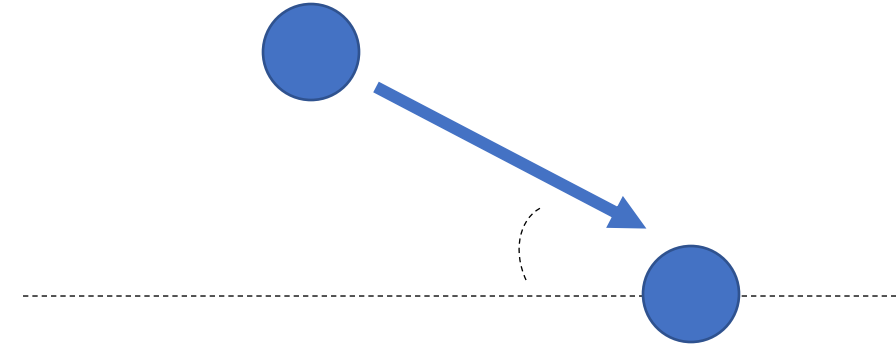
# How do we determine energy transfer?

- Situation: Incident neutron – target atom interaction

Case 1:



Case 2:



Case 3:



Case 4:



# How do we determine energy transfer?

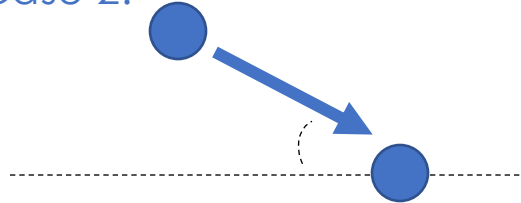
- Situation: Incident neutron – target atom interaction

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

Case 1:



Case 2:



Case 3:



Case 4:





**Half Time!**





# A two-body collision in laboratory (L) coordinates

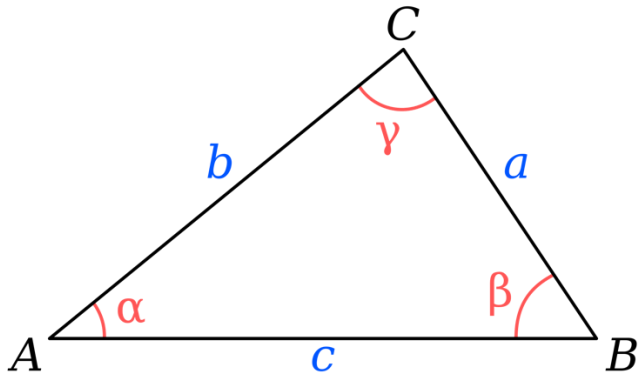
- The momentum of the recoiling (displaced) atom is the parameter that determines the damage and thus our first goal of this class is to calculate it.
  - Thus, we first make several simplifying **assumptions**:
    - We'll only consider the asymptotic values of momentum at distances far from the collision
      - 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:  $p = mv$
- Energy:  $E = \frac{1}{2}mv^2$
- Cosine Law:



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

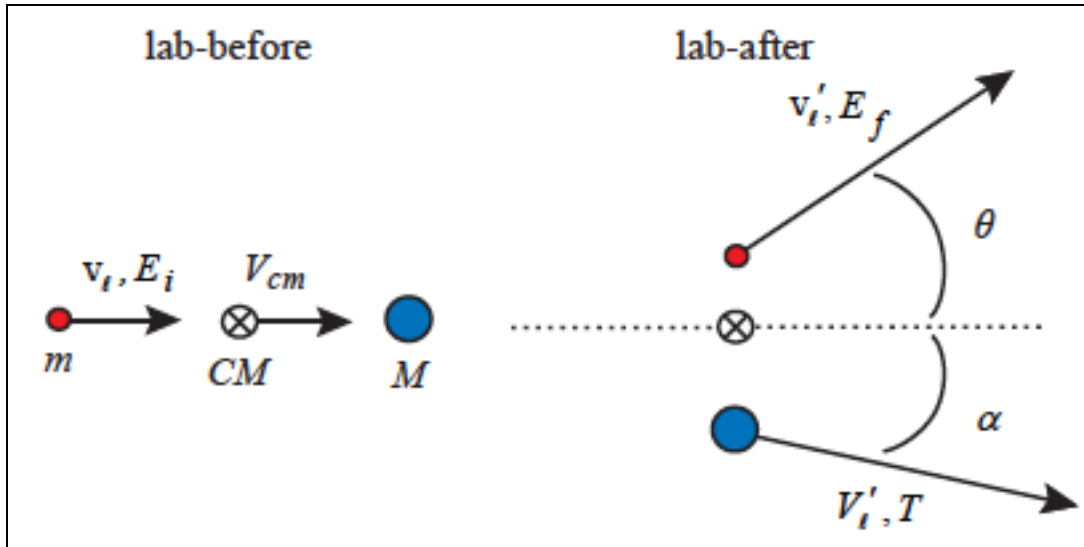
- Cosine-sine half angle identity:

