Nuclear Fission Chain Reaction

Nuclear Chemistry

Introduction

From weapons to electrical power generation, the chain reaction of certain radioisotopes has had a profound effect on society and the environment. How do these chain reactions occur and what do they look like? Use the common domino to create a dramatic visual model of this subatomic process.

Concepts

- Fission
- Chain reaction
- Neutron and neutron capture
- Neutron absorbers

Background

Naturally occurring uranium consists primarily of three isotopes, uranium-238, uranium-235, and uranium-234. All three are radioactive and decay by alpha emission.

$$^{238}_{92}U \rightarrow ^{4}_{2}He + ^{234}_{90}Th \qquad \textit{Equation 1}$$

$$^{235}_{92}U \rightarrow ^{4}_{2}He + ^{231}_{90}Th \qquad \textit{Equation 2}$$

$$^{234}_{92}U \rightarrow ^{4}_{2}He + ^{230}_{90}Th \qquad \textit{Equation 3}$$

In 1938, two chemists, Otto Hahn (1879–1968) and Fritz Strassman (1902–1980), discovered that when uranium was bombarded with neutrons, barium was produced. In collaboration with the chemist Lisa Meitner (1879–1968), they correctly interpreted these findings as resulting from the uranium nucleus splitting into smaller pieces, a reaction labeled nuclear fission. It was later determined that of the three isotopes of naturally occurring uranium, only uranium-235 undergoes nuclear fission (Equation 4).

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n + \Delta E \qquad \textit{Equation 4}$$

In this fission process, more neutrons are produced than are needed to start the process. These additional neutrons can then react with other atoms of uranium-235. Any process that creates reactants that can then initiate the process over and over again is called a *chain reaction*. The fission of uranium-235 is highly exothermic and releases about 2×10^{10} kJ/per mole of uranium atoms. This is roughly 25 million times greater than the amount of energy obtained in the combustion of hydrocarbons!

The chain reaction can be terminated in basically two ways. The extra neutrons may be absorbed by other materials before they collide with another uranium-235 atom, or neutrons may simply escape the container without striking another uranium nucleus. If, on average, less than one neutron produced by each fission reaction strikes another uranium atom and "splits" it, then the reactions ends and the process is called *sub-critical*. If the process averages one "active" neutron per fission, it is called a *critical* process. If the reaction averages more than one active neutron per fission, it is labeled a supercritical process.

Naturally occurring uranium contains only 0.72% uranium-235. This concentration is subcritical and no chain reaction can take place with natural uranium. An increase in the concentration of uranium-235 to three to four percent is needed to achieve a critical reaction, and much greater enrichment is needed to reach a supercritical state.

For weapons, the U-235 enrichment needs to be 90% or higher. This concentration allows the fission process to rapidly continue to explosive levels before too many neutrons escape and terminate the chain reaction. For nuclear reactors, three to four percent enrichment allows the reactor to release energy at a controlled rate.

In this demonstration, domino tiles will be used to simulate both the critical process and the supercritical process. Students will time each event and use the data to estimate the relative energy release rates of each process.

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Materials

Domino tiles, 224

Fission tile location template

Stopwatch, 0.1 to 0.01 sec

Safety Precautions

This activity is considered safe. Follow all standard classroom safety guidelines.

Preparation

Prepare two arrangements of 100 domino tiles.

Critical Process

1. Begin laying tiles in a straight row on the demonstration surface. This surface should be stable, flat, and hard. Space the tiles from one-half to three quarters of an inch apart.
2. When a turn is needed, make a 180 degree curve of at least six tiles, with the tiles closer on the inside of the turn than on the outside (see Figure 1).
3. Continue the straight line parallel to the original row. Continue until all the tiles are positioned.

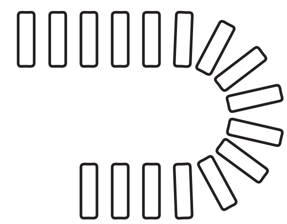


Figure 1.