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

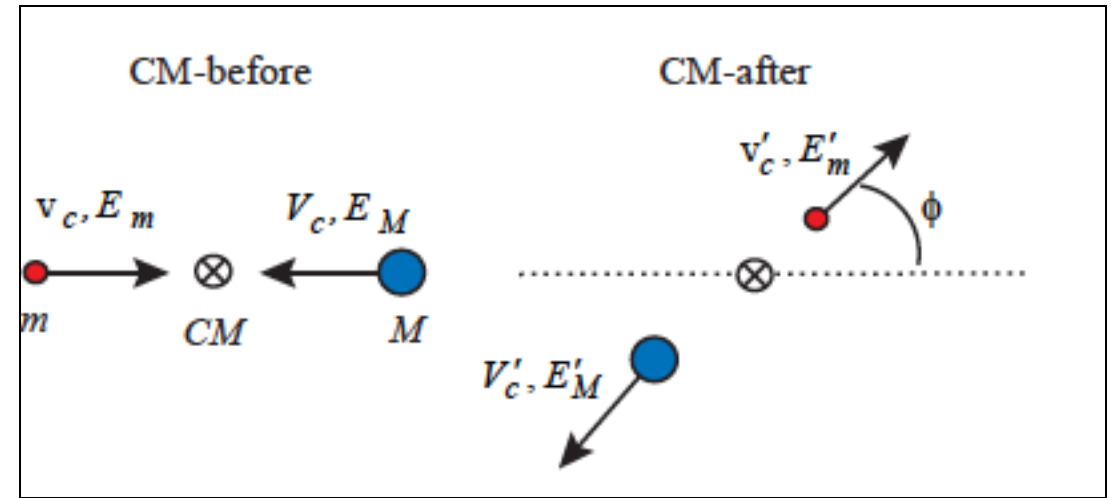


# A visual of a simple two body collision:

Lab coordinates ( $\ell$ ):



Center of Mass Coordinates ( $c$ ):



$m/M$ : mass

$v/V$ : velocity

$E$ : energy

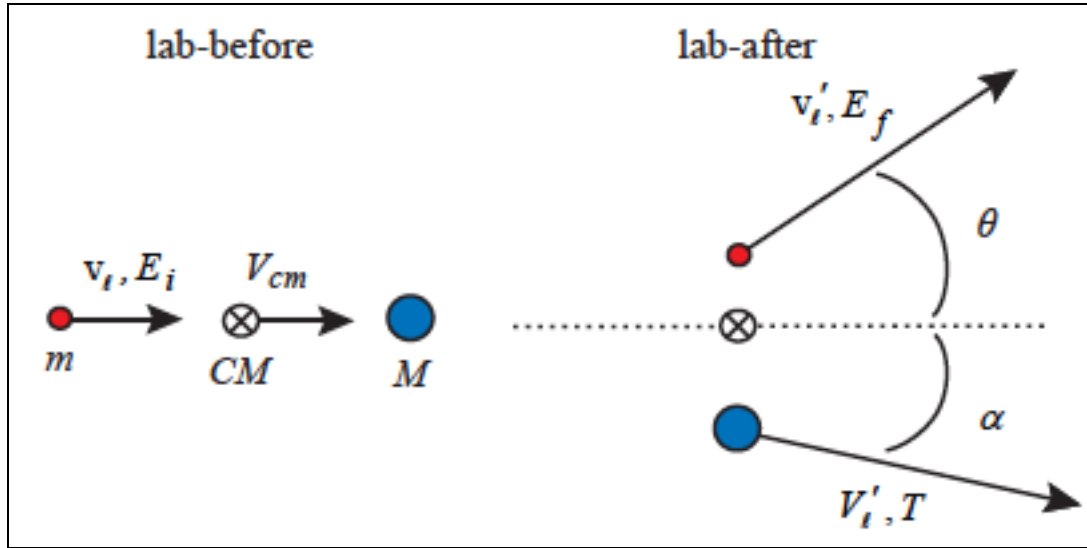
$\theta$ : scattering angle

$\alpha$ : recoil angle in Lab coord.