Supercritical Process

1. Begin by laying out the fission tile location template on the demonstration surface. This surface should be stable, flat, and hard.
2. Place tiles on the designated lines, starting at number one and placing the tiles in numerical sequence. This sequence will minimize the likelihood of accidently knocking over other tiles. Place the tiles *in front of the lines* as they radiate from the center (see Figure 2).
3. Continue until all the tiles are positioned. The tiles that form a straight line to the center are the "initiator" tiles.

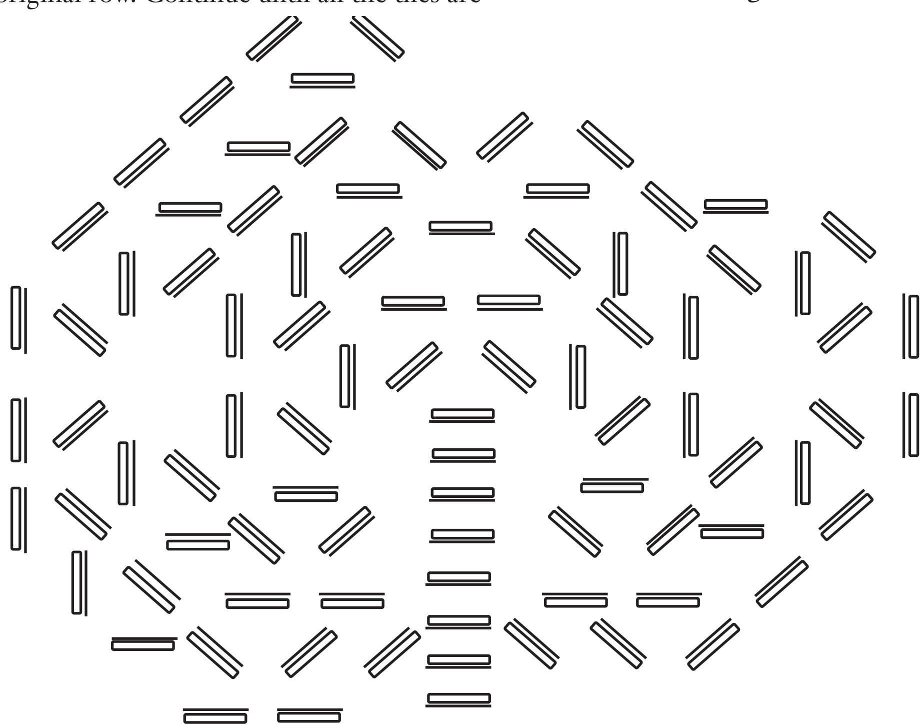


Figure 2.

Procedure

1. *(Optional)* Pass out the demonstration worksheet to each student.
2. Explain to the students that the two domino arrangements represent the two types of nuclear fission chain reactions. The straight-line arrangement will model the critical process, the one used in nuclear reactors. The dense packing arrangement will model the supercritical process, that which occurs in atomic bombs.
3. Before initiating the straight-line chain reaction, alert the students to begin timing when the first domino falls and to stop timing when the last domino falls.
4. Knock over the first tile to start the domino chain reaction. Have the students record the elapsed time in the Data Table.
5. Alert students to be prepared to start timing the supercritical model. Topple over the first "initiator" tile. Start the timing when the first "uranium-235" tile falls. Have students stop timing when all the tiles have fallen. Instruct students to record the time in the Data Table.
6. Have the students calculate the number of tiles toppled per second rate, then answer the *Post-Demonstration Questions*.