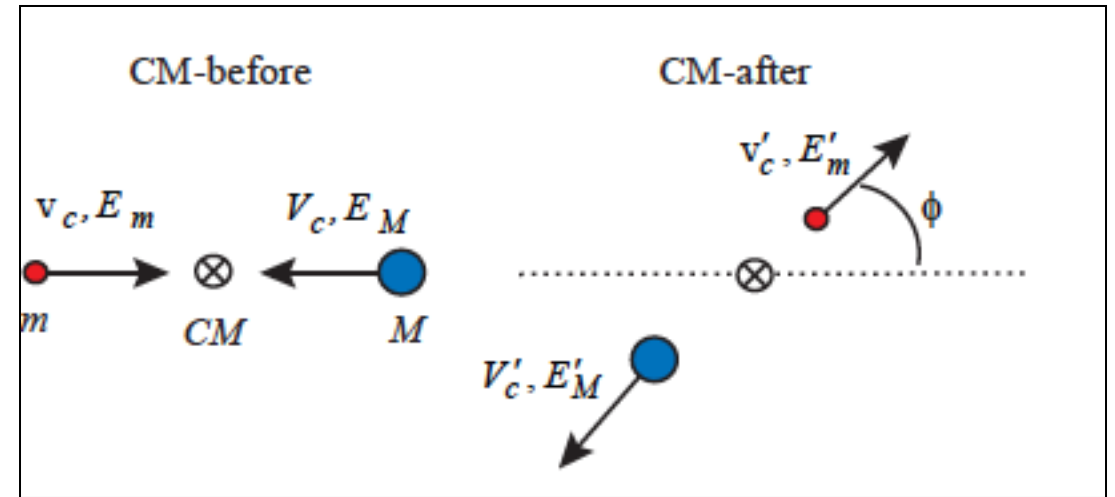
$\phi$ : scattering angle in COM coord.

# A visual of a simple two body collision:

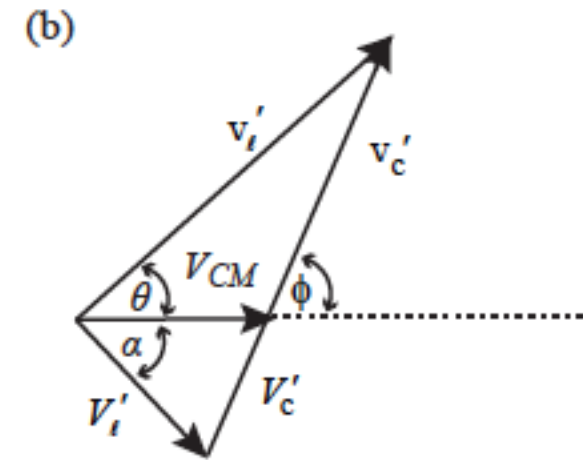
Lab coordinates:



Center of Mass Coordinates

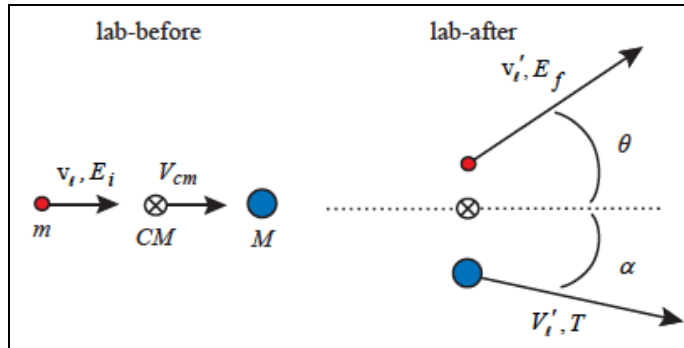


$m/M$ : mass  
 $v/V$ : velocity  
 $E$ : energy  
 $\theta$ : scattering angle  
 $\alpha$ : recoil angle in L coord.  
 $\phi$ : scattering angle in G coord.