NGSS Alignment

This laboratory activity relates to the following Next Generation Science Standards (2013):

Disciplinary Core Ideas: Middle School
MS-PS1 Matter and Its Interactions
PS1.A: Structure and Properties of Matter
PS1.B: Chemical Reactions
Disciplinary Core Ideas: High School
HS-PS1 Matter and Its Interactions
PS1.A: Structure and Properties of Matter
PS1.C: Nuclear Processes
HS-PS3 Energy
PS3.A: Definitions of Energy
PS3.B: Conservation of Energy and Energy Transfer
PS3.C: Relationship between Energy and Forces

Science and Engineering Practices
Developing and using models
Constructing explanations and designing solutions

Crosscutting Concepts
Patterns
Scale, proportion, and quantity
Systems and system models
Energy and matter

Tips

- The nuclear fission domino template is included here in 8½″ × 11″ layout—please enlarge to 11″ × 17″ size by photo copying. Alternatively, call or write to us at Flinn Scientific to obtain a pdf of the 11″ × 17″ layout.
- Practice placing the tiles before attempting the demonstration. Patience may be required to successfully set up all the tiles without knocking them over.
- The dense packing arrangement of tiles yields between one and two tiles per toppled tile. If a unit of time is defined as the time for one tile to topple the next ones in line, then the time needed to topple 100 tiles for the dense packing is 10 units. The first unit topples two tiles, the second unit topples 4, the third topples 6, the fourth 8, the fifth 10, the sixth 12, and so forth. For the straight line, the total time is 100 units, making the dense packing model 10 times more rapid.
- To increase the difference in elapsed time between the two processes, add additional tiles to each setup. 256 tiles would yield a time ratio of 256:17, or 15:1.
- The time for the supercritical process is very quick. Have the students use stopwatches that measure in tenths or hundredths of seconds.

Sample Data Table

Chain Reaction Type	Number of Tiles	Reaction Elapsed Time (sec)	Tiles/second
Critical Process	100	2.24	44.6
Supercritical Process	100	0.41	244

Answers to Worksheet Questions *(Student answers will vary.)*

1. If each tile that is knocked down represents a fission reaction of uranium-235, calculate the energy released per second for each chain reaction process. (The energy released by each fission is 3×10^{-11} J.)

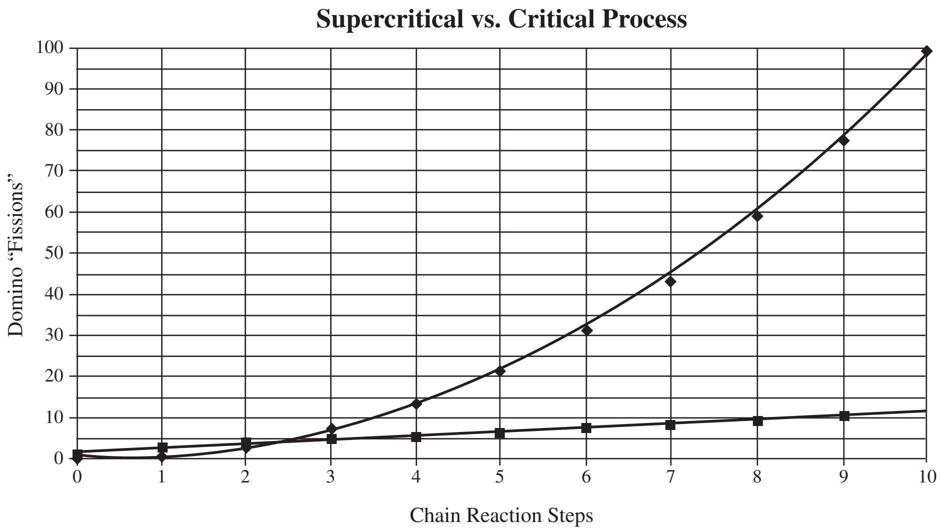
Critical

$$44.6 \text{ fissions/sec} \times \frac{3 \times 10^{-11}\text{J}}{\text{fission}} = 1.34 \times 10^{-9} \text{ J/sec}$$

Supercritical

$$244 \text{ fissions/sec} \times \frac{3 \times 10^{-11}\text{J}}{\text{fission}} = 7.32 \times 10^{-9} \text{ J/sec}$$

2. The graph below represents the total number of tile "fissions" that have occurred for both processes after the first ten chain reaction steps. What happens to the rate of fusion for each process as the chain reaction steps increase?