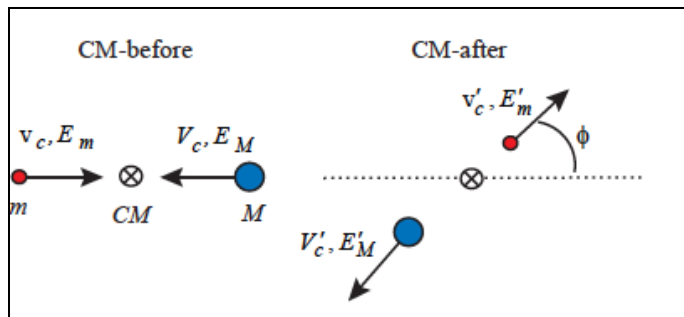


We need to determine  $T$  as a function of initial energy and scattering angle:

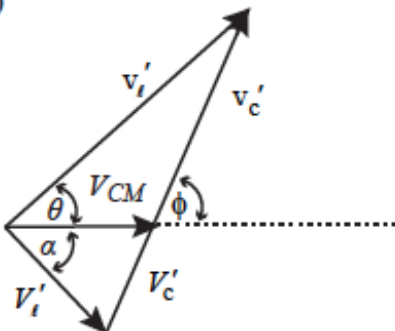
Lab coordinates:



Center of Mass Coordinates



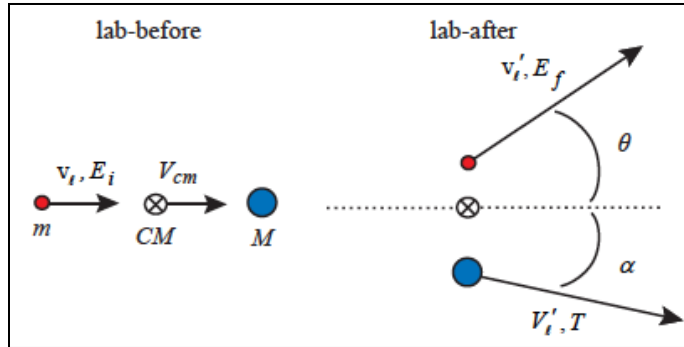
(b)



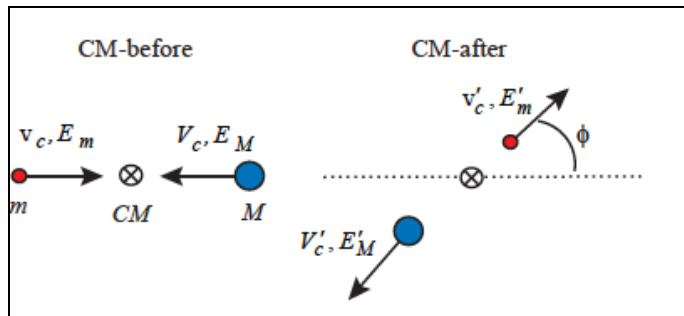
If we assume the CM is stationary in COM coordinates, and  $v'_c$  and  $V'_c$  are in opposite directions but the same plane, we can use our conservation equations to yield:

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

Lab coordinates:



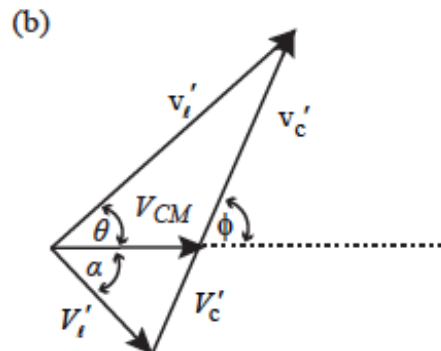
Center of Mass Coordinates



$$\therefore V_c = V'_c \quad v_c = v'_c$$

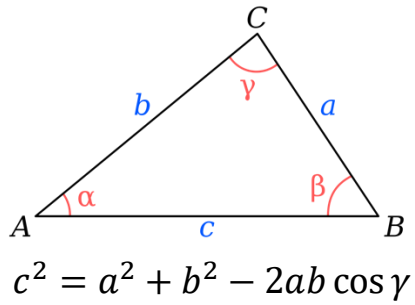
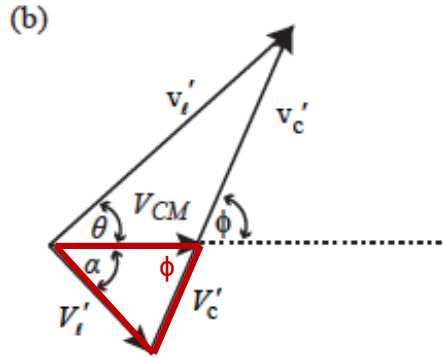
We now need to know how to get  $V_{CM}$  in the lab system:

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:



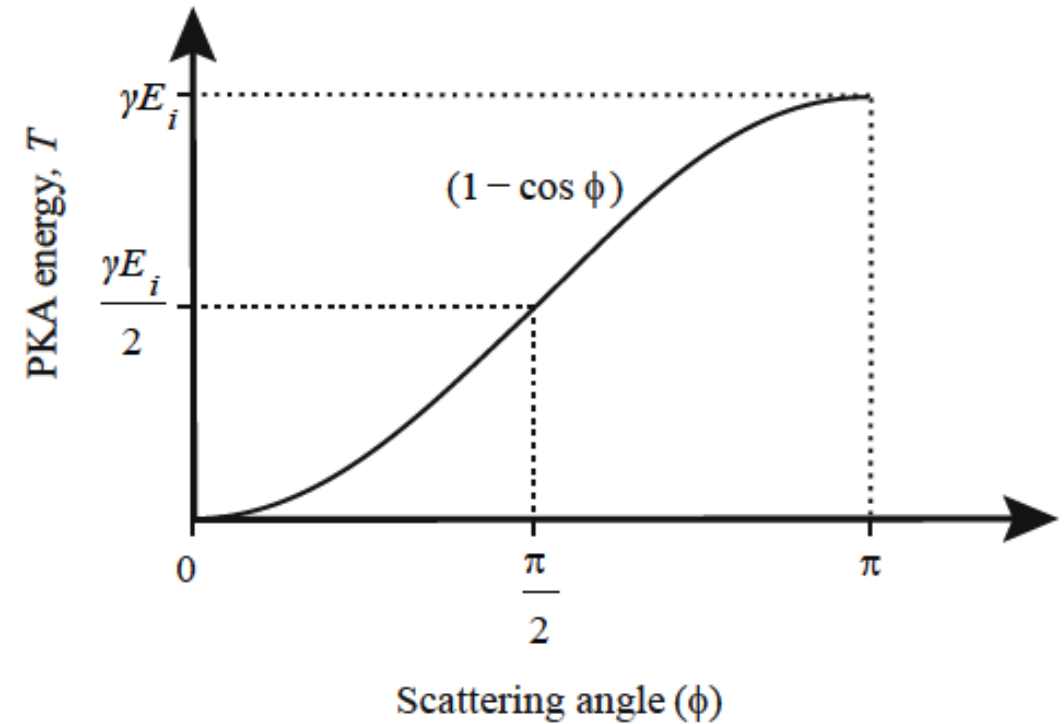
We need to determine  $T$  as a function of initial energy and scattering angle:

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

$$\boxed{V_{cm} = V_c'} \rightarrow V_t'^2 = 2V_{CM}^2 \cos \phi$$

$$V_t'^2 = \frac{2T}{M}$$

$$V_{CM}^2 = \frac{2}{m} E_i \left( \frac{m}{M+m} \right)^2$$

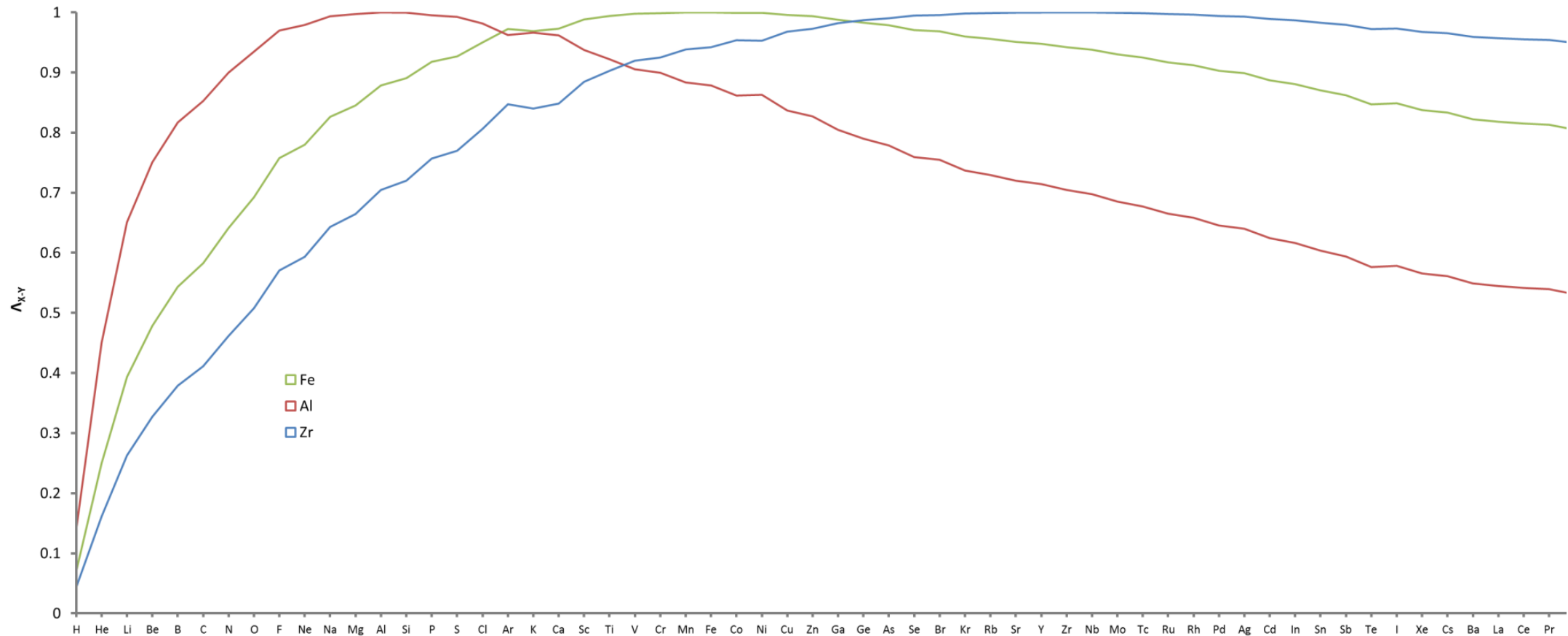


# Example problem:

- 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:

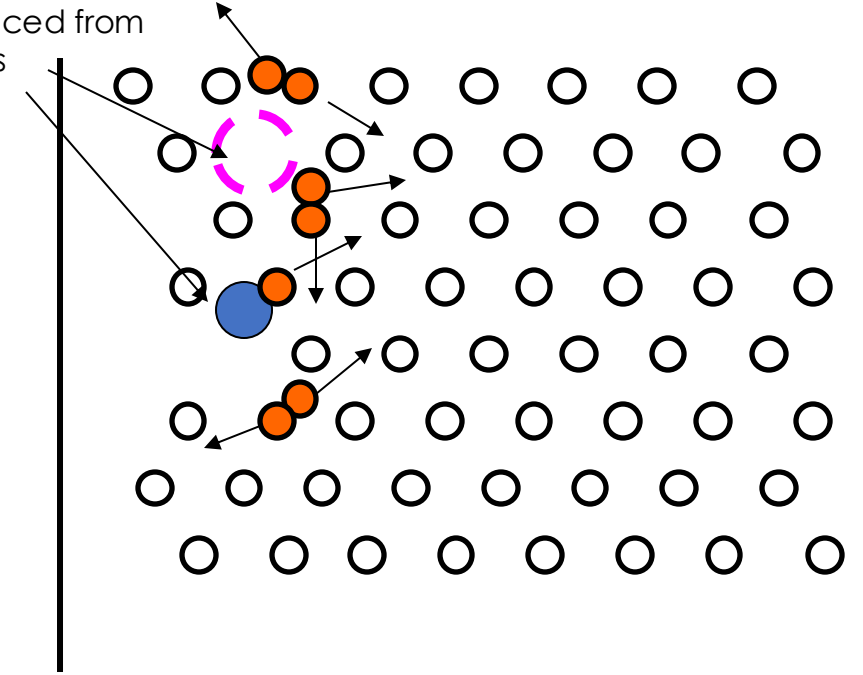
1. Momentum conservation
2. Kinetic energy conservation
3. Velocities in LAB and COM:
4. Cosines law:

$$V_c = V'_c \quad \& \quad v_c = v'_c$$

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

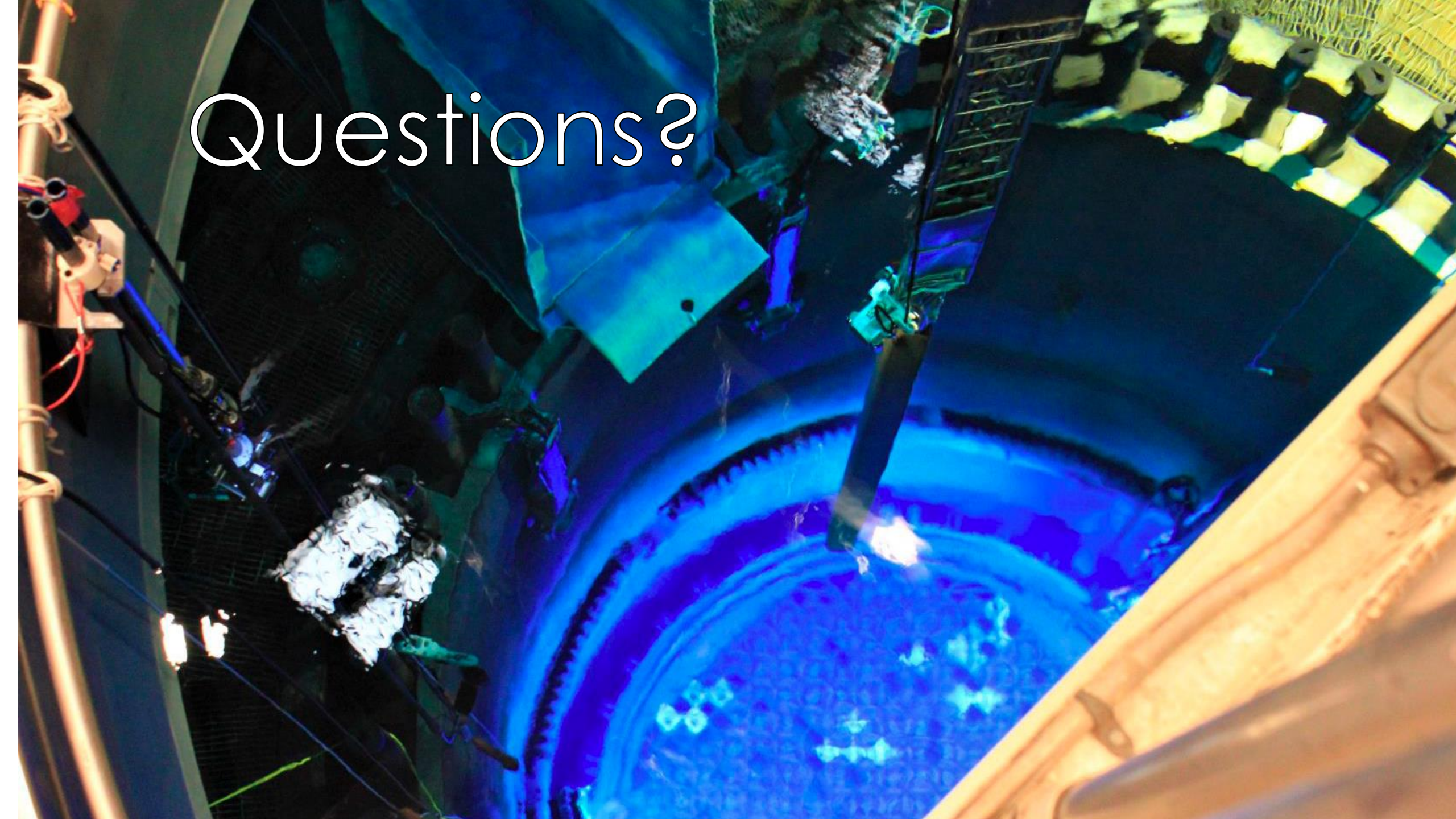
$$V_l'^2 = V_{CM}^2 + V_c'^2 - 2V_{CM}V_c' \cos \phi$$

Defects produced from displacements



T=

Questions?



# Example problem:

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



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