The rate of fissions will rapidly increase for the supercritical process, but remains the same for the critical process.

3. In the combustion reaction of $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

   the energy released per mole of methane is $212.8 \text{ Kcal} \times \dfrac{4184 \text{ kJ}}{1 \text{ Kcal}} = 890 \text{ kJ}$.

   Calculate the energy released by the fission reaction of 1 mole of uranium-235. How does this compare to the combustion of methane?

$$6.02 \times 10^{23} \frac{\text{atoms}}{\text{mole U-235}} \times \frac{1 \text{ fission}}{\text{atom}} \times \frac{3 \times 10^{-11} \text{ J}}{\text{fission}} \times \frac{1 \text{ kJ}}{10^3 \text{ J}} = 1.8 \times 10^{10} \text{ kJ/mole}$$

$$\frac{1.8 \times 10^{10} \text{ kJ/mole}}{0.89 \times 10^3 \text{ kJ/mole}} = 2 \times 10^7 \text{ more energy released}$$

Flinn Scientific—Teaching Chemistry™ eLearning Video Series

A video of the *Nuclear Fission Chain Reaction* activity, presented by Irene Cesa, is available in *Nuclear Chemistry*, part of the Flinn Scientific—Teaching Chemistry eLearning Video Series.

Materials for *Nuclear Fission Chain Reaction* are available from Flinn Scientific, Inc.

Materials required to perform this activity are available in the *Nuclear Chemistry—Chemical Demonstration Kit* available from Flinn Scientific.

Catalog No.	Description
AP6883	Nuclear Fission—Chemical Demonstration Kit

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.

Nuclear Fission Chain Reaction Worksheet

Chain Reaction Type	Number of Tiles	Reaction Elapsed Time (sec)	Tiles/second
Critical Process	100		
Supercritical Process	100		

Questions

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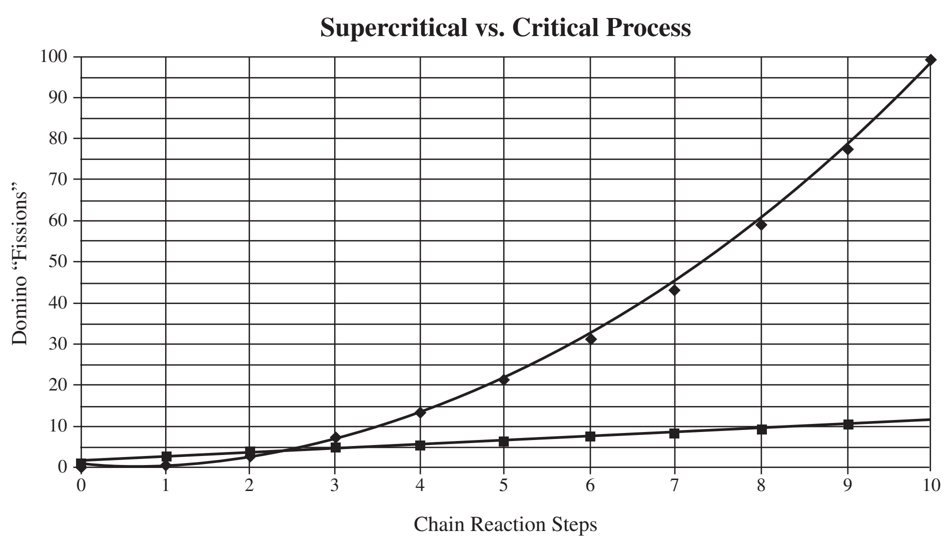
2. The graph below represents the total number of tile "fissions" that have occured for both processes after the first ten chain reaction steps. What happens to the rate of fusion for each process as the chain reaction steps increase?



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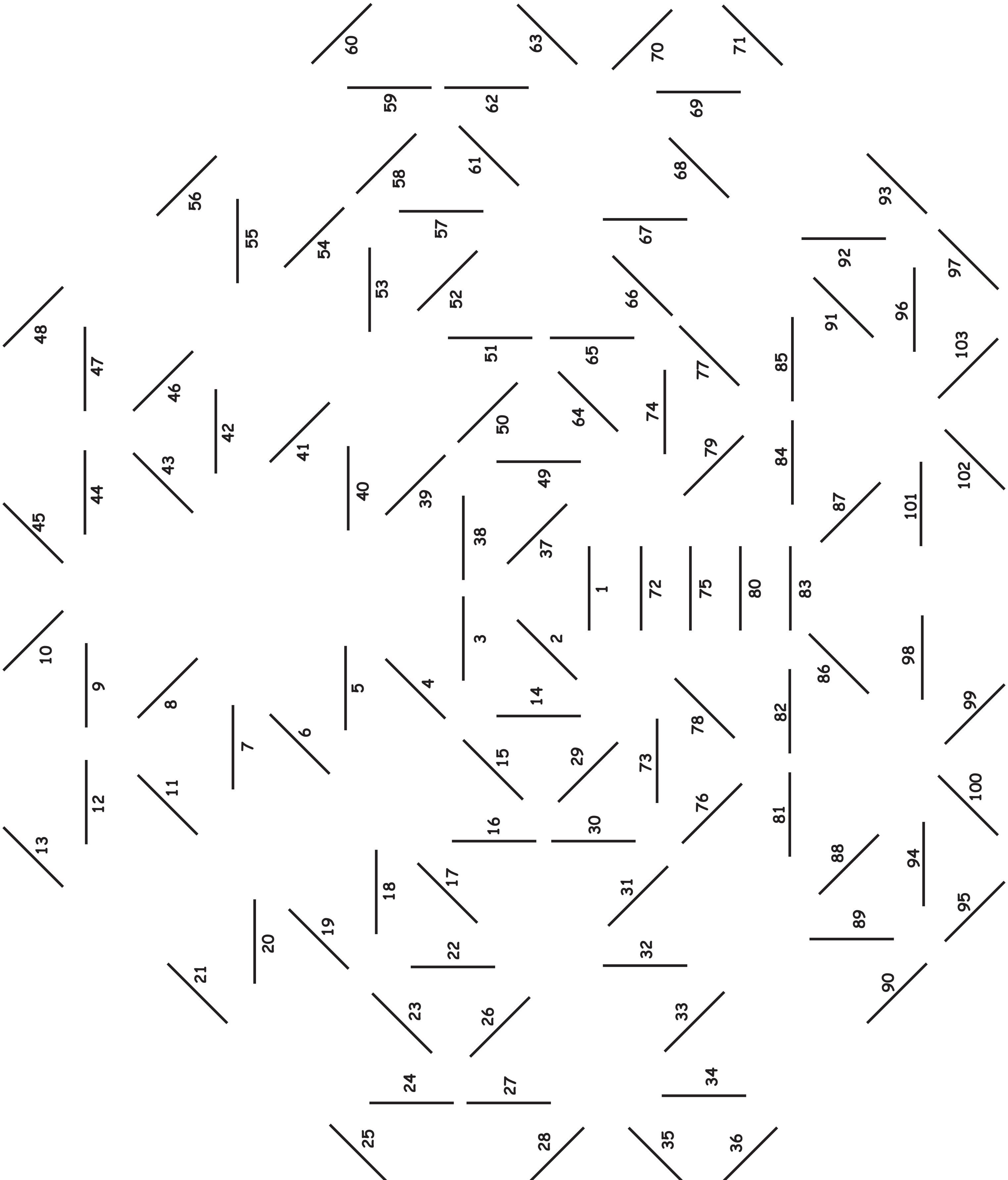
   Calculate the energy released by the fission reaction of 1 mole of uranium-235. How does this compare to the combustion of methane?

Super Critical Process Template



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